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Heat transfer to water at supercritical pressures in a circular and square annular flow geometry

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Abstract

A supercritical water heat transfer facility has been built at the University of Wisconsin to study heat transfer in a circular and square annular flow channel. Operating conditions included mass velocities of 350–1425 kg/m^{2}s, heat fluxes up to 1.0 MW/m^2, and bulk inlet temperatures up to 400 °C; all at a pressure of 25 MPa. The accuracy and validity of selected heat transfer correlations and buoyancy criterion were compared with heat transfer measurements. Jackson's Nusselt correlation was able to best predict the test data, capturing 86% of the data within 25%. Watts Nusselt correlation showed a similar trend but under predicted measurements by 10% relative to Jackson's. Comparison of experimental results with results of previous investigators has shown general agreement with high mass velocity data. Low mass velocity data have provided some insight into the difficulty in applying these Nusselt correlations to a region of deteriorated heat transfer. Geometrical differences in heat transfer were seen when deterioration was present. Jackson's buoyancy criterion predicted the onset of deterioration while modifications were applied to Seo's Froude number based criterion.

Keywords: Supercritical water; Heat transfer; Annular

1. Introduction

In order to improve the efficiency of current Light Water Reactors (LWR's), the Generation IV initiative has included the conceptual design of a Supercritical Water Reactor (SCWR) as one of the next steps in future nuclear reactors (US DOE et al., 2002). A SCWR will achieve efficiencies of about 45–50%, compared with current LWR efficiencies of about 33%, by operating its coolant at higher temperature (500 °C) and pressure (25 MPa) than current LWR's (Smith, 1999). These operating conditions are above the pseudo-critical temperature of water (defined as the temperature, for a given pressure, at which the specific heat exhibits a maximum) and thus the coolant of SCW reactors will undergo large thermophysical property changes (Fig. 1). In addition to these SCWR designs, supercritical fluids have been considered in other advanced nuclear reactor designs as part of the power conversion cycle; i.e., liquid–metal cooled and gas-cooled reactor designs (US DOE et al., 2002).

Two key experiments performed by Yamagata et al. (1971) and Shitsman (1963) investigated the thermophysical property variation effects on supercritical water heat transfer in a heated up-flow tube geometry at high and low mass velocities. Yamagata's data were obtained at a relatively high mass velocity of 1400 kg/m^{2}s with varying heat flux. Yamagata's data show that as the bulk enthalpy is increased through the pseudo-critical temperature, an enhancement in heat transfer occurs (Fig. 2). This enhanced heat transfer is diminished by increasing the heat flux and suggests that at some critical heat flux, the enhancement will be completely inhibited.

Shitsman's data (low mass velocity, 430 kg/m^{2}s) indicate that as the bulk coolant enthalpy is increased towards the pseudo-critical temperature, deterioration in heat transfer

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Nomenclature

c_p	specific heat [J/kg K]
$\overline{c_p}$	integrated specific heat, $\frac{i_w - i_b}{T_w - T_b}$ [J/kg K]
D	deteriorating heat transfer
D_H	hydraulic diameter [m]
E	enhanced heat transfer
Fr	Froude Number [–]
g	gravity [m/s^2]
G	mass velocity [kg/m^2 s]
Gr	Grashof number $\frac{(\rho_b - \rho_w) D_H^3 g}{\rho v^2}$ [–]
$\overline{Gr}$	Grashof number $\frac{(\rho_b - \overline{\rho}) D_H^3 g}{\rho v^2}$ [–]
i	enthalpy [J/kg]
k	thermal conductivity [W/m K]
N	normal heat transfer
Nu	Nusselt number $\frac{h D_H}{k_b}$ [–]
Pr	Prandtl number [–]
$\overline{Pr}$	$\frac{i_w - i_b}{T_w - T_b} \frac{\mu_b}{k_b}$ [–]
Q''	heat flux [W/m^2]
Re	Reynolds number [–]
T	temperature [°C]
μ	kinematic viscosity [m^2/s]
υ	dynamic viscosity [kg/m s]
$\overline{\rho}$	integrated density $\frac{1}{(T_w - T_b)} \int_{T_b}^{T_w} \rho \, dT$ [kg/m^3]
$\rho_T(\rho_{in} - \rho_f)/(T_{in} - T_f)$	[kg/m^3 K]
ρ	density [kg/m^3]

Subscripts

b	bulk
in	inlet
f	film, based on $(T_b + T_w)/2$
pc	pseudocritical
s	film, based on $(T_{in} + T_{pc})/2$
w	wall

can occur (Fig. 3). At a low heat flux there is indication of a localized enhancement in heat transfer. As the heat flux is increased, the heat transfer progresses from an enhanced condition to a deteriorated condition. In fact, at the highest heat flux case, the heat transfer is so poor that it resulted in a localized temperature spike from 400 °C to 600 °C. However, it should be noted that in difference to two-phase CHF phenomena, the heat transfer recovers after deterioration.

Many of the previous heat transfer experiments with supercritical fluids, both for water and carbon dioxide (a surrogate fluid typically used due its lower critical temperature and pressure), have shown similar deviations from normal heat transfer. In general, deviations from normal heat transfer have been found to occur when the wall temperature is greater than the pseudo-critical temperature and the bulk temperature is less than the pseudo-critical temperature ($T_w > T_{pc} > T_b$) (Cheng and Schulenberg, 2001). This condition means that large property variations occur within the near wall region, which one might expect would greatly impact the heat transfer.

The enhancement, impairment, and deterioration of heat transfer have been described by Jackson and Hall (1979a,b) and can be explained with the help of Fig. 4.

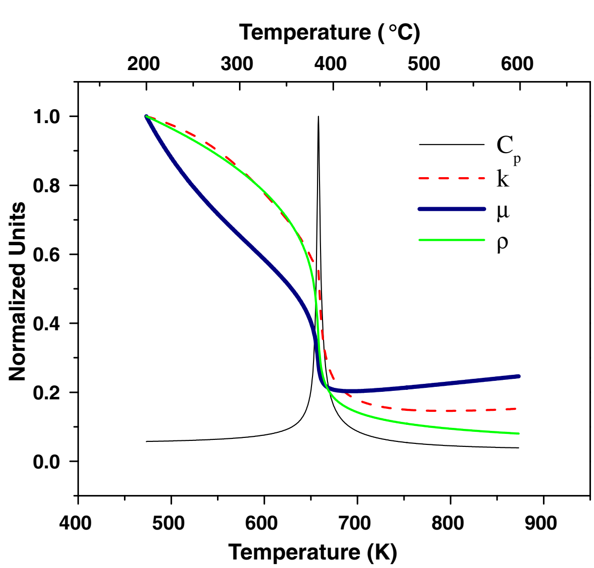

Fig. 1. Thermophysical property variation of water as a function of temperature at 25 MPa.

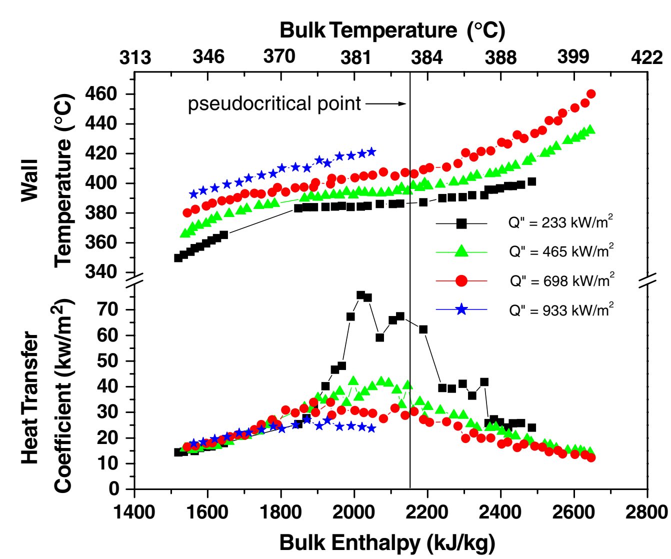

Fig. 2. Yamagata et al. (1971) data exhibits enhanced heat transfer. High mass velocity, low to high heat flux.