# Study on the instability of a conceptual passive containment cooling system

## BAI Jinhua[1, 2], ZHAO Bo[2], WANG Jianjun[1], YU Shengzhi[1], and DAI Bin[1]

1. *Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China (wang-jianjun@hrbeu.edu.cn)*
2. *China Nuclear Power Engineering Co. Ltd, Beijing, 100840, China*

**Abstract:** In this paper, the instability phenomenon of a conceptual passive containment cooling system, which is designed to mitigate the consequences after the release of mass and energy during such scenarios as loss of coolant accident (LOCA) or main steam line break (MSLB), is numerically studied. The system is composed of series of heat exchangers, long connecting pipes with relative large diameter, valves and a water tank, which is located at the top of the system and served as the final heat sink. The simulation results show that the two phase instability may occur when the fluid temperature reaches to some value, even if the fluid remains single phase at the exit of the heat exchanger. This type of two phase flow instability is initiated only by the flashing in the riser. The water tank needs to be cooled or refilled with cooler water due to the possible consequences of the instability phenomenon.

**Keywords**: instability; passive system; open loop; flashing

## 1 Introduction

In order to prevent the radioactive species escaping to atmosphere, high integrity containment has been one of the most active design focuses in recent years especially after the Fukushima accident in 2011. During such design basis accidents scenarios as loss of coolant (LOCA) and main steam line break (MSLB), the expansion and transport of high mass/energy releases material into the containment free volume will make the pressure and the temperature increase dramatically (Jack Tills *et. al*., 2009 [1]). For large dry concrete containment, if above-mentioned accidents are combined with loss of on-site power supply, the active containment controlling system of pressure and temperature may fail to serve the safety function. In such case, the potential risks may be encountered for the integrity of the containment. Till now, there have been worldwide efforts to develop promising passive containment cooling systems which are much safer, more reliable and possibly simpler than traditional design as spray and/or fan cooler systems.

There are several conceptual candidate passive containment cooling systems which have been proposed and studied to date either for steel or dry double-wall concrete containment configuration of interest. In 1988, S.N. Tower, T.L. Schulz, R.P. Vijuk [2] introduced the passive containment cooling system for AP600 through natural circulation, air convection, and thermal radiation. Similar scheme has been proposed by T.L. Schulz for AP000 (2006, [3]). As far as the concrete containment was concerned, a heat pipe design concept (Ahmad *et al.* 1983 [4]), a so-called temperature-initiated passive cooling system (Forsberg *et al.* 1994 [5]), another thermosyphon type conceptual containment cooling system (Leiendecker *et al.* 1997 [6]), and an internal evaporator-only (IEO) concept (Byun *et al.* 2000 [7]) were proposed to meet

---

**Received date: September 29, 2015**
(Revised date: December 11, 2015)

the requirements of the integrity of the containment.

On the basis of the knowledge of above-mentioned passive system concepts, an open-loop passive containment cooling system (OLPCCS) concept was presented in the work of Jianjun Wang *et.al.* (2014 [8]) and Xueqing Guo *et.al.* (2015 [9]) in order to mitigate the consequences after LOCA or MSLB accidents. The system is composed of heat exchangers located in the containment, long connecting pipes with relative large diameter, valves and one water tank located outside the containment. The proposed system may operate at relative low pressure by natural circulation means and free of pumps or other power supply. At present, most investigations on the behaviors of the natural circulation under low-pressure conditions were contributing to the studies of either start-up procedures to cross the instability region (S. Y. Jiang *et al*, 1995 [10]; T.H.J.J. van der Hagen *et al*, 1997 [11]; A. Manera *et al*, 2005 [12]; S. Kuran *et al*, 2006 [13]) or two phase flow instabilities (Aguirre C. *et al*, 2005 [14]; Aritomi M. *et al*, 1992 [15]; van Bragt D.D.B., van der Hagen T.H.J.J., 1998 [16]; Guanghui Su, *et al*, 2002 [17]; *etc.* ) for the Boiling Water Reactors (BWRs).

This paper addresses the model on the basis of HEM formulation for two phase flow. The one dimension computational code is developed in order to numerically investigate the instability which may occur in the system of the OLPCCS.

## 2 Modified OLPCCS

The schematic of OLPCCS design is shown in Fig. 1. The heat exchanger inside the containment is supposed to be located along the containment perimeter. In order to eliminate the influence between the bundles during condensation, the heat exchanger can be designed as single row configuration. The heat exchanger is connected to the water tank through pipes with valves. Some of the design parameters of the OLPCCS are listed in Table 1.

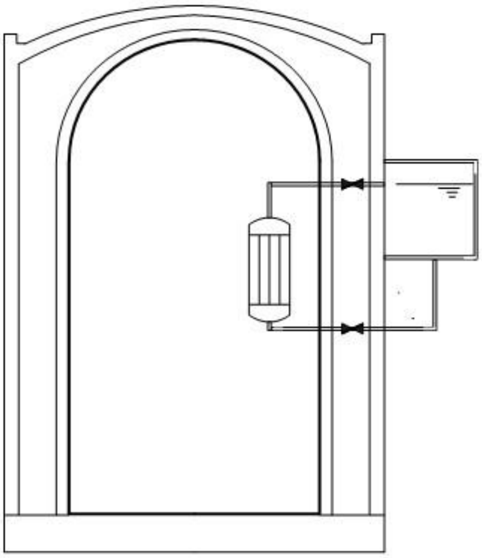

Fig. 1 Schematic of OLPCCS (not to scale).

As shown in Fig.1, in the event of a LOCA or MSLB, the coolant released from reactor vessel or steam line will be flashing into the containment because of sudden decrease of the pressure. Afterwards, the mixture composed of steam and air may be cooled through the heat exchangers located inside the containment. Meanwhile, the fluid in the tube side of the heat exchangers will be heated up, which will supply the original driving force for the natural circulation of OLPCCS.

**Table 1 Parameters of OLPCCS Unit**

| parameter | value |
|---|---|
| Height of heat exchanger/m | 5.0 |
| Height difference between the in-containment heat exchanger and water tank/m | 10 |
| Area of one heat exchanger/m$^2$ | 300 |
| Initial water temperature/℃ | Specified as boundary condition |
| In containment temperature/℃ | 145 |
| Condensation heat transfer coefficient/(W/(m$^2$K)) | 1000 |

# 3 Model setup

In this paper, the following conditions are assumed:

1) The heat can only be transferred via the heat exchangers, which mean the connecting pipes are adiabatic;
2) The OLPCCS is isothermal when it is standing by;
3) The heat transfer coefficient remains constant along the tubes except for in phase change scenario;
4) When the OLPCCS is activated, the temperature in the containment steps to and remains some specified value;
5) Both steam and the liquid in the system are incompressible.

The homogeneous two phase flow model is used in this paper. The main conservation equations are listed as follows.

Mass conservation equation:

$$\frac{\partial(W_m)}{\partial z}=0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial W_m}{\partial t}+\frac{\partial(W_m^2/(A\rho_m))}{\partial z}=-\frac{dp}{dz}+\left(\frac{dp}{dz}\right)_f+\left(\frac{dp}{dz}\right)_g+\left(\frac{dp}{dz}\right)_l \tag{2}$$

Energy conservation equation:

$$A\frac{\partial(h_m\rho_m)}{\partial t}+\frac{\partial(W_m h_m)}{\partial z}=q_l \tag{3}$$

Where $W_m$ is the mass flow rate, kg/s; A is flow area, $m^2$; $\rho_m$ is the average density of the mixture, $kg/m^3$; $h_m$ is the enthalpy of mixture, kJ/kg; $q_l$ denotes the linear power, W/m.

The main constitutive relationships used in the paper are as follows, which include the pressure drop and heat transfer calculation expression.

$$\Delta p_{f,sp}=f\,\frac{L}{d_i}\frac{\rho u^2}{2} \tag{4}$$

$$\text{Where } = \begin{cases} {}^{64}/_{Re} & Re \le 2000 \\ 0.3164Re^{-0.25} & 2000 < Re \le 3.0\times10^4 \\ 0.184Re^{-0.2} & 3.0\times10^4 < Re \le 2.1\times10^6 \\ 0.01 & Re > 2.1\times10^6 \end{cases}$$

$$\Delta p_{f,tp}=\phi_{l0}^2 f\,\frac{L}{d_i}\frac{\rho u^2}{2} \tag{5}$$

In equation (5) , $\phi_{l0}^2$ denotes the two phase friction multiplier, which can be expressed as follows,

$$\phi_{l0}^2=\left[1+x\left(\frac{\rho_L}{\rho_g}-1\right)\right] \tag{6}$$

or L-M method is used for the calculation of $\phi_{l0}^2$.

If the convection heat transfer is in single liquid phase, thus

$$\mathrm{Nu}=\begin{cases} 3.66 & \mathrm{Re} \le 2000 \\ 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} & Re > 2000 \end{cases} \tag{7}$$

Where $Nu=\frac{h_{sp}d_i}{k}$.

The boiling heat transfer coefficient is calculated with the correlations recommended by Shah (1976),

$$h_{tp}=h_{sp}(h_{BL}+h_{CL}) \tag{8}$$

where $h_{tp}$ is the boiling heat transfer coefficient, $W/(m^2K)$;

$$h_{BL}=\begin{cases} 230Bo^{0.5} & Bo>0.0003 \\ 1+46Bo^{0.5} & Bo<0.0003 \end{cases};$$

$$h_{CL}=\frac{1.8}{C_0^{0.8}}$$

PCCSTS (passive containment cooling system transient simulation) code is developed with finite difference method (FDM) based on the models, in which the convection term is discretized with first order upwind scheme and the transient term is discretized with forward difference scheme respectively. Each control volume has the length of 5 cm for connecting pipes and 1 cm for the heat exchanger. The numerical simulation of behaviors of the OLPCCS is performed with PCCSTS code. In current study, the time step for the transient analysis is set to 0.01s and the converging criteria of the calculations are set to less than 1.0e-6 in terms of relative error.

# 4 Results and discussions

## 4.1 The validation of the codes

PCCSTS codes have been validated with experimental data for the OLPCCS [11]. Fig.2 shows the transient process from startup to long term operation. The results show good match between the numerical simulation and the experimental data either in single phase stage or in two phase flow stage or even in two phase oscillation process. In the case shown in Fig.2, the total pressure in containment is 0.36MPa and the mass quality of steam inside the containment is 0.48.

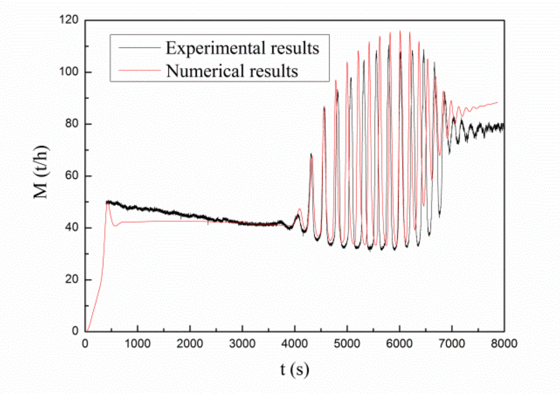

Fig.2 the comparison between numerical results and the experimental data.

## 4.2 The feature of the instability in OLPCCS

In Fig.2, it can be easily found that the system will experience somehow instability after the operation on the one hand. On the other hand, the process of the operation is quite long and thus the phenomenon of instability is only meaningful for such given boundary condition as the water temperature inside the upper tank. Therefore, the study on the behaviors of the system under different water temperature conditions is conducted.

Figure 3 shows the operating curves of the system when the water temperature is from 75℃ to 77.5℃. The numerical results show that the system will operate in a steady mode except for the transient process at the initial stage. Furthermore, the system will keep in single phase state in the heat exchanger if the water temperature in the upper tank is not greater than 77.5℃. The temperature of the coolant at the exit of the heat exchanger is shown in Fig.4. Due to the static head supplied by the down comer, the saturation temperature at the exit of the heat exchanger is about 120℃. Fig.5 depicts the quality of the fluid at the exit of the riser, which shows that the flashing will occur in a very limited way at the exit of the riser.

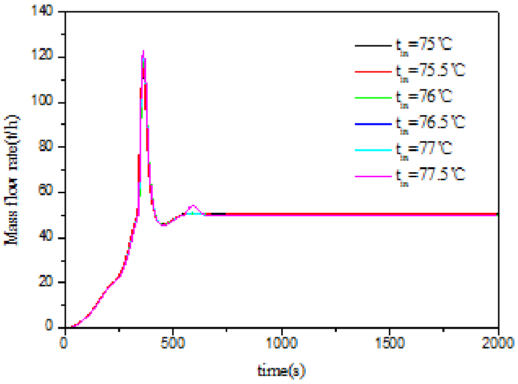

Fig.3 the time series of mass flow rate after startup of the system.

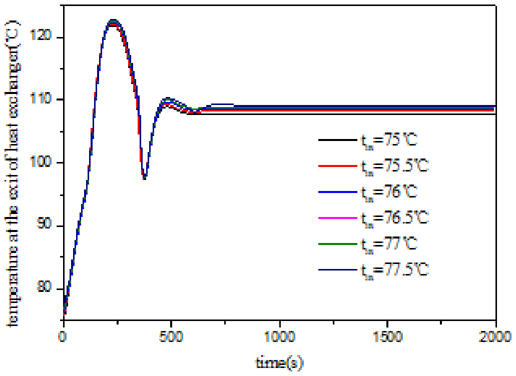

Fig.4 the time series of the fluid temperature at the exit of the heat exchanger after startup of the system.

However, when the water temperature inside the tank becomes greater than 77.5℃, then flashing will enhance the driving force of the natural circulation. Therefore, the flow of the fluid may be accelerated and the temperature at the exit of the heat exchanger and in the riser will decrease. Nevertheless, the delay of the flow and the heat transfer may consequently result in the instability of the system. Figure 6 shows the instability phenomena under different inlet temperature conditions.

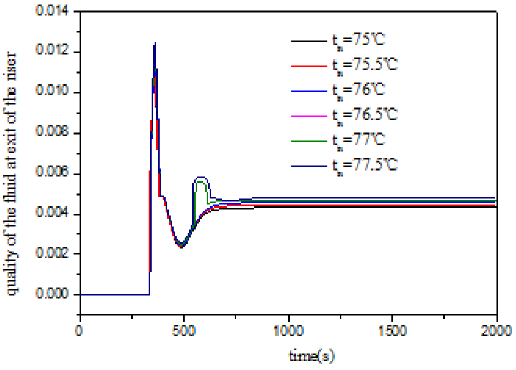

Fig.5 the time series of the quality at the exit after startup of the system.

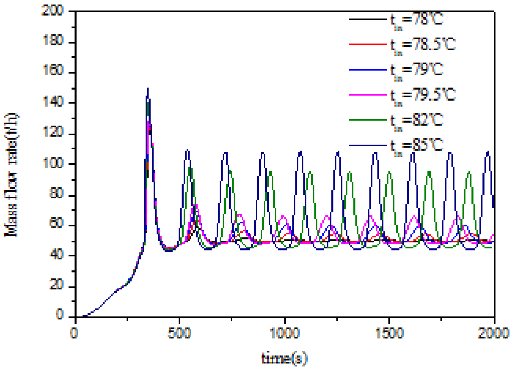

Fig.6 instability phenomenon for the system.

It can be noticed that the system transits from stable state to instable with the fluid temperature only increasing from 77.5℃ to 78℃. When the fluid temperature increase a little to 78.5℃, the oscillation amplitude increases dramatically. Fig.7 shows the time series of the quality at the exit of the riser of the system for different inlet fluid temperature conditions when instability occurs. Due to the harmful effects of instability, the measures should be taken to control the instability occurring in the system. It can be found that the amplitude of the oscillation for the system is quite large for very broad temperature range. Moreover, the instability of the system is mainly generated from the increase of the fluid temperature inside the upper tank, so one of the possible measures is to refill the tank with cool fluid.

As shown in Fig.5 and Fig.7, the quality of the fluid caused by flashing is quite low with about from 0.004 at stable state to less than 0.01 during oscillation process. On the basis of homogeneous two phase flow model, the void fraction at atmospheric pressure increase rapidly with the little increase of the quality. It can be concluded that such instability can be attributed to the response of the quality to the void fraction during flashing and the change of void fraction to the driving force of the system.

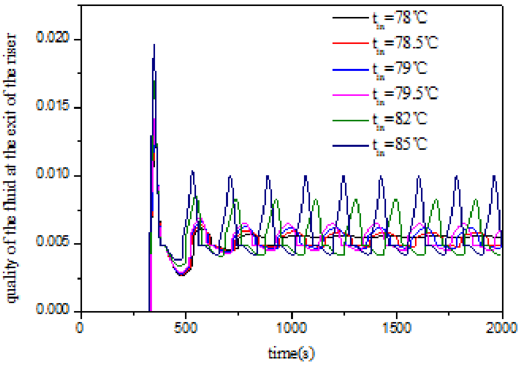

Fig.7 the time series of the quality during the instability process for the system.

## 5 Conclusions

In this paper, the instability phenomenon occurring in the OLPCCS is studied numerically with in-house codes PCCSTS. The following conclusions can be drawn through the studies.

1. When the fluid temperature inside the upper tank is lower than 77.5℃, the system may be in steady operation mode even if the flashing occurs at the exit of the riser.
2. When the fluid temperature inside the upper tank is greater than 78℃, the system may be in oscillation operation mode even if the flashing quality does not change so much.
3. The relationship between the quality, the void fraction, driving force and the flow rate and the delay dominates the instability phenomenon of the system.
4. For the steady operation of the system, the water tank needs to be refilled.

## Acknowledgement

We gratefully thank for the support of Open Fund Program of the Key Laboratory of Advanced Reactor Engineering and Safety, Ministry of Education of China ( ARES201406) and the support of the project (HEUFN1307) and National Defense Key Laboratory for Nuclear Safety and Simulation Technology in Harbin Engineering University.

## References

[1] TILLS Jack, NOTAFRANCESCO Allen, and PHILLIPS Jesse: Application of the MELCOR Code to Design Basis PWR Large Dry Containment Analysis. SANDIA Report, 2009-2858

[2] TOWER, S.N., SCHULZ, T.L., and VIJUK, R.P.: Passive and simplified system features for the advanced Westinghouse 600 MWe PWR, Nulcear Engineering and Design, 109(1988) 147-154

[3] SCHULZ, T.L.: Westinghouse AP1000 advanced passive reactor, Nuclear Engineering and Design, 236 (2006) 1474-1485

[4] AHMAD, A., *et al.*: PWR severe accident delineation and assessment, NUREG/CR-2666; UCLA-ENG-8284, 1983

[5] FORSBERG, C.W., *et al.*: Use of Temperature-Initiated Passive Cooling System (TIPACS) for Modular High-Temperature Gas-Cooled Reactor Cavity Cooling System, Oak Ridge National Laboratory, ORNL, 1994

[6] LEIENDECKER, M., TODREAS, N.E., DRISCOLL M.J., and HURTADO A.: Design and Numerical Simulation of a Two-Phase Thermosyphon Loop as a Passive Containment Cooling System for PWRs. MIT-ANP-TR-053, 1997.

[7] BYUN, C.S., JERNG, D.W., TODREAS, N.E., and DRISCOLL, M.J.: Conceptual design and analysis of a semi-passive containment cooling system for a large concrete containment, Nuclear Engineering and Design, 199(2000)227-242

[8] WANG Jianjun, GUO Xueqing, and YU Shengzhi, *et.al*: Study on the Behaviors of a Conceptual Passive Containment Cooling System, Science and Technology of Nuclear Installations, 2014(2014), Article ID 358365

[9] GUO Xueqing, SUN Zhongning, WANG Jianjun, YU Shengzhi, and GAO Li: Numerical simulation of the transient behaviors in an open natural circulation system with a large scale, Annals of Nuclear Energy, 2015, 3:83-93.

[10] JIANG, S. Y., YAO, M. S., BO, J.H., and WU, S.R.: Experimental simulation study on start-up of the 5MW nuclear heating reactor, Nuclear Engineering and Design, 158 (1995) 111-123

[11]VAN DER HAGEN, T.H.J.J., and STEKELENBERG, A.J.C.: The low-power low-pressure flow resonance in a natural circulation cooled boiling water reactor. Nuclear Engineering and Design. 1997: 229-238

[12] MANERA, A., ROHDE, U., PRASSER, H.M., and VAN DER HAGEN, T.H.J.J.: Modelling of flashing-induced instabilities in the start-up phase of natural circulation BWRs using the two-phase flow code FLOCAL. Nuclear Engineering and Design. 2005: 1517-1535

[13] KURAN, S., XU, Y., SUN, X., CHENG, L., YOON, H.J., REVANKAR, S.T., ISHIII, M., and WANG, W.: Starup transient simulation for natural circulation boiling water reactor in PUMA facility. 2006: 2365-2375

[14] AGUIRRE, C., CARUGE, D., CASTRILLO, F., and DOMINICUS, G., *et al.*: Natural circulation and stability performance of BWRs (NACUSP). Nuclear Engineering and Design, 235(2005)401-409

[15] ARITOMI, M, CHING, J H, and NAKAHASHI, T, *et al.*: Fundamental study on thermo-hydraulics during start-up in natural circulation boiling water reactors, (I) thermo-hydraulics instabilities, J. Nuclear Science and Technology, 29(1992) 631-641

[16] VAN BRAGT, D.D.B., and VAN DER HAGEN, T.H.J.J.: Stability of natural circulation boiling water reactors. Part I —description stability model and theoretical analysis in terms of dimensionless groups. Nucl. Technol. 121(1998)

[17] SU Guanghui, JIA Dounan, KENJI Fukuda, and GUO Yujun: Theoretical and experimental study on density wave oscillation of two-phase natural circulation of low equilibrium quality, Nuclear Engineering and Design, 215(2002)187-198