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Experimental research on internal convection heat transfer of supercritical pressure CO2 in porous media

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EXPERIMENTAL RESEARCH ON INTERNAL CONVECTION HEAT TRANSFER OF SUPERCRITICAL PRESSURE CO_2 IN POROUS MEDIA

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ABSTRACT

The flow and heat transfer of fluids at supercritical pressure in porous media has attracted much attention due to its extensive applications, such as supercritical water-cooled nuclear reactor, CO_2 gas cooled reactor, transpiration cooling and supercritical CO_2 solar thermal power generation system. There are mainly two theories to describe convection heat transfer in porous media, i.e., the local thermal equilibrium model (LTE) and the local thermal non-equilibrium model (LTNE). Compared with LTE model, the LTNE model is a more detailed model that uses two energy equations to describe heat transport in the solid and fluid. The internal heat transfer coefficient is a key parameter for LTNE model which has been studied thoroughly and many correlations have been proposed. However, for the fluids at supercritical pressure, the thermophysical properties vary widely near the pseudo-critical point, which significantly impacts the internal convection heat transfer of the fluid flowing through the porous media. Therefore, we conducted an experimental study aiming to evaluate the internal convection heat transfer of supercritical pressure CO_2 in porous media. The experimental test section was designed with confining pressure to prevent the fluid from flowing through the gap between the sample and holder wall. The internal convection heat transfer coefficients between particles and CO_2 in the sintered bronze porous media with average diameters of 0.5 mm and porosities of 0.42 were determined experimentally.

INTRODUCTION

The thermal hydraulic characteristics of supercritical pressure fluids in porous media has attracted much attention in recent years, due to its extensive applications, such as supercritical water-cooled nuclear reactor, supercritical carbon dioxide gas cooled reactor, transpiration cooling and supercritical carbon dioxide solar thermal power generation system [1-4]. A perspective understanding and a precise numerical simulation model for convection heat transfer of fluid at supercritical pressures in porous media is quite important and essential for engineering applications.

In recent years, some researchers have studied the friction factor and local heat transfer coefficients of CO_2 at supercritical pressure in porous media experimentally, such as vertical sintered porous tubes with particle diameters of 0.1–0.12 mm and 0.2–0.28 mm [5-7], tubes partially filled with metal foam [8], silica sand packed bed [9]. For numerical simulations in porous media, the local thermal equilibrium model (LTE) and the local thermal non-equilibrium model (LTNE) have been widely used in the numerical investigations of convection heat transfer in porous media. Jiang et al presented a numerical model for modeling upward flow and the convective heat transfer of in a vertical porous annulus of water at supercritical [10]. On the basis of the experimental data [5-7], Jiang et al [7] and Fard [11] respectively established and validated a numerical model with the local thermal equilibrium model for describing the heat transfer in the porous media.

The internal heat transfer coefficient, hsf, is of prime importance in the local thermal non-equilibrium model for describing the heat transfer between the solid matrix and fluid in a representative volume element. A variety of experimental investigations have been published to study the internal heat transfer coefficient in porous media, under either steady-state or unsteady-state conditions. As for steady-state experiments, some single spheres or the whole porous media are heated electrically or electromagnetic induction and the heat flux, the particle temperature and the surrounding fluid bulk temperature are measured. Glaser and Thodos [12] heated the particles by passing electric current directly through the bed of metal spheres and the heat transfer coefficient for gas flowing through the packed bed was calculated directly by temperature measurements of both gases and solids within the bed. Meng et al. [13] used the electromagnetic induction heating method to heat the steel spheres stacked bed with diameters of 3 mm and 8 mm, and the local and average heat transfer coefficients were calculated. Jiang and Xu [14-15], Nsofor and Adebiyi [16], Schroder [17] obtained the heat transfer coefficients according to the transient temperature response and the energy balance of solid particles on a basis of the lumped capacitance heat transfer assumption. The transient single-flow method is a popular and classical one-dimensional reverse technique to determine the volumetric heat transfer coefficients between the gas and the porous media, such as sintered porous media [14-15], ceramic foam [18], metal foams [19], and packed beds [20]. In general, the internal heat transfer coefficients in the porous media have been investigated extensively since the 1940 s, and the numerous studies were well summarized and reviewed by Wakao [21], Achenbach [22], Gnielinski [23] at different periods. The previous experiments were almost carried out for determining the internal heat transfer of gas or water flowing in porous media without consideration of the variations of the fluid properties. However, under supercritical pressures, the thermophysical properties of fluid vary widely near the pseudo-critical point. Even with small variations of temperature and pressure, the variations of thermophysical properties and the buoyancy caused by sharp variations of density and flow direction would cause great change on the internal heat transfer coefficient in porous media. Thus, for fluid at supercritical pressure flowing in porous media, the discrepancy of heat transfer performance will occur when these existing correlations of heat transfer coefficient are applied to the LTNE model.

Guardo et al. analyzed the mixed (i.e., free + forced) convection at high pressure (with supercritical CO_2 as the circulating fluid) in a fixed bed by using the geometrical model composed of 44 homogeneous stacked spheres and the turbulent model validated in the previous study [24]. The effect of density gradients, flow stability, flow direction and flow velocity on the velocity distribution and the heat transfer performance were analyzed and a novel correlation was presented for estimating the particle-to-fluid heat transfer coefficient at high pressures, but no experimental data is available for high pressure situations or supercritical fixed bed reactors [25, 26]. Liu et al. experimentally investigated the heat storage and heat transfer behavior of compressed air flowing through a rock bed under the conditions of low pressure and supercritical pressure. And the particle-to-air heat transfer coefficients (force + opposing free convection) were derived based on the unsteady-state measurements and the Schumann model. Thus it can be seen from the few relative studies that the influence mechanism of fluid properties, flow direction and other factors on the internal heat transfer coefficient hsf, have not been investigated thoroughly for mixed convection heat transfer of fluid at supercritical pressures in porous media. For example, the sharp variations of thermophysical properties and the buoyancy caused by sharp variations of density and flow direction would cause great change on the internal heat transfer coefficient in porous media. Moreover, the tortuosity caused by complex flow path in porous media will influence the turbulence kinetic energy of the flow and affect the heat transfer indirectly. In addition, a comprehensive correlation of internal heat transfer coefficient for fluid at supercritical pressure in porous media is essential for the practical applications.

In the present research, an experimental system was designed to evaluate the internal convection heat transfer of CO_2 at supercritical pressures p=8 MPa in sintered bronze porous media with average particle diameters 0.5 mm. The confining pressure was designed to prevent the fluid from flowing through the gap between the porous media and holder wall. With the lumped capacitance method, the internal convection heat transfer coefficients between particles and CO_2 was derived from the measured temperature profiles of fluid and solid matrix at the inlet and outlet. The effect of fluid pressures and temperatures, flow direction and flow velocity on the average internal heat transfer coefficients were analyzed. The influence of sharp variations of thermophysical properties of CO_2 at supercritical pressures and the buoyancy effect on the average Nusselt number were analyzed.

NOMENCLATURE

a = Surface area of particles per unit volume in porous media
c = Isobaric specific heat, J/kg·K
d = Particle diameter, m
c = Isobaric specific heat, J/kg·K
Nu = Nusselt number
Pr = Prandtl number
Re = Reynolds number
T = Temperature, °C
t = time, s
u = Darcy velocity, m/s
h_{sf} = Internal heat transfer coefficient
x = x coordinate, m

Greek Symbols

ε = Porosity
ρ = Density, kg/m^3
λ = thermal conductivity, W/m·K

Subscripts

f = Fluid
p = Particle
s = Solid

1 Experimental system and method

1.1 Experimental system

The experimental system for the investigation of CO_2 at supercritical flow and heat transfer in sintered porous media is presented in Fig. 1. The system, which has a maximum temperature of 280 °C and maximum fluid pressure of 14 MPa, was improved based on a system previously described [5, 27]. The pre-heater on the flow circulation path was designed to heat the fluid and ensured the difference of the fluid temperature at the inlet and the initial porous temperature over a reasonable range. the core-holder containing a sintered porous media sample could be placed horizontally or vertically, in order to study the effect of flow direction on the heat transfer. The schematic diagram of test section is shown in Fig. 2 (a).

An phenylmethyl silicone oil bath in the high pressure vessel was heated by a band heater around the outside wall. The vessel was wrapped in an asbestos-aerogel double insulation jacket. The oil bath was used as a sample heater, which could heat the sample up to the desired temperature. Moreover, the oil bath provides confining pressure to prevent supercritical pressure fluid from flowing through the gap between the sample and the copper tube. The core holder with physical and chemical seal, could achieve multiple temperature measurements under high pressure environment with fine wire duplex insulated thermocouples, improving unsteady measurement accuracy.

The detail structures of peek holders and sample were addressed in Fig. 2(b). The peek holders were insulated and sandwiched between the steel core holders and the sample. The grooves on the inlet core holder and the steel mesh net make the fluid from the tube more uniform before the porous media. The thermocouples for measuring the fluid temperatures at the inlet and outlet of the sample were located immovably at the relative narrow grooves. The thermocouples for measuring the local particle temperatures were welded with pressure on the inlet and outlet surfaces of the sample. And then these thermocouples were extracted through the holes on the core holders and sealed with special element and glue. The sample was a bronze sintered porous media with diameter of 50 mm and thickness of 2 mm. The detailed structure of the sample was quite uniform and homogeneous. The average diameter of the particle is 0.5 mm with relative discrepancy less than 5%. The porosity was 0.41 measured by mercury injection apparatus. The thermal conductivity of the particle was measured as 54 W/m/K, and the specific heat was 355 J/kg/K.

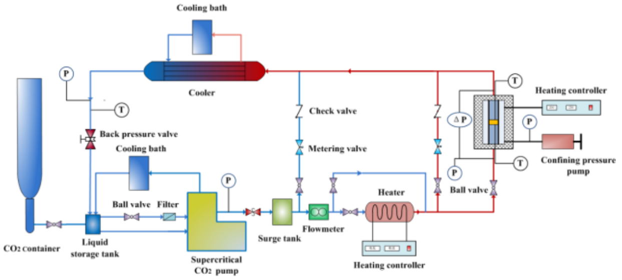
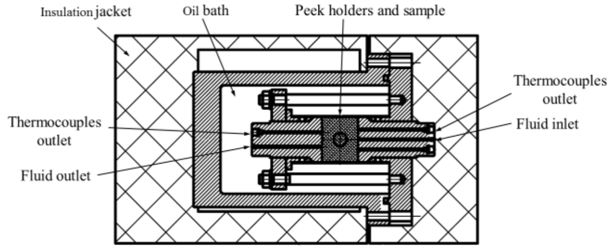
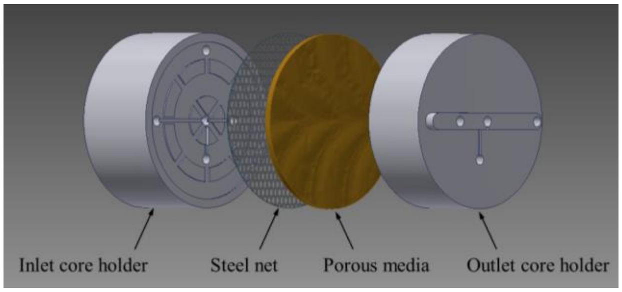


Figure 1: SCHEMATIC DIAGRAM OF EXPERIMENTAL SYSTEM



(a) TEST SECTION



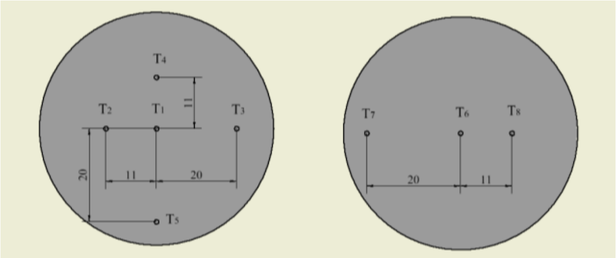
(b) PEEK HOLDERS AND SAMPLE

Fig. 2 SCHEMATIC DIAGRAM OF (A) TEST SECTION AND (B) PEEK HOLDERS AND SAMPLE

1.2 Experimental method

During the experimental period, CO_2 liquid from the container was pressured to a desired pressure by adjusting a supercritical pressure pump and back pressure valve. The CO_2 at supercritical pressures was heated by the preheater and then flowed through the bypass path while the main path was turned off. Once the variations of CO_2 flow rate, inlet pressure variations and CO_2 temperature were within ±0.1% for at least 20 min, the flow was switched from the bypass path to the main path. The heated CO_2 flowed through the sample and all parameters of the transient process were simultaneously recorded by the data acquisition system.

The measured parameters included the porous media temperatures, the fluid temperatures at inlet and outlet, the inlet pressure, the pressure drop across the test section, and the mass flow rate. The temperatures were measured by Omega T-type thermocouples with a diameter of 0.127 mm. The specific locations of the thermocouples on the inlet and outlet surface of the sample are presented in Fig. 3. The inlet fluid temperature was measured averagely by three thermocouples located at the grooves of the inlet peek holder. And the outlet fluid temperature was measured on the average by two thermocouples before sufficiently mixing in the outlet peek holder. The CO_2 inlet pressure was measured by a pressure transducer (Model EJA430A, Yokogama Sichuan, China) and the pressure drop through the test section was measured by two differential pressure transducers set to different measuring ranges according to the experimental conditions (Model EJA110A, Yokogama Sichuan, China, Model RoseMount3051CD, Emerson, USA). The mass flow rate was measured using a Coriolis-type mass flowmeter (Model MASS6000, Siemens, Germany) with the range set at 20 kg/h. An Agilent data acquisition system (Model 34972A, Agilent, USA) recorded and displayed the experimental data.



(a) Inlet surface (b) Outlet surface

Figure 3: THE THERMOCOUPLES LOCATIONS ON THE INLET AND OUTLET SURFACE OF THE POROUS MEDIA

2 Data reduction method and uncertainty analysis

2.1 Data reduction method

According to the previous literature [14, 15, 27], as the Biot number is small in the experimental cases, the assumption of the uniform solid particle temperature of porous media at any time is valid. The energy governing equations of solid and fluid at local non-equilibrium condition are showed as follow:

$$\text{Fluid: } \frac{\partial}{\partial t}\left(\varepsilon\rho_f c_f T_f\right)+\frac{\partial}{\partial x}\left(\rho_f c_f u T_f\right)=a h_{sf}(T_s-T_f) \quad (1)$$

$$\text{Solid: } \left(1-\varepsilon\right)\rho_s c_s \frac{dT_s}{dt}=-a h_{sf}(T_s-T_f) \quad (2)$$

Where T_f and T_s are the temperature of solid and fluid, respectively. $a=\frac{6\left(1-\varepsilon\right)}{d_p}$ is the surface area of particles per unit volume of porous media, d_p is the particle diameter. Eq. (1) describe the convective heat transfer of CO_2 in porous media with consideration of thermophysical properties variations. As the properties of the bronze sintered porous media is constant, the Eq. (2) is used for calculating the internal heat transfer coefficient h_{sf} and the Nusselt number Nu_{sf}, as shown in Eq. (3) and Eq. (4). The transient porous media surface temperature response and the fluid temperatures at the inlet and outlet were recorded with time. The temperature differences of the eight thermocouples measurement results can be ignored and the arithmetic average of these solid temperatures was adopted. The fluid temperature in Eq. (3) was obtained by arithmetic averaging the inlet temperature and outlet temperature. Thus, the internal heat transfer coefficient obtained by using this data reduction method is the description of overall internal convection heat transfer performance in porous media.

$$h_{sf}=\frac{\rho_s c_s d_p}{6(T_s-T_f)}\frac{dT_s}{dt} \quad (3)$$

$$\mathrm{Nu}_{sf}=\frac{h_{sf} d_p}{\lambda_f} \quad (4)$$

2.2 Uncertainty analysis

The maximum measurement uncertainties of internal heat transfer coefficient and Nusselt number in the experiments can be estimated by Eq. (5) and (6). The uncertainties of density and heat capacity of the particle material can be assumed 0.0%. The uncertainties of fluid properties in Eq. (6) were calculated from the NIST software, which is assumed quite accurate [29]. The relative error of particle diameter can be estimated 5.0% from the SEM figure of the porous media, as shown in Fig. 3. The accuracy of the thermocouples measuring the fluid and wall temperatures was within ±0.15 °C, as calibrated by the National Institute of Metrology, China. And the minimum temperature is 30 °C, so the relative error of the solid temperature variations with time is estimated as 0.5%. The relative error of the temperature difference between solid and fluid. The minimum difference from our experiments was 1.5 °C, and the relative error can be calculated as 14.3%. Therefore, the maximum relative uncertainty of internal heat transfer h_{sf} and Nu_{sf} can be estimated as 15.1% and 15.9%, respectively.

$$\left|\frac{\delta h_{sf}}{h_{sf}}\right|=\left[\begin{array}{l}\left(\frac{\delta\rho_s}{\rho_s}\right)^2+\left(\frac{\delta c_s}{c_s}\right)^2+\left(\frac{\delta d_p}{d_p}\right)^2+\left(\frac{\delta(T_f-T_s)}{(T_f-T_s)}\right)^2\\ +\left(\frac{\delta\frac{dT_s}{dt}}{\frac{dT_s}{dt}}\right)^2\end{array}\right]^{1/2} \quad (5)$$

$$\left|\frac{\delta\mathrm{Nu}_{sf}}{\mathrm{Nu}_{sf}}\right|=\left[\left(\frac{\delta h_{sf}}{h_{sf}}\right)^2+\left(\frac{\delta d_p}{d_p}\right)^2+\left(\frac{\delta\lambda_f}{\lambda_f}\right)^2\right]^{1/2} \quad (6)$$

3 Results and discussions

Three experimental cases were carried out with initial porous media temperature 38 °C and fluid pressure 7.6 MPa, at which CO_2 was at supercritical pressure. The cold fluid with three mass flow rates were adopted to cool the porous media, which was heated initially to a desired temperature by the heating controller. The vatiations of temperatures of particle surface and fluid at the inlet and outlet is shown in Figure 4. From this figure, it is noted that the temperature differences of particle solid between the inlet surface and outlet surface are small, especially for mass flow rate 3.48 kg/h. Therefore, the fundamental assumption that the solid temperature in porous media is uniform at any time has been validated. Moreover, the difference between temperature of fluid at the inlet and temperature of fluid at the outlet are not quite large, so the arithmetic average fluid temperature of fluid at inlet and outlet can be used. The average temperatures of solid and fluid variations with time are presented in Figure 5.

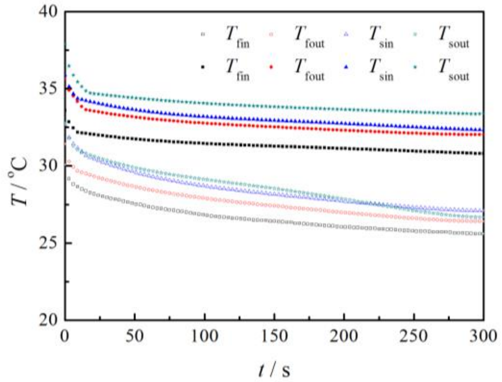


Figure 4: THE TEMPERATURES OF SOLID SURFACE AND FLUID AT THE INLET AND OUTLET (Hollow: 3.48 kg/h; Solid: 1.12 kg/h)

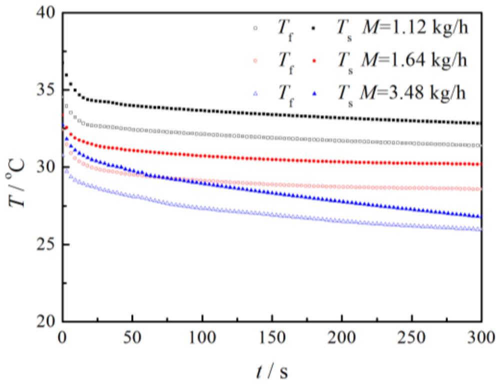


Figure 5: THE AVERAGE TEMPERATURES OF SOLID SURFACE AND FLUID AT THE INLET AND OUTLET

The differences between the average solid temperature and fluid temperature are shown in Figure 6. It is shown that the temperature difference 1.5 ºC with mass flow rate 1.12 kg/h and 1.64 kg/h can be holded during the experimental time, whereas for the case with 3.48 kg/h, the temperature difference decreases with time. The thermal equilibrium state is achieved more easily with relative larger mass flow rate. This is because that the internal heat transfer performance is more intense, and the average Nusselt number is larger for larger particle Renolds number, as shown in Figure 7. The experimental results showed relatively corresponding to the equation in the literature [30], and the data reduction method in this paper has been verified with fluid at supercritical pressures.

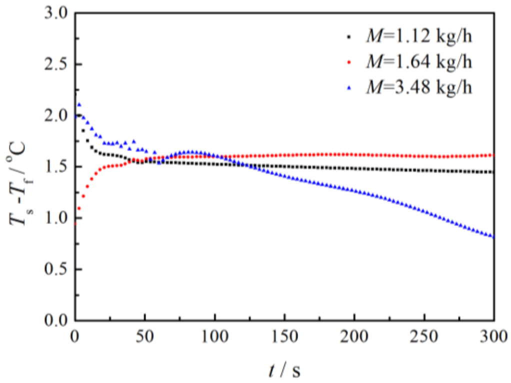


Figure 6: THE AVERAGE TEMPERATURE DIFFERENCE OF SOLID SURFACE AND FLUID

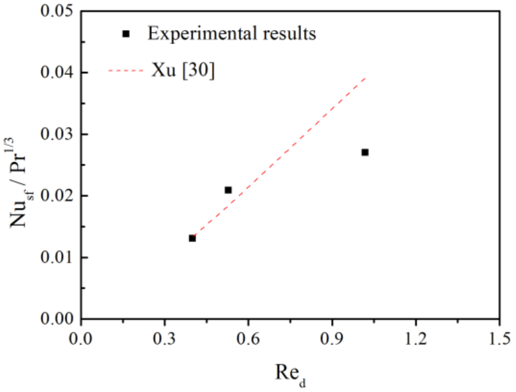


Figure 7: AVERAGE NUSSELT NUMBER

CONCLUSIONS

The experimental test section was designed with confining pressure to prevent the fluid from flowing through the gap between the sample and holder wall under supercritical pressures. The internal convection heat transfer coefficients between particles and CO_2 in the sintered bronze porous media with average diameters of 0.5 mm and porosities of 0.42 were determined experimentally. The data reduction method for internal heat transfer coefficient has been validated. More experimental cases will be carried out to study the effect of fluid properties, buoyancy force and flow direction on the internal heat transfer performance in porous media.

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