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Comparison between heat transfer to supercritical water in a smooth tube and in an internally ribbed tube

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ABSTRACT

Numerical studies on heat transfer to supercritical water in an internally ribbed tube were performed and compared with those in a smooth tube. The Shear–Stress Transport k–ω model was adopted and validated against experimental data from tubes with different geometries. Comparisons between upward and downward flows show that the Jackson buoyancy criterion, which was proposed based on analysis and experiments in smooth tubes, can be used to evaluate effect of buoyancy in internally ribbed tubes. Radial profiles of turbulence and property reveal that in both smooth tube and internally ribbed tube, forced convection heat transfer is mainly influenced by specific heat, and effects of thermal conductivity and viscosity cancel each other out. As heat flux and bulk temperature increased, changes in the integral effect of specific heat resulted in variation in the heat transfer coefficient. The Jackson Nusselt correlation for smooth tubes can also accurately predict heat transfer coefficients of forced convection in an internally ribbed tube. Under conditions of mixed convection, buoyancy had a weaker impact on heat transfer in the internally ribbed tube. Detailed velocities and turbulence explained this weaker effect: the sharp drops in axial velocity gradient and turbulent kinetic energy, which occurred in a heated smooth tube at a radial position similar to the law of the wall region for isothermal flow, did not occur in a heated internally ribbed tube. Moreover, friction factors for internally ribbed tubes were always higher than that for smooth tubes in both forced convection and mixed convection.

1. Introduction

Supercritical water experiences significant thermophysical property changes when flowing in vertical heated tubes, especially near the critical and pseudocritical points [1]. One of the most important features resulting from property variations is the abnormal heat transfer, i.e. enhanced heat transfer and deteriorated heat transfer (definitions of these two terms are specified in [2]). When the former occurs, heat transfer coefficient can be as high as 70 kW/(m^2 K) and heated tubes can be cooled with high efficiency [3–6], which is of great interest in supercritical water boilers and reactors. However, local wall temperature rises sharply [7–9] when deteriorated heat transfer happens. Generally, deteriorated heat transfer is more concerned because it relates closely to safe operation of supercritical water facilities. This deterioration and subsequent recovery of heat transfer have been well explained by Jackson and Hall [10–12], and now it is widely believed that at low mass flux impairment of heat transfer is induced by buoyancy forces.

To enhance heat transfer to supercritical water, early attempts featuring the introduction of mature subcritical heat transfer enhancement techniques have been made by various researchers, such as a flow spoiler [13], twisted tapes [14], internal ribs [15], helical inserts [16], etc. These techniques greatly suppress the heat transfer deterioration which happens in the smooth tube (ST) under the same operating condition. By far, the internally ribbed tube (IRT) is the most widely used one in boilers to enhance heat transfer at supercritical pressures as well as to delay film boiling at subcritical pressures [17]. Various researchers have experimentally studied heat transfer to supercritical water in IRTs under different operating conditions, as shown in Table 1. One common conclusion of these studies, as typically shown in Fig. 1(a), is that at relatively high heat flux heat transfer in an IRT can be greatly improved compared with in a ST. While when the ratio between heat flux and mass flux, q/G, is small (at this condition heat transfer deterioration may not happen even in a ST), it seems that internal ribs have much less effect on heat transfer as depicted in Fig. 1(b). Wall temperatures between the ST and the IRT have little difference when fluid bulk temperature, T_b, is below T_{pc}. A further increase in T_b to above T_{pc} leads to a steeper temperature distribution in the ST. This is maybe because internal ribs enhance the

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Nomenclature

Bo	Jackson buoyancy parameter
c_p	specific heat (J kg^{-1} K^{-1})
d	hydraulic diameter (mm)
d_i	major inside diameter, or diameter to root of ribs (mm)
e	rib height (mm)
f	Darcy friction factor
G	mass flux (kg m^{-2} s^{-1})
$\overline{Gr}$	$(\rho_b - \overline{\rho})d^3g/\rho\upsilon^2$
H	enthalpy (kJ/kg)
k	turbulent kinetic energy (m^2/s^2)
L	length (m)
Nu	Nusselt number
N_s	number of starts (dimensionless)
n	parameter in *Bo* (dimensionless)
Pr	Prandtl number
p	pressure (MPa)
q	area-weighted average heat flux on the inner surface of tube (kW/m^2)
q_o	heat flux on the outer surface of tube (kW/m^2)
R	radial position at the inner wall (mm)
r	radial position (mm), $r = 0$ at the center, $r = R$ at the wall
Re	Reynolds number
s	pitch (mm)
T	temperature (K or °C)
u	axial velocity (m/s)
u^*	friction velocity (m/s)
w	rib root width (mm)
x	axial direction (m)
y^+	dimensionless wall distance, $u^*(R-r)/\upsilon$

Greek symbols

α	helix angle (°)
δ	thickness of tube wall (mm)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg/m^3)
$\overline{\rho}$	average density, $(1/(T_w - T_b))\int_{T_b}^{T_w} \rho dT$ (kg/m^3)
μ	dynamic viscosity (Pa s)
υ	kinematic viscosity (m^2/s)
ε	turbulent dissipation rate (m^2/s^3)
ω	specific turbulent dissipation rate (1/s)

Subscripts

b	bulk
c	constant
cr	critical
cor	correlation
exp	experiment
h	heated
max	maximum
pc	pseudocritical point
w	wall

Abbreviations

HTC	heat transfer coefficient
IRT	internally ribbed tube
ST	smooth tube

mixing between bulk fluid and near-wall gas-like fluid, which has much worse heat transfer capability.

Another interesting comparison is displayed in Fig. 1(c), where two well-validated Nu correlations [10,18] for predicting heat transfer coefficients (HTC) in STs are used to calculate HTC in an IRT. Both correlations show good agreement with experimental data and have comparable or even better accuracy with the equation correlated by IRT data (Yang&Pan Correlation). Thus, due to the lack of experimental data obtained in IRTs, at certain conditions (more specifically, when q/G is small) it is a promising way to predict HTC in IRTs using smooth-tube correlations which have been validated by much more data.

Currently it is found that heat transfer to supercritical water in STs and in IRTs share some common features at low q/G while show some difference at high q/G. Though some researchers [19,20] tried to explain this phenomenon, no satisfactory conclusion has been drawn due to the lack of detailed information on velocity and turbulence. This paper targets to numerically compare integral heat transfer and near-wall behavior of turbulence in smooth tubes with those in internally ribbed tubes, and suggest a better explanation on the heat transfer characteristic of internally ribbed tubes.

2. Calculating methods

2.1. Simulation of IRT

Calculating geometries are vertical internally ribbed tubes with a wall thickness of δ as presented in Fig. 2. A uniform heat is input on the outer surface of tube. Inlet profiles of velocity and turbulence are given as those of fully developed turbulent flow, which are obtained by a preliminary isothermal run.

For all computation cases, structured meshes were generated using the commercial preprocessing software ICEM. The near wall region was carefully meshed with much denser grids, as shown in Fig. 2. The distance between the first node and wall was determined such that the dimensionless wall distance (y^+) is always less than 1. The number of nodes in the near wall region was set such

Table 1
Range of investigated parameters for flow of supercritical water in internally ribbed tubes.

Investigator	G, kg/(m^2 s)	q, kW/m^2	T_b, °C	p, MPa	Empirical *Nu* correlation
Ackerman [15]	404	315, 730	216–372	24.82	–
Nishikawa et al. [21]	399–458	436–469	260–445	24.52	–
Lee and Hall [22]	542–2441	250–1570	260–383	24.1	–
Suhara et al. [23]	800–2000	384	180–385	27.4	–
Matsuo et al. [24,25]	1165–1552	210–876	300–380	22.5–24.5	√
Chen et al. [26–28]	400–1000	360–600	300–400	22.5–25	–
Wang WS et al. [29]	450–1800	200–600	320–430	25–34	√
Wang JG et al. [20,30,31]	600–1250	150–650	200–450	12.6–29	–
Yang et al. [32]	230–1200	130–720	300–470	12.0–30	√
Pan et al. [19]	232–1200	133–719	270–480	12.0–30	√
Wang [33]	400–1500	200–600	320–440	22.5–24	√