International Journal of Thermal Sciences 50 (2011) 2430–2442

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Development of a new forced convection heat transfer correlation for CO_2 in both heating and cooling modes at supercritical pressures

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ARTICLE INFO

Article history:
Received 29 December 2010
Received in revised form
5 July 2011
Accepted 7 July 2011
Available online 6 August 2011

Keywords:
Heat transfer
Supercritical CO_2
CFD
Printed circuit heat exchanger

ABSTRACT

Experimental and numerical investigations on forced convection heat transfer of carbon dioxide at supercritical pressures in a prototypic printed circuit heat exchanger under both cooling and heating conditions have been performed in this present study. The experiment test section has nine semi-circular channels with a hydraulic diameter of 1.16 mm and a length of 0.5 m. Primary operational parameters include inlet pressure of 7.5–10 MPa, mass fluxes of 326 kg/m^2 s and 762 kg/m^2 s, inlet temperatures from 10 °C to 90 °C and the average heat flux was 30 kW/m^2. Beyond reproducing the regular experimental cases, numerical modeling also implemented higher heat fluxes of 60 kW/m^2 and 90 kW/m^2 in order to investigate the effect of heat flux. Good agreement was found between the experiments and FLUENT simulations using an SST k–w model with the near-wall region being completely resolved. The distinctive behavior of convection heat transfer at supercritical pressures between heating and cooling modes was systematically analyzed. A more physically reasonable property-averaging technique, Probability Density Function (PDF)-based time-averaged property, was developed to account for the effect of nonlinear dependency of properties on instantaneous local temperature. Furthermore, experimental and computational data were compared to empirical predictions by the Dittus–Boelter and Jackson correlations. The results showed that Dittus–Boelter correlation has better precision for the average value of the predicted heat transfer coefficient but cannot take account of the effect of heat flux. In contrast, the Jackson correlation, with property ratio correction terms to account for the distribution of the properties in the radial direction, could predict the distinction of heat transfer characteristics under heating and cooling conditions. However, it overestimates the average value of heat transfer coefficient in the whole range of the experiment conditions. Finally, a new correlation evaluated by PDF-based time-averaged properties for forced convection heat transfer of CO_2 in both heating and cooling mode at supercritical pressures was developed. Comparison of experimental and computational data with the prediction results by the new developed correlation reveals that it works quite well; i.e., more than 90% data in either heating or cooling mode with various heat fluxes are predicted within an accuracy of ±25%.

1. Introduction

With the increasing concern for the dual threats of climate change and ozone depletion, environmentally benign working fluids have been subjected to further study to replace the conventional ecologically less favorable fluids. Carbon dioxide, a non-toxic and non-flammable fluid, is a promising alternative refrigerant/working fluid, and has been actively considered in a number of heat transport or energy conversion systems including: innovative air-conditioners and heat pumps based on carbon dioxide trans-critical compression cycles, next generation nuclear reactors using supercritical carbon dioxide Brayton cycle either in direct or indirect versions and solar energy powered thermodynamics systems utilizing supercritical carbon dioxide as working fluid for cogeneration of heat, electricity and/or refrigeration.

The supercritical CO_2 Brayton cycle is well suited for certain Generation IV advanced nuclear reactors, which employ a liquid metal or molten salt as the primary coolant with core outlet temperature above 500 °C. By virtue of its high power conversion

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doi:10.1016/j.ijthermalsci.2011.07.004