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Design of Mixer for Suppressing Partial Dry-out Inside a Channel of a Plate Heat Exchanger During the Evaporation Heat Transfer

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Abstract

To improve the heat transfer efficiency of a plate heat exchanger (PHE), it is necessary to address the flow maldistribution that occurs during two-phase operation. In the case of R-1234ze(E), the liquid phase tends to accumulate near the gasket due to its higher density compared to the vapor phase, causing the two phases to separate before entering the channel. This separation results in partial dry-out along the vapor-preferred path, which reduces the effective heat transfer area and leads to an overall loss in thermal performance. To suppress this maldistribution without redesigning the plates themselves, a helical mixer was installed in the inlet pipe to rearrange the relative positions of the liquid and vapor phases. This approach allows for improved flow mixing with minimal cost, as it requires only an external modification. The mixer design was optimized using numerical analysis that evaluated both flow patterns and pressure-drop characteristics. Although the mixer alters the phase distribution within the inlet pipe, its influence on channel-level flow must also be confirmed; therefore, full PHE simulations and experiments were conducted. Experiments performed under low vapor-quality conditions—typical in practical PHE applications—revealed that the mixer increased the heat transfer coefficient by approximately 5% without causing additional pressure drop. Surface temperature measurements indicated that the dry-out region was reduced, and part of the liquid was redirected toward the previously vapor-preferred path in the lower section of the plate. Additionally, a noticeable temperature drop appeared on the opposite side of the original dry-out zone, suggesting a more balanced overall distribution. These results demonstrate that the helical mixer effectively mitigates two-phase maldistribution and enhances the overall energy efficiency of the PHE.

Keywords: Plate heat exchagner; Boiling;Dry-out;Numerical analysis,Validation;Mixer

1. Introduction

A plate heat exchanger (PHE) is a compact and highly efficient device commonly applied in refrigeration, power generation, and HVAC systems. Enhancing its performance enables further downsizing of equipment and improved economic feasibility. With increasing environmental regulations, the adoption of low-GWP refrigerants has become essential, leading to extensive studies on their two-phase flow characteristics. Because two-phase distribution strongly affects thermal performance, many researchers have attempted to improve heat transfer by modifying the plate geometry, including changes to corrugation patterns, chevron angles, and plate structures. For example, Lao et al. [1] examined mini-wavy corrugations during R-134a boiling and suggested a new Nusselt correlation, while Arsenyeva et al. [2] evaluated how corrugation angle and height influence condensation behavior and pressure drop. Although effective, such modifications require plate redesign and manufacturing of nonstandard geometries, which increases cost and limits practical use. As a result, strategies that adjust flow distribution through external components have become attractive alternatives. Kim et al. [3] demonstrated that an inlet distributor enhanced two-phase uniformity and improved heat transfer by approximately 16%, and Tu et al. [4] verified that a vane-type swirler also promotes more uniform phase distribution. Since maldistribution of liquid and vapor is a key factor reducing PHE efficiency, this study introduces a cost-efficient approach that incorporates a mixer into the inlet pipe. This technique avoids modifications to the plate itself while inducing turbulence and redistributing the phases before they enter the channels. Various mixer geometries, including designs with holes to reduce pressure-drop penalties, were examined numerically. The most effective configuration was then tested experimentally using R-1234ze(E) under mass fluxes of 50 and 70 $kg \cdot m^{-2} \cdot s^{-1}$ and low vapor-quality conditions. The results indicate that the mixer improves heat transfer by 2–8% and significantly reduces dry-out regions, demonstrating its effectiveness in mitigating two-phase maldistribution.

2. Numerical Analysis

2.1. Mathematical modelling

Within the heat exchanger, both conductive and convective heat transfer occur, and the conduction equation is expressed as Eq. (1)

$$Q = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) \tag{1}$$

where Q denotes the heat flux conducted between the plate and the liquid and k denotes thermal conductivity.

In the heat exchanger channel, heat transfer of the refrigerant is governed by convection, while heat exchanger between adjacent channels occurs through conduction. The governing equations in the liquid domain are expressed as follows:

Continuity equation:

$$\frac{\partial \rho U_i}{\partial x_i} = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p'}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + (\rho - \rho_0)g_i \tag{3}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho c_p U_i T) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + \frac{\partial}{\partial x_i}(U_i(\tau_{ij})_{eff}) \tag{4}$$

The effective viscosity (μ_{eff}) and deviatoric stress tensor $(\tau_{ij})_{eff}$ are formally defined in Eqs. (5) and (6), respectively:

$$\mu_{eff} = \mu\left(1 + \sqrt{\frac{C_\mu}{\mu}\frac{k}{\sqrt{\varepsilon}}}\right)^2 \tag{5}$$

$$(\tau_{ij})_{eff} = \mu_{eff}\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) - \frac{2}{3}\mu_{eff}\frac{\partial U_k}{\partial x_k}\psi_{ij} \tag{6}$$

The liquid region was simulated using the Menter shear stress transport (SST) turbulence model. Wall treatment was handled through the software's automatic wall-function option. Because the analysis involved two-phase flow, the liquid–vapor pair was defined with the following settings: (1) a surface tension coefficient of 0.010157 N/m between phases, (2) the Continuum Surface Force (CSF) approach for modelling surface tension effects, and (3) an interphase transfer model based on a free-surface assumption.

2.2. Geometry of mixer

To generate turbulence in the inlet pipe and enhance the mixing of the two phases within the channel, flow-resisting elements were considered. In two-phase flow, gravity, viscosity, and velocity differences cause phase separation, with the heavier liquid accumulating at the bottom of the pipe and the vapor moving above it. To counteract this separation, we designed elements capable of partially inverting the relative positions of the liquid and vapor phases while minimizing disruption to the overall flow. Based on the diameter and length of the inlet pipe, an initial element—referred to here as the mixer—was designed, as shown in Figure 1. The basic configuration consists of two helical flow passages with two full turns formed inside a cylindrical body. These helical paths are intended to induce controlled rearrangement of the two phases as the liquid–vapor mixture passes through the mixer. Additional design variations were subsequently developed by modifying this initial configuration.

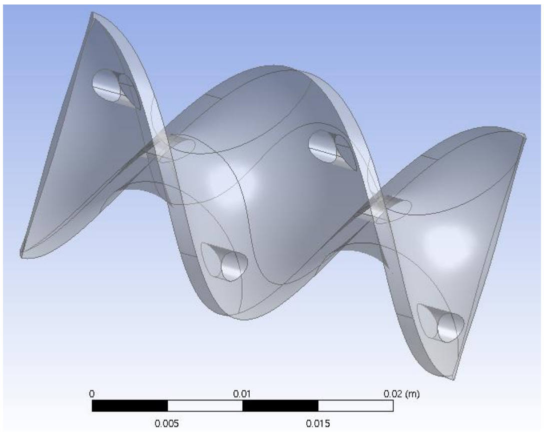

Figure 1 Image of the mixer

All numerical analyses were analysed using Ansys CFX 2021 R2 to examine the flow patterns. The analyses were conducted under saturated conditions with a temperature of 25 ℃ and a pressure of 3 atm, using R-1234ze(E) liquid-vapor as the refrigerant. The mass flow rate was set at 0.05 kg/s, and turbulence modelling was analysed using Shear Stress Transport. Basically, in the case of without a mixer, the liquid and vapor phases flow through the pipe completely separated. The heavier liquid phase occupies the lower part, while the vapor phase flows in the upper part of pipe. It can be observed that the liquid flowing at the bottom transitions into an annular flow after passing through the mixer. On the other hand, due to its relative lightness, the vapor tends to gather towards the centre of the pipe after passing through the mixer. At the pipe outlet, it was also observed that the two phases are not completely mixed randomly, but the distribution state has improved compared to before. Passing through the mixer, more turbulence is generated, resulting in a more irregular flow. When the irregular flow reaches the plate channel, it will generate a new flow pattern different from one without a mixer. As the two-phase flow collides with the channel, additional turbulence will be created at the channel inlet.

Without the mixer, the liquid and vapor phases in the PHE become highly separated, creating distinct preferential paths and severe flow maldistribution. This behavior appears not only in the inlet pipe but also within the channel, where regions with extremely low liquid fractions develop, making partial dry-out highly likely. When the mixer is installed, however, this non-uniform distribution is significantly reduced. The liquid spreads more evenly across the channel, indicating that the mixer effectively suppresses maldistribution and promotes a more uniform two-phase flow throughout both the inlet pipe and the plate channels.

3. Experimental Analysis and Results

3.1. Experimental setup

A transparent gasket-type plate heat exchanger (PHE) was fabricated using polycarbonate to facilitate direct observation of two-phase flow, and the completed assembly is presented in Figure 2. For visualization purposes, the stainless-steel plate in a commercial gasket-type PHE was replaced with a 30-mm-thick polycarbonate plate with a thermal conductivity of 0.2 $W \cdot m^{-1} \cdot K^{-1}$, enabling clear identification of liquid–vapor distribution during operation. To capture temperature variations across the plate surface, ten thermocouples (0.127 mm diameter) were mounted in the central region—five aligned along the liquid-preferred path and five along the vapor-preferred path. The transparent refrigerant-side plate formed the outermost layer, while the water-side plate was positioned immediately behind it, and these components were assembled to complete the experimental PHE. This arrangement allowed simultaneous visualization of internal flow structures and measurement of local temperature behavior within the channel.

Figure 2 Image of test section

3.2. Experimental results

Practically, PHE uses low-quality refrigerants, so the experiment was conducted at low vapor quality conditions. The experiments were conducted at vapor quality of 0.1 and 0.2, and changes were observed as Q was increased to 0.4,0.8,1.2, and 1.6 kW. For a vapor quality of 0.2, the outlet quality exceeded 1, so experiments were not conducted at 1.6 kW. Fig. 5 (a) is the Heat transfer coefficient figure when the heat transfer rate is increasing for a quality of 0.1. At G = 50 kg m^{-2} s^{-1}, there was a maximum increase of 8 % in the heat transfer coefficient up to Q = 1.2 kW. As Q increased, the effect on the increase in heat transfer coefficient was effective; however, after 1.6 kW, strong dry out occurred due to the high Q. Nevertheless, the heat transfer coefficient was calculated to be about 2 % higher than without the mixer. Similarly, there was an overall increase in the heat transfer coefficient at G = 70 kg m^{-2} s^{-1}. The magnitude of the increase was smaller compared to G = 50 kg m^{-2} s^{-1}, but the mixer is effective in enhancing the heat transfer coefficient. Similarly, the same results were observed at a vapor quality of 0.2 as with 0.1. At a vapor quality of 0.2, it was clear that the HTC increased as Q increased. Furthermore, the increase in heat transfer coefficient was also higher at G = 50 kg m^{-2} s^{-1} compared to G = 70 kg m^{-2} s^{-1}. In conclusion, it was confirmed that the mixer is effective at low vapor quality when Q is high and G is low.

Since experiments were conducted under various operating conditions, dry-out suppression was consistently observed in all cases, though its extent varied with the condition. The observed improvement of heat transfer performance, achieved through the suppression of partial dry-out, can ultimately be attributed to the flow redistribution induced by the mixer.

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