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Experimental Study on Suppressing Heat Transfer Deterioration of Supercritical CO_2 Heated in Vertical Tubes Based on Helmholtz oscillator

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ABSTRACT

Heat transfer deterioration (HTD) of supercritical CO_2 heated in a tube will influence the thermal efficiency and safe operation of the energy system due to the occurrence of local high temperatures. To suppress the HTD of supercritical CO_2, the Helmholtz oscillator is applied at the inlet of the test section. The experiments are conducted at the conditions of the mass flux from 121 to 600 kg m^{-2} s^{-1} and the heat flux from 14.7 to 106.1 kW m^{-2} with the operating pressure of 8.0 MPa. The heat transfer and comprehensive thermal performance are discussed with and without the Helmholtz oscillator. The results show that it can significantly suppress the HTD, and the overall thermal performance factor can be up to 2.28. The main reason is that the Helmholtz oscillator can strengthen the mutual disturbance between near-wall fluid with high temperature and central fluid. Therefore, the buoyancy effect is weakened and heat transfer to supercritical CO_2 gets enhanced.

Keywords: Supercritical CO_2, Helmholtz oscillator, Heat transfer deterioration, Buoyancy, Waste heat recovery.

NONMENCLATURE

Symbols	
q	heat flux (kW m^{-2})
G	mass flow rate (kg m^{-2} s^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number
h	heat transfer coefficient
η	thermal performance factor
Subscripts	
pc	pseudo-critical value
b	bulk
wi	inner wall
wo	outer wall
ave	average
Abbreviations	
HTD	heat transfer deterioration
S-CO_2	supercritical CO_2

1. INTRODUCTION

Waste heat recovery is an effective method to reduce carbon emission and mitigate the energy crisis. However, it is difficult to recycle low-grade waste heat resources for traditional power generation cycles. Hence, the trans-critical CO_2 Rankine cycle has attracted increasing interest among various power cycles [1]. It should be noted that the flow and heat transfer characteristics of CO_2 under supercritical pressure are different from those of conventional mediums. Its drastic variations of thermal physical properties with the temperature near the pseudo-critical (T_{pc}) strengthen the effects of buoyancy and thermal acceleration on heat transfer [2], which makes heat transfer deteriorated and accelerates thermal corrosion of the heated tube. Therefore, it is significantly important to design a heat transfer structure with better performance to suppress HTD, and further improve the thermal efficiency of the system.

The traditional measures of suppressing HTD of S-CO_2 are used by enhanced channels, such as helical wire tubes [3], metal foam tubes [4, 5], internally ribbed tubes [6], etc. Although those enhanced channels can suppress and delay the occurrence of HTD, the complicated

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geometrical structure makes manufacturing difficult and is accompanied by a larger pressure drop. Compared with the smooth channel, the pressure drop of foam metal tubes is increased by 50% - 100% [4]. Therefore, considering design and application in industry, it is significantly important to take a simpler structure to suppress HTD of S-CO_2 heated in tubes.

Helmholtz oscillator is a cylindrical cavity with two open ends and a closed perimeter. When the fluid passes through the cavity, it can achieve continuous and efficient pulsation without any dynamic parts [7]. In recent years, in addition to the application of rock drilling [8], jet cleaning [9], and pulsating combustion [10] , some scholars also used the self-sustained oscillation jets to enhance heat transfer to water by destroying the boundary layer, and the mixing between near-wall fluid with high temperature and the core fluid with low temperature. Gao and Zeng et al. [11] added it into the inlet of the heated tube to generate pulsating flow to enhance heat transfer of water. They found that the heat transfer performance can be significantly improved under appropriate inlet conditions and structural parameters. However, to the best of our knowledge, few studies are concentrated on pulsating flow generated by Helmholtz oscillator to enhance heat transfer to supercritical fluid. Therefore, we first conduct the investigation using the pulsating flow generated by Helmholtz oscillator to suppress HTD of S-CO_2 heated in vertical tube, which could be of practical value in helping to improve the heat transfer performance of gas heaters under severe operating conditions.

2. EXPERIMENTAL SYSTEM AND DATA REDUCTION

2.1 Experimental system

As shown in Fig.1, the experiment system is composed of three parts: the CO_2 pressurization system, the CO_2 circulating loop, and the cooling circuit. After removing the non-condensable gases and conducting leak detection, CO_2 from the gas cylinder is charged to the circulating system by a plunger pump. The circulating power is provided by a Micropump magnetic gear pump. The mass flow rate passing through the heating section is regulated by adjusting the frequency of the inverter and measured by an Emerson Coriolis mass flow meter. CO_2 is heated to the required temperature in the thermostatic bath No.1 before entering the heating section. Then S-CO_2 with high temperature flows out of the test section and is cooled down. The back pressure of circulating system is precisely controlled by adjusting the temperature of the thermostatic bath No.2. After reaching the required working conditions, all the experimental data are collected by an Agilent 34972A data acquisition instrument.

The structural diagram and real image of the Helmholtz oscillator are shown in Fig.2. The specific structural parameters are as follows: the inlet diameter of the upstream nozzle, the outlet diameter of the downstream nozzle, and the divergent angle are d_1 = 2.0 mm, d_2 = 1.8 mm, β = 16°, respectively. The structural parameters of the oscillation chamber are D_c = 16 mm, L_c = 2.2 mm, and θ = 120°. The temperature of the Helmholtz oscillator inlet is measured by a Pt 100 sensor with the maximum uncertainty of ±0.2 °C. The inlet pressure is measured by a pressure transducer with an accuracy of ±0.2% (full range). The pressure drop is measured by the EJA110E pressure transmitter. The mass flow rate is measured by a Coriolis-type mass flow meter with a measuring range of 0 - 0.2 kg/s.

The schematic diagram of the test tube is presented in Fig.3. The material of the test section is 304L stainless steel, and the heated length is 1100 mm with the inner diameter and outer diameter of the tube are 4 mm and 6 mm, respectively. In order to measure the local temperature of the outer wall, 24 T-type thermocouples are arranged at equal spacing on the outer wall.

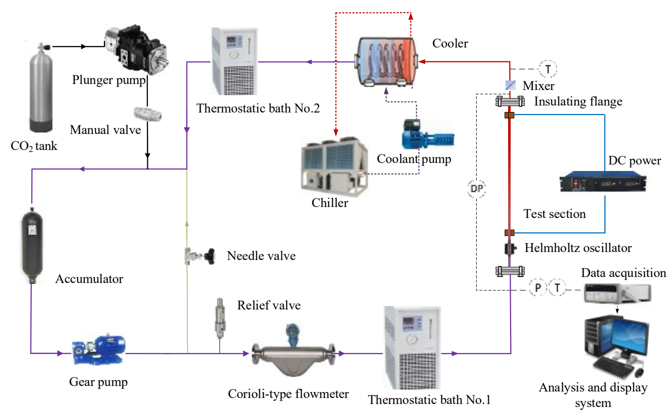
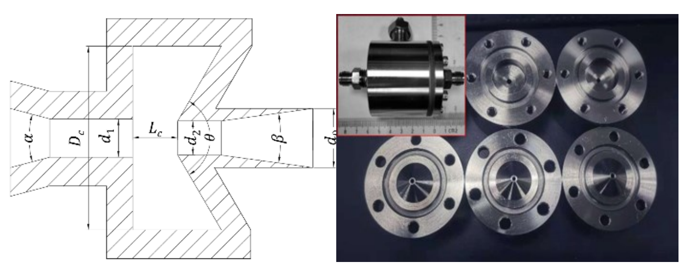


Fig.1. Schematic diagram of the test system.



(a) Structural diagram (b) Processed physical parts

Fig. 2. The Helmholtz oscillator.

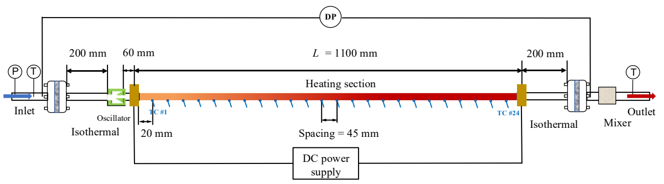


Fig. 3. Test section arrangement.

2.2 *Data reduction*

Assumed the heat flux is uniformly imposed on the outer wall of the heated tube, the inner-wall temperature is calculated as follows:

$$T_{wi,x} = T_{wo,x} + \frac{q_v}{16\lambda_{steel}}(\mathrm{d}_{out}^2 - \mathrm{d}_{in}^2) + \frac{q_v}{8\lambda_{steel}}\mathrm{d}_{out}^2 In\frac{\mathrm{d}_{in}}{\mathrm{d}_{out}} \quad (1)$$

The heat transfer coefficient along flow direction is calculated by:

$$h(x) = \frac{q_w}{T_{wi,x} - T_{b,x}} \quad (2)$$

The resistance factor is obtained from Eq (3):

$$f = \frac{2d_{in}}{\rho_b u^2} \times \frac{\Delta p_f}{\Delta l} \quad (3)$$

The frictional resistance pressure drop Δp_f, the gravitational pressure drop Δp_g and the pressure drop of self-acceleration effect Δp_{ac} are calculated by the following equations [12]:

$$\Delta p_f = \Delta p - \Delta p_g - \Delta p_{ac} \quad (4)$$

$$\Delta p_g = gL(\frac{h_{b,in}\rho_{b,in} + h_{b,out}\rho_{b,out}}{h_{b,in} + h_{b,out}}) \quad (5)$$

$$\Delta p_{ac} = \rho_{b,out}u_{out}^2 - \rho_{b,in}u_{in}^2 = G^2(\frac{1}{\rho_{b,out}} - \frac{1}{\rho_{b,in}}) \quad (6)$$

The thermal performance factor can be calculated by:

$$\eta = (\frac{Nu_{av}}{Nu_{av,0}}) \Big/ (\frac{f}{f_0})^{\frac{1}{3}} \quad (7)$$

2.3 *Measurements and uncertainty analysis*

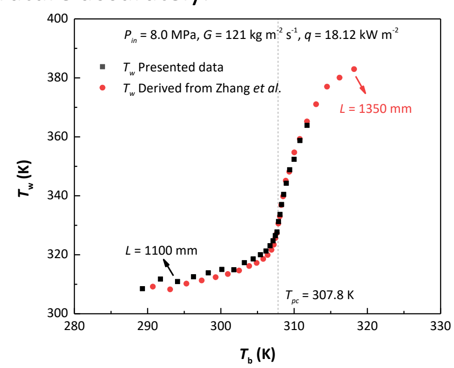
The experiments are conducted at the conditions of the mass flux from 121 to 600 kg m^{-2} s^{-1} and the heat flux from 14.7 to 106.1 kW m^{-2} with the operating pressure of 8.0 MPa and the inlet temperature of 15 °C. The uncertainties of the main parameters calculated according to the experimental working parameters and the accuracy of the instrument are shown in Table 1.

Table 1. Uncertainty of key parameters

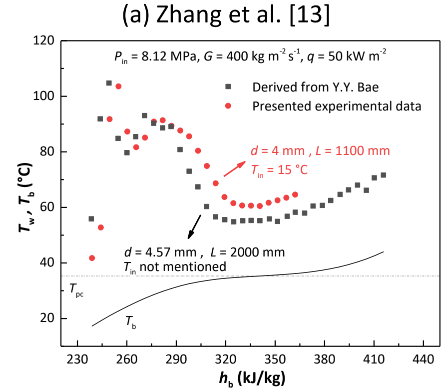
Parameters	Units	Uncertainty
Pressure	MPa	±0.032
Bulk temperature	°C	±0.2
Wall temperature	°C	±0.2
Mass flux	g s^{-1}	±0.1%
Heat flux	kW m^{-2}	±1.24% - 4.67%
Heat transfer coefficient	W m^{-2} K^{-1}	±4.88% - 11.22%

2.4 *Experimental setup validation*

As shown in Fig. 4, to validate the experimental system, the experimental data are collected from Zhang et al. [13] and Bae et al. [2] for comparison. The operating conditions are consistent except for slight differences in tube diameter and inlet temperature. We can see that our test rig has good reproducibility with results from literatures and can capture the abrupt changes in wall temperature accurately.



(a) Zhang et al. [13]



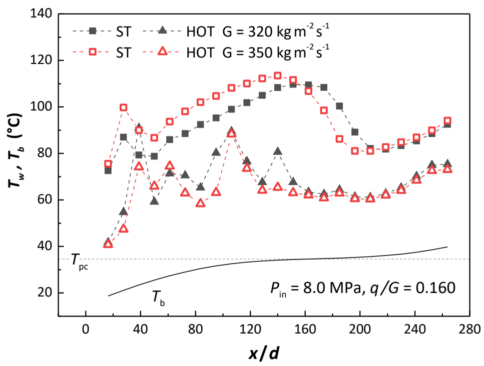
(b) Bae et al. [2]

Fig. 4. Experimental system validation

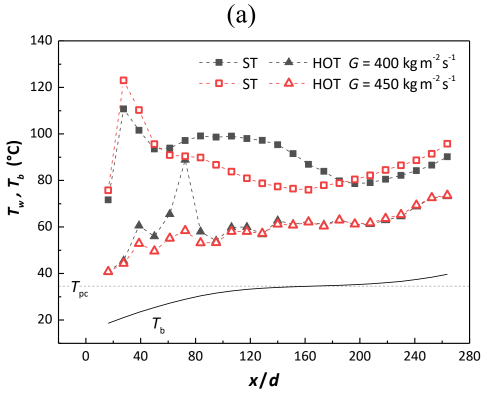
3. RESULTS AND DISCUSSION

3.1 *Heat transfer characteristics*

Fig. 5 shows the influence of the Helmholtz oscillator on the distribution of wall temperature along the tube. As can be seen in Fig. 5(a), the inner wall temperature of the HOT (the tube with the Helmholtz oscillator) fluctuates sharply in the liquid-like region. When q/G is constant and the mass flux increases to 400 kg m^{-2} s^{-1}, the temperature peak is weakened compared to that of smooth tube (ST), and there is a delay in the location where it occurs. As mass flux further increase to a large level (with heat flux increases in equal proportion), the wall temperature of the ST rises suddenly at the entrance. Hence, the heat transfer deterioration (HTD) occurs. But it is no longer observed along the test section of the HOT when $G \geq 450$ kg m^{-2} s^{-1}. The wall temperature along the test section maintains a slight amplitude fluctuation, and the HTD is effectively suppressed. It may be that with the increase of G, the pulsating flow are formed at the outlet of the downstream nozzle under the resonance of the oscillator, which periodically flushes the fluid near the heating wall and promotes the mixing of heat across the boundary layer interface, thus the wall temperature declines.



(a)



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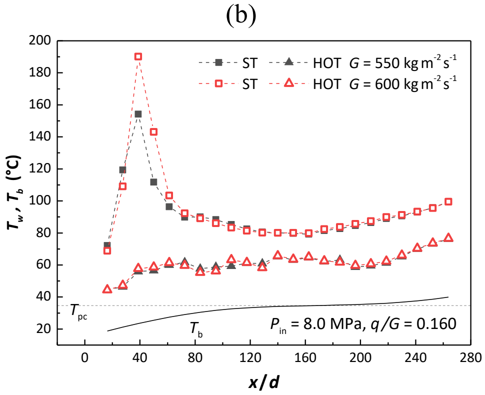
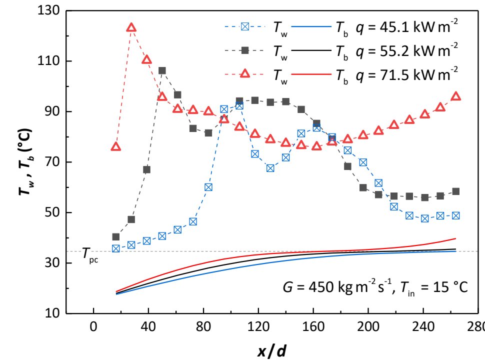


(c)

Fig. 5. Heat transfer performance under the same q/G = 0.160 kJ/kg (Re$_{in}$ = 6.6 ×10^3 - 2.85 ×10^4)



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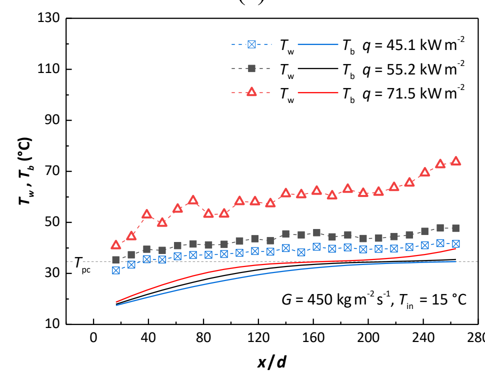

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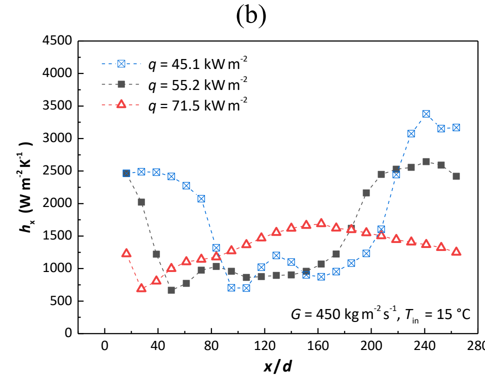

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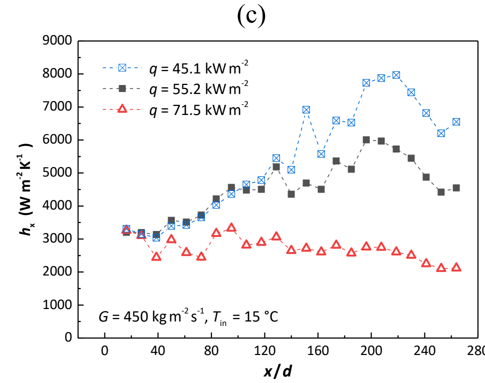

(d)

Fig. 6. Effects of heat flux on heat transfer performance under the fixed mass flux (G = 450 kg m^{-2} s^{-1})

As revealed in Fig. 6, with the heat flux increased from 45.1 to 71.5 kW m^{-2}, there is a rapid increase in wall temperature at the entrance of ST. But it can be effectively suppressed with Helmholtz oscillator under the same heat flux, avoiding the occurrence of large temperature peaks. When q = 45.1 kW m^{-2}, the local heat transfer coefficient is increased by up to about 7 times compared to that of ST, and the average heat transfer coefficient is about 3 times higher.

3.2 Comprehensive performance evaluation

As shown in Fig. 7, the integrated pressure drop of ST and HOT increases with increasing mass flux, and that increases sharply in the HOT. However, the integrated pressure drop of S-CO_2 in the HOT is not very large compared to ST at smaller G. The thermal performance factor η increases and then decreases with increasing mass flux for HOT, which achieves the maximum values of 2.28 at G = 400 kg m^{-2} s^{-1}. Those data indicate that the Helmholtz oscillator has a certain engineering application prospect since it can effectively suppress the HTD and improve thermal performance.

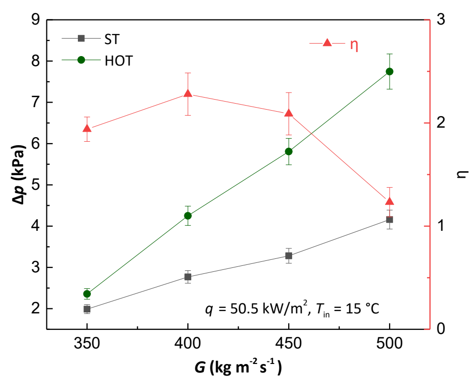

Fig. 7. Pressure drop and thermal performance factor

4. CONCLUSIONS

To improve heat transfer in gas heaters of S-CO_2 Rankine cycle, the experimental study of S-CO_2 that vertically up-flow in the circular tube with and without Helmholtz oscillators was conducted. The main conclusions are summarized as follows:

(1) The Helmholtz oscillator was designed and used to investigate the performance of suppressing heat transfer deterioration (HTD), and typical data are presented in this manuscript. The results show that the Helmholtz oscillator is effective in suppressing the HTD occurred in the smooth tube (ST) and improving the heat transfer performance of S-CO_2 at larger q/G. In the test, the thermal performance factor (η) was up to 2.28. The oscillators could be of practical value in helping to improve the heat transfer performance of gas heaters under severe operating conditions.

(2) Heat flux q and mass flux G has a strong influence on the heat transfer behavior of S-CO_2 in a heated vertical circular tube with the Helmholtz oscillators, especially G. There is a thresholds of G for the Helmholtz oscillator, i.e., when beyond which no serious HTD occurs even at large q/G.

ACKNOWLEDGEMENT

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REFERENCE

[1] Wang X, Dai Y. Exergoeconomic analysis of utilizing the transcritical CO_2 cycle and the ORC for a recompression supercritical CO_2 cycle waste heat recovery: A comparative study. Appl Energy. 2016;170:193-207.
[2] Bae YY. Mixed convection heat transfer to carbon dioxide flowing upward and downward in a vertical tube and an annular channel. Nucl Eng Des. 2011;241:3164-77.
[3] Bae YY, Kim H-Y, Yoo TH. Effect of a helical wire on mixed convection heat transfer to carbon dioxide in a vertical circular tube at supercritical pressures. Int J Heat Fluid Flow. 2011;32:340-51.
[4] Liu Z-B, He Y-L, Qu Z-G, Tao W-Q. Experimental study of heat transfer and pressure drop of supercritical CO_2 cooled in metal foam tubes. Int J Heat Mass Transfer. 2015;85:679-93.
[5] Liu Z-B, He Y-L, Li Y-S, Qu Z-G, Tao W-Q. Heat transfer characteristics of supercritical CO_2 flow in metal foam tubes. J Opt. 2015;101:36-47.
[6] Li Z, Tang G, Wu Y, Zhai Y, Xu J, Wang H, et al. Improved gas heaters for supercritical CO_2 Rankine cycles: Considerations on forced and mixed convection heat transfer enhancement. Appl Energy. 2016;178:126-41.
[7] Rockwell D, Naudascher E. Review—Self-Sustaining Oscillations of Flow Past Cavities. J Fluids Eng. 1978;100:152-65.
[8] Huang M, Kang Y, Wang X, Hu Y, Cai C, Liu Y, et al. Experimental investigation on the rock erosion characteristics of a self-excited oscillation pulsed supercritical CO_2 jet. Appl Therm Eng. 2018;139:445-55.
[9] Wu Q, Wei W, Deng B, Jiang P, Li D, Zhang M, et al. Dynamic characteristics of the cavitation clouds of submerged Helmholtz self-sustained oscillation jets from high-speed photography. J Mech Sci Technol. 2019;33:621-30.
[10] Xu Y, Zhai M, Guo L, Dong P, Chen J, Wang Z. Characteristics of the pulsating flow and heat transfer in an elbow tailpipe of a self-excited Helmholtz pulse combustor. Appl Therm Eng. 2016;108.
[11] Gao Hong ZD. Experimental study of enhanced heat transfer by self-excited oscillating pulse jet. Thermal Power Engineering. 2003:349-51.
[12] Fang X, Xu Y, Su X, Shi R. Pressure drop and friction factor correlations of supercritical flow. Nucl Eng Des. 2012;242:323-30.
[13] Zhang S, Xu X, Liu C, Liu X, Dang C. Experimental investigation on the heat transfer characteristics of supercritical CO_2 at various mass flow rates in heated vertical-flow tube. Applied Thermal Engineering. 2019;157.

