Nuclear Engineering and Design 318 (2017) 1–23

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Convective heat transfer at high subcritical pressures in tubes with and without flow obstacles

Ahmad Eter, Dé Groeneveld, Stavros Tavoularis *

Department of Mechanical Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada

ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 3 April 2017
Accepted 7 April 2017

Keywords:
Convective heat transfer
High subcritical pressure
Carbon dioxide
CHF
Obstacles

ABSTRACT

Heat transfer measurements to CO_2-cooled tubes with and without flow obstacles at high subcritical pressures were obtained at the University of Ottawa's supercritical test facility. Tests were performed for vertical upward flow in a directly heated 8 mm ID tube for a pressure range from 6.6 to 7.2 MPa, a mass flux range from 115 to 1000 kg m^{-2} s^{-1}, and a wall heat flux range from 1 to 122 kW m^{-2}. Cases with spacing between obstacles equal to 250, 500 and 1000 mm were investigated. The results are presented in plots of wall temperature and heat transfer coefficient vs. bulk fluid enthalpy. The effects of flow conditions and obstacle geometry and spacing on high subcritical heat transfer have been discussed. Obstacles were found to suppress nucleate boiling, increase the CHF and lower the maximum post-CHF temperature. The maximum increases in CHF and in post-dryout heat transfer coefficient were observed for the obstacles having a spacing of 250 mm. Comparisons of the experimental data with prediction methods for single-phase heat transfer, CHF and post-dryout heat transfer are also presented.

1. Introduction

During startup or postulated accidents, fuel elements of supercritical water-cooled reactors (SCWR) can experience cooling at high sub-critical pressures instead of supercritical ones. Therefore, accurate prediction of heat transfer and critical heat flux (CHF) characteristics at high subcritical pressures is essential for SCWR design. Knowledge of the effects of flow obstructions, such as fuel rod spacers, under such conditions is also important.

Several early studies have investigated experimentally heat transfer to flow of water in upward vertical, uniformly heated round tubes at high subcritical pressures; these include the studies by Schmidt (1960), Swenson et al. (1962), Miropol'skiy (1962), Bishop et al. (1965) and Herkenrath et al. (1967). Renewed interest on this topic was received in recent years. Some of the main results of the relevant studies will be summarized in the following paragraphs.

Schmidt (1960) performed experiments at high subcritical and supercritical pressures in the range from 17 to 30 MPa for water flows in vertical and horizontal tubes with 8 mm ID. He noted a significant decrease in CHF as the pressure approached the critical value. As a result of this, the CHF location and the maximum temperature location shifted towards lower enthalpies, as pressure was increased under constant wall heat flux. Further increases of the system pressure above the critical pressure at the same heat flux and mass flux led to a gradual disappearance of a maximum in the wall temperature profile at a pressure of 30 MPa ($P/P_c = 1.36$).

Swenson et al. (1962) investigated heat transfer to upwards vertical flow of water in a stainless steel tube with 10.4 mm ID at a pressure of 20.7 MPa, mass fluxes of 994 and 1356 kg m^{-2} s^{-1}, and inlet specific enthalpies in the range 1760–2220 kJ kg^{-1}. They also investigated the case of an internally ribbed carbon-steel tube having an ID of 10.4 mm. Their results showed that, by comparison to the bare tube, the ribbed tube suppressed CHF and maintained nucleate boiling at higher bulk enthalpies. The film boiling data obtained from the bare tube were described within 10% by the modified form $Nu = 0.076\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}$ (Nu, Re and Pr are, respectively, the Nusselt, Reynolds and Prandtl numbers) of the Dittus and Boelter (1930) correlation.

Bishop et al. (1965) performed heat transfer experiments in water flowing in tubes made of hastelloy C and stainless steel 316 with 5.08 and 2.54 mm ID. Their pressure P was in the range 16.69–21.51 MPa ($P/P_c = 0.76$–0.98), the mass flux G was in the range 678–3390 kg m^{-2} s^{-1}, and the exit quality varied from 7 to 100%. With the exception of results at their lowest mass flux of 678 kg m^{-2} s^{-1}, their film boiling data were described within 19% by the expression$\mathrm{Nu} = 0.0193\mathrm{Re}^{0.8}\mathrm{Pr}^{1.23}(\rho_g/\rho_b)^{0.68}(\rho_g/\rho_l)^{0.068}$,

* Corresponding author.
E-mail addresses: eng.eter@yahoo.com (A. Eter), degroeneveld@gmail.com (D. Groeneveld), stavros.tavoularis@uottawa.ca (S. Tavoularis).

http://dx.doi.org/10.1016/j.nucengdes.2017.04.013
0029-5493/

Nomenclature

CHF	critical heat flux, kW m^{-2}
CHF$_{bare}$	critical heat flux in the bare tube geometry, kW m^{-2}
CHF$_{corr}$	predicted CHF using CHF correlation of Appendix B, kW m^{-2}
CHF$_{nfc}$	normalized predicted CHF using CHF correlation of Appendix B at nominal values of P_o/P_c and G_o, kW m^{-2}
CHF$_{obs}$	critical heat flux in the obstructed tube geometry, kW m^{-2}
D	inside diameter of the tube, mm
f	friction factor
G	mass flux, kg m^{-2} s^{-1}
H	heat transfer coefficient, kW m^{-2} K^{-1}
h_b	specific bulk enthalpy, kJ kg^{-1}
h_{fg}	latent heat, kJ kg^{-1}
h_{in}	specific enthalpy at inlet, kJ kg^{-1}
h_{out}	specific outlet enthalpy, kJ kg^{-1}
k	thermal conductivity, kW m^{-1} K^{-1}
L_h	heated length, mm
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number
Nu$_b$	bulk Nusselt number
Nu$_{bare}$	Nusselt number in a bare tube
Nu$_{obs}$	Nusselt number in an obstructed tube
P	system pressure, MPa
P_c	critical pressure, MPa
Pr$_b$	bulk Prandtl number
Q_e	nominal electrical power supplied to the test section, kW
q	heat flux, kW m^{-2}
q_{loss}	heat flux to surroundings (heat losses), kW m^{-2}
q^v	volumetric heat generation, kW m^{-3}
Re$_b$	bulk Reynolds number
r_i	test section inner radius, mm
r_o	test section outer radius, mm
T_b	bulk temperature, °C
T_{in}	test section inlet temperature, °C
T_{Pc}	pseudo critical temperature at supercritical pressures, °C
T_s	saturated temperature, °C
T_w	corrected wall temperature, °C
$T_{w,o}$	tube outer wall temperature (measured by thermocouple), °C
U_g	streamwise gas velocity, m s^{-1}
X	vapour quality
X_{th}	thermodynamic quality
z	axial distance from the unheated test section inlet, mm
z_{do}	boiling crisis (CHF conditions) location, mm
z_h	axial distance from the heated test section inlet, mm

Greek symbols

ΔQ_e	power, W
Δz_{CHF}	axial distance between the CHF location and the downstream edge of the nearest upstream obstacle, mm
Δz_d	axial distance from the downstream end of an obstacle, mm
ε	blockage ratio, %
μ_b	bulk dynamic viscosity, Pa s
μ_g	gas dynamic viscosity, Pa s
ρ_b	fluid density at bulk temperature, kg m^{-3}
ρ_g	gas density at saturation temperature, kg m^{-3}
ρ_l	liquid density at saturation temperature, kg m^{-3}
σ	surface tension, N m^{-1}

Acronyms

DPT	differential pressure transducer
HTC	heat transfer coefficient
ID	tube inner diameter
LHS	left hand side
OD	tube outer diameter
PS	power supply
PT	pressure transducer
RHS	right hand side
SCUOL	University of Ottawa supercritical CO_2 loop
SCWR	super-critical water reactor

where the bulk density was calculated from the gas and liquid densities as $\rho_b = \rho_g(\alpha) + \rho_l(1-\alpha)$ and the void fraction α was calculated by the homogenous model.

Chen et al. (2015) conducted CHF tests for subcooled water at high subcritical pressures in tubes made of Inconel 625 having ID of 4.62, 7.98 and 10.89 mm. The operating conditions were: P = 1–20 MPa (P/P_c = 0.05–0.90), G = 454–4055 kg m^{-2} s^{-1}, and inlet subcooling T_s - T_{in} = 53–361 K. Their data showed that CHF was inversely proportional to $D^{0.35}$, where D is the internal diameter of the tube. The authors correlated their CHF data as CHF $= Cq_s$, where $q_s = (h_s - h_{in})GD/(4L_h)$ was the heat flux that resulted in saturation temperature at the end of the heated length, and $C = \mathrm{Min}\ [2350(1-0.0307P)(G(H_s - H_{in}))^{-0.35}(D/0.008)^{-0.35}, 1.0]$. This correlation predicted the high subcritical data with an error ranging from −15 to 20%.

The experiments in water require expensive high pressure test facilities operating at high temperatures and powers. A more convenient approach for investigating high-pressure subcritical heat transfer is by means of using modelling fluids. Recent studies using refrigerant R-134a as a modelling fluid include the ones by Hong et al. (2004), Vijayarangan et al. (2005), and Chun et al. (2007).

Hong et al. (2004) investigated CHF occurrence for R-134a upward flows in an internally heated vertical annular channel made of Inconel 601. They performed CHF tests at both steady and transient pressures through the critical pressure. The operating conditions were as follows: P = 0.63–3.98 MPa (P/P_c = 0.16–0.98), G = 501, 1002 and 1502 kg m^{-2} s^{-1}, and inlet subcooling T_s - − T_{in} = 14.5, 24.8, 34.5, and 44.3 K. For steady pressures, the CHF value decreased as the pressure approached the critical pressure. Mass flux and inlet subcooling had small effects on the CHF at near-critical pressures. The sharp decrease in the CHF near the critical pressure was attributed to the dramatic decrease in the latent heat h_{fg}. During transient tests with the pressure being reduced from supercritical to high subcritical values, the CHF occurred as soon as the pressure dropped below the critical value.

Vijayarangan et al. (2005) conducted CHF experiments in a vertical stainless steel tube having an ID of 12.7 mm and cooled by R-134a. The operating conditions were as follows: P = 1–4 MPa (P/P_c = 0.25–0.98), G = 200–2000 kg m^{-2} s^{-1}, and exit quality in the range 0.17–0.94. They compared their CHF data with predictions based on the look-up table of Groeneveld et al. (1996) and the correlation of Katto and Ohno (1984). The prediction methods were in good agreement with experimental values for low pressures (P/P_c < 0.5). At high reduced pressures (P/P_c = 0.6–0.94), however, the prediction error varied between 20 and 250% for the correlation of Katto and Ohno (1984) and between −50% and 350% for the look-up table. Vijayarangan et al. (2005) modified the correlation of Katto and Ohno (1984) to the following form