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Study on two-phase flow instabilities in internally-ribbed tubes by using frequency domain method

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HIGHLIGHTS

- A new model is made to study two-phase flow instabilities in internally-ribbed tubes.
- Two significant improvements are made to the conventional models.
- Two-phase flows in internally-ribbed tubes are more stable than that in smooth tubes.
- The 6-head ribs internally-ribbed tube is more stable than the 4-head one.

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ABSTRACT

A new mathematical model was proposed in this paper based on the frequency domain theory to investigate two-phase flow instabilities in internally-ribbed tubes. Two significant improvements were made to conventional models, one of which was that the heat storage of the tube wall metal, the internal wall heat flux and the external wall heat flux were considered as dynamic parameters, and another one was that a new feedback relationship was established. The new model was verified by comparing the prediction results to both the corresponding experimental data in literature and the results obtained with SIMULINK. Then the two-phase flow instabilities in internally-ribbed tubes were studied systematically. It was shown that the stability of two-phase flows increased with pressure, mass flux or inlet resistance coefficient. It was also found that there existed a worst point of the stability (WPS) of the two-phase flows when the inlet fluid subcooling increased. Two-phase flows in the 6-head ribs internally-ribbed tube (ϕ38.1 × 7.5 mm) was more stable than that in the 4-head ribs internally-ribbed tube (ϕ28 × 5.41 mm). The present model and results could provide guidance for the design and operation of boilers.

1. Introduction

In recent decades, the two-phase flow instability attracts lots of scholars' attentions, because it may cause oscillations of flowing and thermal parameters of the two-phase flow systems, such as the boiler water wall in thermal power plants, the steam generators in nuclear power plants and the heat exchangers in chemical engineering, etc. Undesirable oscillations may result in the boiling crisis, and even induce the thermal fatigue of the pipes and the disrepair of the equipment. Therefore, much effort had been made to study the two-phase flow instabilities [1–5].

Based on the results of early research, the two-phase flow instability is usually divided into two categories [6], i.e., the static instability and the dynamic instability. The static instability means there are non-periodic migrations of flow rate of the two-phase flows in tubes, and the dynamic instability refers as the self-sustained oscillations occurred in tubes. Both of the above mentioned two-phase flow instabilities may occur in the smooth tubes and other enhanced heat transfer tubes, such as the internally-ribbed tubes.

Smooth tubes have been widely used in two-phase flow instability studies due to the fact that smooth tubes are the most commonly used pipes in various heat exchangers. The density wave instabilities in smooth tubes of a once-through boiling flow system was analyzed by Takitani et al. [7–9], based on experimental studies and theoretical analyses, and the stability boundaries of the joule-heated and sodium-heated systems were proposed. Pustylnik et al. [10] investigated the instabilities of two-phase flows in parallel smooth channels, and found that the stability of system was affected by the number of channels and the inlet mass flux of the flow. Kakaç & Cao [11] got the stability boundary by using the

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Nomenclature

A	area, m^2
C	intermediate variable
C_w	metal specific heat capacity, J/(kg K)
D	diameter, m
g	acceleration due to gravity, m/s^2
G	mass flux, kg/(m^2 s)
h	enthalpy of fluid, J/kg
K	coefficient of local friction
l	length of the tube, m
L	width of rib, m
N	number of ribs of an internally-ribbed tubes
P	pressure, Pa
Q	heat power per unit length, kW/m
s	Laplace transfer factor
t	time, s
T	temperature, K
V	volume of water filled in the internally-ribbed tube, m^3
x	dryness fraction
$\overline{Z}$	height, m
$\overline{\text{ExternalInput}}$	the external input perturbation of the feedback system
$\overline{\text{Input}}$	the input perturbation of the feedback system
$\overline{\text{Output}}$	the output perturbation of the feedback system
$G(s)$	the forward transfer function
$H(s)$	the feedback transfer function
$K(s)$	the pre-compensator of external input perturbation

Greek letters

α	convective heat transfer coefficient, W/(m^2 K)
λ	coefficient of frictional resistance
π	pi digits (3.1415926)
ρ	density, kg/m^3

Non-dimensional numbers

$\overline{g}$	acceleration due to gravity
$\overline{h}$	enthalpy of fluid
$\overline{\Delta p}$	pressure difference
$\overline{q}$	heat flux
$\overline{t}$	temperature
$\overline{z}$	height

Superscripts

*	static value
′	intermediate variable in the derivation of transfer functions

Subscripts

sr	superheating region
tr	two-phase flow region
pr	preheating region
in	inlet of the tube
out	outlet of the tube
pt	interface between preheating region and two-phase flow region
ts	interface between two-phase flow region and superheating region
f	water
g	steam
w	metal wall
wout	metal wall at the outlet point
hsm	heat storage of wall metal
ex	external of the tube
wpp	water physical property coefficient
cir	the circumferential direction
avg	average

Prefixes

δ	perturbation value of the dynamic parameter
Δ	difference value

Abbreviation

CHF	critical heat flux
M-CHF	minimum critical heat flux
WPS	the worst point of the stability

drift-flux model in both vertical and horizontal tubes. Later, a multivariable frequency domain mathematical model was established by Hou et al. [12], and was applied in the study on the two-phase flow instabilities in once-through steam generators, and it was shown that the methods could conveniently predict the two-phase flow instabilities in parallel smooth channels. Su et al. [13] studied flow instabilities in parallel smooth channels by using the time domain analysis method, and influences of various parameters on system's instabilities were also revealed. Similar results also can be found in some other works [14–18].

Besides the smooth tubes, there are also a few studies on the two-phase flow instabilities in enhanced heat transfer tubes. Mentes et al. [19] studied the two-phase flow instabilities in six vertical enhanced heat transfer tubes, and found that the two-phase flows in these enhanced heat transfer tubes were more stable than that in the smooth tubes. Widmann et al. [20] studied the two-phase flow instabilities in horizontal enhanced heat transfer tubes, and obtained the similar results. Later, Karsli et al. [21] also carried out experiments to investigate the two-phase flow instabilities in five different enhanced heat transfer tubes. All these studies showed that the difference in geometrical structures of tubes might cause great differences in the instability behavior of the two-phase flow.

The internally-ribbed tube, as one of the most widely used enhanced heat transfer tubes, plays an important role in the design and flow stability control of the boiler water-cooled wall system and other heat exchanger systems. Hence, many experimental researches have been conducted to study the instability phenomena in internally-ribbed tubes. Gao et al. [22,23] proposed four semi-empirical equations to predict the critical points of two-phase flow instabilities in the smooth tube (ϕ25 × 2.5 mm) and in the internally-ribbed tube (ϕ38.1 × 7.5 mm), based on the experimental studies. Moreover, experiments were conducted on high pressure two-phase test loops by Huang et al. [24], and revealed the influences of heat flux, asymmetric heat flux, pressure, mass flux, inlet sub-cooling on density wave oscillation in vertical parallel internally-ribbed tubes (two internally-ribbed tubes with the same structures, ϕ31.8 × 6 mm).

It is worthy to note that most of the previous studies on two-phase flow instabilities in the internally-ribbed tubes are carried out by experiments. On the other hand, two-phase flow instability characteristics in different internally-ribbed tubes are greatly different from each other due to the different two-phase flows and heat transfer behaviors caused by different internally-ribbed structures. It is very necessary to build proper theoretical models to facilitate the study of the two-phase flow instability