International Journal of Heat and Mass Transfer 114 (2017) 944–957

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Investigation of in-tube cooling of carbon dioxide at supercritical pressure by means of direct numerical simulation

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ARTICLE INFO

Article history:
Received 26 February 2017
Received in revised form 19 June 2017
Accepted 21 June 2017

Keywords:
Direct numerical simulation
Supercritical carbon dioxide
Turbulent flow
Heat transfer

ABSTRACT

To understand the cooling heat transfer behavior of carbon dioxide at supercritical pressure, direct numerical simulations of the flow and heat transfer in circular tubes have been performed at a pressure of 8 MPa, an inlet temperature of 342.05 K and a moderate inlet Reynolds number of 5400. The tube diameter was 2 mm, which is in the range of the hydraulic diameter of a compact heat exchanger. Both forced (gravity neglected) and mixed convection with upward or downward direction of the flow were simulated while the pipe is in vertical orientation. As result of thermal contraction, flow deceleration was observed primarily in the vicinity of the wall, which is opposite to the acceleration observed with wall heating. It is found that combined effects of deceleration and buoyancy in the upward flow enhance the heat transfer while the heat transfer in the downward flow is deteriorated. Further investigations have educed that in downward flow, when the direction of buoyancy force and flow are the same, all turbulent quantities diminish significantly in the axial direction, which is the reason for heat transfer deterioration. Quadrant and octant analyses are presented here to understand the effects of sweep and ejection events on turbulence. Finally, the anisotropy of the Reynolds stress tensor indicates that turbulence is modulated especially in the near-wall region in both upward and downward flow.

1. Introduction

The lower critical pressure and temperature of carbon dioxide ($P_c = 7.38$ MPa, $T_c = 304.25$ K) as compared to water ($P_c = 22.06$ MPa, $T_c = 674.09$ K) provide an opportunity to generate power in a reduced operating range. The supercritical carbon dioxide (sCO_2) Brayton cycle takes advantage of a low fluid compressibility in the near-critical region to reduce the compression work. Dostal et al. [12] and Ahn et al. [1] investigated different possible layouts for the sCO_2 cycle and recommended the recompression-Brayton power cycle because of its superior thermal efficiency, compactness and simplicity. In this power cycle, isobaric heat addition and rejection, i.e. cooling, take place at 20 MPa and 7.7 MPa, respectively. At the high pressure of 20 MPa, the variation of thermophysical properties is smooth, thus commonly used correlations for constant properties can be applied to predict the heat transfer. The problem of an accurate and reliable prediction of heat transfer arises at the lower pressure of 7.7 MPa, where almost all thermophysical properties change abruptly with temperature as shown in Fig. 1.

Heat transfer deterioration was observed in the near-critical region for heating of sCO_2 in various experiments, in which the wall temperature increased significantly due to poor heat transfer between the wall and bulk fluid. McEligot and Jackson [25] investigated about the heat transfer deterioration and noted that the culprits for this unwanted phenomenon were radial property variations, relaminarization caused by flow acceleration and the effect of natural convection due to buoyancy. Kim and Bae extensively investigated the heat transfer to sCO_2 by means of experiments [19,5,6]. They have conducted a series of experiments in the pressure range of 7.75–8.85 MPa with different mass and heat flux combinations. They observed the heat transfer deterioration as a wall-temperature peak at high heat flux and low mass flux when the fluid properties changed drastically. In the experiments of Kim and Kim [18], similar observations of heat transfer deterioration were observed in upward flow of sCO_2 while in the downward flow, the wall temperature increased monotonically without any peak. The authors concluded that this different nature of wall temperature distribution is due to the relationship between flow direction and buoyancy force in the near-wall region.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.089
0017-9310/

Nomenclature

Latin symbols

B_k	turbulence production due to buoyancy, kg/m s^3
b	normalized Reynolds shear stress tensor
C_f	Darcy friction factor
C_p	isobaric specific heat, J/kg K
D	tube diameter, m
G	mass flux, kg/m^2 s
g	acceleration due to gravity, m/s^2
h	specific enthalpy, J/kg
I_1, I_2, I_3	invariants of Reynolds shear stress tensor
k	turbulent kinetic energy, kg/m s^2
O	octant
P	pressure, MPa
P_k	turbulence production due to shear, kg/m s^3
Q	quadrant
q	heat flux, W/m^2
R	pipe radius, m
r	radial direction, m
T	temperature, K
t	time, s
T_k	turbulent diffusion, kg/m s^3
U	velocity, m/s
u_τ	friction velocity, m/s
y	normalized distance to the wall
V_k	viscous diffusion, kg/m s^3
z	streamwise direction, m

Greek symbols

α	convective heat transfer coefficient, W/m^{-2} K
β	volume expansion coefficient, K^{-1}
δ	Kronecker delta
ϵ	dissipation, kg/m s^3
κ	thermal conductivity, W/m K
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
Π_k	pressure diffusion, kg/m s^3
ρ	density, kg/m^3
ϕ	symbol for state variable
τ	shear stress, Pa

non-dimensional numbers

$\mathbf{Gr}^*$	Grashof Number based on heat flux
Nu	Nusselt Number
$\mathbf{Q}^+$	non-dimensional heat flux
Re	Reynolds Number
$\mathbf{Re}_\tau$	friction Reynolds Number

Subscripts/superscripts

$+$	dimensionless value in conventional wall unit
0	inlet value
b	bulk value
c	critical value
pc	pseudo-critical value
r, θ, z	cylindrical coordinates
w	wall value
x, y, z	Cartesian coordinates

Acronyms

CFD	computational fluid dynamics
DNS	direct numerical simulation
NIST	national institute of standards and technology
N-S	Navier-Stokes
OpenFOAM	open field operation and manipulation
PDE	partial differential equation
PISO	pressure implicit with splitting of operator
QUICK	quadratic upstream interpolation for convective kinematics
RANS	Reynolds averaged Navier-Stokes
REFPROP	reference fluid thermodynamic and transport properties database
RNG	re-normalization group
RSS	Reynolds shear stress
sCO_2	supercritical carbon dioxide
THF	turbulent heat flux
TKE	turbulent kinetic energy

Along with experiments, computational fluid dynamics (CFD) studies are an important tool which provides insight information. Numerous attempts have been made in the past to model the heat transfer to sCO_2 by means of turbulence modeling [33,38,16,31]. He et al. [16] assessed low-Reynolds number turbulence models and found that models either over-predict or under-predict the heat transfer depending upon their damping function characteristics with respect to buoyancy and flow acceleration. Analogous observations were reported by Sharabi et al. [33]. In addition to this, authors reported that the Renormalization Group (RNG) k—ϵ model with two-layer treatment of the near-wall region was not able to reproduce experimental results. Pucciarelli and Ambrosini [30] recently made an attempt to improve Reynolds-averaged Navier–Stokes (RANS) turbulence models. In this work, they incorporated an algebraic heat flux model as an auxiliary tool to calculate the turbulent Prandtl number distribution. This distribution was further used in the energy equation. Through this, buoyancy induced phenomena were captured up to an extent but it was not general for further application with certainty. Therefore, it can be concluded that CFD studies with turbulence models are not reliable at supercritical pressure. However, direct numerical simulation (DNS) is an attractive alternative to overcome this difficulty at low Reynolds numbers.

Bae et al. [2] performed a DNS of heated pipe flow and elucidated the statistics of various turbulent quantities. In their DNS, the low-Mach-Number Navier-Stokes equations were solved with an in-house second-order accurate code based on the finite difference method. Various flow conditions were simulated and they correspond to variations in the heat flux, tube diameter, gravity and flow direction. The authors observed heat transfer deterioration in upward flow and enhancement during the downward flow. Nemati et al. [26] also accomplished DNS while focusing on three cases from Ref. [2]. They illustrated that reduction of the turbulent kinetic energy (TKE) leads to the heat transfer deterioration. They further explained that averaged thermophysical properties differ from that evaluated at mean temperature or enthalpy due to the Jensen inequality. It was an important remark which explains the inability of turbulence modeling to capture the heat transfer at supercritical pressure. Nemati et al. [27] studied the effect of thermal boundary conditions on heat transfer. They reported that the Nusselt number reduced by 7% when wall temperature fluctuations were restrained. Chu and Laurien [10] performed a DNS for a horizontally-oriented pipe, in which the gravity force affected the heat transfer in the transverse direction. They analyzed the heat transfer aspect and documented a secondary flow causing the flow stratification. This flow stratification induced a higher wall