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Investigation on Local Thermal Non-Equilibrium Effect for Convection Heat Transfer of Supercritical CO_2 in Porous Ceramic Medium

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***Abstract* -** Supercritical convection heat transfer in porous mediums are attractive in various new applications, and local thermal non-equilibrium effect is one of the major thermal effects for porous heat transfer under macroscopic scale study. However, conventional studies were developed based on constant property fluids, which is doubtful for supercritical fluids with non-linear thermophysical properties. In this study, supercritical CO_2 heat transfer through a porous ceramic medium, C/SiC composite material, is conducted experimentally. The experimental data under various operating parameters including inlet temperature, mass flow rate, pressure, are further combined with a numerical model to figure out the solid-fluid heat transfer coefficient and the local thermal non-equilibrium effect between supercritical CO_2 and porous ceramic medium. The results show that the local thermal non-equilibrium effect exists widely, and the local thermal equilibrium can only exist under some specific cases, reminding the importance of local thermal non-equilibrium effect for numerical modeling of supercritical CO_2 flow in porous ceramic medium. Besides, all the local thermal equilibrium cases appear near pseudo-critical temperature region, but not vice versa, with the addition of the failure of conventional criteria, implying more complicated heat transfer mechanisms occur due to dramatic thermophysical property changes. This study will be a useful base for clarifying heat transfer mechanisms of supercritical fluids flow through porous medium.

***Keywords*:** local thermal non-equilibrium effect, supercritical CO_2, porous medium, convection heat transfer

1. Introduction

Supercritical fluids are becoming increasingly attractive as working fluids for extracting or releasing thermal energy in various applications related to porous medium, like enhanced geothermal system (EGS) [1], the 3rd generation concentrated solar energy power plant (CSP3) with particle receiver and thermal storage [2], transpiration cooling in high speed hypersonic vehicles [3], etc. Unlike other fluids like water or air, supercritical fluids behave non-linear variation of thermophysical properties as Fig.1 shows, i.e. the pulse-type variation for specific heat and the step-type variation for density and viscosity. New heat transfer characteristics can be observed for convection process in porous medium, the researchers like Jiang et al [4], Hsieh et al [5], and Kkihlefa et al [6], experimentally found the heat transfer peak exist in some conditions caused by the sharp variation of specific heat, and the effect factors on heat transfer show complexity and non-linearity under the influence of dramatic properties, buoyancy effect, thermal boundary, etc. It is crucial to figure out the heat transfer mechanisms between supercritical fluids and porous medium.

Local thermal non-equilibrium (LTNE) effect is one of the major thermal effects for porous heat transfer under macroscopic scale study, as it reflects whether the temperature of the fluid phase and the solid phase in the representative elementary volume (REV) is the same or not, which is quite important to establish suitable energy model to describe thermal transport accurately. Conventional studies have developed several criteria to estimate LTNE or local thermal equilibrium (LTE) [7, 8], and related solid-fluid heat transfer coefficient correlations for modelling [9, 10], however, due to the abnormal properties lead by supercritical fluids, the existing conclusions originated from constant property fluids should be further verification and modification.

In this study, a natural working fluid, supercritical CO_2, applied in lots of new energy systems, is forced to convect through a porous ceramic medium, C/SiC composite material, which is superior in transpiration cooling, by experiments. The data obtained from experiments under various operating parameters like inlet temperature, mass flow rate, pressure, are further combined with a numerical model to figure out the LTNE effect between supercritical fluids and porous ceramic medium.

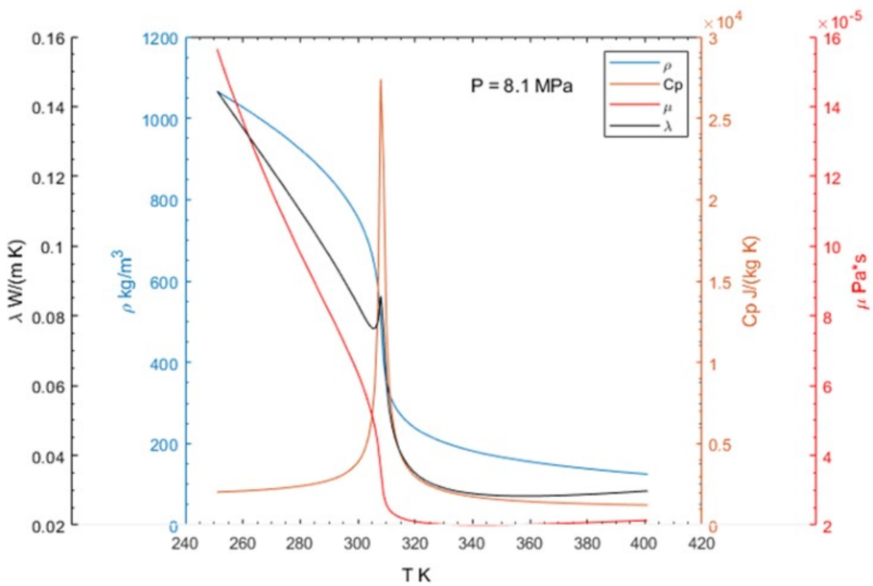

Fig. 1: Non-linear thermophysical properties of supercritical fluids (CO_2, P=8.1 MPa).

2. Methodology

The LTNE effect will be conducted based on experimental data combined with numerical model. Operating parameters, like inlet temperature T_{in}, mass flow rate m, wall temperature T_w, with the addition of output parameters like outlet temperature T_{out}, are measured from the experimental apparatus for convection heat transfer of supercritical CO_2 flow through C/SiC composite porous material. Then the obtained parameters are used as boundary conditions for the numerical model to get the solid-fluid heat transfer coefficient h_{sf} to evaluate LTNE effect. The experiment system and numerical model are briefly introduced below.

2.1. Experimental system

Fig. 2 shows the experimental system which can regulate and maintain high precision temperature and pressure for supercritical CO_2 heat transfer test through porous samples in the clamping test module. After being pressurized to the needed operating pressure by injection pump, CO_2 flows through the preheater being heated to the required temperature in the set state. The key component in this experimental system is the clamping test module, in which the supercritical CO_2 flows through the heated test porous sample, i.e. C/SiC composite material. Local fluid and wall temperature as well as pressure are obtained via data acquisition system, after the flow and heating process being stable for 10 min.

The test sample used in the present study is a 2.5-D carbon fabric reinforced SiC composite, with the diameter of 25 mm, length of 30 mm and porosity of 12%, fabricated by precursor infiltration and pyrolysis (PIP) process. The pore morphology is shown in Fig. 3. As CT scan shows, huge amounts of pores in μm and mm scale exist in the interior of the sample, named the inter-bundle chambers and inter-bundle channels as the red part, and an interconnected pore channels with the size of 0.1-20 μm connecting bigger and smaller pores and offering the flow paths for the fluid are shown in SEM photo (marked as B and C) [11], forming the so-called pore-throat structure for C/SiC porous material. Besides, the density, conductivity and specific heat for the sample are respectively 1.178 g/cm^3, 1.612 W/m·K, and 763 J/kg·K.

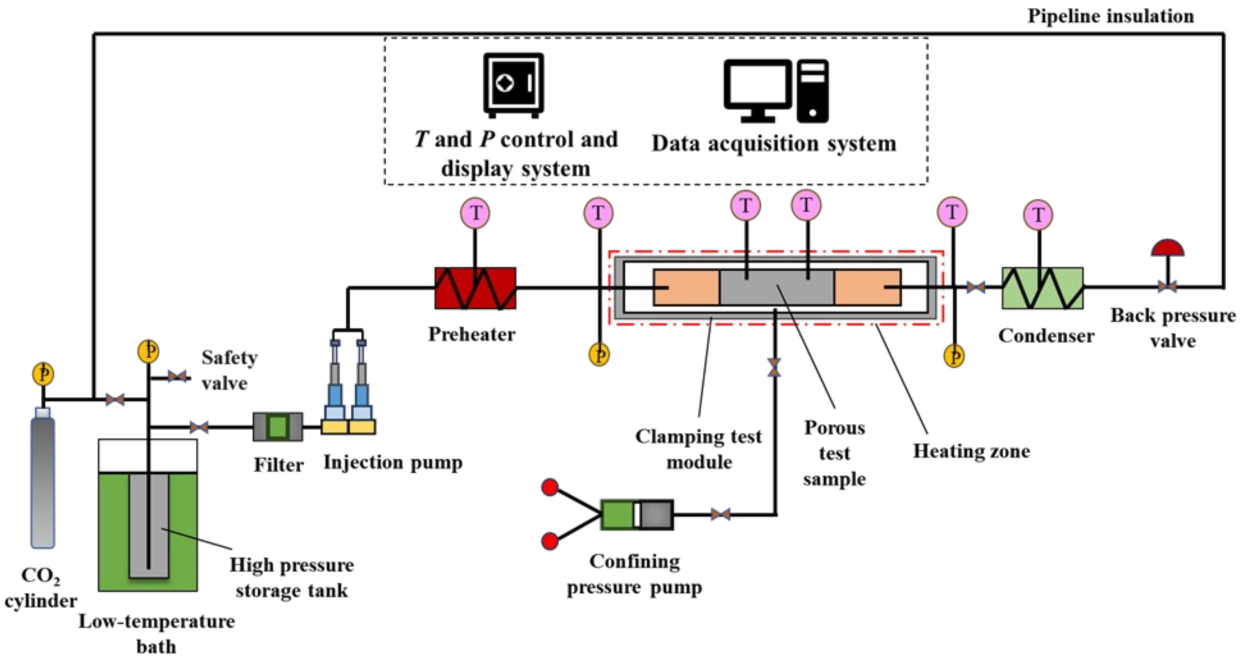

Fig. 2 Schematic diagram of the experimental system.

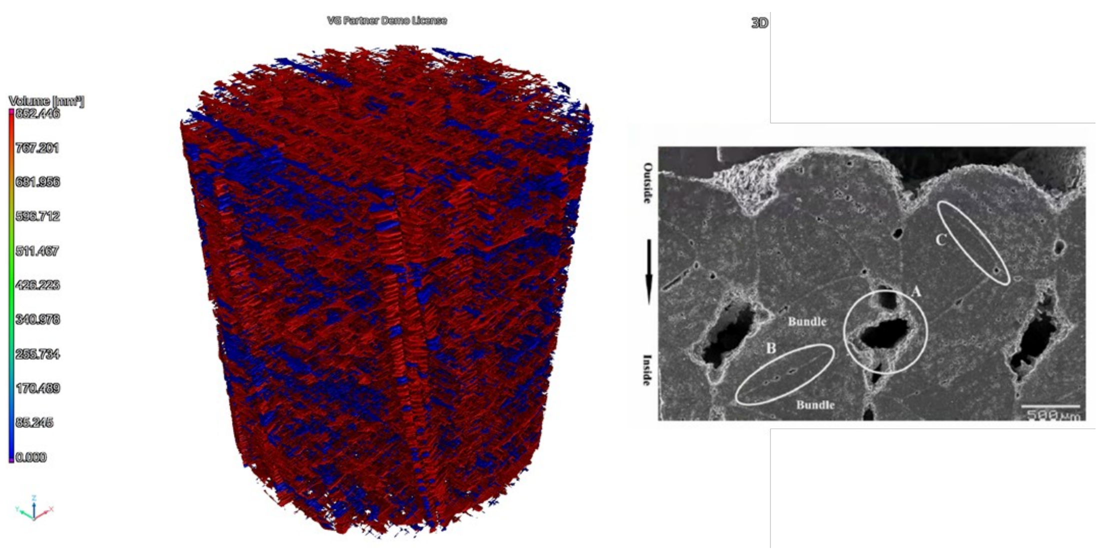

Fig. 3 Pore morphology of C/SiC porous material. Left: pore distribution (red region) by CT scan. Right: pore morphology by SEM [11].

2.2. Numerical model

As for the heat transfer process in C/SiC porous material in the present study, the temperature of local fluid phase and local solid phase are hard to be measured due to the quite small pore scale, thus, it is impossible to get the h_{sf} from experiments directly. Besides, the solid conductivity is relatively small and there is temperature gradient in solid phase, indicating the method of lumped capacitance is not available here. Consider the temperature variation along the flow direction and radial direction, a steady three-dimensional numerical model is used to calculated h_{sf} in an inverse method in this study, which has also been adopted by Jiang et al. [12] and Yang et al. [13] to obtain this coefficient while they simply used one-dimensional transient LTNE model. The calculation flowchart for h_{sf} is shown in Fig. 4. The energy governing equations of LTNE model can be written as follows:

Solid phase:

$$\nabla \cdot \left[\lambda_{s,eff} \nabla T_s \right] = a h_{sf} \left(T_s - T_f \right) \tag{1}$$

Fluid phase:

$$\nabla \cdot \left(\varepsilon \mathbf{u}_p \rho_f c_{pf} T_f \right) = \nabla \cdot \left[\lambda_{f,eff} \nabla T_f \right] + a h_{sf} \left(T_s - T_f \right) \tag{2}$$

where T_s is solid temperature, T_f is fluid temperature, a is specific surface area of porous media and also heat transfer area between fluid and solid with the constant value of 105600 m^{-1},ε is porosity, and effective conductivity of solid and fluid are $\lambda_{s,eff} = (1-\varepsilon)\lambda_s$, $\lambda_{f,eff} = \varepsilon \lambda_f$.

The governing equation of LTE model is shown below, which is the special case of LTNE. The discrepancy obtained by LTNE and LTE can reflect the intensity of the LTNE effect.

$$\nabla \cdot \left(\varepsilon \mathbf{u}_p \rho_f c_{pf} T \right) = \nabla \cdot \left[(\lambda_{s,eff} + \lambda_{f,eff}) \nabla T \right] \tag{3}$$

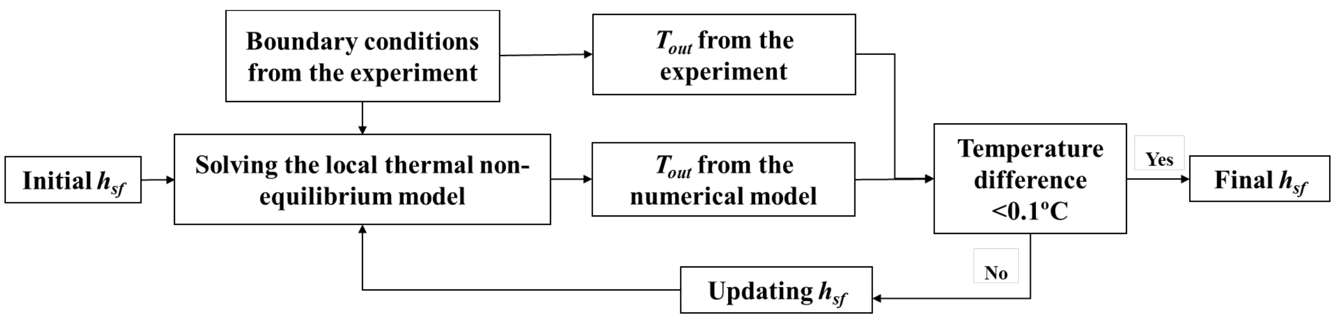

Fig. 4 Calculation flowchart for solid-fluid heat transfer coefficient h_{sf}.

3. Results and discussion

14 cases are investigated in the present study to explore the LTNE effect of supercritical CO_2 flow through porous C/SiC material, under various mass flow rates (0.003-0.018 kg/s), CO_2 inlet temperatures (20-40 ºC, around pseudo-critical temperature T_{pc}), operating pressures (8-10 MPa) and wall temperatures (100 ºC, 150 ºC).

Table 1 shows the calculated volumetric heat transfer ah_{sf}, which is proportional to h_{sf}, and also the deviation of outlet temperature between LTE model and LTNE model ($T_{out,LTE}$-$T_{out,LTNE}$), which can be an indicator to determine whether the LTNE effect is strong or not (i.e. smaller deviation means better prediction accuracy of LTE model, indicating that the LTNE model can be simplified to the LTE model, and the LTNE effect can be neglected). The criteria of ignoring the LTNE effect is set to be ($T_{out,LTE}$-$T_{out,LTNE}$) < 1 ºC in the present work. It can be found that the LTNE effect exist widely in most cases, and the LTE can only exist under some specific cases, which reminds the importance of LTNE for supercritical CO_2 flow in C/SiC material for better results. Besides, the case which is suitable for LTE model has quite large h_{sf}, and it is easy to understand, as better convection between fluid and solid can help smooth out their temperature gap.

Table 1: Investigated cases and its corresponding local thermal non-equilibrium (LTNE) effect in the present study.

Case	T_{in}, °C	T_w, °C	P_{out}, MPa	m, kg/s	ah_{sf}, W/m^{3}K	Deviation, $T_{out,LTE}$-$T_{out,LTNE}$, K	LTNE or LTE*
1	20	100	8.0	0.003	14,784,000	0.27	LTE
2	20	100	8.0	0.006	4,752,000	1.42	LTNE

3	20	100	8.0	0.012	1,626,240	7.09	LTNE
4	20	100	8.0	0.018	4,118,400	3.79	LTNE
5	30	100	8.0	0.003	1,900,800	2.55	LTNE
6	30	100	8.0	0.006	4,752,000	1.53	LTNE
7	30	100	8.0	0.012	770,880	10.25	LTNE
8	30	100	8.0	0.018	1,193,280	8.18	LTNE
9	30	150	10.0	0.003	4,012,800	1.79	LTNE
10	30	150	10.0	0.009	147,840,000	0.06	LTE
11	30	150	10.0	0.015	4,646,400	4.88	LTNE
12	40	100	10.0	0.026	73,920,000	0.14	LTE
13	40	100	8.0	0.003	121,440	15.21	LTNE
14	40	100	8.0	0.006	134,112	17.87	LTNE

*LTE: local thermal equilibrium

Table 1 also shows an information for supercritical fluid flow and heat transfer in porous medium, that the effect of operating parameters on LTNE and h_{sf} are non-linear, like not only smaller mass flow rate leads to larger h_{sf}. The complex relation is then clarified by h_{sf} versus bulk temperature T_b in Fig. 5. T_b is the averaged fluid temperature defined by the averaged value of T_{in} and T_{out}, which can reflect the averaged state of supercritical fluid in the porous medium, and it is synthetically affected by T_{in}, T_w as well as m. Fig. 5 shows clear trends that the maximum heat transfer coefficient appears near pseudo-critical temperature T_{pc}, at which the specific heat of CO_2 reaches a peak. Besides, all the LTE cases appear near T_{pc} but not vice versa, implying more complicated heat transfer mechanisms occurs near this area due to dramatic thermophysical property changes.

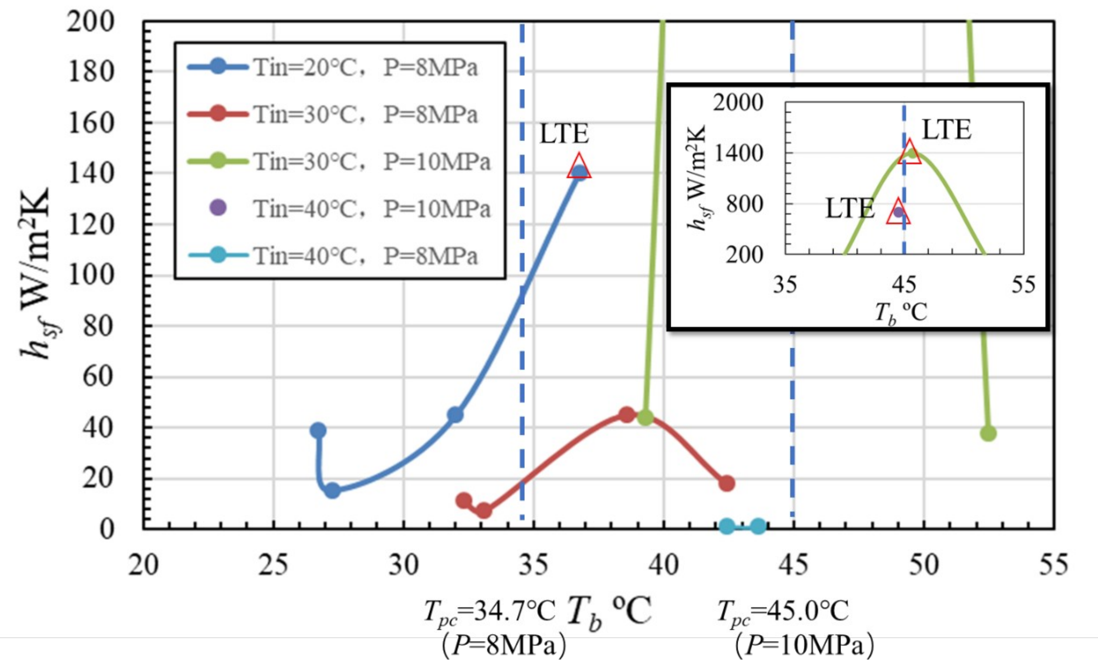

Fig.5 Solid-fluid heat transfer coefficient h_{sf} versus bulk temperature T_b under different cases with various inlet temperature T_{in} and operating pressure P for supercritical CO_2 heat transfer in C/SiC porous material.

One of the most important works for the LTNE study is the development of criteria. Lee and Vafai [7] present a criterion as below,

$$1/(\kappa + Bi/4) < E_a \tag{4}$$

where $Bi = \frac{a h_{sf} R^2}{k_{eff,s}}$ and $\kappa = \frac{k_{eff,f}}{k_{eff,s}}$. If the conditions are within the range shown in eq. (4), the LTNE can be neglected and the LTE can be adopted. After verification of eq. (4) by using the data in the present study, large error can be found as 42% of cases are predicted wrong, indicating that conventional criteria based on constant property fluids may not be suitable for supercritical fluids, which needs to be further verified and modified. Fig. 6 draws the contours of deviation of predicted heat transfer between the LTNE model and the LTE model, the relation between *Bi*, κ and derivation for constant property fluids and for supercritical CO_2 are not consistent, more complex relation and larger *Bi* influence area can be found for supercritical heat transfer. Further study is needed to propose a suitable criterion for supercritical fluids.

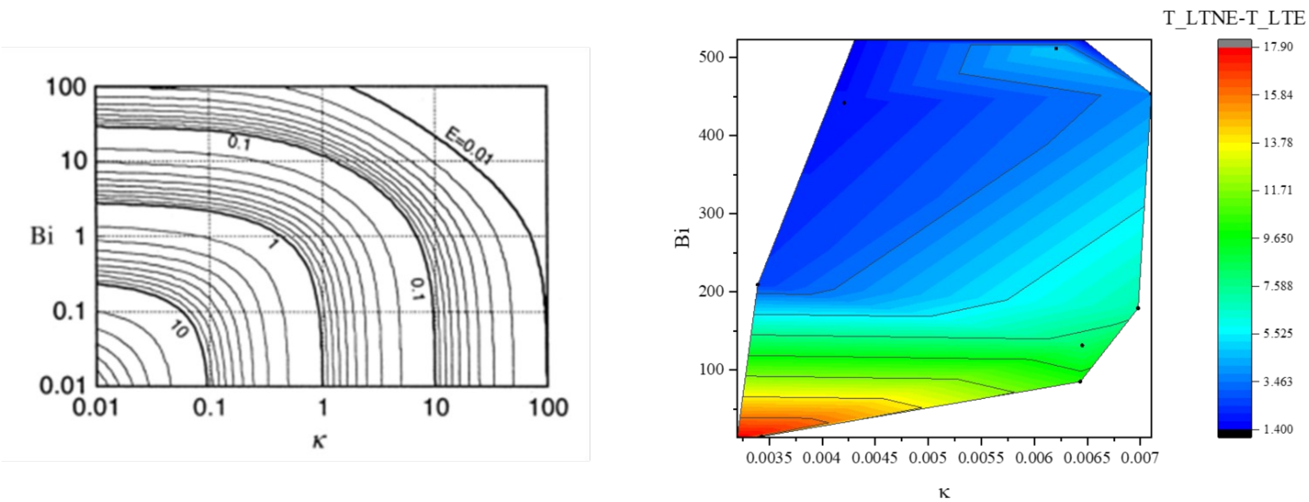

Fig. 6 Deviation of prediction between local thermal non-equilibrium (LTNE) model and local thermal equilibrium (LTE) model. Left: conventional contour for constant property fluids [7]. Right: present contour for supercritical CO_2.

4. Conclusion

In this study, supercritical CO_2 heat transfer through a porous ceramic medium, C/SiC composite material, is conducted by experiments. The experimental data under various inlet temperatures, mass flow rates, pressures, are further combined with a numerical model to figure out the solid-fluid heat transfer coefficient and the local thermal non-equilibrium effect between supercritical CO_2 and porous ceramic medium. The results show that the local thermal non-equilibrium effect exists widely, and the local thermal equilibrium can only exist under some specific cases, reminding the importance of local thermal non-equilibrium effect for supercritical CO_2 flow in C/SiC material for better numerical results. Besides, all the local thermal equilibrium cases appear near pseudo-critical temperature region, but not vice versa, with the addition of the failure of conventional criteria, implying more complicated heat transfer mechanisms occur due to dramatic thermophysical property changes. This study can be a useful reference for the further research of heat transfer mechanisms for supercritical fluids flow through porous medium.

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References

[1] P. Jiang, L. Zhang, and R. Xu, "Experimental study of convective heat transfer of carbon dioxide at supercritical pressures in a horizontal rock fracture and its application to enhanced geothermal systems," *Applied Thermal Engineering,* vol. 117, pp. 39-49, 2017.

[2] J. M. Yin, Q. Y. Zheng, Z. R. Peng, and X. R. Zhang, "Review of supercritical CO2 power cycles integrated with CSP," *International Journal of Energy Research,* vol. 44, no. 3, pp. 1337-1369, 2019.

[3] Y. Zhu, P. Jiang, J. Sun, and Y. Xiong, "Injector head transpiration cooling coupled with combustion in H2/O2 subscale thrust chamber," *Journal of thermophysics and heat transfer,* vol. 27, no. 1, pp. 42-51, 2013.

[4] P.-X. Jiang, R.-F. Shi, Y.-J. Xu, S. He, and J. Jackson, "Experimental investigation of flow resistance and convection heat transfer of CO2 at supercritical pressures in a vertical porous tube," *The Journal of supercritical fluids,* vol. 38, no. 3, pp. 339-346, 2006.

[5] J.-C. Hsieh, D. T. Lin, B.-H. Lee, and M.-C. Chung, "Experimental study on heat transfer of supercritical carbon dioxide in a long silica-based porous-media tube," *Heat and Mass Transfer,* vol. 53, pp. 995-1004, 2017.

[6] B. J. Kkihlefa, A. Jaddoa, and A. H. Reja, "Experimental investigation of heat transfer features for vertical tube using porous media and Carbon dioxide," *Journal of Mechanical Engineering Research and Developments,* vol. 44, no. 5, pp. 188-195, 2021.

[7] D.-Y. Lee and K. Vafai, "Analytical characterization and conceptual assessment of solid and fluid temperature differentials in porous media," *International Journal of Heat and Mass Transfer,* vol. 42, no. 3, pp. 423-435, 1999.

[8] S. J. Kim and S. P. Jang, "Effects of the Darcy number, the Prandtl number, and the Reynolds number on local thermal non-equilibrium," *International Journal of Heat and Mass Transfer,* vol. 45, no. 19, pp. 3885-3896, 2002.

[9] N. Wakao, "Particle-to-fluid transfer coefficients and fluid diffusivities at low flow rate in packed beds," *Chemical Engineering Science,* vol. 31, no. 12, pp. 1115-1122, 1976.

[10] K. Kar and A. Dybbs, "Internal heat transfer coefficients of porous metals," *NASA STI/Recon Technical Report A,* vol. 84, pp. 81-91, 1982.

[11] W. Li, Z. Chen, S. Wang, Y. Yang, and L. Niu, "Pore geometry and permeation characteristic of 3D–C f/SiC composites fabricated via precursor infiltration and pyrolysis," *Journal of Porous Materials,* vol. 21, pp. 1051-1057, 2014.

[12] P.-X. Jiang, R.-N. Xu, and W. Gong, "Particle-to-fluid heat transfer coefficients in miniporous media," *Chemical engineering science,* vol. 61, no. 22, pp. 7213-7222, 2006.

[13] J. Yang, J. Wang, S. Bu, M. Zeng, Q. Wang, and A. Nakayama, "Experimental analysis of forced convective heat transfer in novel structured packed beds of particles," *Chemical engineering science,* vol. 71, pp. 126-137, 2012.