Thermal-Hydraulic Performance and Optimization

Subjects: Construction & Building Technology
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In order to make the heat exchanger achieve high thermal hydraulic performance, researchers have made a lot of explorations. However, most studies only focus on thermal-hydraulic optimization of PCHE core geometric parameters and operating conditions, and pay little attention to the influence of head on flow distribution and flow heat transfer characteristics of PCHE. PCHE is considered as a potential choice of the S-CO2Brayton cycle system, so S-CO2is the most used working fluid in PCHE.

Keywords: compact heat exchangers ; thermal efficiency ; performance analysis ; working fluids ; optimization meth

1. Introduction

It is expected that the limitation of available resources and the environmental problems in the process of energy conversion and utilization have always been the constraints of the rapid development of human society. Therefore, under the current energy mode, the high efficiency of energy conversion has been continuously explored by researchers. Taking power systems as an example, many researchers have continuously followed up the supercritical carbon dioxide (S-CO 2) Brayton cycle technology for years, which is due to its advantages of high efficiency and small occupied space. In addition, its layout is relatively simple. An advanced energy conversion technology has an important impact on improving the overall efficiency and reducing the cost of power systems [1][2]. Studies have shown that the thermal efficiency of steam Rankine cycle is lower than that of S-CO 2 Brayton cycle, which is about 5% [3], and in terms of economy, S-CO 2 Brayton cycle saves 15% compared with helium cycle [4]. The S-CO 2 Brayton cycle owns merits of both the steam Rankine cycle and the gas turbine system [5]. In addition, it must be mentioned that the application of compact heat exchangers is an important reason why the supercritical carbon dioxide Brayton cycle can obtain the above advantages.

Heat exchangers are widely used in electric power, the chemical industry and other industrial fields. The surface area density of the heat exchanger has an important influence on its thermal and hydraulic performance. Generally speaking, the higher the surface area density, the better the heat exchange effect of the heat exchanger. At present, the surface area density of ordinary heat exchangers is generally less than 100 m 2/m 3 [6], while the surface area density of compact heat exchangers is ten times or more than that of ordinary heat exchangers. Shah et al. [7] proposed in the article that surface area density and hydraulic diameter are the two basic elements that define compact heat exchangers. The surface area density of compact heat exchangers with liquid and gas selected as working fluids should exceed 400 m 2/m 3 and 700 m 2/m 3, respectively. Printed Circuit Heat Exchangers (PCHE) has shown great potential in thermal and hydraulic performance, and can withstand a pressure of more than 4 × 10 4 Pa, a temperature of 1000 °C, and a surface area density of nearly 5000 m 2/m 3 [8].

In recent decades, as the global demand for electric energy has risen sharply, lots of researchers have focused on the topic of improving the energy conversion efficiency of power systems. Numerous research results have emerged during this period, especially the research regarding the S-CO 2 Brayton cycle in power systems [9], which opened a new frontier for the development and application of compact heat exchangers. A few of the review papers in this field show current status of this research and provide reference and directions for future research. Cheng et al. [10] reviewed the experimental research on pressure drop and heat transfer of S-CO 2 cooling. Studying the experimental measurement results of S-CO 2 in heat exchanger tubes of different geometries and sizes, Cabeza et al. [11] reviewed the correlations of its heat transfer coefficients. Huang et al. [12] reviewed the convective heat transfer characteristics of PCHE of different structures according to the results of extensive experiments and numerical simulations. Lei et al. [13] reviewed the influence of flow channel geometry characteristics, material selection, manufacturing technology and design optimization on the performance of PCHE. Pandey et al. [14] reviewed and analyzed a hybrid model constructed using thermal resistance networks and computational fluid dynamics concepts which can effectively calculate the heat transfer and pressure of a full-scale PCHE. Liu et al. [15] presented a meritorious bibliographical review on the industrial feasibility and maturity level of PCHE. Kwon et al. [16] reviewed the compact heat exchanger technology for the S-CO 2 power cycle applications and summarized heat transfer mechanisms and correlations.

2. Main Types and Performance Optimization of Compact Heat Exchangers

This chapter reviews several main compact heat exchangers, summarizes and classifies their structure, flow and heat transfer characteristics, and discusses their material selection, pressure resistance, and operating parameters.

Corrugated fins are prominent in increasing the heat transfer area. In addition, the periodic slight disturbance of the fluid caused by the corrugated fins along the corrugation direction can reduce the adverse effects of the boundary layer on heat transfer. The above two aspects make the thermal performance of corrugated fins much better than traditional plate fins, but the pressure drop caused by the corresponding corrugated fins will also increase a lot, which will increase pump power output. The wave angle is the key parameter of the wave fin. Under normal circumstances, the increase of the wave angle will enhance heat transfer, but research has found that the pressure drop increases significantly.

The initial conditions faced by heat exchangers in different working environments are different, such as heat flux and inlet temperature, which will affect the performance of PCHE, and many researchers have conducted relevant research. Li et al. [17] calculated and analyzed the simulation results under different heat flows and found that high heat flow significantly inhibited the heat transfer efficiency in heating mode, but had little effect in cooling mode. In addition, Li et al. [18] got the same conclusion as before in another study of forced convection heat transfer in PCHE. The experimental and simulation results of S-CO 2 cooling flow in tubes by Zhang et al. [19] showed that pressure, mass flux and inner diameter have different degrees of effects on the heat transfer characteristics of S-CO 2 and pressure drop during cooling. Meshram et al. [20] numerically analyzed the state of S-CO 2 in a straight channel under the condition of complete turbulence, and compared this with the zigzag channel. Chai and Tassou [21] established a three-dimensional numerical model considering the inlet effect, conjugate heat transfer effect, thermophysical properties of NIST real gas, and the buoyancy effect. It was found that the inlet effect would cause the local heat transfer to drop rapidly near the inlet and then keep stable along the flow direction, and the pressure gradient was positively correlated with the temperature of S-CO 2. Based on the influence of different boundary conditions on the dynamic response characteristics and equilibrium time of thermodynamic parameters on PCHE, Ma et al. [22] predicted the performance of PCHE through a neural network, which is very helpful for further constructing the dynamic model of the whole S-CO 2 power system.

Because the influence of gravity always exists in the actual operating environment of the heat exchanger, the buoyancy effect caused by gravity must be considered to affect the performance of PCHE. A study on laminar mixed convection heat transfer of S-CO 2 in horizontal microtubes showed that buoyancy significantly enhanced heat transfer in thermal imbalance, especially near the false critical point [23]. Xiang et al. [24] conducted similar numerical simulation, and it showed that temperature was stratified and the secondary flow was produced. In addition, the buoyancy effect led to asymmetric distribution of radial velocity and turbulence kinetic energy on cross-section, and buoyancy effect became more significant as heat flux and pipe diameter increased. Zhang et al. [25], based on the study of coupling heat transfer characteristics of S-CO 2 in horizontal semicircular channels, made a further supplement to the related work of previous scholars. It showed that the buoyancy effect is negatively correlated with mass flow rate, and asymmetric flow performed better than symmetric flow on heat transfer at low mass flow rate. Buoyancy can enhance the heat transfer to the top wall of the hot side, but it will lead to the deterioration of the thermal performance of the bottom wall, while the opposite is true on the cold side.

3. Types of Fluid Working Medium in Compact Heat Exchanger

At present, the enhancement of heat transfer by optimizing the structure of heat exchanger has a new set of challenges, so researchers pay attention to the fluid working medium. This chapter will summarize and analyze the commonly used and potential fluid refrigerants in compact heat exchangers and put forward some suggestions for their development.

Using an external magnetic field to enhance heat transfer of compact heat exchangers is an interesting research direction of nanofluid application. In the study of convection heat transfer of fin-tube compact heat exchanger, the volume fraction of 2% Fe 3O 4-water can bring up to 8.7% enhancement of convection heat transfer. However, when the external magnetic field is applied around the heat exchanger, the maximum convective heat transfer enhancement reaches 52.4% of the case above [26]. It can be seen that applying external magnetic fields to compact heat exchangers using nanofluids containing magnetic particles as a working fluid can greatly improve the thermal performance of heat exchangers, but the influence of applying external magnetic field on the properties of nanofluids and the whole heat exchanger system needs further study.

The overall effect of specific heat and buoyancy effect is the main cause of abnormal heat transfer [27][28], and the influence of buoyancy effect or flow acceleration is caused by uneven density distribution of fluid along radial or axial direction. Some scholars have studied the influence of buoyancy on thermal performance of supercritical water in different types of tubes [29][30]. In horizontal tubes, the large temperature difference between top and bottom surfaces of channel can be clarified by the buoyancy effect. Zhang et al. [31] studied buoyancy effect in horizontal flow, in which asymmetric flow leads to uneven local temperature distribution around the pipe, and the natural convection effect before pseudo-critical is greater than that after pseudo-critical. Zhang et al. [32] conducted experiments and numerical simulation on turbulent convective heat transfer characteristics in vertical flow, and found that shear stress and radial velocity redistribution caused by the buoyancy effect led to the deterioration and recovery of heat transfer. In the downward flow with high flow rate, buoyancy has a weak influence on heat transfer, but flow acceleration may cause heat transfer deterioration in both upward and downward flows. In addition, the buoyancy effect has a significant impact on the turbulence of kinetic energy. When the buoyancy near the heating wall is strong, the velocity distribution will become flat and the turbulence will be suppressed, thus reducing the heat transfer.

Because the thermophysical properties of water near the critical point and pseudo-critical point change dramatically and are difficult to control, it is easy to have extreme working conditions when it is used as a working fluid in a heat exchange system, so supercritical water far away from the critical point is usually selected as the working fluid. Yu et al. [30] found that the heat transfer deterioration in horizontal pipe is not obvious compared with the vertical pipe, and that on the top surface of pipe can be eliminated by reducing heat flux. Wang et al. [33] found that the ratio of heat flux to mass flux largely determines the influence of flow direction on thermal performance of supercritical water. In addition, when the ratio is high, the heat transfer effect of downward flow is greatly improved compared with that of upward flow. The study of Zhao et al. [34] showed that when relatively low heat flux increases further, the heat transfer coefficient of upward flow is slightly lower than that of downward flow because the turbulence intensity near the pipe wall is suppressed. Similarly, under the conditions of high mass flux and high heat flux, Wen and Gu [35] also observed that when the region with drastic changes in properties diffuses to the vicinity of the pipe wall, the turbulence is obviously suppressed and the heat transfer deteriorates. Above the critical temperature of water, the increase of pressure will lead to higher viscosity and thermal conductivity, which may lead to heat transfer deterioration. The research shows that the deteriorated heat flux increases when pressure increases, but the degree of heat transfer deterioration decreases in this case [36]. Increasing the inlet temperature and operating pressure can effectively alleviate the deterioration of the heat transfer process [37].

4. Performance Evaluation Indexes of Compact Heat Exchangers

In the research process of thermal hydraulic performance of compact heat exchangers, it is necessary to evaluate its performance through some parameters, and the evaluation objects are heat transfer performance and hydraulic performance. Take PCHE as an example.

Nu and j are usually used as target parameters for evaluating thermal performance of PCHE. j is defined as a modified Stanton number (St) to consider the moderate change of Pr in fluid. Because St depends on Pr of fluid, j is almost independent of flowing fluid under the condition of $0.5 \le Pr \le 10$. However, j can’t reflect the influence of channel geometry in flow process. j is defined as follows, (1) $j = St \cdot Pr^{2/3} = \frac{Nu}{Pr^{1/3} \cdot Re}$

Nu can be interpreted as the ratio of convective heat transfer to conductive heat transfer, which can reflect the influence of channel geometry in the flow process. Therefore, Nu is more suitable than j as a target parameter for evaluating heat transfer performance in PCHE with complex geometry channels. The global Nu is calculated with an averaged surface heat flux q'', the hydraulic diameter (D_h) of the channel, the thermal conductivity (k), the bulk mean temperature (T_b), and the averaged surface temperature (T_s): (2) $Nu = \frac{hD_h}{k} = \frac{q'' D_h}{k(T_b - T_s)}$

The effectiveness is defined as a ratio of the actual heat transfer to the maximum heat transfer physically possible in heat exchanger. It is defined as follows, (5) $\eta = \frac{T_{hot,inlet} - T_{hot,outlet}}{T_{hot,inlet} - T_{cold,intlet}}$ where $T_{hot,inlet}$, $T_{hot,outlet}$ and $T_{cold,intlet}$ are the temperatures at the inlet and outlet of hot channels and the inlet of cold channels, respectively.

In addition, based on the consideration of heat exchanger volume, some researchers have established new dimensionless parameters as evaluation indexes by using j and f , but they will not be explained here.

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