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Effect of pressure on heat transfer between supercritical CO_2 in tube and pulverized coal combustion flue gas

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ABSTRACT

To further improve the thermal efficiency of coal-fired boilers, lower the environmental impact, and minimize the size of system components, the potential utilization of supercritical CO_2 (S-CO_2) as the working fluid has drawn considerable attention recently. In this study, the thermal characteristics between supercritical CO_2(S-CO_2) in a vertically upward tube and the flue gas in the combustion chamber were investigated numerically using the standard k-ε model, the P-1 radiation model, and the conjugate heat transfer model. The effects of the S-CO_2 pressure on the surface heat flux, the wall temperature, the bulk temperature, the bulk velocity, the surface heat transfer coefficient, and the Nusselt number were examined. The distributions of the flue gas temperature and S-CO_2 temperature were further elaborated. The results show that the supercritical pressure has a significant effect on the S-CO_2 tube wall temperature, the wall temperature is higher under a low S-CO_2 pressure. The wall heat flux is dominated by connection in the entrance region of the tube but is contributed by both convection and radiation at larger axial distances. The heat transfer coefficient increases with increasing the supercritical pressure, and the supercritical pressure has slight impact on the tube wall temperature. The present numerical study helps gain improved understanding of the thermal performance and optimize the design of boilers using S-CO_2 as the working fluid.

1. Introduction

Supercritical flows have been widely applied to enhance the efficiency of the fossil-fuel steam generators to avoid the problems associated with the occurrence of the critical heat flux due to the liquid-vapor phase transition. Recent studies showed that when the steam in the Rankine cycle is replaced with CO_2, the system thermal efficiency would be improved substantially. Since the critical temperature and pressure of CO_2 are only 31 °C and 7.38 MPa, respectively, it is feasible and attractive to use supercritical CO_2 (S-CO_2) to further enhance the system thermal efficiency. When S-CO_2 is used as the working fluid, the system, namely, the Brayton cycle, possesses the advantages of being compact and safe, requiring less operations of deoxidize and desalination, as well as lowering pollutant emissions [1].

Many studies have been conducted to investigate the heat transfer characteristics of S-CO_2 in tubes [2]. Kimet al. experimentally studied the heat transfer process for circular/non-circular tubes under the conditions of constant heat flux [3]. Their results showed that tube size and shape has a great effect on the heat transfer process; an earlier peak of the wall temperature appeared in the case of non-circular tubes. Song et al. [4] explored the criterion of the similarity of heat transfer of supercritical fluid flow in the vertical pipes with the internal diameter of 4.4 and 9.0 mm. It was also noted that the flow in the larger diameter case is more susceptible to the reduction in heat transfer due to the buoyancy effect. Liao et al. obtained similar results for S-CO_2 in heated horizontal and vertical miniature tubes, and it was observed that the buoyancy effects were significant for all the flows [5,6].Cheng et al. examined the buoyancy effect on the wall temperature distribution by numerical simulations [7]. Pandey et al. concluded that the combined effects of deceleration and buoyancy in the upward flow enhance the heat transfer while the heat transfer in the downward flow is deteriorated [8]. Liu et al. performed numerical investigation of the buoyancy effect on heat transfer to carbon dioxide in a tube at the supercritical pressure [9]. Cai et al. [10] analyzed the heat transfer process by various turbulence models, and it was found that the Prandtl number has a strong effect on the heat transfer process. Khivsara et al. researched the heat transfer characteristics of S-CO_2 by considering the combined effects of convection and radiation and pointed out that neglecting the effects of radiative heat transfer can lead to large errors in predicting the wall temperature [11]. Chen et al. found that the heat transfer performance was strongly dependent on the operation pressure for natural circulation loop [12].

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Nomenclature

$C_1\varepsilon, C_2\varepsilon$	constant
d	tube diameter, mm
G	mass flow rate, $kg \cdot m^{-1}$
h	total enthalpy, $J \cdot kg^{-1}$ heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
q_1	convection heat flux, $w \cdot m^{-2}$
S_h	source term ($w \cdot m^{-3}$)
T	temperature, K
U	velocity, m·s-1

Greek symbols

β	thermal expansion coefficient
κ	turbulent kinetic energy, $m^2 \cdot s^{-2}$
μ	Viscosity, Pa·s
ρ	Density, $kg \cdot m^{-3}$

Abbreviations

S-CO_2	supercritical CO_2
Re	Reynolds number

subscripts

fluegas	flue gas
i,j	direction axis
w	wall
C_p	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
G_k	turbulent generation rate
P	supercritical pressure, $N \cdot m^{-2}$
q_2	radiation heat flux, $w \cdot m^{-2}$
S_{ij}	shear strain rate
t	time, s
x	coordinate axis
ε	turbulent dissipation rate, $m^2 \cdot s^{-3}$
λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
μ_t	turbulent viscosity (Pa·s)
σ_k, σ_ε	constant
Pr	Prandtl number
in	inlet
b	bulk
ref	reference temperature

To date, most previous studies have discussed the thermal behaviors of S-CO_2 under conditions of either constant wall temperature or constant heat flux and in S-CO_2 small-sized tubes and the flow and heat transfer of the S-CO_2 tube containing S-CO_2 near the critical region have been widely investigated. For the S-CO_2 boiler with coal burning, the heat transfer characteristics between the flue gas and S-CO_2 tube are important for the design of S-CO_2 boilers and the selection of tube materials with the flue gas temperature greater than 1000 K. However, little work has been done to investigate the flow and heat transfer characteristics of S-CO_2 tube in boilers under realistic heat transfer boundary conditions at the tube surface. Yang et al. analyzed the effect of flame temperature on the wall temperature distribution by numerical simulation of the coupled heat transfer between combustion and fluid heating of a 300 MW S-CO_2 boiler by simplified the heat transfer process as a 1-D case [13]. This paper investigates the effects of the supercritical pressure on the heat transfer coupling between S-CO_2 in the tube and the flue gas to gain insights into the thermal characteristics of boilers using S-CO_2 as the working fluids. A 3-D numerical model of coupled flow and heat transfer between S-CO_2 in the tube and flue gas outside the tube is developed. The effects of the S-CO_2 pressure on the flow and heat transfer between a vertical S-CO_2 tube carrying S-CO_2 and the flue gas are assessed in terms of the surface heat flux, the wall temperature, the bulk temperature, the bulk velocity, the surface heat transfer coefficient, and the Nusselt number. The present study provides a better quantitative understanding of the thermal performance of power plants using S-CO_2 as the working fluid. Moreover, the findings of this study would enrich the flow and heat transfer knowledge of S-CO_2 in the tube that is highly valuable for the conceptual design of S-CO_2 boilers.

2. Physical and mathematical model

The model simulated in this study is shown schematically in Fig. 1. The fluid flow inside the S-CO_2 tube is regarded as axisymmetry and steady state. To take advantage of the axisymmetric nature of the problem under consideration, only one quarter of the geometry is modeled to save computational resources in the numerical simulation. The central tube carrying S-CO_2 is made of stainless steel and has an inner diameter of 0.04 m with a thickness of 0.006 m and the length considered in the simulation is 3 m. The flue gas of pulverized coal combustion (the combustion process is not included in the present study) with the temperature of 1373 K flows through the annulus. The physical properties of flue gas were evaluated according to the gas composition. The thermodynamic properties of S-CO_2 were obtained at the supercritical pressure of 15, 20, 25 and 32 MPa using the NIST refrigerants database as showed in Fig. 2 [14].It can be seen clearly that the pressure has a great influence on the density compared to the specific heat, thermal conductivity, and dynamic viscosity. In addition, it is also evident that all the thermodynamic properties of S-CO_2 increase with the supercritical pressure.

The physical model consists of the governing equations of continuity, momentum, energy, and the standard k-ε equation in a Cartesian coordinate system, which is used to describe the flow and heat transfer in the S-CO_2 tube:

$$\frac{\partial(\rho U_i U_j)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho U_i U_j)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_i}\right)\right] + \rho\beta g_i (T_{ref} - T) \tag{2}$$

$$\frac{\partial(\rho h U_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\lambda}{c_p} + \frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial h}{\partial x_j}\right] + S_h \tag{3}$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k - \rho\varepsilon \tag{4}$$

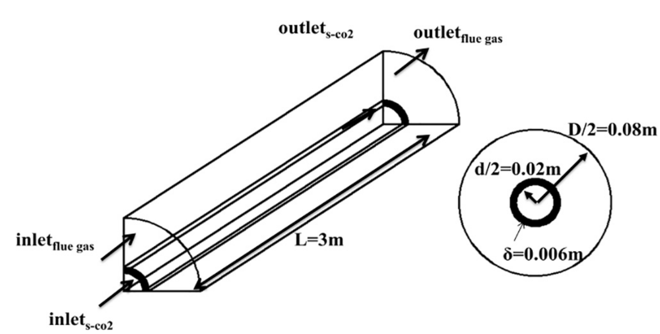

Fig. 1. Schematic of the model tube simulated in this study. S-CO_2 flows in the central tube and the flue gas of pulverized coal combustion flows in the co-annular region.