The study on the flashing induced instability in an open loop natural circulation system using RELAP5/Mod3.3

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Abstract: A numerical study on the operating process of a conceptual passive containment cooling system along with the instability for the simplified natural circulation system is carried out using the system code of RELAP5/Mod3.3. The sensitivity studies of spatial mesh and time step are performed. The feature of the instability occurring in the system is identified as flashing induced and dominated instability. The steady operating point of the natural circulation system is determined by using RELAP5/Mod3.3 under different heat flux and inlet temperature conditions. The characteristics of the steady operating point and the relationship between driving force and resistant force are used to analyze the onset of instability for the natural circulation.

Key words: natural circulation; open loop; flashing induced instability

1 Introduction

With the commercialization of nuclear power plants (NPPs) and the lessons learnt from such severe accidents as TMI, Chernobyl and Fukushima, the modern development of NPPs is characterized by the demands for either more reliable reactors or more inherent safety of NPPs. Due to the simplicity and reliability, natural circulation systems has been widely used in such areas as boilers, steam generators, *etc*.. In nuclear engineering, natural circulation systems are also successfully employed in the design of some nuclear reactors and nuclear power plants because of their intrinsic feature of passive safety. Even though a number of passive systems incorporated in advanced reactors employ natural circulation as the mode of energy removal underlining the importance of natural circulation in nuclear reactor, it needs to be noticed that natural circulation systems are susceptible to several kinds of instabilities due to the strong coupling effect and relative low driving force in nature. In this background, many efforts have been made to the study of flow behaviors and instabilities in both single-phase and boiling (or flashing) two-phase natural circulation systems in several decades.

Natural circulation can be defined as the flow in channels/loop driven by buoyancy force due to density difference of the fluid at different position. Natural circulation can serve by passive means to remove the decay heat from the core during accidents in both pressurized water reactors (PWRs) and boiling water reactors (BWRs). Furthermore, natural circulation is an important mode of operation for removing heat from the core in both normal and abnormal conditions for the economic simplified boiling water reactor (ESBWR) and advanced heavy water reactor (AHWR) and so on. The pioneer work concerning two phase flow instability in natural circulation system[6] was performed by Wissler *et al.* (E. H. Wissler, H. S. Isbin, and N. R. Amundson, 1956). In the past decades, many efforts to investigate the behaviors of the natural circulation system under low-pressure conditions were made and most of them were contributing to the studies of either two phase flow instabilities[17,3,9,16,11] (W.J.M de Kruijf *et al.*, 2003; C. Aguirre, D. Caruge, F. Castrillo *et al.*, 2005; M. Aritomi, J. H. Chiang, T. Nakahashi, M. Wataru, and M. Mori, 1992; van Bragt D.D.B.,

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Received date: December 1, 2016
(Revised date: December 29, 2016)

van der Hagen T.H.J.J.,, 1998; S. Guanghui, J. Dounan, K. Fukuda, and G. Yujun, 2002; *etc*.) for the Boiling Water Reactors (BWRs) or start-up procedures to cross the instability region[14,15,1,12,13] (S. Y. Jiang, M. S. Yao, J. H. Bo, and S. R. Wu, 1995; T. H. J. J. van der Hagen and A. J. C. Stekelenburg, 1997; A. Manera, U. Rohde, H.-M. Prasser and T. H. J. J. van der Hagen, 2005; S. Kuran, Y. Xu, X. Sun *et al.*, 2006). Besides, P.K. Vijayan *et al.* [10] (P.K. Vijayan, M. Sharma, D. Saha, 2007) and D.S. Pilkhwala[5] (D.S. Pilkhwala, W. Ambrosinib, N. Forgioneb, *et al.*, 2007) addressed the single phase instability occuring in natural circulation systems. Y. Kozmenkov *et al.*[19] (Y. Kozmenkov, U. Rohdea, A. Manera, 2012) and Amit Mangal[2] (Amit Mangal, Vikas Jain, A.K. Nayak, 2012) performed the investigation on the capability of RELAP5 in simulating the behaviors of natural circulation system. The common conclusion can be drawn as that care should be taken of the nodalization scheme while using RELAP5 to simulate the transient in natural circulation system. Moreover, in post-Fukushima era, the safe and reliable way to ensure the integrity of the containment in order to avoid the release of the radioactive to environment has become a research focus. The authors proposed a conceptual passive cooling system employing an open-loop natural circulation with large scale to deal with the problem of post-accident cooling-down for the large dry concrete containment of PWRs[7,18] (Jianjun Wang, Xueqing Guo, Shengzhi Yu, *et al.*, 2014; Xueqing Guo, Zhongning Sun, Jianjun Wang, *et al.*, 2015). Some of the unique features of the open-loop natural circulation system are summarized as follows: 1) the pressure boundary of the system remains at atmospheric pressure all the time; 2) the total height of the system is in so-called large scale; 3) there is not any heat source (heat exchanger) as in common circumstance; 4) two phase flow only occurs on the flashing of the water in the riser; 5) the system behaviors are strongly coupled with the in-containment conditions. Experimental evidence has proven that in such system the two phase instability may occur and be induced by the flashing in the long riser.

Therefore, in this paper, the flashing induced instability is investigated by using RELAP5 code for the open-loop natural circulation system with large scale. The mechanism of the flashing induced instability is explained and the effects of the boundary conditions are studied.

2 Models

2.1 Scheme of conceptual PCCS

Figure 1 shows the setup of the conceptual PCCS configuration. The natural circulation system incorporates an open loop scheme with a package of heat exchangers located inside the containment, an isolated adiabatic riser, a large water tank with a large free space connected to atmosphere and without any heat exchanger in it, an isolated adiabatic downcomer, other connecting horizontal pipes and valves. The main design characteristics of the system are summarized in table 1. The open natural circulation system operates under low-pressure condition because the large free space of the water tank is directly connected to the atmosphere environment. All the pipes are filled with the water at the same temperature as in water tank and the fluid remains standing still until the system is activated. In scenarios of such accidents as loss of coolant (LOCA) or main steam pipe break (MSLB), the steam released into the containment makes the pressure and the temperature inside the containment increase. Thus, the heat transfer, including convection and condensation, heats the fluid inside the heat exchanger up at the beginning, which results in the temperature/density difference between the fluid residing at different sections of the system and drives the fluid to circulate. Upon the activation of the system, the energy released into the containment can be removed through the system by passive means and the temperature and the pressure may be controlled if the heat removal capability of the system is sufficient.

2.2 RELAP5 and the nasalization of PCCS

RELAP5 (Reactor Excursion and Leak Analysis Program) is an advanced, best-estimate, reactor thermal-hydraulic simulation code, developed at Idaho National Engineering and Environmental Laboratory (INEEL). The basic hydrodynamic model of RELAP5 is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture. RELAP5 has been widely used in the analysis of transient behavior both in forced circulation system and natural circulation system. In this paper, the RELAP5/MOD3.3 version of the code is used in the series of simulations for the study on the stability occurring in a natural circulation system.

Table 1. Characteristics of the system

Parameters	Value
Length of a heat exchanger tube (m)	5.0
Number of heat transfer tube (-)	136
Total heat transfer area (m^2)	70.0
Length of the downcomer (m)	10.0
Length of the riser (m)	10.0
Diameter of the downcomer (m)	0.15
Diameter of the riser (m)	0.2

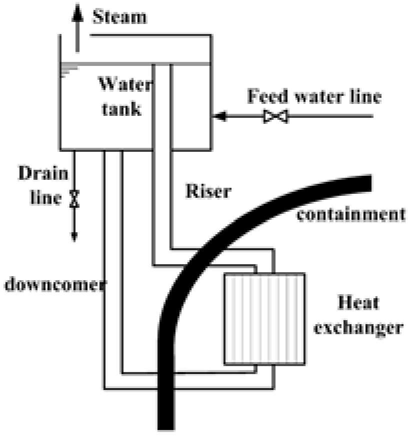
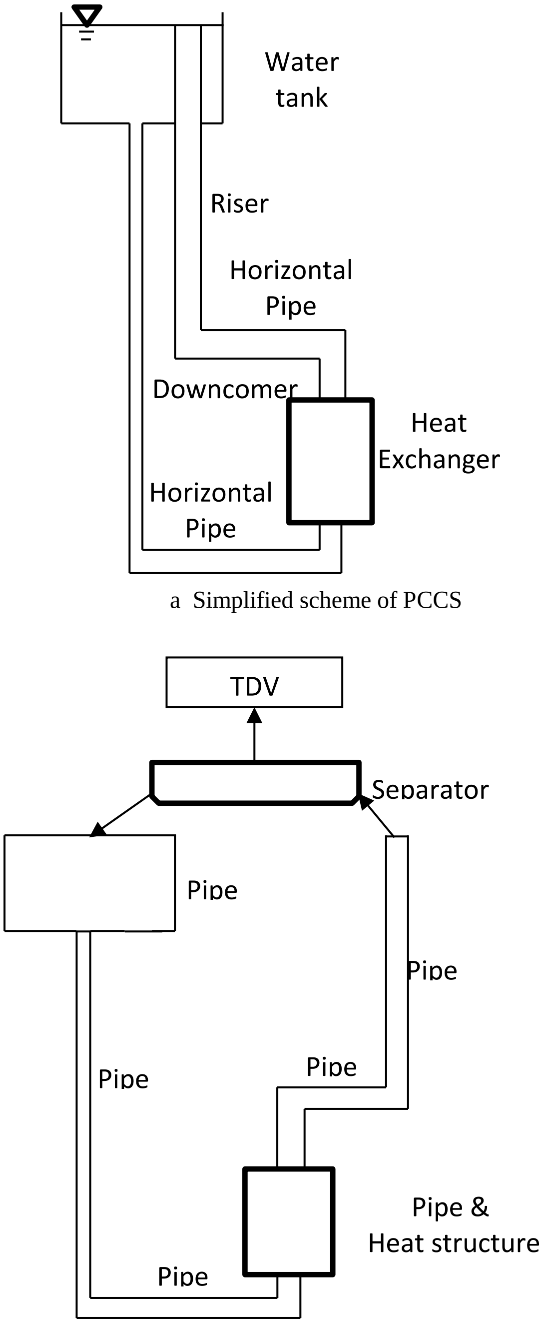


Fig. 1 the scheme of PCCS (not to scale).

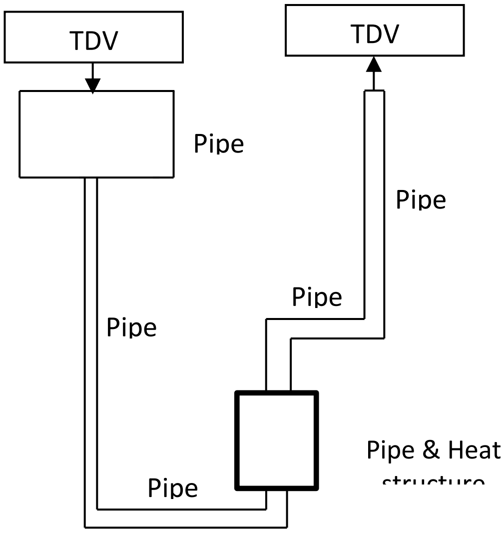
2.2.1 RELAP5 model of the open loop natural circulation system

For the open loop natural circulation representing PCCS shown in Fig.1, the simplified scheme for study is depicted in Fig.2. Three similar but different RELAP5 models are setup according to the purpose of the analysis and all three models are also presented in Fig. 2.

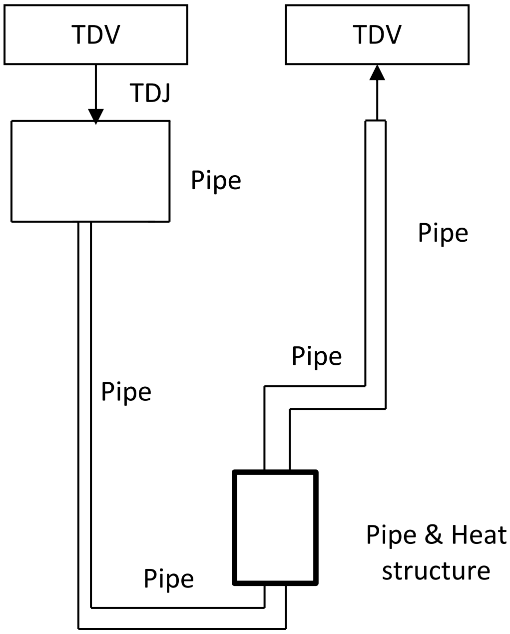


a Simplified scheme of PCCS

b RELAP5 model for PCCS



c RELAP5 model for instability simulation



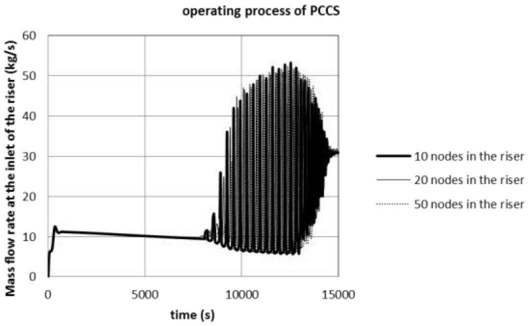
d RELAP5 model for characteristics curve

Fig. 2 RELAP5 models.

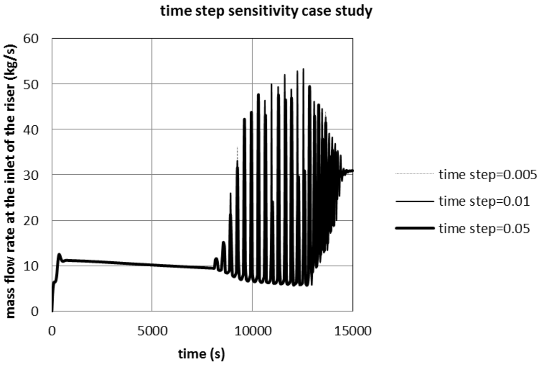
Figure 2b shows the RELAP5 model of PCCS with the consideration of steam separating process along with the openness to the atmosphere. This model is setup for the sake of validation of the RELAP5 with similar data published in reference. The models shown as Fig. 2c and Fig. 2d are designed to study the operating behaviors and the derivation of steady characteristics curve for the open loop natural circulation system respectively.

2.2.2 Nodalization and time step sensitivity studies

To get the proper nodalization scheme in simulating the phenomena occurring in the system, the sensitivity studies on the spatial nodding are carried out. On the basis of the fact that the system is dominated by flashing in the riser when the system operates in two phase flow mode, the nodalization of the riser is selected as the object of sensitivity study for spatial nodding. Figure 3a shows the time series of mass flow rate at the inlet of the riser for different nodalization schemes of the riser.



a. sensitivity study on the nodalization of the riser



b. Sensitivity study on the time step

Fig. 3 sensitivity study on the nodalization scheme of the riser and time step.

Three different cases studies for spatial nodding are shown in Fig. 3a under same initial and boundary conditions, in which all the fluid in the system remains at 333.0 K, the temperature of the heat exchanger is 333.0 K as well, the convective heat transfer coefficient on the outer surface of the heat transfer tubes is kept as 500 $\mathrm{W/(m^2 \cdot K)}$ and the temperature in the bulk of the containment is 400

K at the activation of the system. The results resemble the published operating process of similar system as including startup, single phase steady state, transient two phase flow, quasi-steady state two phase flow[7] (Jianjun Wang, Xueqing Guo, Shengzhi Yu, *et al.*, 2014). It is shown that the operating curves overlap each other in startup and single phase steady state phases (including some part of two phase flow), which means that the results in quasi steady state phases are insensitive with the nodalization scheme of the riser in the range. Due to the main focus in this paper is to investigate the onset of flashing-induced instability through the analysis of steady state characteristics, the nodalization scheme of 10 elements in the riser is used for the further simulation and analysis.

Moreover, the integration time step in RELAP5 is determined mainly in two aspects, *i.e.*, the user defined maximum time step and courant number limitation. In this paper, we also performed the sensitivity study on the maximum time step defined by user. Fig. 3b shows the operating processes after the system is activated for three different used defined maximum time step. Concerning the study purpose, maximum time step of 0.01 is selected for the next work.

Table 2 lists the incorporated spatial nodding scheme for main components in the system of Fig. 2b and pressure boundary conditions for the systems of Fig. 2b through Fig. 2d.

Table 2. RELAP5 mesh scheme and boundary conditions

Component	Number or values
Water tank	10
Downcomer (vertical)	6
Downcomer (horizontal)	6
Heat exchanger	6
Riser (horizontal)	10
Riser (vertical)	10
TMD	1.01325×10^5Pa

3 Results and discussions

3.1 flashing phenomena and flashing induced instability

The flashing phenomenon and the flashing induced instability for the PCCS may be described as follows: in the startup and single phase steady state operating stages, the fluid inside the tank and the pipes as well are gradually heated up through heat transfer; along the riser, the local pressure decreases gradually due to the gravity effect; when the local temperature increase over the local saturation temperature, flashing may occur; once flashing occurring in the riser, the density difference between the cold (including water tank and downcomer) and hot (including heat exchanger and riser) increase dramatically and so do the driving force and the flow rate of the system; on the other hand, due to lower density of two phase mixture in the riser, local pressure reduces somehow, which is beneficial for the development of flashing; however, the dramatic increase of the flow rate results in the decrease of the fluid temperature at the exit of the heat exchanger, which is unbeneficial for the flashing; due to the nonlinearity of the two phase flow system and the lag and the coupling effects of driving force, flow resistance and fluid temperature distribution, instability may occur. In order to identify the instability occurring in the system as flashing induced instability, the operating process of the system shown in Fig. 2b is firstly analyzed based on the finalized nodalization scheme and time step. Figure 4 depicts the time series of the temperature at the exit of the heat exchanger and the saturation temperature under local pressure. The average void fraction of the upmost cell of the heat exchanger is presented in Fig. 5. The results shown in Fig. 4 and Fig. 5 prove that there is no boiling occurring inside the heat exchanger and the instability is purely triggered by flashing in the adiabatic riser. This is the reason for the name of flashing-induced instability in the system. Fig. 6 shows the void fraction at the upmost cell in the riser versus time.

It can be concluded that the instability occurring in the system is induced by flashing in the riser.

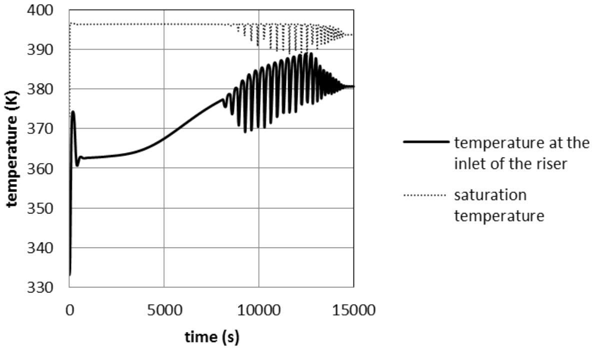


Fig. 4 the time series of temperature and saturation temperature at the inlet of the riser.

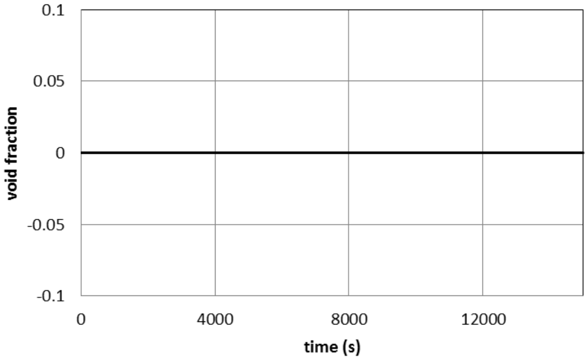


Fig. 5 the time series of void fraction at the upmost cell of the heat exchanger.

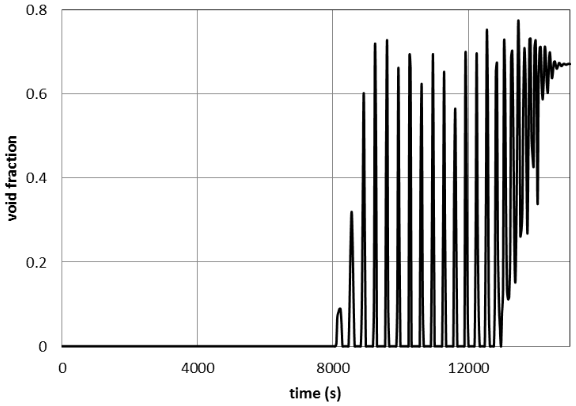


Fig. 6 the time series of void fraction at the upmost cell of the riser.

3.2 The performance of instability for the system

Strictly speaking, PCCS operates in a transient way all the time because there is not any concrete heat sink in the system. However, there is a water tank with large volume, which is helpful to keep the boundary condition at downcomer as quasi steady state. For the sake of better understanding the triggering condition of onset of instability, in this section, we first simplify the system shown in Fig. 2b by eliminating the separator and adding in a time dependent volume to establish the possibilities of reaching steady state or reaching cycling instability. Figure 7 presents the evolution of mass flow rate at the inlet of the riser shown in Fig. 2c with the increase of the fluid temperature inside the water tank while the heat flux on the heat exchanger remains 1.0×10^4W/m^2. The mass flow rate at the inlet of the riser starts to oscillate until the inlet temperature increase to 357K. The time series of the temperature at the exit of the heat exchanger are depicted in Fig. 8 for inlet temperatures of 355K, 357K and 360K.

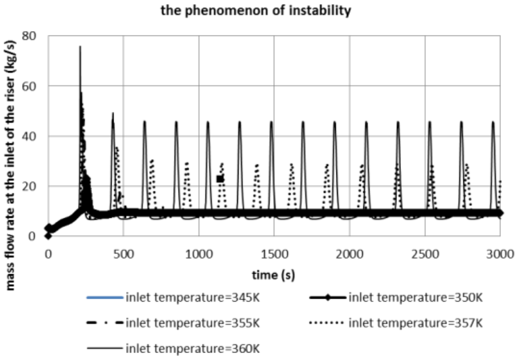


Fig. 7 the evolution of the mass flow rate of the system.

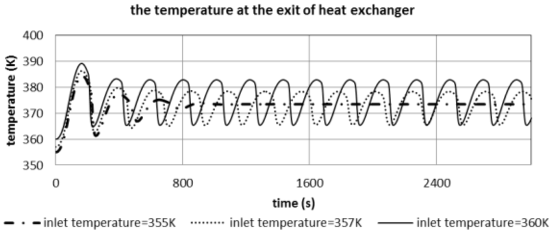


Fig. 8 the evolution of the temperature at the exit of heat exchanger of the system.

Figure 9 through Fig. 14 plots the evolution of the mass flow rate and the temperature at the exit of heat exchanger under different heat flux and different inlet temperature conditions. With the increase of heat flux, the inlet temperature corresponding to the onset of instability decreases near linearly. Commonly, the description of two phase instability is given in terms of subcooling number and phase change number. These two dimensionless numbers are defined from the thermal point of view. However, the occurrence of two phase instability is fundamentally controlled by the relationship and feedback between the force, including driving force and resistant force for the system, and the flow of the fluid. Moreover, the capabilities of the system code RELAP5 in predicting instabilities in single phase natural circulation system were discussed in the reference[4] (D'Auria F., Frogheri, M., Misale, M., 1997) . The author thought that RELAP5, if properly tuned, was able to calculate the single phase natural circulation loop performance especially when a stable flow rate established; but in context of oscillations, the agreement between calculated results and experimental data was poor. Therefore, in this paper, we use RELAP5 to study the characteristics of forces in the system to understand the condition under which the two phase instability may occur.

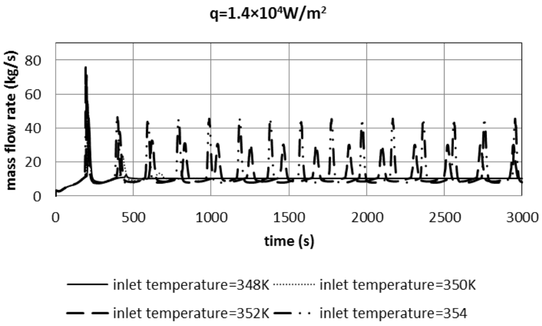


Fig. 9 the evolution of the mass flow rate at inlet of the riser.

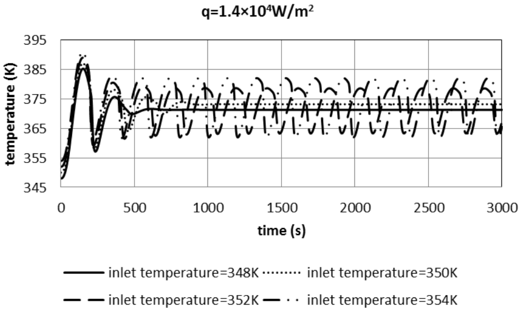


Fig. 10 the evolution of the temperature at the exit of heat exchanger of the system.

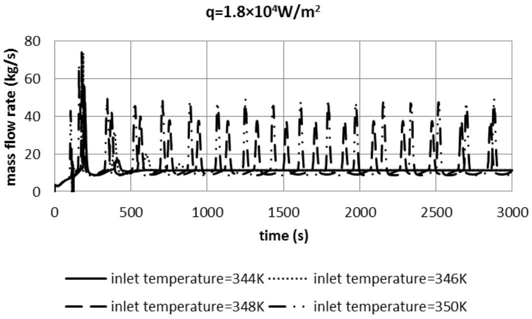


Fig. 11 the evolution of the mass flow rate at inlet of the riser.

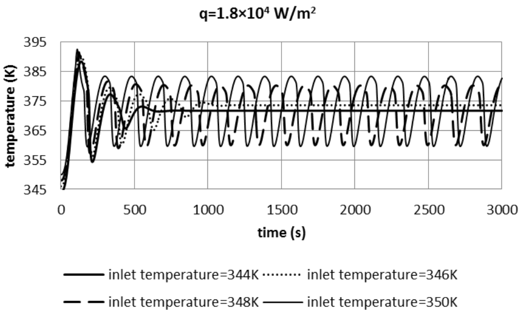


Fig. 12 the evolution of the temperature at the exit of heat exchanger of the system.

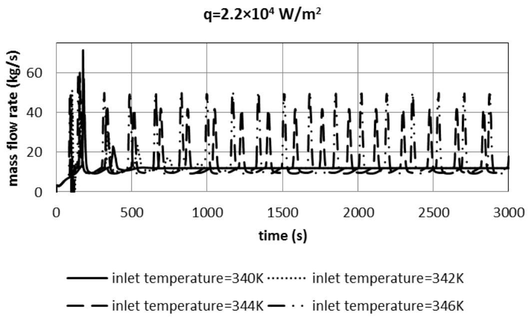


Fig. 13 the evolution of the mass flow rate at inlet of the riser.

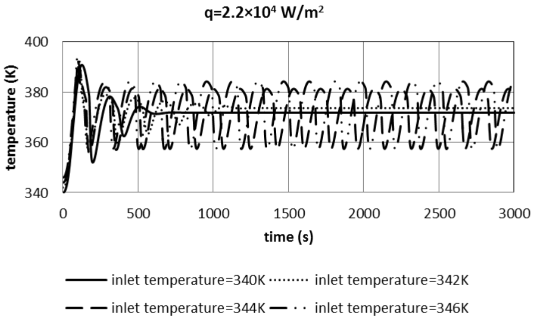


Fig. 14 the evolution of the temperature at the exit of heat exchanger of the system.

3.3 The characteristics of the forces for the system

The PCCS is further simplified from as shown in Fig. 2c to Fig. 2d. The single junction which connects the water tank and the time dependent volume in Fig. 2c is replaced by a time dependent junction in Fig. 2d remaining the same geometry so that the velocity or mass flow rate can be treated as a control parameter to obtain the driving forces and resistant forces under given conditions. The driving force can be defined as the integration of gravitational pressure drop along the loop and the resistant force include the frictional pressure drop, local pressure drop and acceleration pressure drop. Hereinafter, the resistant force is also called as pressure drop in this paper.

The case of fixed heat flux of 1.0×10^4 W/m^2 and inlet temperature of 345 K is firstly analyzed. Fig. 15 shows the driving forces, pressure drop and the difference of driving force and pressure drop as the function of mass flow rate. The intersection point of driving force and pressure drop curves means that the system may operate at corresponding mass flow rate theoretically. Figure 16 presents the characteristics of forces under different inlet temperature conditions of 350K, 355K and 357K respectively. As compared with the results shown in Fig. 7 and Fig. 8, the relationship between driving force and pressure drop changes from linearly to nonlinearly intersected for inlet temperature of from 345K, 350K, and 355K to 357K. In other words, the instability may occur where the curves of driving force and pressure drop are nonlinearly intersected.

Figure 17 through Fig. 19 shows the characteristics of driving force and pressure drop of the system under different heat flux and inlet temperature conditions. It can be found that flashing induced instability occurs where the steady operating point lies in the nonlinear of driving force curve.

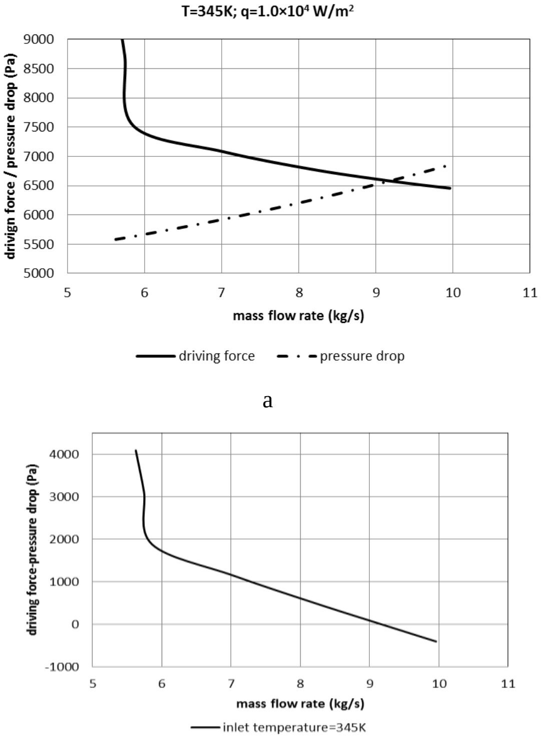


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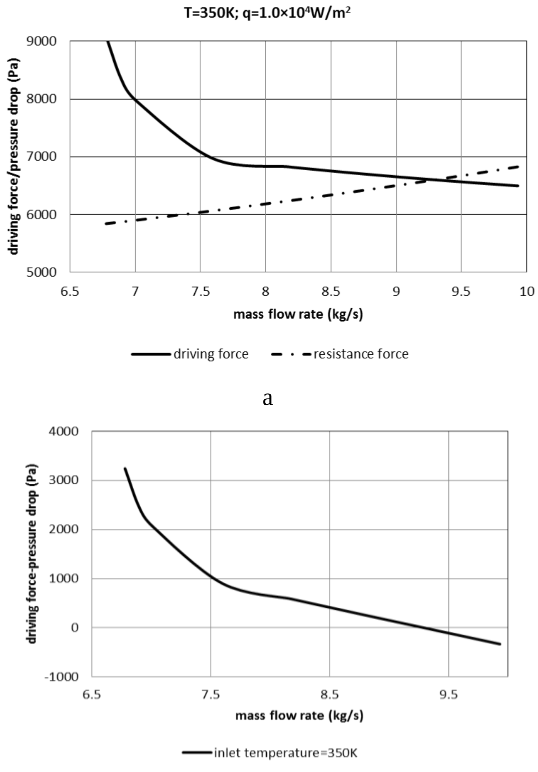
Fig. 15 characteristics of forces of the system.



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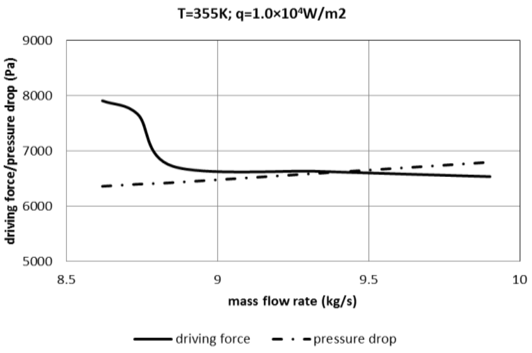

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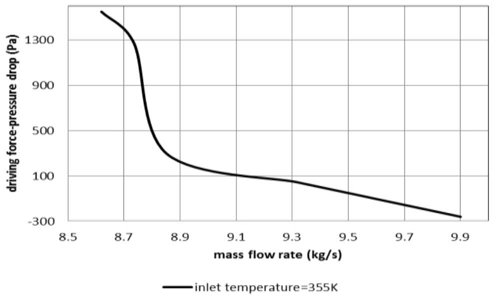

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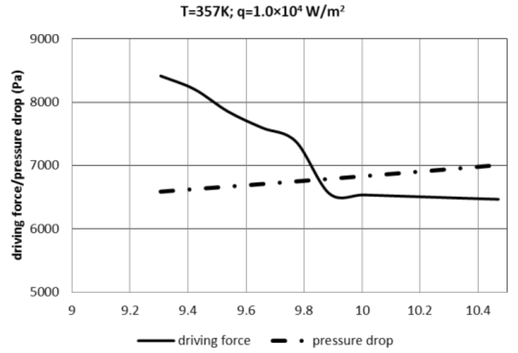

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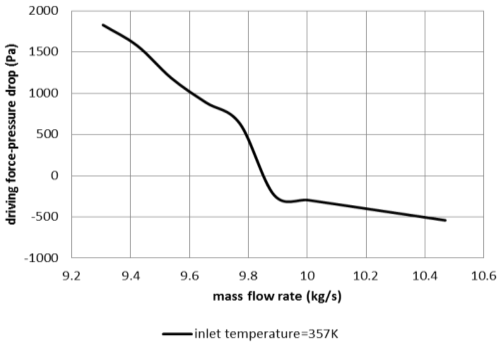

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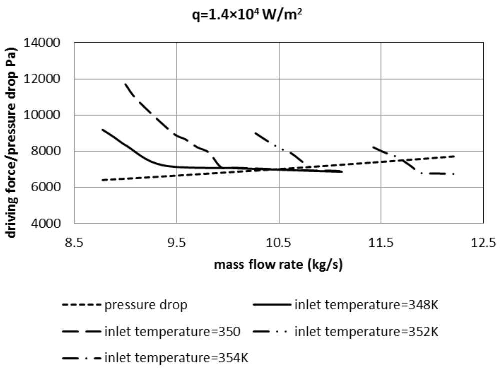
Fig. 16 characteristics of forces of the system under different inlet temperature conditions.



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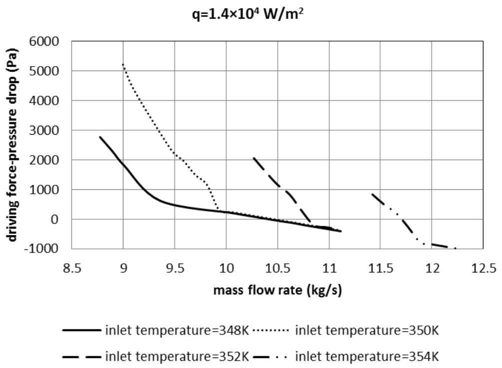

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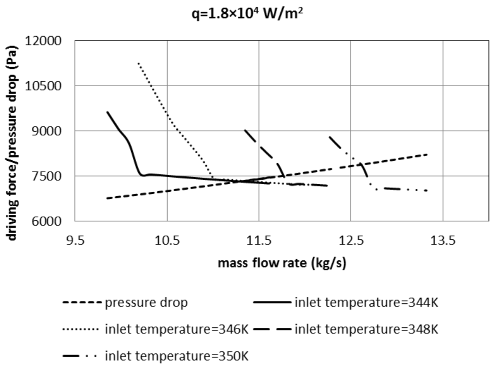
Fig. 17 characteristics of forces of the system (q=1.4×10^4 W/m^2).



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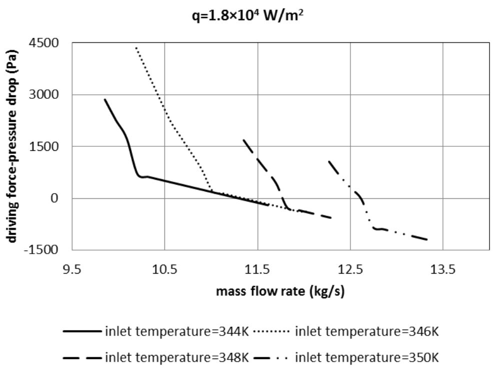

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Fig. 18 characteristics of forces of the system (q=1.8 ×10^4 W/m^2)

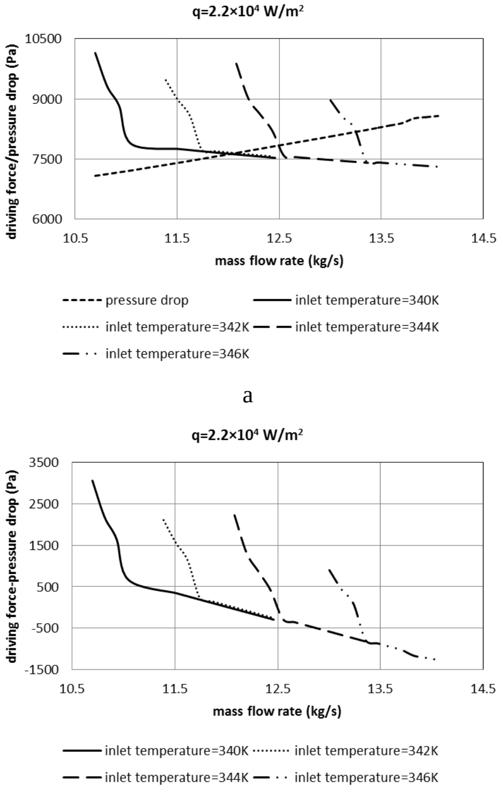

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Fig. 19 characteristics of forces of the system (q=2.2 ×10^4 W/m^2).

4 Conclusions

RELAP5/Mod3.3 code is used in this paper to simulate operating process of PCCS and to study the flashing induced instability of simplified natural circulation system. The relationship between driving force and resistance force of the loop is used to analyze the possibility of onset of instability. The following conclusions are drawn through analyzing the simulation results.

1) PCCS may experience instability induced by flashing in the riser and there is not any phase change in the heated section for the system.

2) Through analysis of static characteristics of the system, it is feasible to judge the conditions under which the instability may occur.

3) For the natural circulation system, the flashing instability may occur when the steady operating point lies in the nonlinear parts of the driving force curve.

Even though the marginal stability boundary may be identified in this manner, more data collection and case and parametric studies are still needed to verify.

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