Postprint: Cooling Heat Transfer Mechanism of Supercritical Pressure CO2 in Horizontal Tubes

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Abstract

Using the SST k- model, a numerical investigation was conducted on the convective heat transfer of supercritical pressure CO in horizontal tubes under cooling conditions, analyzing the effects of fluid properties, heat flux, diameter, and buoyancy on the flow and heat transfer characteristics near the pseudo-critical point, and examining the heat transfer mechanism of supercritical pressure CO from the perspective of field synergy. The results indicate that: buoyancy effects induce asymmetric temperature distribution and secondary flow phenomena in the flow cross-section; the convective heat transfer coefficient at the lower wall reaches its peak earlier than that at the upper wall, but its magnitude is smaller; increasing heat flux has a minor effect on the heat transfer coefficient but shifts its peak toward the inlet region; increasing both heat flux and diameter enhances the influence of buoyancy effects on the fluid heat transfer characteristics; and the field synergy principle can explain the non-uniform heat transfer phenomenon at the same cross-section.

Full Text

Preamble

A Study on the Cooling Heat Transfer Mechanism for Supercritical Pressure CO in Horizontal Tubes

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Abstract

The convective heat transfer of supercritical pressure CO in a horizontal tube under cooling conditions is numerically investigated using the SST k- turbulent model. The effects of thermophysical properties, heat flux, tube diameter, and buoyancy on the flow and heat transfer characteristics near the pseudo-critical point are analyzed, and the heat transfer mechanism of supercritical pressure CO is examined from the perspective of field synergy principle. The results show that buoyancy effects cause asymmetric temperature distribution and secondary flow in the cross-section. The peak heat transfer coefficient on the bottom wall appears earlier than that on the top wall, but its value is smaller. Increasing heat flux has minimal influence on the peak heat transfer coefficient but causes the peak to shift toward the inlet section. Larger heat flux and larger diameter both enhance the influence of buoyancy effects on heat transfer characteristics. The field synergy principle can explain the non-uniform heat transfer phenomenon at the same cross-section.

Keywords: supercritical pressure CO ; convective heat transfer; field synergy principle; buoyancy effect; numerical simulation

Introduction

Supercritical CO offers numerous advantages including non-toxicity, non-flammability, chemical stability, and low cost. Due to its dramatic property variations near the critical and pseudo-critical points, supercritical CO exhibits excellent flow and heat transfer characteristics, making it promising for applications in nuclear reactors, solar energy systems, refrigeration systems, and other advanced energy technologies [1, 2]. Compared with conventional constant-property fluids, supercritical CO undergoes severe property variations near the critical region, resulting in unique and complex heat transfer behavior that has become a research focus in recent years [3].

Dang and Hihara [4, 5] investigated the effects of diameter, mass flow rate, and heat flux on convective heat transfer characteristics of supercritical pressure CO in horizontal tubes using experimental and numerical methods, assuming negligible buoyancy effects. Du et al. [6] found that buoyancy effects enhance heat transfer of supercritical pressure CO near the pseudo-critical point in horizontal tubes. Guo Zengyuan et al. [7-9] proposed the field synergy principle, which states that heat source intensity depends not only on fluid properties and velocity but also on the synergy between velocity and temperature gradient fields. When the angle between velocity and temperature gradient vectors is less than 90°, smaller angles yield better heat transfer performance.

This paper employs numerical methods to investigate convective heat transfer characteristics of supercritical pressure CO near the pseudo-critical point (T c = 307.8 K, p = 8 MPa), focusing on analyzing the effects of heat flux, diameter, and buoyancy on local convective heat transfer intensity. The local heat transfer mechanism is examined from the field synergy perspective to provide theoretical foundations for the development and design of high-efficiency heat exchangers.

1.1 Physical Model

Due to severe property variations of supercritical pressure CO , a three-dimensional model is established to accurately simulate local convective heat transfer characteristics in horizontal tubes, as shown in [Figure 1: see original paper]. The model consists of horizontal tubes with diameters of 2, 4, and 6 mm and a total length of 840 mm, comprising a 240 mm adiabatic inlet section and a 600 mm cooling section. This configuration ensures nearly fully developed flow at the cooling section entrance, minimizing inlet effects.

Fig. 1 Physical model

1.2 Governing Equations

The governing equations in Cartesian coordinates are as follows [10, 11]:

Continuity equation:

Momentum equation:

Energy equation:

where Φ represents viscous dissipation and is the turbulent viscosity based on the turbulence model.

1.3 Numerical Methods and Boundary Conditions

Numerical calculations are performed using ANSYS CFX [12]. Thermophysical properties of supercritical CO are calculated using the NIST Standard Reference Database 23 (REFPROP) Version 7 [13], with property data compiled into RGP files and imported into CFX. Compared with linear interpolation methods, RGP files more accurately capture dramatic property variations. The pressure-velocity coupling algorithm and SST k- model are employed. The SST k- model combines the robustness and independence of the k- model with the near-wall accuracy of the k- model. Convergence is achieved when residuals for all governing equations fall below 10 .

Boundary conditions: Mass flow inlet, pressure outlet, adiabatic inlet section walls, and constant heat flux cooling section walls. Operating parameters: mass flux 100-300 $kg/m^2 \cdot s$, pressure 8 MPa, inlet temperature 340.15 K, heat flux 35-45 kW/m^2, inlet Reynolds number approximately 3×10 .

1.4 Grid Independence Verification and Numerical Validation

The computational grid is generated using ANSYS ICEM with radial mesh refinement to ensure near-wall y < 1, satisfying SST model requirements. Grid quality exceeds 0.6, meeting simulation standards. Grid independence verification results are presented in . The relative error in heat transfer coefficient between mesh cases 3 and 5 is 0.2%. Considering computational cost and accuracy, mesh case 3 is selected for subsequent simulations.

Table 1 Mesh independence verification

No.	Mesh count	h (W · m 2 · K 1)	Error (%)
3			
5			0.2

To validate the numerical method, simulation results are compared with experimental data from Dang and Hihara [4] under identical geometric and operating conditions. The comparison shown in [Figure 2: see original paper] reveals a maximum relative error of 13.5%, confirming the accuracy and reliability of the numerical approach.

Fig. 2 Verification of numerical method [4]

2 Field Synergy Principle

For a general three-dimensional model under steady-state conditions without internal heat sources, the integral form of the convective heat transfer energy equation is [7]:

where , c , and k represent fluid density, specific heat at constant pressure, and thermal conductivity, respectively;   is the thermal boundary layer thickness; and q_w denotes wall heat flux.

Neglecting axial heat conduction, Eq. (4) can be written in vector form:

Introducing dimensionless variables:

where u_b and T_b are the bulk velocity and temperature, respectively, and T_w is the wall temperature.

Substituting Eq. (6) into Eq. (5) yields the dimensionless relationship:

where h is the convective heat transfer coefficient, Re_b = u_bd/ is the Reynolds number, and the subscripts b and w denote bulk and wall conditions, respectively. The term U · T can be expressed as:

where is the angle between the velocity vector and temperature gradient vector, known as the field synergy angle.

Equation (7) indicates that for variable-property fluids, Nu_b depends on flow conditions, fluid properties, channel diameter, and the synergy between velocity and temperature gradient fields, making the relationship complex.

3 Results and Discussion

3.1 Effects of Heat Flux on Flow and Heat Transfer

To investigate heat flux effects on supercritical pressure CO flow and heat transfer characteristics, simulations are conducted for a 6 mm diameter tube at heat fluxes of 35 and 45 kW/m², with pressure 8 MPa and inlet temperature 340.15 K.

Figure 3: see original paper presents the axial distributions of bulk fluid temperature (T_b) and local wall temperature (T_w) under different heat flux conditions. The results show that under constant heat flux cooling, both fluid and wall temperatures gradually decrease below the pseudo-critical temperature. The top wall temperature decreases faster than the bottom wall temperature due to buoyancy effects caused by severe density variations of supercritical pressure CO in horizontal tubes, leading to asymmetric wall temperature distribution. Increasing heat flux accelerates fluid cooling and significantly enlarges the temperature difference between top and bottom walls, indicating that higher heat flux enhances buoyancy effects on supercritical pressure CO flow and heat transfer.

Figure 3: see original paper illustrates the axial distribution of convective heat transfer coefficient (h). The heat transfer coefficient first increases to a peak value then decreases along the flow direction, consistent with the temperature dependence of supercritical CO specific heat at constant pressure. The bottom wall heat transfer coefficient reaches its peak earlier than the top wall, but its magnitude is significantly smaller. Under cooling conditions, near-wall fluid is cooled first. Buoyancy drives hotter, less dense fluid upward, resulting in smaller temperature difference between the top wall and bulk fluid, thus yielding higher heat transfer coefficients on the top wall. Increasing heat flux has minimal effect on the peak heat transfer coefficient but advances its location, as higher heat flux reduces fluid temperature more rapidly toward the pseudo-critical point where the heat transfer coefficient peaks.

Fig. 3 Distributions of (a) temperature and (b) convective heat transfer coefficient along the tube at different heat fluxes

3.2 Effects of Buoyancy on Flow and Heat Transfer

[Figure 4: see original paper] shows the local Nusselt number (Nu_b) distribution at different heat fluxes. The Nu_b peak increases slightly with heat flux, indicating that higher heat flux enhances convective heat transfer intensity. [Figure 5: see original paper] presents the corresponding local field synergy angle distribution. The field synergy angle varies non-uniformly along the tube, with smaller angles near the top wall compared to the bottom wall, demonstrating better synergy between velocity and temperature gradient fields near the top wall and thus superior heat transfer characteristics. Under identical conditions, the difference in field synergy angles between top and bottom walls increases with heat flux, suggesting that higher heat flux amplifies the non-uniformity of convective heat transfer fields induced by buoyancy effects.

To more intuitively understand buoyancy effects on supercritical pressure CO heat transfer characteristics, simulations are performed without gravity (g = 0) and compared with cases including gravity (g_y = -9.81 m/s²).

[Figure 6: see original paper] demonstrates gravity effects on Nu_b distribution. Local convective heat transfer intensity is slightly higher with gravity than without, indicating that buoyancy induced by gravity enhances heat transfer, primarily in the latter half of the cooling section where bulk fluid temperature is below the pseudo-critical temperature. Buoyancy effects become more pronounced with increasing heat flux. [Figure 7: see original paper] shows the corresponding local field synergy angles. The field synergy angle without gravity is smaller than with gravity, suggesting that for supercritical fluids with dramatic property variations, application of the field synergy principle cannot be simply attributed to decreasing synergy angles; multiple influencing factors must be considered comprehensively.

[Figure 8: see original paper] presents the axial distribution of equivalent heat source (- c_pU · T) with and without gravity. The equivalent heat source with gravity is significantly larger than without gravity, and its distribution is non-uniform along the tube, increasing with heat flux. According to Eqs. (5) and (7), larger equivalent heat source enhances heat transfer intensity. The equivalent heat source depends not only on velocity, temperature, and their included angle, but also on fluid properties. For supercritical CO with severe temperature-dependent property variations, these property changes become the dominant factor influencing flow and heat transfer characteristics.

Fig. 4 Distribution of Nu_b along the tube at different heat fluxes
Fig. 5 Distribution of along the tube at different heat fluxes
Fig. 6 Distribution of Nu_b along the tube with or without gravity
Fig. 7 Distribution of along the tube with and without gravity
Fig. 8 Distribution of - c_pU · T along the tube with and without gravity

3.3 Effects of Tube Diameter on Flow and Heat Transfer

To investigate diameter effects on supercritical pressure CO heat transfer characteristics, simulations are conducted for tubes with diameters of 2, 4, and 6 mm at heat flux 45 kW/m², pressure 8 MPa, inlet temperature 340.15 K, and constant inlet Reynolds number of 3×10 .

[Figure 9: see original paper] shows Nu_b distributions for different diameters. Before reaching the peak, Nu_b increases with diameter; after the peak, Nu_b decreases gradually and diameter effects become less significant. The corresponding field synergy angle distribution is presented in [Figure 10: see original paper]. Before fluid temperature reaches the pseudo-critical point, the field synergy angle decreases significantly with increasing diameter, indicating that larger diameter improves synergy between velocity and temperature gradient fields, thereby enhancing heat transfer intensity. When fluid temperature is below the pseudo-critical temperature, diameter has minimal influence on both field synergy angle and heat transfer coefficient.

[Figure 11: see original paper] illustrates temperature, radial velocity, and field synergy angle distributions at the z = 390 mm cross-section for supercritical CO cooling in 2 mm and 6 mm diameter tubes. The temperature distribution is asymmetric, with hotter, less dense fluid accumulating in the upper region and cooler, denser fluid concentrating at the bottom. Buoyancy-induced secondary flow enhances fluid mixing. Field synergy angles are also non-uniformly distributed, with smaller angles in the upper region compared to the bottom. As diameter decreases, temperature and field synergy angle distributions become more uniform, and secondary flow intensity diminishes.

Fig. 9 Distribution of Nu_b along the tube with different diameters
Fig. 10 Distribution of along the tube with different diameters
Fig. 11 Distributions of temperature, velocity and field synergy angle on cross section

Conclusions

This paper numerically investigates convective heat transfer characteristics of supercritical pressure CO in horizontal tubes under cooling conditions. The main conclusions are:

(1) Buoyancy effects cause asymmetric temperature distribution in the cross-section. At the same cross-section, the top wall temperature is higher than the bottom wall. Near-wall fluid is cooled first, creating significant density differences that induce secondary flow.

(2) The bottom wall heat transfer coefficient reaches its peak earlier than the top wall, but its magnitude is smaller. The field synergy angle at the top of the cross-section is smaller than at the bottom.

(3) Increasing heat flux shifts the heat transfer coefficient peak toward the inlet section. Both increasing heat flux and diameter enhance buoyancy effects on heat transfer characteristics.

(4) Compared with the g = 0 case, gravity (g_y = -9.81 m/s^2) yields larger field synergy angles but also larger equivalent heat source, resulting in higher heat transfer intensity.

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