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Heat transfer analysis at supercritical pressure using two layer theory

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ABSTRACT

Supercritical fluids are gaining popularity mostly after introduction of supercritical power plants. Efficiency increment, elimination of dry out problem are some major advantages. But due to steep variations of thermophysical properties at supercritical pressure, heat transfer may ‘enhance’ or ‘deteriorate’ depending upon temperature range. Several correlations specific to supercritical pressure are available in the literature to deal with it but, are mostly unable to take deterioration into account. This study aims to analyze heat transfer phenomena at supercritical pressure. Two layer turbulent theory for heat transfer has been used to analyze the heat transfer phenomena with two separate models viz. wall function and thermal resistance analogy. Theoretical results were compared qualitatively and quantitatively for carbon dioxide and HCFC-22 and agreement was seems to be good at lower heat flux. Theory is able to take deterioration into account at higher heat flux but further work is needed to improve the reliability and accuracy of the theory.

1. Introduction

The Supercritical water cooled reactors (SCWR) are one of the candidates suggested in Gen-IV International Forum (GIF) among other five reactors with the aim of higher cycle efficiency, compact size of steam turbine and re-heaters, omission of steam dryer & steam separator, elimination of dry out problem [1,2]. There are several other advantages, for example high power density, a small core, a small containment structure, better fuel economy, a lighter fuel load, and reduced heat loss [3]. Apart from SCWR, supercritical fluids are extensively used in various other applications for e.g. fuel for supersonic transport (supercritical hydrogen and methane), refrigerant for air-conditioners and refrigerators (supercritical carbon dioxide), working fluid in ultra-supercritical fossil power plants and oxidizer for waste treatment (supercritical water), for the processing of macromolecules and bioactive compounds, transformation of geothermal energy, pharmaceutical industries, high pressure sterilization, jet cutting, and thin-film deposition for microelectronics (other supercritical fluids) [4–6]. Solar CO_2 Rankine system (SCRS), tested with evacuated solar collector, utilizes solar energy as energy source and supercritical-CO_2 as working fluid. The results showed that supercritical CO_2 can be a good working fluid to collect heat efficiently [7].

For almost all applications listed above, heat transfer is a key phenomenon. In nuclear reactors, to prevent material overheating of the core cooling channel it is important to predict heat transfer correctly [9]. Also for any heat transfer equipment (evaporator, condenser, radiator, and other heat exchangers) working with supercritical fluids heat transfer characteristics play an important role in their safe and economical design. Therefore, it is necessary to predict heat transfer in most accurate form. Heat transfer at supercritical pressure is completely different and complicated as compared to sub-critical conditions. Heat transfer at near-critical region and pseudocritical point is significantly influenced by steep and nonlinear variation of thermophysical properties [4] as shown in Fig. 1. Pseudocritical point is the point where specific heat shows its peak at given supercritical pressure, generally at pseudocritical point heat capacity has local value of 25 times as compared to neighboring points [4,9]. At low heat fluxes, there is an ‘enhancement’ in the heat transfer coefficient (HTC) as the temperature is approached to pseudocritical temperature and as the heat flux increased, this is offset by ‘deterioration’ in the HTC where the bulk temperature is lower than pseudocritical temperature and the wall temperature is above it [10].

The ‘deterioration’ can be due to rapid radial property variation, acceleration, buoyancy or combination of these phenomena, depending on the conditions [11]. Since water has much higher critical temperature (373.9 °C) and pressure (22.06 MPa) which will require difficult to handle conditions at laboratory scale. Therefore low supercritical pressure fluids (such as CO_2) are used as surrogate fluid [12] to understand the effects and to calibrate. Numerous

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Nomenclature

Symbols

c	isobaric specific heat [J kg^{-1} K^{-1}]
c_f	friction factor [–]
D	diameter [m]
G	mass flux [kg m^{-2} s^{-1}]
g	acceleration due to gravity [m s^{-2}]
L_h	heated length [m]
P	pressure [Pa]
q_w	wall heat flux [W m^{-2}]
R	pipe radius [m]
RE	relative error [–]
T	temperature [K]
u_m	mean velocity [m s^{-1}]
u_τ	shear velocity [m s^{-1}]
y	wall distance in radial direction [m]
α	heat transfer coefficient [W m^{-2} K^{-1}]
ΔT	temperature difference [K]
ε	pipe roughness [m]
κ	von-Karman constant [–]
λ	thermal conductivity [W m^{-1} K^{-1}]
λ_T	eddy thermal conductivity [W m^{-1} K^{-1}]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	standard deviation [–]
τ	shear stress [N m^{-2}]
ω	$\int_{T_{ref}}^{T} \lambda \mathrm{d}T$
h	enthalpy [J kg^{-1}]

Dimensionless number

Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
Pr_T	Turbulent Prandtl number
Re	Reynolds number

Subscript

b	bulk fluid (mass averaged value)
c	central
cs	conducing sub layer
cr	critical
min	minimum
ref	reference
turb	turbulent
var,p	at variable properties
vs	viscous sub layer
w	at the wall
x	at the heated length 'x'
y	at the boundary layer
pc	pseudocritical

Superscript

+	non dimensional form
b	bulk fluid conditions
w	wall conditions

correlations are given for supercritical pressure for different working fluids. But most of them are unable to take deterioration into account. Table 1 summarizes some of selected correlations from literature:

Most of the correlations are based on experimental results and they lose their generality at higher heat flux when unusual heat transfer behavior encounter. Laurien et al. have developed several explicit and implicit equations to predict heat transfer at supercritical heat transfer [9,16–18] based on quasi developed flow assumption. They extended basic heat transfer theories to develop new correlations for supercritical pressure.

In this study, similar approach has been used, first implicit model equations for hydraulic resistance and heat transfer originally given for water by Laurien [20] were extended for carbon dioxide and HCFC-22 with suitable correction factors. Then a simple heat transfer model based upon thermal resistance analogy has been used, which takes variable thermal conductivity into account. Then Numerical modelling has been done and results were validated with experimental data. In the whole analysis, quasi developed flow was assumed and effect of buoyancy and acceleration were neglected.

2. Two layer theory

When a fluid is flowing in a pipe in turbulent conditions, then it can be considered having two layers, (i) Laminar sub layer where molecular transport is influencing and (ii) Turbulent core layer where turbulent transport is influencing (see Fig. 2). Two different models has been proposed based upon this theory in the following sections.

2.1. Numerical wall function model (NWFM)

Laurien [19] made an attempt to develop implicit equations for wall shear stress and wall temperature for both constant and non-constant property. For deriving set of equations, the standard wall function was used to abridge the large gap between wall and the first grid point in flow [17]. Following equation for wall temperature was obtained

$$T_w = T_b + \Delta T_{\text{turb}} + \Delta T_{cs} \quad (1)$$

where

$$\Delta T_{\text{turb}}^{+b} = \frac{\Delta T_{\text{turb}} u_{\tau b}}{q_w/\rho_b c_b} = \frac{Pr_T}{\kappa}\left(\ln R^{+b} - \ln y_{cs}^{+b}\right) \quad (2)$$

$$\Delta T_{cs}^{+w} = \frac{\Delta T_{cs} u_{\tau w}}{q_w/\rho_w c_w} = Pr_w y_{cs}^{+w} \quad (3)$$

where

$$u_{\tau w} = \sqrt{\frac{\tau_w}{\rho_w}}; \quad u_{\tau b} = \sqrt{\frac{\tau_b}{\rho_b}}; \quad R^{+b} = \frac{\rho_b R u_{\tau b}}{\mu_b}$$

$$y_{cs}^{+b} = \frac{y_{vs}^{+}}{Pr_b^{1/3}}; \quad y_{cs}^{+w} = \frac{y_{vs}^{+}}{Pr_w^{1/3}}$$

$$c_f' = \frac{\rho_b}{\rho_w} c_f; \quad u_m = \frac{G}{\rho_b}$$

$$\tau_w = \frac{c_f'}{8} \rho_b u_m^2 \times \left(\frac{\mu_b}{\mu_w}\right)^{0.9}$$

2.2. Simple heat transfer model (SHTM)

According to simple heat transfer model, both layers will offer thermal resistance in the flow of heat, from wall to central layer of fluid. Using this fact, one can derive the equation of heat transfer coefficient by using energy balance equations with some assumptions. In the following analysis, thermal resistance offered by turbulent core layer is neglected. Wall layer thickness is assumed to be very thin to avoid curvature effect of pipe, this assumption allows to use conduction equation in Cartesian form. Following McEligot and Laurien [20]:

Wall heat flux is conducted through thin laminar sub layer, therefore using Fourier's law for heat conduction (through laminar sub layer)

$$q_w = -\lambda(T) \times \frac{\partial T}{\partial y} \quad (4)$$