Buoyancy Influenced Heat Transfer Performance of Supercritical Carbon Dioxide in Microchannel Heat Exchangers—Horizontal Flow Configuration

Saad A. JAJJA [1], Brian M. FRONK [1,*]

* Corresponding author: Tel.: +1-541-737-3952; Email: brian.fronk@oregonstate.edu
1. School of Mechanical, Industrial & Manufacturing Engineering, Oregon State University, Corvallis, OR, USA

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Introduction

Microchannel based heat exchangers employing supercritical carbon dioxide (sCO_2) as a heat transfer fluid are poised to become integral components of the next generation of highly efficient energy systems. Potential applications include the receivers for concentrated solar power tower systems [1-2], printed circuit heat exchangers (PCHE) for the recuperators in supercritical Brayton cycles [3], and thermal management of high heat generating electronics [4]. The effective design of these next generation of heat exchangers requires a thorough understanding of the heat transfer behavior of supercritical carbon dioxide in microchannel flow geometries. This is especially true in the vicinity of the critical point where the thermophysical properties of sCO_2 change drastically, as shown in Figure 1.

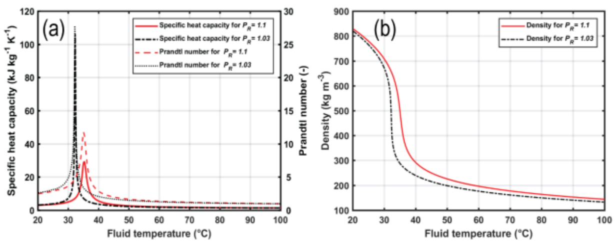

Figure 1. *Variation in the thermophysical properties of carbon dioxide as a function of temperature*

There is a sharp increase in the specific heat capacity and Prandtl numbers at the pseudo-critical point with an attenuation in the peak at increased reduced pressures. In contrast, increasing the temperature at a given pressure causes sCO_2 to transition from a high density 'liquid-like' to a low density 'gas-like' fluid without any discontinuity. The standard approach to predict the heat transfer performance with variable thermophysical properties involves the use of property ratio method which adds some additional correction terms to the Dittus-Boelter type correlations. However, the heat transfer phenomenon in the vicinity of the critical point is further complicated due to the presence of sharp gradients in the fluid density. Presence of these large density gradients induces buoyancy forces which renders the use of single phase turbulent flow correlations to predict the heat transfer performance inappropriate.

The present study experimentally investigates the turbulent heat transfer performance of sCO_2 in a microchannel heat exchanger test section operating in a horizontal configuration. This 316/316L dual certified, high pressure test section has five parallel channels with a 0.75 mm hydraulic diameter, each with an aspect ratio of 1 and a channel length of 50 mm. A single-wall constant heat flux boundary condition is used in the experiments. The channels are fabricated using computer numerical control machining and the test section sealed using a diffusion bonding technique. To systematically confirm the effects of buoyancy on the heat transfer performance of the test section, experimental data is screened for the presence of buoyancy forces by using theoretically proposed criterion and further confirmed by changing test section orientation.

After the confirmation of the presence of buoyancy effects on the heat transfer, experimental data is collected for different Richardson numbers in an effort to understand the mixed convection effects. Experimentally determined heat transfer coefficients are then compared against those predicted by correlations proposed in the open literature.

Experimental Approach

A schematic of the experimental supercritical heat transfer facility is shown in Figure 2. The facility consists of 99.5% food grade supercritical CO_2 flowing through a closed loop system, coupled to a circulating coolant loop. The sCO_2 loop operates at a single pressure and consists of four primary components: pre-heater, test section, post-cooler, and gear pump. The coolant loop consists of a 5 kW air-coupled chiller with a circulation pump. The schematic of the test section used in this study can be found in Figure 3, illustrating the location of the fluid inlet/exit, cartridge heater, flux meter, and development/heated length.

Data Analysis and Results

To ensure a hermetic diffusion bond, a bonding region without flow channels was required. The bonding region and the unheated development length contribute to potential axial conduction and heat

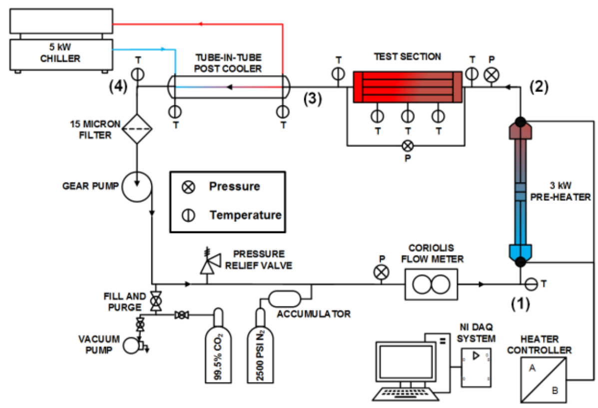

Figure 2. *Schematic of the experimental facility*

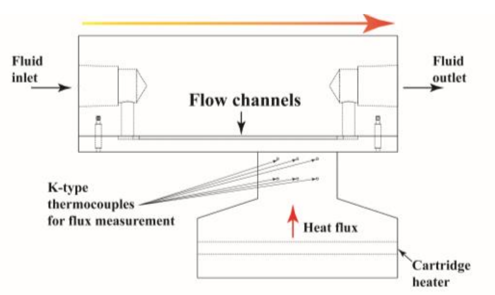

Figure 3. *Schematic of the test section*

spreading at the junction of the flux meter and the main test section that must be accounted for in the data reduction. To address a similar problem of axial conduction in microchannel heat exchangers made of copper, Agarwal and Garimella [5] and Garimella et al. [6] developed a 2D resistance network model to do a segmental conjugate heat transfer analysis of their test section to calculate the refrigerant side heat transfer coefficients. A 2D approach by itself is not sufficient to capture the axial conduction and heat spreading phenomena expected here.

Thus, in the present work, this approach is expanded by using a 3D finite element analysis (FEA) coupled with a 2D resistance network model and solved in an iterative fashion. The 2D model is used to generate a bulk fluid axial temperature profile. The temperature profile is then used in the 3D FEA model as a boundary condition with an unknown convective heat transfer resistance in the microchannel array. Using experimentally measured wall temperatures and applied heat flux, an inverse approach can be used to solve for the unknown heat transfer coefficient. COMSOL Multiphysics was used to carry out the FEA of the test section while the resistance network model was developed in *Engineering Equation Solver* (EES) platform. Initially, experimental data was collected by varying the test section applied heat flux ($20 \le q'' \le 40$ W cm^{-2}), mass flux ($500 \le G \le 1000$ kg m^{-2} s^{-1}) and inlet temperatures ($16 \le T_{in} \le 50$°C) with heat applied from the bottom surface (upward heating). The test section reduced pressure was kept constant at 1.1. Figure 4 shows the trends in the experimentally determined average heat transfer coefficients.

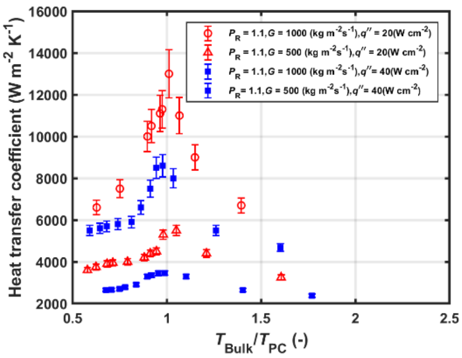

Figure 4. *Trends in the average heat transfer coefficients as a function of the ratio of the bulk fluid temperature and pseudo-critical temperature.*

For supercritical fluids, buoyancy forces across the flow cross section have been found to affect the turbulent flow field which can have a significant impact on heat transfer for both upward vertical, downward vertical and horizontal supercritical flows under high heating and low mass flux conditions. In horizontal orientations, buoyancy can induce circumferential variations of local wall temperature, and likewise heat transfer as a consequence of the stratification of low-density fluid [7-8]. To assess the predictive capability of different correlations objectively, it is essential that the data be screened for the presence of buoyancy effects.

A buoyancy threshold criterion for horizontal flows as defined by Petukhov et al. [9] was used to screen the experimental data in the present study for the presence of buoyancy. Buoyancy forces will affect heat transfer if the ratio of the two Grashof numbers exceeds unity. Figure 5 shows the results of the buoyancy threshold criteria when applied to the experimental test cases investigated in the present study. It is evident that buoyancy effects become significant in the vicinity of the critical point and to further confirm their influence on the heat transfer performance, the test section was inverted (i.e., downward heating). Figure 6 shows the comparison of the average heat transfer coefficients for the two different orientations of the test section for an applied heat flux of 40 W cm^{-2}. In particular, the heat transfer coefficients for a lower mass flux of 500 kg m^{-2} s^{-1} are sensitive to the orientation of the test section which is an indication of buoyancy forces influencing the thermal transport. This is further supported by trends observed for this particular test

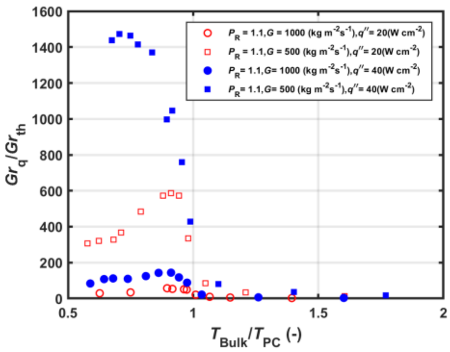

Figure 5. *Buoyancy parameter as a function of the ratio of bulk fluid temperature to the pseudo-critical temperature.*

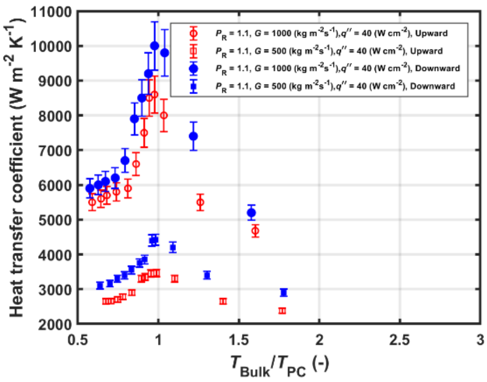

Figure 6. *Comparison of heat transfer coefficients for different orientations of the test section.*

case as shown in Figure 5. This integrative analysis approach confirms the influence of buoyancy forces on the heat transfer performance of sCO_2 in microscale flow geometries.

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