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DECARBONISATION THROUGH INNOVATION

A study on dynamic simulation of absorption heat pump integrated MVR

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Abstract

Absorption heat pumps are widely used in industrial processes due to low grade thermal energy heat source utilization. A mechanical vapor recompression (MVR) integrated absorption heat pump system combines the principles of vapor compression into absorption heat pumps. In this study, a dynamic simulation model is proposed to understand the process of a lithium bromide-water (LiBr-H_2O) solution absorption heat pump system integrated with an MVR. The dynamic cycle is developed considering heat and mass transfer of working fluid through system components. The ordinary differential equations of heat and mass conversion are solved for every component in each timestep. The thermal inertia characteristics and thermal performance of the system are analyzed under different operating conditions including heat source temperature, cooling temperatures, LiBr concentration. Furthermore, the operating conditions of absorption heat pump are controlled to obtain a proper vapor stream supply for the MVR. Different control methods are applied to optimize the performance and energy efficiency of the integrated system. This work contributes to the design and implementation of integrated thermal systems for industrial waste heat recovery and energy reuse.

Keywords: absorption heat pum; dynamic simulation; mechanical vapor recompressor (MVR); LiBr solution;

1. Introduction

The global demand for efficient and low-carbon thermal energy systems has accelerated the development of advanced heat pump technologies that can recover and upgrade low-grade waste heat. Among these, the lithium bromide-water (LiBr-H_2O) absorption heat pump has gained significant attention due to its capability to utilize low-temperature heat sources, chemical stability, and environmental friendliness [1]. However, the performance of conventional absorption heat pumps is often limited by the low driving temperature and poor system responsiveness during transient operation.

To overcome these drawbacks, hybrid configurations integrating absorption cycles with mechanical vapor recompression (MVR) have been proposed [2]. In such systems, the MVR unit compresses and recycles water vapor from the evaporator or absorber, increasing its pressure and temperature before reintroducing it to the generator. This integration enhances the temperature lift, improves coefficient of performance (COP), and enables efficient operation under lower driving heat temperatures. Furthermore, the hybrid MVR heat pump system can achieve thermally driven compression with reduced electricity consumption compared to fully mechanical systems, offering a promising solution for industrial waste heat recovery and renewable energy usage [3].

Despite growing interest in this hybrid configuration, most studies to date have focused on steady-state analysis, while the dynamic behavior of systems remains insufficiently explored. Understanding the transient characteristics is critical for optimizing system control and performance under variable thermal loads. The strong coupling between heat and mass transfer in the absorption cycle and the mechanical compression process requires complicated mathematical solver. Recently, several dynamical models have been developed to simulate different types of absorption heat pump in a wide range of scales. Cai et al. [4] have developed a dynamic model of a single-effect absorption refrigeration cycle of ammonia/water solution with realistic thermodynamics. The equation of state model has demonstrated accurate prediction of heat transfer and coefficient of performance (COP). Calle et al. [5] have developed a dynamic model of double effect absorption heat pump integrated with a solar-assisted multi-effect distillation using equation-based object-oriented Modelica modelling language. The Dymola library has been used to simulate and validate the dynamic model against experimental data from actual facilities, showing a reasonable accurate performance.

In this study, a dynamic model of LiBr absorption heat pump integrated MVR system is developed based on ordinary differential equations using Python codes. The dynamic model is validated with experimental data of an actual pilot-scale absorption heat pump system. Dynamic behavior of component temperatures is studied with variations of inlet temperature conditions.

2. Methodology

2.1. System operation

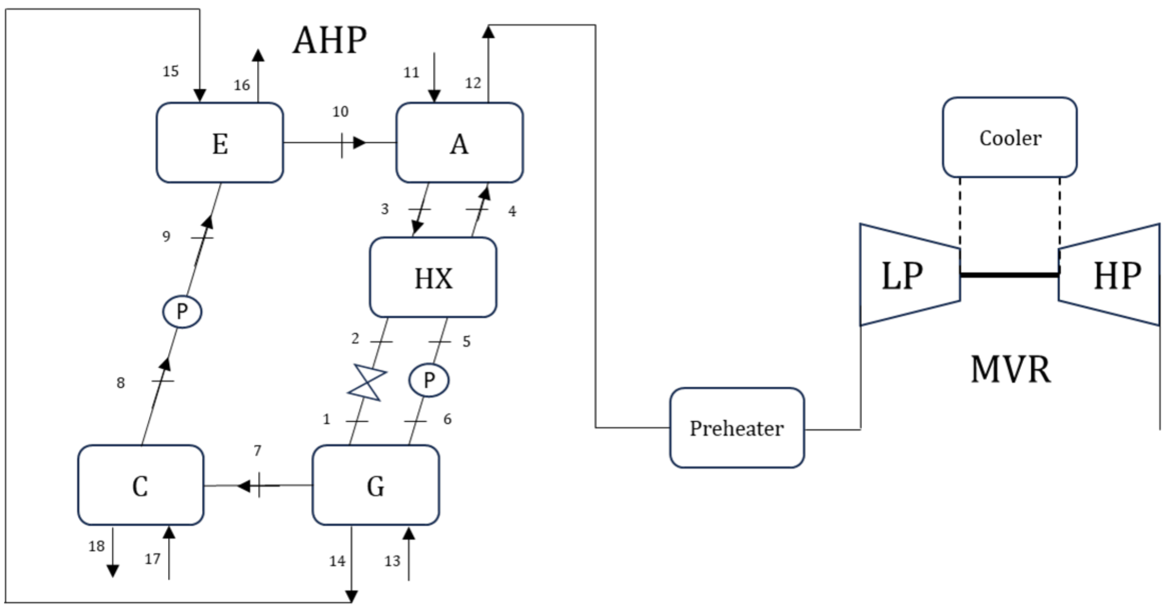

Figure 1. Schematic diagram of absorption heat pump.

The schematic diagram of absorption heat pump system is shown in Fig. 1. The diagram illustrates a typical single-effect absorption refrigeration cycle using a solution heat exchanger. The cycle consists of a generator, condenser, evaporator, absorber, two solution pumps, and a solution heat exchanger. The weak solution is pumped from the absorber to the generator, where it is heated and vaporized. The refrigerant vapor is condensed in the condenser and then expanded into the evaporator, absorbing heat from the cooled space. The resulting vapor is absorbed by the strong solution returning from the generator through the solution heat exchanger, completing the cycle. The solution heat exchanger improves cycle efficiency by preheating the weak solution using heat from the strong solution. The waste heat water is supplied continuously through the generator and evaporator at high temperature to release heat into the system. A high temperature, high pressure water flow circulates through the absorber and absorbs heat from the system. Hot water is evaporated in the enhanced boiling tubes of absorber and generates steam flow. The hot steam flows through a preheater to achieve a specific target temperature before feeding into an MVR to generate high pressure, high temperature steam.

2.2. Mathematical formula

The dynamic simulation is developed based on ordinary differential equations (ODEs) of system components. The mathematical model is solved using Python with CoolProp library for LiBr solution properties. In the dynamic simulation of a heat pump system, the mass and energy conservation equations describe the transient behaviour of each component including evaporator, condenser, adsorber, generator, by accounting for the accumulation, inflow, and outflow of mass and energy within a control volume. The mass conservation equation tracks the variation of working fluid mass over time, ensuring that the rate of mass accumulation equals the difference between inlet and outlet mass flow rates. Meanwhile, the energy conservation equation evaluates the transient energy balance by considering the rate of internal energy change in the control volume as the result of heat transfer, mass flow enthalpy transport, and possible work interactions. In dynamic heat pump models, these equations are typically solved simultaneously over small time steps to predict the time-dependent temperature, pressure, and heat transfer performance during operation cycles such as adsorption/desorption or evaporation/condensation processes.

The governing equations for generation are expressed as follows:

Mass Balance Equations:

$$\frac{dM_{6,LiBr}}{dt} = m_1 \cdot X_1 - m_6 \cdot X_6 \tag{1}$$

$$\frac{dM_{6,H2O}}{dt} = m_1 \cdot (1 - X_1) - m_6 \cdot (1 - X_6) - m_7 \tag{2}$$

$$\frac{dT_6}{dt} = (m_1 \cdot h_1 + m_6 \cdot h_6 - m_7 \cdot h_7 + Q_{13,6}) / ((M_{6,LiBr} + M_{6,H2O}) \cdot c_{p-6} \tag{3}$$

$$\frac{dT_{14}}{dt} = (m_1 \cdot h_1 - m_6 \cdot h_6 - Q_{13}) / (\rho_{14} \cdot V_{13} \cdot c_{p-14}) \tag{4}$$

The governing equations of absorber are calculated:

$$\frac{dM_{3,LiBr}}{dt} = m_4 \cdot X_4 - m_3 \cdot X_3 \tag{5}$$

$$\frac{dM_{3,H2O}}{dt} = m_4 \cdot (1 - X_4) + m_{10} - m_3 \cdot (1 - X_3) \tag{6}$$

$$\frac{dT_3}{dt} = (m_4 \cdot h_4 + m_{10} \cdot h_{10} - m_3 \cdot h_3 - Q_3) / ((M_{3,LiBr} + M_{3,H2O}) \cdot c_{p-3}) \tag{7}$$

$$\frac{dT_{12}}{dt} = (m_{11} \cdot h_{11} - m_{12} \cdot h_{12} + Q3) / (\rho_{12} \cdot V_{11} \cdot c_{p-12}) \tag{8}$$

The equations for evaporator are expressed as:

$$\frac{dM_{10}}{dt} = m_9 - m_{10} \tag{9}$$

$$\frac{dT_{10}}{dt} = (m_9 \cdot h_9 - m_{10} \cdot h_{10-v} - Q_9) / (M_{10} \cdot c_{p-10}) \tag{10}$$

$$\frac{dT_{16}}{dt} = (m_{15} \cdot h_{15} - m_{16} \cdot h_{16} - Q_9) / (\rho_{15} \cdot V_{15} \cdot c_{p-15}) \tag{11}$$

Finally, the governing equations for evaporator are calculated as follows:

$$\frac{dM_8}{dt} = m_7 - m_8 \tag{12}$$

$$\frac{dT_8}{dt} = (m_7 \cdot h_7 - m_8 \cdot h_{8-l} - Q_7) / (M_8 \cdot c_{p-8}) \tag{13}$$

$$\frac{dT_{18}}{dt} = (m_{17} \cdot h_{17} - m_{18} \cdot h_{18} - Q_7) / (\rho_{17} \cdot V_{17} \cdot c_{p-17}) \quad (14)$$

3. Results and discussion

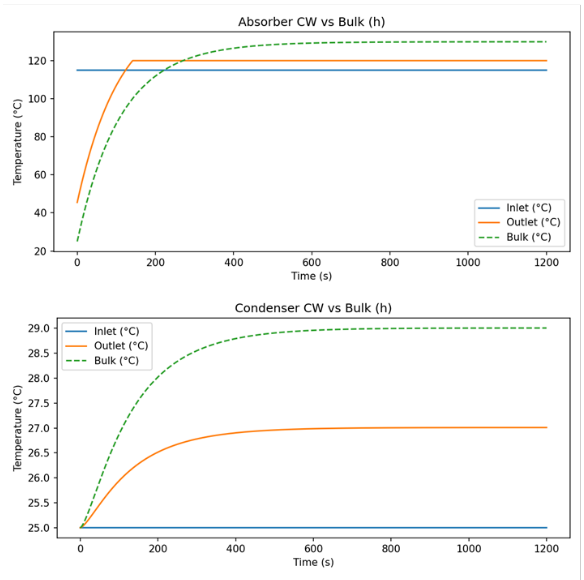

Figure 2. Variation of component temperatures in absorber overtime with stable operating conditions

The transient temperature responses of the four main components including absorber, generator, condenser, and evaporator are presented in Figure 2 to illustrate the dynamic behaviour of the heat pump system during start-up. In the absorber, the cooling water outlet temperature rises rapidly from its initial value and approaches a steady state close to 120 °C, while the bulk temperature of the working solution gradually increases and stabilizes at a slightly higher level, indicating progressive heat accumulation and mass transfer within the absorber. In the generator, a similar transient trend is observed where the outlet temperature slowly approaches the inlet hot water temperature (~90 °C), while the bulk temperature increases from the initial condition and stabilizes at a lower level due to continuous heat utilization for desorption. For the condenser, the cooling water outlet temperature increases slightly from the inlet temperature of 25 °C and reaches a steady value around 27 °C, while the bulk refrigerant temperature stabilizes near 29 °C, reflecting efficient heat rejection to the cooling water. In contrast, the evaporator shows a gradual increase in both outlet and bulk temperatures until a steady state is reached, representing the establishment of a stable evaporation process. Overall, all components exhibit a typical first-order transient response, reaching quasi-steady conditions within approximately 400 to 600 s, which demonstrates the dynamic thermal inertia and stability of the modelled heat pump system.

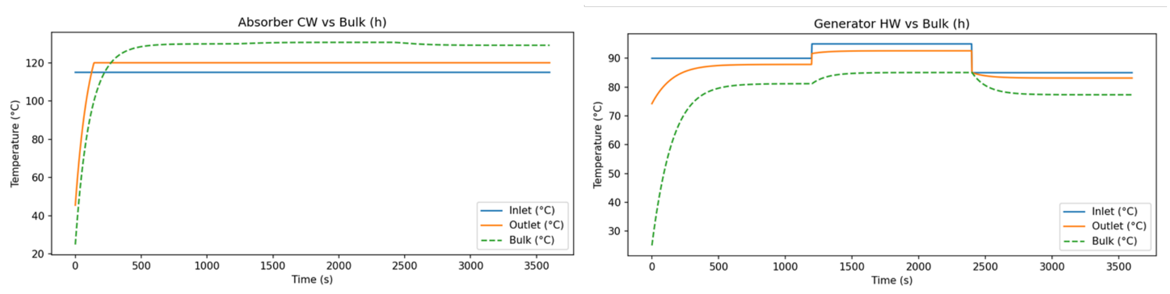

Figure 3. Variation of absorber and generator temperature overtime with unstable waste heat water inlet

Fig. 3 illustrates the transient temperature response of the absorber and generator when the generator inlet hot water temperature is varied during operation. In the absorber, the cooling water outlet temperature increases rapidly from the initial condition and quickly approaches a stable value of approximately 120 °C, while the bulk solution temperature rises more gradually due to the thermal inertia of the working solution and heat transfer surface. After approximately 400–600 s, the absorber reaches a quasi-steady state where both outlet and bulk temperatures remain relatively stable, indicating that the absorption heat release is balanced by heat removal through the cooling water. In the generator, a clear dynamic response is observed when the inlet hot water temperature changes stepwise. Initially, the system stabilizes with an inlet temperature of about 90 °C. When the inlet temperature increases to approximately 95 °C at 1200 s, the outlet and bulk temperatures rise correspondingly, reflecting enhanced heat input and intensified desorption of refrigerant vapor. Subsequently, when the inlet temperature decreases to about 85 °C at 2400 s, both outlet and bulk temperatures decline and gradually reach a new equilibrium. The bulk temperature consistently responds more slowly than the fluid temperatures due to the thermal mass of the generator. Overall, the results demonstrate that the dynamic model successfully captures the transient thermal behaviour of the system under variable heat-source conditions.

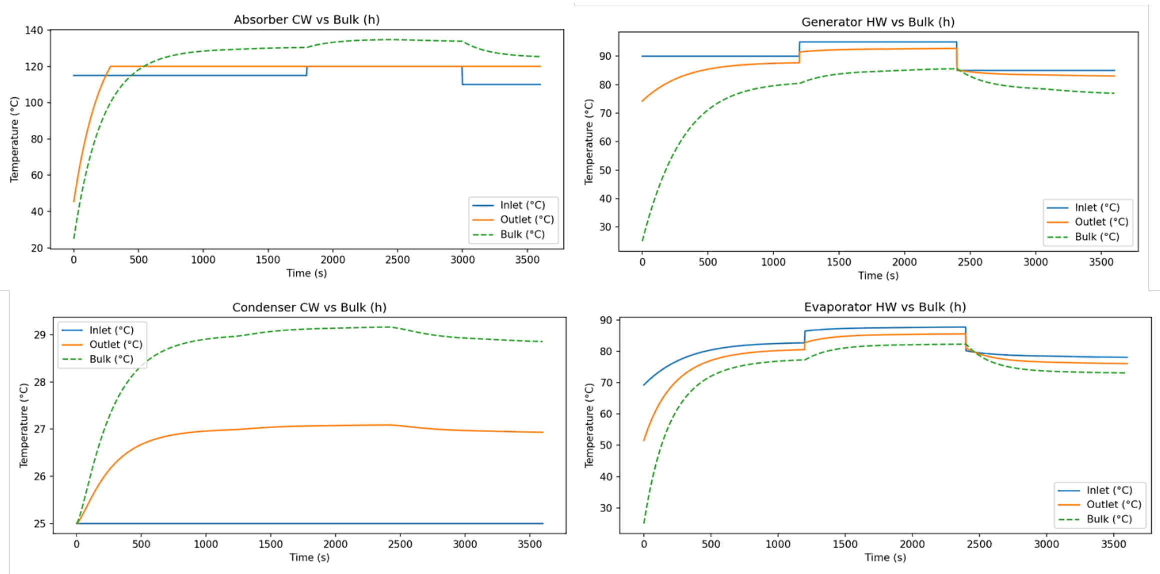

Figure 4. Variation of absorber and generator temperature overtime with unstable inlet conditions

Figure 4 illustrates the transient temperature response of the four primary components including absorber, generator, condenser, and evaporator under variable operating conditions. In the absorber, the cooling water outlet temperature rises rapidly from the initial state, stabilizing near 120 °C, while the bulk solution temperature exhibits a more gradual increase due to the thermal inertia of the working fluid and heat transfer surfaces. Following an initial transient phase of approximately 600 s, the component reaches a quasi-steady state where heat generation from the absorption process is balanced by cooling water removal. The generator displays a distinct dynamic response to stepwise changes in the heat source; as the hot water inlet temperature is modulated between 90 °C, 95 °C, and 85 °C, the outlet and bulk temperatures adjust accordingly, reflecting changes in desorption intensity. Similarly, the evaporator shows a sensitive response to these fluctuations, with the bulk temperature consistently lagging behind the fluid temperatures due to the component's thermal mass. In the condenser, the cooling water inlet remains constant at 25 °C, while the outlet and bulk temperatures approach steady-state values of approximately 27 °C and 29 °C, respectively. Collectively, these profiles demonstrate the model's capability to capture the complex thermal coupling and transient delays inherent in the absorption cycle during heat-source perturbations.

Figure 5 shows the transient response of the MVR power consumption during the system's startup and variable load phases. The figure tracks both the shaft power and electrical power. Following an initial idle period, the power consumption increases rapidly after 300 s, reflecting the ramp-up of the compressor as it establishes the required pressure ratio across the system. A quasi-steady state is initially approached around 1500 s with an electrical power demand of approximately 1.2 kW. When the system load is adjusted stepwise at 1800 s, a secondary rise in power is observed, peaking at roughly 1.4 kW, which corresponds to the intensified compression work required to maintain performance under modified operating conditions. Subsequently, as the load is reduced to 3000 s, both shaft and electrical power decline toward a new equilibrium. The consistent vertical offset between the two curves represents the electrical and mechanical losses inherent in the motor and drive assembly. These results confirm the dynamic model's sensitivity to operational setpoint changes and its ability to accurately quantify the energy requirements of the compression process under transient conditions.

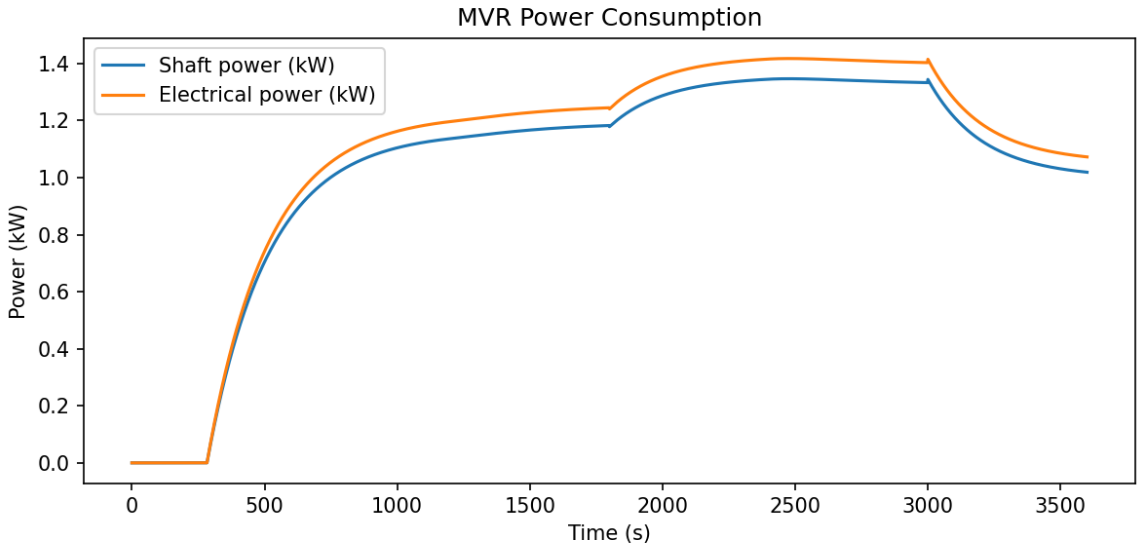

Figure 5. Variation of MVR power consumption with unstable inlet conditions

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