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Modeling and analysis of supercritical flow instability in parallel channels

Ting Xiong [a,b], Xiao Yan [a,*], Shanfang Huang [b], Junchong Yu [a,b], Yanping Huang [a]

[a] CNNC Key Laboratory on Nuclear Reactor Thermal Hydraulics Technology, Nuclear Power Institute of China, Chengdu 610041, China
[b] Department of Engineering Physics, Tsinghua University, Beijing 100084, China

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ABSTRACT

With a view to better utilizing and further expanding the experimental results recently obtained on supercritical flow instability, an in-house code has been developed applying time-domain approach. Different ways of geometrical modeling of the test section in the experiments are studied. Comparison between the numerical and experimental results shows that the numerical code is capable to predict well the stability boundaries. Based on the validated code, the geometrical simplification is further discussed and a relatively simple as well as common geometrical configuration is proposed. Discussions also indicate that the entrance and riser sections cannot be eliminated with respect to numerical modeling of flow stability. Effects of inlet temperature and total mass flow rate are numerically analyzed. Results show that the inlet temperature has a non-monotonic effect on the threshold power, while the threshold power is roughly proportional to the total mass flow rate no matter the system is symmetrical or not. Moreover, the results indicate that it would be more difficult to perform flow instability experiments at higher inlet temperature or total mass flow rate.

1. Introduction

Flow instabilities have been a cause for deep concern in the design and operation of many industrial systems and equipments, such as steam generators, thermosiphons, refrigeration plants and nuclear reactors. As for the nuclear reactors, the mainly concerned instability phenomena refer to the flow excursion (Ledinegg instability) and the periodic flow oscillations (density wave oscillations, for example), which should be highly avoided as they perturb the power production and the heat transfer capabilities. Considerable studies, including both theoretical and experimental, have been carried out for the flow instabilities in boiling systems [1–5]. The research has shown that the density wave oscillations (DWO) can occur due to the feedback effect between the flow rate and pressure drop, which is essentially caused by the large changes of density and delay of perturbation propagation through the channel.

On the other hand, a growing interest has been generated in investigating the flow instabilities for supercritical condition, which is motivated by the proposal of the supercritical water-cooled reactor (SCWR). SCWR is one of the Generation IV advanced nuclear reactor systems with water as the coolant. The coolant reaches beyond the pseudo-critical point and changes significantly while passing through the core, raising the speculation that similar flow instabilities would occur in SCWR.

Solution methods for stability analysis of supercritical flow are mainly developed from those for two-phase flow and can be divided into two kinds, including frequency-domain method [6–8] and time-domain method [9–11]. The former one is based on linearized equations that are converted to transfer functions by Laplace transform, while the latter one is based on some kind of numerical discretization and integration in time [12]. Furthermore, commercial software (such as Relap5 and Fluent) has been used to predict the dynamic behavior in the heated channel with supercritical fluid [13–16].

Despite the fact that several numerical methods have been applied in supercritical flow stability analysis, there is a complete lack of experimental validation due to the difficulties related to the very high pressure and temperature for supercritical water. Scaling procedures have been proposed [17,18] to downscale the supercritical water loop for experimental studies by using fluid-to-fluid modeling, so that a proper fluid (e.g. Freon R-23) could be used in the test facility to simulate the SCWR with considerably reduced pressure, temperature and power.

Meanwhile, a supercritical water loop has been constructed in Nuclear Power Institute of China (NPIC). Experiments have been performed recently in a two-parallel-channel system, aiming to offer validation data and state-of-the-art knowledge of basic phenomena for investigations of supercritical flow instability [19]. In order to better utilizing and further expanding the experimental results, an in-house code have been developed applying time-domain approach. In this paper the geometrical modeling of the test section in the experiments is firstly proposed. Then the numerical code is

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* Corresponding author. Tel.: +86 028 85907362; fax: +86 028 85908889.
E-mail address: yanx_npic@163.com (X. Yan).

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Nomenclature

A	cross section area (m^2)
C	coefficient in momentum equation
C_p	specific heat at constant pressure (J/(kg•K))
D	hydraulic diameter of section (m)
f_r	friction factor
g	gravity (m/s^2)
G	mass flux ($kg/(m^2s)$)
h	specific enthalpy (J/kg)
H	height of section (m)
i	spatial grid index
j	temporal grid index
k	pressure drop coefficient
l	length of section (m)
M	mass flow rate (kg/s)
N_{SPC}	sub-pseudo-critical number
N_{TPC}	true trans-pseudo-critical number
ΔP	pressure drop (Pa)
ΔP_f	pressure drop due to friction (Pa)
ΔP_1	pressure drop due to local resistance (Pa)
ΔP_g	pressure drop due to gravity (Pa)
q_1	linear power density (W/m)
Q	heat power (W)
Re	Reynolds number
t	time (s)
Δt	time step (s)
T	temperature (K)
u	velocity (m/s)
z	axial distance (m)
Δz	spatial grid size (m)

Greek letters

β	isobaric thermal expansion coefficient (K^{-1})
δ_d	dimensional Dirac delta function (m^{-1})
θ	angle of flow direction with respect to horizontal plane (rad)
μ	dynamic viscosity (N•s/m^2)
ρ	density (kg/m^3)
ε	surface roughness (m)

Subscripts

b	bulk
c	calculated value
e	experimental value
fr	friction
g	gravity
in	inlet
k	axial location of local pressure drop
l	local
max	maximum
out	outlet
p	constant pressure
pc	pseudo-critical

Abbreviations

DWO	density wave oscillation
NPIC	Nuclear Power Institute of China
SCWR	supercritical water-cooled reactor

described in detail and validated by the experimental results. Based on the validated code, the geometrical simplification is further discussed. Finally, effects of system parameters on the flow instability are numerically analyzed.

2. System and physical model

2.1. Test section and experimental results

A supercritical water loop has been constructed in NPIC in order to meet the urgent need for validation data in supercritical flow instability analysis [19]. The experiments are briefly described here. Fig. 1 shows the test section, which is a two-parallel-channel system consisting of a lower plenum, flow meters, entrance sections, heated sections, riser sections and an upper plenum. The two heated sections are INCONEL Alloy pipes with inner and outer diameters of 6 and 11 mm, while the heated length is 3000 mm. The application of INCONEL Alloy pipes ensures that the heat flux along the axis is uniform, since the resistance changes little with the temperature.

Flow instability experiments have been performed for different thermal hydraulic conditions. Parallel instability has been observed at pressures from 23 to 25 MPa and inlet temperatures from 180 to 240 °C. All unstable points were collected and the pressures, inlet temperatures, mass flow rates and heat fluxes corresponding to the stability boundaries were translated into dimensionless parameters. Fig. 2 shows the stability boundaries obtained by the experiments. Two dimensionless numbers proposed by other researchers were used (Ambrosini and Sharabi [20]; Ambrosini [21]), namely sub-pseudo-critical number, N_{SPC}, and true trans-pseudo-critical number, N_{TPC}:

$$N_{SPC} = \frac{\beta_{pc}}{C_{p,Pc}}(h_{pc} - h_{in}) \tag{1}$$

$$N_{TPC} = \frac{\beta_{pc}}{C_{p,Pc}}\frac{Q}{M} = \frac{\beta_{pc}}{C_{p,Pc}}(h_{out} - h_{in}) \tag{2}$$

N_{SPC} mainly represents the effect of inlet temperature, while N_{TPC} mainly represents the effects of heat power and mass flow rate.

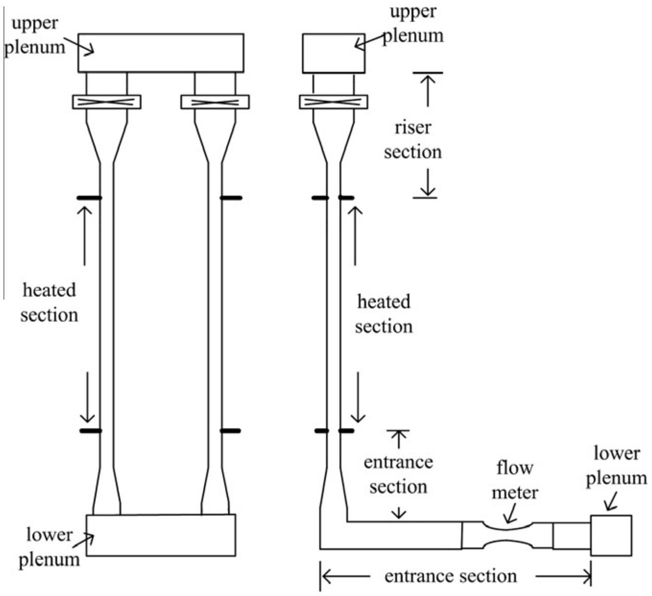

Fig. 1. Schematic diagram of the test section.