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Numerical study on cooling heat transfer of turbulent supercritical CO_2 in large horizontal tubes

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ABSTRACT

This paper presents the results of computational investigations on cooling heat transfer of turbulent sCO_2 in three horizontal tubes with diameter of 15.75 mm, 20.00 mm and 24.36 mm using RANS turbulence models at a pressure of $P = 8.0$ MPa. Four models with good prediction performance demonstrated in literature (RNG $k-\varepsilon$ model and three other low-Reynolds number $k-\varepsilon$ models of LS, YS and AKN) have been validated against experimental measurements and to observe that results from the AKN model are closer to experimental data. Details of heat transfer behaviour of sCO_2 cooled in horizontal tubes within this diameter range are revealed and the influence of heat flux, tube diameter and buoyancy on heat transfer performance have been discussed. Results demonstrate that at $T_b > T_{pc}$ (pseudocritical temperature), sCO_2 heat transfer performance is enhanced as the heat flux and tube diameter increase; whereas at $T_b < T_{pc}$, the heat flux and tube diameter almost do not affect the heat transfer performance. The buoyancy effect only generates slight enhancement for turbulent heat transfer from sCO_2 flowing in horizontal tubes with large diameters. However, as the values of Richardson number Ri that quantifies the buoyancy effects continue increasing within $Ri > 0.1$, the buoyant force is enhanced, which in turn impairs the heat transfer near T_{pc}. This is a result contrary to past reports confined to small diameter tubes, which is mainly attributed to the accumulation of denser cold fluids at the bottom of the pipe when buoyancy effects are strong.

1. Introduction

Supercritical Carbon Dioxide (sCO_2) operating in closed Brayton power cycles offers the potential of higher cycle efficiency versus conventional working mediums (i.e. helium and superheated or supercritical steam) at temperature relevant for Concentrating Solar Thermal (CST) applications [1,2]. Compared to steam, sCO_2 power cycles also have wider scalability, higher power density, and more compact and less complex power blocks. Research on sCO_2 power cycles have been fuelled in recent years [3–9], and the interest in the use of sCO_2 as working fluids has also been extended to other potential applications [10–14].

While most of the recent work quoted above has focussed on sCO_2 expanders, the heat transfer aspect of a sCO_2 cycle is also starting to attract attention. Unlike traditional constant-property heat transfer fluids, supercritical CO_2 exhibits strong temperature- and pressure-dependence thermophysical properties, especially at the vicinity of the pseudocritical temperature (T_{pc}) which is defined as the point where the specific heat (C_p) reaches its peak. The properties vary sharply (as shown in Fig. 1) around this point. Since the heat removal from a sCO_2 cycle is likely to be near the pseudocritical temperature, this sharp variation of the thermophysical properties is of special concern to the design of cooling systems for future sCO_2 power plants. Most of the past studies on sCO_2 heat transfer are concerned with turbulent flows that are more practical to engineering applications due to the superiority in heat transfer over laminar flows. Bea and co-workers [15,16] experimentally measured the local heat transfer coefficients of turbulent sCO_2 flows near the critical point through uniformly heated tubes, with tube diameters of $d = 4.4, 6.3, 9.0$ mm. Liao and Zhao [17] carried out tests with sCO_2 being heated in horizontal mini/micro circular pipes, and the tube diameter ranges 0.7–2.16 mm. Turbulent sCO_2 heat transfer in an annular counter-flow heat exchanger ($d = 4.72$ mm) using water cooling was investigated [18] at different sCO_2 mass fluxes and operating

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Nomenclature

Latin symbols

C_u, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$	constants of turbulence models
c_p	specific heat at constant pressure [J/(kg K)]
d	diameter [m]
D	additional term in the k-equation
E	flow energy [W/kg]
f_1, f_2	functions in the dissipation equation
f_μ	damping function
g	acceleration due to gravity [m/m^2]
Gr	Grashof number
H	enthalpy [J/kg]
h	heat transfer coefficient [W/m^{2}K]
k	turbulence kinetic energy [m^2/s^2]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
P_k	production of turbulence energy due to shear
q	heat flux [W/m^2]
u	component of the velocity vector [m/s]
x, y, z	coordinates
$y+$, y^*	dimensionless distance from wall
Y	dimensionless characteristic length

Greek symbols

β	volume expansion coefficient [K^{-1}]
ε	dissipation rate of turbulence energy [m^2/s^3]
λ	thermal conductivity [W/mK]
θ	angle with y axis on y-z plane [°]
μ	dynamic viscosity [N•s/m^2]
v	kinematic viscosity [m^2/s]
σ_k, σ_ε	turbulent Prandtl number for k and ε
τ	shear stress [N/m^2]
Θ	dimensionless temperature
Δ	difference

Subscripts

b	bulk fluids
h	heated section
in	inlet
out	outlet
pc	pseudo-critical
s	sublayer
t	turbulent quantity
w	wall

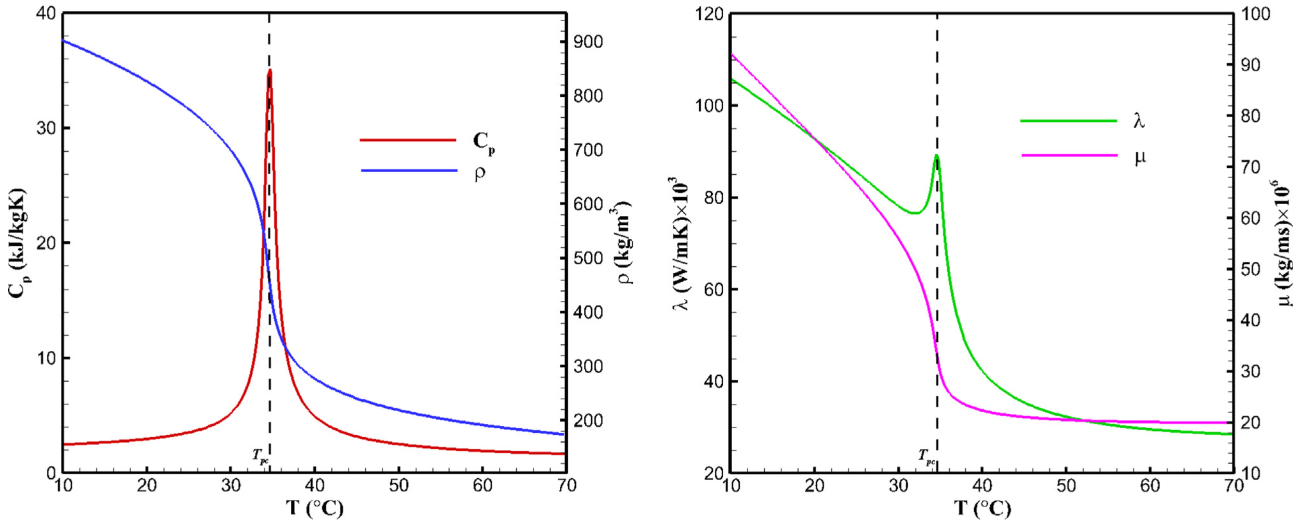

Fig. 1. Variations of thermophysical properties for sCO$_2$ at 8.0 MPa.

pressures. Dang and Hihara [19] experimentally studied the cooling heat transfer of sCO$_2$ and pressure drop characteristics in horizontal micro/macro tubes within diameter range of $d = 1.0$–6.0 mm, and explored the impact of operating conditions, including the heat flux. More recently, Liu et al. [20] experimentally investigated turbulent heat transfer from sCO$_2$ cooled in large horizontal tubes with diameters up to 10.7 mm to observe that the pipe diameter has a significant influence on heat transfer performance, which was also concluded in earlier studies for smaller tubes [16,17,19,21–23].

With experimental analysis, the heat transfer features of turbulent sCO$_2$ have been identified to some extent. However, limits still exist for experimental measurements, such as on turbulence statistics and parameters affecting the local heat transfer coefficients. Numerical methods validated by experimental data offer the potential for detailed investigations. Dealing with the drastic variation of sCO$_2$ thermophysical properties, in particular near the critical regime, Direct Numerical Simulations (DNS) is regarded as the most reliable approach. Bae et al. [24,25] conducted DNS studies on heating of turbulent sCO$_2$ in vertical micro tubes and annuli. However, DNS is prohibitively (computationally) expensive when it comes to analysing high Reynolds numbers flows. For the Reynolds number range encountered in industrial applications, also in the current research, the Reynolds-Averaged Navier-Stokes (RANS) turbulence models offer fine balance between accuracy and computational cost. A number of RANS models have been validated and used in turbulent sCO$_2$ heat transfer simulations and the literature suggests a preference for low-Reynolds number $k - \varepsilon$ models. RNG $k - \varepsilon$ model with the two-layer approach [26,27], LS (Launder and Sharma [28]) [29], YS (Yang and Shih [30]) [31,32] and AKN (Abe, Kondoh and Nagano [33]) [34–36] models were all able to capture the flow and heat transfer behaviour of