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Development of a Falling Film Evaporator for Refrigerant Charge Reduction in Industrial 160°C High-Temperature Heat Pumps

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Abstract

Recently, driven by the need to achieve carbon neutrality, research on the electrification of industrial heat using high-temperature heat pumps has intensified. The Korea Institute of Energy Research has developed a high-temperature heat pump using the low-GWP refrigerant R1336mzz(Z). The system is capable of producing 350 kW of steam at 160 °C from an 80 °C heat source. The cycle is a two-stage compression system equipped with an economizer, and it employs a falling-film evaporator. While conventional flooded evaporators are filled entirely with refrigerant, the falling film configuration requires only a minimal amount of refrigerant to wet the tube surfaces. This design significantly reduces the refrigerant charge, making it advantageous when using expensive, low-GWP refrigerants. Although falling film evaporators present challenges in design and control, they offer benefits in reducing both system cost and environmental impact from refrigerant leakage or disposal. In this study, the falling film heat transfer coefficient was experimentally measured for enhanced heat transfer tubes such as E-tubes. Based on the results, a 200 kW-scale falling film evaporator was designed, fabricated, and evaluated through preliminary performance testing.

Keywords: High Temperature; Heat Pump; Falling Film Evaporator; Refrigerant; Charge Amoun

1. Introduction

In 2024, thermal energy accounted for nearly half of the global final energy consumption, with its associated CO_2 emissions representing approximately 37% of total energy-sector emissions [1]. This high carbon intensity primarily originates from the thermal energy sector's strong dependence on fossil fuels. Consequently, substantial technological and policy-driven efforts are being directed worldwide toward the electrification of thermal energy systems using heat pump technologies. In Europe, for example, heat pump sales have continued to rise [2], particularly within the building sector. In contrast, adoption in the industrial sector remains relatively limited, because its thermal requirements such as heat source temperature, supply temperature, and thermal duty differ significantly depending on the industrial process.

Industrial heat pumps are generally classified according to their heat-supply temperature: systems supplying temperatures above 100 °C are categorized as high-temperature heat pumps, while those exceeding 150 °C are referred to as very high-temperature heat pumps [3]. In 2019, roughly 39% of industrial thermal energy demand was for temperatures below 200 °C [4]. Thus, if very high-temperature heat pumps are capable of delivering heat up to 200 °C, a substantial fraction of industrial thermal energy could be decarbonized. However, as the heat-supply temperature increases, heat pumps face several challenges, including reduced COP, limited availability of suitable refrigerants, and accelerated component degradation. For this reason, recent research trends favor systems that generate heat in the range of approximately 150–160 °C using a very high-temperature heat pump, followed by a mechanical vapor recompression (MVR) stage to further elevate the temperature.

Selecting an appropriate refrigerant is critical for ensuring stable operation of very high-temperature heat pumps. Due to the elevated operating temperatures, refrigerants with relatively high critical temperature and low evaporation pressures are preferred. In addition, low-GWP HFO refrigerants are actively studied to mitigate greenhouse gas emissions from leakage. Representative refrigerants for very high-temperature heat pumps include R1233zd(E) and R1336mzz(Z). However, both refrigerants are produced in relatively small volumes compared to conventional HFCs, resulting in significantly higher costs. This issue is exacerbated in industrial applications, where large thermal capacities and large-scale heat exchangers require substantial refrigerant charge, thereby increasing capital costs. Accordingly, heat-exchanger design strategies that reduce refrigerant charge while maintaining performance are essential.

Falling film evaporators are a key technology for reducing refrigerant charge. Unlike flooded evaporators—where all heat-transfer tubes are fully immersed in liquid refrigerant—falling film evaporators introduce refrigerant at the top, allowing it to flow downward along the tube surface while heat transfer occurs. Because the heat-transfer performance remains comparable while the shell volume no longer requires complete flooding with refrigerant, the total charge can be significantly reduced. For these reasons, a wide range of studies on the design of falling film evaporators have been actively conducted in recent years. Min *et al.* experimentally investigated the falling film heat transfer coefficients of the low-GWP refrigerant R1233zd(E) on horizontal tubes with various fin pitches and proposed corresponding empirical correlations [5]. Ishaque *et al.* applied a segment-by-segment design methodology and CFD analysis for the development of a 2.2 MW falling film evaporator using R1336mzz(Z), and identified critical local nonuniformities occurring in the lower tube rows through CFD simulations [6]. Lin *et al.* developed a design algorithm for falling film evaporators and validated it for various refrigerants, including R134a and R600a, by incorporating heat transfer coefficient correlations and evaporator thermal performance data from existing [7].

In this study, the falling film heat transfer coefficients of R1336mzz(Z) were measured under the specified design conditions. Based on these results, a 200 kW falling film evaporator was designed, fabricated, and subjected to preliminary performance testing for application in a 350 kW-class very high-temperature heat pump capable of producing 160 °C steam.

2. Numerical Analysis of Falling Film Evaporator

A flooded evaporator is a type of heat exchanger in which the shell side is filled with refrigerant such that the tubes remain fully submerged during heat transfer. Because the refrigerant level must reach the height of the tube bundle, this configuration requires a large refrigerant charge, and performance degradation may occur due to vapor–liquid interaction. In contrast, a falling film evaporator distributes refrigerant from the top of the shell through a distributor, allowing it to flow uniformly over the tube surfaces as a thin liquid film where evaporation and heat transfer occur. While this configuration significantly reduces the required refrigerant charge, insufficient refrigerant flow can lead to maldistribution, thinning of the liquid film, and localized dry-out. To mitigate these limitations, the present work adopts a hybrid falling film configuration in which a portion of the lower tube rows remains submerged in refrigerant.

The configuration of the hybrid falling-film evaporator is illustrated in Figure 1. The exchanger consists of 120 tubes arranged in a two-pass layout. The heat-source water enters the lower pass, is cooled, and then exits through the upper pass. Refrigerant is charged into the shell so that only the lowest two tube rows are submerged. The operating conditions of the evaporator are summarized in Table 1.

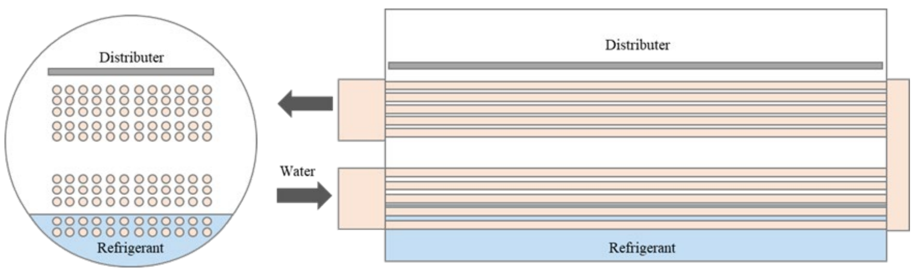

Figure 1. Schematic of Hybrid Falling Film Evaporator

Table 1. Design conditions of falling film evaporator

Conditions	Value
Inlet flow rate of refrigerant (kg/s)	1.679
Inlet quality of refrigerant	0.172
Saturation temperature of refrigerant (℃)	70
Inlet flow rate of heat source water (kg/s)	9.66
Inlet/outlet temp. of heat source water (℃)	80/75

For refrigerant R1336mzz(Z), the tube length required to achieve a heat-transfer capacity of 200 kW was determined through numerical analysis. The numerical procedure is shown in Figure 2. Each heat-transfer tube was discretized into uniform nodes, and mass and energy conservation equations were solved for each node. Iterative calculations were carried out using in-house Python code by varying the tube length until the total vaporized refrigerant mass approached the amount corresponding to 200 kW of latent heat. A key characteristic of falling film evaporators is that the liquid film thins as the refrigerant evaporates along the tube, such that the falling-film heat transfer coefficient depends on the local film flow rate. Falling film heat transfer typically comprises two regimes: a slope region and a plateau region [8]. When the film Reynolds number is low, the system lies in the slope region, while higher film Reynolds numbers correspond to the plateau region. The boundary between these regimes is commonly referred to as the threshold film Reynolds number. In the slope region, the heat transfer coefficient increases with the film Reynolds number, whereas in the plateau region it remains nearly constant due to the absence of local dry-out. Accurate falling-film heat transfer coefficients are therefore essential for designing the hybrid evaporator.

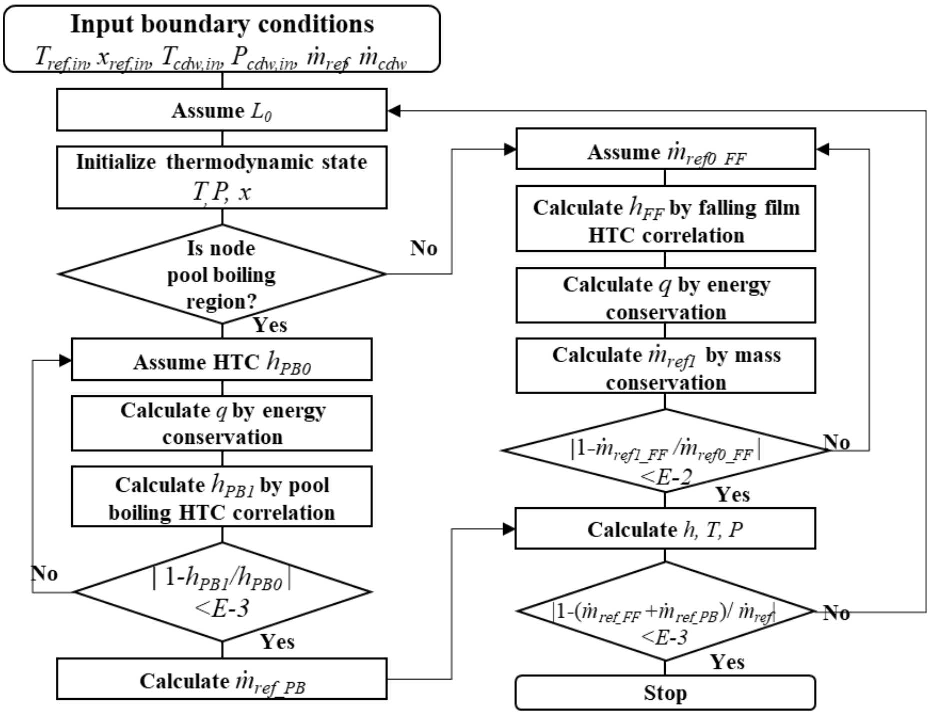

Figure 2. Flowchart of the design procedure for the falling film evaporator.

For this reason, the test loop shown in Figure 3 was constructed, and falling-film heat transfer coefficients were measured for E-tube. The measured threshold film Reynolds number was approximately 300, and the plateau-region heat transfer coefficient was ~3.85 kW/m²·K. The analysis results indicate that, for 120 E-tubes with an outer diameter of 19.05 mm and a wall thickness of 0.7 mm, an appropriate tube length for a 200 kW hybrid falling-film evaporator is 2 m. The calculated heat source water temperature distribution along the tubes is shown in Figure 4. The heat transfer contributions were estimated to be 47.8 kW for the flooded region and 155 kW for the falling-film region.

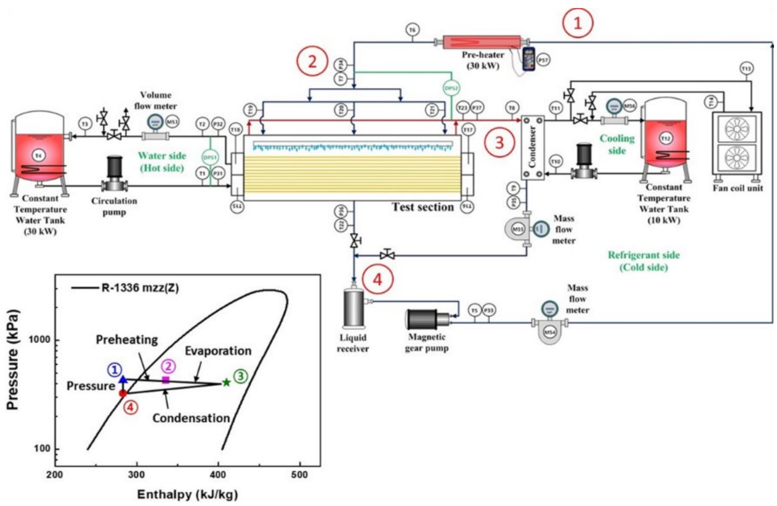

Figure 3. Test loop for falling film heat transfer coefficients measurements

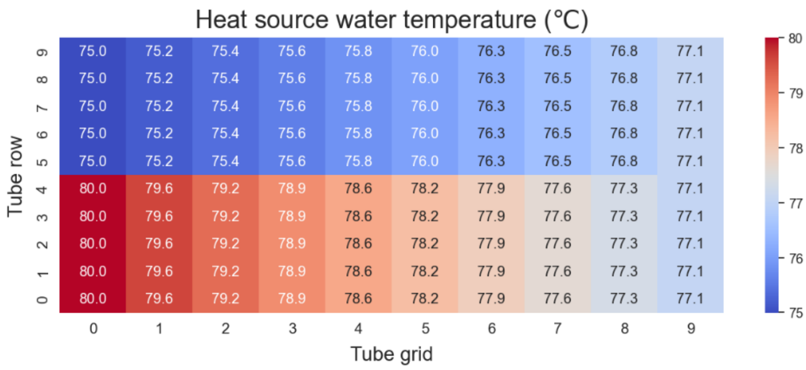

Figure 4. Temperature distribution of heat source water for falling film evaporator

3. Preliminary Test of 200kW Falling Film Evaporator

Based on the numerical analysis, the detailed design of the 200 kW falling-film evaporator is shown in Figure 5. The total length of the unit is 2 m, and it consists of a distributor for refrigerant distribution, heat-transfer tubes, and sight glasses for visualization of the distribution. Using the fabricated evaporator, a 350 kW-class heat pump capable of producing 160 °C steam was constructed, and preliminary tests were conducted. Under operating conditions with a refrigerant saturation temperature of approximately 71.8 °C and heat-source water inlet and outlet temperatures of 79.5 °C and 75.4 °C, respectively, a heat-transfer capacity of approximately 154 kW was achieved. The slight performance deficit relative to the design value is attributed to the reduced refrigerant circulation rate and the degradation of heat-transfer performance caused by partial contamination of the tubes during fabrication. In future work, the test will be repeated after ensuring proper maintenance and cleaning of the heat-transfer tubes.

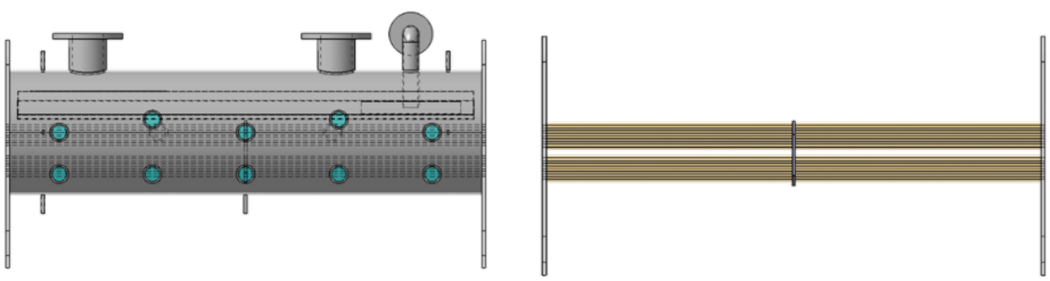

Figure 5. Design of 200kW falling film evaporator

4. Conclusion

In this study, a falling film evaporator was designed, fabricated, and preliminarily tested to reduce the refrigerant charge required for industrial high-temperature heat pumps. The working fluid of the falling film evaporator is R1336mzz(Z), and the operating conditions are a refrigerant saturation temperature of 70 °C, heat-source water inlet and outlet temperatures of 80 °C and 75 °C, respectively, and a design heat-transfer capacity of 200 kW. The tube bundle consists of 120 tubes arranged in a 10 × 12 configuration with a two-pass layout, and numerical analysis was conducted to determine the required tube length. The falling film heat transfer coefficients used in the analysis were obtained experimentally using a test loop. The numerical results indicated that an appropriate tube length is 2 m. The evaporator was subsequently manufactured, and preliminary testing under similar operating conditions yielded a heat-transfer capacity of 154 kW.

Acknowledgements

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