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Distribution Characteristics and Structure Optimization of Printed Circuit Heat Exchangers

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Abstract

Based on the structural characteristics of actual PCHEs, a primitive header model suitable for predicting and analyzing the flow distribution characteristics of gas-liquid two-phase flow inside PCHEs was established by taking the heat exchanger header and twelve microchannels as the modeling objects and using natural gas liquid-vapor mixture as the working fluid. The model considers the interaction between gas and liquid phases and tracks the interfacial movement of gas-liquid two-phase flow based on the VOF method. Single-phase flow studies were carried out with liquid methane and gaseous methane as working fluids respectively, and numerical simulations were performed on the primitive header model and hyperbolic header models with different curvatures under various inlet parameters. Meanwhile, an improved hyperbolic header structure was proposed. The geometric feature of the hyperbolic structure is that the cross-sectional area changes continuously and smoothly along the flow direction. This design prevents eddies and dead zones caused by sudden cross-section expansion during fluid diffusion, gradually homogenizes the fluid velocity field, and ensures smaller flow deviation into each microchannel. Furthermore, the smooth wall of the hyperbolic structure suppresses the generation of turbulent eddies, allowing the fluid to maintain a more stable laminar or transitional flow regime during expansion.

Keywords

Printed Circuit Heat Exchanger (PCHE); Header Structure Optimization; Single-phase Flow; Distribution.

1. Introduction

Conventional LNG vaporizers for onshore applications mainly adopt open-rack vaporizers, ambient air-heated vaporizers, etc. These vaporizers feature large footprint and heavy weight, which cannot meet the requirements of high efficiency and compactness for FSRUs [1]. As a novel microchannel heat exchanger, the printed circuit heat exchanger (PCHE) has flow channel dimensions reduced to 0.5–3 mm, exhibiting remarkable advantages such as small volume, large heat transfer area, high heat transfer efficiency, high compactness, and wide applicability. Existing studies have shown that for vaporizing the same mass of LNG, the size and weight of PCHEs are only 1/50 and 1/10 of those of open-rack vaporizers, respectively. Thus, PCHEs have become the preferred vaporizers in offshore LNG floating storage and regasification units[2].

Uneven working fluid distribution can lead to considerable differences in temperature and thermophysical properties among different channels, further affecting the heat transfer process of LNG in each channel. Channels with excessively low flow rates may even suffer from heat transfer deterioration, which severely reduces the overall vaporization efficiency of the heat exchanger. Studies at home and abroad have demonstrated that non-uniform fluid distribution can degrade the overall performance of heat exchangers by more than 30% [3]. During the application of heat exchangers, inappropriate component design, manufacturing processes, and installation issues can cause maldistribution of internal flow, which reduces heat exchanger efficiency and may even lead to serious deviation from the design conditions. Meanwhile, traditional headers mostly adopt straight-inlet or simple diameter-expansion designs[4].

After fluid enters the rectangular header from a circular inlet, it is prone to form a non-uniform velocity field due to inertial effects, boundary layer separation, and geometric constraints of the channels, resulting in significant flow rate deviation among heat exchange channels. Under gas-liquid two-phase flow conditions, phase separation can also occur.

Previous studies have indicated that when the flow rate deviation of PCHE channels exceeds 15%, local channels will suffer from heat transfer deterioration or wall overheating[5].This not only reduces the overall heat transfer efficiency by more than 20%, but may also cause fatigue failure at the joint between the header and the core due to thermal stress concentration, seriously threatening the long-term operational safety of the system.Therefore, it is of great significance to investigate the influence of PCHE structural improvement on flow distribution characteristics.

2. Numerical Model

2.1. Physical Model

In this paper, a three-dimensional model of a printed circuit heat exchanger with a conventional header structure is established according to the actual operating conditions of PCHEs, to investigate the working fluid flow distribution characteristics in each microchannel of the PCHE with a conventional header. As shown in the figure, the radius r of the inlet pipe is 2.5 mm, the header adopts a semi-circular arch structure, the number of microchannels is set to 12, the length is 50 mm, and the cross-sectional radius is 1 mm.

Figure 1 shows the schematic diagram of the PCHE with a conventional header structure.

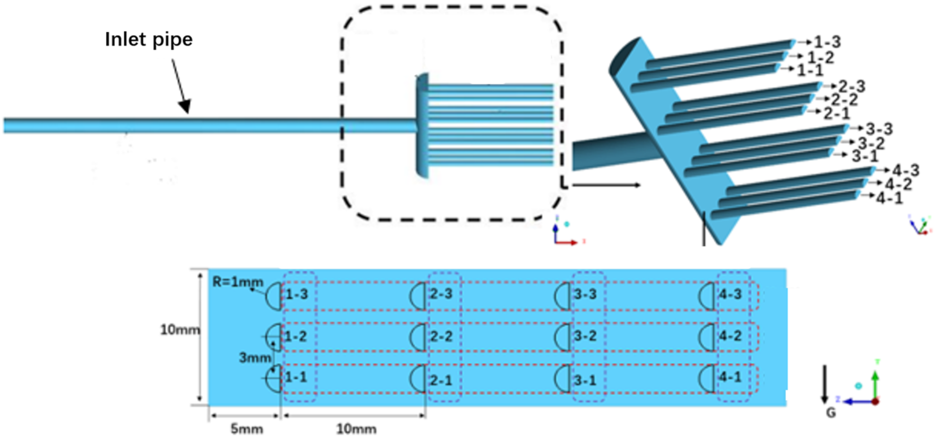

Figure 1. Schematic of PCHE with conventional header

In this paper, the header structure is improved on the basis of the conventional PCHE, and a three-dimensional model of a printed circuit heat exchanger with a hyperbolic header is established to investigate the flow distribution characteristics of the working fluid in each microchannel. To explore the optimal hyperbolic curvature of the header, the header length is denoted as p, the inlet pipe radius is r=2.5mm, and a dimensionless constant n=p/r is defined. By varying the value of n, the influence of different hyperbolic curvatures on the flow characteristics of the working fluid is examined. Figure 2 shows the schematic diagram of the PCHE with a hyperbolic header structure.

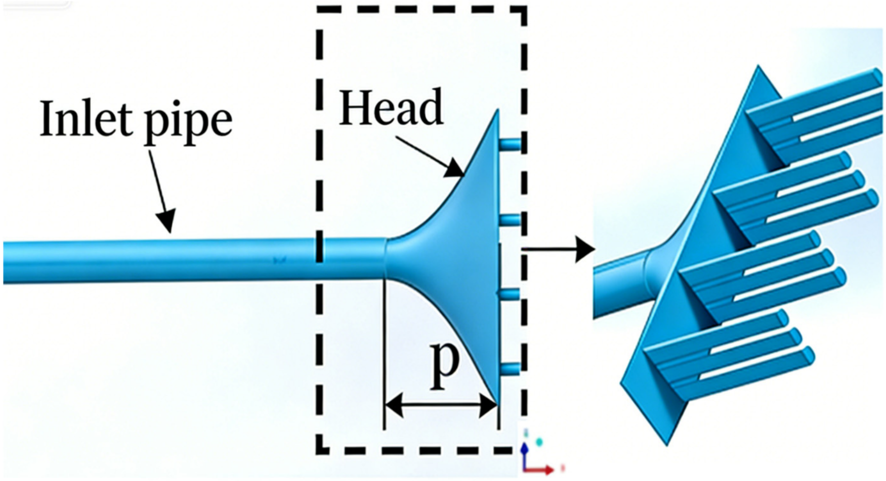

Figure 2. Schematic of PCHE with hyperbolic header

2.2. Boundary Condition Settings

In this simulation, the real thermophysical properties of natural gas are adopted.

Since methane is the main component of natural gas, methane is selected as the working fluid in the simulation to simplify the calculation.

Its thermophysical properties in the simulation are listed in Table 1.

Table 1. Thermophysical Properties of Gas-Liquid Two-Phase Methane

Property	Vapor Methane	Liquid Methane
Densityρ/(kg·m^{-3})	52.69	294.31
Enthalpy$h$/(kJ·kg^{-1})	612.28	278.35
Viscosityμ/(kg·m^{-1}·s^{-1})	0.94×10-5	3.37×10^{-5}
Surface tensionσ/(mN·m^{-1})	1.89	1.89

All inlet channels of the heat exchanger are set as velocity inlet boundary conditions, and all outlets are set as pressure outlet boundary conditions.The wall conditions are adiabatic and no-slip.The pressure-velocity coupling scheme is the SIMPLE algorithm.A second-order upwind scheme is used to discretize momentum, turbulent kinetic energy, and specific dissipation rate.Meanwhile, the residual stopping criterion for each iterative calculation is set to 1×10^{-5}.

3. Results and Discussion

In this paper, the single-phase flow field distribution in PCHEs with different header structures is investigated. Considering actual operation, the single-phase flow at the PCHE inlet exhibits different flow patterns under different structures, resulting in significant differences in flow distribution among channels. Therefore, to explore the flow distribution characteristics of PCHEs with different structures, four numerical cases are designed, as listed in Table 2.

Table 2. Cases under different header structures

	Header structure	Working fluid	Velocity (m/s)
case1	Conventional header	Gaseous methane	0.2
case2	n=4	Gaseous methane	0.2
case3	n=6	Gaseous methane	0.2
case4	n=8	Gaseous methane	0.2

Figure 3 shows the calculated results and standard deviation of the single-phase flow distribution characteristics in the PCHE with the conventional header and different improved hyperbolic headers.

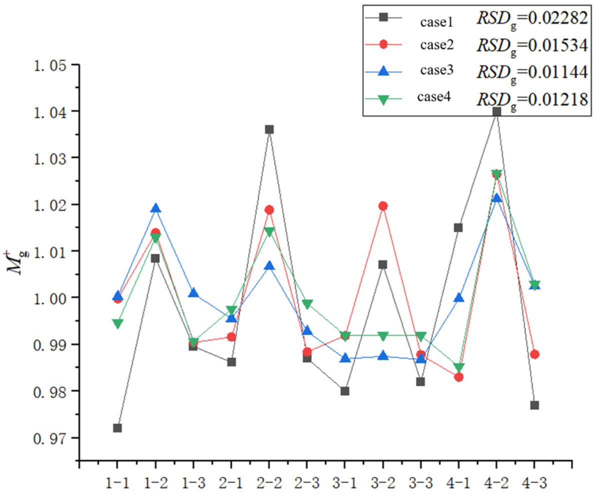

Figure 3. Flow Distribution Characteristics of Gaseous Single-Phase Flow in PCHE with Different Header Structures

It can be seen from Figure 3 that the single-phase flow distribution follows a similar pattern under different structures, and the mass flow rate among different channels varies significantly. Since the effect of gravity is neglected, the second column of channels is closer to the inlet channel, so liquid methane preferentially flows into this column and then diffuses outward. Consequently, the mass flow rate of the second column is obviously higher than that of the other two columns. In addition, flow distribution is more uniform with hyperbolic headers than with the conventional header. This is because the conventional header has a sudden expansion with a right-angle profile, which leads to a strong mainstream concentration due to inertia. In contrast, the hyperbolic profile provides a continuous, smooth, streamlined transition, guiding the fluid to diffuse gradually along the profile and enabling the fluid to cover the inlets of all parallel channels more uniformly.

Figure 4 shows the velocity streamline distribution of single-phase flow in the header region at n=6.

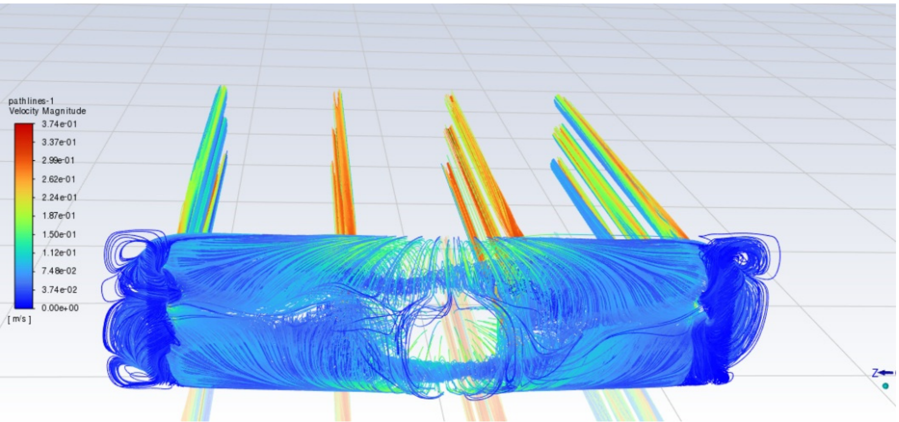

Figure 4. Schematic diagram of velocity streamlines for single-phase flow in the header at n=6

It can be seen from Figure 4 that the improved header eliminates the local high-velocity zone existing in the conventional header, and the velocity gradient is much gentler.After entering from the inlet pipe, the fluid diffuses continuously and uniformly toward all channels along the hyperbolic profile. Meanwhile, the large-scale eddies and backflows near the wall in the conventional header are greatly reduced in the hyperbolic header, with only slight disturbances at the profile transition. This leads to a more balanced kinetic energy distribution in each region, which is the direct reason for its optimal relative standard deviation (RSD) in flow distribution.

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