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Numerical study on the hydraulic and thermal performance of internally ribbed tubes in supercritical pressure and sub-critical two-phase flows

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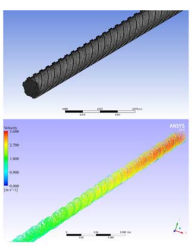
GRAPHICAL ABSTRACT



Streamlines of the supercritical flow inside the internally ribbed tube

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ABSTRACT

This paper numerically investigates the hydraulic and thermal performances of internally ribbed tubes under both sub-critical and supercritical water flows. A real case has been adopted to compare and validate the results with the experimental data. Heat transfer behavior and pressure drop characteristics have been analyzed under different fluid enthalpies. 15 and 25 MPa pressures are used to simulate the water flow inside the ribbed tube. Results indicate that computational method can provide a reliable framework which is capable of predicting the ribbed tubes performance. In sub-critical two-phase flow, vapor volume fraction increases continuously along the tube. It has been observed that the tube maintains the liquid near the wall region and delay the critical heat flux to the post dry-out condition. In supercritical flow, the spiral flow has been captured inside the tube. In addition, the heat transfer enhancement due to the pseudocritical thermophysical properties of the water is resolved.

1. Introduction

Developing power plant boilers working under supercritical pressures along with the supercritical water-cooled reactors (SCWR) make the supercritical flows more of interest nowadays [1,2]. Therefore, prediction of heat transfer and pressure drop in supercritical pressure water flows plays an important role in the design of efficient energy systems. As other applications of supercritical flows one can mention chemical industries, cooling power transmission cables, etc. [1,3]. On the other hand, vapor-liquid multiphase flow still has its applications throughout the industry. Prediction of heat transfer and pressure drop inside the tubes in thermal power plants, refrigeration and heat pump systems leads to the optimum performance of process equipment in these industries [4,5]. Considering the crucial role of tubes performance in both sub-critical and supercritical flows, and increase in energy price imply that enhancing the heat transfer in tubes is a necessary action. In this way, there are a lot of techniques in order to provide heat transfer enhancement (HTE) which are classified as active technology, passive technology and the compound ones [6,7]. As it can be inferred, the passive methods do not employ any additional power source and are of

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Nomenclature

Acronyms

FVM	Finite volume method
HTE	Heat transfer enhancement
CHF	Critical heat flux
RPI	Rensselaer Polytechnic Institute

Symbols

T	Temperature
h	Enthalpy
$\dot{m}$	Mass flow rate
v	Velocity
F	Force
p	Pressure
g	Gravity
d	Diameter
V	Volume
t	Rib height
b	Rib width
d	Tube diameter
f	Bubble departure frequency
N	Nucleate site density
q	Heat flux
Q	External heat transfer

Greek Letters

α	Volume fraction
ρ	Density
μ	Shear viscosity
λ	Bulk viscosity

Subscripts

p	Phase p
q	Phase q
w	Wall
l	Liquid
v	Vapor
d	Bubble or drop
b	Bubble or drop
fv	Latent heat of evaporation
min	Minimum
s	Solid material
wl	Wall lubrication
vm	Virtual mass
td	Turbulent dispersion
G	Gas
E	Evaporation
Q	Quenching

more practical use. To name a few, surface roughness, corrugated channels, twisted tape inserts, and internally ribbed tubes have been used in recent years. Among these tube configurations, the internally ribbed tube is one of the most promising HTE techniques which benefits both sub-critical and supercritical flows.

For the sub-critical flows and in smooth tubes, it is well known that at certain values of vapor fraction, the wall gets dry and heat transfer will be reduced sharply at these locations. This sudden deterioration of heat transfer corresponds to critical heat flux (CHF) that occurs inside the tube [8]. Spirally ribbed tubes can induce a swirl flow and consequently delays the CHF due to the higher inertia of the liquid [5,9]. In the case of supercritical flows, the induced rotational velocity can enhance the turbulence and provide a more uniform velocity profile inside the tube. Hence, the HTE would be observed in supercritical condition too [10,11]. Thus, careful study of internally ribbed tubes improves the energy efficiency below and upper the critical pressure.

There are numerous experimental works focusing on the HTE with the help of ribbed tubes both in sub-critical and supercritical pressures; however, there is a lack of numerical works in this area. One of the pioneers in this area is a work by Zarnett et al. [12] in which the concurrent gas-liquid flow has been analyzed in a tube with spiral ribs. They observed that the gas moves away from the tube wall in air-liquid flow pattern. In another relatively old work, Ackerman [13] investigated the heat transfer inside the smooth and ribbed tubes for supercritical pressure water. He found out that unexpected heat transfer phenomena occur when the pseudocritical temperature locates between the bulk flow and wall temperatures. He called the supercritical heat transfer deterioration pseudo-film boiling to resemble two flow regimes to each other. Cheng et al. [14] conducted some experiments of CHF with smooth and internally ribbed tube. In this work, subcritical pressures were tested under different mass fluxes. They concluded that CHF increases by a factor of 1.3–1.5 especially in the lower pressures. In a similar work by Cheng et al. [4], frictional pressure drop in vapor-liquid boiling flow were investigated. Their experiments showed 60–170% increase in frictional pressure loss in spirally ribbed tubes. Kim et al. [5] studied the CHF inside two ribbed tubes with different number of ribs for R-134a boiling flow. They reported that CHF increase in ribbed tubes depends on rifled geometry and flow parameters such as pressure and mass flux. After developing supercritical power plant boilers, heat transfer characteristics of internally ribbed tube were studied by Wang et al. [3]. In their experiments with supercritical water, they varied the pressure and wall heat flux and analyzed the reasons behind the heat transfer deterioration and enhancement in this region. They recognized three heat transfer modes for supercritical pressure and resembled the heat transfer deterioration to DNB at subcritical pressures. In two recent works presented by the authors [7,15], it was tried to address the issues in both subcritical and supercritical pressure flows. First, an inclined ribbed tube were tested under different mass flux and heat flux conditions. It was observed that effect of mass flux variations is highlighted in supercritical regime. In the second work, effect of inclination was investigated for internally ribbed tubes in different pressures. It was shown that frictional pressure drop reaches its minimum value at 5°. It is also worth noting that there are a lot of works studying the similar passive heat transfer methods in different tubes such as the corrugated channels and tubes with twisted tape inserts [16–21].

As it was mentioned, there are no numerical works on three-dimensional simulation of such flows in the spirally internally ribbed tube. The most relevant works have focused on similar artificial geometries or two-dimensional ribs in the channels. For instance, Ma et al. investigated the effect of rib height inside the channels with a 2D model [22]. They reported that increased rib height leads to a heightened disturbance which enhances the heat transfer. In another work by Desrues et al. [23], some geometric parameters were defined for the ribbed channel and friction factor was calculated for different Reynolds numbers. On the other hand, there are several works in which the supercritical or two-phase flow is tried to be modelled. However, these studies are all allotted to the smooth tubes [24–29].

In this study, heat transfer and pressure drop in internally ribbed tubes have been investigated numerically in both sub-critical and supercritical pressures. ANSYS Fluent software package is chosen as the flow solver so as to model both phase change in sub-critical and drastic changes of thermophysical properties in the supercritical region. Euler-