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A liquid-solid phase diagram based operational feasibility analysis for three-phase absorption heat storage

Jinfang You,Ruzhu Wang,Zhenyuan Xu

Shanghai Jiao Tong University

Three-phase absorption heat storage (TPAHS) with partial crystallization in absorbent offers substantially enhanced energy storage density and heat exchange performance compared to conventional liquid absorption and solid adsorption systems, respectively. However, the operational feasibility of TPAHS is critically constrained by crystal clogging risks, which has not been thoroughly explored due to the absence of a systematic thermodynamic framework. To delineate the feasible operation scope of TPAHS, this study establishes a liquid-solid phase diagram methodology to illustrate the composition of absorbent in liquid-solid equilibrium state. The crystallization ratio is introduced as a key state parameter to characterize the amount evolution of absorbent crystals through charging, storage, and discharging processes. Applying this proposed methodology to a LiBr-water absorption heat storage system that stores solar heat for space heating, distinct operational regions are identified on the liquid-solid phase diagram, corresponding to different combinations of cycle performance and clogging risk. The graphical results intuitively reveal that short-term condition with elevated storage temperature guarantees high-performance and anti-clogging TPAHS. In summary, this work provides a graphical thermodynamic guideline for the rational design and safe operation of high- performance TPAHS systems.

Key Words Heat storage, Absorption, Liquid-Solid Phase Diagram, Crystal, Crystallization Ratio.

Anti-corrosion, Non-outgassing Coatings for Sorption Vacuum Systems and Sorption Heat Transformer Applications

Neda Afzali,Milad Ebadi,Ilya Girnik,Claire McCague,Majid Bahrami

Laboratory for Alternative Energy Conversion (LAEC), Simon Fraser University (SFU)

Corrosion, and the associated outgassing, create significant challenges in vacuum systems and heat pumps, leading to material degradation, accumulation of non-condensable gases, and reduced system efficiency. These effects are particularly critical in waste-heat driven sorption heat pumps and sorption heat transformer systems, where chloride (Cl^-) contamination originating from sorbent composites can accelerate corrosion of aluminum and stainless steel components in the presence of water vapor.

This study evaluates protective coatings for key components of sorption heat pumps and sorption heat transformer systems, including heat exchangers (evaporator, sorber bed, and condenser) and vacuum chamber walls. Five coatings were applied to Al3003 substrates for heat exchanger applications, while a fusion-bonded epoxy coating (3M Scotchkote 134) was tested on four substrates (Al6061, SS304, SS316L, and carbon steel) for use in vacuum chambers. Coating performance was assessed using accelerated corrosion testing (Modified Acidified Synthetic Sea Water Test, ASTM G85 A3) and outgassing characterization (ASTM E595).

For heat exchangers, powder coating demonstrated the best overall performance, followed by electrophoretic coating and AkzoNobel paint, while chromate conversion and electroless nickel-phosphorous exhibited inferior corrosion resistance, with the latter failing under test conditions. The selected powder coating exhibited low outgassing (Total Mass Loss = 0.38%, Collected Volatile Condensable Material < 0.01%). For vacuum chambers, 3M Scotchkote demonstrated consistent corrosion resistance across all substrates, with slightly reduced performance on carbon steel (Total Mass Loss = 0.54%, Collected Volatile Condensable Material < 0.01%). Prototype level observations indicate improved operational stability and reduced contamination following coating implementation. These findings provide practical guidance for coating selection to enhance durability and maintain performance in sorption heat pumps, sorption heat transformer systems, and other vacuum-based technologies.

Key Words Sorption Vacuum Systems, Corrosion, Non-condensable Gasses, Aluminium, Stainless steel, Chloride, Salt in Porous Matrix

Decoupling quantity and quality in thermal energy storage via a two-stage heat pump

Haotian Lv[1],Rogério Oliveira[2],Xinyi Yang[1],Weishen Zhou[1],Shuai Du[1],Baoshan Xie[3],Ruzhu Wang[1]

1. Institute of Refrigeration and Cryogenics, MOE Engineering Research Center of Solar Power and Refrigeration, Shanghai Jiao Tong University

2. Department of Energy and Sustainability, Federal University of Santa Catarina, Araranguá 88900-000, Brazil

3. School of Energy and Power Engineering, Changsha University of Science & Technology, Changsha 410114, China

Thermal energy storage (TES) faces an inherent trade-off between stored heat quantity and delivered temperature quality: low-melting-point phase change materials (PCMs) offer high energy density but limited output temperature, whereas high-temperature PCMs are constrained by stability, safety, cost, and material availability. Here, this trade-off is decoupled by coupling sodium acetate trihydrate PCM storage at 58°C with a two-stage compression heat pump, enabling heat amplification and temperature upgrading. A central composite design (CCD) with 18 experiments quantified the effects of heat source temperature (3.9–34.1°C), temperature lift (66.6–83.4 K), and charging duration (2.64–9.36 h). The coefficient of amplification (COA) ranged from 1.60 to 2.14, with second-law efficiencies of 25.3–40.4% and repeatability within ±1.4%. Temperature lift was the dominant factor; reducing it from 74.9 to 66.6 K increased COA by 20.2%, whereas heat source temperature had only a weak direct effect. After 24 h standby, COA decreased by 5.3%. Under an extreme condition with a 3.9°C source and 109°C heat output, COA remained 1.44, exceeding a 95%-efficient natural gas boiler by 32.7% in second-law efficiency. The response surface model ($R^2 = 0.91$) and discharge-delay tests indicate that the system can support time-of-use thermal scheduling by shifting electricity consumption to off-peak periods while maintaining high-temperature heat delivery.

Key Words heat pump; latent thermal energy storage; coefficient of amplification; decarbonization

Multi-objective optimization and life cycle assessment of a PV/T assisted dual-source heat pump with PCM for domestic hot water

Longxiao Wei,Baoyue Wang,Lei Wang,Wengang Hao

Yantai university

This study proposes a photovoltaic-thermal assisted dual-source heat pump integrated with phase change material (PVTHP-PCM) for domestic hot water supply in cold regions, aiming to resolve the mismatch between intermittent solar energy and continuous heating demand as well as the conflict between system performance and economic viability. The TRNSYS simulation model of the proposed system is built and validated against experimental data. Orthogonal experimental design and Latin hypercube sampling are used to generate 300 sample points, and four machine learning algorithms are compared to develop a surrogate model, with XGBoost showing the highest prediction accuracy. Multi-objective optimization is then performed using the NSGA-II algorithm to maximize solar fraction and coefficient of performance while minimizing annual cost, followed by TOPSIS for decision-making. In addition, life cycle assessment based on the ReCiPe 2016 method is carried out to evaluate environmental impacts, including sensitivity analyses on climate zone, system lifetime and system configuration. The results show that compared to the initial design, the solar-fraction-optimal solution increases solar fraction by 24.22% and coefficient of performance by 27.95%, while reducing annual cost by 22.45%. The annual average coefficient of

performance of the PVTHP-PCM system reaches 3.65, significantly higher than the 2.29 of a conventional air-source heat pump. Life cycle assessment reveals that the operation phase accounts for 76.35% of the total environmental impact. Relative to the conventional system, the PVTHP-PCM system reduces human health damage by 62.89%, ecosystem damage by 67.18% and resource depletion by 58.36%. In regions with high solar radiation such as Sanya, the system even achieves a negative environmental impact of −11.19 mPt/year, and extending the system lifetime to 30 years cuts the annual environmental impact by 31.12%. Overall, the PVTHP-PCM system offers superior energy, economic and environmental performance for cold climates, and the proposed framework integrating machine learning, multi-objective optimization and life cycle assessment provides a robust design methodology for sustainable domestic hot water systems.

Key Words Photovoltaic-thermal, Dual-source heat pump, Phase change material, Multi-objective optimization, Life cycle assessment, TRNSYS

Potentials of Joule Heating-assisted Pumped Thermal Energy Storage

Jiatong Jiang[1,2],Jian Song[2],Yongliang Li[2],Ruzhu Wang[1]

1. Shanghai Jiao Tong University

2. University of Birmingham

Pumped thermal energy storage (PTES), or Carnot battery technology, has attracted increasing attention as a large-scale and long-duration energy storage solution. In existing Carnot battery studies, additional thermal inputs such as solar heat or industrial waste heat are commonly introduced to reduce heat pump power consumption and compensate for the energy imbalance between charging and discharging cycles, thereby improving round-trip efficiency (RTE). However, for a fully electricity-to-electricity Carnot battery without external thermal input, the inherent mismatch between heat pump charging and Brayton discharge becomes a critical challenge and remains insufficiently understood.

This study investigates a Joule heating-assisted transcritical CO_2 Carnot battery operating without any supplementary heat source. A thermodynamic model was developed for the charging and discharging processes under practical operating constraints, with particular focus on the mismatch caused by thermal storage imbalance. The mismatch arises from unequal thermal exchange between charge and discharge, especially on the hot and cold storage sides, leading to insufficient energy recovery and additional compensation requirements.

Results show that under a representative condition with a low pressure of 8 MPa and a high pressure of 28 MPa, the theoretical RTE reaches 39.7% when the mismatch is neglected. However, when the practical thermal imbalance is considered, direct Joule heating is required to compensate for the energy deficit, reducing the actual RTE to 28.2%. System optimisation further indicates that Joule heating can improve performance when used to elevate the high-temperature thermal storage level rather than replacing heat pump operation. For storage temperatures of 100°C and 300°C, an optimal pressure ratio of 4.0 achieves a peak RTE of 30.6%, while additional EH raising the hot storage temperature to 340°C further improves the RTE to 33.2%.

These findings clarify the thermodynamic limitations of electricity-only CO_2 Carnot batteries and demonstrate the selective role of electric heating in mitigating storage mismatch and enhancing system performance.

Key Words Carnot battery, Joule heating, CO_2 Brayton system, Round-trip efficiency

Next-Step COP Prediction of Air-Source Heat Pumps in Extremely Cold Environments and Energy-Economic Evaluation Based on Predicted Results

Tianhang Zhou[1],Lei Zhuang[1],Saikee Oh[2],Seokhoon Jang[2],Sanghun Lee[2],Jaehong Kim[2],Dongkeun Yang[1],Beomsoo Seo[2],Heejoong Jang[2],Jinho Kim[2],Jian Wu[1]

1. 哈尔滨工业大学

2. LG Electronics Co., Ltd.

This study investigates next-step COP prediction and its engineering application for air-source heat pumps operating in extremely cold environments, where frosting and defrosting processes cause strong COP fluctuations and increase the uncertainty of energy consumption and operating cost evaluation. Winter operating data were collected from the Mohe cold-region heat pump test platform. Four readily available variables, including outdoor air temperature, outdoor heat exchanger temperature, indoor air temperature difference between outlet and inlet, and compressor discharge temperature, were selected as input features. Based on a dataset with a sampling interval of 20 s, a one-step-ahead COP prediction task was established to predict the COP at the next sampling moment. Using LSTM as the baseline model, a CNN-LSTM-Attention model was developed and evaluated with chronologically divided training, validation, and test datasets. The results show that the proposed model can effectively capture the dynamic COP variations during stable heating, frosting deterioration, defrost switching, and recovery stages, and achieves better overall prediction performance than the baseline model. On this basis, the predicted COP sequence was combined with heating capacity, input power, and electricity price to estimate the electricity consumption and operating cost during the winter monitoring period. The economic performance of the air-source heat pump was further compared with electric resistance heating and conventional heating methods. The results indicate that, under the same heating demand, the cold-region air-source heat pump can reduce electricity consumption and operating cost compared with traditional heating approaches, demonstrating its energy-saving potential in severely cold regions. The proposed framework, linking short-term COP prediction, energy consumption estimation, and economic comparison, provides a practical method for evaluating and promoting air-source heat pump applications in extremely cold environments.

Key Words Air-source heat pump; Extremely cold environment; COP prediction; CNN-LSTM-Attention; Energy consumption estimation; Economic assessment; Environmental assessment.

Analysis of a High-temperature $SrBr_2$–H_2O Thermochemical Heat Pump Applied for Industry Heating above 200°C

Ding Lu,Yuxing Liao,Yaran Cao,Maoqiong Gong

Technical Institute of Physics and Chemistry, Chinese Academy of Sciences

Industrial heating processes are important contributors to energy consumption and carbon emissions, making efficient high-temperature decarbonized heating technologies essential for achieving carbon neutrality. Thermochemical heat pumps construct thermodynamic cycles through reversible chemical reactions, enabling the absorption of low-temperature waste heat and the release of high-temperature thermal energy, and thus provide an effective approach for thermal energy upgrading. However, existing studies on salt hydrate working pairs have largely focused on thermochemical heat storage systems, low-temperature applications, and steady-state performance analyses, while overlooking the inherent intermittency of gas-solid reactions and the transient variations in system performance during dehydration and hydration processes.Based on reaction kinetics and energy balance relations, this study develops a mathematical model of a high-temperature $SrBr_2$–H_2O thermochemical heat pump to investigate the dynamic evolution of

dehydration and hydration processes. The dynamic variations in reaction conversion, conversion rate, temperature, and output power during dehydration and hydration are analyzed, and the system performance is evaluated in terms of COP and exergy efficiency. The results show that the system can achieve a temperature lift of approximately 87°C and deliver high-grade thermal energy above 200°C, with COP and exergy efficiency reaching 0.50 and 0.67, respectively. Parametric analysis indicates the existence of a minimum driving heat source temperature, which is positively correlated with the condensation temperature.This study reveals the dynamic heat upgrading mechanism of the $SrBr_2$–H_2O thermochemical heat pump under realistic operating conditions and provides guidance for operating parameter selection, heat source fluctuation response, and control strategy optimization.

Key Words Thermochemical heat pump, Salt hydrate, Dynamic modeling, High-temperature heat upgrading.

Research on Key Technologies for High-Temperature, High-Efficiency Heat Pumps Utilizing Safe and Eco-Friendly Working Fluids

Chaofan Zhou[1,2],Yanchang Song[1],Yu Zhang[1,2],Zhentao Zhang[1]

1. Technical Institute of Physics and Chemistry, CAS

2. 天津科技大学

Efficiently extracting low-grade thermal energy from the ambient environment and converting it into high-grade thermal energy is of vital strategic significance for advancing energy conservation, emission reduction, and the green energy transition. This not only significantly reduces reliance on fossil fuels but also effectively curbs greenhouse gas emissions at the source. To this end, based on a cascade heat pump architecture and multi-temperature zone thermal storage technology, and utilizing safe, eco-friendly working fluids with a low GWP, a theoretical simulation model and an experimental platform were established for this system. By adjusting and calculating different operating conditions, such as the evaporating and condensing temperatures of both the high- and low-temperature stages, a detailed performance analysis was conducted. At an ambient temperature of 25°C, the system successfully achieved a stable output of high-temperature hot water exceeding 140°C while maintaining a COP of 2.2.

Key Words Cascade heat pump; Multi-temperature zone thermal storage technology; Safe and eco-friendly working fluids; Performance analysis

Next-Generation Dew-Point Evaporative Cooling: Overcoming the Air-Loss Penalty for High-Efficiency, Refrigerant-Free Air Conditioning

Ducthuan Bui,Lianchuang Wu,Weijie Zhao,Xialong Li,Duc Thuan Bui

Jiangsu University

This study presents a systematic advancement in dew-point evaporative cooling (DPEC) technology, addressing the fundamental limitations of conventional single-stage M-cycle systems that sacrifice 30–60% of product air to achieve sub-wet-bulb cooling. Through a progression of architectural innovations—from single-stage optimization to two-stage and dual-source configurations—we demonstrate that the air-loss penalty is an architectural, not thermodynamic, limitation. The developed two-stage DPEC distributes cooling load across sequential stages, preserving 88–90% of product air while achieving a coefficient of

performance (COP) of 10.6–14.2 and wet-bulb effectiveness up to 129%. Exergy analysis reveals a second-law efficiency of 70–74%, significantly surpassing the single-stage M-cycle benchmark. The dual-source dew-point evaporative cooler (DSDPEC) represents the paradigm shift: by employing a novel -B-A-B-C-B-A- channel arrangement that physically isolates the process air stream, the system achieves 100% product air preservation with wet-bulb effectiveness of 128%, peak cooling capacity exceeding 5.2 kW, and an exergy efficiency of 89%. For humid climates, a fully integrated 3D numerical model coupling a desiccant wheel with the two-stage DPEC demonstrates electrical COP of 8–40 and thermal COP up to 1.35, effectively decoupling latent and sensible cooling. Global climate simulations confirm robust performance across diverse regions, with COP reaching 160 in hot-dry climates and 40–45 in humid tropics. This work establishes evaporative cooling as a viable, refrigerant-free alternative to vapor-compression systems, offering significant potential for building decarbonization and 100% fresh air ventilation without energy penalties.

Key Words Evaporative Cooling, Dew-Point Cooler, Maisotsenko Cycle, Refrigerant-Free Cooling, COP, Energy Efficiency, Sustainable Cooling, Low-GWP Alternatives.

Elastocapillary Modelling in Micro-Structured Porous Media Next to A Flat Surface

Niloofar Mokhtari,Milad Ebadi,Majid Bahrami

Simon Fraser University

Flexible wick structures (ideally cylinders with zero contact angle) have applications in thermal management, metal brazing, fabric dying and biological liquid-transport phenomena where liquid spreading and replenishment affect mass and heat transfer characteristics. Existing models for capillary rise, such as those developed by Princen [1] for two adjacent cylinders and a cylinder near a flat surface, assume rigid cylinders configurations; however, in flexible micro-arrangements, capillary-induced forces [2] can cause structural deflection and alter the meniscus shape along the capillary height and ultimately, heat and mass transfer properties.

This study presents a new coupled elastocapillary model for an array of slender flexible cylindrical microstructure adjacent to a flat surface (Fig. 1a, 1b). This framework extends rigid capillary rise models by incorporating structural deflection of the cylinders, under the lateral capillary forces and axial pretension force. The present model predicts the variation in gap-spacing, and capillary rise for a specific pitch, initial gap, pretension and length of cylinders. The proposed model will be validated through experimental measurements. The results can be used to investigate the effect of pretension on heat and mass transfer properties.

The predicted cylinder deflection profiles for three different initial gaps are shown in Fig. 2a, showing inverse relation of initial gap to total deflection of the cylinders. Figure. 2b shows the effect of strain and initial gap on normalized deflection of cylinders. Elastocapillary effect can reduce the cylinders gap up to 90%, suggesting that, neglecting structural elasticity in heat and mass transfer can underestimate ultimate capillary rise, and overestimate the critical heat transfer in compliant systems.

Key Words Capillary Rise, Capillary Forces, Axial tension, Heat Transfer

Compact Transient model of a sorption heat transformer for district energy network applications

Thanh Dat Phan,Salman Hassanabadi,Ilya S. Girnik,Milad Ebadi,Majid Bahrami

Simon Fraser University

The increasing global demand for air conditioning is driving significant growth in electricity consumption, particularly in developing regions [1]. Sorption-based thermal systems, such as sorption chillers, offer a promising alternative by utilizing low-grade heat sources, including industrial waste heat, while operating with natural refrigerants and minimal electrical input [1-2].

This study presents a new dynamic lumped-capacitance model for a sorption heat transformer prototype developed in our lab, as shown in Fig 1.

The model represents heat transfer processes using a thermal resistance–capacitance network [1], where thermal masses of system components are treated as capacitances and heat transfer paths as thermal resistances. This approach provides a computationally efficient framework suitable for performance analysis and control-oriented applications.

Model validation is conducted against experimental data obtained from our small-scale prototype tested at Burnaby City Hall, operating under inlet temperatures of 21.17°C (chilled water), 34.14°C (cooling water), and 79.44°C (hot water). Each sorber bed contains 0.75 kg of silica gel grace as the adsorbent and operates with a 12-minute cycle time. Simulation results show good agreement with experimental measurements for outlet temperatures across all components, as shown in Fig. 3. The predicted COP and SCP values are consistent with experimental data, with an average relative difference of 2.13 % and 4.48 %, respectively.

Key Words Lumped capacitance model, District energy systems, Sorption heat transformer

Model Predictive Control for COP Optimization of a Transcritical CO_2 Heat Pump with Flash Tank Vapor Injection

Luigi Fusco[1],Giulio Lenzi[2],Michele Manno[1],Stefano Mazzoni[1]

1. University of Rome Tor Vergata

2. Officine Mario Dorin S.p.A

Transcritical CO_2 heat pump systems have gained increasing attention as an environmentally sustainable alternative to conventional HFC-based systems, owing to the favorable thermodynamic properties of CO_2 and its negligible environmental impact. Among the various cycle configurations, the Flash Tank Vapor Injection (FTVI) cycle offers enhanced heating capacity and improved COP by injecting a vapor mass from the flash tank directly into the compression chamber through a solenoid valve. In such systems, the discharge pressure remains the dominant parameter governing system performance, and its real-time optimization under variable boundary conditions represents a key control challenge. Conventional PID-based controllers require a target setpoint for the discharge pressure; however, such a setpoint is typically derived from empirical correlations that may not correspond to the true optimal value under off-design conditions, motivating the development of more advanced control strategies. In previous work, the authors developed a dynamic model of the FTVI cycle in the MATLAB/Simulink environment and implemented an Extremum Seeking Control (ESC) strategy to optimize the discharge pressure. Building on this foundation, the present work exploits the same dynamic model to implement a nonlinear Model Predictive Control (MPC) strategy, with the aim of assessing its performance and comparing with the ESC results. During a pre-processing phase, a four-dimensional Look-Up Table (LUT) is generated from steady-state simulations of the dynamic model of the FTVI cycle, mapping the system COP as a function of discharge pressure, water inlet temperature, water temperature rise, and ambient air temperature. At each time step, the nonlinear MPC controller takes these four operating parameters as inputs, along with the current measured COP, and solves a receding horizon optimization problem to compute the optimal discharge pressure that maximizes the system COP under the current off-design operating conditions. The overall control architecture also includes three additional PID controllers, responsible for regulating the water temperature difference across the gas cooler, the air temperature difference across the evaporator, and the refrigerant superheating degree. Furthermore, the optimal discharge pressure computed by the MPC is used as a setpoint for an additional PID controller, which tracks the measured discharge pressure by acting on the opening of the back-pressure valve located downstream of the gas cooler. The results show that the MPC achieves more accurate results compared to the ESC, identifying the exact optimal discharge pressure values and consequently the

maximum COP. On the other hand, the MPC requires a higher computational effort during the pre-processing phase and delivers accurate results only when no component performance degradation is present. Therefore, future work will be dedicated to evaluating the controller under degraded component conditions, for instance by simulating a progressive increase in the fouling factor of the heat exchangers, in order to assess its performance and operational limits. In this context, a fifth input parameter describing the performance degradation of a specific component — such as the gas cooler — could be introduced to extend the applicability of the MPC framework.

Key Words COP, CO_2, FTVI, MPC, Transcritical cycle

Dynamic Modeling of a Transcritical CO_2 FTVI Heat Pump with Custom Simscape Components: System Regulation under Variable Hot Water Production Draw-Off Conditions

Luigi Fusco[1],Giulio Lenzi[2],Michele Manno[1],Stefano Mazzoni[1]

1. University of Rome Tor Vergata

2. Officine Mario Dorin S.p.A

Growing concerns over climate change and the phase-down of high-GWP refrigerants under the Kigali Amendment have accelerated the adoption of natural refrigerants in heating applications. Among these, CO_2 (R744) stands out for its negligible global warming potential (GWP = 1), zero ozone depletion potential (ODP = 0), non-flammability, and favorable thermodynamic properties at high delivery temperatures. Transcritical CO_2 heat pump cycles reject heat at supercritical pressure through a gas cooler — rather than a condenser — exploiting the large temperature glide of CO_2 above the critical point to achieve high delivery temperatures with competitive efficiency. The flash tank vapor injection (FTVI) architecture further enhances this cycle by throttling the refrigerant to an intermediate pressure into a flash tank, from which saturated vapor is drawn off and injected into the compression chamber around bottom dead centre, thereby increasing both heating capacity and COP over a wide range of operating conditions, making it particularly suited for hot water production applications. Dynamic simulation of such systems, however, presents modeling challenges that the Simscape standard component libraries are ill-equipped to address. The gas cooler operates in a thermophysical regime dominated by strongly non-linear CO_2 properties near the pseudocritical point, where standard heat transfer formulations break down. At the same time, the stratified storage tank introduces time-varying thermal boundary conditions that couple directly to refrigerant-side transients, while the cold-side thermal storage adds a further layer of dynamic complexity through its charge and discharge cycles. Capturing these interactions with sufficient fidelity requires purpose-built component models that go beyond what general-purpose Simscape simulation libraries provide. Building on previous work by the authors — which developed a dynamic model of the reciprocating compressor with vapor injection, the FTVI dynamic model, and a segmented shell-and-tube gas cooler with explicit treatment of CO_2 thermophysical variations near the pseudocritical point — this paper extends the simulation platform by introducing two original custom Simscape components: a stratified hot-water storage tank based on a 1-D multi-node architecture with effective destratification conductivity and thermal losses, and a packed-bed phase-change material (PCM) thermal energy storage unit for the cold side, implementing the 1-D Schumann framework with an effective heat capacity formulation to encode the latent heat of the encapsulated PCM. Together, these additions complete a full-system dynamic model capable of simulating the coupled thermal-hydraulic behavior of the FTVI heat pump with both hot water production and cold-side thermal energy storage. The platform is then used to assess cascaded PI control strategies under realistic off-design transient conditions, evaluating system-level performance metrics including COP and temperature delivery compliance.

Key Words CO_2, FTVI, Heat Pump, Stratified Tank

An Iterative Optimization Strategy for Heat Pump System Energy Efficiency via iTransformer-Guided Genetic Algorithm with Search Space Narrowing

HengdaCHENG[1],HuanxinCHEN[1],XiangdongCHENG[2]

1. Huazhong University of Science and Technology

2. Wuhan Textile University

1. Introduction and Objectives

Heat pump systems constitute a significant component of building energy consumption, and advanced optimal control is crucial for improving their efficiency. Traditional model predictive control and metaheuristic methods often suffer from prediction inaccuracies, premature convergence, and the difficulty of maintaining heating/cooling capacity while minimizing energy use. This study proposes an integrated data-driven framework that combines accurate state forecasting based on iTransformer with iterative genetic algorithm with search space narrowing to maximize the coefficient of performance (COP) and reduce total power consumption under tight operational constraints.

2. Methodology

The framework consists of three core modules (Fig. 1): an EnergyPlus simulation model of an actual heat pump station, an iTransformer-based forecasting module, and a genetic algorithm (GA) optimizer with iterative search space narrowing.

Fig 1. Schematic of the proposed iterative optimization framework. The simulation module provides operational states x for given control parameters u; the iTransformer predicts capacity Q(u,x) and power P(u,x) to guide the GA optimization**[Figures included in the extended abstract file]**.

The iTransformer model embeds the full time series of 10 physical variables (temperatures, flow rates, power, etc.) as independent tokens, allowing the multi-head attention to capture inter-variable dependencies while the feed-forward network learns sequential patterns. This forecasting method provides highly reliable predictions of cooling demand and heat pump power under varying control schedules.

The GA adjusts four parameters: chilled water supply temperature, condenser water outlet temperature, chilled water flow ratio, and condenser water flow ratio. The optimization problem minimizes a weighted sum of capacity deviation and power consumption while respecting predefined bounds. An iterative search space narrowing strategy is applied: starting from a rule-based schedule, each iteration generates tightened bounds around the smoothed schedule from the previous iteration (bound width narrowed by factor narrow rate(NR)). After GA optimization, a moving-window smoothing (5 steps) produces the reference for the next round. This iterative optimization strategy refinement balances global exploration and local exploitation, preventing premature convergence and reducing fluctuations in control schedule.

Fig.2 shows a schematic of the iterative optimization strategy. The different gradations of gray represent the progressively refined search ranges across the first to 4th iterations. The curves labeled as Sch-1-Sch-4 depict the optimization results of all 4 iterations.

Fig 2.Schematic of the iterative optimization strategy**[Figures included in the extended abstract file]**.

3. Results and Discussion

The framework was tested for a one-week period in cooling mode. The iTransformer model achieved near-perfect accuracy during optimization (R^2>0.999 for both cooling demand and power), confirming its strong generalization. Table 1 summarizes the performance of the heat pump unit.

Table 1. Performance improvement over baseline (heat pump unit level, current simulation)**[Table included in the extended abstract file]**.

The iterative optimization progressively improved both COP and power consumption. The final schedule (GA-Sch4) raised the unit COP by about 5% and saved over 2200 kWh over the week, while

cooling capacity was maintained within 1.6–2.5% of demand. At the plant level (including pumps and cooling tower), the COP increased from 3.9 (baseline) to 4.4. The iterative narrowing strategy also enhanced operational stability: the maximum COP degradation rate (MCDR) dropped to 1.06% at the unit level and 0% at the plant level in the final iteration, indicating a low risk of efficiency penalty during the week.

4. Conclusions

The proposed iTransformer-guided GA with iterative search space narrowing significantly boosts heat pump system efficiency under rigorous capacity constraints. The method achieves up to 5% unit-level COP improvement and 10% plant-level energy savings compared to a fixed-parameter baseline, with excellent prediction accuracy and better operation stability. The framework is compatible with existing building automation systems and model predictive control architectures. Future work will extend validation to heating conditions and incorporate fault-tolerance mechanisms.

Keywords: Heat pump system, genetic algorithm, iTransformer model, data-driven forecasting, iterative optimization, energy efficiency, intelligent control

关键词 Heat pump system, genetic algorithm, iTransformer model, data-driven forecasting, iterative optimization, energy efficiency, intelligent control

Primary Energy and Economic Evaluation of Air-Source Heat Pump Heating Systems in Extremely Cold Regions: Field Evidence from Mohe and Harbin

Lei Zhuang[1],Tianhang Zhou[1],Saikee Oh[2],Cheunghyun Bae[2],Bongsoo Choi[2],Eunjun Cho[2],Seongmin Jang[2],Junho Hwang[2],Seungtaek Oh[2],Yeoji Jung[2],Zhiying Zheng[1],Jian Wu[1]

1. Harbin Institute of Technology

2. LG Electronics Co., Ltd.

Air-source heat pumps are considered a promising clean heating technology for cold and severe-cold regions, yet their energy-saving and economic advantages under extremely low ambient temperatures remain uncertain. This study evaluates air-source heat pump heating systems over the entire heating season in Mohe and Harbin, two representative cold-climate cities in northern China. Based on long-term field measurements, the measured heating output of the heat pump was taken as the equivalent useful heating demand of the building. Under the same heating demand, the primary energy consumption of coal-fired heating, gas-fired heating, and direct electric heating was calculated using a primary energy conversion method and compared with that of the heat pump system. Outdoor temperature bins were further used to quantify energy performance under different low-temperature conditions, with particular attention to extremely low ambient temperature ranges. This analysis was conducted to examine whether the heat pump system could maintain primary energy-saving advantages as outdoor temperature decreased. In addition, a simplified economic analysis was performed by comparing the operating cost and unit heating cost of different heating methods. The results provide field-based evidence for assessing the feasibility of air-source heat pump applications in extremely cold regions and offer practical references for clean heating technology selection in northern China.

Key Words Air-source heat pump; Extremely cold region; Primary energy consumption; Economic analysis

Performance Analysis of Dual-Suction Refrigeration Cycle for Dual-Compartment Refrigerators

Shangyu Sun,Guoyuan Ma,Shuxue Xu,Weilai Rong,Haoyan Chai

Beijing University of Technology

Driven by carbon neutrality and energy-efficiency requirements, household dual-temperature refrigerators urgently need low-GWP refrigerants and compact cycle designs. Conventional single-compressor cycles have difficulty matching the different evaporation temperatures required, which increases irreversible losses. This study proposes a modified refrigeration cycle using a dual-suction compressor. A thermodynamic model is developed to compare the proposed cycle with the conventional cycle under different conditions. The results show that the proposed cycle allows the two evaporators to operate at their respective evaporation temperatures, thereby achieving higher energy efficiency. This work provides a potential design solution for efficient, environmentally friendly, and low-cost refrigerator systems.

Key Words Dual-compartment refrigerator, Dual-suction compressor, Energy efficiency

ReaxFF Molecular Dynamics Study on Oxidative Combustion Characteristics of R-32/R-1233zd(E) Blends

Hao Yang[1],Zijian Lv[1,2],Tingxiang Jin[1,2],Yubo Chen[3]

1. Zhengzhou University of Light Industry

2. Henan International Joint Laboratory of Energy Efficient Conversion and Utilization, Zhengzhou 450002, Henan, China

3. Key Laboratory of Agricultural Products Low Carbon Cold Chain, Ministry of Agriculture and Rural Affairs, Tianjin University of Commerce Tianjin 300134, China

With the continued phase-down of high global warming potential working fluids, low-GWP alternatives have received increasing attention in heat pump and refrigeration systems. R-32 is regarded as a promising alternative working fluid because of its relatively low GWP, favorable thermophysical properties, and high system performance. However, R-32 is classified as a mildly flammable A2L refrigerant, and leakage under accidental conditions may still lead to fire hazards when exposed to hot surfaces, electric sparks, or other ignition sources. R-1233zd(E), as a typical HCFO working fluid with zero ODP, low GWP, and non-flammable characteristics, has shown application potential in heat pump and organic Rankine cycle systems. Owing to the presence of Cl and F atoms in its molecular structure, R-1233zd(E) may affect the radical evolution, halogen-containing product formation, and carbon oxidation pathways of R-32 under high-temperature oxidative environments. Therefore, understanding the influence of R-1233zd(E) on the high-temperature reaction behavior of R-32 is important for evaluating the safety of low-GWP working fluids in heat pump applications.

In this study, ReaxFF reactive molecular dynamics simulations were performed to investigate the effect of R-1233zd(E) on the high-temperature oxidative combustion characteristics of R-32. The R-1233zd(E)/R-32/O_2 system was constructed to examine two key factors: temperature and composition ratio. For the temperature effect, the R-1233zd(E)/R-32 ratio was fixed at 80:100, while the temperature was varied from 1000 to 3000 K (Step500 K). For the composition effect, the temperature was fixed at 2500 K, and different R-1233zd(E)/R-32 ratios were considered. The temporal evolution of R-32, major products, and key radicals was analyzed to clarify the molecular reaction mechanism.

The results indicate that R-1233zd(E) alters the oxidative combustion behavior of R-32 through halogen-containing radical pathways. With increasing temperature, the decomposition of both R-32 and R-1233zd(E) is enhanced, resulting in a larger radical pool and faster oxidative reaction progress. The increased concentrations of H, OH, O, F, Cl, and CF_3 radicals promote the formation of HF, HCl, COF_2, CO, and CO_2. Among these products, HCl formation confirms that chlorine-containing fragments released from R-

1233zd(E) participate in reactions with hydrogen-containing active species, thereby modifying the chain-radical environment. The rapid generation and subsequent consumption of CF_3 radicals suggest that fluorinated carbon fragments are not stable end products, but key intermediates that further transform into COF_2, CO, and CO_2 through oxidation reactions. At 2500 K, increasing the R-1233zd(E) content further changes the reaction network and product distribution, as shown in Fig. 1. Under the present simulation setup, the amount of O_2 was adjusted according to the complete oxidation requirement of both refrigerants; therefore, a higher R-1233zd(E) ratio also increases the total molecular number and the number density of the system. The increased number density enhances molecular collision frequency and raises the probability of reactive encounters among R-32, O_2, and radical fragments generated from R-1233zd(E). Meanwhile, the decomposition of R-1233zd(E) introduces additional Cl-, F-, and CF_3-containing fragments, which further participate in hydrogen abstraction, formation of halogen-containing products, and carbon oxidation reactions. As a result, the yields of HF, HCl, COF_2, and CO increase, whereas CO_2 formation does not increase proportionally with the R-1233zd(E) content, indicating that a higher R-1233zd(E) content changes the competition between complete oxidation and the formation of fluorinated carbonyl intermediates.

Fig. 1. Effect of R-1233zd(E)/R-32 ratio on the evolution of major products and radicals at 2500 K.

In conclusion, R-1233zd(E) significantly affects the high-temperature oxidative combustion behavior of R-32 by altering radical evolution and halogen-containing reaction pathways. Increasing temperature mainly enhances the overall reaction intensity, promoting refrigerant decomposition, radical generation, and the formation of HF, HCl, COF_2, CO, and CO_2. In contrast, increasing the R-1233zd(E) content mainly changes the product distribution and oxidation routes. Chlorine-containing fragments from R-1233zd(E) participate in reactions with hydrogen-containing radicals, leading to HCl formation and modifying the chain-radical environment. Fluorinated carbon fragments, especially CF_3-related species, contribute to the formation of HF and COF_2 and further convert to CO and CO_2. These results indicate that the role of R-1233zd(E) is not merely associated with thermal decomposition behavior, but with the regulation of radical chemistry and oxidation pathways of halogen-containing intermediates, providing molecular-level support for the safety assessment of R-32-based low-GWP working fluids.

Key Words R-1233zd(E); R-32; oxidative combustion; heat pump; low-GWP working fluid

Optimal Operating Strategy for a Low-Temperature Regeneration Heat Pump-Desiccant Dehumidification

Kijeong Seo,Jongjin An,Minsung Kim

Chung-Ang University

Dehumidification is an important process in building air-conditioning systems because it directly affects indoor thermal comfort and energy consumption. Conventional cooling-based dehumidification requires a low evaporating temperature to remove latent heat, which reduces system efficiency and increases reheating demand. As an alternative, desiccant wheels using solid desiccants have attracted attention. In particular, super desiccant polymer (SDP) can be regenerated at a relatively low temperature of approximately 50–60°C, which makes it suitable for regeneration using the condenser heat of a heat pump. In this study, a simulation model of a heat pump hybrid desiccant dehumidification system was developed by coupling a one-dimensional transient desiccant-wheel model with a vapor-compression heat-pump cycle model. The system performance was analyzed according to the heat exchanger arrangement and operating conditions. Four configurations were considered by placing the evaporator and condenser either upstream or downstream of the desiccant wheel, which alters the process and regeneration inlet states and thus the coupled adsorption–desorption behavior within the rotor. The system performance was evaluated using DCOP, MRC, and SMER under different compressor speeds and outdoor air temperatures. The results showed that placing the evaporator upstream of the process side and the condenser upstream of the regeneration side simultaneously reduced the process moisture load and enhanced the desorption driving force, yielding the highest dehumidification performance. Based on this most favorable arrangement, performance maps were obtained with respect to the compressor speed and desiccant wheel cycle time. The maps were used to identify suitable operating conditions considering both dehumidification performance and system efficiency. This study provides a basis for the design and operation of heat pump hybrid desiccant

dehumidification systems.

Key Words Desiccant dehumidification, Super desiccant polymer (SDP), Heat pump, Desiccant wheel cycle time.

Agentic Generative AI for Frontier Heat Pump Innovation

Hanlong Wan Southwest

Jiaotong University

Heat pumps are a key technology for decarbonizing buildings, industry, and thermal infrastructure, but their next stage of development requires rapid innovation across system design, refrigerants, controls, simulation, commissioning, and field operation. Conventional heat pump research often relies on separated workflows: engineers build component or system models, manually tune control logic, run simulations, interpret results, and then translate findings into design or operational decisions. As heat pump systems become more complex, involving low-GWP and natural refrigerants, cold-climate operation, high-temperature applications, hybrid thermal systems, storage, and grid-interactive control, this fragmented workflow can limit the speed and scalability of innovation.

This presentation introduces agentic generative artificial intelligence as a frontier approach for heat pump research and deployment. Unlike a standalone language model that only provides text responses, an AI agent can plan tasks, call engineering tools, generate and revise code, interact with simulation engines, inspect outputs, preserve workflow state, and request human confirmation when needed. In this context, Gen-AI is not merely a writing or brainstorming assistant; it becomes a coordinating layer for heat pump auto-modeling, control synthesis, simulation-based evaluation, and field-informed decision support.

The proposed framework connects three major directions. First, heat pump auto-modeling agents can help generate, modify, and validate component-level and system-level models, including vapor-compression cycles, hydronic systems, thermal storage, hybrid heat pump configurations, and building-integrated heat pump applications. Second, heat pump control agents can assist in producing and testing supervisory control sequences, fault-response logic, model-predictive control strategies, and grid-responsive operation under comfort, efficiency, and safety constraints. Third, deployment and diagnostic agents can connect sensor data, digital twins, commissioning records, fault detection, refrigerant leakage monitoring, and user feedback to support reliable operation in real buildings and infrastructure systems.

The presentation will also discuss key technical challenges, including hallucination control, executable verification, physical consistency, uncertainty propagation, safety constraints for flammable refrigerants, cyber-physical reliability, and benchmarking of AI-assisted engineering workflows. The central argument is that Gen-AI should not replace thermodynamics, experiments, or engineering expertise. Instead, agentic Gen-AI can act as an intelligent interface between heat pump physics, simulation tools, control platforms, field data, standards, and human experts. By combining domain knowledge with tool-using AI agents, the heat pump community can accelerate innovation while maintaining the reliability, safety, and decarbonization impact required for large-scale deployment.

Key Words Agentic AI; generative AI; heat pumps; auto-modeling; heat pump control; digital twins; low-GWP refrigerants; intelligent operation; building decarbonization

Configuration Optimization and Comprehensive Evaluation of a PV/T Coupled Transcritical CO_2 Heat Pump System under Wide Ambient Temperature Conditions

Xu Feng[1],Ruotong Wang[2],Yinhai Zhu[1]

1. Tsinghua university

2. Xinjiang University

To improve the operating performance of building heat pumps under low-temperature and wide ambient-temperature conditions, this study comprehensively investigates the configuration optimization, environmental mode switching, and performance enhancement mechanism of a PV/T coupled transcritical CO_2 heat pump system. A system model including the PV/T collector, transcritical CO_2 heat pump, dual-source evaporator, ejector, and vapor injection process was established. The effects of solar radiation, ambient temperature, gas cooler pressure, vapor injection pressure, and PV/T area on system performance were analyzed. The results show that the PVT module can simultaneously provide electricity and low-grade thermal energy, thereby improving the heat transfer condition on the evaporation side of the heat pump. Under low ambient temperatures ranging from −28.1 to −19.8°C, the average COPs of the PV/T coupled dual-source system and the water-source system reached 2.41 and 2.48, respectively, while the daytime power self-sufficiency ratios reached 63.3% and 66.7%, respectively. After introducing the ejector, vapor injection, and environmental mode switching strategy, the system COP was increased by 5.32%–14.03% compared with the conventional PV/T coupled dual-source heat pump. Under typical sunny and cloudy winter conditions in Xinjiang, the daily average COPs reached 3.25 and 2.33, respectively. On a sunny day, the daily average comprehensive conversion efficiency of the PV/T module was 35.49%, and the photovoltaic power generation could cover 63.48% of the system electricity consumption during the solar radiation period. The results indicate that coupling PV/T with a transcritical CO_2 heat pump can significantly improve the solar energy utilization, low-temperature adaptability, and overall operating efficiency of building heat pump systems.

Key Words Heat pump, PV/T, Transcritical CO_2, Ejector

KDE-Based Modeling and Clustering of Multi-Climate Public Thermal Loads for Heat Pump Design

Xi BAI[1],Yuan YU[1],Caihua LIANG[2]

1. Institute of Resources and Environment, Beijing Academy of Science and Technology

2. School of Energy and Environment, Southeast University

Building thermal load characteristics play a critical role in HVAC and heat pump system design, as they directly determine system sizing and operational performance. However, traditional load analysis brings high simulation cost and poor universality. This paper develops an integrated thermal load processing framework combining Kernel Density Estimation (KDE), inverse transform sampling and K-Means clustering. EnergyPlus models of 450 public buildings across 14 climate zones and 7 functional types are established. Gaussian KDE is adopted to generate continuous load probability curves, with bandwidth optimized via MSE and R^2 criteria. Inverse transform sampling compresses 3000 original hourly load samples into 500 equivalents, cutting simulation time by 83% while energy efficiency error remains below 1%. AIC and BIC criteria confirm 11 optimal load clusters. Compared with building function classification, the average intra-cluster Euclidean distance of load profiles decreases by 50.9%, and a positive correlation between thermal load and outdoor wet-bulb temperature is quantified. Eleven standardized thermal load templates are obtained, which can serve as lightweight standard inputs for dynamic simulation and unit capacity matching of heat pump thermal systems in various public buildings.

关 键 词 Building energy load, Kernel density estimation, Load distribution, Thermal demand characterization, Clustering analysis

Operating strategy optimization of an absorption-based waste heat recovery system for district heating

Jongjin An,Kijeong Seo,Minsung Kim

Chung-Ang University

District heating plants have introduced HTC systems to utilize waste heat contained in exhaust gas, but the target system has recently shown reduced heat recovery performance under actual operating conditions. This decrease motivates the need to reassess the operating strategy of the absorption-based waste heat recovery system using calcium nitrate aqueous solution. Rather than treating the HTC system as a simple heat exchanger, this study interprets it as an absorption-based thermal cycle analogous to an absorption heat pump, in which water vapor absorption, solution cooling, solution regeneration, and vapor condensation are coupled through the concentration variation of the solution. In the absorber, the calcium nitrate solution absorbs water vapor from the exhaust gas while recovering sensible and latent heat, thereby contributing to waste heat utilization and visible plume reduction. As absorption proceeds, the solution becomes diluted, and changes in solution concentration and temperature affect the absorption potential, heat transfer characteristics, and regeneration requirement. The diluted solution is regenerated in the desorber using hot water, and the generated vapor is condensed to provide additional heat to the district heating water. In this study, the operating characteristics of the HTC system are analyzed by focusing on the coupled responses between exhaust-gas heat recovery, solution concentration control, regeneration heat demand, and district-heating water heat supply. The effects of solution concentration, solution temperature, circulation flow rate, desorber heat input, and district-heating water condition are evaluated to identify operating conditions that improve waste heat recovery while maintaining stable solution concentration. The results are expected to provide practical guidance for improving absorption-based waste heat recovery systems applied to district heating plants.

Key Words District heating, Waste heat recovery, Absorption-based system, Calcium nitrate aqueous solution, Water vapor absorption, Solution regeneration, Operating strategy optimization

Magnetic refrigeration system for hydrogen liquefaction applications

Mohamed Gado,Kyohei Natsume,Koji Kamiya

National Institute for Materials Science

Magnetic refrigeration technology has been recognized as an efficient and clean refrigeration system when it is compared to conventional liquefaction technologies. Magnetic refrigeration technology has been introduced as a viable technology for energy-intensive liquefaction of hydrogen. The system mainly consists of an active magnetic regenerator (AMR) packed with $HoAl_2$ as a magnetocaloric material, and driven by a NbTi split superconducting magnet. A shielding superconducting magnet is used to reduce the stroke of the AMR bed. Owing to the significant magnetocaloric effect and broad operating temperature range of $HoAl_2$, it has been extensively employed in hydrogen liquefaction applications. To enhance the performance of AMR systems and extend the operating temperature span, multilayer regenerators have been proposed. At first, an experimental design of a magnetic refrigeration system is demonstrated, highlighting its potential for hydrogen liquefaction. Hence in the present study, compositions of $ErAl_2$ + $HoAl_2$ and HoB_2 + $HoAl_2$ are investigated and compared to $HoAl_2$. Meanwhile, different filling ratios are used to attain optimal composition. A finite element model using Multiphysics COMSOL is developed to explore the magnetocaloric characteristics and the performance of the AMR refrigeration system. The results show that HoB_2 + $HoAl_2$ attains a quite higher cold-end temperature (13.5K) than that of the $ErAl_2$ + $HoAl_2$ dual-layer (12.8K). Achievable lower-end temperature of 16.6K using the single-layer $HoAl_2$. Accordingly, the cooling power and COP are relatively higher when the hot end temperature approaches the phase transition temperature. Mainly, $ErAl_2$ +$HoAl_2$ and HoB_2 + $HoAl_2$ outperform $HoAl_2$ in refrigeration power; while, $ErAl_2$ + $HoAl_2$ becomes increasingly efficient (57.4%) over the temperature range of 20-35K. Besides,

HoB_2 + $HoAl_2$ only improves performance by 10.1% compared to $HoAl_2$, at TH = 25K, outperforming $ErAl_2$ + $HoAl_2$. These results indicate that the performance of the magnetic refrigeration technology is comparable to conventional liquefaction techniques, which can pave the way toward cost-competitive magnetic liquefaction technology.

Key Words Magnetic refrigeration, Hydrogen liquefaction, Multilayer AMR.

Digital twinning and deep reinforcement learning controller for adsorption heat pumps

Mohamed Gado

National Institute for Materials Science

Thermally driven adsorption systems have found widespread applications in both cooling and heating technologies. Their popularity stems from their strong potential to utilize waste heat and harvest surplus renewable energy resources, contributing to sustainable energy management. Adsorption systems are increasingly favoured because they rely on eco-friendly refrigerants, require minimal maintenance, and can be powered by clean and renewable energy sources. These advantages make adsorption systems an attractive solution for decarbonized thermal energy applications, including air conditioning, refrigeration, and industrial cooling processes. The present study proposes a hybrid Digital Twin framework for real-time modelling, performance prediction, and adaptive control of adsorption cooling systems. The developed digital twin integrates ANFIS-based surrogate modelling with real-time sensor feedback. This framework offers: a novel integration of digital twinning and RL for intelligent thermal system optimization, and high-fidelity, data-driven modelling validated by experimental datasets. It shows there is a good agreement between the actual datasets and the ANFIS prediction datasets, indicating an RMSE, MAE, and R^2 of 1.0558, 0.4751, and 0.9782, respectively. Similarly, the ANFIS model of the COP is compared against the actual datasets of the adsorption cooling system. A higher ANFIS model precision can be reported, given the RMSE, MAE, and R^2 of 0.0180, 0.0084, and 0.9833, respectively. Meanwhile, reinforcement learning (RL) agent has been introduced to dynamically adjust system operating parameters to maximize cooling output and minimize energy consumption. Moreover, A waste-heat-driven adsorption cooling system is introduced and integrated into the pharmaceutical ointment manufacturing process, where flue gases from ingredient preparation (70–80°C) provide the driving heat, while the produced chilled water is used to control the homogenization temperature within the desired range of 30–35°C.

Key Words Adsorption heat pumps, Digital twinning, Reinforcement Learning, Industrial applications.

Simulation Study on Soft Start-Stop Characteristics of Air-Source Heat Pumps and Their Grid Impact in integrated energy system

Sen Kang

Shanghai University of Electric Power

Simulation Study on Soft Start-Stop Characteristics of Air-Source Heat Pumps and Their Grid Impact in integrated energy system

Sen KANG(a), Fang LIU(a)

(a) College of Energy and Mechanical Engineering, Shanghai University of Electric Power, 2103 Pingliang Road, Yangpu District, Shanghai 200090, China

Corresponding author: Fang LIU, e-mail: fangliu@shiep.edu.cn

ABSTRACT

To address the grid power impact caused by clustered hard start-stop of air-source heat pumps (ASHPs) in integrated energy system, this paper proposes a ramp-type soft start-stop control strategy and carries out quantitative simulation verification. Based on Modelica language and Buildings library, a complete integrated energy system model is built on the Dymola platform, consisting of a 200 kW photovoltaic array, a 200 kW wind turbine, a 2 MWh battery energy storage system, base AC/DC loads and a 3-unit ASHP cluster. Coupled with a weather bus and 480 V three-phase AC low-voltage distribution network, a full 24-hour (86 400 s) dynamic co-simulation is implemented. The soft start-stop strategy realizes linear load ratio transition within 60 s, with unified start at 3 600 s and stop at 7 200 s. Simulation results indicate that compared with conventional hard start-stop, the proposed strategy reduces the power change rate of a single unit by 95%, eliminates step-like power shock, and significantly smooths the grid-side active power transition. Meanwhile, the high COP of ASHPs reduces the overall system electricity load. This strategy can effectively mitigate voltage flicker and line overload risks from concentrated start-stop events, providing device-level technical support for large-scale integration and flexible regulation of ASHPs in source-grid-load-storage scenarios.

Key Words Keywords: Air-source heat pump, Soft start-stop, integrated energy system, Power impact, Modeling and simulation

the Application of a Large Lift High-Temperature Coupled Heat Pump System for Data Center Waste Heat Recovery

Chen Zhu

Johnson Controls Air Conditioning, Wuxi Co., Ltd., Wuxi

In response to the high energy consumption of data center cooling systems, the insufficient utilization of low-grade waste heat, and the mismatch between heat supply and demand in industrial parks, this study proposes a low-pressure refrigerant, large temperature-lift, two-stage centrifugal high-temperature heat pump coupled system. The system enables simultaneous realization of data center cooling and high-grade heat supply.

The low-temperature loop meets the cooling requirements of the data center, while the high-temperature loop produces high-temperature hot water and high-pressure steam to support district heating and industrial processes. The system configuration, process flow, key technological innovations, and integrated control strategies are systematically analyzed. A typical industrial park application scenario is further designed, and the energy efficiency and economic performance are quantitatively evaluated.

The results indicate that the proposed system enables efficient cascade utilization of low-grade waste heat from data centers, demonstrating significant energy-saving and carbon-reduction benefits, along with strong engineering application potential.

Key Words High temperature-lift heat pump; Low-pressure refrigerant; Data center cooling; Waste heat recovery; Steam upgrading; Control strategy; Industrial park application

Study on performance of internal heat exchanger and refrigerant characteristics in steam compression heat pump cycle

Biao Feng,Guoqing Shi,Miao Shi,Hongying Wu,Dan Wang,Suxia Ma

Taiyuan University of Technology

In recent years, research on heat pumps has developed rapidly, with high-temperature lift heat pumps—specifically low-temperature heating heat pumps and high-temperature industrial heat pumps—becoming research hotspots. To counteract the degradation of the Coefficient of Performance (COP) caused by the increasing temperature lift, internal heat exchangers (IHXs) have been widely adopted in heat pump cycles. Numerous studies indicate that the performance of IHXs varies across different refrigerants.

To investigate the relationship between refrigerant properties and the optimization efficacy of IHXs, this study utilizes the REFPROP database to examine 28 pure refrigerants—either commonly used or possessing substitution potential. Specifically, the impacts of the source-sink temperature lift and the temperature rise of the cold fluid within the IHX on the COP across two types of high-temperature lift heat pumps are evaluated, and the correlation between the thermophysical properties of refrigerants and the optimization performance of the IHX is further scrutinized.

The results demonstrate that under the same temperature lift, the variation in COP generally exhibits a linear relationship with the temperature rise of the cold fluid in the IHX. The impact of the IHX on the COP of different refrigerants is strongly correlated with the at the saturated vapor points of both the condensing temperature and evaporating temperature, overall exhibiting an exponential growth trend. Compared to the percentage change in COP, shows a stronger correlation with COP, and displays a more pronounced monotonic relationship within the same refrigerant. The conclusions obtained in this study enable the performance prediction of heat pump cycles integrated with IHXs based on fundamental refrigerant properties, and conversely, facilitate the inverse design and search for new high-performance refrigerants.

关键词 Vapor compression heat pump, Internal heat exchanger, Refrigerant properties, COP.

Experimental Study on R290/CO_2 Cascade Refrigeration and Heat Pump System with Two-Stage Compression and Intercooling

Baomin Dai,Xuan Zhang,Ronghua Miao,Yu Wang,Bo Song,Shengchun Liu

Tianjin University of Commerce

Considering the fact of high compression ratio, high discharge temperature, and poor energy efficiency in the low-temperature stage CO_2 cycle of the conventional R290/CO_2 cascade refrigeration and heat pump system at low evaporation temperature, An experimental test setup is developed for a R290/CO_2 cascade refrigeration and heat pump system with two-stage compression and intercooling in the low-temperature stage CO_2 cycle (TSCI). Comparative experiments were conducted against a conventional R290/CO_2 cascade refrigeration and heat pump system (Base). The high-temperature stage cycle employed R290 as working fluid, while the low-temperature stage cycle uses CO_2. An intercooler was introduced between the two compression stages to reduce the superheat degree at the second-stage suction of CO_2 compressor. The system performance was experimentally studies under the working conditions with CO_2 evaporation temperature ranging from -10°C to -35°C and heat sink inlet/outlet water temperature of 40/50°C. The results indicate that the maximum COP is obtained at the optimum intermediate temperature. The TSCI system achieves a higher COP than that of the Base system. As the CO_2 evaporation temperature decreases from -10°C to -35°C, the heating COP improvement rate of the TSCI system rises from 2.99% to 13.54%, and the cooling COP improvement rate increases from 3.98% to 30.96%. Furthermore, the CO_2 mass flow rate increased by 21.73% to 30.33%, and the second-stage discharge temperature is reduced by up to 10.7°C.

As shown in Fig. 1, the R290/CO_2 cascade refrigeration heat pump system consists of a cascade system, a water-loop control system, and a data acquisition system. The cascade system comprises a CO_2 variable-frequency compressor, a CO_2 electronic expansion valve, a CO_2 evaporator, an intercooler, an R290 variable-frequency compressor, an R290 condenser, an R290 liquid receiver, an R290 electronic expansion valve, and a condenser-evaporator.

As shown in Fig. 2, in the low-stage cycle of the TSCI system, low-pressure CO_2 vapor enters the

compressor for first-stage compression. After being superheated, it flows into the intercooler, where it is cooled by the two-phase R290 fluid. Subsequently, the CO_2 enters the compressor for second-stage compression, reaching a high-pressure state. The discharge gas then flows into condenser-evaporator, where it is cooled by the R290. Thereafter, it passes through the electronic expansion valve, where it is throttled and depressurized to a two-phase state. The two-phase CO_2 then enters the evaporator, absorbing heat from a 60% by volume ethylene glycol/water solution and becoming superheated vapor. Finally, it returns to the first-stage suction port of the CO_2 compressor, thus completes the low-temperature stage cycle.

In the high-temperature stage cycle of the TSCI system, R290 is drawn into the compressor and compressed to a superheated vapor state. It then enters the condenser, where it heats the hot water. After being subcooled, the R290 flows into the electronic expansion valve, where it is throttled and depressurized to a two-phase R290 fluid. This two-phase fluid then enters the intercooler to cool the superheated CO_2 from the first-stage CO_2 compressor. Subsequently, it flows into the condenser-evaporator, where it exchanges heat with the second-stage CO_2 discharge gas. Finally, the R290 becomes superheated gas and returns to the compressor, thus completes the high-stage cycle.

Compared with the TSCI system, the Base system does not incorporate an intercooler. In the Base system, the CO_2 in the low-stage cycle undergoes two consecutive stages of compression within the compressor before entering the condenser-evaporator, where it exchanges heat with the two-phase R290 fluid that is throttled by the low-stage expansion valve. All other processes and the refrigerant charge amount remain the same as those in the TSCI system.

As shown in Fig. 3, the heating COP (COP_H) is presented as a function of the R290 evaporation temperature at a CO_2 evaporation temperature of -30°C and heat sink inlet/outlet water temperature of 40/50°C. It can be observed that for both the Base and TSCI systems, the COP_H first increases and then decreases with increasing R290 evaporation temperature, indicating the existence of a maximum COP_H and a corresponding optimal R290 evaporation temperature (hereinafter referred to as the optimal intermediate temperature). For the Base system, the maximum COP_H is 1.606 at the optimal intermediate temperature of -13.07°C, while for the TSCI system, the maximum COP_H is 1.795 at the optimal intermediate temperature of -8.08°C, representing an 11.77% improvement in COP_H.

As shown in Fig. 4, the second-stage discharge temperature of the CO_2 compressor is presented as a function of the CO_2 condensation temperature. It can be observed that, at a given CO_2 evaporation temperature, the second-stage discharge temperature increases with rising CO_2 condensation temperature. At CO_2 evaporation temperatures of -10, -20, -30, and -35°C, under the optimal intermediate temperature conditions, the second-stage discharge temperature is reduced by 10.7, 8.48, 3.92, and 10.37°C, respectively.

Keywords: CO_2 two-stage compression; intercooling; R290/CO_2 cascade system; refrigeration and heat pump; discharge temperature

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关键词 CO_2 两级压缩；中间冷却；R290/CO_2 复叠；制冷热泵；排气温度

Experimental Study on Thermal Response Characteristics of the CO_2 Ejector with External Wall Active Heating

Chao Huang[1],刘方 [1,2]

1. Shanghai University of Electric Power

2. 上海非碳基能源转换与利用研究院

This paper presents a transcritical CO_2 two-phase ejector with a heating film on its external wall. Combined with experiments on a heat pump test rig and CFD numerical simulations, the study investigates

the effects of active heating on the ejector and system performance. Experiments were conducted under five operating conditions covering both transcritical and subcritical regimes. The variations of inner and outer wall temperature distributions, entrainment ratio, ejector efficiency, and system COP were analyzed, and simulations further revealed the evolution of temperature and pressure fields inside the ejector before and after heating. The experimental results indicate that, under transcritical conditions, the steady-state outer wall temperature is negatively correlated with the primary flow inlet pressure. The inner wall temperature rise is much smaller than that of the outer wall, and the temperature rise in the diffuser is higher than that in the mixing chamber. The subcritical case exhibits the highest inner wall temperature rise (5.67°C) and the fastest response time (58.2s), while transcritical case 5 shows the smallest inner wall rise (0.99°C) and the slowest response (105.4s). The entrainment ratio increases by 2.24% to 10.13% across all cases, while the pressure lift ratio varies within ±1%. The ejector efficiency simultaneously improves by 2.52% to 9.67%, confirming that the entrainment ratio gain originates from genuine internal flow improvement rather than passive reduction of the primary flow. The maximum COP improvement reaches 21.0%. In summary, external wall active heating can enhance the entrainment ratio without compromising the ejector's energy conversion quality, and can achieve significant COP improvement under suitable operating conditions. This study provides new experimental evidence and control strategies for active thermal management of ejectors.

关键词 CO_2 Ejector, External Wall Heating, Transcritical Cycle, Entrainment Ratio, COP, Heat Pump System

Dynamic characteristics of 873.15 K-class ultra high-temperature CO_2 heat pump equipped with single tank inventory control system_V2

Tianliang Chang[1],Yulong Song[1],Feng Cao[1],Yong Zhang[2],Wanqing Liu[2,3]

1. Xi'an Jiaotong University

2. Shengu Group Co. Ltd.

3. Dalian Jiaotong University

A key aspect of improving the technology readiness level of ultra high-temperature CO_2 heat pump systems is the stable control of main-cycle parameters under off-design and transient operating conditions (i.e. temperatures at compressor and expander inlet or outlet). A further challenge in pilot-scale (> 10 MWe) systems is the limited number of control variables due to the complex integration of key components. Among the possible control strategies, the regulation of system inventory, which consists of the variation of CO_2 fluid charge in the power-to-heat conversion loop to achieve a given control target. Such a strategy relies on an inventory tank to inject/withdraw working fluid into/from the system. However, the resulting redistribution of working-fluid inventory, pressure-field reconstruction, flow disturbance, and thermal-inertia coupling remain insufficiently understood. To address this gap, this study investigates the dynamic characteristics of an inventory-controlled system. The investigated system is a simple recuperated ultra-high-temperature CO_2 heat pump proposed by Xi'an Jiaotong University for a 50 MWe-rated energy storage scenario. A high-fidelity one-dimensional dynamic simulation platform is developed, and transient simulations are performed to evaluate the influence of inventory control on system operation. The dynamic responses of key thermodynamic variables in both the main loop and inventory tank, including pressure, temperature, mass flow rate, and working-fluid mass, are analyzed. The effects of inventory regulation on system stability are further discussed, with emphasis on the coupling among loop pressure gradients, compressor inlet conditions, heat-exchanger thermal inertia, and tank charging/discharging processes. The results provide theoretical support for load-following control, inventory-tank design, and safe operation of pilot-scale ultra-high-temperature CO_2 heat pump energy storage systems.

Key Words Carnot Battery; ultra high-temperature CO_2 heat pump; load-following operation, dynamic characteristics, control strategies.

Distributed-Parameter Assessment of R1123- and R1132(E)-Based Low-GWP Blends in Condensing Heat Recovery Air-Conditioning Systems

Hongfei Guan,Xi Wu,Mingxu Nie,Weijie Kong

Dalian University of Technology

Low-global-warming-potential blends containing R1123 or R1132(E) are promising alternatives for air-conditioning and heat-pump applications, but their suitability in condensation-heat-recovery systems cannot be inferred from ideal-cycle COP alone. This study evaluates R410A, three R1123/R32 mixtures, three R1132(E)/R1234yf mixtures, and R479A in conventional and dual-condenser air-conditioning systems using a validated distributed-parameter model. The evaporator, water-cooled condenser, and air reheater were discretized to resolve local properties, heat-transfer coefficients, pressure drops, temperature glide, and secondary-fluid states. By coupling refrigerant thermodynamics with local heat-transfer and flow-distribution mechanisms, the model provides a theoretical framework for identifying refrigerant–system matching principles and key operating constraints in advanced heat-pump systems. Model predictions were compared with R454B experiments at reheater-branch mass-flow ratios of 0.268 and 0.490; the absolute deviations of heat duties, compressor power, COPs, and pressures were within 5.54%. Under identical hardware, R1123/R32 blends increased cooling and volumetric cooling capacities by 13–16% and reduced refrigerant charge by 5–11% relative to R410A, but operated at higher pressures and lower COPs. By contrast, R1132(E)/R1234yf blends achieved the highest COPs and lowest pressures, although cooling capacity decreased by 24–33% and charge increased by 24–27%. The condenser minimum pinch-point temperature difference ranged from 1.15 to 8.36 K, and local profiles showed the closest refrigerant–cooling-water temperature match for R474A. In the dual-condenser system, increasing the reheater-branch mass flow ratio raised reheating capacity and outlet-air temperature while reducing net cooling capacity and COP. These findings reveal the key role of temperature glide, local pinch constraints, and branch-flow allocation in heat-pump performance enhancement and provide design guidance for low-GWP dual-condenser heat-pump systems. Thus, refrigerant selection should balance efficiency, capacity, pressure, charge, temperature glide, and reheating range rather than rely solely on COP ranking.

Key Words R1123, R1132(E), distributed-parameter model, dual-condenser system, condensation heat recovery.

Effects of Sorbent Grain Shape, Size, and Packing on Performance of Sorption Heat Transformers

Ilya Girnik,Thanh Dat Phan,Milad Ebadi,Claire McCague,Majid Bahrami

Simon Fraser University

Sorption heat transformers and chillers are emerging technologies capable of utilizing low-grade waste heat and negligible electricity for heat upgrading and cooling, respectively. They can facilitate the utilization of low-grade waste heat in district energy networks by upgrading the temperature for injection into the network or transforming heat to cooling at transfer stations for buildings on the network. The benefits include of decarbonization of the district energy network and reduced stress on the electricity grid.This work presents the study on performance of a sorption heat pump prototype, using water/silica gel as working pair. Sorber beds were created by filling finned microchannel heat exchangers (3.2 L available volume) with silica gel grains of different shapes (spherical and irregular) and sizes (0.5 – 1.5 mm) using a vibration system (shaker) for consistent packing. Irregular shaped grains pack more closely than spherical grains, resulting in 65% greater mass in the heat exchanger silica gel grains (1.95 kg vs. 1.15 kg) The sorption heat pump prototype produced peak cooling powers of 2.0 kW and 1.1 kW at 15°C ($_{TL}$), for sorber beds with irregular and spherical grains, respectively, when operated at 80°C, desorption/regeneration temperature ($_{TH}$), 30°C ambient ($_{TM}$), and cycle time of 12 min, with a cooling coefficient of performance (COP) of 0.6 and electrical efficiency of 42.6, respectively. When operated for temperature

upgrading with a sorber bed filled with irregular grains, the prototype provided 10°C temperature lift from 60-80°C with ambient, $_{TM}$, of 30°C (COP=0.5).

Key Words Sorption Heat Transformer, Silica gel, Packing, Grains Shape

Intermediate Pressure Staging in a 2.5 MW Three-Stage Ammonia Heat Pump with Volumetric Ratio

Kamil Smierciew,Jerzy Gagan,Dariusz Butrymowicz,Pawel Jakonczuk

Bialystok University of Technology

The paper presents a thermodynamic analysis of a 2.5 MW three-stage ammonia (NH_3) heat pump designed for high-temperature industrial applications with a supply temperature of 90°C and an evaporation temperature of –20°C.

In the initial stage, a geometric division of pressures between evaporation and condensation levels was applied. Although this approach provides balanced compression ratios, it does not necessarily reflect real operating conditions once actual compressor characteristics are considered.

To account for this effect, volumetric ratio (Vi) matching was introduced by comparing theoretical volumetric ratios derived from calculated compression ratios with manufacturer-recommended values. A penalty factor was implemented to represent the reduction of isentropic efficiency caused by volumetric mismatch.

The results show that neglecting volumetric mismatch leads to an overestimation of the coefficient of performance (COP). For the investigated case, inclusion of Vi mismatch reduces COP from 2.42 to 2.32 and significantly affects discharge temperatures and the distribution of compression power among stages.

A parametric study of the second intermediate pressure level was subsequently performed. The analysis indicates that the geometric pressure staging does not correspond to the highest system efficiency when compressor characteristics are taken into account. Adjustment of the intermediate pressure level leads to a more balanced power distribution and improved overall energetic performance.

The presented approach demonstrates the importance of incorporating real compressor characteristics in the design of large-scale multi-stage ammonia heat pumps.

Key Words ammonia heat pump, multi-stage compression, volumetric ratio (Vi) matching, compressor efficiency degradation, high-temperature heat pump

Experimental Identification of Pressure Recovery and Condensation Wave Structure in a Two-Phase Propane Ejector

Dariusz Butrymowicz,Jerzy Gagan,Andrzej Pawluczuk,Kamil Smierciew,Adam Dudar,Michał Łukaszuk

Bialystok University of Technology

Two-phase ejectors operating with natural refrigerants exhibit complex internal flow structures governed by rapid phase change, momentum exchange, and pressure recovery processes. Among these phenomena, the formation of a condensation wave within the mixing chamber plays a crucial role in determining ejector performance. Despite its importance, experimental identification of this structure in real operating systems remains limited.

This paper presents a detailed experimental investigation of pressure distributions along a two-phase propane (R290) ejector under controlled operating conditions. High-resolution pressure measurements were

performed at multiple locations along the mixing chamber and diffuser for two ejector geometries and various nozzle positions.

The results reveal distinct pressure recovery regions associated with condensation-induced momentum redistribution. The location and intensity of the pressure rise depend strongly on operating parameters and nozzle configuration. Under certain regimes, a rapid pressure increase consistent with condensation wave behaviour was observed, indicating non-equilibrium phase interaction.

The study provides experimentally grounded insight into the internal pressure structure of two-phase ejectors and highlights the importance of interpreting measured pressures within the framework of non-equilibrium thermodynamics.

Key Words two-phase ejector, propane (R290), condensation wave, pressure recovery, non-equilibrium flow

Performance of a Decoupled Liquid Air Energy Storage System with CO_2 Heat-Pump Reheating for Offshore Energy Transport

Shiyu Zhou,Wensheng Lin,Haobin Zhu,Bin Hu

Shanghai Jiao Tong University

A spatially decoupled liquid air energy storage (LAES) configuration is proposed for deep-far offshore energy, in which wind/solar power is converted into liquid air offshore, transported to shore, and released near the load centre. Unlike conventional coupled LAES, the central advantage of the decoupled configuration is that charging and discharging stations need not be co-located; liquid air acts simultaneously as an energy-storage medium and a transportable energy carrier. A steady-state Aspen HYSYS model was established for an offshore Claude liquefaction train with compression-heat organic Rankine cycle (ORC) recovery and an onshore release plant comprising cryogenic pumping, two-stage ORC cold-energy recovery, four-stage air expansion and optional CO_2 heat-pump reheating. A MATLAB-HYSYS genetic algorithm was used to minimise heat-pump compressor power while maintaining a minimum temperature difference of 3°C in the two constrained heat exchangers. The liquefaction system achieved an 18.39% liquefaction ratio and a net specific electricity consumption of 0.545 kWh/kg after accounting for Claude-expander and compression-heat ORC power recovery. In the base discharge case, the known net power output was 105.25 kW. Reheating to 40°C provided the highest incremental net benefit: the four-stage expansion output increased by 13.60 kW, whereas heat-pump consumption was 10.83 kW, giving a net increase of 2.77 kW (3.18%). The results identify a practical reheat range of 30–50°C under the investigated low-temperature seawater boundary and demonstrate the importance of local compression-heat utilisation and onshore cold-energy recovery for improving the performance of geographically decoupled LAES chains.

Key Words liquid air energy storage, offshore wind energy, Claude cycle, CO_2 heat pump, organic Rankine cycle, genetic algorithm

Thermodynamic analysis of a novel recuperation-enhanced CO_2 heat pump cycle for high-temperature and high-pressure industrial steam generation

Shaoqiang Li[1],Jingjing Guo[1],Yulong Song[1],Feng Cao[1],Yong Zhang[2],Wanqing Liu[2,3],Jiajian Tan[2]

1. Xi'an Jiaotong University

2. Shengu Group Co., Ltd.

3. Dalian Jiaotong University

Industrial steam is a major form of process heat, and high temperature heat pumps offer an important pathway for replacing coal and gas boilers in electrified and low carbon industrial heating. To meet the demand for 300°C industrial steam generation, our research group previously proposed a CO_2 heat pump steam generation cycle. By utilizing the temperature glide of supercritical CO_2 during heat rejection, the cycle integrates pressurized water heating, flash evaporation after throttling, and saturated steam superheating, enabling the production of 300°C steam through a pure heat pump process. Nevertheless, our previous results showed that the cycle performance decreases markedly as the steam supply pressure increases. This degradation is mainly attributed to the pressure-dependent thermodynamic state of water after flash evaporation, which introduces high-grade recirculated water and creates an unfavorable thermal coupling with the CO_2 gas cooling process. As a result, high-pressure CO_2 cannot be sufficiently cooled in the gas cooler. This behavior is similar to the performance sensitivity of conventional CO_2 heat pumps to high return water temperature. However, in the present steam generation cycle, the high-temperature return boundary is generated internally by the steam generation process and varies with the steam supply pressure. Therefore, conventional approaches developed for CO_2 heat pump water heating systems cannot be directly applied. To mitigate the performance degradation caused by this internal thermal feedback under high steam supply pressure, this study proposes a novel recuperation-enhanced CO_2 heat pump steam generation cycle (REC), based on the concept of heat redistribution. The previously proposed CO_2 heat pump steam generation cycle is used as the baseline cycle (BC). In REC, the return path and matching target of high-grade water-side sensible heat are rearranged so that this heat is converted into an effective heat input to low-pressure CO_2 before compression. This reduces its adverse influence on CO_2 cooling in the gas cooler and enhances the ability of the system to produce ultra-high-temperature steam under small pressure ratio conditions. A steady-state thermodynamic model is developed for both BC and REC, and the effects of recuperation effectiveness, pressurized water outlet temperature, and transcritical and supercritical operating modes are investigated. The results show that REC enhances CO_2 cooling in the gas cooler and improves the overall system performance. In the transcritical operating mode at a steam supply pressure of 0.9 MPa, REC shifts the optimal pressurized water outlet temperature from 270°C to 305°C and increases the maximum COP to 1.65, which is 11.89% higher than that of BC. The steam generation rate increases by 14.98%, and the CO_2 outlet temperature of the gas cooler decreases by 52°C. A similar trend is observed at a steam supply pressure of 0.5 MPa, indicating that the improvement achieved by REC is not limited to a single steam supply pressure condition. In the supercritical operating mode at a steam supply pressure of 0.9 MPa, REC increases the maximum COP to 1.84, which is 12.42% higher than that of BC. The steam generation rate increases by 14.78%, and the CO_2 outlet temperature of the gas cooler decreases by 42°C. After further reducing the system pressure ratio, REC still achieves a COP comparable to that of BC under the representative condition, with an approximately 22.5% lower pressure ratio and a slight increase in steam generation rate. These results demonstrate that REC can improve system performance under high steam supply pressure and enhance the capability of the CO_2 heat pump to generate steam under small pressure ratio supercritical operation. This study provides a new cycle improvement strategy for extending CO_2 heat pump steam generation toward higher pressure steam production and multiple operating modes.

关键词 CO_2 Heat Pump, Industrial Steam Generation, Recuperation-Enhanced Cycle, Thermodynamic Analysis

Experimental characterization of an innovative adsorption chiller for industrial cooling applications

Mohamed Gado[1],CALO Matto[2],Salvatore VASTA[3],Antonio FOTIA[3],Valeria PALOMBA[3],Walter MITTELBACH[2],Andrea FRAZZICA[3],Matto CALO

1. National Institute for Materials Science

2. Sorption Technologies GmbH

3. Consiglio Nazionale delle Ricerche, Istituto di Tecnologie Avanzate per l'Energia

In the European Union, the industrial sector accounts for 26.1% of final energy consumption, with electricity representing approximately 33% of this demand. Around 150 TWh per year are used to operate vapor-compression chillers for process cooling, mainly at temperatures above 0°C. Within this context, the EU-funded RE-WITCH project aims to develop and demonstrate innovative technologies that exploit low-grade waste heat to provide process cooling in industrial plants, thereby reducing electricity use.

This work presents the development and experimental assessment of a novel patented adsorption chiller concept. The system comprises two adsorber reactors operating in counterphase, while water is used as the refrigerant and stored in liquid form in two separate vessels. Hydraulic pumps distribute the refrigerant within each adsorber, where it directly evaporates or condenses over a pouring structure. The associated cooling and condensation heat is then transferred to the external source and sink through plate heat exchangers.

A first full-scale prototype with a nominal cooling capacity of 20 kW has been developed. The unit employs finned-coil heat exchangers as adsorbers, incorporating microporous silica gel as the active adsorbent material. Its modular design enables multiple units to be stacked to match different process-cooling demands. Preliminary experimental results demonstrate promising performance, with a thermal COP of up to 0.47 and an EER above 30. Further laboratory characterization will be conducted to establish a complete performance map, optimize control strategies, and identify design improvements for the next prototype, which will be deployed in two industrial demonstration plants.

Key Words Adsorption chiller, industrial cooling, COP, EER

Closed-Circuit Transcritical CO_2 Heat Pump Drying System: A MATLAB-Based Steady-State Simulation Study

Xiaoqing Pan,Yanchang Song,Zhentao Zhang

Technical Institute of Physics and Chemistry, CAS

Driven by the dual strategic goals of "Carbon Peak" and "Carbon Neutrality," addressing the challenge of high energy consumption in industrial drying applications has become a critical research focus. Relevant data shows that the energy consumption for drying in developed countries accounts for 7 ~ 15% of the national industrial energy consumption, while in China, the energy used for drying constitutes approximately 12% of the total national energy consumption. The heat pump drying calculation shows an energy-saving rate of 15~27% compared to traditional electric heating drying technology, and is regarded as a highly promising alternative solution. However, Conventional heat pump drying technologies face multiple technical bottlenecks, including persistently high energy consumption, suboptimal product quality and stability, low efficiency, and the excessive Global Warming Potential (GWP) of traditional fluorocarbon-based refrigerants. The transcritical CO_2 heat pump cycle, due to its unique temperature slip characteristic, can achieve a good thermal match between the gas cooling process and the air heating process during the process, thereby reducing irreversible losses and improving system efficiency. Meanwhile, as a natural refrigerant, CO_2 has significant advantages such as GWP = 1, ODP = 0, non-flammability, and low cost, and is regarded as one of the most promising alternative solutions in the field of heat pump drying. This study aims to:

1. Propose a simple-structured design scheme for a cross-critical CO_2 heat pump drying system;

2. Establish a steady-state simulation model that couples the drying heat load on the air side with the closed-loop circulation on the CO_2 side.

3. Systematically investigate the influence laws of environmental temperature (0 ~ 30°C) and drying outlet temperature (60 ~ 90°C) on the system's heating capacity and COP.

4. Revealing the mechanism of the key parameters functions provides a theoretical basis for the optimization design of industrial heat pump drying systems.

This paper constructs a mathematical coupling model consisting of two sub-modules based on MATLAB. The first one is the heat and mass transfer model of the drying chamber, which calculates the heat load required at different temperatures. The second is the cross-critical CO_2 heat pump cycle sub-model,

which establishes steady-state thermodynamic control equations for the four core components (compressor, gas cooler, throttling expansion valve, and evaporator), and solves the thermodynamic parameters of CO_2. The schematic diagram of the entire system is shown in Figure 1.

In this simulation, two sets of key engineering variables were selected for analysis: the temperature range of the drying outlet air was 60 to 90°C, and the environmental temperature range was 0 to 30°C; The system's heating capacity and COP were chosen as the core performance evaluation indicators to analyze the influence laws of the dual variables of environmental temperature and drying air temperature on the system's energy efficiency and heating capacity.

The results of multiple sets of simulation calculations for varying operating conditions show that the two core performance indicators of the system exhibit distinct changing patterns:

(1) The system COP continuously increases with the rise of environmental temperature and continuously decreases with the increase of the set drying temperature. When the environmental temperature exceeds 20°C, the variation range of COP due to the change in environmental temperature significantly increases; when the drying temperature exceeds 70°C, the rate of COP decrease slows down.

(2) The trend of the system's heating capacity is opposite to that of COP. It gradually decreases overall as the ambient temperature rises, and steadily increases as the temperature of the dry exhaust outlet rises.

By comparing all the operating conditions, the optimal matching operating condition of the system was obtained: the ambient temperature was 30°C and the hot air temperature at the drying outlet was 60°C. Under this condition, the system's heating performance coefficient reached its peak value of 5.89.

This simulation verifies the technical feasibility and significant energy-saving potential of a closed transcritical CO_2 heat pump drying system in industrial drying applications. The study elucidates the coupled mechanism between ambient temperature and drying air temperature on the thermodynamic performance of the heat pump cycle, providing theoretical support and optimization references for structural design of similar low-carbon heat pump drying equipment. To address limitations in existing simulation studies, future work may involve prototype testing to compare simulation data with experimental results, refine the model, and investigate the applicability of this CO_2 heat pump drying system in drying processes. Additionally, multi-parameter optimization can be conducted focusing on compressor discharge pressure and gas cooler outlet temperature.

Key Words Transcritical; CO_2; Heat pump drying; Thermal Simulation; Carbon neutrality

Attention Gradient Attribution for Interpretable Cross-Domain Fault Diagnosis in Solar-Assisted Air Source Heat Pump Systems

Weijun Xu,Weiyang Li,Tao Li,Chengliang Xu,Yuan Yuan,Guannan Li

Wuhan University of Science and Technology

Solar-Assisted Air Source Heat Pump (SAASHP) systems exhibit significant variations in operational characteristics and system configurations when deployed across different climate regions, posing challenges for data-driven fault diagnosis models. While domain-adversarial neural networks (DANN) have shown promise in cross-domain fault diagnosis, their black-box nature undermines field engineers' trust in diagnostic results. This study proposes an Attention Gradient Attribution (AGA) method, an intrinsically interpretable paradigm deeply coupled with DANN training, to address the opacity of transfer learning models in SAASHP cross-domain fault diagnosis. A feature attention module is embedded after the DANN input layer and jointly optimized with domain-adversarial and classification losses, enabling attention weights to automatically preserve focus on domain-invariant and classification-critical features. Sample-wise attribution values are computed as the element-wise product of attention weights and input gradients. A multi-dimensional evaluation framework comprising Localization Accuracy, Sparsity, Feature Sensitivity, and Composite Interpretation Quality (CIQ) is constructed for quantitative comparison against Integrated Gradients (IG) and SHAP. Simulation results demonstrate that AGA achieves improved interpretability performance, with average CIQ scores of 0.925 across both subsystems, outperforming IG (0.870) and SHAP (0.840) by 6.3% and 10.1%, respectively. Systematic robustness is further validated across varying

measurement variable combinations, domain discrepancy levels, target-domain labeled sample sizes, and fault severity levels. Additionally, fine-grained attribution analysis of missed and misdiagnosed samples reveals the underlying mechanisms of fault signal loss and spurious signal activation.

Key Words Solar-assisted air source heat pump; Attention gradient attribution; Domain-adversarial neural network; Transfer learning; Interpretable artificial intelligence; Fault diagnosis.

Design Considerations and Application Analysis of Air-source Heat Pump Heating in Coal Washing Plants

Bingbing Liu[1],Tian Wen Ren[2]

1. CIMC ARCO (Heilongjiang) Technology Co., Ltd.

2. Guangdong Niuentai New Energy Technology Co., Ltd.

This paper takes the heating renovation project of a coal washing plant in Heilongjiang Province as the research object, and conducts a comprehensive analysis of system design essentials, unit operating energy efficiency, economic benefits, and environmental benefits. The results show that the ultra-low temperature air source heat pump using air injection enthalpy technology can meet the heating needs of different functional areas in the coal washing plant. At a low ambient temperature of -20°C, the coefficient of performance (COP) of the unit can reach above 2.0. When the water supply temperature is between 45°C and 50°C, the combined cost of renovation and operation is optimal. The operating cost per unit building area has significant economic and environmental advantages over gas boilers and electric boilers, and the static investment recovery period is relatively considerable. This study provides a theoretical basis and engineering reference for the application of air source heat pumps in clean heating for industrial buildings in severe cold regions.

Key Words Air source heat pump; coal washing plant; severe cold region; heating design; Economic analysis

Design-Space Mapping of Mechanical Vapour Recompression for Industrial Heat-Pump Steam Generation

Pouya Pourkashani,Bo Yang,Maziar Arjomandi

Adelaide university

Industrial process heat remains a major source of energy demand and greenhouse-gas emissions, particularly in sectors that rely on low- and medium-pressure steam. Mechanical vapour recompression (MVR) is a heat-pump-based pathway that can recover low-temperature vapour or waste heat and upgrade it to useful steam conditions, reducing the need for direct electric or fossil-fuelled steam generation. This study presents a design-space mapping approach for assessing MVR systems for industrial steam generation.

A thermodynamic and techno-economic screening model was developed to evaluate the influence of waste-heat temperature, target steam temperature, pressure ratio, compressor staging and steam output on system performance. The framework estimates key performance indicators including coefficient of performance, electricity demand, number of compression stages and levelised cost of heat. MVR performance is compared with direct electric steam generation under consistent operating and economic assumptions to identify conditions where heat-pump-based steam generation becomes favourable.

The results show that the viability of MVR is strongly governed by temperature lift and total compression ratio. Lower temperature lifts lead to higher performance and improved economic

competitiveness, while large lifts require additional stages and increase compressor work. The design-space maps provide a practical method for identifying feasible operating regions, estimating the required compressor configuration and screening industrial waste-heat streams before detailed equipment design.

The proposed approach supports early-stage decision-making for industrial heat decarbonisation by linking thermodynamic performance with practical system constraints. It is particularly relevant to energy-intensive industries where low-grade vapour or waste heat is available and where electrified steam generation is being considered as part of broader decarbonisation strategies.

Key Words Mechanical vapour recompression; Industrial heat pumps; Waste-heat recovery; Steam generation; Techno-economic assessment; Industrial decarbonisation

Maintenance-Aware Optimal Chiller Loading for Data Center Cooling: Energy–Reliability Trade-offs under Compressor Cycling Constraints

Mauro Alfonso William,Adelso Flaviano Passarelli,Francesco Pelella,Valeria Piscopo,Luca Viscito

Università degli Studi di Napoli Federico II

The rapid growth of hyperscale data centers and Artificial Intelligence (AI) factories is increasing both the magnitude and variability of cooling demand, making the efficient and reliable operation of large multi-chiller systems increasingly important. Optimal Chiller Loading (OCL) strategies generally aim at minimizing energy consumption by continuously identifying the most efficient combination of active units and their load allocation. However, under highly variable cooling loads, pursuing the thermodynamic optimum may require frequent changes in compressor operating status. These start-stop events introduce mechanical, thermal and electrical stresses that are not captured by energy consumption alone and may increase maintenance requirements and reduce equipment lifetime. This work therefore investigates the trade-off between energy efficiency and compressor cycling, with the objective of identifying control strategies that account for both thermodynamic performance and maintenance-related effects.

The investigated 10 MW cooling plant, shown in Fig. 1, supplies a hyperscale data center or AI factory through Computer Room Air Handler units and consists of three parallel air-cooled chillers, each equipped with three variable-speed screw compressors using R1234ze, together with a dry free-cooling heat exchanger and a chilled-water storage tank. A physics-based dynamic model is used to reproduce the operation of the complete system. Annual simulations are carried out with a 10 min time step for Sydney, Rome and Vancouver, representative of warm, intermediate and cold climatic conditions. The same highly variable IT load profile is considered for the three locations and combined with the climatic contribution associated with heat transfer through the building envelope.

Figure 1. Scheme of the investigated 10 MW multi-chiller cooling system serving a data center or AI factory, including three parallel chillers, free cooling and chilled-water thermal storage.

At each operating condition, the OCL algorithm searches among the admissible combinations of active compressors, compressor frequencies and free-cooler operating levels and selects the configuration providing the maximum overall Energy Efficiency Ratio while satisfying the required cooling load. With the adopted discretization, approximately possible operating configurations are available. The brute-force optimization is conceived as an offline procedure, since the resulting optimal operating maps can subsequently be implemented as lookup tables within a supervisory controller.

Annual simulations show that pure OCL operation achieves the highest seasonal efficiency but leads to 3284 compressor start-ups in Sydney, 3291 in Rome and 2897 in Vancouver. An ON-status constraint is therefore introduced to prevent temporary changes in compressor status whenever the cooling demand can still be satisfied. Increasing the constraint duration strongly reduces compressor cycling, eventually bringing intermediate start-stop events close to zero. This improvement in operating stability is obtained at the expense of lower energy performance: for constraint durations up to 120 h, SEER decreases from 5.72 to 5.22 in Sydney, from 6.73 to 5.67 in Rome and from 9.18 to 7.42 in Vancouver. The energy penalty is

particularly evident in the colder Vancouver climate, where the constraint may also reduce the exploitation of favorable free-cooling conditions.

Figure 2. Effect of the ON-status constraint duration on the annual number of compressor start-ups and seasonal energy efficiency for Sydney, Rome and Vancouver.

To account for equipment degradation, the thermo-economic assessment introduces the concept of Equivalent Operating Hours (EOH), combining actual compressor operating time with an additional ageing contribution associated with each start-up event. Increasing the ON-status constraint therefore produces two competing effects: fewer start-stop events reduce cycling-related degradation, while longer continuous operation increases the actual running hours. Consequently, EOH and the associated running cost do not vary monotonically with the constraint duration.

Sensitivity analyses are performed by varying the equivalent ageing attributed to each start-up and the relative importance of maintenance and energy costs. For low start-up penalties, the optimal solution remains close to pure OCL. Conversely, when compressor cycling has a significant impact on degradation and maintenance, a clear minimum in the overall running cost appears. For a start-up penalty of 15 equivalent hours per start and sufficiently high maintenance weighting, the optimal ON-status constraint is approximately 10 h for all three investigated climatic conditions. Although the numerical optimum depends on the adopted load profile and economic assumptions, the results demonstrate that the energy-optimal strategy is not necessarily the one minimizing lifetime operating cost. Maintenance-aware supervisory control can therefore provide a more realistic basis for operating large multi-chiller systems serving data centers and AI-intensive facilities.

Figure 3. Effect of the ON-status constraint duration on the thermo-economic running cost for different assumptions (in Vancouver location) on compressor start-up degradation and maintenance-related costs.

Key Words data center cooling; multi-chiller systems; optimal chiller loading; compressor cycling; equivalent operating hours; thermo-economic optimization

Critical Heat Flux and Dryout Characteristics of Low-GWP Refrigerant in Additive Manufacturing Micro-channels

Luyao Guo,Long Huang

Xi'an Jiaotong-Liverpool University

Flow boiling in microchannels offers high heat-transfer capability for compact refrigeration and thermal-management systems, but its operating range is constrained by critical heat flux and the subsequent development of wall dryout. Experimental evidence for low-global-warming-potential refrigerants in additively manufactured microchannels remains limited. This study investigates the heat-transfer deterioration and dryout evolution of R454C during saturated flow boiling in a 3D-printed metallic microchannel. Thermal–hydraulic measurements were combined with high-speed visualization to relate the variation in heat transfer coefficient (HTC) to local two-phase flow behavior. Representative experiments were conducted at a saturation temperature of 5 °C, a mass flux of 300 $kg \cdot m^{-2} \cdot s^{-1}$, and heat fluxes ranging from 7 to 11 $kW \cdot m^{-2}$. The HTC evolution with vapor quality was divided into enhancement, oscillation, and deterioration regions. The initial HTC decline was identified as the onset of incipient dryout, whereas sustained dryout was characterized by persistent HTC deterioration and suppressed wall rewetting. Visualization results show that dryout develops progressively from intermittent local dry patches to persistent vapor-covered regions as the wall-adjacent liquid film becomes increasingly difficult to replenish. Increasing heat flux from 7 to 11 $kW \cdot m^{-2}$ raises the average HTC from 2675.24 to 3396.08 $W \cdot m^{-2} \cdot K^{-1}$, but shifts the incipient dryout quality from 0.34 to 0.29 and the sustained-dryout onset quality from 0.55 to 0.515. Meanwhile, the heat transfer contribution ratio of the deterioration region increases from 0.235 to 0.284, indicating a reduced dryout-free operating margin at higher heat flux. A modified HTC correlation incorporating dryout-region deterioration reduces the mean absolute error from 21.92% for the original Kim–

Mudawar correlation to 7.35% for the pre-dryout data and 8.63% for the complete database. These findings clarify the transition from incipient to sustained dryout and provide a predictive basis for evaluating R454C flow boiling in 3D-printed microchannels.

Key Words R454C; flow boiling; 3D-printed microchannels; incipient dryout; sustained dryout; heat transfer coefficient

Analysis of the Energy-Saving and Carbon Reduction Potential of Household Heat Pump Heating Systems

Hengyi Zhao[1],Long Ni[2],Yuanbo Zheng[3]

1. China Heat Pump Alliance

2. Harbin Institute of Technology

3. Northeast Forestry University

This study develops a multi-scale dynamic assessment framework to quantify the energy-saving and carbon reduction potential of replacing conventional household heating systems with air-source heat pumps (ASHPs) in China's hot summer and cold winter (HSCW) zone and cold zone. Addressing the research gaps of lacking systematic upscaling from household to regional level and overlooking dynamic grid decarbonization as well as regional emission factor differences, this research simulates typical residential heating loads, compares the performance of ASHPs, electric boilers and gas-fired boilers, and conducts multi-scenario dynamic projection at regional scale. Results indicate that ASHPs achieve the lowest primary energy consumption and carbon emissions. In new buildings of the HSCW zone, ASHPs realize approximately 34% and 70% energy savings compared with gas-fired and electric boilers, with corresponding carbon reductions of 18–21% and up to 70%. In the cold zone, the energy savings reach 29% and 68%, with emission reductions of 9–12% and 67–68%. Higher ASHP penetration and ongoing grid decarbonization will continuously amplify the carbon reduction benefits. Under the ideal high-growth scenario, the cumulative emission reductions of representative HSCW and cold regions will reach 303.38 and 360.73 million tons by 2060 respectively. This study provides a scientific basis for formulating region-specific heating policies.

Key Words Air-source heat pump; Household heating; Carbon reduction; Multi-scenario analysis; Regional scale; Energy efficiency

Experimental Study on the Heating Performance of an R290 Electric-Vehicle Compressor under Low-Temperature Conditions

Lihao HUANG[1,2],Chuanyu WANG[1],Fuan AI[3],Shangyou LU[3],Jianhong CHEN[4],Leren TAO[1,2],Xingjiang LI[1]

1. University of Shanghai for Science and Technology

2. Shanghai Key Laboratory of Multiphase Flow and Heat Transfer in Power Engineering

3. Zhejiang Oulun Electric Co., Ltd.

4. Zhejiang Minglun New Energy Co., Ltd.

To investigate the heating performance characteristics of an R290 electric vehicle (EV) compressor under low-temperature conditions, this study established a dedicated EV air-conditioning compressor test

platform and experimentally investigated its operating characteristics and performance trends under various low-temperature conditions. Oil circulation ratio (OCR) was monitored using a density method, and the influence of lubricating oil on evaporator heat transfer was analyzed. The results showed that the compressor power and heating capacity increased with rotational speed approximately linearly, while the coefficient of performance (COP) decreased as rotational speed increased. The effects of operating temperatures on system performance were significantly stronger than those of rotational speed. Specifically, when the evaporation temperature decreased by 5°C, the heating capacity decreased by 10.6%~15.3% and COP decreased by 7.1%~10.7%; when the condensation temperature increased by 10°C, COP decreased by 11.8%~14.8%. The volumetric efficiency reached a peak in the medium-speed range, and the isentropic efficiency decreased overall with increasing rotational speed. Both efficiencies were more strongly affected by evaporation emperature than by condensation temperature. Under high-OCR conditions, the adverse impact of lubricating oil on evaporator heat transfer became more pronounced. These findings indicate that the R290 compressor maintains satisfactory heating performance under low-temperature conditions. The quantified effects of OCR on system performance provide quantitative guidance for the design and optimization of R290 air-conditioning systems, and support the technical feasibility of using R290 as an environmentally friendly refrigerant in EV air-conditioning applications.

Key Words R290, Electric Vehicle, Compressor, Heating Performance, Oil Circulation Rate.

Flow Boiling Heat Transfer and Pressure Drop Characteristics of R513A in Horizontal Smooth and Microfin Tubes

Xicai Wei[1],Lihao HUANG[1,2],Fuan AI[3],Leren TAO[1,2],Shangyou LU[3],Jianhong CHEN[4]

1. University of Shanghai for Science and Technology

2. Shanghai Key Laboratory of Multiphase Flow and Heat Transfer in Power Engineering

3. Zhejiang Oulen Electric Co., Ltd.

4. Zhejiang Minglun New Energy Co., Ltd.

To investigate the boiling heat transfer and pressure drop characteristics of R513A in horizontal tubes with different fin configurations, an integrated horizontal single-tube test rig for condensation and evaporation was constructed. The experiments covered a mass flow rate of 20~40kg/h, evaporation temperature of 5~10 °C, heat flux of 0~56 kW/m², and outlet vapor quality of 0~1. The effects of fin structure, evaporation temperature, mass flow rate, and outlet vapor quality were investigated, and the experimental results were compared with empirical correlations. At an evaporation temperature of 10°C and a mass flow rate of 40 kg/h, the boiling heat transfer coefficient of the microfin tube was 38.28%~124.42% higher than that of the smooth tube, although its pressure drop was also higher. Increasing the helix angle by 44.44% and decreasing the tooth tip angle by 14.29% further enhanced heat transfer but increased pressure drop. At constant mass flow rate and evaporation temperature, the heat transfer coefficient first increased and then decreased with increasing outlet vapor quality. Increasing mass flow rate enhanced both the heat transfer coefficient and pressure drop, whereas increasing evaporation temperature increased the heat transfer coefficient but reduced the pressure drop. For heat transfer prediction, the Liu-Winterton and Tran correlations showed the best agreement for the smooth and microfin tubes, with average relative errors of −6.91% and −4.24%, respectively. The Chisholm correlation provided the best prediction of pressure drop in the microfin tube, with an average relative error of 0.75%.

Key Words R513A; Flow boiling; Heat transfer coefficient; Pressure drop; Correlation

3D Printed Xerogel–MOF Composites for Atmospheric Water Harvesting with Potential Heat-Pump-Assisted Regeneration

Dejan Trajkovski[1],Ana Pereira[2],Alexandre F. P. Ferreira[2],Primož Poredoš[1]

1. University of Ljubljana, Faculty of Mechanical Engineering

2. Laboratory of Separation and Reaction Engineering - Laboratory of Catalysis and Materials, Faculty of Engineering, University of Porto

Atmospheric water harvesting (AWH) offers a promising approach for decentralized freshwater production by capturing water vapour directly from ambient air. However, practical sorption-based AWH systems require sorbent architectures that combine high water uptake, rapid mass transport, structural stability, and energy-efficient regeneration. This study investigates a 3D-printed hierarchical xerogel-MOF composite designed for atmospheric moisture capture and potential integration with heat-pump-based regeneration systems. Sodium alginate was used as the printable hydrogel matrix and reinforced with cotton microfibers (CMF) to improve structural integrity and provide sites for LiCl crystallization and retention of the hygroscopic solution. Functionalized multi-walled carbon nanotubes (MWCNTs) were incorporated to enhance photothermal conversion, while MIL-100(Fe) provided additional nanoporous adsorption sites. Extrusion-based 3D printing generated interconnected macroporous channels, while the hydrogel/xerogel matrix and MOF introduced smaller-scale transport and adsorption pathways, creating a hierarchical structure for enhanced vapour diffusion. The fabricated xerogels were evaluated at 20°C under 75% and 33%, 95% relative humidity. Rapid initial water uptake followed by gradual equilibration was observed for all samples. LiCl-containing composites exhibited the highest equilibrium adsorption capacities, while CNT incorporation further enhanced moisture uptake and enabled efficient photothermal heating. These characteristics demonstrate the potential of the developed composites for cyclic atmospheric moisture capture and low-energy regeneration. In heat-pump-assisted configurations, regeneration could be supplied by low-grade heat from the heat-pump condenser, enabling utilisation of otherwise rejected thermal energy for water production. The proposed approach therefore provides a pathway toward integrated heat-pump systems capable of combining thermal-energy management with atmospheric water recovery.

Key Words Atmospheric water harvesting, Heat pumps, Hydrogel, Xerogel, Metal-organic frameworks, LiCl, 3D printing, Photothermal regeneration, Thermal energy recovery

Thermodynamic Performance Analysis of an Integrated PEMFC-High Temperature Heat Pump System

Jie Wang,Zhenqian Chen

southeast university

The integrated PEMFC-HTHP configuration enables cascaded utilization of hydrogen energy by converting fuel-cell waste heat into industrial steam while simultaneously generating electricity. The results reveal a clear power-steam trade-off: current density primarily controls system output magnitude, stack temperature redistributes energy between electricity and recoverable heat, and steam temperature determines the HTHP compression burden. Higher stack temperature can improve COP, but may suppress steam output; excessive current density and large temperature lift reduce overall efficiency. These findings provide a thermodynamic basis for selecting operating conditions according to the actual electricity-to-steam demand ratio of industrial parks and for subsequent experimental development of PEMFC-assisted high-temperature steam heat-pump systems.

Key Words Proton exchange membrane fuel cell; High-temperature heat pump; Steam generation; Power-steam cogeneration; Energy efficiency.

Development and Performance Analysis of a Multi-Energy Complementary CCHP System Coupled with Thermochemical Heat Storage and an Absorption Heat Pump

Shaowu Yin[1,2],Jiarui Zeng[1],Lige Tong[1],Meimei Xiao[1]

1. University of Science and Technology Beijing

2. Xinjiang Institute of Engineering

The growing imbalance between global energy supply and demand, compounded by rising end-user energy consumption that widens the peak-to-valley grid difference, calls urgently for efficient, clean, and actively controllable multi-energy complementary systems. This study develops a multi-energy complementary combined cooling, heating and power (CCHP) system that integrates thermochemical heat storage with an absorption heat pump. The core idea is to exploit the long-term storage capability of solar thermal energy and the advantage of the absorption heat pump driven by low-grade thermal energy instead of high-grade electricity, thereby enhancing overall energy efficiency and enabling peak load shifting. The research is carried out in two interrelated aspects: system-level integration and storage material development.

At the system level, a solar-CCHP model is built in Aspen Plus, and multi-objective optimization is employed to determine the optimal operating parameters for summer cooling and winter heating modes, respectively. Under the obtained optimal conditions, thermodynamic and thermo-economic performances are comprehensively evaluated based on mass, energy and exergy balance equations, quantifying the exergy destruction distribution and economic feasibility of key components.

At the material level, a thermochemical storage material suitable for the medium-temperature range of 80–130°C is developed to match solar collector operation. The material's microstructure and thermophysical properties, including thermal conductivity and storage density, are characterised using simultaneous thermal analysis (STA) and the transient plane source (TPS) method. The developed material is then integrated into the CCHP system, and a multi-dimensional evaluation framework covering "material performance – system efficiency – economic cost" is introduced, establishing a full-chain assessment from material R&D to engineering application.

Economic analysis shows that the Mg-Cu-EG composite, owing to its high volumetric energy density and in-situ heat storage capability, eliminates the need for complex auxiliary systems in the storage tank. The tank cost is reduced by 63.04% and 36.64% compared with conventional thermal oil and HDPE solutions, respectively. These results confirm the technical and economic superiority of this material for medium-low temperature multi-energy complementary applications, and provide theoretical and material-level support for the engineering deployment of solar-driven CCHP systems.

Key Words Thermochemical Energy Storage, Absorption Heat Pump, Combined Cooling, Heating and Power (CCHP) System, Multi-energy Complementarity, System Development

A Sustainable Path Towards Hyperscale AI Data Centres Using Radiative Cooling: Energy and Water Savings Potential

Primož Poredoš[1],Davide Forte[2],Matteo Fasano[2],Lorenzo Patelli[3],Dejan J. Trajkovski[1],Higgins M. Wilson[1],Abdallah Y. M. Ali[1],Tej Žižak[1],Eva Zavrl[1],Ciril Arkar[1],Sašo Medved[1]

1. Laboratory for Sustainable Technologies in Buildings,

2. Department of Energy, Politecnico di Torino

3. Istituto Nazionale di Ricerca Metrologica

The rapid expansion of large language models and AI agents is intensifying data-centre cooling demand: training compute for AI models is doubling every five months, while data-centre electricity consumption is projected to rise from 415 TWh in 2024 to 945 TWh by 2030. This growth matters climatically, as data-centre electricity-related emissions may increase from 180 $MtCO_2$ today to 300 $MtCO_2$ by 2035, within an energy system that emitted a record 37.8 $MtCO_2$ in 2024. Water security is equally urgent: 2.1 billion people, about one in four still lack safely managed drinking water, and the water-supply shortfall could reach 40% by 2030.

Against this energy–water nexus, spectrally engineered radiative cooling materials offer a heat-rejection pathway by combining solar reflectivity exceeding 95% with strong thermal emission through the 8-13 μm atmospheric window, enabling passive heat rejection even under sunlight. This study evaluates their integration with a vapour-compression heat-pump/chiller system for a 500-kW data centre. Three integration positions: liquid-line subcooling, pre-condenser refrigerant cooling, and evaporator load-side precooling upstream of the evaporator, are each combined with dry and evaporative condensers, yielding six configurations. All cases use the same 504 m2 radiative cooling collector field, flow, weather profile, parasitic-power accounting, and same-timestep loop convergence.

Evaporator load-side integration delivered the strongest savings potential. With a dry condenser, electricity use decreased by 12.86%, system COP/EER increased by 14.76%, and cooling partial PUE decreased by 2.66%. With an evaporative condenser, electricity and water use decreased by 9.74% and 13.01%, respectively, while system COP/EER increased by 10.79%. Liquid subcooling with dry cooling reduced electricity use by 6.53%. Pre-condenser cooling achieved 6.82% water saving with an evaporative condenser but only 0.33% electricity saving because condensing pressure remained fixed. Similar collector heat rejection in pre-condenser and load-side cases produced different energy savings, demonstrating that integration position determines thermodynamic leverage. Scaling corresponds to approx. 1008 m2 MW-1, or 0.504 km2 for a 500 MW AI campus.

Key Words Data centre thermal management, Radiative cooling, Water savings, Energy efficiency, COP/EER.

"Indoor airflow control for zonal thermal comfort: a sequential meta reinforcement learning approach"

Shanxuan Tang

Shanghai Jiao Tong University

Indoor environment control is evolving toward intelligence, personalization, and refinement, where precise indoor airflow control has become the core bottleneck. The underutilization of controlled variables, along with infeasible spatial distributed sensing of indoor temperature, hinders effective control and leads to unsatisfactory control performance in conventional zero-dimensional temperature control methods. This paper aims to develop an algorithm for precise temperature regulation in targeted indoor regions to achieve a comfortable local microclimate. This paper reformulates traditional zero-dimensional control into a field control problem. Instead of treating the entire indoor environment as a single, homogeneous entity and adjusting only the overall average temperature, the paper takes into account spatial variations in temperature through continuous spatial zones. The study reveals temporal invariance in the jet centerlines of heat pumps, enabling steady-state sequential control models to replace dynamic coupled control models. A sequential reinforcement learning control architecture is therefore proposed. The high-level policy regulates jet centerlines for directing airflow toward the target, and the low-level policy adjusts outlet air state to modify the local thermal sensation. This sequential structure decouples airflow direction and ambient adjustment, reducing the control complexity under field control conditions. Validated in real-world residential environments, the proposed method achieves an average temperature control error of 0.40°C within a 1m×1m×1m targeted microclimate cube. The method fills the research gaps in airflow control under large-action space and complex residential environments, providing a reliable modelling solution for indoor environment control.

关键词 HVAC, Indoor Environment, Airflow Control, Reinforcement Learning, Meta Learning.

Life cycle assessment of adsorption and compression chillers in terms of exergy

Atsushi Akisawa,Taisei Nishimura

Tokyo University of Agriculture and Technology

Adsorption chillers consume heat to supply cooling while compression chillers use electric power. Because heat and electric power are physically different, it is not appropriate to compare these technologies simply from energy consumption. The objective of this study is to analyze life cycle assessment (LCA) of an adsorption chiller and to compare the life cycle exergy consumption with a compression chiller. The study adopted an IO table-based method to estimate the coefficient of exergy consumption of each industrial sector, which presents the indirect exergy consumption in materials such as steel, plastics and so on. The exergy consumption to operate chillers is also estimated. As for the exergy consumption through materials, the adsorption chiller takes 4 times larger than the compression chiller due to the heavy weight. In contrast, the adsorption chiller consumes 1/4 as much exergy for running as the compression chiller. Because the temperature of heat for the adsorption chiller is 70°C, the contained exergy is enough small. It should be noted that the exergy consumption to operate chillers is dominant, therefore, the life cycle exergy consumption by the adsorption chiller is approximately 1/4 of that of the compression chiller. Consequently, the LCA results suggest that adsorption chillers are advantageous even though the COP is as low as 0.5.

Key Words Life cycle assessment, Exergy, Adsorption chiller, Compression chiller, Low grade heat

Passive moisture pump for efficient indoor latent load management

Dae Young Jung,Yong Tae kang

Korea university

Regulating indoor humidity is essential for building energy conservation and thermal comfort, yet it remains a rate-limiting factor in heating, ventilation, and air conditioning (HVAC) performance. Heat pumps efficiently manage sensible heating and cooling loads, but latent-load management still lacks a comparable solution. Existing dehumidifiers are either energy-intensive or, in their passive forms, limited to intermittent or small-scale operation. Here, we present a passive counterpart to the heat pump for latent load management: a liquid-state moisture pump that continuously transports water vapor against an air-side vapor pressure gradient using only low-grade heat at 40-50°C. An aqueous potassium formate solution circulates through a multistack membrane contactor by buoyancy-driven flow generated by the same heat input that drives desorption. A single heat source therefore sustains both moisture release and solution circulation, while the solution composition self-adjusts to balance absorption and desorption fluxes under varying operating conditions. A three-channel prototype removes 72.2 g h-1 with zero electrical input, and a validated model predicts a moisture removal rate of 0.8 kg h-1 for the full fifteen-channel design. When integrated with a residential energy-recovery ventilator, the device achieves a total heat exchange efficiency of 93.2% in heating mode and 74.1% in cooling mode.

Key Words Humidity control, Liquid desiccant, Moisture pump, Thermosyphon, Passive system

Comparative energy and environmental impact assessment of R-410A, R-32 and R-290 air-to-water heat pumps through dynamic building simulation

Maurizio Sasso,Elisa Marrasso,Chiara Martone,Giovanna Pallotta,Ilenia Perugini,Carlo Roselli

Università degli Studi del Sannio

The decarbonization of the building sector is increasingly driven by the electrification of heating and cooling systems and the transition toward refrigerants with lower global warming potential (GWP) [1]. In this context, air-to-water heat pumps (AWHPs) represent a key technology for improving the energy efficiency of buildings while reducing their reliance on fossil fuels. Among the refrigerants currently used in these applications, R-410A has been widely adopted due to its established technological maturity [2]. However, its relatively high GWP has led to its progressive replacement by lower-GWP alternatives, such as R-32 and R-290 [3,4]. The latter, while offering a particularly low GWP, is highly flammable and therefore requires appropriate safety measures [5].

Previous studies have widely demonstrated the potentialities of these refrigerants, while highlighting the strong dependence of their performance on operating conditions, system configurations, and heat-exchanger characteristics [6]. A key gap concerns the assessment of environmental impacts, which is often based on stationary approaches that assume, for instance, constant equivalent carbon dioxide (CO_2eq) emission factors for the power grid. Such approaches may fail to capture the temporal variability of the electricity-production mix and, consequently, may not adequately represent its evolution over time or the prospective environmental implications of electric heat pumps. Based on these premises, this work aims to assess the energy and environmental performance of an AWHP using different refrigerants, with particular focus on the comparison between the conventional R-410A and lower-GWP alternatives. The analysis combines dynamic building-plant simulation with a dynamic Total Equivalent Warming Impact (TEWI) assessment, accounting for both direct refrigerant-related emissions and indirect CO_2eq emissions associated with electricity demand.

The AWHP under analysis serves the EX-INPS building of the University of Sannio in Benevento, Italy. The building is a historical three-storey structure used for offices, laboratories, and teaching activities, with a total floor area of approximately 1820 m2. The building envelope is characterized by tuff masonry and wooden-frame single glazing, resulting in thermal transmittance values of 0.76 W/m2K for the external walls, 1.22 W/m2K for the roof, 2.64 W/m2K for the intermediate floor, and 5.87 W/m2K for the windows [7]. The existing AWHP has nominal heating and cooling capacities of 293.5 and 230.7 kW, respectively, and uses 76 kg of R-410A, corresponding to a GWP of approximately 2088. The alternative systems use 19 kg of R-32 (GWP 771) and 9.7 kg of R-290 (GWP 3), respectively.

A detailed dynamic building-plant model was developed in TRNSYS 18. The building was represented using Type 56 and divided into 15 thermal zones. The AWHPs were simulated using Type 525 from the TESS library, and their behaviour was characterized through custom-made performance maps generated from manufacturer data. The maps accounted for outdoor air temperature, water supply temperature, and partial load ratio, allowing the performance of each configuration to be reproduced under variable operating conditions. The simulation was performed using a 1.5-min time step over a one-year period.

The energy performance of AWHPs was evaluated using the coefficient of performance (COP) in heating mode and the energy efficiency ratio (EER) in cooling mode. Two calculation approaches were adopted: on the one hand, performance indicators were determined directly from monthly energy balances; on the other, as monthly averages of the corresponding hourly values. The environmental assessment was performed using a dynamic Total Equivalent Warming Impact (dyTEWI) index. Unlike conventional TEWI, the proposed approach employs time-dependent CO_2eq emission factors for the Italian power grid. Historical data was considered for 2015-2023, while the results for 2024-2029 were estimated through linear regression under two forecasting scenarios. Refrigerant leakage was also modelled dynamically over a 15-year service life, considering monthly charge variations, maintenance and recharge operations, and end-of-life losses.

The building simulation resulted in annual heating and cooling demand of 58.5 and 14.1 MWh, respectively. Heating demand was concentrated mainly between January and March and during November and December, with a maximum monthly value of 14.6 MWh in January. Cooling demand was concentrated

between June and September, reaching a maximum of 7.0 MWh in July. The comparative analysis of the three AWHP configurations showed clear differences in electricity demand. The R-410A-based system generally exhibited the highest monthly electricity needs, whereas the R-290 configuration consistently required the lowest amount of electricity. For example, the electricity consumption in January decreased from approximately 8.0 MWh for R-410A to 6.5 MWh for R-290. The total annual electricity demand of the AWHPs was approximately 34.5, 35.4, and 29.6 MWh for R-410A, R-32, and R-290, respectively.

The performance analysis confirmed the advantage of R-290 under the operating conditions considered. The maximum monthly COP obtained for the R-290 configuration was 3.7, while the corresponding maximum EER was 3.9. R-32 generally showed intermediate performance, whereas R-410A exhibited the lowest values in the monthly assessment. The analysis based on hourly averages confirmed the same general trend, with R-290 providing the highest performance in both heating and cooling operation.

The environmental analysis further emphasized the advantages of low-GWP refrigerants. The direct contribution to dyTEWI was substantially higher for R410A than for R-32 and was almost negligible for R-290, primarily because of the very low GWP of propane. The indirect contribution showed a decreasing trend over the 2015-2023 period for all three configurations, reflecting the progressive spreading of renewable plants in the Italian electricity production mix. For R-410A, annual indirect emissions decreased from 16.3 tCO_2eq in 2015 to 12.1 tCO_2eq in 2023; corresponding values for R-32 decreased from 15.5 to 11.3 tCO_2eq, while R-290 decreased from 13.0 to 9.6 tCO_2eq.

To estimate the environmental impact over the entire operational lifetime, two forecasting approaches based on linear regression were considered. The conservative scenario used the complete 2015-2023 dataset and resulted in a coefficient of determination of approximately 0.63. The relatively moderate fit was influenced by the anomalous increase in the CO_2eq emission factor of the power grid observed in 2021-2022, associated with the post-pandemic recovery and the energy crisis. An optimistic scenario was therefore developed using only the 2015-2020 period, characterized by a steadier decreasing trend. This approach resulted in a substantially higher coefficient of determination of approximately 0.96, providing a more consistent representation of the historical trend.

The life-cycle environmental results confirmed the superiority of the R-290 configuration. Over the 2015-2029 assessment period, the total dyTEWI was 144.6 and 139.3 tCO_2eq for R-290 under the conservative and optimistic scenarios, respectively. These values were substantially lower than those obtained for R-32, equal to 177.5 and 147.2 tCO_2eq, respectively, and for R-410A, equal to 248.4 and 216.9 tCO_2eq, respectively. Therefore, the results showed a consistent advantage of R-290 in both energy and environmental terms.

The dynamic approach adopted in this study enabled a realistic representation of variable operating conditions through alternative building-plant simulations applied to the same real building and system configuration. These aspects are crucial for accurately assessing the long-term sustainability of heating and cooling systems and for supporting the selection of alternative technologies aimed at mitigating climate change. Future research could extend the present analysis by investigating the integration of AWHP systems with on-site renewable energy supply and could also consider alternative control strategies capable of optimizing the operation of the AWHP based on energy, environmental, and economic criteria.

Key Words Air-to-water heat pump; Environmental impact assessment; Dynamic Total Equivalent Warming Impact; Low-global warming potential refrigerants

Research on the Performance of All-Weather Thermal Management System for Lunar Cabin Based on CO_2 Heat Pump Hybrid System and In-Situ Lunar Soil Energy Storage

Zhicheng Zhu[1],Yuan Ma[1],Yulong Song[1,2],Feng Cao[1,2],Yiying Bao[3],Anyi Xu[3],Yimin Ji[3]

1. Xi'an Jiaotong University

2. School of Smart Energy Storage, Xi'an Jiaotong University

3. Aerospace System Engineering Shanghai

This study proposes an innovative thermal management system for lunar cabin based on the CO_2 heat pump hybrid system and In-Situ lunar soil energy storage, which addresses the temporal mismatch between the power supply and thermal management requirements of the lunar cabin during the lunar day and night periods by integrating heat pump technology with a high-capacity thermal storage medium. Through switching valves, the proposed system can be switched between the heat pump mode and pump-driven mode, enabling both temperature-lift thermal storage and direct thermal energy recovery.

In addition, a cross-period thermal energy management strategy is developed by utilizing modified lunar soil as a sensible thermal storage medium. During the day period when the solar cells have sufficient power and the lunar cabin has a need for heat dissipation, the system first slightly employs pump-driven circulation to recover low-grade waste heat from cabin, then highly operates in the heat pump mode to elevate the storage temperature and increase the stored thermal capacity. During the night period when the electric power is deficient and the lunar cabin need to be heated, the stored thermal energy is preferentially released through the pump-driven mode for saving power, while compressor-based heat pump heating is activated only when the storage capacity or heat release capability becomes insufficient.

Furthermore, a supervisory control strategy based on thermal load demand, storage temperature, CO_2 operating parameters, available power, and battery state of charge is developed to achieve autonomous switching among multiple operating modes. The results demonstrate the potential of combining advanced CO_2 heat pump technologies with lunar soil thermal energy storage, providing valuable insights for future applications in the thermal management support technologies for more complex space missions.

Key Words CO_2 Heat Pump, Thermal Energy Storage, Lunar Soil, Pump-Driven Cycle, Lunar Thermal Management, Multi-Mode Control

Comprehensive study of an R134a ejector-enhanced dual-evaporator refrigeration system

Cong You[1],Xing Fang[2],Kan Chen[2],Peixue Jiang[1],Yinhai Zhu[1]

1. Tsinghua University

2. 美的集团股份有限公司

Ejectors are thermally driven devices with no moving parts that recover expansion work otherwise dissipated across throttling valves, thereby reducing compressor power demand and increasing the coefficient of performance (COP) in vapor-compression refrigeration systems. Despite this potential, ejector technology has been predominantly demonstrated in high-pressure CO_2 transcritical systems. While these high-pressure conditions favor ejector performance, they concurrently introduce significant safety concerns and impose stringent requirements on system components, resulting in elevated manufacturing and operational costs. Conversely, applications with conventional low-pressure refrigerants such as R134a have received comparatively less attention, with most studies confined to laboratory-scale experiments. To further augment the performance of ejector-enhanced cycles, integrating a dual-evaporator configuration presents a compelling strategy. However, the fixed geometry of two-phase ejectors makes their performance highly sensitive to off-design operating conditions, so the coupling between the ejector and the dual-evaporator loop must be properly coordinated through both modeling and control.

This study presents an experimental investigation and coordinated control framework for an R134a vapor-compression cycle integrating a two-phase ejector with a dual-evaporator loop. The system comprises a high-temperature evaporator (HTE) and a low-temperature evaporator (LTE), coupled with a ejector module. A coupled thermodynamic-CFD co-simulation is first established to determine the optimal operating setpoints: the system model supplies the primary and secondary flow states as boundary conditions to the CFD solver, while the CFD simulation of ejector returns the entrainment ratio to the system model.

An iterative loop continues until convergence, accurately capturing the ejector characteristics under varying thermal loads.

The co-simulation reveals that the ejector entrainment ratio and pressure lift are strongly governed by the inter-evaporator load distribution. As the HTE and LTE loads shift, the suction condition of the ejector changes, driving the operating point along its characteristic curve. These insights motivate a coordinated control strategy that dynamically matches the ejector module to the real-time load demand.

An experimental prototype was tested to verify operational feasibility and to support the coupled modeling. The results demonstrate consistent COP improvements from 2.02% to 4.29% over a conventional single-evaporator baseline across various part-load conditions, with the peak gain of 4.29% occurring at 25% part-load. These results show good agreement with the simulation predictions.

While the present work is demonstrated as a chiller producing chilled water cooled from 12°C to 7°C, the underlying coordinated control methodology is directly transferable to heat pump applications. In such scenarios, the high-temperature evaporator can function as a heat recovery source, supplying useful thermal energy while maintaining high system efficiency. This provides a replicable framework for low-pressure refrigerant systems in both refrigeration and heat pump sectors.

关键词 Ejector, Dual-evaporator, Coordinated control, Experimental investigation, CFD

Decarbonisation NHS estates: Multi-energy management via Carnot battery for improved energy efficiency and flexible operation

Xiao Liu[1],Jiatong Jiang[1,2],Jiajia Fan[1,3],Jian Song[1]

1. University of Birmingham

2. Institute of Refrigeration and Cryogenics, Engineering Research Centre of Solar Power & Refrigeration, Shanghai Jiao Tong University, Shanghai, 200240, China

3. Institute of Information Studies, Shanghai Academy of Social Sciences, Shanghai, 200235, China

The NHS is the largest single energy user in the public sector and accounts for approximately 4-5% of the UK's greenhouse gas emissions. It has committed to achieving net-zero emissions across its estate by 2040, requiring a rapid transition from fossil-fuel based heating towards low-carbon electrified solutions. Heat pumps (HPs) are expected to play a key role in this transition. However, their widespread deployment may increase electricity demand and peak loads, creating additional challenges for energy system operation. Integrating HPs with thermal energy storage (TES) can mitigate these impacts by shifting electricity consumption across time and decoupling heat generation from heat demand. The coordinated integration of HPs and TES within Carnot battery-based multi-energy systems therefore offers a promising approach to improving energy efficiency and operational flexibility while supporting the decarbonisation of NHS estates. In this work, a Carnot battery-based multi-energy management framework integrating HPs, TES, an organic Rankine cycle (ORC), and flexible demand responding strategies is developed for NHS hospital energy systems. Queen Elizabeth Hospital (QEH) in King's Lynn is selected as a representative case study to evaluate and optimise the proposed system under different seasonal operating conditions. Key system parameters and operating strategies are optimised under time-varying energy demand and price conditions to minimise energy bills while improving energy efficiency and operational flexibility. Performance indicators including coefficient of performance (COP), round-trip efficiency, life-cycle cost (LCC), payback period, and carbon emissions are evaluated to assess the technical, economic, and environmental performance of the proposed system. The results provide technical insights and decision support for NHS Estates teams in future decarbonisation planning.

Key Words heat pumps, thermal energy storage, system integration, operational optimisation, multi-energy management

Numerical study on climate-adaptive zonal operation of borehole thermal energy storage for long-term seasonal heating in cold regions

Yu Zhang,Xuan Wu,Yan Xue,Guibo Wan,Huiling Chen

Inner Mongolia University of Science and Technology

Borehole thermal energy storage (BTES) can improve renewable heat utilization in cold regions, but long-term operation may cause thermal accumulation. A three-dimensional transient model of a 57-borehole array was developed in ANSYS Fluent and validated against measured borehole-wall temperatures, with a maximum relative error of 2.94%. Five operating strategies were compared over five annual cycles in severe cold and cold regions. Mode 4, combining overall storage with demand-based time-dependent zonal release, showed the best comprehensive performance, with fifth-cycle soil temperature recovery rates of 99.52% and 99.75%, respectively.

Key Words Borehole thermal energy storage; Borehole heat exchanger array; Climate-adaptive zonal operation; Seasonal thermal energy storage; Zonal control strategy

Development of a Heat Transfer Correlation for Industrial High-Temperature Condensation Tubes with Various External Surface Geometries

Pyeongse Lee

Korea University

High-temperature heat for industrial processes has traditionally been supplied by fossil-fuel boilers; however, alternative technologies are increasingly required due to rising fuel costs and carbon reduction demands. High-temperature heat pumps (HTHPs) have emerged as a promising solution, with condenser performance playing a key role in overall system efficiency. In this study, the external condensation heat transfer characteristics of three enhanced carbon-steel tubes with different fin and knurling geometries were experimentally investigated using R1233zd(E) at a saturation temperature of 110°C. The effects of external surface geometry on condensation performance were analyzed, and a modified Nusselt-number correlation incorporating geometric parameters was developed. The proposed correlation predicted all experimental data within ±8% and can be applied to the design and performance prediction of condensers for industrial HTHP systems.

Key Words High-temperature heat pump, Condensation heat transfer, Enhanced tube

Numerical Investigation of Zonal Operation Strategies for Long-Term Seasonal Borehole Thermal Energy Storage

Yan Xue,Xuan Wu,Guibo Wan,Yu Zhang,Huiling Chen

Inner Mongolia University of science and technology

A borehole thermal energy storage (BTES) array with 57 boreholes was investigated under zonal inlet-temperature control over three consecutive years. Four non-uniform modes were compared using soil temperature, heat transfer per unit borehole depth, and storage-release efficiency. Mode 3 produced the

largest average soil-temperature increase, whereas Mode 4 achieved the highest Year 3 efficiency of 16.11%.

Key Words Borehole thermal energy storage, Zonal control, Non-uniform intensity, Soil temperature, Storage-release efficiency.

Energy Analysis of a Heat Pump Integrated Desiccant Rotor System for Ultra-low Humidity Dry Rooms

Sanghyeon Lee[1,2],Minjae Kim[1,2],Dae Young Jung[2],Yong Tae Kang[1,2]

1. Korea university

2. Research Center for Plus Energy Building Innovative Technology

1. Introduction

Ultra-low humidity dry rooms requiring dew points below -60°C, are essential for manufacturing lithium-ion and solid-state batteries [1]. However, these facilities are characterized by substantial energy consumption [2], primarily due to the high-temperature requirements for desiccant regeneration and the subsequent cooling processes. Conventional systems relying on separate heaters and chillers, provide heating and cooling independently, resulting in significant energy penalties. To address this structural inefficiency, this study proposes the integration of a heat pump with a desiccant rotor system. The proposed architecture provides a dual thermal benefit: simultaneous utilization of the condenser heat for regeneration and the evaporator cooling capacity for process air cooling.

2. Methodology

The proposed system achieves ultra-low humidity via two-stage dehumidification, using silica gel in the first stage and zeolite 13X in the second stage (Fig.1). The process air first passes through the 1st rotor, where substantial adsorption heat is generated. To prevent the degradation of dehumidification performance, the heated process air is cooled to 10°C before entering the 2nd rotor. Meanwhile, the first-stage desiccant requires a regeneration source at 120°C for continuous operation. To support this process, a high-temperature cascade heat pump is employed, utilizing R1233zd(E) in the top cycle and R513A in the bottom cycle. The bottom-cycle evaporator provides cooling for the 15°C inter-cooling process, while the recovered heat is upgraded through the top-cycle condenser to supply the 120°C regeneration air.

To evaluate the performance of this proposed system, a modular simulation framework was developed, integrating a transient desiccant rotor model with a steady-state heat pump model. The governing equations for coupled heat and mass transfer [3] within the desiccant rotors were numerically solved using a Lagrangian approach to track the transient states of the air streams and desiccants. For the cascade heat pump, an approach temperature of 18 K was assumed for the air-to-refrigerant heat exchangers, while 5 K was assumed for the refrigerant-to-refrigerant.

Fig.1 System description

A load-tracking control strategy was implemented to address the inherent thermal load mismatch between the heating and cooling streams. The heat pump operation aims to meet the heating demand of the first stage, while using the available cooling capacity to cover the inter-cooling load.

3. Results

The simulation was conducted under a humid ambient condition with incoming air pre-cooled to 10°C at 90% relative humidity before entering the first-stage rotor. Based on a commercial-scale configuration, the system processes a total airflow of 40,000 CMH, which is divided into 30,000 CMH for the main supply air and 10,000 CMH for the regeneration streams. Table 1 summarizes the calculated thermal loads and the performance comparison between the baseline and the proposed system. For the baseline evaluation, the chiller for cooling assumed to have a COP of 3.5, and the electrical heater was assumed to have an efficiency of 1.0.

While the baseline consumed 557.8 kW of total electrical power, the proposed system fully supplied the 194.8 kW first-stage heating demand, and simultaneously recovered 87.6 kW of cooling, which is correspond to 81.5% of the intercooling load. Consequently, the total system power consumption of the proposed system was reduced to 450.8 kW, demonstrating a 19.2% reduction compared to the baseline. Additionally, system-level dehumidification COP (DCOPsys) increased from 0.247 to 0.306, a 23.7% enhancement. When considering the regeneration energy only, the thermal DCOP (DCOPth) improved 32.6% (increasing from 0.414 to 0.549). It is important to note that the overall system efficiency is heavily constrained by the large capacity of the pre-cooling coil.

4. Conclusion

This study proposed a heat pump integrated desiccant rotor system that thermally couples the regeneration and inter-cooling processes. Compared to the baseline system, the proposed architecture reduced total electrical power consumption by 19.2% and improved the DCOPsys by 23.7%. These results demonstrate the potential of heat recovery between heating and cooling demands to improve the energy efficiency of dry-room operation.

Table 1 Summary of system loads and performance comparison

Baseline	Parameter	Baseline	Proposed system	Percentage (%)
Thermal Loads & offset by heat pump [kW]	Pre-cooler	631.8	-	-
	1st stage regeneration	194.9	194.9	100%
	Inter-cooler	107.5	87.6	81.5%
Baseline	Parameter	Baseline	Proposed system	Percentage (%)
	2nd stage regeneration	138.2	-	-
	After-cooler	47.3	-	-
System performance comparison	Compressor power [kW]	-	112.9	-
	Total electrical power [kW]	557.8	450.8	-16.9%
	DCOPsys	0.247	0.306	+23.7%
	DCOPth	0.414	0.549	+32.6%

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References

[1] Liu, B., and Fang, C., 2026, From Mechanism to Metrics: Quantitative Insights into Moisture Stability of Solid-State Electrolytes, ACS Energy Letters, Vol. 11, No. 3, pp. 1154-1160.

[2] Yuan, C., Deng, Y., Li, T., and Yang, F., 2017, Manufacturing energy analysis of lithium ion battery pack for electric vehicles, CIRP Annals - Manufacturing Technology, Vol. 66, No. 1, pp. 53-56.

[3] Ge, T. S., Ziegler, F., and Wang, R. Z., 2010, A mathematical model for predicting the performance of a compound desiccant wheel, Applied Thermal Engineering, Vol. 30, No. 8-9, pp. 1005-1015

Key Words Dry rooms, Heat pump, Heat recovery, Cascade heat pump, Desiccant rotor

Experimental investigation on frosting characteristics and energy efficiency optimization of a semi-open air cycle heat pump with booster turbo-expander

Haotian Xu,Zhaowei Xu,Yingxia Yang,Binfei Zhan,Zhichao Wang

China Academy of Building Research

To address the key industrial challenge of severe frosting and sharp performance degradation in conventional vapor-compression air source heat pumps under low-temperature and high-humidity environments, this paper proposes a semi-open air cycle heat pump system equipped with a booster turbo-expander. Based on the constructed experimental prototype, 7 groups of steady-state tests over a wide temperature range and 92-min high-frequency dynamic tests under the typical frosting condition of 2°C are conducted. The performance parameters across all operating conditions and the frosting evolution law are systematically presented first, followed by in-depth analysis from three dimensions: component characteristics, self-maintenance mechanism, and optimization path. The results show that: within the wide temperature range of −30°C to 7°C, the COP attenuation of the system is no more than 15%, and its low-temperature adaptability is significantly better than that of conventional heat pumps. For the first time, the frosting process is quantitatively divided into three stages: initial frosting period, fluctuation adjustment period, and stable operation period; during the stable operation period, the COP fluctuation amplitude is less than 4.2%. A triple mechanism of performance self-maintenance is revealed from structural, thermodynamic, and systematic perspectives, which can offset approximately 42%~48% of the frosting-induced performance degradation on average across all operating conditions. Combined with exergy analysis and parameter sensitivity analysis, it is clarified that the isentropic efficiency of the compressor is the primary direction for energy efficiency optimization, and the collaborative optimization of the compressor and expander can increase the COP by approximately 21.2%. Calculations show that under the heating season conditions in severe cold regions, the system can save approximately 22%~28% of heating energy consumption compared with conventional air source heat pumps. This work provides theoretical and data support for anti-frosting design and engineering application of semi-open air cycle heat pumps.

Key Words semi-open air cycle; booster turbo-expander; air source heat pump; dynamic frosting characteristics; energy efficiency optimization

A multistage-heating heat pump system for data-center waste-heat recovery: Heating-stage number optimization and experimental validation

Hongfei Wang[1],Yifan He[2],Jianmin Gao[1],Heming Dong[1],Hong Liu[3],Qian Du[1],Min Xie[4],Riying Wang[3],Yu Zhang[1],Ximei Li[1]

1. Harbin Institute of Technology

2. Chongqing Changan Kaicheng Automobile Technology Co., Ltd.

3. China Mobile Group Design Institute Co., Ltd.

4. Harbin Electric Science and Technology Co., Ltd.

To address the challenge of achieving sensible heating of a heat-sink fluid over a wide temperature range using low-grade waste heat, such as data-center chilled-water return, this study proposes and experimentally evaluates a multistage-heating heat pump (MSHP) system. The system divides the continuous temperature rise of the heat-sink fluid into multiple stages, each matched to its temperature interval by an independent vapor-compression cycle. We developed a screening model for one to five heating stages and a four-stage, five-cycle simulation model consistent with the prototype, and constructed an experimental platform with refrigerants allocated by temperature range. The coefficient of performance for heating (COPh) increased with the number of stages, although the marginal gain progressively diminished. When the heat-sink fluid was heated from 40°C to 50°C, the marginal improvement from four to five stages was only 0.51%; the four-stage configuration was therefore selected as a practical balance between energy efficiency and system complexity. At the design point, the system heated the heat-sink fluid from 43.7°C to 82.7°C, delivering a heating capacity of 14.73 kW, a total compressor electric power of 6.97 kW, and a COPh of 2.11. Under the same conditions, the absolute deviations between model predictions and experimental measurements ranged from 0.21% to 2.20% for compressor power and from 2.43% to 5.08% for stage heating capacity. Increasing the fraction of M5 refrigerant directed through the condenser branch from 58% to 100% increased the system COPh from 2.04 to 2.15. These results clarify the effects of heating-stage number, heat-sink inlet conditions, and high-temperature-stage flow distribution, and provide a basis for stage selection and operating-parameter optimization in large-temperature-lift systems driven by low-grade waste heat.

Key Words Multistage-heating heat pump; Data-center waste-heat recovery; Large-temperature-lift heating; Heating-stage number optimization; Experimental validation

Heat and Mass Transfer on Cold Surface of Heat Pump Evaporator Based on Schlieren Method

Zhongqi Zuo,Zixu Yang,Lige Tong,Li Wang

University of Science and Technology Beijing

In this paper, a Schlieren visualization system is constructed to study the frosting characteristics of horizontal cold plate surfaces under forced convection. The influence of wind velocity on the heat and mass transportation characteristics near the frosting is quantitatively studied. The results provide solid references for the design of evaporators in heat pumps, especially those in high-humidity and low-temperature regions. Thermal boundary layers and the transitions from laminar to turbulent flow were characterized by the visualization data. The flow patterns are related to the black-white stripes above the cold plate. The coupled effect of air velocity and temperature gradient on frosting was analysed with the help of Schlieren images.

Key Words Keywords: Frosting, Heat pump, Schlieren method, Heat and mass transfer, Evaporators.

System-level assessment of DCHE dehumidification with waste heat regeneration for electric vehicle heat pumps

Hongkuan Chen,Zhiwei Ma,Huashan Bao

Durham University

1. Introduction

Dehumidification is one of the primary functions of heat pump systems in electric vehicles. It contributes to cabin comfort and helps prevent windshield fogging or frosting under winter conditions, thereby maintaining visibility and driving safety. A conventional approach is condensation dehumidification, in which the heat pump cools the supply air below its dew point to condense and remove water vapour. When the resulting air temperature is below the required supply temperature, the air must be reheated before entering the cabin. During winter operation, this reheating is generally provided by an electric heater, increasing electricity consumption and potentially reducing vehicle driving range.

Adsorption dehumidification provides an alternative approach. It removes water vapour without cooling the air below its dew point and can approximate an isenthalpic process. It can therefore reduce the need for deep cooling and subsequent electric reheating. Because moisture removal does not depend directly on heat pump cooling, latent load treatment can be separated from sensible conditioning, providing greater flexibility for the independent control of cabin air temperature and humidity. The heat required for desiccant regeneration may also be supplied by waste heat from the battery and drive system.

In this study, MOF-801 was applied to heat exchanger surfaces by spray coating to produce desiccant coated heat exchangers (DCHEs). The DCHEs were integrated with an electric vehicle heat pump to provide adsorption dehumidification, with waste heat used for desiccant regeneration. Simulations of the complete system were used as the primary method to assess the feasibility and performance of the proposed configuration under two representative summer conditions and two representative winter conditions.

2. System design

The electric vehicle air conditioning system proposed in this study consists of a heat pump subsystem and a DCHE dehumidification subsystem. The cabin supply air first passes through the DCHE operating in adsorption mode and then through either the condenser or the evaporator of the heat pump, depending on the operating mode. This arrangement enables the latent and sensible loads to be treated separately. The DCHE dehumidification subsystem contains two DCHEs that operate alternately. While one DCHE adsorbs moisture from the air, the other undergoes desorption and regeneration. Their operating modes are switched periodically to prevent interruption of the dehumidification process and maintain continuous moisture removal. During regeneration, heat is supplied to the desorbing DCHE by a heat transfer fluid that recovers waste heat from the electric vehicle, while ambient air is passed through the unit to carry away the desorbed water vapour.

3. Methodology

3.1 Water adsorption characteristics of MOF-801

The equilibrium water uptake of MOF-801 was measured using dynamic vapour sorption (DVS) at 15, 30, 45 and 60°C over a relative humidity range of 0% to 95%. A modified Dubinin-Astakhov equation with a temperature correction was fitted to the measured isotherms, giving a mean relative error of 3.26%.

3.2 DCHE fabrication and experimental testing

MOF-801 was dispersed in ethanol and homogenised by stirring and ultrasonication. Vinyl acetate was added as a binder to form a sprayable coating suspension. The suspension was applied to a commercial fin and tube heat exchanger while water at approximately 60°C circulated through the tubes, followed by curing in a vacuum oven at 130°C. The fin pack measured 173 × 144 × 46 mm and was coated with 16.98 g of MOF-801, corresponding to a loading of 18.40 g/m² of coated fin area.

A packed humidifier with PID control supplied air at stable humidity to the DCHE test rig. Inlet and outlet air temperature and relative humidity were measured during adsorption and desorption tests under different operating conditions.

3.3 DCHE heat and mass transfer model

A transient control volume model was developed to describe coupled heat and mass transfer within the DCHE. Nusselt and Sherwood numbers were used to calculate the respective transfer coefficients, while the fitted isotherm equation determined the equilibrium water uptake. Under five boundary conditions, the model achieved a mean absolute relative error of 7.07% for outlet humidity ratio and a mean absolute error of 1.34°C for outlet air temperature.

3.4 System simulation model

The system model included moist air and R1234yf refrigerant circuits, while the heat transfer fluid was represented by prescribed temperature boundaries. The DCHE was spatially resolved, whereas the remaining components were represented by low order or lumped parameter models.

The model included cabin thermal and moisture loads, windshield fogging and frosting risk, effectiveness NTU heat exchangers, and compressor efficiency interpolated as a function of pressure ratio. Cabin and DCHE states were calculated dynamically, while the refrigerant cycle was solved quasi steadily at each time step by enforcing refrigerant mass flow closure and checking energy residuals.

The WLTC Class 3b City cycle was repeated four times over 4088 s. The traditional and proposed systems were simulated for winters in Lillehammer and London and summers in Shenzhen and San Francisco.

4. Results and discussions

The simulations used a main moist air mass flow rate of 0.12 kg/s, four adult occupants and a zero outdoor air fraction for both systems. Each DCHE bed measured 0.173 × 0.432 × 0.046 m, had a face area of 0.0747 m² and contained 50.94 g of MOF-801, giving 101.88 g in total for both beds. With regeneration heat at approximately 60°C, the proposed system increased the combined comfort time from 44.94% to 79.90% in Lillehammer and from 89.11% to 90.31% in London. Compared with conventional heat pump dehumidification and electric reheating, it reduced the calculated electrical energy use by 21.87% and 43.06%, respectively, and eliminated the 11.07% fogging or frosting risk observed in Lillehammer. Across the two summer climates, however, a robust energy saving benefit was not demonstrated.

Regeneration temperatures of 40, 50 and 60°C were examined in winter, while 60, 70, 80 and 90°C were considered in summer. Although the 40 and 50°C cases remained numerically feasible, they could not maintain winter humidity control and windshield safety, indicating that approximately 60°C was required.

In Shenzhen, the DCHE was unavailable at 60 and 70°C but operated effectively at 80 and 90°C. At 80°C, the DCHE adsorbed 161.55 g of the total 311.01 g of removed water, meaning that approximately 48% of the dehumidification was still provided by the heat pump. Moreover, the higher regeneration temperature increased the cooling load and waste heat demand, while 90°C offered no further benefit. Elevated temperatures also produced diminishing benefits in San Francisco. Summer application should therefore be considered only where independent temperature and humidity control is essential and would probably require a larger DCHE and greater adsorbent mass.

Finally, a combined parameter analysis of DCHE face area and airflow was conducted for the two winter climates. At a regeneration temperature of 60°C and zero outdoor air fraction, approximately 0.075 m² was the smallest tested face area that maintained windshield safety and cabin comfort. This corresponded to around 51 g of MOF-801 per bed and 102 g in total. An air mass flow range of 0.09–0.15 kg/s was considered practical, although 0.09 kg/s remained close to the lower limit. Within this airflow range, both combined comfort and compressor electricity consumption increased modestly with increasing airflow.

Overall, regeneration of MOF-801 DCHEs using waste heat is most feasible and beneficial for winter electric vehicle climate control, while summer application remains limited to cases requiring independent temperature and humidity control.

Key Words Electric Vehicle Heat Pump, Adsorption Dehumidification, Desiccant Coated Heat Exchanger (DCHE), MOF-801, Windscreen Fogging and Frosting Prevention, Energy Efficiency of Electric Vehicle Air Conditioning.

Progress on an Ultra-High Temperature Heat-Driven Thermoacoustic Heat Pump

Guilai Zhou[1,2],Yupeng Yang[1,2],Hao Chen[1,2],Rui Yang[1],Ercang Luo[1,2]

1. State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

2. University of Chinese Academy of Sciences, Beijing 100049, China

Approximately 63% of industrial energy is lost as waste heat [1], with nearly 50% of industrial waste heat being low-grade and difficult to utilize effectively because of its low temperature level [2]. To address this challenge, heat-driven thermoacoustic heat pump is an emerging energy-saving technology with great potential in industrial waste heat recovery and low-temperature heat upgrading [3].

Heat-driven thermoacoustic heat pumps achieve energy conversion based on the thermoacoustic effect and offer environmentally benign working fluids (He, N2, etc.), high reliability, and good adaptability. However, existing heat-driven thermoacoustic heat pumps have generally been limited to heat delivery below 100°C. Large temperature lifts make efficient energy conversion and effective acoustic-field matching difficult to achieve. Consequently, heat-driven thermoacoustic heat pumps capable of delivering heat above 400°C have not yet been demonstrated.

To further increase the heat-delivery temperature of heat-driven thermoacoustic heat pumps, we designed and experimentally developed a novel bypass-configured heat-driven thermoacoustic heat pump. The system consists of a thermoacoustic engine and a thermoacoustic heat pump. The engine converts heat into acoustic power, while the heat pump consumes acoustic power to pump heat. To regulate the acoustic power distribution between the two subsystems, a bypass branch equipped with a ball valve was introduced. By adjusting the valve opening, the acoustic power splitting ratio can be actively controlled, thereby facilitating acoustic-field matching under large temperature lifts. The performance of the developed system was experimentally evaluated at an ambient temperature of 15°C and a heat-source temperature of of 300°C. The effects of average pressure and supply temperature on the heating power and heating coefficient of performance (COP_h) were systematically investigated. The maximum supply temperature achieved was 491°C. At 4 MPa, the system delivered 1258 W of heating power with a COP_h of 0.2466 at 480°C. When the average pressure was increased to 5 MPa, the maximum heat supply temperature reached 491°C, while the system delivered 1382 W of heating power with a COP_h of 0.264. These results demonstrate that the designed heat-driven thermoacoustic heat pump system can raise the heat-supply temperature to above 490°C, while enabling kilowatt-level ultra-high-temperature heat supply and providing a practical route for upgrading low-grade waste heat to high-temperature industrial heat.

Key Words Thermoacoustics, Thermoacoustic Heat Pump, Heat Pump, High-Temperature Heat Pump

Multi-objective optimization of an ionic-liquid absorption refrigeration system driven by waste heat from high-temperature liquid-cooled data centers

Bo Tian,Shuangquan Shao Huazhong

university of science and technology

The rapid deployment of liquid cooling in high-density data centers provides a promising opportunity for recovering low-grade waste heat; however, the relatively low temperature of liquid-cooling return water restricts its efficient utilization by conventional thermally driven refrigeration systems. This study proposes

a waste-heat-driven absorption refrigeration system for high-temperature liquid-cooled data centers using H_2O–[DMIM][DMP] as the working pair. Liquid-cooling waste heat at 50–70°C is directly supplied to the generator, with a minimum heat-transfer temperature difference of 5°C. A thermodynamic model incorporating the vapor–liquid equilibrium and thermophysical properties of the ionic-liquid solution is established to investigate the effects of generator temperature (50–65°C), evaporation temperature (5–25°C), condensation temperature (30–50°C), and absorption temperature (25–45°C) on system performance. An artificial neural network surrogate model is subsequently developed and coupled with the NSGA-II algorithm to maximize the coefficient of performance (COP) and life-cycle benefit (LCB) simultaneously. Results indicate that increasing the generator and evaporation temperatures improves the refrigeration performance, whereas higher condensation and absorption temperatures significantly deteriorate the cycle performance. The Pareto-compromise solution is obtained at generator, evaporation, condensation, and absorption temperatures of 63.1, 19.8, 34.2, and 29.6°C, respectively, yielding a COP of 0.731. Compared with the baseline condition, the optimized system increases COP and LCB by 24.7% and 40.3%, respectively, while reducing the discounted payback period from 4.9 to 3.6 years. These results demonstrate the potential of ionic-liquid absorption refrigeration for converting high-temperature data-center waste heat into useful cooling and provide a thermodynamic–economic design framework for low-carbon data-center thermal management.

Key Words Liquid-cooled data center; Waste heat recovery; Absorption refrigeration; Ionic liquid; H_2O–[DMIM][DMP]; Multi-objective optimization

Spatiotemporal Evolution of Thermal Non-Uniformity and Inter-Layer Airflow Redistribution in a Multilayer Belt Dryer

Bo Ma[1,2,3],Ming Li[1,2,3],Muchi Yao[1,2,3],Xudong Wang[1,2,3]

1. Yunnan Normal University

2. Key Laboratory of Advanced Technique & Preparation for Renewable Energy Materials, Ministry of Education, Yunnan Normal University, Kunming, Yunnan 650500, China

3. Southwestern United Graduate School, Kunming, Yunnan 650500, China

Thermal non-uniformity limits stable heat allocation and drying consistency in continuous multilayer through-flow drying, yet its transient evolution, dominant spatial direction, and linkage with inter-layer airflow redistribution remain unclear. To resolve these gaps, field measurements of temperature, relative humidity, and air velocity were combined with a three-dimensional porous-media CFD model for a five-layer dryer processing fresh Codonopsis pilosula. The thermal response exhibited three stages: feeding-induced cooling, heating-evaporation, and stable drying. Vertical inter-layer temperature fluctuations were stronger and more persistent than horizontal variations, showing that uneven heat allocation mainly occurred among successive layers. CFD reproduced the main spatial trends and revealed airflow redistribution and local recirculation as bottom-up air passed through the multilayer porous structure. The combined evidence shows that accumulated porous resistance modifies inter-layer airflow allocation and drives thermal non-uniformity. This work establishes a field-validated diagnostic framework linking temporal response, directional non-uniformity, and airflow redistribution, providing a basis for targeted layer-to-layer airflow balancing.

关键词 Multilayer through-flow drying; Thermal non-uniformity; Airflow redistribution; Spatiotemporal evolution; CFD; Porous media

Low-Temperature-Driven Optimal-State Migration in Transcritical CO_2 Heat-Pump Drying via Physics-Interpretable Surrogate Modeling

Muchi Yao,Ming Li,Bo Ma,Yixun Kong

Yunnan normal university

Low-temperature operation of transcritical CO_2 heat pumps involves more than efficiency degradation, because variations in evaporation temperature, high-side pressure, and gas-cooler outlet temperature continuously shift the thermodynamically favorable operating state. This study develops a physics-interpretable surrogate framework to characterize such low-temperature-driven optimal-state migration in a transcritical CO_2 heat-pump drying system. An experimentally validated thermodynamic model was used to establish the coupled operating domain defined by evaporation temperature, high-side pressure, and gas-cooler outlet temperature. Five feature groups representing external operating variables and internal thermodynamic states were evaluated using random-forest regression, followed by SHAP analysis, temperature-layer holdout validation, and low-temperature anchor correction. As the evaporation temperature decreased from 15 to −15°C, heating capacity decreased from 122.2 to 64.7 kW and COP from 3.25 to 1.98. At an evaporation temperature of 0°C, increasing the high-side pressure from 7.5 to 11.0 MPa increased specific heating capacity from 201.97 to 251.88 kJ kg^{-1}, while specific compression work increased from 46.65 to 72.73 kJ kg^{-1}, causing COP to decrease from 4.329 to 3.463. The discharge-state feature group achieved the best prediction performance, with an R^2 of 0.9928 and a MAPE of 1.76%. SHAP analysis identified discharge enthalpy, gas-cooler outlet temperature, and discharge entropy as the dominant performance descriptors, with mean absolute contributions of 0.5518, 0.2743, and 0.2252, respectively. Temperature-layer extrapolation increased MAPE to 10.36%, whereas low-temperature anchoring reduced it to 3.60%. The results establish a boundary–state–performance relationship and provide a physically interpretable basis for tracking condition-dependent optimal states of transcritical CO_2 heat-pump drying systems.

Key Words Transcritical CO_2 heat pump, Heat-pump drying, Low-temperature operation, Optimal-state migration, Physics-interpretable surrogate modeling

Defrosting Control of an Air-Source Heat Pump Based on Coupled Indoor and Outdoor Coil Temperature Mapping

Chuanmin Dai[1,2],Wei Wenzhe[1],Wang Wei[1],Sun Yuying[1],Zhu Wanpeng[1,2],Teng Zhaolong[2]

1. Beijing University Of Technology

2. Qingdao Haier Smart Technology R&D Co., Ltd.

During winter heating operation, frost accumulation on the outdoor heat exchanger can increase thermal resistance, reduce heat-transfer performance, and cause a decline in heating capacity. Defrost initiation is therefore required to be both timely and selective. In conventional control schemes, the temperature measured at one outdoor-coil location is used as a proxy for the evaporating temperature and pressure. Its representativeness is readily compromised by finite sensor resolution, the contact thermal resistance between the sensor and the tube wall, and the spatially nonuniform temperature field of a multi-circuit outdoor coil. Frost growth further changes the local thermal resistance and airflow distribution, so the measured surface temperature can deviate from the refrigerant saturation state that is relevant to defrosting. A fixed threshold applied to this point measurement can consequently be crossed before sufficient frost has formed or after the heat-transfer penalty has become substantial. The resulting false initiation and delayed initiation increase reverse-cycle losses, disturb the indoor heat supply, and reduce confidence in the controller. A state variable that is less sensitive to local contact and spatial effects is therefore required for accurate defrost control.

To address this problem, a defrost control method based on coupled indoor-outdoor coil-temperature mapping was developed. During heating operation, the indoor coil functions as the condensing-side heat exchanger, and its temperature field is expected to be more spatially uniform than that of the outdoor evaporating coil. Synchronized indoor- and outdoor-coil measurements were used to establish a correspondence between the two temperature fields. The indoor-coil value was then used to estimate the evaporating temperature and pressure indirectly, so that the decision was not controlled by the temperature at a single outdoor-coil location. In parallel, the relationship between evaporating and condensing states under the same outdoor condition was identified and introduced as an operating-condition-dependent correction to the defrost initiation criterion. Experiments were conducted in an enthalpy-difference chamber using an R410A air-source heat-pump air heater with a rated heating capacity of 5 kW. Measurements from the existing indoor and outdoor coil temperature sensors and the refrigerant-side pressure signals were synchronized during heating, frosting, and defrosting cycles. The mapping relationship was identified from the measured coil response, and the state-coupling correction was subsequently embedded in the controller. The proposed strategy was evaluated against the conventional outdoor-coil-temperature strategy using evaporation-pressure estimation error and the rate of false defrost initiation as the primary indicators. The resulting control sequence is summarized in Fig. 1.

The experimental results demonstrated that the proposed indoor-outdoor coil-temperature mapping procedure estimated the evaporation pressure with a mean absolute error of 11 kPa and a root mean square error of 14 kPa. Relative to the conventional outdoor-coil-temperature method, the estimation error was reduced by approximately 22 percent. When the mapping model and the state-coupling correction were incorporated into the controller, the false defrost initiation rate was reduced from 33 percent to 12 percent. This reduction indicates that the criterion was made less sensitive to local temperature fluctuations and more responsive to the combined evaporating and condensing operating state. Because the indirect estimate was derived from the existing indoor-coil temperature and available refrigerant-side measurements, no additional sensor was required. The controller was configured so that the mapped state was checked continuously, whereas a defrost command was issued only when the corrected criterion was met. This sequencing separates state estimation from actuation and makes the source of each defrost decision traceable during commissioning and field diagnosis. The improved decision reliability is expected to reduce unnecessary reverse-cycle operation, preserve heating delivery during frosting periods, and limit the thermal disturbance perceived indoors. The method also provides a practical calibration framework: the mapping can be identified for a product family and then updated when coil circuitry or operating conditions are changed. Within the tested 5 kW R410A air-heater configuration, the results support the feasibility of using coupled coil temperatures for engineering defrost control. Further work should examine long-duration fouling, sensor ageing, and transferability to different refrigerants and heat-exchanger geometries. In practical deployment, the workflow can be implemented in three steps: the indoor-outdoor temperature correspondence is identified during product calibration, the evaporating-condensing relationship is fitted for the intended operating envelope, and the corrected criterion is embedded in the existing defrost state machine. The approach therefore improves the information used by the controller without requiring a hardware redesign.

关键词 空气源热泵；除霜；盘管温度；耦合算法；误差

Ammonia Leakage Mitigation Using Zeolite 13X for Integrated Ammonia Energy Systems in Ships

Nayeon Kim,Jaeyoon Cho,Huiseung Lee,Min Yoon,Jae Won Lee

Ammonia is attracting attention as a carbon-free marine fuel and a natural refrigerant with favorable thermodynamic properties. Its use as both a fuel and refrigerant offers potential for integrated thermal energy systems in ammonia-fueled ships, including refrigeration and heat pump applications. However, ammonia leakage and associated safety concerns remain key barriers to the broader deployment of ammonia-based equipment onboard ships. This study experimentally investigated the effects of Zeolite 13X placement on ammonia concentration reduction and dispersion control in a model ship engine room. An NH_3/N_2 mixture containing approximately 0.60 vol% NH_3 was released for 10 min from leakage points at three different levels under fixed ventilation conditions. Three Zeolite placement configurations were evaluated. Dual-level placement reduced NH_3 concentrations at all six sensors for first- and second-level leakage, with reductions

of 6.0–14.3 ppm and 19.7–40.3 ppm, respectively, and a maximum reduction rate of 80.4%. In contrast, single-level placement increased concentrations at several sensors under certain leakage conditions, indicating ammonia redistribution. The results demonstrate that leakage location and adsorbent placement strongly affect ammonia reduction and dispersion. These findings provide design data for adsorption-based leakage mitigation and support the safe implementation of ammonia refrigeration and heat pump systems in ammonia-fueled ships.

Key Words Ammonia-fueled ship; Ammonia refrigeration; Ammonia leakage; Zeolite 13X; Leakage mitigation

Efficient single-unit liquid-resonator heat-driven thermoacoustic heat pump

Yunxiao Jia[1,2],Lei Xiao[3],Zhanghua Wu[1],Ercang Luo[1,2]

1. Chinese Academy of Sciences

2. University of Chinese Academy of Sciences

3. School of Energy and Power Engineering, North University of China

Hot water is widely used in various fields such as industrial production, building heating, and food processing. Currently, fuel-fired boilers remain the primary means of hot water production; however, their efficiency is relatively low, typically around 90%, which results in substantial energy consumption.

Heat-driven heat pumps enable efficient heat supply under the drive of high-temperature heat sources, and their substitution for boilers offers a viable means of energy conservation. As an emerging heat pump technology, the heat-driven thermoacoustic heat pump (HDTHP) employs inert gases such as helium and nitrogen as the working gas, thereby offering environmental friendliness. Moreover, it contains no mechanical moving parts, which endows it with high reliability and a long service life. Finally, it operates on a single-phase thermodynamic cycle and is thus not constrained by the critical temperature, making it suitable for large temperature lifts. After decades of development, the performance of heat-driven thermoacoustic systems has been significantly improved. In particular, the replacement of conventional gas resonator with liquid resonator can greatly enhance system compactness, output power density, and efficiency. However, existing liquid-resonator HDTHPs are all looped double traveling-wave systems, consisting of more than three units connected in series, each unit comprising an engine core, a heat pump core, and a liquid resonator. A system composed of only a single unit is fundamentally infeasible in principle. The multi-unit series configuration suffers from several inherent drawbacks. First, the large number of components entails complex manufacturing and assembly processes. Second, the series operation exhibits low fault tolerance, as a failure in any unit will result in the complete shutdown of the entire system, thereby compromising system reliability. Finally, a single unit cannot operate independently, which hinders modular development. Therefore, the development of a single-unit HDTHP with liquid resonator is of critical importance.

This study proposes a single-unit liquid-resonator heat-driven thermoacoustic heat pump. Firstly, the proposed HDTHP operates with only a single unit, which greatly simplifies the manufacturing and assembly processes, enhances system reliability, and facilitates modular development. Secondly, the incorporation of the bypass tube removes the limitation on the heating temperature, thereby enabling high efficiency at elevated heating temperatures. Finally, the application of the W-tube facilitates passive vibration damping of the proposed HDTHP.

In this study, the proposed HDTHP is simulated using the commercial software Sage, which is specifically designed for the numerical computation of regenerative heat engines. The structure of the proposed HDTHP is optimized under operating conditions of a mean pressure of 10 MPa, a heating temperature of 600°C, a heat-pumping temperature of 70°C, and an ambient temperature of 0°C to maximize the COPh, with simulation results showing that the operating frequency, heat-pumping power, and COPh are 19.18 Hz, 27.44 kW, and 2.012, respectively. The influence of the bypass tube on the heat-pumping power and COPh is examined at different heating temperatures. For the HDTHP with a bypass tube, the bypass tube diameter is optimized to maximize the COPh. With increasing heating temperatures,

the heat-pumping power rises for both the HDTHPs, but the rate of increase is higher for the HDTHP without the bypass tube. At the heating temperature of 500°C, the heat-pumping powers of the HDTHPs with and without the bypass tube are 21.38 kW and 256.70 kW, respectively. As the heating temperature increases, the COPh of the HDTHP without the bypass tube first increases and then decreases, reaching a maximum value of 1.548 at the heating temperature of 300°C, whereas the COPh of the HDTHP with the bypass tube exhibits a continuous upward trend. At the heating temperature of 500°C, the COPh of the HDTHPs with and without the bypass tube are 1.923 and 1.393, respectively, indicating that the bypass tube significantly enhances the COPh. In addition, the effects of the bypass tube diameter on the heat-pumping power and COPh are also investigated. With increasing bypass tube diameter, the heat-pumping power decreases, whereas the COPh first increases and then decreases, reaching its maximum value at the bypass tube diameter of 96 mm. Furthermore, the heat-pumping power can be regulated by adjusting the bypass tube diameter. Specifically, at bypass tube diameters of 56 mm, 66 mm, and 76 mm, the heat-pumping powers are 122.70 kW, 87.85 kW, and 46.62 kW, respectively, with corresponding COPh of 1.728, 1.838, and 1.923.

关键词 Thermoacoustic heat pump, Liquid resonator, Single unit, Bypass tube, High efficiency

Experimental Study on the Variable-Performance Characteristics of Hundred-Kilowatt High-Temperature Heat Pumps for Industrial High-Temperature Heat Supply

Zhikang Yu,Jiawei Zhang,Minghao Cheng,Shifang Huang,Xiaosong Zhang

Southeast University

Industrial waste-heat upgrading and high-temperature heat-supply applications impose stringent requirements on the wide-range operating performance of high-temperature heat pumps. In this study, a hundred-kilowatt-class high-temperature heat pump experimental platform using R1233zd(E) as the working fluid and employing economizer was established. Under heat-source temperatures of 70–95°C and pressurized hot-water supply temperatures of 110–130 °C, the effects of heat-source inlet temperature, heat-source-side flow rate, heating-side outlet temperature, heating-side flow rate, and compressor frequency on heating capacity and the coefficient of performance (COP) were systematically investigated. The results show that when the heat-source inlet temperature increased from 70°C to 95°C, the heating capacity and COP increased by 24.0% and 28.6%, respectively; when the heating-side outlet temperature increased from 110°C to 130°C, the COP decreased from 5.82 to 3.37. As the heat-source-side flow rate increased from 22 t/h to 42 t/h, the COP rose from 4.06 to 4.87; when the heating-side flow rate increased from 27 t/h to 47 t/h, the COP increased from 4.07 to 5.03. When the compressor frequency was raised from 30 Hz to 60 Hz, the heating capacity increased from 147.0 kW to 274.4 kW, whereas the COP decreased from 5.21 to 4.69. A model validated against the experimental data can correctly reproduce the variation of COP with the operating parameters, with maximum and mean relative errors of 6.53% and 4.22%, respectively. The findings indicate that temperature boundaries are the dominant factors determining the energy efficiency of the unit, that flow-rate regulation can improve heat-transfer matching, and that frequency regulation requires a coordinated trade-off between heating capacity and energy efficiency. These results can provide a basis for equipment selection and operational regulation in industrial waste-heat upgrading and high-temperature hot-water supply.

Key Words High-temperature heat pump; Industrial waste-heat upgrading; Industrial high-temperature heat supply; Off-design experiment; Coefficient of performance

Development and Validation of an RSM-Based Model for Dynamic Heat Pump Performance Prediction

Min Seong LEE,Yong Geun KIM,Tae Hyeon PARK,Van Cong LE,Chan Woo PARK

Jeonbuk National University

Response surface methodology (RSM) has been widely used for prediction and optimization in various engineering fields because of its simple structure and low computational cost. In heat pump research, RSM has also been applied to performance prediction and operating-condition optimization, but most applications have been limited to steady-state conditions. Meanwhile, various approaches have been proposed for dynamic heat pump performance prediction. However, these methods often require detailed information on system components, complex physical models, or large amounts of training data. To address these limitations, this study develops a computationally efficient RSM-based model for dynamic performance prediction of a water-to-water heat pump using R1234ze(E). The steady-state RSM framework was extended to dynamic operation using readily measurable variables, including water-side temperatures and flow rates, compressor frequency, superheat, and other operating parameters. The model was developed using experimental data from a lab-scale heat pump and validated using an independent dynamic dataset. Approximately five to six days of data were used for training, while an independent one-day dataset was used for validation. The model achieved coefficients of determination above 0.97 for key performance indicators, including heating capacity and system coefficient of performance, despite the relatively small training dataset. The proposed modeling approach was also applied to a heat pump at a demonstration site and maintained high prediction accuracy, suggesting potential applicability to other heat pump systems using measured operating data. Its simple equation-based structure and low computational demand make it suitable for real-time performance prediction and future applications such as model predictive control and optimal operation.

Key Words Response surface methodology (RSM), Dynamic performance prediction, R1234ze(E), Data-driven modeling

Machine Learning-Based Methods for Efficient and Adaptive Heat Pump Control

Yang Song,Ashwini Unnikrishnan Menon,Davide Rolando,Hatef Madani

KTH Royal Institute of Technology

Conventional heat pump heating-curve control determines the required supply temperature mainly from outdoor air temperature and therefore cannot fully account for short-term solar gains and other weather effects. This study proposes a physics-aware machine-learning framework for solar-aware heating-curve correction using publicly available weather and solar data. The objective is to retain the robustness and simplicity of conventional heating curves while introducing predictive information to improve their responsiveness to changing solar conditions.

The proposed framework consists of two modelling stages. First, short-term solar transmittance is predicted using meteorological variables, solar-geometry information, and memory-based features. Solar transmittance is defined relative to clear-sky irradiance, providing a normalized representation of atmospheric attenuation. Machine learning models are evaluated using leakage-safe chronological training and testing at multiple forecast horizons. Second, the predicted solar signal is combined with the baseline heating-curve supply temperature and physics-aware features representing heating demand, solar compensation, recent solar conditions, thermal inertia, and overheating risk. These inputs are used to generate a bounded supervisory correction to the conventional supply-temperature setpoint.

The results demonstrate that short-term solar information can be translated into physically meaningful heating-curve corrections, with larger supply-temperature reductions during periods of strong expected solar contribution and milder heating conditions. The proposed approach provides an intermediate solution between fixed rule-based heating-curve control and more complex model predictive control. By relying only on publicly available weather and solar data, the framework offers a scalable basis for future adaptive heat

pump control.

Key Words Heat Pump; Machine Learning; Data-Driven Control; Energy Efficiency; Control Optimization

An Experimental Study and Thermodynamic Evaluation on of the PV/T Heat Pump Coupled with Radiant Floor Heating System

Jijin Wang,Bo Han,Jianxiang Guo,Long Liu

Qingdao University of Technology

To address the challenges of unstable solar heating and performance degradation of air-source heat pumps at low temperatures, this paper set up a hybrid solar photovoltaic/thermal (PV/T) heat pump integrated with radiant floor heating system. Experimental investigations were carried out under outdoor ambient temperatures 2°C, evaluating the heating and power generation performance under three different supply water temperatures (35°C, 40°C, and 45°C) and various heat pump operating modes. The results indicate that higher supply water temperatures lead to faster indoor temperature rise rates. Even at a supply water temperature of 35°C, the indoor temperature remains above 21°C, with a maximum vertical temperature difference below 0.6°C and a horizontal temperature difference less than 0.3°C above 0.6 m height, demonstrating excellent thermal uniformity; the indoor PMV/PPD indices meet the Class I thermal comfort requirement. In PV/T mode, the operating temperature of PV modules decreases by about 20°C, resulting in an average increase of 9.45% in power generation. Meanwhile, the evaporation temperature in this mode increases by an average of 5°C, and the heating capacity is improved by 14.37% on average. The maximum and average coefficient of performance (COP) of the system reach 4.9 and 3.58, respectively, while the maximum and average combined performance coefficient (CPC) reach 6.9 and 4.81. The exergy efficiency of the system is increased by 45.12% compared with the pure air-source system. Additionally, the daily average CO_2 emission is reduced by 35.9%, and the dynamic investment payback period is about 9.05 years, demonstrating good energy-saving, economic, and environmental benefits.

Key Words PV/T heat pump; radiant heating; heat and power cogeneration, heating performance, exergy efficiency

Ultra-low-grade waste heat driven cooling for data centers using switchable multistage absorption chiller

Zhaopeng Cui,Ruzhu Wang

Shanghai Jiao Tong University

Data centers (DCs) are becoming major energy consumers while releasing substantial amounts of low-grade waste heat. Utilizing this waste heat to drive cooling systems offers a promising approach to reducing cooling energy use while improving heat recovery. In this study, we develop a mass-coupled multistage absorption chiller driven by ultra-low-grade heat that can switch flexibly between triple- and double-stage modes. Experimental results show that the chiller provides 30 kW of cooling at a chilled-water temperature of 18°C, with hot-water and cooling-water inlet temperatures of 50°C and 32°C, respectively. Under limited heat-source supply, the stage-switching strategy increases cooling capacity by 76% as the cooling-water inlet temperature decreases from 32°C to 24°C. These results demonstrate the feasibility of using ultra-low-grade data-center waste heat for absorption cooling and offer a practical route to improving energy efficiency in future high-performance computing facilities.

Key Words ultra-low driving temperature, absorption chiller, stage switching, data center cooling, waste heat recovery

Olefin-Based Refrigerants for High-Temperature Heat Pumps: A Cross-Study Synthesis of Thermodynamic Performance, Environmental Trade-offs, and Technical Challenges

ABRAHAM ADERA BEZABIH,Reji Kumar Rajamony,Bimrew Tamrat Admasu,Dessie Tarekegn Bantelay

Ethiopian

Heat pumps are promising technologies for decarbonization of the heating sector, yet their performance at industrially relevant temperatures depends critically on the choice of refrigerant. This review synthesizes recent theoretical and experimental advances in olefin based refrigerants which are hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) as low global warming potential (GWP) alternatives to conventional hydrofluorocarbons (HFCs) in high-temperature heat pumps (HTHPs) operating at sink temperatures of 100-160°C and above. From the reviewed literature, olefin refrigerants such as HFO-1336mzz(Z/E), HCFO-1233zd(E), HCFO-1224yd(Z), and R1234yf/ze(Z) offer ultra-low global warming potential (GWP) and competitive thermodynamic performance, achieving coefficients of performance (COP) in the range of 2.3-4.6 and heating capacities of 10-35 kW in laboratory and pilot-scale prototypes. Compared with conventional HFCs such as HFC-245fa and R134a, and according to the individual studies, TEWI reductions amount to approximately 30–70%, depending on the system and operating assumptions used as comparison measures while advanced cycle strategies such as economized vapor injection (EVI) and internal heat exchangers (IHX) deliver efficiency gains of 12-30%. Nonetheless, trade-offs persist such as: higher volumetric heating capacity (up to 117% gain) often comes with efficiency penalties of 7-20%, and discharge temperatures exceeding 160-180°C raise concerns over compressor durability and material compatibility. Cross study comparison further shows that some reported performance differences reflect test rig and heat-exchanger design choices as much as intrinsic refrigerant behavior, underscoring the need for standardized testing conditions. In addition, fragmented regulations on refrigerant charge limits, ranging from EU F-gas thresholds and PFAS restrictions to IEC safety codes, create market uncertainty and hinder scalability. By integrating thermodynamic performance data, environmental assessments, and a synthesis of where independent studies agree and disagree, this review positions olefin refrigerants as technically promising candidates for next-generation high temperature heating. Identified research gaps are compressor durability, material compatibility, and industrial scale validation.

Data centre cooling and waste heat upgrading using compressor-assisted thermochemical resorption

Alessandro Giampieri,Zhiwei Ma,Anthony Paul Roskilly,Huashan Bao

Durham University

Data centres (DCs) are characterised by large, continuous electricity consumption, with almost all electrical input ultimately converted into heat. The increasing deployment of high-performance computing and artificial intelligence is expected to increase both cooling requirements and the quantities of low-temperature heat available from DC cooling systems. Although this heat represents a potentially significant energy resource, its relatively low temperature restricts direct reuse. At the same time, cooling remains an important contributor to DC electricity consumption. Technologies that use low-temperature heat to reduce cooling demand or deliver heat at a more useful temperature could therefore improve the overall energy efficiency of DCs.

This work investigates compressor-assisted thermochemical resorption as an alternative approach for integrating low-temperature heat recovery, cooling and heat upgrading within DCs. The system consists of two solid salt/ammonia (NH_3) reactors operating at different equilibrium pressures and connected through a closed NH_3 circuit. During alternating adsorption and desorption processes, NH_3 is transferred between the two reactors, producing useful cooling or upgraded heat. Mechanical compression is introduced where required to maintain the pressure driving force needed for NH_3 transfer. This allows the resorption process to operate with heat sources at lower temperatures or across larger temperature lifts than a conventional

thermochemical cycle.

Three integration configurations are investigated in this study. In the first configuration, heat rejected by the condenser of the conventional DC chiller is recovered to drive the thermochemical system and provide supplementary cooling. In the second configuration, the warm return stream from liquid-cooled servers is used directly as the driving heat source. In this case, useful cooling is produced during both halves of the thermochemical cycle, referred to here as double cooling. The third configuration uses condenser heat as the low-temperature heat source and upgrades it to provide useful heat to an external thermal user.

A transient thermodynamic model was developed to simulate the alternating operation of the two salt/NH_3 reactors and the NH_3 compressor. The model was applied to a reference DC with a 1 MW power demand from information technology equipment and a total cooling requirement of 1.2 MW. Three salt pairs were compared: $SrCl_2/MnCl_2$, $CaCl_2(4/2)/MnCl_2$ and $SrCl_2/MgCl_2(6/2)$. The analysis considered the transient conversion of the reactive salts, compressor electricity consumption, reactor sizing and auxiliary loads. The resulting thermochemical performance was integrated with the DC energy model to calculate power usage effectiveness (PUE) and electricity consumption. A techno-economic analysis was also performed, accounting for the system size, compressor, salt inventory, installation and operating costs. The effects of different switching periods between the charging and discharging processes, as well as different operating conditions, were also investigated to assess the sensitivity of the proposed configurations.

The results show significant differences between the three integration strategies. For supplementary cooling, $CaCl_2(4/2)/MnCl_2$ provides the strongest performance, supplying approximately 617 kW of cooling under the baseline conditions. This cooling contribution reduces the load on the conventional chiller and therefore also reduces the condenser heat available to drive the thermochemical process. As a result, the overall electricity saving is limited to approximately 34.3 kW and PUE decreases only from 1.44 to 1.405 (−2.4%). The economic value of this configuration is therefore insufficient to recover the additional capital investment under the baseline assumptions.

The double cooling configuration provides a substantially larger benefit. Because cooling is generated during both thermochemical half-cycles and the driving heat is obtained directly from the chip cooling return stream, the complete 1.2 MW DC cooling demand can be supplied by the thermochemical system. Using $CaCl_2(4/2)/MnCl_2$, PUE is reduced to 1.32 (−8.3%) and the DC electricity demand decreases by 119.7 kW. This configuration provides a positive economic result, with an installed capital cost of approximately £1.21M, annual net savings of £194k, a net present value of approximately £0.85M, a simple payback period of 6.2 years and an internal rate of return of 15.1% under the baseline assumptions.

Heat upgrading also shows strong potential, with $CaCl_2(4/2)/MnCl_2$ producing approximately 765 kW of useful heat at 60°C using heat recovered from the DC, although this results in an increase in electricity consumption due to the compressor and auxiliary components of the thermochemical system. $SrCl_2/MgCl_2(6/2)$ provides a slightly higher thermal output, but its larger compression requirement results in poorer overall performance. $CaCl_2(4/2)/MnCl_2$ therefore provides the best balance between thermochemical output and electricity consumption. Heat upgrading gives the strongest baseline economic performance, with a net present value of approximately £1.86M, a payback period of 4.4 years and an internal rate of return of 22.1% under the baseline assumptions.

The operating conditions have a significant influence on the performance of the proposed system. Higher condenser and chip cooling return temperatures generally reduce the compression requirement and improve performance, while increasing ambient temperature has the opposite effect. The heat delivery temperature also affects the electricity required for heat upgrading, demonstrating the importance of matching the thermochemical system to the available heat source and required output temperature. The economic sensitivity analysis shows that the cooling configurations are particularly affected by capital cost and electricity price assumptions, while the feasibility of heat upgrading depends strongly on the value of the exported heat.

Overall, the results demonstrate that the value of compressor-assisted thermochemical resorption depends strongly on how the technology is integrated with the DC cooling system. Supplementary cooling from condenser heat is limited by the interaction between recovered heat availability and conventional chiller operation. On the other hand, direct integration with the warm return stream from liquid-cooled servers provides a favourable route for reducing DC cooling electricity consumption. Heat upgrading also offers strong potential where a suitable external thermal demand is available. Future work should focus on experimental validation, improved compressor and switching control strategies and the evaluation of the system under time-varying DC operating conditions, different climates and heat demand profiles. The results

show that compressor-assisted resorption could provide a flexible approach for improving the utilisation of low-temperature DC heat, with the most promising applications being double cooling and external heat supply.

From Waste Heat to Steam: A Case Study on a Process-Integrated MVR Steam Generating Heat Pump in the Chemical Sector

Orlando Parra Ruiz[1],Jeongik Lim[1],Jeff Choong[2]

1. Piller Blowers & Compressors GmbH

2. Piller Blowers & Compressors GmbH

Within the industrial sector, the chemicals industry is one of the largest energy users, accounting for 12% of global industrial energy use [1], with thermal energy in the form of steam representing the dominant heat carrier for unit operations such as distillation, stripping, evaporation, and chemical reactions. Conventional steam generation is still largely based on fossil fuel combustion, leading to high primary energy demand and significant CO_2 emissions. At the same time, large quantities of low-grade heat are continuously rejected to cooling water systems, revealing a structural inefficiency in traditional utility system configurations.

High-temperature heat pumps (HTHPs) are widely recognized as a key electrification technology for industrial process heat decarbonization. According to the IEA HPT Annex 58 technology assessment, industrial heat pump systems are now technically available for supply temperatures between 100°C and 280°C and for capacities ranging from tens of kilowatts up to several tens of megawatts. Beyond the heat pump technology itself, a decisive factor for achievable efficiency is the integration level within the industrial energy system. The Annex 58 decarbonization guideline [2] distinguishes between process-level, unit-level, utility-level, and sector-level heat pump integration and states that efficiency generally increases when the heat pump is integrated closer to the process. Conversely, centralized utility-level heat pump systems are exposed to thermodynamic penalties due to larger temperature lifts and additional losses in thermal distribution networks.

Against this background, this paper presents and evaluates a real-life implementation of a fully process-integrated Mechanical Vapor Recompression (MVR) heat pump system applied to a chemical process. The project serves as empirical evidence for the performance advantages of decentralized MVR heat pump systems when compared with equivalent centralized utility-level solutions.

计及变工况特性的恒功率外送型卡诺电池新能源基地配置-调度双层优化

Tianhe Wang[1],Tianhe Wang[1,2],Lu Wang[1,2],Xianglong Zhao[2],Hongwei Zhang[2]

1. North China Electric Power University

2. 北京低碳清洁能源研究院

To improve capacity planning and operational coordination for long-duration storage systems under high renewable penetration, this study develops a configuration–operation bi-level optimization framework

for a Carnot-battery-based renewable energy base with constant-power electricity export. A 100 MW export scenario is established using 8760 h of meteorological data from a representative site in China. Seasonal representative-day profiles are generated through mean-statistical analysis and K-means clustering and subsequently interpolated to a 5 min resolution. A thermodynamic model is developed to characterize the nonlinear relationships between input power and coefficient of performance (COP), as well as between output power and turbine efficiency. These off-design performance characteristics are incorporated into a lower-level mixed-integer linear dispatch model using SOS2-based piecewise linearization, while a genetic algorithm determines the upper-level component capacities. An ε-constraint method combined with TOPSIS is employed to obtain and rank solutions considering economic, carbon, and reliability objectives. Compared with a nominal-condition constant-efficiency benchmark, the variable-efficiency model yields larger CSP capacities of 310–560 MW, compared with 220–380 MW, and lower TES capacities of 3250–3480 MWh, compared with 3350–3630 MWh. The annualized investment cost increases from 4.09 to 5.00 billion yuan as ε decreases from 1.0 to 0.1, indicating that the benchmark underestimates investment requirements by 0.01–0.30 billion yuan. Annual emissions decrease from 8.04×104 to 3.19×104 t, while shortage penalties become zero at $\varepsilon \leq 0.3$. The results demonstrate that off-design efficiency coupling substantially reshapes capacity allocation and operational characteristics, providing more credible boundary conditions for evaluating the energy consumption, energy losses, and lifetime performance of Carnot-battery-based renewable energy systems.

Experimental and CFD Investigation of Thermal performance enhancement of a Mixed Mode solar dryer through internal flow modification and Phase Change Thermal Storage

Mohammed Abdelbassit KHERRAFI[1],Abdelouahab BENSEDDIK[2],Yunfeng WANG[1],Ming LI[1]

1. Yunnan normal university

2. Renewable Energy Development Center CDER-URAER

Improving the thermal and airflow conditions within solar drying chambers is essential for achieving efficient, uniform, and reliable drying of agricultural products. This study presents a combined experimental and three-dimensional Computational Fluid Dynamics (CFD) investigation of a mixed-mode solar dryer incorporating internal airflow modification and phase-change thermal storage (PCM). Experiments were conducted under real semi-arid climatic conditions to evaluate the effects of internal modification on chamber temperature, thermal efficiency, drying behavior, and moisture removal. Integrating PCM was also investigated to assess the potential of thermal energy storage for stabilizing the drying environment and improving solar-energy utilization during periods of reduced solar availability.

The internal modification substantially improved the thermo-fluid behavior of the drying chamber by promoting airflow redistribution and enhancing air–product interaction. The maximum chamber temperature reached above 50°C, while the maximum thermal efficiency increased to 80%, compared with 45% for the conventional configuration. Drying time was reduced by up to 50%, reaching more than 60% under optimized airflow conditions. The CFD analysis provided detailed insight into the resulting airflow and temperature fields, revealing improved flow distribution, enhanced mixing, reduced poorly ventilated regions, and greater thermal uniformity. The predicted uniformity index increased from 0.6 for the reference configuration to 0.81 following internal modification, supporting the experimental observations. The enhanced thermo-fluid conditions promoted higher drying rates and improved effective moisture transfer. Meanwhile, PCM integration demonstrated the potential to moderate temperature fluctuations, store excess thermal energy, and maintain useful drying conditions as solar radiation declined. The combined experimental and numerical results demonstrate that integrating internal flow modification with thermal energy storage can enhance solar-energy utilization, drying performance, and process stability. With an estimated payback period of approximately six months, the proposed approach offers a practical and economically attractive pathway for sustainable agricultural drying in solar-rich and semi-arid regions.

Safety Design and Analysis of Ultra-long Inner Pipe in Coaxial Borehole Heat Exchangers

Shihao Dong,Ni Long

Harbin institute of Technology

Medium-deep geothermal energy has attracted increasing attention as a promising solution for low-carbon heating due to its stable thermal characteristics, large resource potential, and independence from outdoor climatic fluctuations. Among various geothermal utilization technologies, closed-loop coaxial borehole heat exchangers (CBHEs) coupled with ground-source heat pumps provide significant advantages, including no groundwater extraction, reduced environmental impact, and long-term operational stability. However, with the increasing application of kilometer-scale CBHE systems, the safety of super-long inner pipes has become a critical engineering challenge. The inner pipe simultaneously experiences complex thermal, hydraulic, and mechanical interactions caused by depth-dependent temperature fields, external pressure from annular flow, axial tensile forces, and long-term operational variations. Existing design methods mainly focus on thermal performance optimization while neglecting mechanical failure mechanisms, especially external pressure collapse caused by annulus-inner pressure differences. Consequently, inappropriate flow rate and depth designs have resulted in repeated inner pipe deformation and failure in practical applications.

This study aims to establish a comprehensive design methodology for super-long inner pipes in medium-deep CBHE systems by developing a thermal-hydraulic-mechanical coupled algorithm. First, full-scale experimental investigations were conducted to characterize the external pressure resistance and tensile strength of commonly used PE-RT II inner pipes under realistic pressure-temperature conditions. An external pressure testing platform was developed to reproduce the actual pressure environment of CBHE operation, where the annulus pressure gradually increased until pipe collapse occurred. Tensile tests were also performed under different temperatures to quantify temperature-dependent mechanical degradation. Based on experimental results, temperature-dependent external pressure resistance and tensile strength models were developed and integrated into a multi-physics design framework.

The proposed algorithm consists of three coupled modules: thermal calculation, hydraulic-force analysis, and mechanical strength evaluation. The thermal model calculates the transient temperature distribution of fluids inside the annular and inner pipes considering heat exchange with surrounding geological formations. The hydraulic model discretizes the CBHE along depth and determines the pressure distribution by considering frictional and local resistance losses in both flow channels. The external pressure acting on the inner pipe is obtained from the pressure difference between annular and inner fluids. Meanwhile, the axial mechanical model incorporates buoyancy, pipe self-weight, counterweight tension, hydraulic friction forces, and wellhead constraints to determine tensile stress distributions. By coupling temperature-dependent material strength with hydraulic pressure and axial stress conditions, the algorithm identifies the critical safety limits of flow rate, differential pressure, and borehole depth.

Experimental results demonstrated that the mechanical properties of PE-RT II pipes significantly deteriorate with increasing temperature. The external failure pressure decreased exponentially with temperature, while the tensile strength exhibited a quadratic decreasing trend. For example, the external failure pressure of a Φ110 × 10 mm pipe decreased from approximately 20×10^5 Pa at 20°C to 4×10^5Pa at 90 °C, representing a reduction of nearly 80%. The tensile strength also declined from approximately 21 MPa at 25°C to 6.8 MPa at 90°C. These results indicate that conventional internal-pressure-based pipe design methods cannot accurately evaluate CBHE inner pipe safety because the dominant failure mechanism is external pressure collapse rather than internal pressure failure.

The coupled algorithm was applied to a 2900 m CBHE system in Shenyang to investigate the spatial distribution of mechanical risks. Results showed that external pressure safety and tensile safety are controlled by different weak locations. The wellhead region is the critical position for external pressure collapse because the annulus-inner pressure difference reaches its maximum value there, whereas the borehole bottom is the critical location for tensile stress due to accumulated axial forces. Under a flow rate of 30m³/h, the calculated pressure difference approached the design limit near the wellhead, while increasing the flow rate to 35m³/h caused the pressure difference to exceed the external pressure resistance and resulted in inevitable pipe collapse. In contrast, tensile stress remained within the allowable range under all investigated conditions, indicating that external pressure resistance is the dominant mechanical constraint for CBHE inner pipe design.

Furthermore, sensitivity analysis revealed that geological temperature characteristics are the dominant factors affecting operational safety limits. The Spearman correlation analysis showed that geothermal gradient had the strongest influence on allowable flow rate and pressure difference limits, followed by ground surface temperature, whereas formation thermal conductivity and volumetric heat capacity had relatively limited impacts. Based on the developed algorithm, engineering design charts were established to determine allowable flow rate, pressure difference, and depth limits under different geological conditions. The results showed that both flow and pressure limits decrease with increasing borehole depth, while the reduction rate gradually decreases due to enhanced thermal interaction between inner and annular flows.

The influence of pipe specifications was also evaluated. Among the investigated PE-RT II pipes, the Φ110 × 12.3 mm pipe exhibited the highest pressure and flow safety limits because its enhanced wall thickness significantly improved external pressure resistance. Although thicker pipes slightly increased hydraulic resistance, their mechanical advantages dominated under deep geothermal conditions. The maximum heat extraction capacity increased with depth following an S-shaped trend, and performance differences among pipe sizes became more significant at greater depths. Therefore, the Φ110 × 12.3 mm configuration was identified as the optimal pipe structure for maximizing heat extraction potential while maintaining operational safety.

In conclusion, this study develops a comprehensive thermal-hydraulic-mechanical coupling framework for evaluating the safety boundaries of super-long CBHE inner pipes. The proposed method provides a theoretical basis for determining allowable depth, flow rate, and pressure difference limits, overcoming the limitations of previous thermal-performance-oriented designs. The developed design charts and pipe selection recommendations can support safer deployment and standardized design of medium-deep geothermal heat pump systems. Future studies should further investigate the long-term mechanical degradation of different pipe materials under cyclic thermal and pressure loading conditions and explore microscopic fluid-flow effects on pipe reliability.

闭式循环热泵密集烤房烟叶烘烤阶段性失水响应与能耗性能

Shilai Kuai,Wenfeng Gao,Qiong Li,Guodong Yang,Baihong Liu,Yufeng Guo,Rongchen Dou,Xiang Ding

Yunnan Normal University

Closed-loop heat-pump tobacco curing integrates heating, dehumidification, and air recirculation, but practical performance under bulk loading is constrained by spatial non-uniformity and stage-dependent attenuation of moisture response. A full-cycle field experiment was conducted in a 90 m^3 closed-loop curing barn loaded with 3,063.3 kg of fresh K326 tobacco. Temperature, relative humidity, air velocity, representative sample mass, and electricity consumption were monitored throughout the 205 h cycle, and moist-air states were reconstructed at the local atmospheric pressure of 82.1 kPa. The barn satisfied the required heating schedule, but vertical non-uniformity exceeded longitudinal non-uniformity and the lower return path remained cooler, more vapor enriched, and lower in vapor pressure deficit (VPD) than the supply side. From yellowing to color fixing/leaf drying and stem drying, mean supply-air VPD increased from 1.013 to 5.924 and 17.687 kPa, whereas stage moisture removal decreased from 1,459.33 to 848.18 and 69.81 kg. Whole-cycle electricity use was 1,917.94 kWh; SEC increased from 0.307 to 1.025 and 8.605 kWh kg^{-1} H_2O, while SMER decreased from 3.260 to 0.975 and 0.116 kg H_2O kWh^{-1}. The results identify a transition from an air-side-responsive yellowing stage to a low-response, high-penalty late stage, supporting stage-adaptive coordination of airflow, dehumidification, temperature, and endpoint determination.

How AI and Digitalization Are Redefining Heating and Cooling

Hatef Madani

KTH Royal Institute of Technology

In the heating, cooling, and refrigeration sector, current literature frequently discusses how artificial intelligence (AI) and digitalization may improve control, energy management, and system efficiency, although these concepts are often vaguely defined. However, broad real-world deployment remains limited, as these applications must operate reliably across diverse building types and conditions (Aghili et al., 2025; Zhou et al., 2023). Rather than reiterating the theoretical advantages of AI prevalent in the literature, it is instructive to first consider the sector's historically traditional nature. Heating and cooling account for more than half of global end-use energy consumption (International Energy Agency [IEA], n.d.)., yet these needs are still largely met by relatively basic supply technologies. The fundamental methods used to heat and cool buildings today do not differ significantly from those established centuries ago at the advent of modern building structures. While modern mechanically delivered comfort cooling is approximately a century old, the underlying functions—transferring heat and managing airflow and moisture—long predate modern HVAC systems. Similarly, fossil-fuel space heating, which remains dominant worldwide, has a long, albeit geographically uneven, history; for instance, documented coal burning in Britain dates back to the early Middle Ages (Hatcher, 1993).

Although modern research and development efforts have sought to resolve many of these longstanding challenges, the evolution of the urbanized life has inadvertently generated new thermal management issues, such as the urban heat island effect. The critical question now is how advances in AI and digitalization will alter the sector in both the short and long term. Viewing AI and digital tools as enabling technologies for more efficient solutions, their impact on the heating and cooling sector will likely include the following areas:

- AI enabled manufacturing: Digitalization is shifting the sector toward cost-effective, labor-optimized, and automated manufacturing processes, streamlining how technical solutions are produced and delivered to a scaled-up mass market.

- Data-Driven decision making: AI will support system designers, developers, property owners, and industrial actors in making more informed decisions regarding heating, cooling, and refrigeration. Stakeholders will have the analytical tools to navigate trade-offs between conflicting objectives—such as cost minimization, decarbonization, security, and resilience—thereby accelerating the transition to sustainable solutions.

- Global accessibility and service models: AI-driven solutions will make heating, cooling, and refrigeration more affordable and accessible, particularly in the developing countries. Traditional capital-intensive business models will likely be replaced by service-oriented approaches that treat thermal comfort as a human-centric service rather than merely a technology application.

- Cross-sector coordination and integration: Driven by the electrification of the mobility sector and the expansion of digital infrastructure (e.g., data centers), digitalization will enable high-level system coordination. This integration will blur the boundaries between demand, supply, and storage across different sectors. Electricity and thermal grids will interact dynamically with buildings, transportation, industry, and digital infrastructure, e.g. data centers, to provide integrated urban energy systems.

- Lifecycle and complementary services: Digital tools will advance services across the entire system lifecycle, including design, implementation, installation, operation and control, maintenance, fault detection and diagnosis, and end-of-life recovery at both the component and system levels.

These prospective changes primarily stem from integrating AI and digital solutions into existing heating and cooling systems. However, perhaps one of the most transformative impacts on the sector lies in harnessing the heat rejected by data centers and other digital infrastructure. This necessitates a holistic, systems-level perspective on thermal management for computing facilities. A recurring shortcoming in current practice is treating data center cooling technologies and downstream "waste heat recovery" as isolated processes. Instead, the cooling of computing infrastructure and the thermal supply for buildings and industry must be approached as coupled components of the same energy system. From a systems perspective,

the low-grade heat from computing is not merely "waste" to be retroactively recovered; rather, digital infrastructures can function as primary heat sources, substantially reducing the demand for standalone heating systems.

To conclude, discussions regarding the impact of AI and digitalization often focus on how advanced algorithms—such as digital twins, AI-driven control, or automated fault detection and diagnosis—can improve the operation and maintenance of existing systems. Despite these promising digital advancements, it is unlikely that the fundamental thermodynamic principles of heating, cooling, and refrigeration will depart significantly from established cycles, such as vapor compression or absorption and adsorption. While innovative cycles may be adopted for niche industrial applications, AI and digitalization will not revolutionize the basic thermodynamics underlying current technologies.

Instead, the most substantial impact of AI and digitalization on the heating and cooling sector lies in the challenge of cooling fast-growing digital infrastructure and utilizing this dissipated heat as a primary thermal source. Heat pumping technologies will likely be deployed at scale to achieve the necessary temperature levels across various systems; nevertheless, computing infrastructure itself constitutes a major heat source for the future. This transition introduces new techno-economic challenges concerning system architecture, operating temperatures, proximity to heat demand, and access to thermal networks and storage (Yuan et al., 2023; Chicherin, 2025). While this increases system complexity, the forthcoming challenges extend beyond technical issues, demanding interdisciplinary research that encompasses the social, behavioral, economic, and political dimensions of the energy system.