CONDENSATION HEAT TRANSFER PERFORMANCE OF REFRIERANTS IN MULTIPORT MINI-CHANNEL TUBES: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

This research presents experimental results on convective heat transfer coefficients for the refrigerants R410A, R32, R22, and propane during condensation within a multiport mini-channel tube. The experiments were carried out under controlled conditions with an average saturation temperature of 48°C and a mass flux ranging from 50 to 300 kg/m²s. The findings indicate a direct relationship between mass flux and heat transfer coefficient across all tested refrigerants, with propane demonstrating the highest heat transfer coefficient followed by R410A, R22, and R32. These new correlations showcasing predictive performance with a maximum deviation of less than 15.3% from experimental values. This study offers valuable insights for the design and enhancement of mini-channel multiport heat exchangers employing refrigerants such as R410A, R32, R22, and propane.

Keywords: *Condensation, Heat transfer coefficient, Correlation, Multiport tube.*

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1. INTRODUCTION

Heat transfer performance in a refrigerant can be influenced by many different factors, including the properties of the refrigerant, flow conditions, and the geometry of the heat exchanger. Heat exchangers using multi-port mini-channel tubes have outstanding advantages. This design provides an expanded surface area to enhance heat transfer and promote increased turbulence in the fluid flow. Some studies [1-8] have shown that using mini multi-channel tubes instead of traditional methods can improve heat transfer efficiency. These investigations typically conclude that the use of mini multi-port tubes results in a higher overall heat energy exchange rate than traditional tubes to achieve similar cooling system results.

Zhang et al. [9] studied the heat transfer coefficient of R134a in mini multichannel tubes with different channel sizes and numbers of channels. They found that the heat transfer coefficient was higher in tubes with smaller channels and more ports because created a larger heat transfer surface area. The heat transfer coefficient in small channel pipes is often affected by the thickness of the liquid layer on the pipe wall. This assumption usually ignores the influence of gravity in mini-channels and assumes that surface tension is dominant. This results in fluid accumulation at the corners of the rectangular or triangular channel. A promising theoretical model for heat transfer in microchannels was proposed by Jige et al. [10]. This model assumes a thin fluid film of constant thickness across the entire circumference of the channel. They introduced the terms vapor shear stress effect and surface tension effect on the Nusselt number. These terms capture the relative influences of mass flow and vapor quality on heat transfer. Sakamatapan et al. [11] investigated the condensation heat transfer characteristics of R-134a flowing inside multi-port small channels. They found that the condensation heat transfer coefficient increases as the channel size, number of channels, and mass flux decrease.

The introduction of hydrochlorofluorocarbons (HCFCs) as a replacement for chlorofluorocarbons (CFCs) is an important step in minimizing ozone layer depletion. HCFCs offer an important advantage: their ozone depletion potential (OPD) is significantly lower than that of CFCs. However, the focus on protecting the ozone layer has shifted to concerns about a global warming potential (GWP) with recognition of the contribution of HCFCs to this environmental problem. Propane, or R290, is a natural refrigerant that has garnered significant interest because of its thermodynamic properties that are similar to those of the commonly used R22. Because of this closeness, R290 can be used with existing systems with little to no adjustments. R290 does have one major drawback, though, and that is that it is flammable. This presents safety issues that should be carefully considered before application. Researchers like Yu et al. [12] and Higashi [13] suggested a near-azeotropic refrigerant mixture as a solution to this flammability problem. R290 and R32 are combined in these mixes in weight ratios ranging from 70/30 to 60/40. It is a promising substitute because it has a lower GWP than several HFCs and has more cooling capacity per unit volume [14].

This study focuses on the condensation heat transfer characteristics of refrigerants R410A, R22, R32, and R290 in horizontal multi-port mini-tubes. The multi-channel tube geometry has a high surface area-to-volume ratio, making it ideal for applications requiring high-intensity heat exchange. The refrigerants used in this study represent a wide range of existing and alternative refrigerants, allowing for specific comparative analysis of their heat exchange capabilities during condensation in multiport minichannel. In this study, a theoretical model was created to comprehend the underlying heat transmission mechanisms on a deeper level. The goal of the model is to forecast the condensation heat transfer coefficient, a crucial variable in heat exchanger design and optimization. This model takes into account the influence of several key factors, including channel size, which indicates the surface area available for condensation; number of channels, which affects the flow distribution of the refrigerant and affects the film thickness; mass flow, which affects turbulence and promotes heat transfer through better mixing; and vapor quality, which is important because the liquid phase offers superior thermal conductivity compared to vapor.

The strong agreement that exists between the experimental data and the model predictions highlights how well the model captures these significant influences. This opens up important new information that will guide future efforts to optimize condensation heat transfer in comparable small channel layouts through research and development.

2. EXPERIMENTAL APPARATUS

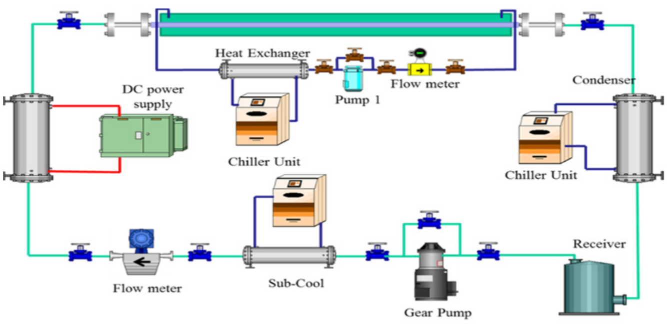

Fig. 1. Experimental Apparatus

The experimental setup is illustrated in a schematic diagram shown in Fig. 1. This apparatus consists of four closed loops. The main component is the refrigerant loop, responsible for circulating the test refrigerants (R410A, R22, R32, and R290) through the test section - the horizontal multiport minichannel tube. The cooling water loop acts as a heat sink, removing the heat extracted from the refrigerants during condensation inside the minichannel tube. This water pump and water mass flow meter uses a controlled water flow through a heat exchanger to maintain a desired temperature. An ethylene glycol circulation loop is often incorporated to ensure precise temperature control within the test section. Ethylene glycol flows from two chiller units to the heat exchanger and the sub-cooler, providing a stable and controllable thermal environment. Finally, the experimental apparatus is equipped with a data acquisition system that facilitates the real-time monitoring and recording of all experimental parameters. These parameters include the temperature and pressure of the refrigerants, the tube wall temperature, the heat flow rate in the pre-heater, the mass flow rate of all fluids, and the heat flow rate across the mini channel tube wall. By controlling and measuring these parameters, the experimental setup allows for a thorough investigation of the factors influencing condensation heat transfer within the specific geometry of the horizontal multiport minichannel tube.

The experimental investigation on a multiport minichannel tube for determining the condensation heat transfer coefficients of refrigerants R22, R410A, R32, and R290. These test sections tube has 18 rectangular channels, offering a high surface area to volume ratio ideal for condensation heat transfer studies. Two test section lengths were used (200mm and 500mm) to optimize the heat flow rate in the test section to be more accurate. For the shorter test section, a range of mass fluxes (50, 100, and 200kg/m^{2}s) were examined to analyze the effect of refrigerant flow rate on condensation. The longer test section was evaluated at a single, higher mass flux of 300kg/m^{2}s to explore the behavior at higher flow conditions. Details of test section is show in Fig. 2.

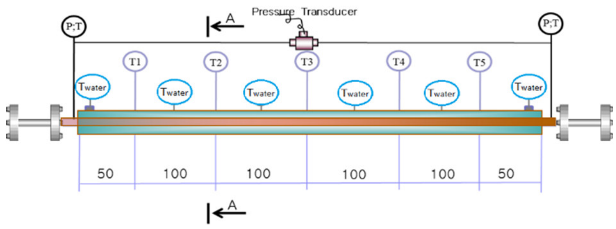

Fig. 2. Details of test section

To ensure accurate and high-resolution temperature measurements, a group of 20 T-type thermocouples, each with a small diameter of 0.13 mm, was attached at five points along both the top and bottom sides of the test section tube. This placement minimized thermocouple intrusion into the flow path while providing detailed temperature data across the entire length and perimeter of the test section. Additionally, four class-A resistance temperature detectors (RTDs) were installed at the inlet and outlet of both the refrigerant and cooling water loops. These RTDs, known for their high accuracy and stability, served to monitor the inlet and outlet temperatures of the working fluids.

The reliability of the experimental setup, particularly the ability to accurately quantify heat transfer, was verified through initial experiments using single-phase water-water heat transfer within the test section. This initial test is a baseline for energy balance calculations. The resulting heat balance error between the cooling water side and the inner hot water was consistently maintained within ±3%, demonstrating the high level of accuracy achieved by the measurement system. Further details regarding the thermocouple attached in the test sections can be found in Fig. 3. This figure provides a valuable visual representation of the experimental setup of temperature sensors for improved understanding.

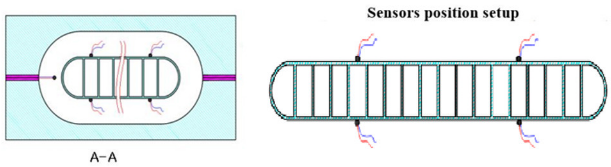

Fig. 3. Attached thermocouple in the test section

Table 1 presents a comparison of thermal properties for R22, R410A, R32, and R290 at a saturation temperature of 48°C. Notably, propane (R290) exhibits a higher latent heat of vaporization compared to conventional refrigerants (R22 and R410A). This translates to a greater capacity for heat removal per unit mass of refrigerant during the condensation process. Conversely, R290 possesses a lower density compared to the other refrigerants, while maintaining a comparable saturation pressure at the same saturation temperature, this lower density can influence factors like mass flow rate and pressure drop within the test section.

Table 1. Thermal properties for refrigerants at 48°C

Property	R410A	R32	R22	R290
Liquid density, (kg/m^3)	921.7	850.8	1091.9	452.75
Vapor density, (kg/m^3)	132.3	92.8	81.5	36.771
Liquid viscosity, (μPa.s)	84.6	85.5	126.03	75.785
Vapor viscosity, (μPa.s)	15.8	14.5	13.6	9.2911
Surface tension, (mN/m)	2.25	3.32	4.99	4.3099
Density ratio	0.14	0.11	0.07	0.08
Viscosity ratio	0.19	0.17	0.11	0.12
Latent heat (kJ/kg)	140.9	215.5	156.8	289.54
Thermal cond. (mW/mk)	76.71	108.55	72.85	83.451
GWP	2088	675	1700	3
ODP	0	0	0.05	0

The energy balance on the cooling water side was used to calculate the heat transfer rate through the test section. The cooling water flow rate and the temperature differential between the inlet and the outlet of the waterside are all collected. The change in refrigerant quality along the test section length was computed by utilizing the mass conservation principle for the refrigerant inside the closed loop system. The measured input and outlet pressures, thermodynamic property relations, and the measured refrigerant mass flow rate and change in enthalpy across the test section are used in this computation.

The vapor quality at the inlet of the test section was controlled by a variable DC power supply is calculated as follows:

$$x_{in} = \frac{1}{i_{fg}}\left[\frac{Q_{pre}}{m_r} - C_{p,r}\left(T_{sat} - T_{pre,in}\right)\right] \quad (1)$$

The vapor quality at the inlet of the test section:

$$x_{out} = x_{in} - \left(\frac{m_{water}C_{p,water}\left(T_{water,out} - T_{water,in}\right)}{m_r i_{gf}} - \right) \quad (2)$$

And the average condensation heat transfer coefficient was calculated as:

$$h = \frac{Q}{A_{in}(T_{sat} - T_{w,in})} \quad (3)$$

Where Q_{pre} is the heat supplied to the pre-heater and $T_{pre,in}$ is the refrigerant temperature into the pre-heater. A_{in} is the inner area surface of test tube, Q is the wall heat flow rate based on the outer surface area of the test tube, and $T_{w,in}$ is the internal wall temperature. The physical properties in data reduction of each experiment are calculated using the REFPROP Version 8.0.

3. RESULTS AND DISCUSSION

In this work, the condensation heat transfer coefficients (HTC) of four refrigerants R22, R410A, R32, and R290 were investigated to different operating situations. The tests investigated a range of vapor quality (0 - 0.9) at the test section intake, mass flow rate (50 - 500kg/m^{2}s), and heat flux (3 - 12kW/m^2) at a constant saturation temperature of 48°C. For all tested refrigerants, the data show a continuous trend of increased HTC with higher mass flux, details in Fig. 4. Higher flow velocities produce more intense turbulence at the liquid-vapor interface, which is the cause of this augmentation. In this work, the condensation HTC of four refrigerants R22, R410A, R32, and R290 were investigated concerning different operating situations.

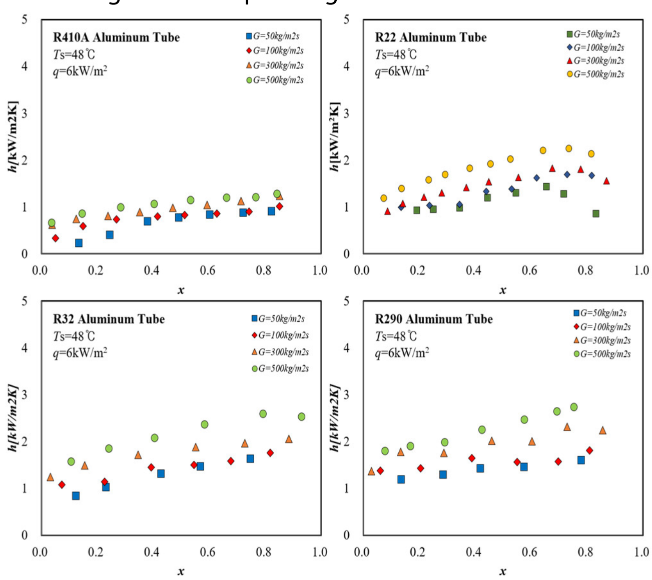

Fig. 4. Effect of mass flux on the HTCs

HTC is greatly influenced by the surface tension and shear stress inside the refrigerant flow, in addition to mass flux. Better heat transfer between the refrigerant and the cooling side during the condensation process is made possible by surface tension, which acts to produce a thinner and more uniform liquid film on the condenser tube wall. On the other hand, shear stress results from the movement of the liquid and vapor phases inside the test section. This shear stress enhances the turbulence at the interface, which facilitates an even more effective heat transfer coefficient. The total HTC for each refrigerant under different operating conditions is determined by the intricate interaction between these parameters. The experimental result observed a minimal influence of mass flux on the condensation HTC at low vapor qualities and mass fluxes. This behavior can be explained by the dominant role of surface tension is more dominant on the heat transfer under these conditions. Especially along the borders of the rectangular mini-channels, the liquid refrigerant film's surface tension produces a layer that is thinner and more homogeneous. Improved heat transfer results from this thin film's reduction of thermal resistance between the tube wall and the refrigerant.

On the other hand, shear stress effects and forced convective condensation, contribute more significantly as mass flux rises. Better mixing of the refrigerant and improved heat transmission between the bulk liquid and vapor phases are two benefits of forced convective condensation, which is typified by turbulent flow within the mini-channels. Furthermore, the movement of the vapor and liquid phases causes shear stress, which amplifies turbulence at the liquid-vapor interface. Further improving heat transfer, this increased turbulence breaks the liquid film and encourages improved vapor-wall contact. This change in dominance indicates that, at high mass fluxes, surface tension is not as important in heat transfer as enhanced turbulence brought forth by higher flow velocities. Conversely, surface tension has a greater impact than shear stress on preserving a thin and effective liquid layer when mass flux is modest. Since there is less shear stress produced by the lower flow velocities, surface tension is more dominant and a thin coating is maintained for ideal heat transfer.

The experiment result shows significant implications for optimizing refrigeration system design and operation. By adjusting operational parameters such as mass flux and vapor quality, engineers can manipulate the balance between surface tension and turbulence effects on the liquid film. At low vapor qualities, maintaining a low mass flux can be beneficial to ensure a thin film and efficient heat transfer. However, at higher vapor qualities, increasing mass flux can promote turbulence and enhance heat transfer efficiency. This optimization approach has the potential to achieve a higher overall HTC for refrigerants, ultimately leading to improved system performance and energy efficiency.

Fig. 5 illustrates the relation between the average heat flux and the condensation heat transfer coefficient. There is a rise in the heat transfer coefficient according to the heat flux. The subcooling phenomenon has been accountable for this behavior. The temperature differential between the condensing surface and the saturated vapor temperature is referred to as subcooling. Increased heat flux causes more subcooling in the condensate, increasing its thermal conductivity. The result is a significant increase in the heat transfer coefficient due to the enhanced thermal conductivity. In the results presented in the study of Zhang et al. [9], they similarly observed a rise in the heat transfer coefficient with increasing heat flux. This aligns with their explanation that both mass flux and heat flux influence the temperature at the interface between the liquid film and bulk vapor.

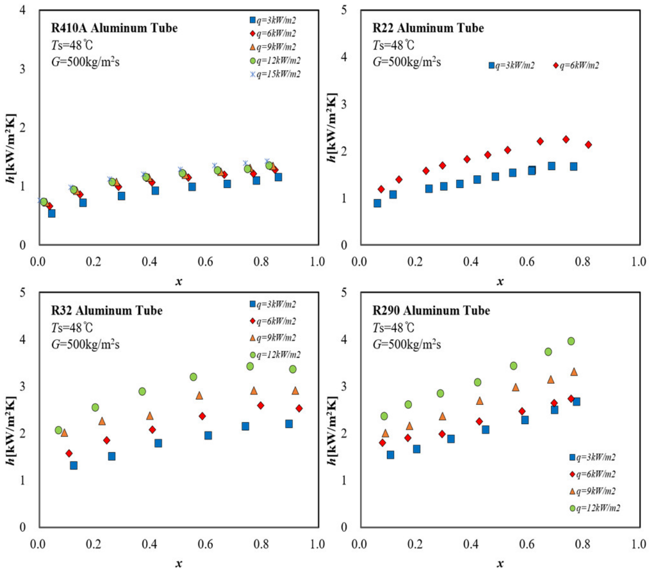

Fig. 5. Effect of heat flux on the HTCs

Significant differences in the heat transfer coefficients of R22, R410A, R32, and propane may be seen in Fig. 6. The different thermophysical properties of each refrigerant are the cause of these differences. In comparison to the other refrigerants, propane has lower surface tension, liquid and vapor densities, and liquid and vapor viscosities, and its latent heat is higher. The heat transfer coefficient is influenced directly by the variations in physical characteristics. In this respect, R410A's condensation heat transfer coefficient is 3 - 11% lower than R22's and much lower (17.8 - 52.2%) than R32's. These physical characteristic differences may be the primary cause of these notable differences.

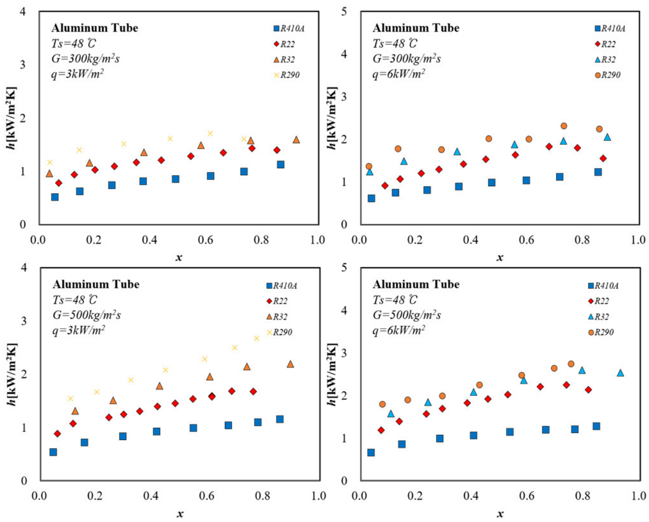

Fig. 6. Comparison of heat transfer coefficient between four refrigerants

Surface tension and liquid density play a significant role in the condensation heat transfer coefficient in the case of a multiport tube. At 48°C, R22 has a 13% higher liquid density than R410A. The higher liquid density leads to a higher heat transfer coefficient as the condensed liquid film on the top wall falls more easily. Additionally, R22's increased surface tension results in a thinner liquid film compared to R410A, reducing thermal resistance and further improving heat transfer.

The main purpose of this study is to assess, investigate, and enhance the designs of heat exchangers used in air conditioning, heat pumps, and refrigeration systems. However, the current models may not accurately predict the results of this study due to differences in experimental setup and channel geometry. Therefore, a revised correlation for the condensation heat transfer coefficient has been developed, taking into account data from tests conducted on four different types of tubes under various conditions. The suggested correlation builds upon the heat transfer correlation for a multiport rectangular channel initially presented by Pham et al. [15]. This correlation serves as the foundation for the newly proposed methodology.

$$h=2.67Bo^{0.128}Re_{eq}^{0.507}\left(\frac{1-x}{Pr_l}\right)^{-0.154}\left((1-x)^{0.8}+\frac{x}{Pr}\right)^{0.092}\left(\frac{q}{Gh_{lv}}\frac{A_{external}}{A_{internal}}\right)^{0.293}\left(\frac{\phi_v}{X_{tt}}\right)^{-0.034}\frac{k_l}{d} \quad (4)$$

The correlation mentioned above provides a better understanding of how channel geometry and heat transfer interact. Creating this correlation involved using regression analysis techniques to formulate equations that accurately represent the relationship between the different parameters.

Fig. 7 presents a compelling comparison between the experimentally acquired data and the predicted values of the condensation heat transfer coefficient derived from the newly proposed correlation. The results demonstrate excellent agreement between the proposed correlation and established models, with a mean deviation of only 15.31%.

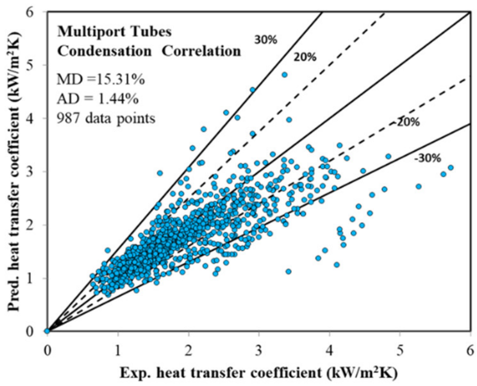

Fig. 7. Comparison between the measured data and developed correlation

These novel equations and correlations provide a significantly more precise and accurate tool for predicting the condensation heat transfer coefficient. This enhanced capability accounts for the inherent complexities associated with the experimental setup and channel geometry. By incorporating these advancements, researchers and engineers can elevate the design and performance of heat exchangers employed in refrigeration, heat pump, and air-conditioning systems. Ultimately, these advancements will lead to substantial improvements in system efficiency and effectiveness.

4. CONCLUSION

This investigation explores the influence of various parameters on the condensation HTC of refrigerants within a multiport mini-channel tube. A positive correlation between mass flux and HTC was observed. This enhancement can be mainly attributed to the increased velocities and turbulence at the liquid-vapor interface, and intensification of heat transfer processes. Furthermore, the relationship between average heat flux and HTC shows a positive trend. As heat flux rises, the subcooling effect strengthens, leading to a corresponding increase in the thermal conductivity of the condensate film and a subsequent rise in HTC.

The impact of thermophysical properties on HTC was elucidated by comparing the coefficients of different refrigerants. Variations in properties such as liquid density, vapor density, viscosities, surface tension, and latent heat were found to influence HTC. The study delved deeper into the effect of channel geometry on HTC by suggesting a novel correlation that incorporates the influence of channel geometry, surface tension, and shear stress. This correlation, derived through regression analysis, offers a deeper understanding of the relationship between these parameters and facilitates accurate predictions of the condensation HTC.

In conclusion, the findings presented in this study contribute significantly to the optimization of heat exchanger design and operation in refrigeration, heat pump, and air-conditioning systems. By meticulously considering parameters such as mass flow rate, vapor quality, and heat flux, engineers can achieve improved HTC, ultimately leading to improved system efficiency. Additionally, the proposed, correlation incorporates the influence of channel geometry, and offers a more accurate prediction method, aiding in the design and performance optimization of heat exchangers.

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