Numerical Simulation of Heat Transfer and Flow Characteristics of U-tube Shell-and-tube Heat Exchanger for Molten Salt Reactor

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Abstract

To better understand and characterize the operational features of molten salt heat exchangers and to accumulate experience for the design and operation of heat exchangers in molten salt reactors, this study investigates the main heat exchanger employed in the 10MWt Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory, USA. Based on the design parameters of this heat exchanger, theoretical calculation methods for shell-and-tube heat exchangers (including the Kern method and the Bell-Delaware method), the heat exchanger design software HTRI Xchanger Suite, and Computational Fluid Dynamics (CFD) were utilized to analyze the key performance indicators of the heat exchanger (such as heat transfer coefficient, pressure drop, and heat duty), and these results were compared with experimental data from the MSRE main heat exchanger. The results demonstrate that discrepancies between the results obtained from the two theoretical calculation methods (Kern method and Bell-Delaware method), HTRI software, and CFD simulation and the experimental data all fall within acceptable limits; specifically, the Kern method exhibits the maximum deviation from the heat duty obtained from MSRE experiments at approximately 15%, while the HTRI software simulation exhibits the minimum deviation from the overall heat transfer coefficient obtained from MSRE experiments at 0.16%. Theoretical calculation methods, heat exchanger design software, and CFD simulation are all applicable to varying degrees for molten salt-to-molten salt heat exchanger design, and CFD simulation can also provide intuitive visualization of the internal heat transfer and flow details within the heat exchanger.

Full Text

Simulation Analysis of Heat Transfer and Flow Characteristics of a U-Tube Heat Exchanger for Molten Salt Reactors

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Abstract

To better understand and characterize the operational behavior of molten salt heat exchangers and to accumulate design and operational experience for molten salt reactors, this study investigates the primary heat exchanger (PHX) used in the 10MWt Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL). Based on the design parameters of this exchanger, we analyze key performance metrics—including heat transfer coefficient, pressure drop, and heat transfer power—using theoretical calculation methods for shell-and-tube heat exchangers (Kern method and Bell-Delaware method), the HTRI Xchanger Suite design software, and computational fluid dynamics (CFD) simulations. These results are compared with experimental data from the MSRE PHX. The findings indicate that discrepancies between both theoretical methods, HTRI software, and CFD simulations relative to experimental data are all within acceptable margins. Notably, the Kern method shows the largest deviation, with a difference in heat transfer rate of approximately 15% compared to MSRE experimental values, while HTRI software simulation yields the smallest discrepancy, with only a 0.16% difference in overall heat transfer coefficient. Theoretical calculation methods, heat exchanger design software, and CFD simulations are all applicable to varying degrees for molten salt-molten salt heat exchanger design, with CFD additionally providing intuitive visualization of internal heat transfer and flow details.

Keywords: Molten Salt Heat Exchanger, Kern Method, Bell-Delaware Method, HTRI Xchanger Suite, CFD Simulation

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Introduction

With growing global energy demands and increasingly prominent environmental concerns, developing safe, efficient, and clean new nuclear energy systems has become a consensus in the international nuclear community. Among Generation IV reactors, molten salt reactors have attracted significant attention due to their inherent safety, high thermal efficiency, and versatility [1]. Molten salt reactors can operate at temperatures exceeding 700°C, enabling efficient and

compact Brayton cycle power generation with theoretical efficiencies reaching 44%, substantially higher than the approximately 33% efficiency of conventional pressurized water reactors [2].

Heat exchangers represent critical components in molten salt reactor systems, with performance directly impacting safety, economics, and reliability [3]. In liquid-fueled molten salt reactors, fuel salt containing fissile material circulates through the primary loop, transferring heat to secondary loop coolant salt via the primary heat exchanger (PHX). This process involves not only material and structural safety at high temperatures but also complex thermodynamic and hydrodynamic issues, making research on flow and heat transfer characteristics in molten salt heat exchangers essential.

The thermophysical properties of molten salts—including density, viscosity, specific heat capacity, and thermal conductivity—are key parameters for heat exchanger design. During 20th-century experiments such as the Molten Salt Reactor Experiment (MSRE), Oak Ridge National Laboratory (ORNL) conducted detailed measurements of various molten salt systems, providing foundational data for subsequent research [4-6]. However, due to experimental limitations at the time, much of this data lacked reliability. With the recent resurgence of molten salt reactor research, molten salt thermophysical properties have again become a focus, with researchers obtaining more reliable and comprehensive data through combined experimental measurement and phase diagram calculations [7].

Design of molten salt heat exchangers requires deep understanding of molten salt heat transfer and flow characteristics. Existing experimental and numerical simulation results show that for turbulent and transitional flow regimes, convective heat transfer characteristics of molten salts in circular tubes agree well with classical correlations. However, experimental data on complex heat transfer processes inside molten salt heat exchangers remain relatively scarce, primarily concentrated in solar energy applications with lower-temperature HITEC salt as the working fluid [8-13]. The most detailed experimental reports on high-temperature molten salt-molten salt heat exchangers in molten salt reactors come from the MSRE project' s main heat exchanger (MSRE-PHX) [14]. This shell-and-tube molten salt-molten salt heat exchanger operated at temperatures ranging from 538-663°C, with fuel salt on the shell side (hot side) and coolant salt on the tube side (cold side), operating stably for over 13,000 hours without any degradation in heat transfer performance or failure.

Unfortunately, despite providing crucial data for molten salt reactor technology, in-depth studies on the MSRE-PHX have been rarely reported in the half-century since the MSRE project concluded. Recently, Malcolm Akner from Sweden [15] modeled and simulated the MSRE-PHX using technical documentation and open-source software (Onshape and Simscale), investigating the applicability of computational fluid dynamics (CFD) for predicting molten salt heat transfer behavior and providing useful references for industrial numerical simulation of molten salt heat exchanger performance, while noting significant uncertain-

ties in MSRE historical data. Additional domestic and international research on actual operational characteristics and simulation analysis of molten salt reactor heat exchangers includes: He et al. [16] from Sun Yat-sen University conducted experiments on HITEC salt flow on the shell side of a baffle-free shell-and-tube heat exchanger at Reynolds numbers of 400-2300, finding shell-side heat transfer coefficients 3-5 times higher than Sieder-Tate correlation predictions, likely due to thin boundary layers formed by the tube bundle structure enhancing heat transfer. Qian et al. [17] built a molten salt heat exchanger experimental system for the thorium-based molten salt reactor project, conducting heat transfer experiments on finned tube molten salt-gas exchangers, circular tube molten salt-gas exchangers, and prototype shell-and-tube molten salt-molten salt exchangers using HITEC salt, showing good agreement between tube-side HITEC salt convective heat transfer characteristics and traditional empirical correlations in transitional and turbulent regimes, but deviations exceeding 30% in laminar flow, with significant differences between shell-side HITEC salt and heat transfer oil characteristics. Chen et al. [18-21] compared experimental data and simulation results for a 300kW U-tube molten salt heat exchanger using Ansys Workbench, analyzing temperature and stress fields through fluid-thermal-solid coupling methods, validating CFD simulation accuracy.

Overall, research on heat exchangers in molten salt reactors remains limited, particularly regarding simulation analysis of their heat transfer and flow characteristics. This study applies modern computational tools such as CFD software and heat exchanger design programs (HTRI Xchanger Suite), combined with traditional design methods (Kern and Bell-Delaware methods), to conduct detailed heat transfer and flow characteristic analysis of the MSRE-PHX. We compare these computational results with historical MSRE operational data to validate the applicability and accuracy of these tools in high-temperature molten salt environments.

1.1 Structural Parameters

[Figure 1: see original paper] shows a schematic diagram of the MSRE primary heat exchanger (MSRE-PHX) used in the 10MWt molten salt reactor at Oak Ridge National Laboratory. The original design was completed in 1961, equipment manufacturing in 1963, with partial modifications in 1964 before formal operation as a key MSRE system component. The MSRE-PHX employs a classic shell-and-tube heat exchanger configuration, with its shell inclined 3° upward from horizontal to facilitate gravity drainage of fuel salt from the shell side while also aiding installation and maintenance. The tube side uses U-tube bundles for simple, compact structure with good thermal compensation performance. Single-segmental baffles are installed on the tube bundle to increase heat transfer area and efficiency while reducing tube bundle vibration and stress. Structural parameters are listed in Table 1 [22].

1.2 Design Conditions and Operating Parameters

The MSRE-PHX design conditions [22] are as follows: fuel salt (LiF-BeF_2-ThF_4-UF_4-ZrF_4, 70-23-1-1-5 mol%) enters the heat exchanger at 662.78°C and is cooled to 635°C with a volumetric flow rate of 0.075708 $m^3 \cdot s^{-1}$; coolant salt (LiF-BeF_2, 66-34 mol%) enters at 551.67°C and is heated to 593.33°C with a volumetric flow rate of 0.053627 $m^3 \cdot s^{-1}$. The MSRE-PHX operating power was determined through thermal balance calculations of the fuel salt and coolant salt systems. Due to significant deviations in molten salt properties used during the design phase, the MSRE-PHX heat transfer performance was lower than expected, limiting full-power output of the MSRE (design value of 10MW). Table 2 presents partial operating parameters of the MSRE-PHX, while Table 3 compares properties used during MSRE-PHX design versus actual properties [14], with current recommended values for coolant salt FLiBe obtained from literature [7] and used in subsequent calculations.

After correcting molten salt property data, the nominal full power from thermal balance calculations was 8MWt. However, analysis of uranium and plutonium isotopic composition changes in the fuel salt revealed actual power was 7-10% lower than this 8MWt full power. ORNL researchers attempted to explain this power deviation, concluding the most likely source was coolant salt flow measurement issues [25].

Under 1960s experimental conditions, flow measurement errors for coolant salt were understandable. Additionally, observations and analysis of MSRE-PHX operational performance indicated that traditional heat transfer correlations remained applicable to molten salt heat transfer. Over more than 14,000 hours of operation under MSRE conditions, molten salts caused no significant corrosion or fouling of structural materials (Hastelloy-N alloy), as evidenced by stable heat transfer capacity without degradation from corrosion, fouling, bypassing, or flow restrictions. This demonstrates that MSRE-PHX structural design and material selection were reasonable and effective. The primary reason for lower-than-expected heat transfer performance was the use of significantly deviated molten salt thermophysical property data during design, while coolant salt flow measurement error represents the most probable cause for actual heat transfer power being below nominal power.

2.1 Theoretical Calculation Methods

Theoretical calculations for shell-and-tube heat exchangers can be divided into tube-side and shell-side aspects. This study employs the Gnielinski method [26] for tube-side calculations and two methods for baffled shell-side calculations: the Kern method and Bell-Delaware method [27]. The Kern method, developed in 1950, was used during MSRE-PHX design; the Bell-Delaware method, developed in 1963, represents the most advanced publicly available method.

2.1.1 Shell-Side Calculation: Kern Method The Kern method is a classic heat exchanger design approach based on extensive experimental studies of commercial shell-and-tube heat exchangers manufactured to standard tolerances. Its main advantage is simplicity and ease of use, while its primary disadvantage is neglecting shell-side leakage flow effects when calculating shell-side heat transfer coefficients and pressure drop.

Since shell-side flow cross-sectional area varies along the shell length, shell-side velocity in the Kern method is calculated based on shell-side crossflow area. The equivalent diameter varies with tube bundle arrangement; for the MSRE-PHX' s equilateral triangular arrangement, this allows calculation of shell-side mass velocity and velocity, as well as Reynolds number. The shell-side Nusselt number (Nu_s) is expressed as:

$$Nu_s = C \cdot Re_s^m \cdot Pr_s^n$$

where C, m, and n are empirical constants.

For shell-side pressure drop, the Kern method similarly provides a dimensionless friction coefficient (f_j) based on shell-side Reynolds number:

$$f_j = \exp(0.576 - 0.19 \ln(Re_s))$$

2.1.2 Shell-Side Calculation: Bell-Delaware Method The Bell-Delaware method considers numerous factors affecting shell-side fluid distribution, providing greater accuracy. Based on Tinker' s flow model, it divides shell-side fluid into five flow paths, as shown in Figure 2 [Figure 2: see original paper]:

- Path A: Leakage flow between baffle tube holes and tubes
- Path B: Crossflow, same direction as ideal flow path without leakage, representing the main flow path affecting shell-side heat transfer and flow resistance
- Path C: Bypass flow between tube bundle periphery and shell inner wall
- Path E: Leakage flow between baffle and shell inner wall
- Path F: Bypass flow at tube pass partition locations

In shell-and-tube heat exchanger design, Path B fraction should be maximized for better heat transfer performance.

1. Geometric parameter calculation formulas for single-segmental baffles and tube bundle arrangements:

The crossflow area (A_m) can be expressed as:

$$A_m = B \cdot \frac{D_s - n_t \cdot d_o}{P_t}$$

where B is baffle spacing, D_s is shell inner diameter, n_t is number of tubes, d_o is tube outer diameter, and P_t is tube pitch perpendicular to flow direction.

The diameter of the imaginary circle through centers of outermost tubes in the bundle (D_{ctl}) is:

$$D_{ctl} = D_s - d_o$$

The central angle (_{ctl}) corresponding to baffle cut intersection with tube bundle diameter is:

$$\theta_{ctl} = 2\arccos(1 - 2B_c)$$

where B_c is the ratio of baffle cut height to shell inner diameter.

The ratio of tubes in the baffle window region to total tube count (F_w) and the ratio of tubes in the crossflow region between baffle windows to total tube count (F_c) are calculated based on geometry. The number of tube rows in the crossflow direction between baffle windows (N_c) is:

$$N_c = \frac{D_{ctl}}{P_t} \cdot (1 - 2B_c)$$

The effective tube rows exposed to crossflow in the window region (N_w) account for the fact that flow in the window region is partially parallel and partially perpendicular to the tube axis, using a coefficient of 0.8:

$$N_w = 0.8 \cdot \frac{D_{ctl}}{P_t} \cdot B_c$$

For Path A (leakage flow between baffle tube holes and tubes), the area (S_{tb}) is calculated by:

$$S_{tb} = \frac{\pi}{4} \cdot (d_o + \delta_{tb})^2 - \frac{\pi}{4} \cdot d_o^2$$

where δ_{tb} is the diametral clearance between baffle hole and tube outer diameter, taken as 0.8 mm or 0.4 mm per TEMA standards if unknown.

For Path E (leakage flow between baffle and shell inner wall), the leakage area (S_{sb}) can be expressed as:

$$S_{sb} = \pi \cdot D_s \cdot \delta_{sb}$$

where δ_{sb} is the clearance between baffle and shell.

For Path C (bypass flow between tube bundle and shell inner wall), the cross-sectional area (S_b) is:

$$S_b = B \cdot (D_s - D_{ctl})$$

For Path B (crossflow), the net crossflow area through the window region equals total crossflow area minus tube cross-sectional area:

$$A_w = A_m - n_t \cdot \frac{\pi}{4} \cdot d_o^2$$

In the Bell-Delaware method, to better approximate actual flow, ideal crossflow heat transfer and friction coefficients perpendicular to the tube bundle are first calculated, then corrected by flow path correction factors to obtain final results.

The shell-side heat transfer coefficient under ideal pure crossflow conditions (h_{ideal}) is:

$$h_{ideal} = j_i \cdot G_s \cdot c_p \cdot Pr^{-2/3}$$

where j_i is the ideal Colburn j-factor obtained from relevant empirical tables, G_s is shell-side mass velocity, c_p is specific heat capacity, and Pr is Prandtl number.

The characteristic length in the Bell-Delaware method is tube outer diameter (d_o). Shell-side mass velocity (G_s) and velocity (v) are:

$$G_s = \frac{\dot{m}}{A_m}, \quad v = \frac{G_s}{\rho}$$

2. Flow path heat transfer correction factor calculations:

The baffle cut and spacing correction factor (J_c) accounts for flow distribution effects.

The leakage flow correction factor for baffle-to-tube and baffle-to-shell (J_l) is:

$$J_l = 0.44 \cdot (1 - r_s) + [1 - 0.44 \cdot (1 - r_s)] \cdot \exp(-2.2 \cdot r_{lm})$$

where r_s is the ratio of shell-to-baffle leakage area to total leakage area, and r_{lm} is a leakage flow parameter.

The bypass correction factor for tube bundle flow paths C and F (J_b) is:

$$J_b = \exp\left[-C \cdot \frac{S_b}{A_m} \cdot \left(1 - \sqrt[3]{2N_{ss}}\right)\right]$$

where C is 1.35 when Re $<$ 100 and 1.25 when Re $\geq$ 100, and N_{ss} is the number of sealing strip pairs.

The inlet/outlet heat transfer correction factor (J_r) is only considered when Re $<$ 100, thus taken as 1 for this study.

3. Pressure drop calculation:

The Bell-Delaware method divides shell-side pressure drop into three components: end zone (inlet/outlet) crossflow bundle pressure drop (ΔP_e), non-end zone crossflow bundle pressure drop (ΔP_c), and window region bundle pressure drop (ΔP_w):

$$\Delta P_s = \Delta P_c + \Delta P_w + \Delta P_e$$

The non-end zone crossflow pressure drop (ΔP_c) is calculated as:

$$\Delta P_c = (N_b - 1) \cdot \Delta P_{ideal} \cdot R_b \cdot R_l$$

where N_b is the number of baffles, R_b is the bypass correction factor, and R_l is the leakage correction factor.

The ideal crossflow pressure drop (ΔP_{ideal}) is:

$$\Delta P_{ideal} = 4 f_i \cdot N_c \cdot \frac{G_s^2}{2\rho}$$

where f_i is the ideal friction factor obtained from relevant empirical tables.

The bypass correction factor (R_b) is:

$$R_b = \exp\left[-1.33 \cdot (1 + r_s) \cdot \left(\frac{S_b}{A_m}\right)^{0.15-0.8 r_s}\right]$$

For Re $\geq$ 100, the exponent coefficient is 3.7.

For window region pressure drop, when Re $>$ 100, the ideal pressure drop is:

$$\Delta P_{w,ideal} = \frac{\dot{m}^2}{2\rho A_m A_w} \cdot (2 + 0.6 N_w)$$

Thus, the actual window region pressure drop is:

$$\Delta P_w = \Delta P_{w,ideal} \cdot R_l$$

For end zone pressure drop:

$$\Delta P_e = 2\Delta P_{ideal} \cdot \left(1 + \frac{N_w}{N_c}\right) \cdot R_b \cdot R_l$$

where b_i and b_o are distances in the baffle inlet/outlet regions.

2.2 HTRI Xchanger Suite

HTRI Xchanger Suite is professional heat exchanger design, rating, and simulation software developed by the Heat Transfer Research Institute (HTRI). Based on over half a century of industrial heat transfer equipment test data, it enables flexible yet rigorous design of heat exchanger geometries, allowing precise performance evaluation using HTRI' s proprietary empirical correlations [29].

Theoretical heat exchanger calculations estimate performance using general heat transfer equations and property data without considering internal details. As specialized heat exchanger design software, HTRI considers specific design parameters such as tube bundle layout, dimensions, and fluid flow, dividing tube and shell sides into multiple zones with independent heat transfer and hydrodynamic iterative calculations for each zone, thereby more accurately estimating performance while accounting for internal details.

2.3 CFD Simulation Method

To better understand flow and heat transfer mechanisms within the MSRE-PHX, this study employs commercial CFD software Ansys Fluent for full-scale modeling and analysis, providing detailed investigation of velocity, pressure, and temperature field distributions and their impact on heat exchanger performance. Additionally, global parameters including heat transfer coefficients and pressure drops are calculated and compared with empirical correlation-based theoretical calculations and professional heat exchanger design software HTRI, exploring the possibilities and limitations of full-scale CFD modeling and analysis for large heat exchangers.

2.3.1 Computational Model and Physical Properties The computational model is shown in Figure 1, with physical properties listed in Table 3.

2.3.2 Boundary Conditions Boundary conditions in the numerical simulation are set as follows: inlet boundaries are mass flow inlets for both sides; outlet boundaries are pressure outlets; wall boundaries are no-slip adiabatic walls on the shell-side outer surface.

2.3.3 Mesh Generation The MSRE-PHX computational domain includes fuel salt fluid domain, coolant salt fluid domain, and solid domain comprising metal structures. Due to the large size of MSRE-PHX (approximately 2.5m$\times 0.5m \times$0.5m) and numerous tubes (159 U-tubes), commercial software Fluent Meshing is employed after multiple trials. Fluent Meshing features high meshing speed, flexible mesh handling, and ability to generate Poly-Hexcore volume meshes based on "mosaic" meshing technology, maximizing hexahedral cell count to improve solution efficiency and accuracy [30].

To accurately simulate molten salt flow in the heat exchanger, boundary layer meshes are applied at fluid-solid interfaces including shell inner walls and tube bundles. For boundary layer meshes, Fluent Meshing can similarly apply "mosaic" technology, achieving transition from layered Poly meshes near walls, through pure Poly meshes in transition regions, to hexahedral meshes in core regions, further improving overall mesh quality while effectively reducing total cell count and solution time. Mesh schematic is shown in Figure 3 [Figure 3: see original paper].

2.3.4 Grid Independence Analysis and Solver Control Settings With mesh counts of 38,957,352, 55,713,541, and 74,893,211, convergence was achieved after approximately 5,000 iterations based on residual convergence and mass flow/temperature balance criteria, yielding shell-side outlet temperatures of 637.5°C, 639.61°C, and 639.4°C respectively. Considering computational resources and time, results from the 55,713,541-cell mesh with 10,000 iterations are selected for analysis.

The COUPLED algorithm is chosen for solution, which converges with fewer iterations. Convergence criteria are based on iterative residuals of all physical quantities, uniformly set to less than 10^{-12} to ensure full convergence. In addition to monitoring residuals, inlet/outlet mass flow rates and temperatures are simultaneously monitored to assist convergence judgment.

3.1 Theoretical Calculation Verification Results

Table 4 presents theoretical verification results for the MSRE-PHX. For heat transfer coefficients, the experimentally measured overall heat transfer coefficient averages 3724.74 $W \cdot m^{-2} \cdot K^{-1}$. The Bell-Delaware correlation yields 4087.3 $W \cdot m^{-2} \cdot K^{-1}$, higher than experimental values, while the Kern correlation gives 3506.3 $W \cdot m^{-2} \cdot K^{-1}$, lower than experimental values. Comparing individual side coefficients, Gnielinski-calculated tube-side coefficients differ from measurements by within -14%, while Kern and Bell-Delaware shell-side coefficients differ by 4.7% and 62% respectively, indicating theoretical tube-side coefficients are 偏低 while shell-side coefficients are 偏高. The Gnielinski correlation does not consider heat transfer in curved tubes, where turbulence intensity is high and actual heat transfer is enhanced. Both correlations idealize shell-side fluid flow, leading to theoretical coefficients higher than actual values. The Kern method, being conservative and not considering flow path variations from shell-side geometry, yields lower coefficients, while the more comprehensive Bell-Delaware method produces higher coefficients due to deviations between actual structural parameters such as U-tube arrangement, MSRE-PHX insulation layer configuration, and ideal assumptions, plus differences in coolant salt properties used versus those employed in original experimental calculations.

For pressure drop, experimental values are 165.5 kPa (shell side) and 199.9 kPa (tube side). Note that ORNL measured flow using differential pressure-based Venturi tubes; since flow measurements contained errors, experimental pressure drop values should be considered reference only. In Table 4, reduced tube-side flow leads to reduced pressure drop, with calculated tube-side values of ~211 and ~177 kPa, within acceptable deviation from experimental values. For shell-side pressure drop, Kern correlation yields significantly low values (~140 kPa), while Bell-Delaware gives significantly high values (~250 kPa).

3.2 HTRI Simulation Results

Figures 4(a)-(e) show segmented calculation results for MSRE-PHX from HTRI. Figure 4(a) presents gradual volume temperature variations along length for both tube and shell fluids. Figure 4(b) shows pressure drop values per interval, with overall stable trends but shell-side inlet pressure drop reaching 113 kPa while other intervals remain below 40 kPa. Figure 4(c) displays cumulative heat transfer during flow, totaling 8.1222 MW. Figure 4(d) shows Reynolds numbers, revealing minimal variation in main heat transfer length except at shell-side inlet and outlet sections. Figure 4(e) presents tube-side, shell-side, and overall heat transfer coefficient variations along length, yielding final tube-side coefficient of

8012.1 $W \cdot m^{-2} \cdot K^{-1}$, shell-side coefficient of 16536 $W \cdot m^{-2} \cdot K^{-1}$, and overall coefficient of 3731.1 $W \cdot m^{-2} \cdot K^{-1}$.

3.3.1 Temperature Field Analysis

Figure 5 [Figure 5: see original paper] shows temperature distribution contours (shell side) and temperature-colored streamlines (tube side) for MSRE-PHX. CFD simulation yields shell-side outlet temperature of 639.61°C and tube-side outlet temperature of 582.85°C. Tube-side coolant salt shows clear temperature distribution trends, continuously absorbing heat and gradually increasing temperature from inlet to outlet. On the shell side, single-segmental baffles cause periodic transverse tube bundle 冲刷 by fuel salt, enhancing turbulence and heat transfer. Temperatures are relatively low in baffle wake regions due to recirculation phenomena where fuel salt flow is obstructed, preventing effective heat exchange with other regions while exchanging more heat with tubes and internal coolant salt, resulting in lower temperatures than mainstream fuel salt.

3.3.2 Pressure Field Analysis

Figure 6 [Figure 6: see original paper] shows pressure distribution contours (shell side) and pressure-colored streamlines (tube side) for MSRE-PHX. Baffles cause significant flow direction changes after impact, creating large velocity gradients due to blocking and diversion effects. Additionally, as fuel salt passes through baffles, flow cross-sectional area changes significantly, causing corresponding velocity changes that affect fluid pressure and create large local pressure losses. In baffle wake regions, blocking and disturbance create recirculation zones with flow direction and velocity changes that also generate local pressure losses. Pressure differences between baffle upstream and downstream faces impose structural strength requirements; insufficient strength may cause damage from these pressure differentials, requiring careful consideration during baffle design to ensure stability and safety.

3.3.3 Velocity Field Analysis

Figure 7 [Figure 7: see original paper] shows velocity distribution contours (shell side) and velocity-colored streamlines (tube side) for MSRE-PHX. Single-segmental baffles create obvious periodic "Z" -shaped flow of shell-side fuel salt. In baffle window regions, fuel salt flows parallel to tubes (co-current flow) with velocity gradient perpendicular to temperature gradient, resulting in poor heat transfer according to field synergy theory. In baffle upstream regions, transverse tube bundle 冲刷 (crossflow) occurs with velocity gradient nearly aligned with temperature gradient, yielding optimal heat transfer.

Figure 8 [Figure 8: see original paper] shows velocity vectors for MSRE-PHX. Fuel salt velocity clearly decreases in baffle wake regions after passing baffles. Enlarged observation of this region in Figure 8(a) reveals obvious recirculation zones behind baffles where fuel salt is nearly stagnant, creating so-called flow

"dead zones" that may cause severe fouling and deposition, consistent with temperature and pressure field distributions. Small gaps in baffles create leakage zones where some fluid bypasses baffles to reach wake regions directly, increasing co-current flow area, reducing flow-induced vibration probability from crossflow, decreasing shell-side resistance, and slowing fouling rates. Generally, window region velocities exceed crossflow region velocities, while wake region velocities are lowest—typical flow characteristics for single-segmental baffles that cause significant pressure losses and reduce heat transfer efficiency. Additionally, Figure 8(b) shows maximum shell-side velocity occurs where fuel salt impacts the impingement plate. In the inlet region, the impingement plate divides fuel salt into two streams with small vortices, increasing velocity. After passing the impingement plate, velocity decreases significantly, reducing impact on inlet region tubes and minimizing tube vibration. In the fuel salt outlet region, a retention zone is created to reduce high-temperature effects on the tube sheet, as shown in Figure 8(c). Fuel salt enters this narrow retention zone and nearly stops flowing; combined with temperature distribution from Figure 5, retention zone fuel salt temperature is significantly lower than mainstream temperature, preventing large temperature gradients on the tube sheet and protecting structural integrity.

3.4 Comparative Analysis

Table 5 summarizes comparisons between MSRE-PHX experiments, theoretical calculations, HTRI software, and simulation analysis. For both overall heat transfer coefficient U and heat transfer rate Q, differences between two theoretical methods and two simulation approaches versus experimental results are within acceptable margins. The Kern method shows maximum deviation of 15% from MSRE experimental heat transfer rate, while HTRI software simulation shows minimum deviation of 0.16% from experimental overall heat transfer coefficient, demonstrating considerable applicability and effectiveness of theoretical calculations and simulation analysis for MSRE-PHX performance prediction.

For heat transfer, HTRI software and CFD simulation predict shell-side outlet temperatures with very small errors of 0.6% and 0.72% respectively compared to MSRE experiments, indicating accurate prediction of complex shell-side flow. For tube-side coolant salt outlet temperature, both HTRI and CFD predictions are slightly lower than experimental results with errors of -1.6% and -1.7% respectively.

For pressure drop, theoretical calculations and simulation analysis yield higher results than experiments for both shell and tube sides. MSRE-PHX reports noted that actual pressure drop could reach twice experimental values due to large inlet/outlet losses, consistent with HTRI and CFD results showing shell-side inlet pressure drops of 113 kPa (HTRI) and 349.03 kPa (CFD). Additionally, experimental condition limitations at the time (such as molten salt corrosion of measurement instruments) may have caused data deviations between experimental and theoretical/simulation predictions.

Comprehensive analysis using three categories of four methods (theoretical calculations, HTRI software, and CFD simulation) reveals that HTRI software and CFD simulation results are closest to experimental data, while the conservative Kern theoretical method shows greatest deviation. This indicates that assumptions and simplifications in Kern method cause significant deviations from actual performance, while HTRI software and CFD better simulate complex flow and heat transfer processes. As an improved theoretical method, Bell-Delaware results are relatively close to HTRI software (also based on flow path analysis), but calculation procedures are extremely cumbersome. While HTRI software and CFD simulation are more accurate, they differ in application: HTRI is more convenient, especially suitable for engineering design reference with commercially mature heat exchanger configurations; CFD simulation is necessary for in-depth investigation of internal temperature distribution and flow characteristics, particularly for novel heat transfer fluids and innovative flow field structures, requiring more computational resources but providing more precise, detailed, and intuitive information.

4 Conclusions

This study investigates the primary heat exchanger used in the 10MWt molten salt reactor at Oak Ridge National Laboratory. Based on design parameters, theoretical calculation methods (Kern and Bell-Delaware methods), HTRI Xchanger Suite software, and CFD simulation are applied to analyze key performance metrics (heat transfer coefficient, pressure drop, and heat transfer power), yielding the following conclusions:

1. Detailed analysis of three heat exchanger design approaches—two theoretical calculations, HTRI software, and CFD simulation—shows all results differ from experimental values within acceptable margins. The Kern method shows maximum deviation of 15% from MSRE experimental heat transfer rate, while HTRI software simulation shows minimum deviation of 0.16% from experimental overall heat transfer coefficient, demonstrating considerable applicability and effectiveness of theoretical calculations, HTRI software, and CFD simulation for MSRE-PHX performance prediction.

2. Comparative analysis of heat transfer and pressure drop performance shows HTRI software and CFD simulation temperature predictions differ minimally from MSRE experimental results, with maximum errors of -1.6% and -1.7% respectively. For shell-side and tube-side pressure drops, theoretical calculations and simulation analyses yield higher results than experiments, consistent with MSRE-PHX reports indicating actual pressure drop could reach twice experimental values due to large inlet/outlet losses.

3. Comprehensive analysis indicates HTRI software and CFD simulation results are closest to experimental data, while the conservative Kern theo-

retical method shows greatest deviation. HTRI software is more convenient than CFD simulation, particularly suitable for engineering design reference with commercially mature configurations. CFD simulation is necessary for in-depth investigation of internal temperature distribution and flow characteristics, especially for novel heat transfer fluids and innovative flow field structures, requiring more computational resources but providing more precise, detailed, and intuitive information. This work provides substantial theoretical support and practical guidance for future design and improvement of molten salt heat exchangers.

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