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Study of flow and heat transfer of CO_2 at supercritical pressure

Fangbo Li
Xi'an Jiaotong University
Xi'an, China

Binbin Pei
Xi'an Jiaotong University
Xi'an, China

Zhentao Chen
Xi'an Jiaotong University
Xi'an, China

Bofeng Bai*
Xi'an Jiaotong University
Xi'an, China

ABSTRACT

In this paper we present our work on the flow and heat transfer of supercritical CO_2. Firstly, the flow and heat transfer of supercritical CO_2 in the helically-coiled tube under half-side heating condition are investigated numerically, and the influential mechanism of heat transfer under half-side heating condition is discussed. Then we present our work on the design and evaluation of a new type of ultra-compact plate heat exchanger (UCPHE) which could be used as the regenerator in supercritical CO_2 Brayton cycle. The UCPHE with a honeycomb core has the advantage of high temperature and pressure resistance. It is found that this new compact heat exchanger has an equivalent thermal hydraulic performance with PCHE and owns broad application prospect.

INTRODUCTION

Carbon dioxide has very peculiar thermo-physical properties at supercritical pressures [1], leading to its wide applications on the new type of power cycles. The specific heat of CO_2 significantly increases at the pseudo-critical region, causing obvious heat transfer enhancement. At supercritical pressures, CO_2 has excellent compressibility therefore the energy consumption of the circulation could be greatly reduced. Moreover, the critical temperature of CO_2 is very close to the ambient temperature, thus the efficiency of the thermodynamic cycles could be obviously improved.

Heat transfer of supercritical CO_2 would be strongly affected by the intense change in the physical properties. Licht et al. [2] and Xu et al. [3] pointed out that the effect of specific heat and buoyancy effect have significant impact on heat transfer of supercritical fluid. The experiment conducted by Kurganov et al. [4] offered a good insight into the mechanism of heat transfer deterioration under high heat flux, the M-shaped velocity profile was observed and it was considered to be closely associated with heat transfer deterioration. Bae et al. [5, 6] obtained the budget of the turbulent kinetic energy in deteriorated heat transfer by using direct numerical simulation, and the mechanism of buoyancy and flow acceleration were also analyzed. Supercritical CO_2 Brayton cycle is being extensively used in energy and power fields. The efficiency of the supercritical CO_2 Brayton cycle is strongly dependent on the performance of the regenerator [7, 8, 9]. The printed circuit heat exchanger (PCHE) is known to be an attractive type of the regenerator because of its high compactness (heat transfer area to volume ratio is up to 2500 m^2/m^3) and high temperature and pressure resistance [10]. Thermal hydraulic performances of PCHE have been investigated by several literatures [11, 12].

In some engineering applications, such as the water cooled wall in boilers and the special heat exchangers used in the chemical reaction process, the tubes are subjected to half-side heating. In these cases, the thermal hydraulic characteristics of the flow are more complex than the case with uniform heating due to the non-uniform heat flux distribution. In this study, we conducted the investigation on heat transfer of supercritical CO_2 in the helically-coiled tube under half-side heating condition. The heat transfer characteristics and mechanism near the critical region are discussed. Additionally, we proposed a new kind of ultra-compact plate heat exchanger (UCPHE). The heat transfer and flow resistance of UCPHE are evaluated numerically and compared with PCHE. It seems that the thermal hydraulic performance of UCPHE is equally excellent as PCHE.

RESULTS AND DISCUSSION

1. Study of flow and heat transfer of supercritical CO_2 in the helically-coiled tube.

Numerical simulation on flow and heat transfer of supercritical CO_2 in the helically-coiled tube under half-side heating is conducted, the steady RNG k-ε model [13] with enhanced wall function is chosen as the turbulence model. The relationship between thermo-physical properties and temperature of supercritical CO_2 is obtained by piecewise liner fitting, and all the properties come from NIST Standard Reference Database. Fig. 1 shows physical model of the helical tube, the inside diameter is 9.0mm and the outside diameter is 12.0mm, the wall thickness is considered here. The tube is made of 316L stainless steel and the physical properties are: ρ=7980kgm^{-3}, λ=16.3Wm^{-1}K^{-1}. The diameter of the coil is 283.0mm and the pitch of the tube is 32.0mm. The height of the helically-coiled tube is 192.0mm, which means the tube has 6 turns. The inner side of the coil is heated and the outer side is adiabatic.

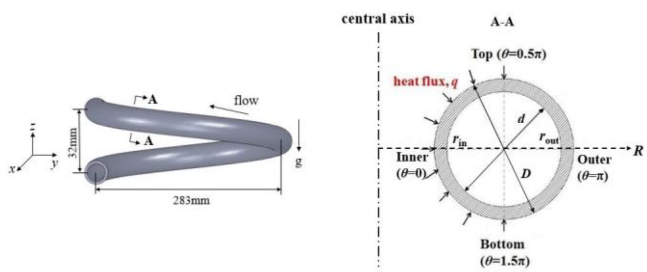


Fig. 1. Physical model of the helical tube

The variations of heat transfer coefficients under uniform heating condition and half-side heating condition are shown in Fig. 2. The heat flux of the inner side of the coil is twice as much as that under uniform heating condition to ensure the same heat transfer rate for all conditions. As can be seen, uniform heating has better heat transfer performance than half-side heating. The discrepancy of heat transfer coefficients under different heating conditions reaches the peak at the pseudo-critical enthalpy.

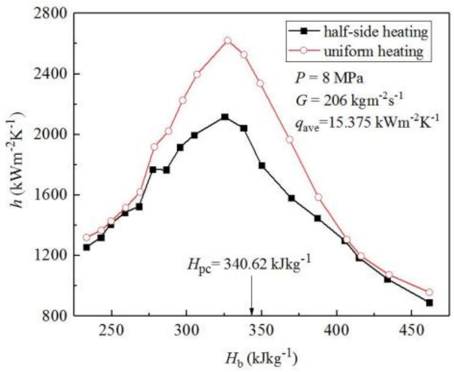


Fig. 2. Heat transfer coefficients under half-side heating and uniform heating conditions

Fig. 3 shows the distributions of the specific heat from the inner side to the outer side of the coil on different cross-sections under half-side and uniform heating conditions (The left and the right side of x-axis represent the inner and outer side respectively, the same below). As can be seen, at the same bulk enthalpy, the c_p in the core region under half-side heating condition is almost the same as that under uniform heating condition. However, the c_p near the inner wall is obvious lower than that under uniform heating condition, leading to the poor heat transfer performance of half-side heating. This is because the inner wall temperature of half-side heating is higher than that of uniform heating due to the higher heat flux, and the near-wall fluid is in a low-density gas-like state. When H_b exceeds H_{pc}, as is shown for H_b = 424 kJkg^{-1}, the physical properties are insensitive to the temperature. Therefore the the gap of heat transfer coefficients between uniform heating and half-side heating narrows accordingly.

In Fig. 4, the axial velocity and turbulent kinetic energy distributions from the inner side to the outer side of the coil under the two heating conditions are compared. Under uniform heating condition, the velocity at the outer side is obviously higher than that at the inner side due to the centrifugal force. Therefore, the velocity gradient is created over the cross-section obviously. Nevertheless, under half-side heating condition, the buoyancy effect near the inner wall caused by the density gradient is much stronger than that under uniform heating condition. Therefore, the fluid near the inner side is obviously accelerated and the velocity gradient of the fluid is lower than that under uniform heating, as can be seen from Fig. 4(a). Fig. 4(b) shows the turbulent kinetic energy distribution from the inner side to the outer side of the coil under the two heating conditions. As is shown, the turbulent kinetic energy under half-side heating condition is much lower than that under uniform heating. The formation of the flat velocity profile in half-side heating mentioned above indicates the modification and reduction of the shear stress in the flow field. As a result, the production of turbulent kinetic energy, and the turbulent kinetic energy itself, are diminished, leading to reduced mixing of the fluid thus lower heat transfer coefficients.

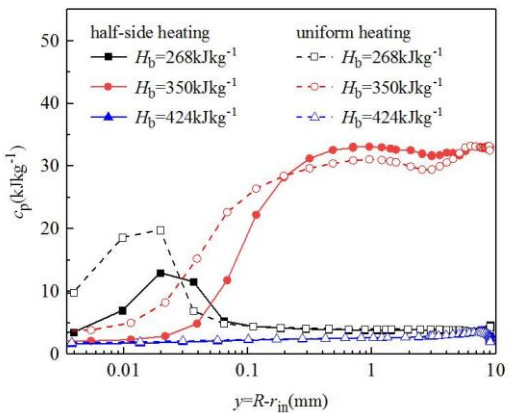


Fig. 3. Specific heat distribution under half-side heating and uniform heating conditions

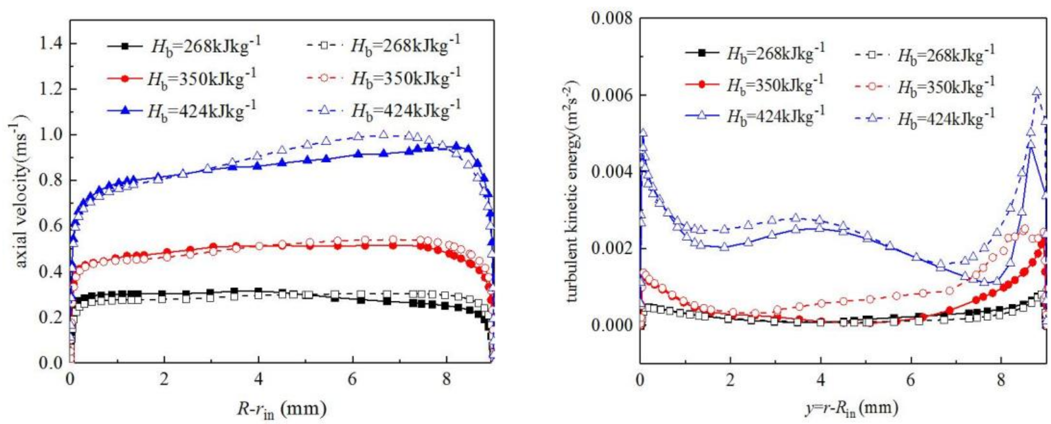


Fig. 4. Streamwise velocity and turbulent kinetic energy distribution under half-side heating and uniform heating conditions.

2. The evaluation of a new type of ultra-compact plate heat exchanger (UCPHE) for the supercritical CO_2 Brayton cycle

We proposed a new type of ultra-compact plate heat exchanger (UCPHE) as a candidate of the regenerator for the supercritical CO_2 Brayton cycle. The sketch of UCPHE is shown in Fig. 5.

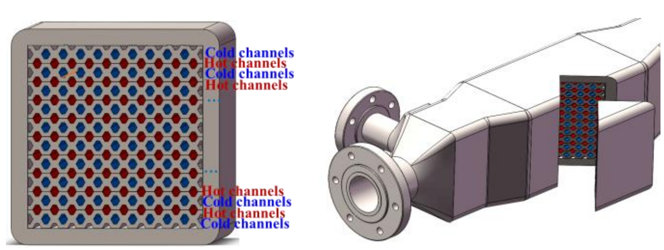
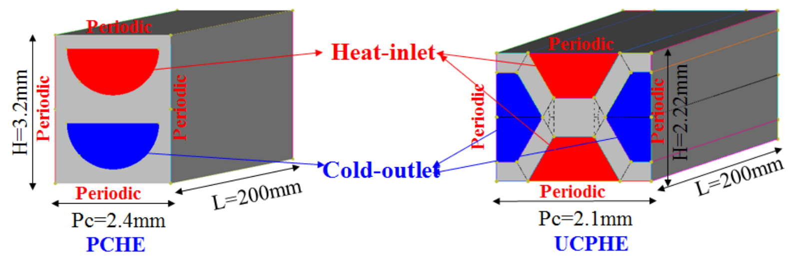


Fig. 5. The sketch of UCPHE

In the present work, the heat transfer and flow resistance performances of UCPHE with straight channels are analyzed and compared with PCHE using Fluent 14.0, the steady shear stress transport (SST) k-ω model [14] is opted for modeling turbulent flow. Fig. 6 gives the numerical model of UCPHE and PCHE (the hydraulic diameters are both 1.22mm). Owing to the periodicity of the structure of the UCPHE core, the heat transfer in a unit cell with periodic boundary conditions are modeled. The Nusselt numbers and friction factors of hot and cold sides against Reynolds numbers are shown in Fig. 7. It could be seen that the Nusselt numbers and friction factors of UCPHE are extremely close to those of PCHE under the same hydraulic diameter and Reynolds number.



(a) (b)

Fig. 6. Numerical model of PCHE (a) and UCPHE (b).

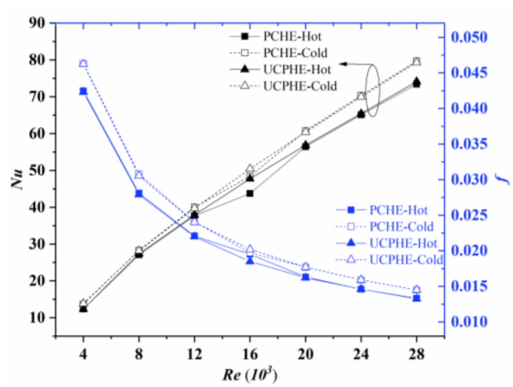


Fig. 7. Comparison between UCPHE and PCHE: Nusselt number and friction factor variation against Reynolds number

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