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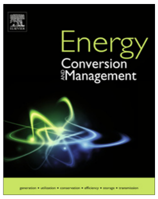

Numerical simulation of stability behaviors and heat transfer characteristics for near-critical fluid microchannel flows

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ABSTRACT

This paper deals with the CO_2 near-critical convective flow inside channels of micro-scale. Under near critical conditions, the CO_2 fluid is very much expandable/compressible, the density and thermal conductivity change to be near one order of magnitude lower when temperature goes near the critical point. At the same time the Prandtl number and specific heat also form high peaks. In microchannels the effect of natural convection becomes much smaller and the highly thermal expansive fluid with very small thermal diffusivity will act like a periodic thermal plume structure evolution mode. The current study, transient stability and heat transfer characteristics of near-critical microchannel flow are analyzed by solving conservative equations of Mass, Momentum and Energy together with non-Boussinesq incorporation of thermal physical properties. The numerical study is conducted under the ranges of $\varepsilon_T = 0.00023 - 0.06533$ and $\varepsilon_P = 0.01626 - 0.21951$ (for critical distance parameters) with boundary heat flux (from several hundreds to 50,000 W/m^2). It is found that in microchannels vortex flow is generated by applied boundary heat flux. The thin hot boundary perturbation and thermal–mechanical process of near-critical fluids are major factors. The local span-wise and horizontal parameter changes are also analyzed for the unique near-critical fluid flow. The heat transfer characteristics, especially horizontal acceleration and expanding features are also discussed in this study.

1. Introduction

With the fast developing of micro-electrical engineering, the demand of miniaturized structures and much more intensified heat and/or mass transportation has brought about new challenges. For example, in micro-chips, both the capacity and amount of information flow increase day by day while the size also goes down very quickly (now even nano-sized chips are not rarely seen), leading to orders of magnitude increased energy intensity. Micro-scale pipe/channel flow can be of great importance when treating those kinds of micro technologies and critical flow conditions and in solving the problem of high intensity micro-scale heat and mass transportation [1–5]. Due to the micro-scale scaling effects, large discrepancies have been found between theoretical and experimental results. In addition, when results of different groups are compared, great differences are also usually seen [6].

In recent years, supercritical fluids have also been proposed in such micro-scale energy transportation systems [7]. The stability and heat transfer behaviors of such fluids show advantages over traditional kinds [8,9] and new mechanisms have also been identified in related systems [9,10]. Indeed, the micro-scale effects have been reviewed by Gad-et-Hak [11]. Such effects may include rarefied gas effect, fluid properties, compressibility effect, boundary slip effect, wall roughness and wall structure, surface tension and wettability, etc. Rosa et al. [3] made a concise review on the micro channel single phase convective heat transfer and suggested that differences among published results still exist and there is no generally accepted model for the prediction of single-phase heat transfer in microchannels. Rostami et al. [12] reviewed the micro channel gas heat transfer and convective flow and recommended the study into local heat transfer and pressure behaviors in microchannel flows to explore the deviations from traditional sized channels. Later, Morini [5] and others [12] also reviewed the experimental studies of single phase microchannel flow and heat transfer in different cross section shapes, the review stressed again the scaling factors and deviations from macro scale correlations. Hetsroni et al. [13] summarized and analyzed the heat transfer correlations and comparisons with experiments, the effects of microchannel cross section geometry, axial conduction of channel walls and viscous dissipation are also included. Traditional heat transfer correlations and continuous Navier–Stokes models are

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Nomenclature

A	inner area of pipe (m^2)
C_p	specific heat (J/kg K)
D	height of the channel (m)
F	viscous dissipation
h	mean heat transfer rate (W/m^2 K); enthalpy (J/kg)
λ	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/h)
Nu	Nusselt number
p	pressure (MPa)
Q	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°Cor K)
V	velocity (m/s)

Greek symbols

β_P	isobaric thermal expansion coefficient (1/K)
ε	dimensionless proximity to the critical point
ρ	density (kg/m^3)
μ	viscosity (kg/m s)
v	kinematic viscosity (m^2/s)
χ_T	isothermal compressibility (1/Pa)
$\Phi = \sigma_{ij}(\partial u_i/\partial x_i)$	dissipation function
σ_{ij}	viscous stress tensor

Subscripts

0	initial state
b	bulk fluid
c	critical value
in	inlet
out	outlet
pc	pseudo-critical
w	wall

found valid for microchannel flows under low Knudsen number condition.

However, special care should be taken when supercritical fluids with nonlinear changing properties or when it reaches the critical point. Also, this situation can be more complicated and also interesting as such kinds of fluids are often proposed to be the loading fluid of micro mechanical parts [3]. In this study, we focus on supercritical CO_2 fluid. CO_2 has no Ozone Depletion Potential (ODP) and much lower GWP than other typical working fluids (e.g. CFCs, HCFs, etc.). With its nonflammable, nontoxic and easy accessibility and its preferable thermal properties, CO_2 has been widely utilized in energy systems [7–10]. Also it should be noted that the use of CO_2 inside closed energy systems will reduce the amount of CO_2 emission to the atmosphere. Near-critical fluids are generally chosen due to their favorable specific heat and transport properties. In Fig. 1, the fluid properties' variations are plotted (from two phase region to above the critical region). The supercritical lines show continuous evolutions with temperature while for sub-critical conditions the lines show breaks, which indicates the phase change process in sub-critical region. In practice CO_2 is more chosen as its critical operation pressure (7.38 MPa) is much lower than that of water (22.06 MPa) [7,8,14–17].

Here we present the concept of micro pipe/channel near critical CO_2 flow and the temperature/pressure variation set in the parameter range slightly above the critical point. As the critical point for CO_2 is 304.13 K (with critical pressure at 7.38 MPa), it is easily reached in micro structure and processes [17,18]. In literature, Bringer and Smith have reported the basic performance of near critical CO_2 pipe/channel flows in the mid of 20th century. Later, more and more supercritical CO_2 channel heat transfer topics have been investigated [7–10,14–23]. However, the mechanisms and critical behaviors of CO_2 fluid flow and heat transfer are still unknown or not clearly explained [9,10], especially for the new behaviors in micro-scales. The major challenges for micro pipe/channel flow with near critical CO_2 fluid can be summarized: (1) near-critical CO_2 is very much expandable and has non-linear thermal-transport properties [24], which may bring about new effects in convective flow structure [9,10]; (2) in micro-scales, supercritical CO_2 has no surface tension, and typical friction laws are found different from traditional ones [7–10] (much different from traditional fluids); (3) complex effect of micro-convection and heat transfer mechanisms in micro channels/pipes [25,26], but without surface tension and in dense phase; (4) expected piston effect and several time scales related with thermal equilibrium process [27], etc.

Due to the above reasons, the micro channel near critical fluid flow and heat transfer is both of importance and at the same time less interpreted in literature [28]. Pioro group [15,16] have made status review about supercritical CO_2 channel flow empirical correlations in millimeter scale and heat transfer classification and reported significant difference in heat transfer from model to model. Also as discussed, less study comes to micro-scale (less than 1 mm) is found. More recently in 2011, Ducoulombier et al. [29] made a quick review of microchannel CO_2 studies and pointed out that very limited publication on microchannel smaller than 0.8 mm can be found. Several experimental and theoretical studies of sub-critical and supercritical CO_2 fluid flow have provided useful information on the friction loss and heat transfer behaviors, but discrepancies are also found for different groups: (1) under specific microchannel designs, the flow correlation becomes difficult for comparison; (2) if the same standard or reduced parameters are used, comparison becomes obviously strange and large deviations can be found; (3) due to the special properties of near-critical CO_2, the correlation is seen to be greatly case-dependent. Indeed, only several groups have done related work in micro-scale fluid flow and heat transfer as summarized in Table 1. It is seen from Table 1 that very limited geometric design and operation parameters can be referred in literature. Furthermore, it is reported in those studies that both the pressure loss laws and heat transfer behaviors are very different from previous studies of ordinary pipes/channels, which are still left less explained. Also it should be noted that, due to the recent results of Chen and Zhang group [9,10], near-critical CO_2 fluid flow in microchannels with height of 100–500 μm will show abnormal scaling effect from stable laminar flow to vortex evolution, and finally the flow can be dominated by thermal plume structures. The discussion of near-critical region from supercritical region mainly falls in the slightly above critical point, or from the critical point to the pseudo-critical point and the nearby region where the fluid properties go through dramatic changes [9,10]. In that study, the specialties of near-critical fluid dynamics and stability controlling factors are also discussed [10], showing that future work is urgently needed to meet the new challenges of flow and heat transfer of near-critical fluid in micro-scales.

The current study is one continuation of previous studies in microchannel supercritical fluid convective flow [9,10]. By using