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A new model for studying the density wave instabilities of supercritical water flows in tubes

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HIGHLIGHTS

- A new model is made to study the density wave instabilities of supercritical water.
- A new regional partition of SCW is proposed and employed in this model.
- Three previous models proposed by different researchers are used for comparison.
- The present model is proved to be more suitable and accurate.

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ABSTRACT

A new model is presented in this paper to study the density wave instabilities of supercritical water (SCW) flowing in tubes. A new regional partition of SCW is proposed in this model for better dealing with the great variations of physical properties of SCW in the neighborhood region of pseudo critical point, based on the analyses of the physical properties of SCW. According to the frequency domain method, the new model is employed to study the density wave instabilities of SCW flowing in tubes, and the calculation results are compared with the experimental data in literature, together with the calculation results of three previous models proposed by different researchers. According to the comparisons, the present model is proved to be more reasonable and accurate than the other three models. The relative error of the present model is less than 26%, while that of the other three models are all greater than 30%. Hence, it is believed that the present model can provide well guidance for the design and operation of supercritical boilers, steam generators and other relevant heat exchangers.

1. Introduction

The supercritical water (SCW) has been widely used in various industries such as power engineering, chemical engineering, aerospace engineering and refrigeration engineering [1]. Great efforts have been made by many scholars [1–3] to study how to use SCW safely and efficiently.

Since the density wave instability of SCW will lead to heat transfer deterioration and equipment damage, it has been the hot topic in the study of the safe use of SCW. However, it is difficult and complex to study the density wave instability of water under supercritical pressures, due to the tremendous changes of the physical properties under supercritical pressure conditions. Based on the developments of test technologies, many relevant experiments at supercritical pressures are carried out in the recent decades. Zhang et al. [4]. conducted experiments with different system pressures (21–25 MPa) on the supercritical water test facility in Xi'an Jiaotong University's (XJTU), and large amplitudes of mass flow flux as well as inlet pressure were found in various operation conditions. According to their study, similar effects of parameters were found at near-critical and supercritical conditions, compared with two phase flow instabilities. Joen & Rohde [5] studied the flow instabilities at supercritical pressure by using Freon R23 on a scaled version test facility, and made the relevant stability maps. Flow instability experiments had been also performed in a two parallel-channel system with SCW by Xiong et al. [6], and it was found that the flow became more stable with increasing pressure or decreasing inlet temperature in the range of their experiments (23–25 MPa, 600–800 kg/(m^2 s)).

Because of the limitations of experiment and the complex characters of SCW, theory analysis is another indispensable way to study the density wave instabilities of SCW in tubes. Generally, the

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Nomenclature

A	the point of pseudo saturated water
A'	flow area, m^2
B	the point of pseudo saturated steam
C	intermediate variables
C_p	specific heat at constant pressure, kJ/(kg K)
C_w	metal specific heat capacity, kJ/(kg K)
D	diameter, m
g	acceleration due to gravity, m/s^2
G	mass flux, kg/(m^2 s)
h	enthalpy of fluid, kJ/kg
L	heated length, m
m	constant
n	constant
N_d	number of anticlockwise encirclements of the point (-1, j_0) by Nyquist locus
P	pressure, Pa
q'	surface heat flux, kW/m^2
Q	heat power per unit length, kW/m
S	heated perimeter, m
t	time, s
T	temperature, K
u	velocity, m/s
Z	height, m

Greek letters

α	coefficient of volume expansion, 1/K
λ	coefficient of frictional resistance
ρ	density, kg/m^3

Non-dimensional numbers

N_{SUBPC}	Sub-Pseudo-Critical Number
N_{TPC}	True Trans-Pseudo-Critical Number

Superscripts

*	static value
–	non-dimensional numbers

Subscripts

ex	external region of the tube
pc	pseudo critical point
PSW	pseudo critical water
PSS	pseudo critical steam
opt	the optimal value of coefficient of volume expansion
hr	heavy fluid region
hsm	heat storage of wall metal
mr	heavy & light fluid mixture region
lr	light fluid 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

Prefixes

δ	perturbation value of the dynamic parameter
Δ	difference value

Abbreviation

CHF	critical heat flux
H-F	the heavy fluid region
H-L-M	the heavy & light fluid mixture region
L-F	the light fluid region
SCW	supercritical water
PSW	pseudo critical water
PSS	pseudo critical steam
SVR	the region where physical properties of SCW experience sharp variations

theory analysis methods can be grouped into two categories, i.e., the time domain method and the frequency domain method. Many researchers [7–11] used the time domain method to investigate the density wave instabilities of SCW flows in tubes. However, it always occupied much time for the calculation, and might get the results without any physical meanings sometimes because of the characters of mathematical solution.

The frequency domain method is also widely employed to study the density wave instabilities of SCW flows in tubes [12–19]. As a graphical method, it avoids solving lots of complex governing equations. Zuber [12] carried out a two-region model for the stability analyses of SCW in tubes, where the whole flow region of SCW was considered as the gas-like region and the liquid-like region. Based on the two-region model, the characteristics of density wave instabilities were simply revealed. Antoni & Dumaz [13] proposed a three region model to investigate the density wave instabilities of SCW in tubes, where a specific region of SCW was defined as “two-phase mixture”, and the demarcation points of three regions were the pseudo critical point and a point with “latent heat” of 400 kJ/kg. The three region model was proved better than the two region one. Zhao [14,18] proposed another three-region model for the analyses of density wave instabilities of SCW in tubes, on the basis of the partition method different from that of Antoni & Dumaz [13].

A linear stability analysis code in the frequency domain was developed by Yi [15–17] to study the thermal-hydraulic stability of the supercritical pressure light water reactor at constant supercritical pressure. Then, the thermal-hydraulic stability of supercritical pressure light water reactor for both full-power condition and partial-power condition was investigated. To carry out the steady state and linear stability analysis of a SCW natural circulation loop, Sharma [19] proposed a computer code by using supercritical water properties.

However, because of the complexity of the physical properties of SCW, there is still not a unified model for studying the density wave instabilities of SCW flows in tubes. Concerning the previous studies as mentioned above, the three commonly used mathematical models for the study of density wave instabilities of SCW flows are carried out by Zuber [12], Antoni & Dumaz [13] and Zhao [14], respectively, based on frequency domain method. The three models are derived based on the different partition methods of SCW. Detailed information is shown in the following section.

2. History review

Under subcritical pressures, the flow region in a tube was usually divided into three parts, i.e., the preheating region, the boiling region and the superheating region, for studying density wave instability [20,21]. Considering the similar features of subcritical water and SCW, the models [20,21] derived at the subcritical pressure may also be employed for the relevant study at the supercritical pressure, if the flow region in tubes at the supercritical