Numerical Simulation Study of Passive Containment Closed Cooling System

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Abstract

The containment vessel serves as the final barrier of a nuclear power plant, capable of withstanding internal pressure generated during accidents under extreme conditions and preventing the release of radioactive materials. The passive containment cooling system can promptly remove heat from within the containment vessel to an external circulation water tank, thereby reducing the temperature and pressure inside the containment vessel during accidents, which plays a crucial role in ensuring the integrity of the containment vessel. To effectively evaluate the safety and reliability of the passive closed-loop containment cooling system and reduce the probability of nuclear accidents, numerical simulation methods were utilized to conduct scaling analysis of the passive closed-loop containment cooling system in the HPR1000, with model validation performed through comparison with existing experimental results. The influence patterns of parameters such as the heat transfer coefficient outside the heat exchanger tubes within the containment vessel, PCS water tank temperature, and relative height of the heat exchanger on the performance of the passive closed-loop cooling system and its flow and heat transfer characteristics during startup were obtained, and these were employed to estimate the critical values of the containment vessel for optimizing the passive closed-loop containment cooling system, thereby enhancing its safety and reliability.

Full Text

Preamble

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Numerical Simulation Study of Passive Containment Closed Cooling System

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Abstract

[**Background**] The containment vessel serves as the final barrier in nuclear power plants, capable of withstanding internal pressure under extreme conditions to prevent radioactive material leakage. The passive containment cooling system efficiently transfers heat from the containment interior to an external circulating water tank, reducing temperature and pressure during accidents and playing a critical role in maintaining containment integrity. [**Purpose**] To effectively evaluate the safety and reliability of passive containment closed cooling systems and reduce the probability of nuclear accidents, this study employs numerical simulation to model and analyze the passive containment closed cooling system of HPR1000, with model validation through comparison with existing experimental results. [**Methods**] The investigation obtains the influence laws of parameters such as the external heat transfer coefficient of containment heat exchanger tubes, PCS water tank temperature, and relative heat exchanger height on the performance and flow-heat transfer characteristics during system startup. [**Results**] These findings are used to estimate critical containment values for optimizing the passive containment closed cooling system, thereby enhancing containment safety and reliability.

Keywords: Passive containment closed cooling system; Natural convection; Modeling analysis; Thermal stratification
CLC Classification: TL334

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Abstract

[**Background**] The containment vessel, as the final barrier of a nuclear power plant, can withstand internal pressure in extreme circumstances, preventing the leakage of radioactive materials. The passive containment cooling system efficiently removes heat from the containment vessel to an external circulating water tank, reducing internal temperature and pressure during accidents, thereby crucially maintaining the integrity of the containment vessel. [**Purpose**] This study aims to effectively assess the safety and reliability of the passive containment cooling system and reduce the probability of nuclear accidents. [**Methods**] Numerical simulation was employed to analyze the passive containment cooling system of HPR1000, comparing results with existing experimental data for model validation. [**Results**] The influence of parameters such as the heat transfer coefficient of the heat exchanger tubes, the temperature of the passive containment system water tank, and the relative height of the heat exchangers on the system' s performance and flow heat transfer characteristics were obtained. [**Conclusion**] This is done to estimate the critical values of the containment vessel for optimizing the passive containment cooling system, thus enhancing its safety and reliability.

Keywords: Passive containment closed cooling system, Natural convection, Modeling analysis, Thermal stratification

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The containment vessel is a critical barrier ensuring nuclear reactor safety. Once breached, large quantities of radioactive materials such as uranium and plutonium would be released into the environment, emitting high-energy particles and electromagnetic waves that generate substantial heat and radiation, causing devastating harm to humans and the ecological environment [1], affecting regional economic and social development with long-term irreversible consequences [2].

During reactor operation, substantial heat is generated. The containment cooling system typically circulates coolant (usually water) to the nuclear reactor to remove heat and release it to the external environment [4]. If the containment cooling system cannot dissipate heat in a timely manner, it will lead to reactor overheating and potentially trigger a nuclear accident [3][5].

The HPR1000 (Hualong One), China' s independently developed third-generation pressurized water reactor (1000 MW) nuclear power plant, proposes the safety concept of "combining active and passive systems," adding a "passive" safety system to the existing "active" safety system. When the "active" safety system cannot operate, the "passive" safety system can promptly remove reactor heat [6], preventing overpressure and overtemperature from compromising containment integrity under accident conditions [7][8].

The principle of HPR1000' s main safety systems is shown in Figure 1 [Figure 1: see original paper], where the passive safety systems include the Passive Secondary Side Residual Heat Removal System (PRS), Passive Containment Heat Removal System (PCS), and Passive Core Injection System (CIS) [9-10]. The PCS, illustrated in Figure 2 [Figure 2: see original paper], operates solely relying on inherent thermophysical properties and natural circulation for cooling [11]. High-temperature working fluid discharged into the containment under accident conditions heats the fluid inside the system heat exchangers, and the density difference between hot and cold fluids in the loop drives natural circulation [12].

Figure 1 Schematic diagram of active and passive safety systems
Figure 2 Introduction to PCS cooling system

Numerous researchers have conducted studies on the safety assessment of passive containment cooling systems. K.N.V. Adinarayana [13] investigated the influence of the Passive Containment Cooling System (PCCS) on containment pressure and temperature transients during a postulated severe accident for a 220 MWe heavy water reactor. The study found that using passive cooling systems like PCCS can significantly reduce peak pressure and temperature in the containment building during severe accidents. Zheng Huang [14] studied the performance of a PWR containment cooling system (PCS) using coupled RELAP5/GOTHIC simulations, finding that the natural circulation loop (NCL) height significantly affects PCS heat transfer capacity, with an optimal loop height maximizing power, and developed a simplified analytical model for engineering design. Xiangjie Qi [15] experimentally investigated flow characteristics of an open natural circulation system, examining the effects of heating power, inlet subcooling, and cooling water tank level on system flow characteristics. The study found that two-phase unstable flow consists primarily of boiling and flashing, which individually or jointly determine open natural circulation behavior. Kai Hui [16] conducted experimental research on the transient thermal-hydraulic characteristics of a nuclear power plant passive circulation cooling system (PCCS), revealing the influence of various parameters on thermal-hydraulic characteristics and proposing a dimensionless empirical correlation to reveal the relationship between natural and forced circulation heat transfer capabilities. Jianjun Wang [17] proposed a system model based on a homogeneous two-phase flow model and used a one-dimensional computational code to simulate transient flow behavior and heat removal capacity. Results showed the system experiences four distinct operational phases and performs well in advanced integral reactors, with OLPCCS demonstrating good adaptability to internal containment conditions. Sun Taek Lim [18] studied a two-phase natural circulation loop passive containment cooling system (PCCS) experimentally by controlling heat loop pressure and inlet temperature, investigating the heat capacity that PCCS can passively remove and comparing heat transfer performance using Chen and Dittus-Boelter correlations. Results indicated that two-phase natural circulation loops have high heat transfer performance and can serve as reference data for improving PCCS performance. Keyuan Zhang [19] investigated PCCS performance under different filling ratios and non-condensable gas contents, conducting parametric studies on key parameters. Results showed these parameters significantly affect loop heat transfer rates, with filling ratio having a greater influence than optimal filling ratio on loop performance. Xuan Xin [20] used the VOF method to track phase interfaces and the Lee model to determine mass exchange between vapor and liquid during boiling, with the shear stress transport k-ω model handling turbulence effects. Numerical simulation studied a two-phase thermosiphon circulation evaporator, emphasizing the importance of understanding evaporator heat transfer and flow characteristics for determining TPTL operation and heat transfer stability.

Liu Yusheng [21] et al. conducted dimensionless analysis of the containment refueling water tank and designed relevant experimental facilities based on similarity criteria. Modeling analysis showed that natural convection in the containment refueling water tank follows similarity criteria, enabling isothermal, isobaric, and same-medium simulation when three similarity criteria numbers are maintained, with the cube of characteristic length ratio in the water tank inversely proportional to heat transfer temperature difference. Zhencheng Huang [22] et al. established a SINDA/FLUINT homogeneous model to study steady-state characteristics of natural circulation loops (NCL). Through analysis of system heat load, cooling temperature, loop friction, and driving forces, new dimensionless scaling criteria numbers were proposed. Li Jun [23] conducted modeling analysis and experimental research on passive containment open systems, comparing theoretical scaling calculation results with experiments when using equal-height, equal-pressure, and equal-medium simulation methods for open natural circulation systems, showing good consistency and proving the correctness and accuracy of the scaling method to some extent. Results indicated that the scaled open cooling system can meet heat removal requirements under corresponding conditions. Liu Zhuo [24] et al. conducted separate and integral effect scaling analyses for large PWR nuclear power plant test facilities, using verification procedures to demonstrate the feasibility of 2/5 scale numerical simulation for CAP1400. Specific design methods were provided, and through test analysis of the PCS integral test facility, it was shown that when the height ratio is below 0.25, natural circulation dominated by external forced convection cannot be achieved.

1 Passive Containment System Scaling Model

Based on prototype parameters of the passive containment cooling system, this study conducts scaling analysis on the designed system. While ensuring flow similarity, geometric similarity, and heat transfer similarity, the scaling model is used to analyze parameters affecting the prototype model. As shown in Figure 3 [Figure 3: see original paper], when a nuclear reactor experiences a breach accident, temperature and pressure inside the containment increase instantaneously, triggering the passive containment cooling system. Gas inside the containment transfers heat to the internal heat exchanger through condensation, and the working fluid inside the closed system forms a density difference with the external cooling water tank to drive fluid circulation, gradually transferring heat from the containment to the external cooling water tank. This ultimately maintains containment internal temperature and pressure within safe limits without active equipment, preventing radioactive material release.

Figure 3 Introduction of the closed passive containment cooling system

1.1.1 Geometric Model

This section introduces the geometric model of heat exchangers in the passive containment cooling system. As mentioned, the passive containment closed cooling system heat exchangers are located both inside the containment and in the external circulating water tank, together with connecting components forming a circulation loop. The passive containment cooling system heat exchanger consists of 132 stainless steel smooth tubes with a height of 5 m and diameter of 38 mm. The tubes connect to header devices at both ends in a single-row arrangement with 100 mm tube spacing. The total heat exchanger area is 78.8 m^2, and the height difference between the two heat exchangers is 10 m. Due to the enormous computational resources required for the complete model, simplifications were made during simulation. The simplified PCS heat exchanger geometry is shown in Figure 4 [Figure 4: see original paper], with other parameters listed in Table 1 .

Figure 4 Schematic diagram of heat exchanger

Table 1 Geometric parameters of PCS heat exchanger

Parameter	Value
Single tube height	10.0 m
Height difference between shell-and-tube heat exchanger and water tank heat exchanger	0.044 m
Riser pipe diameter	0.032 m
Downcomer diameter	(not specified in table)
Heat transfer area of single heat exchanger	(not specified in table)
Horizontal distance between shell-and-tube heat exchanger and water tank heat exchanger	(not specified in table)

1.1.2 Numerical Methods

Continuity Equation:
is fluid density (kg/m^3), v is fluid velocity in three dimensions, x, y, and z are coordinate directions, and t is time (s).

Momentum Equations:
(1-1)
(1-2)
(1-3)
(1-4)
where P represents hydrostatic pressure, τ represents shear stress in different directions, and g represents gravitational acceleration in three directions.

Energy Equation:
The three-dimensional expression of the energy equation in this model is:
(1-5)
where Cp is fluid specific heat capacity, Q represents heat input or output from the loop, and k is fluid thermal conductivity. Based on model assumptions, the one-dimensional energy equation for incompressible flow is:
(1-6)

where h represents the external convective heat transfer coefficient (W/(m^2 · K)).

Turbulence Model:
The RNG k- turbulence model offers advantages including wide applicability, economical computational cost, and reasonable accuracy [25-26]. Compared with other turbulence models, the RNG k- model emphasizes low-Reynolds-number effects and includes swirl effects, improving calculation accuracy for external convective heat transfer [27]. Additionally, it provides non-specified constant values for turbulent Prandtl number. These characteristics make the RNG k- turbulence model more accurate and reliable for solving external convective heat transfer in large-space natural convection [28]. Previous studies found that the RNG k- turbulence model with full buoyancy effects enabled typically demonstrates better simulation performance than other cases for natural convection [29]. Therefore, the RNG k- turbulence model was selected in this work to account for turbulence vortex effects on heat and mass transfer.

1.1.3 Physical Properties

Natural convection is essentially driven by density differences caused by temperature variations. CFD offers two methods to implement variable fluid properties in natural convection: the Boussinesq approximation for fluid density, or temperature-dependent fitting functions to reflect property changes with temperature. To achieve more accurate simulations, this study adopts the second method instead of the Boussinesq approximation. Variable property functions for water were obtained by fitting relationships between density, specific heat, viscosity, and thermal conductivity at different temperatures. Water property functions are listed in Table 2 .

Table 2 Physical properties of water

Property	Function
Density ( )	(function not specified)
Thermal conductivity (λ)	(function not specified)
Viscosity (v)	(function not specified)
Specific heat (cp)	(function not specified)

1.1.4 Basic Assumptions and Boundary Conditions

The following assumptions were adopted for the passive containment cooling system:

1. The water tank and containment internal environment maintain isothermal conditions, including contained media;
2. This simulation models a closed cooling system where all internal pipes are initially water-filled, ignoring other equipment such as gas-liquid separators;

3. Water compressibility is negligible;
4. Considering tube arrangement and heat transfer characteristics, temperature differences between heat exchanger tube rows are ignored, assuming containment internal temperature and external water tank are in a constant-temperature external fluid;
5. To ensure conservative performance analysis of the passive cooling system, only external convective heat transfer is considered for containment internal heat exchangers, ignoring radiative heat transfer;
6. To ensure conservative performance analysis, heat loss to the external environment is ignored;
7. In the passive closed cooling system, the heat exchanger configuration in the external water tank is identical to the internal heat exchanger.

To evaluate passive cooling system circulation characteristics and heat removal capacity, containment internal environmental parameters must be provided to calculate temperatures near internal heat exchangers and heat transfer coefficients during steam condensation. Considering PCS operational requirements and preliminary estimates of condensation heat transfer coefficients under different containment gas mixture compositions, calculations were performed using specified containment internal temperature and external heat transfer coefficient of internal heat exchanger tubes. The environmental temperature was set at 150°C [30], with condensation heat transfer coefficients varied in the range of 500-1400 $W/(m^2 \cdot K)$ [31]. Using constant parameter conditions, stable operating characteristics of the passive cooling system can be obtained.

This study investigates single-phase water driven by buoyancy-induced natural convection. Momentum, energy, and turbulence equations were discretized using second-order upwind schemes, while pressure discretization employed the PRESTO scheme. The RNG k- turbulence model was selected with enhanced wall treatment, considering viscous heat generation. Loop fluid was maintained in the single-phase region at an operating pressure of 0.55 MPa. The characteristic temperature is the average of containment internal temperature and PCS water tank temperature.

2 Numerical Simulation and Model Validation

2.1 Grid Independence Verification

Grid generation for the PCS closed cooling system was completed using Fluent meshing. The surface mesh had a minimum size of 5 mm, maximum size of 20 mm, maximum skewness of 0.6, and a total of 1 million cells. Boundary layers were added near tube walls using the smooth-transition method. Considering the PRESTO pressure discretization scheme, the volume mesh generation method was Hexcore with maximum surface mesh skewness of 0.8.

To ensure computational results are independent of grid quantity, grid independence tests were conducted. Six grid densities were tested. Figure 5 [Figure 5: see original paper] shows the Reynolds number variation in horizontal pipes under conditions of PCS water tank temperature at 363 K, containment internal heat exchanger temperature at 423 K, and convective heat transfer coefficient of 500 $W/(m^2 \cdot K)$ at both ends. As grid number increases, Reynolds number gradually approaches a constant value. When grid number reaches 3.2 million, the variation in Reynolds number within the tube does not exceed 2%, indicating that numerical simulation results are no longer affected by grid quantity beyond this point. All subsequent numerical simulation results were obtained using grids exceeding 3.2 million cells.

Figure 5 PCS grid independence verification

2.2 Model Validation

Figure 6 shows the relationship between steady-state heat transfer capacity of the PCS heat exchange system and temperature difference between containment interior and PCS circulation water tank. The results indicate good agreement with the RELAP5 calculation program [70], with deviations less than 3%, demonstrating that the current model achieves flow similarity with the prototype system and proving the correctness of the scaling approach. As shown in Figure 7 [Figure 7: see original paper], based on Vijayan' s uniform-tube natural circulation loop theoretical model, errors between the current model and previous theoretical models remain within 10%, further confirming model validity.

Figure 6 Model verification of heat transfer capability of PCS system

Figure 7 Comparison between current research and experimental data

3 Results and Discussion

3.1 Temperature and Flow Fields in PCS Closed System

As shown in Figure 8 [Figure 8: see original paper], when the external heat transfer coefficient of the containment internal heat exchanger is 600 $W/(m^2 \cdot K)$, the working fluid in the containment internal heat exchanger (0-5 m) has an inlet temperature of 378.3 K and outlet temperature of 402.5 K. Subsequently, in the riser section (5-15 m), the fluid enters the circulation water tank internal heat exchanger with an average temperature of 402.9 K. This process is adiabatic in the model, with slight temperature increase due to viscous heating. In the circulation water tank heat exchanger (18-23 m), fluid average temperature decreases from 402.9 K to 402.5 K. In the downcomer section (23-36 m), fluid returns to the containment heat exchanger. Due to high-pressure conditions, the working fluid remains in single-phase state.

When containment internal pressure increases further, the heat transfer coefficient between containment interior and internal heat exchanger continuously changes. At a heat transfer coefficient of 800 $W/(m^2 \cdot K)$, the average inlet and outlet temperatures of the containment heat exchanger are 381.0 K and 406.6

K, respectively. At 1000 W/($m^2 \cdot$K), temperatures are 382.8 K and 409.3 K. At 1200 W/($m^2 \cdot$K), temperatures are 384.1 K and 411.2 K. When the external heat transfer coefficient reaches 1400 W/($m^2 \cdot$K), fluid enters the containment heat exchanger at 385 K and is heated to 412.8 K. The PCS cooling system temperature continuously changes while attempting to reach dynamic equilibrium. Simultaneously, as the external heat transfer coefficient increases, the average fluid temperature rises, and the temperature difference between inlet and outlet of both containment and circulation water tank heat exchangers also increases.

Figure 8 PCS closed system heat exchanger temperature changes along the flow path

Figure 9 [Figure 9: see original paper] shows velocity vectors of fluid entering and exiting heat exchanger tube bundles in the PCS closed cooling system. As shown in Figure 9(1), heated fluid enters the first header from containment internal heat exchanger tubes, where flow velocity decreases. Upon entering the riser, the flow cross-sectional area decreases and velocity increases, reaching 0.951 m/s at the center of the riser. Figure 9(2) shows fluid entering the header at the top of the PCS water tank internal heat exchanger from the riser. Under gravity influence, center velocity is significantly higher than at the sides, with obvious backflow at the ends. Figure 9(3) shows partial velocity vectors at the center interface as fluid exits the PCS heat exchanger and enters the header. Flow velocity is relatively uniform in the header before entering the downcomer where cross-sectional area decreases and velocity increases. Figure 9(4) shows fluid entering the containment internal heat exchanger from the downcomer, revealing that center region velocity in the header is higher than in peripheral areas.

Figure 9 Fluid flow vector diagram

3.2 Influence of External Boundary Conditions on PCS Passive Cooling System

Figure 10 [Figure 10: see original paper] shows the influence of PCS water tank internal temperature on system performance, with initial parameters of containment internal temperature at 423 K and heat transfer coefficient at 600 W/($m^2 \cdot$K). As water tank temperature increases from 323 K to 363 K, fluid mass flow rate gradually decreases while system heat transfer rate decreases linearly from 60.93 kW to 35.78 kW. This occurs because as water tank temperature increases, the temperature difference between fluid in the containment heat exchanger and PCS heat exchanger decreases, reducing buoyancy force and consequently decreasing heat transfer performance and mass flow rate.

Figure 10 Influence of the internal temperature of the PCS water tank on the system

During actual operation, as the passive containment closed cooling system activates, containment internal temperature and pressure gradually decrease, and the heat transfer coefficient between containment internal fluid and heat exchanger also decreases. Figure 11 [Figure 11: see original paper] shows the influence of the external heat transfer coefficient of containment internal heat exchanger tubes, with initial parameters of containment internal temperature at 423 K and PCS water tank temperature at 363 K. As the heat transfer coefficient increases from 600 $W/(m^2 \cdot K)$ to 1400 $W/(m^2 \cdot K)$, system mass flow rate and heat transfer performance gradually increase. Mass flow rate increases from 0.407 kg/s to 0.444 kg/s (9.1% increase), while system heat transfer rate increases from 35.78 kW to 44.14 kW (2.3% increase). This indicates that increasing the containment internal heat transfer coefficient enhances system heat transfer capacity, though the effect is not substantial.

Figure 11 Effect of heat transfer coefficient outside the shell heat exchanger tube

Figure 12(1) shows local Nusselt number (Nu) variation in heat exchanger tubes under different PCS water tank temperatures and containment internal heat transfer coefficients. Nu increases from 72 to 87 throughout the system. The lowest Nu occurs at PCS water tank temperature of 363 K and containment heat transfer coefficient of 600 $W/(m^2 \cdot K)$, while the highest Nu occurs at 323 K water tank temperature and 1400 $W/(m^2 \cdot K)$ containment heat transfer coefficient. Lower PCS water tank temperature creates maximum temperature difference between heat exchangers, increasing fluid-to-wall conduction and density difference-driven buoyancy, resulting in higher fluid velocity and enhanced convective heat transfer. In this process, convective heat transfer enhancement exceeds conductive enhancement, increasing Nu. Meanwhile, increasing containment external heat transfer coefficient provides greater buoyancy force, enhancing convective heat transfer and increasing Nu.

Figure 12(2) shows the influence of external conditions on pressure drop in the downcomer. Pressure drop increases from 8 kPa to 14 kPa throughout the system. Maximum pressure drop occurs at PCS water tank temperature of 323 K and containment convective heat transfer coefficient of 1400 $W/(m^2 \cdot K)$, while minimum pressure drop occurs at 373 K water tank temperature and 600 $W/(m^2 \cdot K)$ containment heat transfer coefficient. Lower PCS water tank temperature and higher containment external heat transfer coefficient increase system flow velocity and resistance pressure drop, resulting in greater pressure loss from piping geometry.

Figure 12 The influence of external system conditions on Nu and ΔP

3.3 Influence of Height Difference on PCS Closed Cooling System

This section investigates the influence of relative height difference between the two heat exchangers, calculated as the vertical distance between centers of the containment internal heat exchanger and PCS water tank internal heat exchanger. The external heat transfer coefficient of containment internal heat exchanger is 600 $W/(m^2 \cdot K)$ and PCS water tank temperature is 363 K. Relative heights of 4 m, 6 m, 8 m, 10 m, 12 m, and 14 m were selected.

As shown in Figure 13 [Figure 13: see original paper], PCS closed cooling system mass flow rate increases with relative height. Flow rate increases by 7.76% when relative height increases from 4 m to 6 m, 4.4% from 6 m to 8 m, 3.44% from 8 m to 10 m, 2.85% from 10 m to 12 m, and 1.08% from 12 m to 14 m. As relative height between heat exchangers increases, the growth rate of mass flow rate gradually decreases, indicating that height influence on mass flow rate diminishes with increasing height. This occurs because system resistance increases with flow path length, gradually reducing mass flow rate growth. When system height increases from 12 m to 14 m, mass flow rate change is only 1.08%, suggesting height increase beyond this point is meaningless and only increases equipment costs.

Figure 13 Effect of the height on the system

Figure 14(1) shows Nu variation in heat exchanger tubes with increasing relative height. At 4 m relative height, Nu is 65.9, increasing to 82.3 at 14 m (24.9% increase). As relative height between heat exchangers increases, Nu gradually increases, indicating convective heat transfer capacity in tubes gradually exceeds conduction between fluid and external water tank. Although growth rate decreases with increasing relative height, closed system internal velocity increases, enhancing convective heat transfer.

Figure 14(2) shows pressure drop variation with different relative heights. At heights of 4 m, 6 m, 8 m, 10 m, 12 m, and 14 m, closed system pressure drops are 7.25 kPa, 8.42 kPa, 9.43 kPa, 10.56 kPa, 11.32 kPa, and 11.80 kPa, respectively, representing a 62.7% increase. This demonstrates that increasing internal heat exchanger height lengthens flow path and increases system pressure drop.

Figure 14 Effect of relative height on Nu and ΔP

4 Conclusions

To further investigate passive containment closed cooling system performance, this study conducted scaling analysis of the closed system, analyzing temperature and velocity fields during flow and heat transfer processes. The effects of PCS circulation water tank temperature, external heat transfer coefficient of containment heat exchanger tubes, and relative height between heat exchangers on PCS closed cooling system performance were considered. Main conclusions are as follows:

1) All discussed models can obtain a prototype PCS closed cooling system with identical behavioral characteristics, differing only by scaling factors in heat transfer performance. Flow characteristics remain constant with height, identical to the original model.

2) Under certain heat transfer conditions, the PCS closed cooling system

can achieve quasi-steady state, characterized by constant average fluid temperature along the flow path. As containment external heat transfer coefficient increases, the system reaches a new quasi-equilibrium state.

3) Numerical calculations show that with containment internal temperature maintained at 150°C, system heat transfer performance negatively correlates with PCS circulation water tank fluid temperature—lower PCS water tank temperature yields better closed PCS heat transfer performance. As PCS water tank temperature increases, deviation between maximum and final stable mass flow rate gradually increases, with greater heat transfer deviation amplitude. Increasing containment internal heat transfer coefficient enhances system heat transfer capacity and mass flow rate, though the effect is not substantial. The strongest convective heat transfer capacity (Nu up to 86) and maximum pressure drop occur at lowest PCS water tank temperature and highest containment internal heat transfer coefficient.

4) Numerical simulation reveals that relative height difference between containment internal heat exchanger and PCS circulation water tank heat exchanger does not always positively affect closed PCS heat transfer capacity. The optimal relative height for this model does not exceed 16 m. As height increases, mass flow rate growth gradually decreases—only 1.08% increase when system height changes from 14 m to 16 m. However, increasing relative height enhances heat exchanger Nusselt number and convective heat transfer capacity, while also increasing pressure drop. Greater relative height between heat exchangers prolongs the time required to reach stability during system startup.

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Note: Figure translations are in progress. See original paper for figures.