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Research Article

Study on the Behaviors of a Conceptual Passive Containment Cooling System

Jianjun Wang, Xueqing Guo, Shengzhi Yu, Baowei Cai, Zhongning Sun, and Changqi Yan

National Defense Key Laboratory for Nuclear Safety and Simulation Technology, Harbin Engineering University, Harbin 150001, China

Correspondence should be addressed to Jianjun Wang; wangjianjunheu@163.com

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The containment is an ultimate and important barrier 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). In this investigation, a passive containment cooling system (PCCS) concept is proposed for a large dry concrete containment. The system is composed of series of heat exchangers, long connecting pipes with relatively large diameter, valves, and a water tank, which is located at the top of the system and serves as the final heat sink. The performance of the system is numerically studied in detail under different conditions. In addition, the influences of condensation heat transfer conditions and containment environment temperature conditions are also studied on the behaviors of the system. The results reveal that four distinct operating stages could be experienced as follows: startup stage, single phase quasisteady stage, flashing speed-up transient stage, and flashing dominated quasisteady operating stage. Furthermore, the mechanisms of system behaviors are thus analyzed. Moreover, the feasibility of the system is also discussed to meet the design purpose for the containment integrity requirement. Considering the passive feature and the compactness of the system, the proposed PCCS is promising for the advanced integral type reactor.

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. Under the internal effects of 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 into the containment free volume will make the pressure and the temperature increase (Tills et al. [1]). In conventional nuclear power plant, the sprays and/or fan coolers are employed to control the containment peak pressure and temperature for ensuring the integrity of the containment. However, either sprays or fan coolers are dependent on the power supply, which is unreliable if LOCA or MSLB scenarios are coupled with the loss of power supply. Moreover, if there is no effective way to transfer the energy, the pressure and the temperature in the containment may exceed the allowed value. Therefore, there may be potential risks for the containment integrity. 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 designs as spray and/or fan cooler systems.

There are several conceptual candidate passive containment cooling systems which have been proposed and studied to date for either steel or dry double-wall concrete containment configuration of interest. For example, passive containment cooling by natural circulation and air convection and thermal radiation has been proposed for AP600 (Tower et al. [2]) and AP1000 (Schulz [3]) reactors. Gavrilas et al. [4] proposed a containment design concept, in which heat rejection through the steel shell was enhanced by using an air-convection annulus on the upper portion and an external moat on the lower portion.

However, as compared to steel containment design for AP600 or AP1000, it may be more difficult to remove the energy released in the accidents from a concrete containment due to the lower thermal conductivity of the concrete than steel.

Thus, a passive containment cooling system may be preferable and essential for the safety of containment in harsh postaccident conditions, which is completely independent of mechanical, electrical, instrumentation, and control system. There are several conceptual candidate passive containment cooling systems which have been proposed and studied to date for the large dry double-wall concrete containment configuration of interest. Ahmad et al. [5] raised a heat pipe design concept for a passive containment heat removal system. Forsberg and Conklin [6] presented a so-called temperature-initiated passive cooling system. A thermosyphon loop concept for double-shell concrete containment was developed by ENEL. Similarly, Leiendecker et al. [7] had investigated another thermosyphon type conceptual containment cooling system. On the basis of thermosyphon type design schemes, Byun et al. [8] raised an internal evaporator-only (IEO) concept and the performance of the system was then investigated with the GOTHIC computer code. They concluded that four IEO loops could be utilized to meet design criteria for severe accident scenarios. In 2000, Liu et al. [9] performed an experimental investigation for a passive IEO cooling unit, in which the condensation heat transfer coefficients are thoroughly studied.

Enlightened by IEO design concept, we present an open-loop passive containment cooling system (OLPCCS) concept, which is composed of heat exchangers located in the containment, long connecting pipes with relatively large diameter, valves, and one water tank located outside the containment. The proposed system may operate by natural circulation means and free of pumps or other power supplies. The OLPCCS is designed to serve as the accidental consequence mitigation for the large dry containments of conventional PWRs. The OLPCCS is designed to control the pressure and the temperature in the containment after some accidents. As such, the operating pressure of the proposed system must be lower than permitted pressure in the containment due to heat transfer requirement, which means the OLPCCS is a system with very low pressure (near to atmosphere pressure). 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 (Jiang et al. [10], van der Hagen and Stekelenburg [11], Manera et al. [12], and Kuran et al. [13]) or two-phase flow instabilities (Aguirre et al. [14], Aritomi et al. [15], Van Bragt and van der Hagen [16], Guanghui et al. [17], etc.) for the boiling water reactors (BWRs). Among these studies, the authors were dealing with the performance of closed loop natural circulation system which was rather different from OLPCCS. Furthermore, several codes were developed to study the flow instabilities which may occur in those natural circulation systems in time domain or frequency domain (Inada et al. [18] and Van Bragt et al. [19]). Even though thermal-hydraulic codes had been used for the numerical simulations of natural circulation with lower pressure (Tiselj and Černe [20], Kozmenkov et al. [21], and Mangal et al. [22]), it is still debatable for the validation of those codes in this field.

Thus, it is clear that there is not proper code for the simulation of operating behaviors of such a natural circulation system as OLPCCS. Therefore, this paper addresses the model on the basis of HEM formulation for two-phase flow. The model allows for the thermal properties change, which is calculated with open code package named WASPCN, along the flow path both in single phase and two-phase zone. The one-dimensional computational code is developed by incorporating the above-mentioned model in order to numerically investigate the operation characteristics of the OLPCCS. With the code, transient flow behaviors are simulated from startup to quasisteady state and from single phase flow to two-phase flow. Besides, the heat removal capabilities of the system are also analyzed.

2. OLPCCS

The schematic of OLPCCS design and the structure of the heat exchangers are shown in Figure 1. The heat exchanger inside the containment is supposed to be located along the containment perimeter. With the consideration of components arrangement inside the containment, the heat exchangers of OLPCCS are designed to locate above the ring lifting. 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.

As shown in Figure 1, in the event of a LOCA or MSLB, the coolant released from the reactor vessel or steam line will be flashing into the containment because of the 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 tubes of the heat exchangers will be heated up, which will supply the original driving force for the natural circulation of OLPCCS.

3. Model Setup

In this paper, the following conditions are assumed.

(1) The heat can only be exchanged via the heat exchangers, which means 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 in phase change scenario.

(4) When the OLPCCS is activated, the temperature in the containment steps to and remains some specific 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:

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

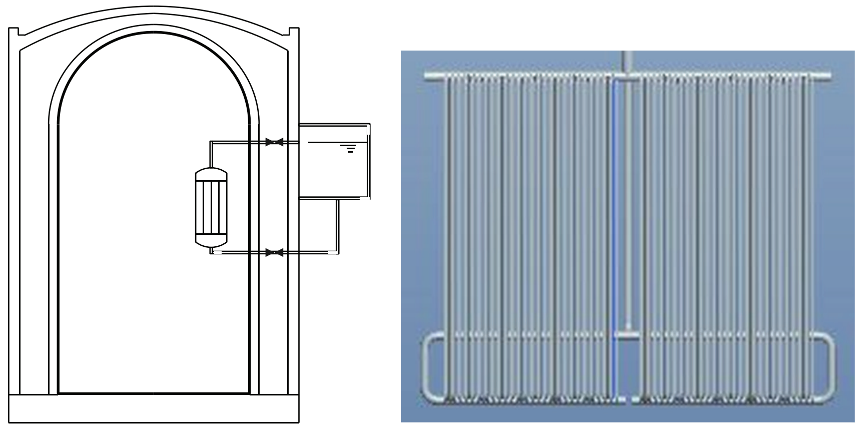

Figure 1: Schematic of OLPCCS (not to scale).

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/°C	30~70
Condensation heat transfer coefficient/(W/(m^{2}K))	500~1000

Momentum conservation equation:

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

Energy conservation equation:

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

where W_m is the mass flow rate, kg/s; A is flow area, m^2; ρ_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:

$$\Delta p_{f,\mathrm{sp}} = f\frac{L}{d_i}\frac{\rho u^2}{2}, \quad (4)$$

where

$$f = \begin{cases} \dfrac{64}{\mathrm{Re}} & \mathrm{Re} \le 2000 \\ 0.3164\mathrm{Re}^{-0.25} & 2000 < \mathrm{Re} \le 3.0\times 10^4 \\ 0.184\mathrm{Re}^{-0.2} & 3.0\times 10^4 < \mathrm{Re} \le 2.1\times 10^6 \\ 0.01 & \mathrm{Re} > 2.1\times 10^6, \end{cases} \quad (5)$$

$$\Delta p_{f,\mathrm{tp}} = \phi_{l0}^2 f\frac{L}{d_i}\frac{\rho u^2}{2}. \quad (6)$$

In (6), ϕ_{l0}^2 denotes the two-phase friction multiplier, which can be expressed as follows:

$$\phi_{l0}^2 = \left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right], \quad (7)$$

or Baroczy method is used for the calculation of ϕ_{l0}^2.

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

$$\mathrm{Nu} = \begin{cases} 3.66 & \mathrm{Re} \le 2000 \\ 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} & \mathrm{Re} > 2000, \end{cases} \quad (8)$$

where $\mathrm{Nu} = h_{\mathrm{sp}} d_i/k$.

The boiling heat transfer coefficient is calculated with the correlations recommended by Shah [23]:

$$h_{\mathrm{tp}} = h_{\mathrm{sp}}\left(h_{\mathrm{BL}} + h_{\mathrm{CL}}\right), \quad (9)$$

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

$$h_{\mathrm{BL}} = \begin{cases} 230\mathrm{Bo}^{0.5} & \mathrm{Bo} > 0.0003 \\ 1 + 46\mathrm{Bo}^{0.5} & \mathrm{Bo} < 0.0003; \end{cases}$$
$$h_{\mathrm{CL}} = \frac{1.8}{C_0^{0.8}}. \quad (10)$$

PCCSTS (passive containment cooling system transient simulation) code is developed with the finite difference method (FDM) based on the models. The schematic of the control volumes of main parts of the system is shown in Figure 2. The numerical simulation of behaviors of the OLPCCS is performed with PCCSTS code. In the current study, the time step for the transient analysis is set to 0.01 s and the converging criteria of the calculations are set to less than 1.0$e-6$ in terms of relative error.

4. Results and Discussions

4.1. Overall Operating Behaviors of OLPCCS. From the conservation point of view, it is supposed that the temperature

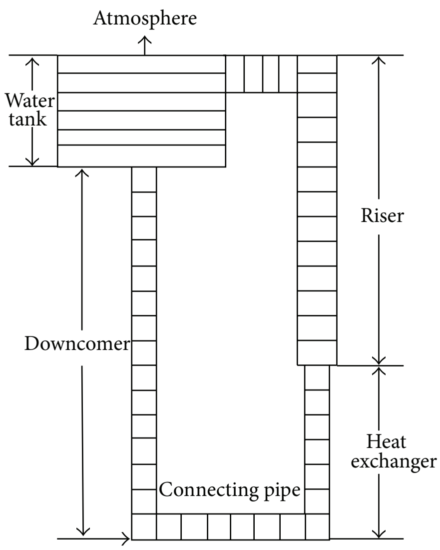

FIGURE 2: Schematic of the nodalization.

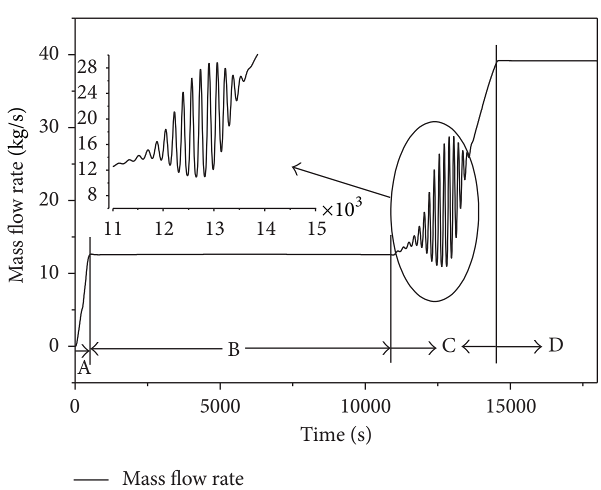

FIGURE 3: Mass flow rate evolution after OLPCCS being activated.

inside the containment steps from the same value as that inside water tank to some value and remains afterward. Firstly, such case is studied that the OLPCCS remains standing by with the water tank temperature of 50°C and is activated and the temperature inside the containment steps to 150°C since then. According to the study of Liu et al. [9] the condensation heat transfer coefficient of steam in the presence of incondensable air changes from about 500 W/(m^{2}K) to almost 2500 W/(m^{2}K). From conservation point of view, the heat transfer coefficient is set to 500 W/(m^{2}K)in this case. Furthermore, the height difference between the water tank and the heat exchanger is 10. Figure 3 depicts the mass flow rate evolution of the OLPCCS in time after being activated.

It can be found that the mass flow rate will increase quickly after the system is activated. With the temperature inside the containment suddenly increasing from 50°C to 150°C, the fluid in the heat exchanger will be heated up simultaneously and its temperature gradually increases, which will make the density difference of the fluid between downward pipe and the riser pipes. Therefore, the force generating from the density difference drives the fluid to move along the loop. During the early stage in startup process, denoted as A in Figure 3, the velocity grows faster and faster, which is because the flow enhances the heat transfer capacity of the heat exchanger and the driving force increases consequently. After the OLPCCS fully starts up, the system operates in single phase mode and the mass flow rate remains barely constant for a relatively long time as shown in Figure 3 with B. Therefore, the period of operation is named as single phase quasisteady stage. During single phase quasisteady operating stage, the fluid that flows through the heat exchangers maintains single phase along all the pipes, even if the system is heated up gradually. Moreover, the fluid temperature difference between inlet and outlet of the heat exchangers changes very slowly. Therefore, the driving force and the mass flow rate of the system are almost changeless. With the increase of the fluid temperature inside the water tank, the temperature increases at the exit of the heat exchangers and reaches saturation point at the outlet of the riser. This causes the flashing of the fluid and then results in the sharp increase of driving force for natural circulation of the system. Thus, the mass flow rate of the system begins to increase when the flashing occurs in the riser. Along with the development of the flashing downward, the system is being speeded up more and more. However, the speeding up process will not continue all the time because the quick increasing velocity may have the effects in two aspects: (1) it will help enhance the heat transfer capability of the heat exchanger; (2) it also may result in the decrease of outlet temperature because of high mass flow rate. Furthermore, the coupling and the lag effect between heat transfer and fluid flow result in the oscillation occurrence. Under given conditions, the oscillation of the mass flow rate will vanish when the temperature of the fluid inside the water tank reaches 90°C as shown in Figure 4. After that, the natural circulation capability will be enhanced continuously until the fluid reaches the saturate temperature inside the water tank. This transient process denoted as C in Figure 3 is named as flashing speed-up transient stage. Finally, the system operates in two-phase quasisteady mode and is dominated by flashing which supplies the main driving head for the system. This stage is marked as D in Figure 3.

According to the description of the operating stages for OLPCCS, it can be concluded that there are two transient phases and two quasisteady phases from A to D. From system design point of view, quasisteady operating stages, marked with B and D, make sense as far as the long-term cooling is concerned in single phase and two-phase mode, respectively. Hence, the flow characteristics of both single phase and flashing dominated two-phase quasisteady stages are studied in the following parts.

4.2. Mass Flow Rate in Single Phase Quasisteady Stage of OLPCCS. Figure 5 shows the mass flow rate in single phase quasisteady stage of OLPCCS under different conditions, which include different condensation heat transfer coefficients and different containment temperatures.

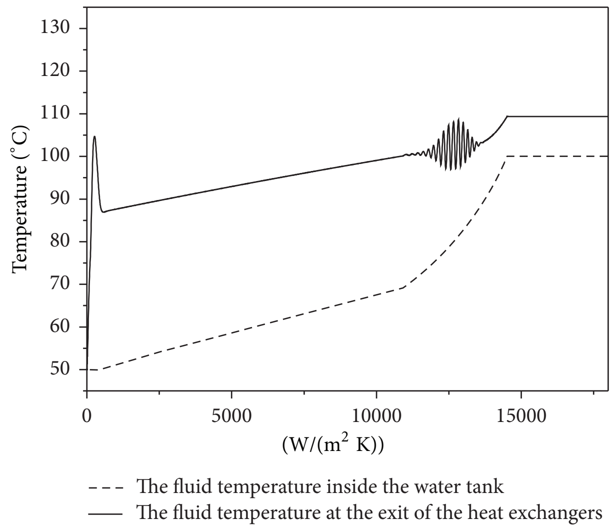

Figure 4: The temperature evolution at typical position after OLPCCS being activated.

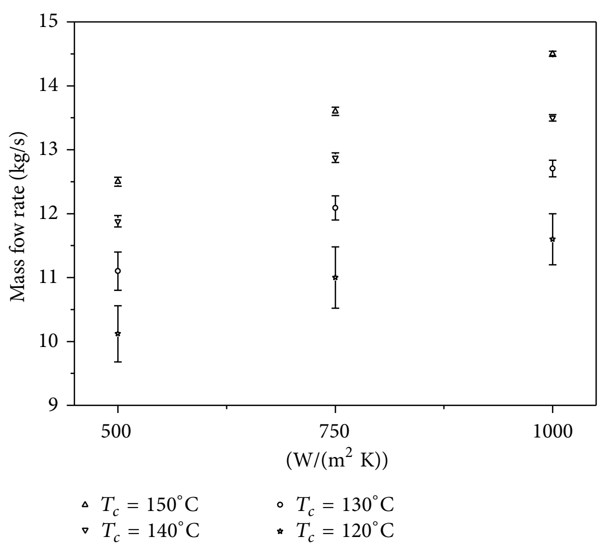

Figure 5: Mass flow rate in single phase quasisteady stage under different conditions.

It can be found in Figure 5 that the maximum relative error of the mass flow rate, which is defined as the ratio of the maximum over the average mass flow rate during single phase quasisteady operating stage, is not more than 5%. In addition, with the increase of either condensation heat transfer coefficient or the containment temperature, it is easy to understand that the mass flow rate of the system may increase for single phase quasisteady operating stage. Furthermore, it is interesting that the larger the mass flow rate is, the less variation the flow shows in single phase quasisteady operating stage. This is helpful for the passive cooling of the containment because of the good adaptability.

4.3. Mass Flow Rate in Two-Phase Quasisteady Stage of OLPCCS. Figure 6 presents the mass flow rate of OLPCCS

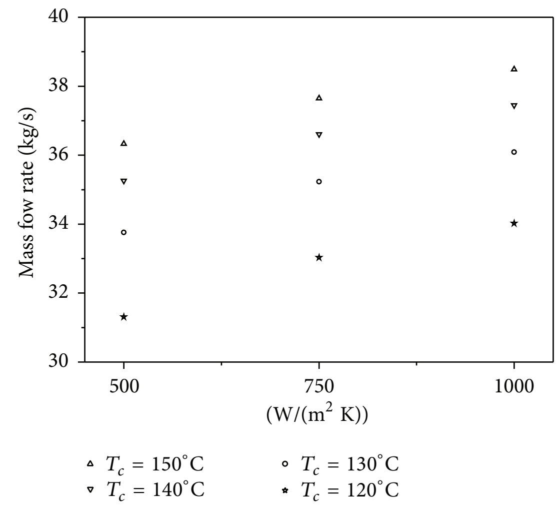

Figure 6: Mass flow rate in two-phase quasisteady stage under different conditions.

under different conditions when the system operates in two-phase quasisteady stage. The two-phase frictional pressure drop is calculated based on homogeneous model in this figure.

As stated before, the OLPCCS will not operate in two-phase quasisteady stage until the water inside the water tank reaches the saturation condition at atmosphere pressure. Afterwards, the flashing two-phase fluid drained from riser will not heat the water inside the tank any more, which is the reason why the system can operate in quasisteady state. The results shown in Figure 6 reveal that the OLPCCS mass flow rate increases with the increase of condensation heat transfer coefficient at given containment temperature condition or the OLPCCS mass flow rate increases with the increase of containment temperature at specified condensation heat transfer coefficient if the OLPCCS operates in two-phase quasisteady phase. With the consideration of the coupling relationship between fluid flow and heat transfer, it can also be concluded that the OLPCCS exhibits good adaptability to the containment thermal conditions in two-phase operating stage. It needs to be noticed that the flow behavior of OLPCCS in two-phase quasisteady stage is quite important for the long-term cooling and integrity insurance of the containment during LOCA or MSLB scenario.

4.4. The Influence of Different Frictional Two-Phase Pressure Drop Models. Commonly, the correlations for the evaluation of frictional pressure drop in two-phase flow can be categorized into such two typical branches as homogeneous model and separated flow model based methods. The former is proper for bubble flow pattern and the latter is suitable for the annular flow pattern. In this paper, the influence of different frictional two-phase pressure drop models on the mass flow rate in quasisteady operating phase for OLPCCS is also discussed. As shown in Figure 7, (7) based on homogeneous model and Baroczy method are used for the evaluation of

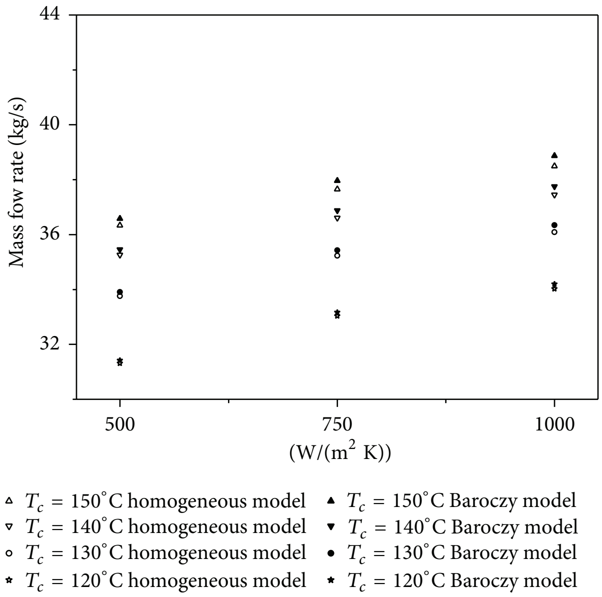

Figure 7: Mass flow rate evaluated based on different two-phase frictional pressure drop models.

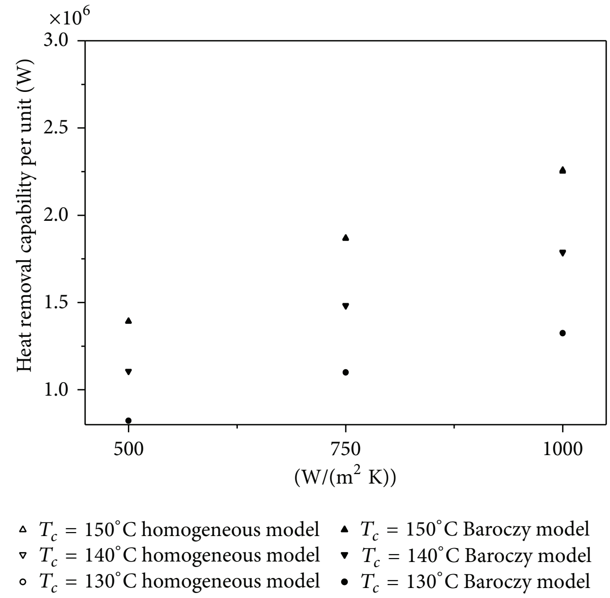

Figure 8: The heat removal capability per OLPCCS unit under different conditions.

mass flow rate of OLPCCS during two-phase quasisteady operating stage.

From the results shown in Figure 7, the predicted mass flow rate of OLPCCS may change a little under different two-phase frictional pressure drop models. The maximum relative error of mass flow rate is under 1%. Therefore, the prediction of the performance of OLPCCS is not sensible for the model selection of two-phase frictional pressure drop.

4.5. The Long-Term Heat Removal Capability of OLPCCS Unit. In order to assess the feasibility of the OLPCCS to the mitigation of LOCA or MSLB consequences, the long-term heat removal capability, which means the system operates in two-phase quasisteady stage, of the OLPCCS is also simulated with the codes and the results are shown in Figure 8.

It can be found that at given containment temperature and condensation heat transfer coefficient condition, the results of long-term heat removal capability are almost the same for different two-phase frictional pressure drop models. For the large dry concrete containment, the design pressure limit is mostly less than 0.52 MPa and the requirement of the containment temperature is less than about 150°C. To match the requirement on the temperature after accidents, the proposed OLPCCS may provide over 1.3 MW heat removal capability per unit if the condensation heat transfer coefficient is not less than 500 W/(m^{2}K). Actually, during LOCA or MSLB scenario, the condensation heat transfer coefficient onto the stainless pipes will vary and be larger than 500 W/(m^{2}K) in most cases. Furthermore, the actual heat removal capability of OLPCCS is higher than long-term heat removal capacity in calculated cases because of the large temperature difference and relative small condensation heat transfer coefficient as compared to the conduction through pipes and convection inside the pipes. Therefore, the proposed OLPCCS is promising for the containment integrity after such accidents as LOCA or MSLB.

5. Summary and Conclusions

In order to ensure the integrity of the containment after typical accidents, the conceptual OLPCCS is proposed and the PCCSTS code is developed to simulate the behavior of OLPCCS. The performances of the system under relative conservative conditions, such as low condensation heat transfer coefficient and high standing-by water temperature, are numerically studied. Analysis of simulation results and the comparison of different models lead to following conclusions.

Based on the PCCSTS code developed by ourselves, the conceptual open loop passive containment cooling system behaviors and the influence of different in-containment conditions are simulated and analyzed. From the results, the following can be concluded.

(1) The proposed OLPCCS shows good self-adaptability to the in-containment conditions, which means the more steam is drained into containment, the more heat can be transferred to the final heat sink.

(2) The OLPCCS is a fully passive system and can be used in the advanced integral type reactor design because of its simplicity and compactness.

(3) The OLPCCS can experience such four different operating stages as startup, single phase quasisteady state stage before flashing occurring, transient process, and long-term two-phase quasisteady state operating stage. Even if instability may occur in the OLPCCS during transient process, there is very little impact on the heat removal capability of the system.

(4) The proposed OLPCCS is a system dominated by flashing regarding the long-term cooling of the containment after typical accidents.

6. Future Work

The new model for the evaluation of onset condition of flashing should be developed to account for the thermal inequilibrium effect in the future.

Nomenclature

A: Flow area m^2
d_i: Inner diameter m
f: Frictional resistance coefficient
h_m: Enthalpy of mixture kJ/kg
h_{sp}: Single phase heat transfer coefficient W/(m^{2}K)
h_{tp}: Two-phase heat transfer coefficient W/(m^{2}K)
k: Thermal conductivity
L: Pipe length m
Nu: Nusselt number
p: Pressure Pa
Pr: Prandtl number
q_l: Linear power W/m
Re: Reynolds number
u: Velocity m/s
W_m: Mass flow rate kg/s
x: Quality
$\Delta p_{f,\text{sp}}$: Single phase pressure drop Pa
$\Delta p_{f,\text{tp}}$: Two-phase pressure drop Pa
ρ_l: Density of liquid phase kg/m^3
ρ_g: Density of gas phase kg/m^3
ρ_m: Density of mixture kg/m^3
ϕ_{l0}^2: Two-phase multiplier.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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