Experimental Study on Flow and Heat Transfer Characteristics of Additively Manufactured Microchannel Heat Exchangers

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Abstract

Small reactors impose demands for the miniaturization of heat exchange equipment. Addressing the miniaturization requirements of a certain shell-and-tube heat exchanger, a high-performance rectangular microchannel heat exchanger suitable for additive manufacturing technology (additive manufacturing rectangular microchannel heat exchanger, AMRMHE) was designed. Based on the characteristics of metal additive manufacturing, stainless steel prototypes were fabricated using Selective Laser Melting (SLM) technology. The prototype features 120 cold-side microchannels with a channel dimension of 3.9 mm and 97 hot-side microchannels with a channel dimension of 3 mm, achieving a heat transfer surface compactness of 480 m^2/m^3. By establishing an AMRMHE flow and heat transfer experimental platform, experimental investigations were conducted on the flow and heat transfer characteristics of both the cold and hot sides of the AMRMHE. The results demonstrate that a maximum volumetric heat transfer power of 4058.1 kW/m^3 can be achieved in the 211 mm $\times$ 98 mm $\times$ 992 mm AMRMHE test specimen, which is five times that of the prototype shell-and-tube heat exchanger. The overall heat transfer performance of the AMRMHE is closely related to fluid flow rate and temperature, with the hot-side flow rate exerting a significantly greater influence on the heat transfer coefficient than the hot-side temperature. The pressure drop on both the cold and hot sides of the AMRMHE increases with rising flow rate, and due to the smaller hydraulic diameter of the channels, the flow resistance on the hot side is higher than that on the cold side. The research results indicate that AMRMHE represents an effective solution for meeting the high-efficiency and compactness requirements of heat exchange equipment in small nuclear reactors.

Full Text

Preamble

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Experimental Study on Flow and Heat Transfer Characteristics of Additively Manufactured Microchannel Heat Exchangers

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Abstract

The miniaturization of heat exchange equipment is essential for small modular nuclear reactors. To address the downsizing requirements of a specific shell-and-tube heat exchanger, a high-performance Additively Manufactured Rectangular Microchannel Heat Exchanger (AMRMHE) was designed specifically for fabrication via additive manufacturing technology. Leveraging the characteristics of metal additive manufacturing, a stainless-steel prototype was produced using Selective Laser Melting (SLM). The prototype features 120 cold-side microchannels with a channel size of 3.9 mm and 97 hot-side microchannels with a channel size of 3 mm, achieving a compact heat transfer surface density of 480 m^2/m^3. An experimental platform was established to investigate the flow and heat transfer characteristics on both the cold and hot sides of the AMRMHE. Experimental results demonstrate that the prototype (dimensions: 211 mm × 98 mm × 992 mm) can achieve a maximum volumetric heat transfer power density of 4058.1 kW/m^3—representing a fivefold increase compared to the conventional shell-and-tube prototype. Data analysis indicates that the overall heat transfer performance of the AMRMHE is closely correlated with fluid flow rate and temperature, with the hot-side flow rate exhibiting a significantly stronger influence on the heat transfer coefficient than the hot-side temperature. Pressure drops on both the cold and hot sides increase with rising flow rates, with the hot side experiencing higher flow resistance due to its smaller hydraulic diameter. These findings confirm that the AMRMHE provides an effective solution for meeting the demands of high efficiency and compactness in heat exchange equipment for small nuclear reactors.

Keywords: Microchannel heat exchanger, Compact heat exchanger, Pressure

drop, Additive manufacturing

1. Introduction

Advances in global military technology, scientific progress, and increasing energy demands have drawn significant attention to small modular nuclear reactors, which offer advantages such as compact footprint and high power density [1]. Heat exchangers are critical components in these reactor systems, with their safety performance and heat transfer power directly impacting overall system safety and efficiency. However, due to space constraints, harsh operating environments, and high system pressures and temperatures, conventional plate-type and shell-and-tube heat exchangers cannot meet requirements, necessitating the adoption of compact heat exchangers capable of withstanding high temperature, high pressure, and corrosion.

Microchannel heat exchangers are gradually being applied in high-power heat transfer applications due to their compact size, dense structure, and high heat transfer efficiency [2]. In current practice, Printed Circuit Heat Exchangers (PCHE) are commonly used, offering large specific surface area and strong heat transfer capability [3]. However, heat transfer in PCHEs occurs only vertically between plate surfaces, as shown in Figure 1 [Figure 1: see original paper]-a, resulting in significant loss of effective heat transfer area. In recent years, researchers have proposed a rectangular microchannel heat exchanger design concept that involves stacking a series of plates with 90° step features to form square channels, as illustrated in Figure 1-b. In this configuration, each hot channel is surrounded by four cold channels, and each cold channel is surrounded by four hot channels, enabling heat transfer in four lateral directions and substantially increasing heat transfer area and performance [4].

Additive manufacturing (AM) technology creates three-dimensional objects by adding material layer-by-layer under CAD file guidance [5]. Compared with conventional manufacturing, AM offers several advantages for microchannel heat exchanger production: 1) Greater design freedom enables higher compactness and power-to-weight ratio [6]; 2) More intricate three-dimensional channel structures increase heat transfer area and enhance thermal performance; 3) Absence of welds and gaskets reduces leakage risk [4]; and 4) Higher machining precision, material compatibility, and material savings [7].

Numerous studies have investigated heat transfer in microchannel heat exchangers with various cross-sectional shapes. Wang et al. [8] examined the effects of different cross-sectional shapes and aspect ratios on microchannel heat exchanger performance at fixed cross-sectional area, finding that rectangular microchannels exhibited the lowest thermal resistance while triangular channels showed the highest. Additionally, for rectangular microchannels with identical cross-sectional area, increasing the aspect ratio generally reduced thermal resistance.

Hushtaq I. Hasan et al. [9] employed numerical simulation to model counter-flow heat exchangers with various cross-sectional configurations (rectangular, triangular, etc.), analyzing internal flow and heat transfer characteristics and developing new correlations. Their research demonstrated that reducing channel cross-sectional size (i.e., increasing microchannel count) significantly enhanced heat transfer performance while increasing pressure drop, at constant total volume. P. Gunnasegaran et al. [10] comparatively studied flow field and heat transfer characteristics of rectangular, trapezoidal, and triangular microchannel heat sinks at Reynolds numbers of 100–1000. By analyzing hydraulic diameter effects on flow and temperature fields and using average fluid temperature and heat transfer coefficient as metrics, they concluded that both heat transfer coefficient and Poiseuille number increased with Reynolds number, with rectangular microchannels achieving the highest values, triangular the lowest, and trapezoidal channels intermediate.

These studies collectively demonstrate the advantages of rectangular microchannel heat exchangers, including low thermal resistance and high heat transfer coefficients. However, current domestic research on microchannel heat exchangers has primarily focused on theoretical design and numerical simulation, with significant gaps in prototype fabrication and experimental system design. This paper addresses the practical application requirements for residual heat removal exchangers in marine nuclear reactors by designing a compact, high-temperature, high-pressure, high-performance counter-flow rectangular microchannel heat exchanger (AMRMHE) manufactured modularly using selective laser melting additive manufacturing technology. A thermal-hydraulic experimental platform was constructed to investigate flow, heat transfer, and resistance characteristics under various operating conditions. The experimental results provide valuable data support and technical foundation for future compact heat exchanger design and application in small nuclear reactors, offering important engineering guidance for improving space utilization and operational stability of critical components.

1.1 Heat Exchanger Model

Based on rectangular microchannel heat exchanger design principles and prototype parameters (cold-side fluid: 1 MPa pressure, 1.1 t/h flow rate, 25°C inlet temperature; hot-side fluid: 15 MPa pressure, 0.6 t/h flow rate, 200°C inlet temperature; 800 kW/m^3 volumetric heat transfer power), this paper proposes a new AMRMHE design scheme shown in Figure 2 Figure 2: see original paper. The central straight section constitutes the core heat transfer zone, with cold and hot fluid inlet/outlet connections, distributors, collectors, and flow guides on both sides. After entering the main inlet manifold, hot/cold fluids connect directly to 45° inclined separators. Post-separation, fluids flow straight through collectors before entering curved guide channels that direct flow into the core heat transfer zone. The cross-sectional arrangement of hot and cold channels in the core zone is shown in Figure 2(b). Based on prototype parameters, the AMRMHE rated design specifications are listed in Table 1, with a design volumetric heat transfer power of 4000 kW/m^3—five times that of the prototype—and a compactness of 480 m^2/m^3, four times the prototype value, indicating substantially enhanced heat transfer capability.

The AMRMHE core heat transfer zone employs an octagonal frustum housing containing 120 cold channels and 97 hot channels in an alternating arrangement to enhance heat transfer. Detailed geometric parameters are provided in Table 2.

1.2 Additive Manufacturing of Heat Exchanger

Due to the highly complex geometry of the AMRMHE, conventional manufacturing methods (casting, forging) or subtractive processes (machining) are impractical. Additive manufacturing technology, using 3D models as input and building structures through layer-by-layer material addition, resolves the complexity challenge.

Various AM technologies have been developed for different application scenarios [11]. For the AMRMHE designed in this study, Selective Laser Melting (SLM) is appropriate, involving continuous powder spreading and solidification layer-by-layer. SLM offers high precision and superior surface quality. Prior to printing, support structures were designed for the AMRMHE model to ensure stability of overhanging features. Post-printing, solution heat treatment was applied to homogenize material composition and improve strength, toughness, and fatigue resistance; cleaning treatment prevented microchannel clogging; and surface polishing reduced surface roughness to decrease flow resistance. The final AMRMHE prototype is shown in Figure 3 [Figure 3: see original paper].

2.1 Experimental System

To evaluate AMRMHE applicability in marine small nuclear reactor systems, a performance test bench was constructed to measure heat transfer and resistance characteristics.

The experimental system comprises remote start/stop controls, deionized water circulation, secondary cooling, flow regulation, instrumentation, and data acquisition. Primary equipment includes the test specimen, preheater, multistage centrifugal pump, plunger metering pump, and plate heat exchanger for cooling (Figure 4 [Figure 4: see original paper]). The working fluid circulates through heating and cooling loops. In the heating loop, deionized water from the tank is delivered by a plunger metering pump through a needle valve, heated by the preheater, and enters the AMRMHE hot inlet. After heat exchange, the fluid exits through a high-temperature regulating valve for pressure reduction, is cooled by the plate heat exchanger, and returns to the deionized water tank, forming a closed loop. In the cooling loop, deionized water is pumped by a multistage centrifugal pump into the AMRMHE cold inlet, absorbs heat from the heating loop, exits through a high-temperature regulating valve, is cooled by a large plate heat exchanger, and returns to the tank.

During experiments, heating loop pressure is controlled via high-temperature regulating valve opening, and inlet temperature via preheater power; cooling loop pressure is regulated by multistage centrifugal pump frequency. Temperature, pressure, and differential pressure at the heat exchanger inlet/outlet are measured by corresponding sensors. Flow meters in both loops measure working fluid flow rates. Remote control systems enable real-time adjustment of valve openings and preheater power. Instrument ranges and accuracies are listed in Table 3. To ensure data reliability, heating section external surfaces were insulated with thermal cotton, and all instruments were calibrated prior to testing.

2.2 Experimental Conditions

To characterize performance across broad parameter ranges, experiments were conducted with hot-side pressure at 15 MPa and cold-side pressure at 1 MPa. Hot-side inlet temperature was varied from 200–320°C in 20°C increments, while cold/hot-side flow rates were set at 20%–120% of rated values in 20% increments. Measured data included inlet/outlet temperatures, pressures, differential pressures, and flow rates for both sides.

3.1 Heat Transfer Model

During data processing, average inlet/outlet temperatures of the AMRMHE were used as reference temperatures, with fluid properties obtained from NIST REFPROP software. Based on energy conservation, total heat transfer rate was calculated from hot-side fluid enthalpy difference:

$$Q = G_h(h_{in} - h_{out}) \tag{1}$$

where Q is heat transfer rate (kW), G_h is hot-side mass flow rate ($\mathrm{kg \cdot s^{-1}}$), h_{in} and h_{out} are inlet and outlet fluid enthalpies ($\mathrm{kJ \cdot kg^{-1}}$).

Overall heat transfer coefficient was determined from total heat transfer rate and logarithmic mean temperature difference:

$$H = \frac{Q}{A\Delta T_m} \tag{2}$$

where ΔT_m is logarithmic mean temperature difference (°C).

3.2 Pressure Drop Model

For single-phase fluid flow, total pressure drop comprises four components: gravitational pressure drop due to elevation change, acceleration pressure drop due to velocity change, frictional pressure drop due to flow resistance, and form pressure drop due to sudden geometry changes [12]. In these experiments, the AMRMHE was vertically oriented with straight, uniform channels, rendering form pressure drop negligible. Thus, total pressure drop includes three components: frictional pressure drop Δp_f, gravitational pressure drop Δp_g, and acceleration pressure drop Δp_a due to heating-induced momentum change:

$$\Delta p = \Delta p_f + \Delta p_g + \Delta p_a \tag{3}$$

Gravitational and acceleration pressure drops are calculated as:

$$\Delta p_g = \frac{(\rho_{in} + \rho_{out})}{2} gH \tag{4}$$

$$\Delta p_a = G^2(\nu_{out} - \nu_{in}) \tag{5}$$

where ρ_{in} and ρ_{out} are inlet/outlet fluid densities ($\text{kg} \cdot \text{m}^{-3}$), H is AMRMHE straight channel height (m), ν_{in} and ν_{out} are inlet/outlet specific volumes ($\text{m}^3 \cdot \text{kg}^{-1}$), and G is mass flux ($\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$).

Frictional pressure drop is the measured total pressure drop minus calculated gravitational and acceleration components:

$$\Delta p_f = \Delta p - \Delta p_g - \Delta p_a \tag{6}$$

Measured parameters include inlet/outlet temperatures, pressures, differential pressures, flow rates, and preheater current/voltage. Calculated quantities include logarithmic mean temperature difference ΔT_m (°C), heat transfer rate Q (kW), and heat transfer coefficient H ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$). Uncertainty is calculated using:

$$\frac{\Delta Y}{Y} = \sqrt{\sum_{i=1}^{n} \left(\frac{\Delta X_i}{X_i} \right)^2} \tag{7}$$

where Y is a calculated quantity, ΔY its uncertainty, X_i are related variables, and ΔX_i their uncertainties. Resulting uncertainties are 0.9% for ΔT_m, 0.7% for

Q, and 0.91% for H. Thermal balance verification showed deviations between hot and cold sides were less than 1%, confirming measurement reliability.

4.1 Hot-Side Flow and Heat Transfer Characteristics

With cold-side flow rate held at 1.10 t/h, inlet pressure at 1 MPa, and inlet temperature at 25°C, hot-side flow rate was varied from 0.12 to 0.72 t/h at constant 15 MPa pressure and 300°C inlet temperature to investigate performance variations. Results in Figure 5 [Figure 5: see original paper] show that heat transfer capability increases monotonically with hot-side flow rate, with overall heat transfer coefficient exhibiting approximately linear growth, indicating enhanced hot-side convection with increasing Reynolds number.

At rated conditions, measured heat transfer rate was 81.2 kW, corresponding to a volumetric heat transfer power density of 4058.1 kW/m^3—meeting the design target and representing a fivefold improvement over the conventional shell-and-tube prototype, achieving both high performance and miniaturization.

With hot-side flow rate at 0.60 t/h and cold-side flow rate at 1.32 t/h, varying hot-side inlet temperature yielded the results shown in Figure 6 [Figure 6: see original paper]. As hot-side inlet temperature increases, the temperature difference between fluids grows, significantly increasing heat transfer power. However, the overall heat transfer coefficient only increased from 1250.2 to 1346.0 $W \cdot m^{-2} \cdot K^{-1}$ (7.66% rise), indicating limited temperature effect on the coefficient.

4.2 AMRMHE Pressure Drop Characteristics

Experimental pressure drop data are presented in Figure 7 [Figure 7: see original paper]. Pressure drops on both sides increase with flow rate. For the hot side (Figure 7(a)), higher inlet temperatures yield lower pressure drops, primarily due to reduced fluid viscosity at elevated temperatures. Compared to the cold side (Figure 7(b)), the hot side exhibits higher overall pressure drop because its smaller hydraulic diameter creates greater flow resistance.

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5 Conclusions

For heat exchanger applications in small nuclear reactor systems, this paper proposes an additively manufactured rectangular microchannel residual heat removal heat exchanger (AMRMHE) design, completes prototype fabrication, and establishes an experimental platform. Flow and heat transfer characteristics under various conditions were investigated, yielding the following conclusions:

1) AMRMHE heat transfer capability increases with hot-side flow rate and temperature. Increasing hot-side Reynolds number significantly enhances convective heat transfer coefficient, while raising hot-side inlet temperature has limited effect on the coefficient.

2) Both cold and hot sides employ microchannel designs with compact structure. Experimental verification achieved a volumetric heat transfer power of 4058.1 kW/m^3—meeting design targets and exceeding conventional shell-and-tube performance by five times—realizing high heat transfer performance and miniaturization.

3) Frictional pressure drops on both sides increase with flow rate, with hot-side pressure drop exceeding cold-side due to smaller hydraulic diameter.

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Note: Figure translations are in progress. See original paper for figures.