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Local heat transfer coefficient measurements using thermal camera for upward flow of Freon 22 in a vertical tube at supercritical conditions and development of correlations

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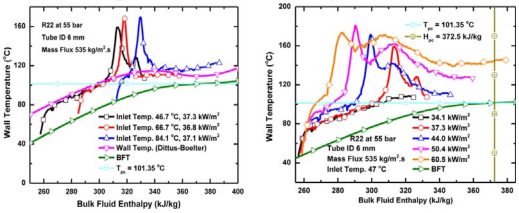
GRAPHICAL ABSTRACT

Heat Transfer at Supercritical Conditions
Wall Temperature Measurement by Thermal Camera



Effect of Inlet Temperature **Effect of Heat Flux**

$$h_{cor} = h_1 - \Delta h_{htd}\, e^{-\frac{\left(H_b - H_{b-\min}\right)^2}{2\sigma^2}}, \text{ Where } Nu_b(h_1) = 0.023\,\mathrm{Re}_b^{0.8}\,\mathrm{Pr}_b^{0.4}\left(\frac{Cp_{ref}}{Cp_b}\right)^x$$

ARTICLE INFO

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ABSTRACT

This paper presents experimental results obtained towards characterizing heat transfer behaviour in supercritical fluids employing R22 as a simulant fluid. It is well known that two regimes exist in supercritical heat transfer, viz., heat transfer enhanced regime and heat transfer deteriorated regime and very limited data exist in the heat transfer deteriorated regime. The use of thermal camera has resulted in obtaining high resolution wall temperature data leading to the identification of the bulk enthalpy at which the peak wall temperature occurs. The results bring out the effect of inlet temperature very precisely, on which not much information is available in the literature. Finally the work identifies a criterion for the onset of heat transfer deterioration and correlations to predict the complete heat transfer behaviour exhibited by supercritical fluids. These correlations are shown to predict satisfactorily with a large number of experimental data available in the literature.

1. Introduction

The heat transfer behaviour of a fluid in the supercritical state is an important input for the performance evaluation of the Super-Critical Water cooled Reactor (SCWR) of Generation IV nuclear power plants. SCWRs have a high overall thermal efficiency of about 45–50% due to

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Abbreviations: CV, Control Valve; DPT, Differential Pressure Transducer; HTC, Heat Transfer Coefficient; HTD, Heat Transfer Deterioration; HTE, Heat Transfer Enhancement; PIEs, Postulated Initiating Event; PT, Pressure Transducer; RMSD, Root Mean Square Deviation; SCWR, Super-Critical Water cooled Reactor; TC, Thermo-Couple; TS, Test Section; V, Valve (isolation Valve)

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Nomenclature

English Symbols

Cf_1	correction factor
Cp	specific heat at constant pressure, J/kg K
$\overline{Cp}$	average specific heat within the range of $(T_W - T_b)$ $\overline{Cp} = \frac{H_w - H_b}{T_w - T_b} = \frac{1}{(T_W - T_b)} \int_{T_b}^{T_W} Cp dT$, J/kg
G	mass flux, kg/m^2s
g	acceleration due to gravity, m/s^2
H	enthalpy, J/kg
h	heat transfer coefficient, W/m^2K
P	pressure, Pa
q	heat flux, W/m^2
T	temperature, K
T_1	where bulk fluid temperature is less than pseudocritical temperature and specific heat is 1.4 times Cp_{ref}
T_2	where bulk fluid temperature is more than pseudocritical temperature and specific heat is 1.4 times Cp_{ref}
x	exponent in ND_{0m}

Greek Symbols

β	volumetric thermal expansion coefficient, 1/K, $\left(-\frac{1}{\rho}\frac{\partial\rho}{\partial T}\right)$
Δ	difference
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
θ	Non-dimensional temperature
ρ	density, kg/m^3

Non-Dimensional Numbers

Bo^*	buoyancy Number; $\left(Bo^* = \frac{\overline{Gr}}{\mathrm{Re}^{2.7}\overline{\mathrm{Pr}}^{0.5}}\right)$
$\overline{Gr}$	average Grashof number; $\left(\frac{g(\rho_b - \bar{\rho})d^3}{\rho_b \nu_b^2}\right)$
ND_0	new non-dimensional number; $\left(\frac{q\mu_{pc}}{G\mathrm{Pr}_{pc}^{0.5}k_{pc}\Delta T_0}\right)$
ND_{0m}	modified new non-dimensional number, $\left(\frac{q\mu_{pc}}{G\mathrm{Pr}_{pc}^{0.5}k_{pc}\Delta T_0}\right)\left(\frac{C_{pc}}{C_{pc^*}}\right)^{0.55}$
Nu	Nusselt number; $\left(\frac{hd}{k}\right)$
Pr	Prandtl number; $\left(\frac{\mu Cp}{k}\right) = \left(\frac{\nu}{\alpha}\right)$
$\overline{\mathrm{Pr}}$	average Prandtl number; $\left(\frac{\mu\overline{C}_p}{k}\right)$
Re	Reynolds number; $\left(\frac{\rho \mathrm{v} d}{\mu}\right)$
θ	non-dimensional temperature $\left(\theta = \frac{T - T_{pc}}{\Delta T_0} = \frac{T - T_{pc}}{T_{pc} - T_c}\right)$ for Cheng et al. (2011)
θ	non-dimensional temperature $\left(\theta = \frac{T - T_{pc}}{\Delta T_0} = \frac{T - T_{pc}}{T_2 - T_1}\right)$ proposed presently
θ_i	non-dimensional inlet temperature $\left(\theta = \frac{T_i - T_{pc}}{\Delta T_0} = \frac{T_i - T_{pc}}{T_2 - T_1}\right)$ proposed presently

Subscript

b	properties at bulk fluid temperature
cor	correlation
c	critical point
DB	Dittus-Boelter
htd	heat transfer deterioration
h-min	*minimum heat transfer coefficient*
min	minimum
M	*model*
P	prototype
p	primary
pc	pseudocritical
pc^*	at the reduced pressure of 1.1022
ref.	reference value.
0m	modified
1	where bulk fluid temperature is less than pseudocritical temperature and specific heat is 1.4 times Cp_{ref}
2	where bulk fluid temperature is more than pseudocritical temperature and specific heat is 1.4 times Cp_{ref}

Super-subscript

x	exponent of new non-dimensional number ND_0
*	ratio of thermo-physical properties at bulk fluid temperature to its value at pseudocritical temperature

their high operating pressures and temperatures. Previous experimental studies towards characterizing heat transfer behaviour of a fluid in the supercritical state have shown that there is a large enhancement in Heat Transfer Coefficient (HTC) at low heat flux values and a progressive reduction in the HTC near the pseudocritical temperature as the heat flux to mass flux (q/G) ratio increases. However, at high values of q/G, there is a sharp drop in the HTC well before the fluid reaches the pseudocritical temperature after which there is some recovery. The behaviour of heat transfer can be classified into three classes, viz., Heat Transfer Enhancement (HTE), Normal Heat Transfer (NHT) and Heat Transfer Deterioration (HTD) respectively (Refer Pioro and Duffey (2006)). The third phenomenon is important as it leads to a sharp rise in the wall temperature in the reduced HTC region. Such a rise in the nuclear fuel clad temperature during high q/G experienced during reactor off-normal conditions may lead to its failure and result in the release of radioactive nuclides into the coolant streams. The procedure for licensing a nuclear reactors requires deterministic safety analyses to be carried out for several Postulated Initiating Events (PIEs) to ensure that a proposed design is capable of meeting the acceptance criteria (like maximum clad temperature, thermal strain, etc.) prescribed for the safety of nuclear plants. Accident analyses for licensing are carried out using system thermal hydraulics codes in which well established and validated correlations for HTC have to be built in. However, satisfactory correlations do not exist to predict the HTC in the HTD regime. This has been one of the prime motivations for the present study.

Several studies have been reported characterizing the heat transfer behaviour at supercritical conditions using water as the working fluid. Yamagata et al. (1972) investigated forced-convective heat transfer in a tubular test section having vertically upward flow of water at supercritical conditions and reported a substantial increase in HTC in the vicinity of the pseudocritical temperature. The peak value of HTC decreased as the heat flux was increased and the bulk fluid enthalpy at which the peak HTC appears was reported to decrease slightly with the increase in heat flux. Similar behaviour has also been reported by Swenson et al. (1965), Kondratev (1969), Yoshida et al. (1972) etc., in the HTE regime.

Shitsman (1963) and Alekseev et al. (1976) reported experimental data for heat transfer in tubes for vertically upward flow of supercritical water. The threshold value of q/G beyond which HTD appears was reported to be 0.7 kJ/kg by Shitsman (1963) and 0.92 kJ/kg by Alekseev et al. (1976). The magnitude of peak wall temperature was reported to increase with the increase in heat flux and its position shifted progressively towards the lower bulk fluid enthalpy region. However, these two experimental studies were carried out at different inlet temperatures and at different test specifications. Many other