Experimental Study on Thermal Stratification Characteristics of Core Makeup Tank Under Marine Conditions

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Abstract

The Core Makeup Tank (CMT) is a passive safety injection technology that maintains isobaric conditions with the Reactor Coolant System (RCS), and has been widely applied in large commercial pressurized water reactors and multi-purpose small modular reactors. During CMT injection, hot and cold fluids within the tank form a significant stratified interface, which directly modifies the driving force for CMT injection and significantly affects the transient injection flow rate. Based on a CMT injection experimental facility, this study investigates the thermal stratification phenomenon inside the CMT and its influencing factors under typical motion conditions including heaving, tilting, and rolling. Experimental results demonstrate that: the influence of heaving motion on thermal stratification depends on the relative magnitude of heaving acceleration to gravitational acceleration; tilting conditions exhibit an insignificant effect on hot-cold stratification within the CMT; rolling motion accelerates the diffusive mixing process between hot and cold fluids inside the CMT, resulting in a reduced axial temperature gradient within the stratified region and a thicker stratification layer. Under rolling motion conditions, a decrease in period or an increase in maximum angle both enhance the mixing and diffusion effects of hot and cold fluids, ultimately causing the entire internal region of the CMT to evolve toward a thermocline region.

Full Text

Preamble

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Experimental Study on Thermal Stratification Characteristics of Core Makeup Tank Under Ocean Conditions

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Abstract

[**Background**] The Core Makeup Tank (CMT) is a passive safety injection technology that maintains equal pressure with the Reactor Coolant System (RCS) at all times and has been widely applied in large commercial pressurized water reactors and small modular reactors. During CMT injection, significant thermal stratification forms inside the tank, directly altering the injection driving force and substantially impacting transient injection flow rates.

[**Purpose**] Based on a CMT injection experimental facility, this study investigates the thermal stratification phenomenon and its influencing factors within the CMT under typical ocean motion conditions including heaving, tilting, and rolling.

[**Methods**] The CMT test setup was designed and constructed according to similarity principles and installed on a six-degree-of-freedom motion platform to simulate ocean conditions. Temperature data were obtained through multi-layer measurement points arranged axially and radially inside the CMT. The evolution of thermal stratification under different ocean conditions was compared and analyzed to characterize thermal stratification features and influencing factors under ocean conditions.

[**Results**] Experimental results demonstrate that ocean conditions affect thermal stratification to varying degrees. Heave motion impact depends on the relative magnitude of heave acceleration to gravitational acceleration. Tilting represents a static condition that does not enhance mixing between hot and cold fluids, showing no significant influence on CMT thermal stratification. Rolling motion accelerates the diffusion and mixing process between hot and cold fluids inside the CMT, reducing the axial temperature gradient within the stratified region and thickening the stratified layer. Under rolling conditions, decreasing the period or increasing the maximum angle enhances the mixed diffusion effect of hot and cold fluids, ultimately transforming most of the CMT interior into a thermocline region.

Conclusions Rolling motion substantially affects thermal stratification. Under rolling conditions, a decrease in period or increase in maximum angle enhances the mixed diffusion effect of cold and hot fluids, eventually causing the entire internal region of the CMT to transform into a thermocline zone.

Keywords: Passive injection, Core Makeup Tank, Ocean conditions, Natural circulation, Thermal stratification

Introduction

The Core Makeup Tank (CMT) constitutes a critical component of the Passive Safety Injection System (PSIS), primarily providing passive safety injection during Loss of Coolant Accidents (LOCA) and enabling emergency core makeup and boron injection during non-LOCA conditions. With its simple structure and high reliability, the CMT system has been widely adopted in third-generation nuclear power plants represented by AP1000 and in multi-purpose small modular reactors.

Extensive research has been conducted by domestic and international scholars on CMT system operational characteristics and key thermal-hydraulic phenomena under static conditions. Small Break LOCA experiments performed on the Rig of Safety Assessment-AP600 (ROSA-AP600) demonstrated CMT operating characteristics in natural circulation and steam replacement drainage modes, with clear hot-cold stratification forming at the CMT top during natural circulation mode. Experiments on the Parallel Channel Test Loop (PACTEL) and KARD-1 test facilities showed that thermal stratification inside the CMT effectively isolates injection cold water from high-temperature steam, reducing direct contact condensation and helping maintain stable injection flow. These studies indicate that CMT internal hot-cold stratification characteristics directly affect natural circulation injection mode stability and are crucial for early-phase core makeup and cooling during SBLOCA.

As multi-purpose small modular reactor applications expand from land-based to ocean environments, thermal stratification characteristics and influencing factors inside the CMT under ocean conditions have become key issues constraining passive equal-pressure injection technology application in marine scenarios. This paper employs a CMT injection experimental facility to experimentally investigate thermal stratification phenomena during natural circulation injection mode, obtaining thermal stratification characteristics and influencing factors under ocean conditions and comparatively analyzing evolution features under different ocean motion conditions. The findings provide experimental data and guidance for CMT design optimization and program model development.

1 Experimental Apparatus and Conditions

The CMT injection experimental apparatus is illustrated in Figure 1 [Figure 1: see original paper], consisting primarily of a CMT simulator, Reactor Pressure Vessel (RPV) simulator, water circulation loop, and corresponding valves. The CMT was designed as a spherical tank to mitigate liquid surface shape variation effects on thermal stratification during motion. The entire experimental apparatus was installed on a six-degree-of-freedom motion platform.

The experimental facility was equipped with various measurement instruments for fluid pressure, CMT liquid level, injection flow rate, and fluid temperature. This study primarily utilized T-type thermocouples to measure fluid temperatures at different CMT locations, with measurement accuracy of $±$0.788°C. To obtain detailed temperature distributions, multiple measurement layers were arranged inside the CMT both axially and radially, as shown in Figure 2 [Figure 2: see original paper]. Axially, measurement points were densely arranged in the upper tank and sparsely in the lower portion following the principle of similarity. Radially, two layers were arranged at the middle and near-wall surfaces.

Based on the CMT injection experimental facility, two types of tests were conducted: static flow and injection flow tests. To analyze the influence of different ocean motion conditions on CMT hot-cold stratification characteristics, three typical ocean motion forms—heaving, tilting, and rolling—were selected as experimental conditions for each test type. The parameter ranges for different ocean motion conditions are shown in Table 1 .

2 Results and Analysis

2.1 Thermal Stratification Characteristics Under Land-Based Conditions

The temperature variation inside the CMT under land-based conditions is shown in Figure 3 [Figure 3: see original paper]. Hot water entering the CMT forms a stable hot-cold stratification interface with the internal cold water. After injection begins, the CMT outlet temperature maintains its initial low-temperature state, with the stratification interface located in the upper CMT tank. As injection proceeds, this thermal stratification interface gradually moves downward. When hot fluid reaches the tank bottom, the thermal stratification interface exits the CMT tank, causing the injection fluid temperature at the outlet to begin rising. The density difference between hot and cold sections of the CMT branch decreases significantly, and the corresponding natural circulation driving force rapidly declines, causing the natural circulation injection flow rate to shift from linear decrease to exponential decay, as shown in Figure 4 [Figure 4: see original paper].

2.2 Thermal Stratification Characteristics Under Heaving and Tilting Conditions

The temperature variation inside the CMT under four different heaving conditions is shown in Figure 5 [Figure 5: see original paper]. The temperature rise curves at various measurement points nearly overlap under different heaving motion conditions, indicating that heaving motion does not significantly affect temperature distribution within the thermal stratification region. Studies in references 14 and 15 show that heaving motion effects on thermal-hydraulic systems primarily manifest as periodically varying additional inertial acceleration in the vertical direction, with the composite characteristics of additional inertial acceleration and gravitational acceleration determining fluid response. In this study, the maximum heaving acceleration achievable by the six-degree-of-freedom test platform was 0.1 g, far smaller than gravitational acceleration. Consequently, the diffusion and mixing process of hot and cold fluids within the thermal stratification is minimally affected by heaving motion, and the energy transfer process inside the thermal stratification shows no significant difference from that under static land-based conditions.

The temperature variation inside the CMT under tilting conditions is shown in Figure 6 [Figure 6: see original paper]. Different tilt angles result in varying natural circulation driving forces, causing changes in injection flow rate and consequently different temperature rise initiation times at various measurement points. Due to the spatial distribution characteristics of the CMT tank and RPV simulator, positive and negative tilting produce different effects, though fundamentally caused by differences in effective height. Larger effective height differences produce greater natural circulation forces, higher injection flow rates, earlier arrival of hot fluid at the CMT bottom, and earlier temperature rise initiation. However, under different tilt angles, the temperature rise rates at various measurement points are essentially identical, indicating similar temperature distributions within the thermal stratification and demonstrating that tilting has minimal influence on thermal stratification. This occurs because tilting conditions represent a type of static condition that does not enhance mixing between hot and cold fluids.

2.3 Thermal Stratification Characteristics Under Rolling Motion Conditions

The temperature variation inside the CMT under rolling conditions is shown in Figure 7 [Figure 7: see original paper]. While heaving and tilting conditions have minimal impact on CMT internal thermal stratification and can be neglected, rolling motion has substantial influence with obvious phenomena, requiring focused investigation of rolling motion effects on CMT internal thermal stratification. More severe rolling conditions—characterized by larger rolling angles and smaller periods—produce smaller temperature curve slopes at different axial positions in the CMT tank, correspondingly lower temperature gradients within the hot-cold stratification region. This demonstrates that rolling motion intensifies mixing effects between hot and cold fluids, causing earlier CMT outlet temperature rise, with more severe rolling motion producing stronger mixing effects.

3 Analysis of Thermal Stratification Distribution Characteristics

3.1 Thermal Stratification Distribution Characteristics Under Static Flow Conditions

To investigate thermal stratification characteristics inside the CMT under ocean conditions, dedicated thermal stratification experiments were conducted under static flow conditions. First, natural circulation injection through the CMT was used to shift the hot-cold stratification interface to the region between thermocouples T6-T7. Then the Direct Vessel Injection (DVI) line valve was closed to eliminate injection flow effects on thermal stratification. The experiment lasted 0.5 hours, with temperature variations from 11 axial thermocouples (T1-T11) monitored to obtain thermal stratification distribution patterns under static flow conditions.

The axial temperature distribution inside the CMT at different times under static flow conditions is shown in Figure 8 [Figure 8: see original paper]. During the experiment, the hot-cold stratification interface remained within the 240mm~400mm interval from the CMT bottom without significant diffusion. Based on temperature gradients, the CMT can be divided into five regions from top to bottom: high-temperature zone, high-temperature transition zone, thermocline zone, low-temperature transition zone, and low-temperature zone. The region between high-temperature and low-temperature zones is typically called the thermal stratification region, specifically including the high-temperature transition zone, thermocline zone, and low-temperature transition zone, with the thermocline zone having the maximum temperature gradient. During the experiment, the low-temperature transition zone temperature increased while high-temperature and high-temperature transition zone temperatures decreased slightly, with the axial temperature gradient in the thermocline zone decreasing slightly. The essence is that energy transfer occurred within the thermal stratification region under thermal diffusion.

3.2 Thermal Stratification Characteristics Under Rolling Conditions

Figure 9 [Figure 9: see original paper] shows the axial temperature distribution variation inside the CMT over time under rolling conditions of A=20°, T=20s. The initial thermal stratification distribution was consistent with static conditions. At 200s, the low-temperature transition zone temperature increased, the high-temperature transition zone temperature decreased, and the thermal stratification region boundaries diffused to 460mm and 200mm from the CMT bottom. This shows that rolling motion significantly increased the thermal stratification region and notably reduced the temperature gradient in the thermocline zone. As experimental duration increased, the thermal stratification region continued expanding, with the thermocline zone range noticeably expanding and its internal temperature gradient further decreasing. At 1000s, most regions inside the CMT had transformed into a thermocline zone, high-temperature zone fluid temperature decreased significantly, and axial temperature tended toward uniformity.

Compared with thermal stratification characteristics under static flow conditions, rolling conditions significantly enhanced thermal stratification diffusion effects. Under static conditions, the thermal stratification region had a relatively fixed temperature range, but under rolling conditions, this region expanded with decreasing temperature gradients, eventually transforming most fluid regions inside the CMT into a thermocline zone. This occurs primarily because rolling motion enhances mixing effects between hot and cold fluids, intensifying energy transfer processes within the stratification region. To investigate the influence of different parameters on thermal stratification evolution, analysis was conducted from three aspects: initial temperature difference, rolling period, and maximum rolling angle.

Analysis of Initial Temperature Difference Between Hot and Cold Ends

Using the initial temperature difference between thermocouples T6 and T7 (maxTD) as a reference value, the real-time temperature difference between T6 and T7 under different conditions was normalized to obtain the dimensionless temperature difference ΔDth, used to measure and compare temperature difference changes across different temperature difference conditions.

The variation curves of dimensionless temperature difference between hot and cold ends over time under three initial temperature difference conditions are shown in Figure 10 [Figure 10: see original paper]. The results show that under different initial temperature difference conditions, the dimensionless temperature difference between hot and cold ends changes almost identically over time, indicating no significant correlation between initial temperature difference and thermal stratification evolution under rolling conditions.

The axial normalized temperature distribution of the CMT at different times under different temperature difference conditions for the rolling motion case of A=10°, T=15s is shown in Figure 11 [Figure 11: see original paper]. Under different initial temperature difference conditions, the evolution characteristics of thermal stratification over time are nearly identical, demonstrating that initial temperature difference does not significantly affect thermal stratification under ocean conditions.

Analysis of Rolling Period Influence

Rolling parameters significantly affect the mixing and diffusion process of hot and cold fluids inside the CMT. The axial temperature variation of the CMT at different times under different rolling periods is shown in Figure 12 [Figure 12: see original paper]. In the case with a 10s rolling period, diffusion appeared in the low-temperature and high-temperature transition zones by 200s, whereas in the T=20s case, a similar diffusion process did not begin until 500s. The temperature change rate in the transition zone under short rolling period conditions was significantly faster than under long rolling period conditions, indicating more intense diffusion evolution of thermal stratification. In summary, with constant maximum rolling angle, period shortening increases the additional inertial force on fluids, enhancing mixing effects between hot and cold fluids within the thermal stratification region. This manifests as increased diffusion speed of the thermal stratification region toward its upper and lower sides and increased temperature change rates in the transition zone.

Analysis of Rolling Angle Influence
Thermal stratification characteristics inside the CMT under different maximum rolling angles are shown in Figure 13 [Figure 13: see original paper]. Similar to rolling period variation cases, increasing the maximum rolling angle causes the thermal stratification region to diffuse toward its upper and lower sides as experimental duration increases, with temperature gradients within the thermocline zone gradually decreasing and those within transition zones gradually increasing. In Figure 13(b), at 200s experimental duration, fluid in the thermocline zone under larger rolling angle conditions showed smaller temperature gradients. For rolling angles of 15° and 20°, thermal stratification diffusion occurred, with the high-temperature transition zone extending to 400~460mm. Figure 13(c) shows that different maximum rolling angles produce significantly different diffusion degrees of the low-temperature transition zone toward its lower portion, with larger maximum rolling angles producing faster fluid temperature change rates in transition zones and faster thermal stratification evolution. The above analysis indicates that increasing the maximum rolling angle increases additional inertial forces on hot and cold fluids within the thermal stratification region, enhancing fluid diffusion and mixing processes, accelerating diffusion speed of the thermal stratification region toward its upper and lower sides, significantly reducing temperature gradients of fluid within the thermocline zone, and consequently accelerating thermal stratification structure evolution.

Conclusions

Experimental studies were conducted on fluid thermal stratification characteristics inside the CMT under different ocean operating conditions during CMT injection processes. The distribution characteristics of thermal stratification and its influencing factors under different conditions were analyzed, with main conclusions as follows:

1. The influence of heaving motion on hot-cold fluid mixing within thermal stratification depends on the relative magnitude of additional inertial acceleration to gravitational acceleration; tilting conditions do not enhance mixing between hot and cold fluids.
2. Rolling motion enhances diffusion and mixing effects of hot and cold fluids inside the CMT, accelerating energy transfer within thermal stratification and continuously reducing axial temperature gradients. The relatively fixed thermal stratification region under static conditions expands significantly, eventually transforming most fluid regions inside the CMT into a

thermocline zone.

3. Under rolling motion conditions, initial temperature difference does not significantly affect thermal stratification changes. Decreasing rolling period or increasing maximum rolling angle both enhance diffusion and mixing processes within thermal stratification transition zones, reducing thermocline temperature gradients.

Author Contributions

LIU Yusheng was responsible for experimental condition and boundary condition design, experiment execution, and manuscript drafting. RUAN Haoyu was responsible for experimental result analysis and phenomenon analysis. WANG Shuguang was responsible for experiment execution and data analysis. TANG Jinlin was responsible for experimental data analysis. LI Dongyang was responsible for experimental phenomenon mechanism analysis and research. TAN Sichao was responsible for manuscript review, revision, and overall supervision.

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