Preliminary Experiment on Upward Supercritical Carbon Dioxide Flow in a Vertical Tube with Metallic Surrounding

Hyung M. Son[a], Jae S. Yoo[a], Kune Y. Suh[a,b*]
[a]*Department of Energy System Engineering, Seoul National University*
599 Gwanak-Ro, Gwanak-Gu, Seoul, 151-744, Korea
[b]*PHILOSOPHIA, Inc.*
599 Gwanak-Ro, Gwanak-Gu, Seoul, 151-744, Korea
[*]*Corresponding author: kysuh@snu.ac.kr*

1. Introduction

Supercritical fluid has the nature of the gas and liquid properties at the same time. Although every fluid can become supercritical by increasing the pressure or temperature conditions, only few of them are being considered or have been utilized for working fluid for the power conversion system due to safety and economic concerns. Among them, CO_2 has such benefits as non-toxicity and abundance while maintaining higher density which results in smaller footprint and reduction in manufacturing cost. For this reason, CO_2 became a strong candidate for the Brayton cycle working fluid in the energy conversion system for next generation power plants. Under normal operation, CO_2 always maintains a supercritical state for the overall cycle. However, under transient conditions, the operating range might become close to the critical point, which results in abrupt change in thermophysical properties and heat transfer characteristics. Therefore, it is quiet important to study the heat transfer characteristics and behavior of the supercritical fluid under the critical or pseudo-critical conditions [1].

2. Experimental Apparatus

2.1 Overall Configuration

The Pressure Applied CO_2 Operation (PACO) is constructed to measure the heat transfer characteristics of the fluid near the critical point. The facility is built to be leak tight up to 9 MPa and booster pump connected with compressor is used to effectively increase the system pressure and the heater is placed before the test section to control the inlet temperature of the working fluid. A gear pump is used to control the mass flow rate of the fluid.

The PACO test section shown in Fig. 1 is of a small circular tube with the inner diameter of 8.1 mm, in which CO_2 flows upward. The outer diameter of the tube is 14.5 mm and is made of type 316 stainless steel (SS316), which is one of the reference structural material used in liquid metal reactor design [2]. A total of 39 thermocouples are installed at the outer wall of the pressure tube, and 2 thermocouples are installed at inlet and outlet location of the flow. The tube is surrounded by metal (copper alloy) block to equilibrate the distribution of heat input in circumferential and axial direction, and 6 cartridge heaters are installed around the inner brass block. The heaters are fixed with outer annulus block which surrounds the inner one. Total height of the section is 2100 mm, of which 800 mm is for the entrance and 100 mm is for the exit, leaving 1200 mm of heated length. The test section is insulated against heat loss in radial direction but top and bottom part is exposed to the atmosphere to enhance the axial thermal diffusion of the surrounding structure.

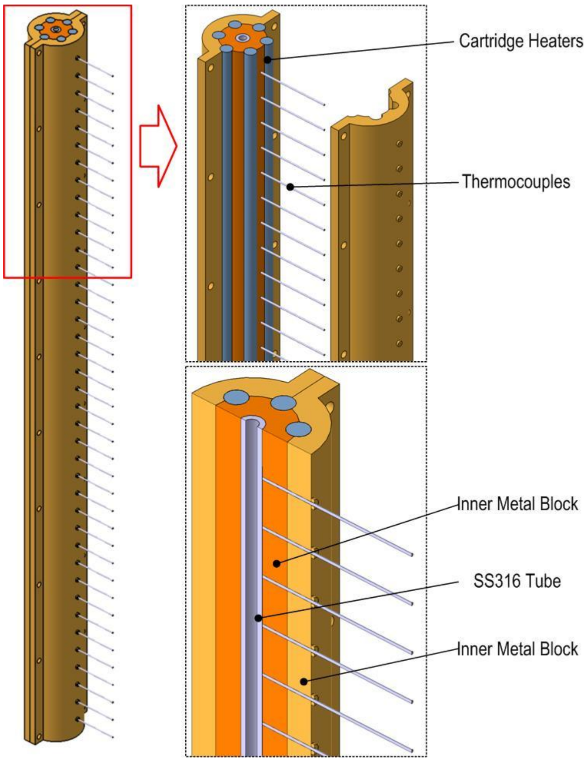

Fig. 1. PACO test section.

2.2 Test Condition

Preliminary test on CO2 fluid flow is carried out. In this study, pressure is maintained around 8.23 MPa, while temperature is kept near 307.15K in the PACO test section inlet to preclude the erratic behavior of the working fluid. Due to free convective boundary conditions on both top and bottom of the test section, the amount of actual heat input from the heaters to the flow region is evaluated by solving steady state form of momentum and energy equations shown below [3]:

$$P_{out} = P_{in} - \left(\frac{\dot{m}}{A}\right)^2 \left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}}\right) - \frac{f}{2D_e\bar{\rho}}\left(\frac{\dot{m}}{A}\right)^2 \Delta z - \bar{\rho} g \Delta z \qquad (1)$$

$$h_{out} = h_{in} + \frac{\dot{Q}_h}{\dot{m}} \qquad (2)$$

where, P is pressure [Pa], $\dot{m}$ is mass flow rate [kg/s], A is cross sectional area of the flow, ρ is density of the fluid [kg/m^3], f is friction factor, D_e is equivalent diameter [m], Δz is height difference [m], g is gravitational constant [m/s^2], h is enthalpy [J/kg] and $\dot{Q}_h$ is heater power [W].

Figure 2 shows the calculated input heat flux and pressure drop along the test section, and the impact of this pressure variation on the fluid properties are quiet minor.

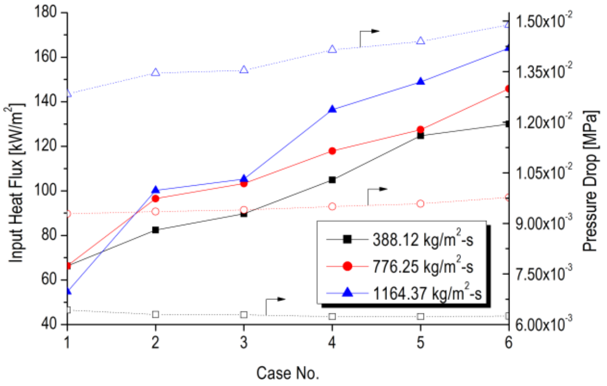

Fig. 2. Input Heat Flux and Pressure Drop on Test Section.

3. Test Results

Figures 3 and 4 show tube wall temperature distribution measured by controlling inlet heat input with mass flow held at specific one for each cases. The high conductivity structure surrounding the test tube seems to smooth out the shape of temperature peaks easily shown on literatures when abrupt change in heat transfer characteristic occurs.

In order to investigate underlying phenomena, numerical analysis code is being developed to test the available heat transfer correlations and uncertainty analysis is underway to evaluate bias error and accuracy of the measured data.

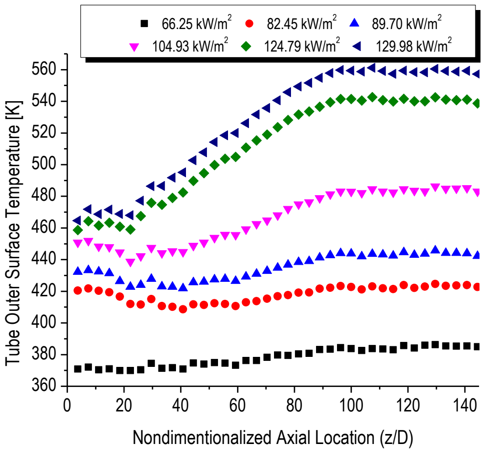

Fig. 3. Tube outer surface temperature distribution (388.12 kg/m^2-s).

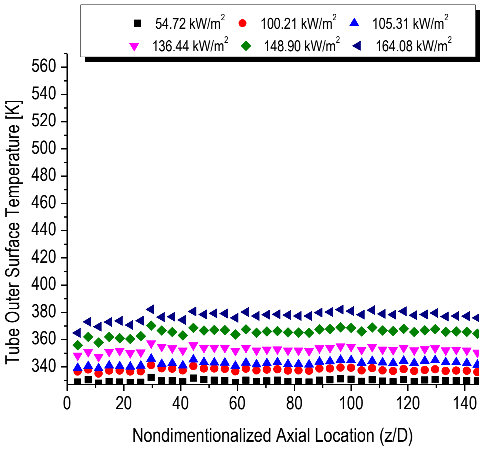

Fig. 4. Tube outer surface temperature distribution (1164.37 kg/m^2-s).

Acknowledgments

This work was performed under the auspices of the Brain Korea 21 Program and as part of the Basic Science Research Program through National Research Foundation of Korea (NRF) funded by the Korean Ministry of Education, Science and Technology (MEST) (NRF-2011-0000906).

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