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EXPERIMENTAL ASSESSMENT OF OIL FREE LIQUID INJECTION TWIN SCREW COMPRESSOR

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ABSTRACT

The demand for energy-efficient and environmentally friendly compression technologies has fueled the exploration and development of innovative compressor designs. Among these, oil-free liquid injection twin screw compressors have gained significant attention due to their potential for improved performance and reduced environmental impact. This research article presents an experimental assessment of the oil-free ammonia-water liquid injection twin screw compressor, aiming to evaluate its initials, operational characteristics, and suitability for various applications. The study encompasses an in-depth analysis of the compressor's thermodynamic performance and overall system reliability. The results obtained from the experimental investigation provide valuable insights into the capabilities and limitations of this emerging compressor technology, facilitating informed decision-making in selecting appropriate compression systems for specific industrial applications.

Keywords: Idustrial High Temperature Heat Pump, Hybrid Absorption-Compression Heat Pump, Ammonia-Water Mixture, NH3 Compressor

1. INTRODUCTION

Compressor technologies play a critical role in various industrial applications, such as refrigeration, air conditioning, and chemical processes. With the growing demand for energy efficiency and environmental sustainability, there is a pressing need for innovative compressor designs that can minimize energy consumption and reduce greenhouse gas emissions. Many industries require heat within the 80-200°C range, and ongoing research in high-temperature heat pump technology is focused on achieving these temperatures (Hamid et al., 2023; Marina et al., 2021; Rehfeldt et al., 2018). Currently, only a few industrial high-temperature heat pumps operate within this range, primarily due to limitations in working fluids and available equipment, particularly compressors (Stosic et al., 2005). Studies indicate that most wet twin screw compressors are lubricated or injected with oil, which is the most effective lubricant. Consequently, there is extensive research on oil-injected screw compressors. However, using oil for lubrication has the drawback of necessitating the separation of oil and gas after compression. If this separation is inadequate, residual oil can be carried into the heat exchangers, absorber, and desorber, leading to the formation of an oil layer on the heat exchanger surface, which diminishes their performance (Hwang et al., 2007). Additionally, the presence of oil in the mixture requires extra equipment to separate the oil from the gas. Apart from lubrication, oil serves other purposes in compressors, such as reducing blowholes and clearances in leakage paths between the rotors and between the rotors and the housing. Furthermore, oil absorbs heat generated during compression, helps maintain a low compressor temperature, and reduces wear on the rotor lobes. The selection of an appropriate lubricant is therefore a critical aspect of screw compressor design and operation. By eliminating the need for oil lubrication, oil-free liquid injection compressors offer several advantages. They deliver a continuous supply of clean, oil-free compressed air or gas, free from any oil contamination that could adversely affect downstream equipment or processes. This makes them suitable for critical applications where oil contamination can have severe consequences. Additionally, oil-free operation reduces maintenance requirements and costs associated with oil changes, filtration, and disposal. One such design that has gained considerable attention in recent years is the oil-free liquid injection twin screw compressor. Oil-free liquid injection twin screw compressors have emerged as a promising solution to address the aforementioned concerns. Unlike their oil-lubricated counterparts, these compressors employ a liquid injection method to provide internal cooling and sealing, eliminating the need for oil lubrication. The injection of a suitable liquid into the compression chamber not only ensures efficient cooling of the process gas but also enhances the volumetric efficiency and reduces the discharge temperature. This innovative approach presents several advantages, including enhanced energy efficiency, reduced environmental impact, and improved reliability. While the concept of oil-free liquid injection twin screw compressors has been explored in recent literature(Li et al., 2009; Madhav & Kovačević, 2015; Ous et al., 2012; Wang et al., 2018), there is still a need for comprehensive experimental investigations to validate and quantify their performance characteristics.

The subsequent sections of this research article will present the experimental setup, methodology, results, and analysis, followed by a discussion of the implications and potential avenues for future research. The ultimate goal is to use the liquid phase of the ammonia/water mixture as a lubricant for sealing, bearing and shaft seal to shed light on the feasibility and performance of oil-free twin-screw compressors, facilitating their wider adoption and contributing to a greener and more sustainable future.

2. EXPERIMENTAL TEST RIG

In order to investigate thermal performance of cycle, the most basic type of the Absorption-Compression Heat Pump (ACHP) system with ammonia-water mixture as working fluid is often referred to as Osenbrück cycle in recognition of its inventor Osenbrück (1895) was constructed. This ACHP cycle with a single-stage solution circuit consists of seven main components, namely: three heat exchangers, a liquid-vapor separator, an expansion valve, a solution pump, and a compressor. Figure 1 shows a schematic representation of this basic ACHP cycle. In Figure 1(a) Evaporator and condenser are particularly substituted in the ACHP cycle by desorber and absorber, which provide heat to the heat source and sink. The temperature increases and the ammonia's absorption in water decreases throughout the entire heat transfer process with the heat source in the desorber, forcing ammonia vapor to dissipate. A two-phase mixture leaves the desorber and transfers toward the liquid-vapor separator as the consequence (1). Before being delivered to the compressor (2) and solution pump (4), the liquid-vapor separator separates the low-pressure vapor and ammonia-lean solution. The compressor increases the vapor's pressure and temperature (2–3), and the pump increases the lean solution's pressure (4–5) in a similar way. An internal heat exchanger (IHX) is installed to connect the solution streams in order to enhance cycle performance. Lean solution temperature increases (5–7) and rich solution temperature reduces (9–10) as a result of heat transfer between the lean and rich solutions. The lean solution (7) is then combined with the superheated NH3 vapor from the compressor (3) at the entrance of the absorber (8) on the high-pressure side. The liquid in the absorber absorbs vapor, releasing heat which is then transferred to the fluid in the heat sink. A saturated solution comes at the absorber's outlet as a consequence of the steady increase in the mass fraction of NH3 in the solution phase during the absorption process (9). Figure 1(b) shown the visual representation of a saturated liquid with a log p-(1/T) for an ammonia-water mixture, in addition to the primary components and flows of the explained absorption-compression heat pump cycle (ACHP) cycle. The diagram does not represent the actual compression pathways or temperature levels, but rather the qualitative working principle and characteristics of the ACHP system with the zeotropic mixture of ammonia-water. Figure 1(a) also illustrated the same absorption-compression heat pump cycle (ACHP) with additional injection line (6) to the screw compressor to evaluate further investigate the performance of wet compression. Figure 2 shows the photograph of actual installed lab scale test unit with oil free twin screw compressor.

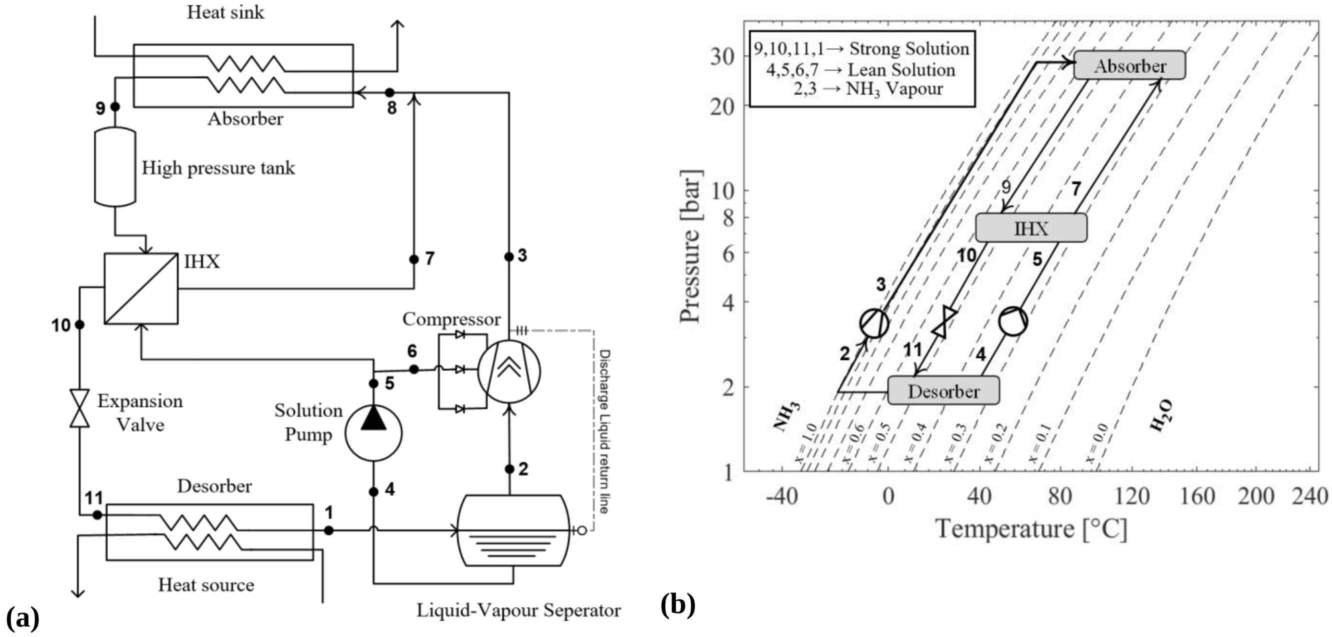

Figure 1: (a) Schematic of the fundamental absorption-compression heat pump cycle with injection line (b) Ammonia-water log p-(1/T) diagram.

Figure 2: Experimental Test facility photograph.

3. DATA REDUCTION

To assess the performance of an oil-free ammonia-water mixture injection screw compressor, experimental studies would generally involve testing the compressor under different operating conditions, such as varying compressor speeds, discharge temperature & pressures, different efficiencies and refrigerant compositions. The key characteristics of the test unit cannot be effortlessly measured. They are calculated from other parameters that have been measured. The absorbed power and gas flow are the two crucial performance characteristics of screw compressors. One of the fundamental performance criteria in the refrigeration industry is refrigeration capacity, which is closely connected to gas flow. Compressor manufacturers struggle to improve performance characteristics through reducing internal leakages, reducing power losses in bearings and shaft seals, and optimizing the compression process's thermodynamic efficiency. The following forms of the equations have been employed for energy and mass conversation:

$$\omega\left(\frac{\partial u}{\partial \theta}\right) = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \dot{Q} - \omega p\frac{\partial v}{\partial \theta} \qquad \text{Eq. (1)}$$

where θ is angle of rotation of the male rotor, $h = h(\theta)$ is specific enthalpy, $\dot{m} = \dot{m}(\theta)$ is mass flow rate, $p = p(\theta)$ fluid pressure in the compressor chamber $\dot{Q} = \dot{Q}(\theta)$, heat transfer between the fluid and the compressor surrounding, $V = V(\theta)$ local volume of the compressor working chamber. In the above equation the index in denotes inflow and the index out the fluid outflow.

The fluid total inflow enthalpy consists of the following components:

$$\dot{m}_{in}h_{in} = \dot{m}_{suc}h_{suc} + \dot{m}_{l,g}h_{l,g} + \dot{m}_{mix}h_{mix} \qquad \text{Eq. (2)}$$

where indices l, g denote leakage gain suc, suction conditions, and mix denotes the mixture of ammonia water lean solution injection to the compression chamber. The fluid total outflow enthalpy consists of:

$$\dot{m}_{out}h_{out} = m_{dis}h_{dis} + \dot{m}_l h_l \qquad \text{Eq. (3)}$$

where indices l denote leakage loss and d_{is} denotes the discharge conditions with m_{dis} denoting the discharge mass flow rate of the ammonia vapor contaminated with ammonia water lean solution mixture injected.

The mass conversation equation:

$$\omega\left(\frac{\partial \dot{m}}{\partial \theta}\right) = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} \qquad \text{Eq. (4)}$$

$$\dot{m}_{in} = \dot{m}_{suc} + \dot{m}_{l,g} + \dot{m}_{mix}$$

The suction mass flow rate can be calculated as:

$$\dot{m}_{suc} = \rho_{in} \times Vol_{com} \times N_{com}/60 \times \eta_{vol} \qquad \text{Eq. (5)}$$

$$\dot{m}_{out} = m_{dis} + \dot{m}_l h_l$$

Each of the mass flow rates satisfy the continuity equation $\dot{m} = \rho v A$ were v denotes the fluid velocity, ρ denotes the fluid density, and A denotes the cross-section area.

The isentropic efficiency of compressor is defined as:

$$\eta_{is} = \dot{m}_{com}(h_{id\cdot com} - h_{suc})/W_{com} \qquad \text{Eq. (6)}$$

The compressor mass flow rate $\dot{m}_{com}$ is the sum of two flows: the suction mass flow rate and injection mass flow rate.

The volumetric efficiency η_v is an important evaluation criterion to evaluate intake performance, which can be obtained in term of mass flow rate:

$$\eta_v = \frac{\dot{m}_{suc,real}}{m_{th}} \qquad \text{Eq. (7)}$$

where $\dot{m}_{suc,real}$ and m_{th} are the actual and ideal inlet mass flow rates, respectively.

In twin-screw compressors, clearance is crucial for machining process's reliability, force deflection, and thermal expansion. The compressed working fluid can leak into and out of the control volume through these clearances. In general, leakage pathways in twin-screw compressors are categorized into five distinct categories: contact line, rotor sealing tip, blow hole, suction end face, and discharge end face (Fleming & Tang, 1995; Fleming et al., 1998; Wu et al., 2004; Xing et al., 2000).

4. PRELIMINARY RESULTS AND DISCUSSION

A series of experiments were performed to investigate preliminary results of the test rig facility. The tests were carried out with a constant mass flow and inlet temperature for both heat sink and heat source medium. The heat sink and heat source mass flow rates were 0.45 kg/s and 0.50 kg/s, respectively, with inlet temperatures of 60 °C. The compressor RPM was maintained about 2900 RPM. Figure 3 demonstrates that as the liquid injection mass flow rate increases, the compressor discharge temperature decreases, particularly during the last stages of injection. At the begging the maass flow keep constant 0.015 kg/s to keep the compressor discharge temperature around 140°C. However, after a certain point, the effect of additional liquid injection becomes more pronounced, leading to a more stable discharge temperature.

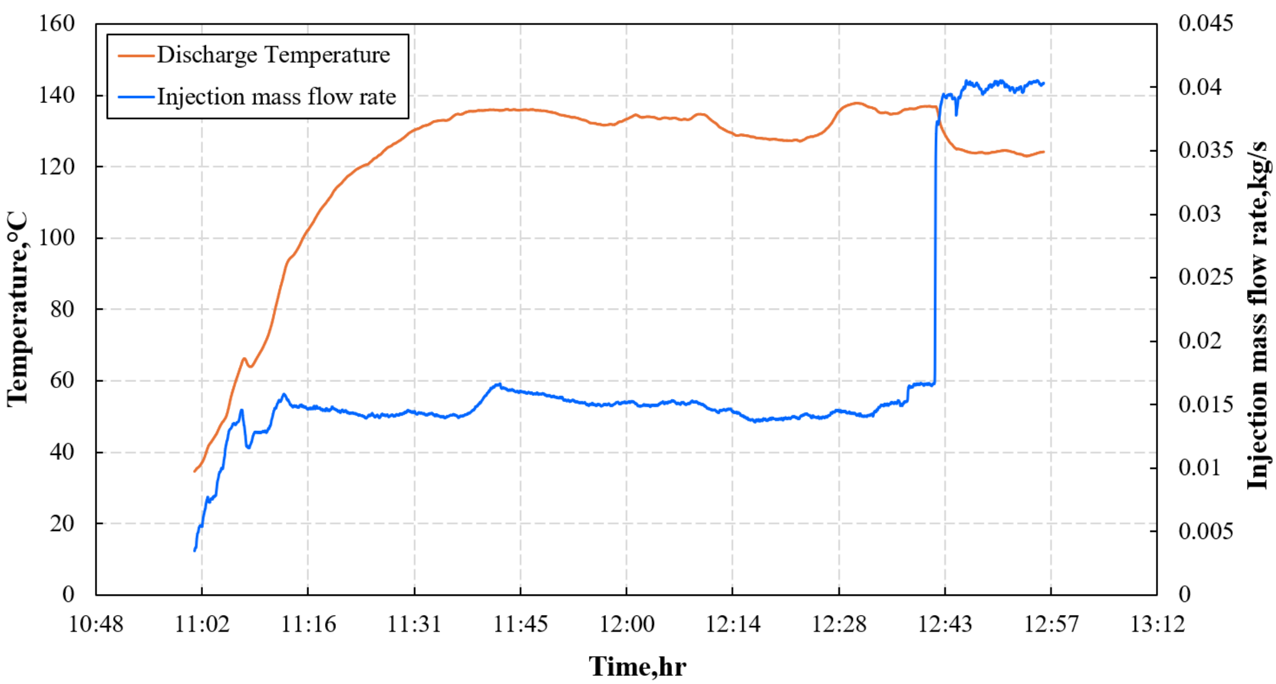

Figure 3: Effect of liquid injection mass flow rate on compressor discharge temperature

Over the observed time period, the pressure ratio and power consumption exhibit distinct patterns as shown in figure 4. Initially, the pressure ratio remains stable slightly, indicating consistent compressor performance. As time progresses, there might be a gradual increase in the pressure ratio, possibly due to increasing the discharge pressure. Correspondingly, the power consumption increases in tandem, reflecting the compressor's need to work harder to achieve the desired pressure ratio. In cases where the pressure ratio decreases, a similar trend is observed in power consumption, which declines due to the reduced workload on the compressor. Significant fluctuations in the pressure ratio and power consumption might suggest transient operating conditions, load changes, or potential copressure backflow or internal leakges.

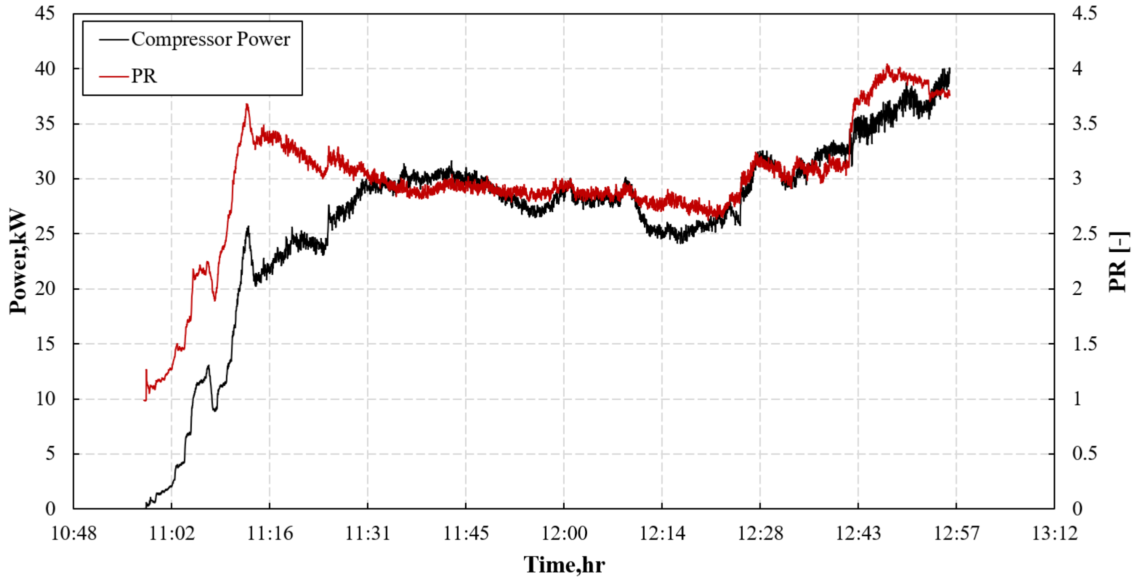

Figure 4: Variation of pressure ratio and power consumption over time

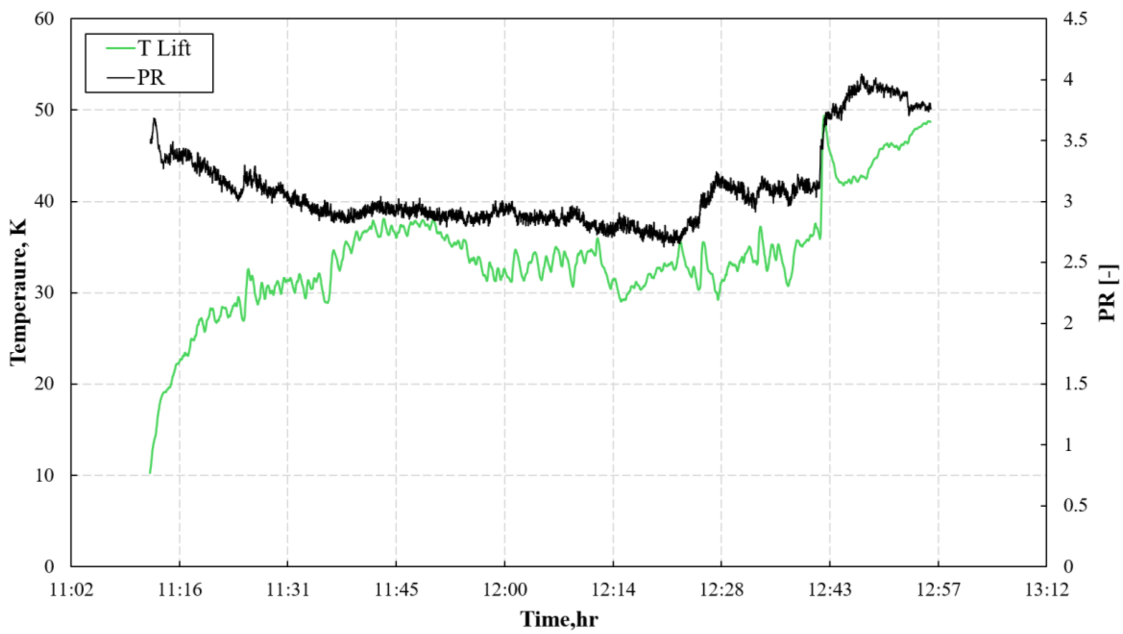

Figure 5: Variation of pressure ratio and temperature lift over the time

Figure 5 illustrates the relationship between temperature lift (measured in Kelvin, left Y-axis) and pressure ratio (right Y-axis) as they vary over time (X-axis). The temperature lift ranges between 10 K and 50 K, indicating the difference between heat sink outlet and heat source inlet from water side. The pressure ratio fluctuates between 3 and 4, representing the ratio of discharge pressure to suction pressure in the compressor. The graph shows how these two parameters evolve over time, highlighting the system's response to changing operating conditions and its impact on overall efficiency.

5. CONCLUSION

To study the thermal performance of oil free twin screw compressor, the simplest form of the absorption-compression heat pump (ACHP) system, known as the Osenbrück cycle was develoved. The initial analysis demonstrates that increasing the mass flow rate of the ammonia-water mixture injection from 0.015 kg/s to 0.040 kg/s significantly reduces the compressor discharge temperature from 140°C to 120°C. This decrease in discharge temperature, coupled with a temperature lift between 10 K and 50 K and a pressure ratio of 3 to 4, highlights the effectiveness of liquid injection in managing thermal stresses within the twin-screw compressor. The optimized injection not only enhances system efficiency by lowering energy consumption but also reduces mechanical wear, contributing to a more reliable and cost-effective operation.

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