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EVALUATION OF THE OPERATIONAL CHARACTERISTICS OF THIRD-GENERATION ADSORPTION HEAT PUMPS

Buxorov Habibullo Jahongir o‘g‘li
Karshi State Technical University student

Abstract. Advances in adsorption heat pump (AHP) technology significantly improve their energy efficiency and the utilization of waste heat, making them a promising solution for sustainable cooling applications. However, challenges such as large system size and unforeseen costs limit their widespread adoption. A novel third-generation adsorption technology, incorporating two adsorption modules with direct evaporation/condensation and liquid-phase refrigerant distribution, addresses these issues by eliminating the need for expensive and bulky vacuum valves and enabling the implementation of compact vacuum systems, thereby unlocking their full market potential.

Keywords: adsorption heat pumps, coefficient of performance (COP), heat exchanger, medium-temperature heat exchanger, low-temperature heat exchanger, logarithmic mean temperature difference (LMTD), heat transfer fluid.

Аннотация. Достижения в технологии адсорбционных тепловых насосов (АТН) значительно повышают их энергетическую эффективность и эффективность использования сбросного тепла, что делает их перспективным решением для устойчивого охлаждения. Однако такие проблемы, как большие габариты и непредвиденные затраты, ограничивают их широкомасштабное применение. Новая адсорбционная технология третьего поколения, включающая два адсорбционных модуля с прямым испарением/конденсацией и распределением хладагента в жидкой фазе, решает эти проблемы за счёт устранения необходимости в дорогостоящих и громоздких вакуумных клапанах и внедрения компактных вакуумных систем, что позволяет полностью раскрыть их рыночный потенциал.

Ключевые слова: адсорбционные тепловые насосы, коэффициент производительности (COP), теплообменник, среднетемпературный теплообменник, низкотемпературный теплообменник, средняя логарифмическая разность температур, теплоноситель.

Annotatsiya. Adsorbsion issiqlik nasoslari (AIN) texnologiyasidagi yutuqlar ularning energetik samaradorligini va issiqlik tashlamalaridan foydalanishni sezilarli darajada yaxshilaydi, bu ularni barqaror sovutish uchun istiqbolli yechimga aylantiradi. Biroq, katta o‘lchamlar va rejalashtirilmagan xarajatlar kabi muammolar ularning keng ko‘lamli qo‘llanilishini cheklaydi. To‘g‘ridan-to‘g‘ri bug‘lanish/kondensatsiya va suyuq fazali sovutish agenti taqsimotiga ega ikkita adsorbsion modullarni o‘z ichiga olgan yangi uchinchi avlod adsorbsion texnologiyasi qimmat va katta vakuum klapanlariga ehtiyojni bartaraf etish va

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ixcham vakuum tizimlarini ishga tushirish orqali ushbu muammolarni hal qiladi, bu ularning to‘liq bozor salohiyatini ochib beradi.

Kalit so‘zlar. adsorbsion issiqlik nasoslari, samaradorlik koeffitsienti, issiqlik almashingich, o‘rta haroratli issiqlik almashingich, past haroratli issiqlik almashingich, o‘rtacha logarifmik haroratlar farqi, issiqlik tashuvchi suyuqlik

1. INTRODUCTION.

Absorption cooling systems represent a thermodynamically driven next-generation alternative to vapor-compression refrigeration systems, contributing significantly to decarbonization efforts and the mitigation of global warming [1]. Adsorption cooling systems possess unique advantages, such as easy regeneration, minimal corrosion, flexible operation, and the use of environmentally friendly working fluids [2]. They are capable of providing cooling by utilizing low-grade heat sources in the temperature range of 50–90°C or even higher, through the recovery of solar energy or waste heat. Furthermore, water is used as a safe refrigerant, which also reduces corrosion-related issues. Unlike absorption chillers, the use of adsorption cooling systems eliminates crystallization problems. Nevertheless, their wider application is limited by lower efficiency compared to absorption chillers (i.e., coefficient of performance (COP) < 0.6). In addition, the cost and compactness of adsorption chillers demonstrate their advantages over conventional refrigeration systems [3].

In recent decades, two main generations of adsorption heat pumps (AHPs) have been widely applied. First-generation adsorption heat pumps, produced by Mayekawa (Japan), Pahwa (India), Sortech and Viessmann (Germany), as well as large-scale laboratory units, have been extensively studied both numerically and experimentally. These systems, including double- and multi-layer configurations, single- and multi-stage schemes, and heat or mass recovery cycles, have been widely investigated [4].

In recent years, researchers have intensified efforts to develop innovative adsorption heat pumps by focusing on improved reactor/heat exchanger designs, optimized thermodynamic cycles, and next-generation sorbent materials. The novelty of this study lies in the development of a third-generation adsorption heat transformation system consisting of two adsorption modules with direct evaporation/condensation, liquid-phase refrigerant distribution, and minimal thermal mass for evaporation/condensation processes. In this configuration, large and expensive vacuum valves are eliminated, enabling the creation of a highly compact and energy-efficient vacuum system. Furthermore, each adsorber utilizes 37.5 kg of composite adsorbent (mesoporous silica gel impregnated with calcium chloride), and its adsorption isotherms and kinetics are characterized. The

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performance, scalability, and cost reduction of the developed AHP are demonstrated and compared with conventional adsorption heat pumps.

2. METHODS.

In this study, the mathematical model of the adsorption heat pump was developed based on strict application of the laws of mass and energy conservation. The system consists of a switching process with a half-cycle time of 20 s and adsorption/desorption processes with a duration of 800 s.

The dynamic analysis of the model was performed through simulation using a time step of 1 second, and the ODE15s solver, which is efficient for solving stiff differential equations, was employed. In the current numerical model, the relative error is:

$$| s_{n+1} - s_n | = 10^{-6}$$

accepted.

Considering the structural features and boundary conditions of the existing adsorption heat pump (such as cycle time and inlet temperatures of hot water, cooling water, and chilled water), the dynamic characteristics of system components—including temperature distribution, degree of sorption, cooling capacity, heating capacity, and COP—were investigated and compared with experimental results. The structure and design of the existing adsorption heat pump are shown in Figure 1.

This dynamic model is based on mass and energy balances, as well as sorption isotherms and kinetics.

The adsorber modules include the following:

• sorption equilibrium (isotherms) to evaluate the adsorption of the refrigerant as a function of temperature and pressure.

• a kinetic model to evaluate the transfer of vapor between the evaporator/condenser and the adsorber, and vice versa;

• heat and mass balance equations for the adsorber module.

The main and auxiliary condenser/evaporator heat exchangers were also modeled based on heat and mass balance equations.

3. PRINCIPLES OF OPERATION OF ADSORPTION COOLING SYSTEMS.

The evolution of adsorption cooling systems progresses through three generations (Table 1). The first generation consists of four separate chambers (i.e., adsorber/desorber, desorber/adsorber, evaporator, and condenser), which ensures flexible operation due to the use of vacuum valves in separated condenser/evaporator heat exchangers. However, it relies on large and expensive vacuum valves and systems for vapor-phase refrigerant flow [6].

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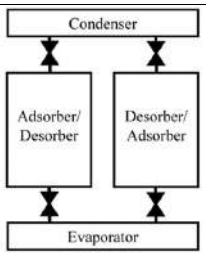
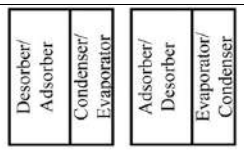
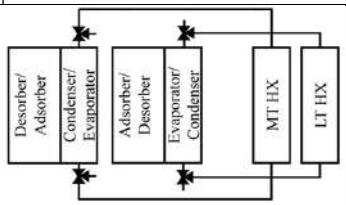
Second-generation designs were simplified to two combined chambers (adsorber/desorber and evaporator/condenser), eliminating large vacuum valves; however, they suffered from higher heat losses and lower performance [5].

Third-generation systems developed by Sorption Technologies GmbH [7] introduce liquid-phase refrigerant distribution, enabling direct evaporation/condensation within the adsorption module and eliminating the need for complex vacuum systems [8].

The description of the third-generation adsorption cooling system is shown in Figure 1. In the desorption/condensation mode, the liquid refrigerant (water) passes through a mixing condenser located within the desorber module. The mixing condenser is concentrically arranged inside the module, where the liquid refrigerant accumulates as a wetting film over porous structures/surface-enhancing contours, enabling direct condensation of the desorbed refrigerant and thereby heating the refrigerant. The liquid refrigerant is then supplied to a medium-temperature external heat exchanger as a heat transfer medium, from where it is pumped into the condenser tank.

1- table

Stages of development of adsorption cooling systems

Stages	1st generation (from the 1990s to the present)	2nd generation (from the 2005s to the present)	3rd generation (from the 2020s to the present)
Configuration			
Advantages	• Flexible operation (due to their separated condenser/evaporator design)	• Compact design with a single condenser/evaporator • Direct vapor transport without valves • Coated adsorbent with improved adsorption performance	• Liquid-phase refrigerant distribution • Direct phase change (i.e., evaporation/condensation) of the liquid refrigerant within the sorption reactors • Reduced heat losses due to minimal thermal mass of the condenser/evaporator

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		• Simplified vacuum system	(made of plastic) • Controlled pumping of the liquid-phase refrigerant at low pressures
Disadvantages	• Vapor-phase refrigerant distribution• Katta vakuum klapanlari • Complex and expensive vacuum system	• Heat losses and fluctuations in condenser/evaporator heat exchangers • Mixing of cycles and system separation • High requirements for external heat exchangers	
Manufacturer	Mayekawa (Japan), Pahwa (India), Sortech (Germany)	Sortech/Fahrenheit (Germany)	Sorption Technologies (Germany)

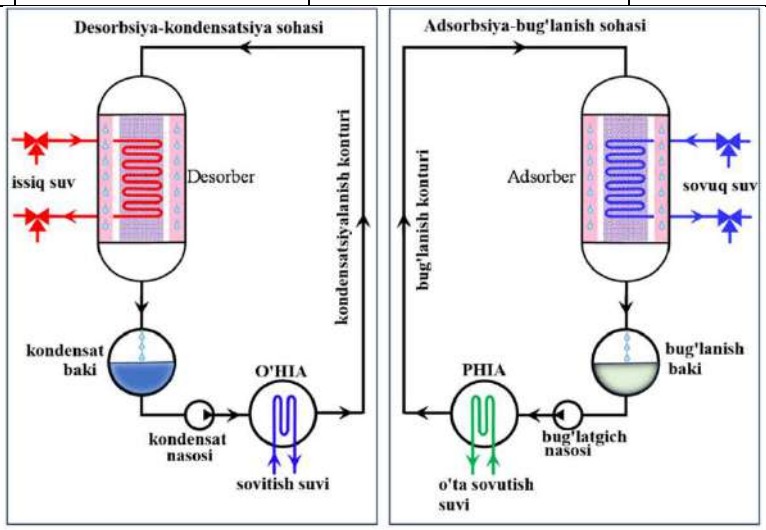


Figure 1. Schematic of the third-generation adsorption heat pump (AHP)

4. DEVELOPMENT OF THE CALCULATION SCHEME.

Conversely, in the adsorption/evaporation mode, the liquid refrigerant passes through the mixing evaporator located inside the adsorber module. Similarly, direct evaporation of the adsorbed refrigerant occurs, resulting in cooling of the refrigerant. The liquid refrigerant is also pumped into the evaporator reservoir.

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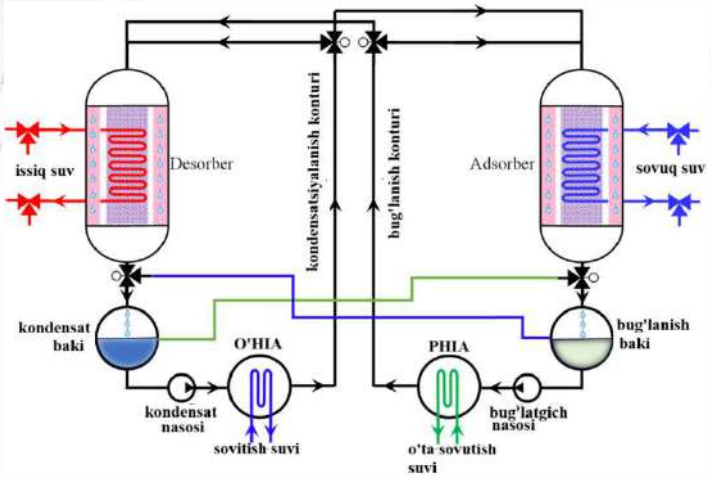


Figure 2. Integrated schematic of the adsorption heat pump (AHP)

For continuous or semi-continuous operation, two sorption modules with a mixing evaporator/condenser, a medium-temperature heat exchanger (MTHX), a low-temperature heat exchanger (LTHX), two hydraulic pumps, and four three-way valves are used, as shown in Figure 2. The desorption/condensation and adsorption/evaporation modes are alternately implemented within the sorption modules, while the external MTHX and LTHX maintain their respective functions.

5. NUMERICAL MODELING.

The presented mathematical model includes governing equations for the adsorption isotherms/kinetics of CaCl2@SG_25, mass and energy balances of the main system components, and performance indicators of the adsorption heat pump (AHP).

5.1. Adsorption Equilibrium and Kinetics

Using the Dubinin–Astakhov (D–A) equation, CaCl2@SG_25 the adsorption equilibrium of water vapor is described as follows [9]:

$$W = W_0 \exp\left[-\left(\frac{RT_s}{E}\ln\left(\frac{P}{P_{sat}}\right)\right)^n\right] \quad (1)$$

where: W_0 – maximum equilibrium adsorption capacity; n – heterogeneity constant; T_s – sorbent temperature; E – adsorption characteristic energy. Also: P_{sat} – saturation pressure at the corresponding temperature; P – vapor pressure.

$$RT_s \ln\left(\frac{P}{P_{sat}}\right)$$

the expression represents the adsorption potential and is denoted by **A**.

CaCl2@SG_25/ the sorption kinetics of the vapor pair (w) is determined using the linear driving force (LDF) model as follows [10]:

$$\frac{\partial w}{\partial t} = k(W - w), \quad (2)$$

where the kinetic coefficient (k) is expressed as follows [11]:

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$$K = M\exp\left(-\frac{N}{RT_s}\right). \quad (3)$$

where M and N are correction parameters, as listed in table 2.

2-table

CaCl2@SG_25 required parameters for adsorption isotherms and kinetics.

Parameter	Description	Unit of measurement
W_0	maximum equilibrium uptake capacity	0.8 (kg/kg)
E	characteristic energy	174.4 (kJ/kg)
n	heterogeneity constant	1.08 (-)
M	flexibility parameter	2.73E–03 (m^2/s)
N	flexibility parameter	15.993558 (kJ/kg*K)
H_{st}	isosteric heat of adsorption	155.1 ln(W)+2381.5 (kJ/kg)

5.2. Energy balance

The energy balance of the adsorber reactor is modeled as follows [12]:

$$(Mc_p)_{ad}\ \frac{dT_{ads}}{dt} = M_s H_{st}\frac{dw_{ads}}{dt} + \dot{m}_{cw}c_{p,cw}(MT_{in} - MT_{out}). \quad (4)$$

The energy balance of the desorber reactor is modeled as follows:

$$(Mc_p)_{des}\frac{dT_{des}}{dt} = M_s H_{st}\frac{dw_{des}}{dt} + \dot{m}_{hw}c_{p,hw}(HT_{in} - HT_{out}). \quad (5)$$

The energy balance for the direct condensation process is given as follows:

$$(Mc_p)_{cond}\frac{dT_{cond}}{dt} = -[M_s h_{fg}]\frac{dw_{des}}{dt} + \dot{m}_{cond}c_{p,w}(T_{cond,in} - T_{cond,out}). \quad (6)$$

The energy balance for the direct evaporation process is given as follows:

$$(Mc_p)_{cond}\frac{dT_{evap}}{dt} = -[M_s h_{fg}]\frac{dw_{ads}}{dt} + \dot{m}_{evap}c_{p,w}(T_{evap,in} - T_{evap,out}). \quad (7)$$

The energy balance of the plate heat exchanger (condenser) used for external heat rejection is given as follows:

$$(Mc_p)_{cond}\frac{dT_{p-con}}{dt} = -\phi[M_s h_{fg}]\frac{dw_{des}}{dt} + \dot{m}_{cw}c_{p,cw}(MT_{in} - MT_{out}). \quad (8)$$

The energy balance of the plate heat exchanger (evaporator) used for external chilled water supply is given as follows:

$$(Mc_p)_{cond}\frac{dT_{p-ev}}{dt} = -\phi[M_s h_{fg}]\frac{dw_{des}}{dt} + \dot{m}_{chw}c_{p,chw}(LT_{in} - LT_{out}). \quad (9)$$

where the symbol ϕ is assumed to be equal to zero during the preheating/precooling switching period when the refrigerant hydraulic pump is turned off.

The outlet temperatures of the system components are evaluated using the **Logarithmic Mean Temperature Difference (LMTD)** method as follows [13]:

$$T_{HX,out} = T_{HX} + (T_{HX,in} - T_{HX})\exp(-NTU). \quad (10)$$

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The **Number of Transfer Units (NTU)** is determined from the overall heat conductance as follows where $\mathbf{UA_{hx}}$ is the overall heat transfer conductance of the heat exchanger, and **HTF** denotes the heat transfer fluid flow rate ($\dot{m}c_p$) and is determined as the ratio between the overall heat transfer conductance and the heat transfer fluid (HTF) flow rate.

It should be noted that the **UA** values are estimated from this experimental study as follows:

$$UA_{HX} = \frac{Q}{LMTD}, \quad (11)$$

$$LMTD = \frac{T_{HX,out} - T_{HX,in}}{\ln \frac{T_{HX} - T_{HX,in}}{T_{HX} - T_{HX,out}}}. \quad (12)$$

where the heat exchanger temperature corresponds to the equilibrium temperature of the adsorber/desorber or the saturation temperature of the condenser/evaporator.

The number of transfer units (NTU) is defined as the ratio of the overall heat transfer conductance (UA_{HX}) to the heat capacity flow rate of the heat transfer fluid $(\dot{m}c_p)$is equal to this ratio.

5.3. Mass balance

The adsorbed or desorbed mass flow rate is determined as follows:

$$\dot{m}_{ads/des} = M_s \frac{dw_{ads/des}}{dt}. \quad (13)$$

The adsorption/desorption mass flow rate, overall heat transfer conductance, and heat capacity values of the main components are presented in Table 3.

The specific cooling power (SCP) and specific heating power (SHP) are evaluated as follows:

$$SCU = \frac{Q_{PH}}{M_s}, \quad (14)$$

$$SIU = \frac{Q_{O'H}}{M_s}. \quad (15)$$

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Constants and parameters of the new AHP.

Parametr	Qiymat	Birlik
Ms	37.5	kg
$(Mcp)_{ads/des}$	120	kJ/kg
$(M\ cp)_{cond}$	3.0	kJ/kg
$(M\ cp)_{evap}$	3.0	kJ/kg
$UA_{ads/des}$	2.0	kW/K
UA_{cond}	3.0	kW/K
UA_{evap}	3.0	kW/K
$UA_{p\text{-}cond}$	3.5	kW/K

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$UA_{p\text{- evap}}$	3.5	kW/K
$\dot{m}_{ads/des}$	0.63/0.95	kg/s
$\dot{m}_{cond}$	0.29	kg/s
$\dot{m}_{evap}$	0.28	kg/s
$\dot{m}_{MT}$	0.63	kg/s
$\dot{m}_{LT}$	0.34	kg/s

The coefficient of performance (COP) for cooling and heating is evaluated as follows:

$$COP_c = \frac{Q_{LT}}{Q_{HT}} \quad (16)$$

$$COP_h = \frac{Q_{MT}}{Q_{HT}}. \quad (17)$$

6. RESULTS AND DISCUSSION.

This section presents the operating principle and dynamic performance of the adsorption heat pump.

6.1. Proof of Concept (Validation of the Concept)

System dimensions:

$$2{,}1 \times 0{,}99 \times 2{,}46 \text{ м}^3$$

The volumes of the adsorber module and the condenser/evaporator tanks are 0.23 m³ and 0.025 m³, respectively.

The adsorber module consists of two sections:

1. direct evaporation;
2. direct condensation.

Water droplets flow through porous structures into the refrigerant tanks. Three-way and two-way valves coordinate the adsorption and desorption cycles. Temperature, pressure, and flow sensors are used to monitor system operation.

To improve condensation and evaporation efficiency, the adsorber modules are installed in an inclined position and insulated with 10 mm polyurethane. This ensures proper drainage of water droplets into the tanks.

The flow rates of the refrigerant and HTF are controlled by three-phase hydraulic pumps. The HTF supply is provided by three water storage units that ensure high (HT), medium (MT), and low (LT) temperature levels for the system.

It should be noted that the overall heat transfer conductance (UA) for the falling-film condenser and evaporator is approximately 3 kW/K.

$$UA \approx 3 \text{ kW/K}$$

This value is significantly higher than those reported in other studies. Such high UA values are mainly explained by the direct evaporation–condensation process and the continuous movement of liquid droplets over the porous structure.

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Temperature lift—the thermal difference between the heat source and the cooling medium—is a key performance indicator of adsorption heat pumps. The experimental results (Figure 8) show a strong inverse relationship between cooling capacity and temperature lift. As the temperature lift increases from 27 K to 32 K, the cooling capacity decreases from approximately 8 kW to 2 kW.

Similarly, the COP decreases from approximately 0.5 at a temperature lift of 25–26 K to about 0.35 at around 30 K. This indicates that higher temperature lifts require greater heat input, resulting in reduced system efficiency.

Overall, the analysis confirms that the adsorption heat pump achieves its highest efficiency at low temperature lift conditions.

It can be concluded that by simply modifying the system architecture and eliminating the need for large vacuum valves, capital costs per machine can be reduced by more than €10,000. The actual cost difference also depends on production scale, component suppliers, and other factors. Nevertheless, this analysis provides a solid basis for further development and optimization investment in the proposed technology.

CONCLUSION.

This study developed a new generation adsorption technology, referred to as "third-generation adsorption technology," and validated it through both experimental setup and numerical modeling. The operating conditions were systematically investigated, and a comparative analysis was performed to evaluate the feasibility of this advanced technology. The proposed adsorption heat pump demonstrated stable thermal performance comparable to conventional systems, owing to its ability to ensure high heat output, efficient phase-change management, and improved internal heat transfer.

The results of dynamic modeling showed close agreement with experimental data, with deviations of less than 10% across all key performance indicators, confirming the reliability of the model. Under operating conditions of 90/20/20 °C, the system achieved a cooling capacity of 3.84 kW and a heating capacity of 11.07 kW, with COP values of 0.43 and 1.16, respectively. An increase in inlet hot water temperature and cooling water inlet temperature significantly improves system performance, while higher cooling water temperatures negatively affect efficiency. Longer half-cycle durations ensure more complete adsorption/desorption processes, thereby enhancing thermal efficiency and operational stability.

Compared with conventional adsorption transformation systems, the third-generation design significantly reduces capital costs by replacing large vacuum valves with compact pumps and smaller valves. Overall, the innovative system architecture demonstrates high thermodynamic efficiency and economic feasibility, making it a promising solution for utilizing low-grade heat sources.

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Future research may focus on long-term energy efficiency assessment as well as the integration of the system into hybrid energy systems, including solar thermal technologies, district heating and cooling networks, and waste heat recovery systems. In particular, systems adapted to intermittent or variable heat sources are of special importance. Such improvements will further enhance energy utilization efficiency and expand decarbonization opportunities in industrial and urban infrastructure.

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