Large Eddy Simulation of Thermal Stratification in the HDR Experimental Reactor Pressure Vessel-Horizontal Piping System (Postprint)

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Abstract

Thermal stratification phenomenon is one of the primary causes of thermal fatigue failure in pressurized water reactor (PWR) piping systems. This study aims to investigate the transient thermal distribution characteristics in piping structures induced by thermal stratification phenomena in reactor configurations, and to identify thermal fatigue sensitive locations. Referencing the HDR (Heiss Dampf Reaktor) piping thermal stratification experiments, a full-scale simulation model of the HDR experimental reactor incorporating the reactor pressure vessel (RPV) was established. In this research, the flow field was computed using the large eddy simulation (LES) numerical method to account for the effects of large-scale and small-scale turbulent motions on unsteady flow and heat transfer processes, coupled with solid heat conduction equations, to complete a conjugate heat transfer analysis of the horizontal piping system. The results demonstrate that the large eddy simulation method is suitable for thermal stratification research, with predictions of flow field and structural temperature distribution showing good agreement with experimental data. The study identified the location of maximum structural temperature fluctuation intensity when thermal stratification occurs in horizontal pipes, which can serve as a sensitive point for thermal fatigue analysis. The numerical simulation methodology and analysis results of this study can provide references for structural integrity and safety assessments of PWR piping systems and equipment.

Full Text

Preamble

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Large Eddy Simulation of Thermal Stratification in HDR Pressurized Vessel-Horizontal Piping System

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Abstract

Thermal stratification is one of the primary causes of thermal fatigue failure in pressurized water reactor (PWR) piping systems. This study investigates the transient thermal distribution characteristics in reactor structures induced by thermal stratification to identify thermal fatigue-sensitive locations. Referencing the Heiss Dampf Reaktor (HDR) pipeline thermal stratification experiments, a full-scale HDR test reactor simulation model incorporating the reactor pressure vessel (RPV) was established. The flow field was computed using large eddy simulation (LES) to capture the influence of large- and small-scale turbulent motions on unsteady flow and heat transfer processes, coupled with solid heat conduction equations to complete conjugate heat transfer analysis of the horizontal piping system. Results demonstrate that the LES method is well-suited for thermal stratification research, with predictions of flow field and structural temperature distributions showing good agreement with experimental data. The study identifies the location of maximum temperature fluctuation intensity in the horizontal pipe during thermal stratification, which can serve as a sensitive point for thermal fatigue analysis. The numerical simulation methodology and analytical results provide valuable references for structural integrity and safety assessments of PWR piping systems and components.

Keywords: pressurized water reactor; thermal stratification; large eddy simulation; conjugate heat transfer
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1. Computational Model and Simulation Parameter Settings

1.1 Geometric Model

In the German HDR project, researchers constructed a full-scale reactor structure and conducted extensive experimental studies on thermal stratification in horizontal pipelines. Referencing the HDR experiments [14-19], a simplified HDR test reactor model was established as shown in [FIGURE:1]. The model comprises three main components: the reactor pressure vessel (RPV), piping components, and the internal flow domain. The Q25 cross-section of the horizontal pipe was selected as a typical section for subsequent result analysis and comparison. At the initial moment, the pressure vessel and piping were filled with stationary high-temperature, high-pressure fluid. Coolant was injected through the lower end of the vertical pipe, flowed through the horizontal pipe section, and finally entered the pressure vessel.

1.2 Mesh Generation

Professional meshing software ICEM CFD was employed to generate high-quality structured grids for the HDR test reactor and internal flow region. Since the numerical simulation focused on the horizontal pipe section where thermal stratification occurs, local mesh refinement was applied to both the pipe structure and internal flow field. Considering LES requirements, the first layer grid height in the pipe region was controlled at 0.1 mm to ensure the dimensionless wall distance y^+ was approximately 2. The boundary layer mesh consisted of 25 layers with a growth factor of 1.1. The final model contained 6.57 million grid cells, including 1.19 million cells for the pipe structure and 4.7 million cells for the internal flow region. The global mesh and detailed views of the bend and pipe inlet are shown in [FIGURE:2].

1.3 Boundary Conditions and Solution Parameter Settings

The numerical simulation conditions reference the HDR T33.19 test group [19]. At the experimental initial state, the pressure vessel and piping were filled with stationary fluid at 210°C and 2.24 MPa, reaching stable conditions. At a certain moment, low-temperature coolant began injecting from the lower end of the vertical pipe at 60.5°C with an average velocity of 0.106 m/s. Corresponding boundary conditions for the numerical simulation were set as follows: the lower end of the vertical pipe was assigned a velocity inlet boundary with random perturbations introduced through the vortex method, and the inlet temperature was set as constant. The upper outlet of the pressure vessel was designated as a pressure outlet boundary with gauge pressure set to zero, backflow temperature of 210°C, reference pressure of 2.24 MPa, and the reference pressure location at the center of the upper outlet. Both hot and cold fluids coexisted in the pipe. Hot fluid heated the pipe while cold fluid flowing through removed some heat. Since the internal fluid temperature was significantly higher than the ambient gas and the fluid thermal conductivity was much greater than that of the external environment, heat exchange between the pipe and external ambient gas was minimal and could be neglected; thus, adiabatic boundary conditions were applied to all external solid walls. Heat transferred from hot fluid to solid and then to cold fluid, with coupled heat exchange occurring between internal fluid and pipe, so conjugate heat transfer boundary conditions were applied at fluid-solid interfaces.

The numerical analysis time step was determined by the Courant condition given in Equation (1):

$$CFL = \frac{u \cdot dt}{dx}$$

where u is the average inlet velocity, dt is the simulation time step, and dx is the minimum grid size along the flow direction. The total physical simulation duration was 280 s, with a time step of 0.01 s. The numerical computation employed the SIMPLE algorithm, with pressure interpolation using the PRESTO! scheme and momentum and energy equations discretized using the bounded central differencing method. The turbulence model was large eddy simulation with the dynamic Smagorinsky-Lilly subgrid-scale model. Convergence residuals were set to 10^{-5} for momentum and continuity equations and 10^{-6} for the energy equation.

For the studied conditions, the temperature difference between hot and cold fluids was large, causing significant density variations that invalidated the Boussinesq approximation. To accurately model the strong effects of density differences between fluids at different temperatures, a full buoyancy model was adopted, with fluid density, viscosity, specific heat capacity, and thermal conductivity expressed as polynomial functions of temperature [30]. The fluid property variation curves at 2.24 MPa are shown in [FIGURE:3]. The solid material was bainitic steel with a density of 7,850 $\text{kg} \cdot \text{m}^{-3}$, specific heat capacity of 510 $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and thermal conductivity of 46.4 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 200°C.

Referencing the thermocouple arrangement in the HDR experiments, eight monitoring points were placed in the Q25 cross-section as shown in

. The monitoring points were divided into two categories: the first category was located in the near-wall flow region at a normal distance of 10 mm from the pipe inner wall; the second category was located on the pipe inner wall surface, where the circumferential angle θ represents the position in the YZ plane. The height direction of the pipe cross-section was defined as follows: the bottom inner wall surface served as the zero reference point, with vertical distance along the Z-axis from this reference point defined as height, denoted as H in the figure.

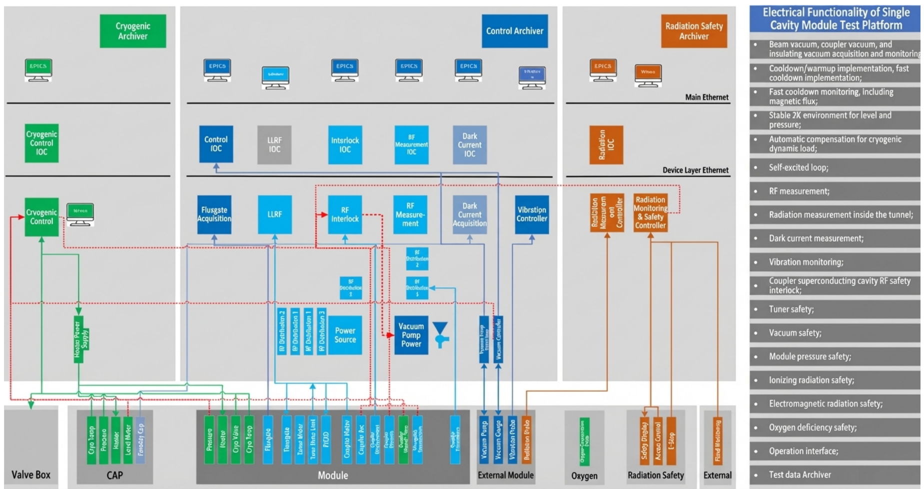

Figure 1: Figure 4

2. Numerical Results and Analysis

Temperature distributions at the mid-plane of the horizontal pipe at different times are shown in [FIGURE:5], revealing the evolution of stratified flow in the pipe. At $t = 70$ s, cold fluid deposited in the lower portion of the pipe under gravity and flowed along the bottom, creating a temperature gradient in the pipe cross-section. At $t = 80$ s, distinct thermal stratification appeared in the horizontal pipe, with cold fluid flowing along the bottom and hot fluid occupying the upper space due to buoyancy effects. Irregular flow profiles appeared at the hot-cold fluid interface, accompanied by thermal striping phenomena that caused rapid temperature oscillations at the interface. Temperature contours at $t = 160$ s and $t = 260$ s show smoother temperature profiles at the hot-cold interface, with the mixed layer height remaining approximately constant, forming relatively stable stratified flow with small temperature fluctuation amplitudes. During the cold water injection process in the horizontal piping system, thermal stratification occurred (around 70 s) and persisted until cold water injection ceased. The total physical simulation duration was 280 s, with thermal stratification existing throughout the 70–280 s period.

illustrates the flow characteristics of thermal stratification in the pipe at the typical moment $t = 100$ s. [FIGURE:6(a)] shows streamlines at the pipe outlet, where cold fluid exits below and deposits at the bottom of the RPV, while hot fluid above creates a recirculation flow into the upper space of the horizontal pipe. [FIGURE:6(b)] presents velocity vectors in the hot-cold interface region (arrow length represents velocity magnitude), showing that below the dashed line, cold fluid flows toward the pipe outlet at relatively high velocity. Due to the significant relative velocity between hot and cold fluids, a shear layer exists at the interface, causing high-velocity cold fluid to entrain some hot fluid toward

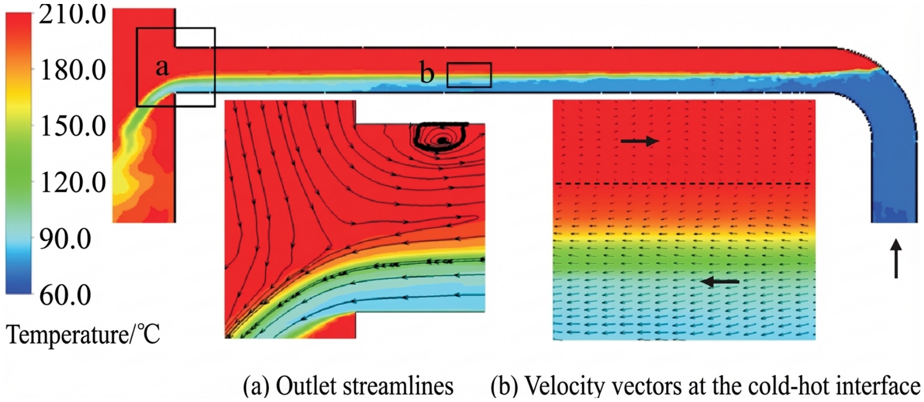

Figure 2: Figure 6

the outlet. These results reveal that during thermal stratification in horizontal pipes, hot fluid in the upper space forms a recirculation zone, and the stratification eventually reaches a quasi-steady state with approximately constant stratification height, consistent with experimental observations by WOLF et al. [15,19].

The temperature distribution characteristics at the Q25 cross-section were investigated, with

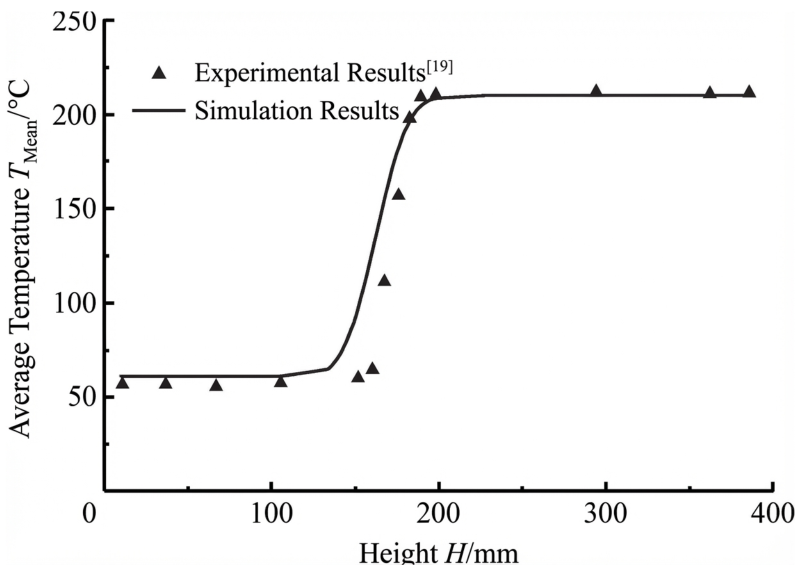

Figure 3: Figure 7

showing the variation of near-wall fluid mean temperature with monitoring point height. Numerical results represent statistical averages of temperature from 240 s to 280 s. In the height range H = 140–200 mm, a large temperature gradient exists in the flow field, with near-wall fluid mean temperature increasing sharply with height, indicating mixing between hot and cold fluids in this region. Both ends of the temperature distribution curve are approximately horizontal, with hot fluid in the upper pipe region and cold fluid in the lower region, where near-wall fluid mean temperature remains nearly constant. The numerical results show good agreement with experimental data from WOLF et al. [19], demonstrating that conjugate heat transfer analysis based on LES can accurately predict temperature distribution patterns in pipe cross-sections, validating the accuracy of the LES numerical computation.

[FIGURE:8] presents temperature time history curves for different monitoring points in the near-wall region and on the pipe inner wall at the Q25 cross-section. The temperature difference shows a trend of initially increasing and then stabilizing. After flow initiation, at approximately t = 70 s, cold fluid reached the Q25 cross-section, and temperatures at monitoring points at 95°, 100°, and 105° began to decrease, with points near the bottom of the horizontal pipe cooling faster. Eventually, monitoring point temperatures reached steady state with fluctuations around the stable value. Comparing [FIGURE:8(a)] and [FIGURE:8(b)] reveals that temperature fluctuations in the near-wall fluid region induce pulsations in wall temperature, though pipe inner wall temperature fluctuations are significantly attenuated compared to fluid temperature fluctuations.

Temperature fluctuation intensity is quantified by the root-mean-square temperature T_{RMS} defined in Equation (2):

$$T_{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_{mean})^2}{n}}$$

where T_{RMS} represents temperature fluctuation intensity. The RMS temperature was calculated for near-wall fluid and pipe inner wall temperatures between 240–280 s, as shown in

. Temperature fluctuation intensity initially increases then decreases with increasing circumferential angle θ. Both near-wall fluid and pipe inner wall temperature fluctuations reach maximum values around 105°, with pipe inner wall temperature fluctuations being much smaller than near-wall fluid temperature fluctuations. At the 105° position, the height H is 147.1 mm, and according to

, the location of maximum temperature fluctuation intensity lies in the mixing region between hot and cold fluids, near the cold fluid layer at the bottom of the pipe. During thermal stratification, a shear layer exists between hot and cold fluids, and Kelvin-Helmholtz instability theory indicates that such shear layers cause thermal striping phenomena in the mixing region, inducing temperature fluctuations [19,32]. The cold fluid at the bottom of the pipe has higher flow

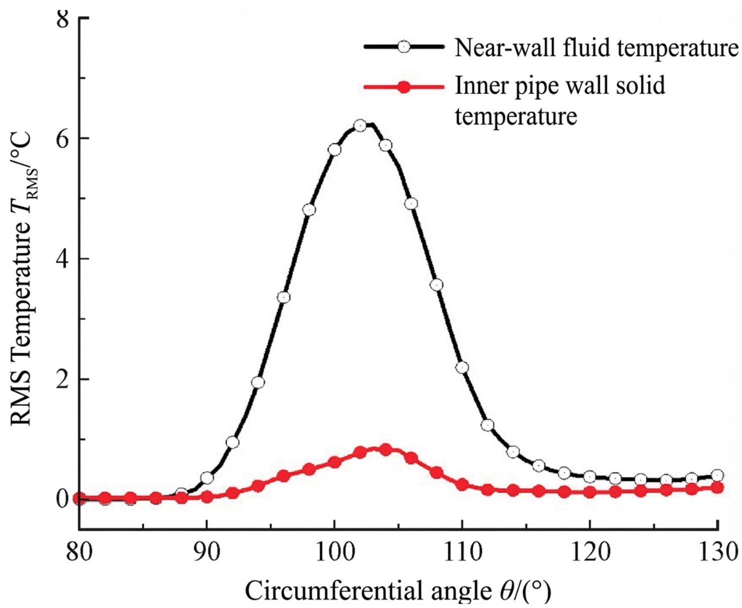

Figure 4: Figure 9

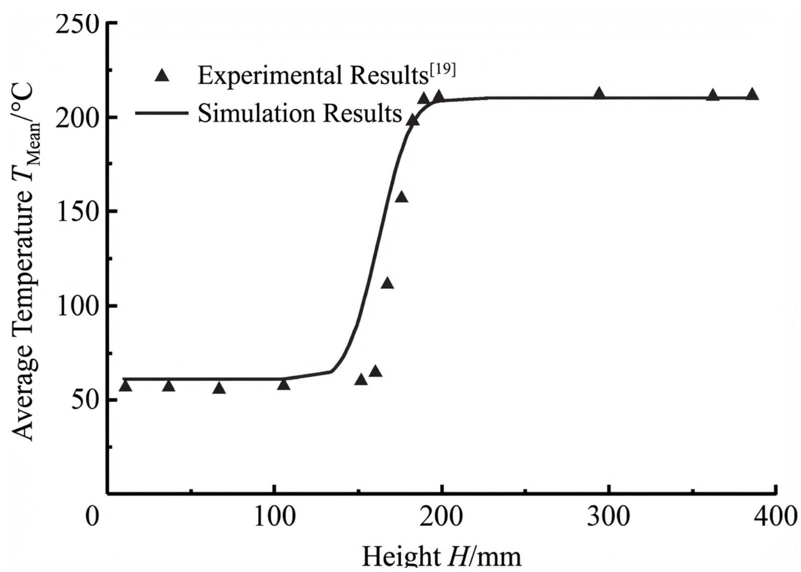

Figure 5: Figure 7

velocity, and turbulent vortices cause larger temperature fluctuations in fluid near the cold fluid region. Therefore, fluid temperature fluctuations are most intense at the 105° position in the pipe cross-section. Temperature fluctuations in the pipe wall cause transient variations in structural thermal stress; when fluctuation intensity is high, it can lead to structural thermal fatigue and cracking, affecting pipe service life and jeopardizing reactor normal operation. Thus, investigation of temperature fluctuations is of significant importance. In nuclear engineering, locations most prone to fatigue problems are of primary concern. Based on

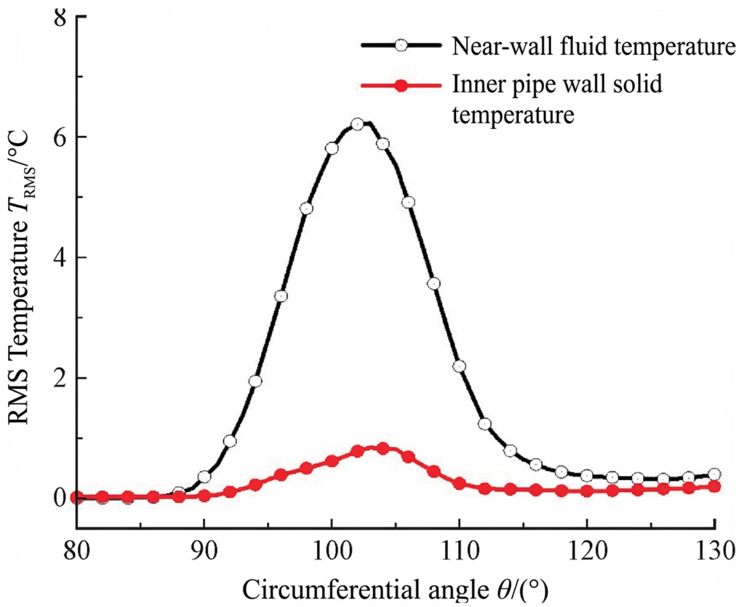

Figure 6: Figure 9

, the region of most intense temperature fluctuation in the typical pipe cross-section Q25 after thermal stratification occurs is at the 105° position, which is identified as the thermal fatigue-sensitive point for this cross-section. Applying this analysis method to different pipe cross-sections can identify locations of maximum temperature fluctuation in each cross-section, ultimately determining thermal fatigue-sensitive points for the operating condition.

Conclusions

This study performed conjugate heat transfer analysis of thermal stratification in the horizontal pipe of the HDR test reactor using large eddy simulation, correctly capturing the unsteady temperature distribution characteristics of the pipe structure. The conclusions are as follows:

1) Conjugate heat transfer analysis of horizontal pipe thermal stratification based on the LES method can satisfactorily predict cross-sectional temperature distribution and correctly capture flow field and pipe wall temperature fluctuation information, validating the reliability of the LES method for investigating pipe thermal stratification problems.

2) Based on the current computational model, the location of maximum temperature fluctuation in the pipe cross-section during thermal stratification can be reasonably predicted. Considering that local thermal stress is proportional to temperature oscillation, the thermal fatigue-sensitive point can be identified. The computational results can provide references for subsequent pipe thermal stress analysis and fatigue life assessment. The numerical simulation methodology and analytical results of this study can serve as a valuable reference for thermal fatigue analysis and structural reliability evaluation of piping systems and components in nuclear reactors.

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