Experimental study on heat transfer performance of a fluoride salt to salt heat exchanger for Molten Salt Reactors

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Abstract

This study experimentally investigated the heat transfer performance of a novel shell-and-tube fluoride Salt to Salt Heat Exchanger (SSHX) featuring baffles with integrated drainage ports, designed to mitigate salt freeze blockage risks during shutdown in Molten Salt Reactors (MSRs). Experiments were conducted in a Scaled Simulation Fluoride Salt-cooled Reactor (SF0) test facility. A new empirical correlation for tube-side heat transfer was proposed as Nu=0.0246Re0.8Pr0.267 (valid for Re=9000~15000 and Pr=8~12), demonstrating excellent agreement with experimental data within a maximum deviation of 5%. Comparative analysis revealed the modified Dittus-Boelter equation is still a suitable choice for predicting fluoride salt convective heat transfer behavior in tubular geometries, outperforming the Gnielinski and Sieder-Tate models, which overpredicted data by 17-25%. For shell-side heat transfer, applying a 31% enhancement factor (=1.31) to the Kern correlation aligns predictions with experimental results within an error range of -6.0% to 7.0%. These findings address a critical engineering challenge in SSHXs while preserving thermal efficiency, offering essential experimental data and valuable insights for the design of fluoride SSHXs in MSRs.

Full Text

Experimental Study on Heat Transfer Performance of a Fluoride Salt-to-Salt Heat Exchanger with Baffles Featuring Drainage Ports

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Nomenclature

Abbreviations

ASHX: Air-cooled fluoride salt heat exchanger
CFD: Computational Fluid Dynamics
MSR: Molten Salt Reactor
MSRE: Molten Salt Reactor Experiment
SF0: Scaled Simulation Fluoride Salt-cooled Reactor
SSHX: Salt-to-salt heat exchanger
TMSR: Thorium Molten Salt Reactor

English symbols

A: Heat transfer surface area
A_c: Cross-sectional area of tube bundle
A_s: Cross-sectional area of baffled tubes
c_p: Fluid specific heat (J/g · K)
D: Diameter (m)
F: Log-mean temperature difference correction factor
k: Tube thermal conductivity (W/m · K)
l_b: Baffles spacing
Nu: Nusselt number
Pr: Prandtl number
P_t: Tube spacing
Q: Heat transfer rate
Re: Reynolds number
T: Temperature (℃)
U: Overall heat transfer coefficient (W/m^2 · K)
v: Mean velocity (m/s)
V: Volume flow rate (m^3/h)

Greek symbols

λ: Fluid thermal conductivity (W/m · K)
: Fluid density (kg/m^3)
: Fluid viscosity (Pa · s)
ϕ: Correction factor for transition flow
: Correction factor for baffle's impact

δ: Relative difference

Subscripts
h: Hydraulic
e: Equivalent
i: Inside tube
m: Mean temperature
o: Outside tube
w: Tube wall surface temperature
lm: Logarithmic mean
in: Import
out: Export
si: Shell inner

Highlights

- Novel fluoride Salt-to-Salt Heat Exchanger (SSHX) with baffles featuring passive drainage port
- New empirical correlation for tube-side heat transfer shows <5% deviation from experimental data
- Kern correlation enhanced by 31% matches shell-side fluoride salt heat transfer measurements
- Compact drainage port integrated within baffles exhibits limited impact on heat transfer performance

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Abstract

This study experimentally investigated the heat transfer performance of a novel shell-and-tube fluoride Salt-to-Salt Heat Exchanger (SSHX) featuring baffles with integrated drainage ports, designed to mitigate salt freeze blockage risks during shutdown in Molten Salt Reactors (MSRs). Experiments were conducted in a Scaled Simulation Fluoride Salt-cooled Reactor (SF0) test facility. A new empirical correlation for tube-side heat transfer was proposed as $\mathrm{Nu}=0.0246\mathrm{Re}^{0}\cdot{}^{8}\mathrm{Pr}^{0}\cdot{}^{267}$ (valid for Re=9000~15000 and Pr=8~12), demonstrating excellent agreement with experimental data within a maximum deviation of 5%. Comparative analysis revealed the modified Dittus-Boelter equation is still a suitable choice for predicting fluoride salt convective heat transfer behavior in tubular geometries, outperforming the Gnielinski and Sieder-Tate models, which overpredicted data by 17-25%. For shell-side heat transfer, applying a 31% enhancement factor (=1.31) to the Kern correlation aligns predictions with experimental results within an error range of -6.0% to 7.0%. These findings address a critical engineering challenge in SSHXs while preserving thermal efficiency, offering essential experimental data and valuable insights for the design of fluoride SSHXs in MSRs.

Keywords: Fluoride Salt Heat Exchanger, Heat Transfer Coefficient, Salt Drainage Port, Empirical Correlation, Molten Salt Reactors

1. Introduction

The integration of Molten Salt Reactor (MSR) and thorium energy is poised to become a key technology for advancing sustainable nuclear energy, leveraging their inherent safety, adaptability to online fuel recycling, and low-carbon features [1,2]. At the heart of their operation are Salt-to-Salt Heat Exchangers (SSHXs), which directly transfer nuclear heat from fuel salts to coolant salts. Unlike air-cooled fluoride salt heat exchangers (ASHXs) designed primarily for residual heat removal [3], SSHXs face unique challenges: salt retention during shutdown poses critical risks of freezing and blockage, compromising reactor safety and maintenance. Recent studies on ASHXs [4] have improved thermal management, yet SSHXs demand specialized design innovations to ensure complete gravity-driven salt drainage without sacrificing heat transfer performance. Addressing these challenges is essential for accelerating MSR commercialization [5].

Despite their critical role, SSHX designs have evolved minimally since the 1960s MSRE experiment [1,6]. With renewed interest in MSRs [7,8], while early SSHXs in MSRE [9] achieved basic functionality, modern MSRs require enhanced designs to tackle operational challenges. For example, in both molten salt cooled liquid fuel reactors (e.g., TMSR-LF1[10-12], IMSR[13]) and molten salt cooled solid fuel reactors (e.g., TMSR-SF1[10,11], KP-FHR[14]), incomplete salt drainage will lead to maintenance delays, highlighting the urgency of structural redesigns. Additionally, SSHXs serve as key components in residual heat removal systems of MSRs [3,15,16], where their efficient heat transfer capabilities are essential for preventing core component overheating. However, SSHX optimization efforts remain constrained by a paucity of experimental heat transfer data, introducing considerable uncertainties in thermal-hydraulic modeling and safety assessments, and necessitating targeted research to resolve these gaps.

SSHXs are safety-class components in MSR nuclear islands, subject to stringent compliance with international standards (e.g., ASME III [17], RCC-M [18]) and nuclear safety regulations (e.g., IAEA SSR-2/1 [19], NRC [20]). While novel heat exchangers like printed circuit [21,22], plate-type [23], and helical coil [24] designs offer superior efficiency and compactness, their adoption in nuclear primary circuits is hindered by complex manufacturing [25], inadequate validation of radiation and corrosion resistance [21], flow blockage risk [26], and maintenance limitations (e.g., incompatibility with eddy current testing) [27]. In contrast, conventional shell-and-tube structures dominate nuclear reactor applications, including MSRs, thanks to mature manufacturing and inspection techniques (UT/RT/ultrasonic testing), proven operational experience [28], safety redundancy (e.g., single-tube rupture tolerance [29]), established repairability (e.g., tube plugging [30]), and regulatory compliance. Though advanced heat exchangers may emerge in Generation IV reactors with material advancements [31], nuclear safety conservatism demands prolonged technical validation and regulatory approval [8,32], ensuring that shell-and-tube SSHXs remain irreplaceable for MSR primary systems in the foreseeable future. This emphasizes the imperative to thoroughly examine their thermal-hydraulic performance for MSR advancement.

Thermal-hydraulic performance in heat exchangers is primarily governed by their geometric configuration. For SSHXs, a key design consideration is enabling gravity drainage of molten salt during shutdown, to avoid molten salt retention and subsequent freezing and clogging. To address this, a novel salt drainage port has been strategically integrated into the baffles. This design represents a marked departure from traditional shell-and-tube configurations. However, its impacts on thermal performance and flow resistance characteristics are still unclear. Our preliminary simulation analysis demonstrated that both heat transfer and flow resistance may slightly decrease in the proposed design [33], while experimental validation under prototypical operating conditions is yet to be conducted.

Comprehensive experimental data on the overall heat transfer performance of such innovative SSHX remains unreported. Existing studies on similar shell-and-tube molten salt heat exchangers provide limited insights. For instance, a traditional shell-and-tube fluoride SSHX performance was first evaluated in MSRE; while it satisfied reactor cooling demands, thermal performance underperformed design expectations [34-36]. Despite prior studies that have experimentally and computationally characterized molten salt thermal behavior in shell-and-tube heat exchangers with unbaffled [37], traditional segmental baffles [38], and trefoil-hole baffles [39,40], these geometries are fundamentally distinct from the proposed design. Although experimental evaluations of tube arrays with airflow guide plates [4] and U-tube bundles in hairpin heat exchangers [41] have been conducted, data on fluoride salt heat transfer within tubes and baffled shell-side geometries remain unreported.

These results cannot be directly extrapolated to baffled tube bundle geometries due to differences in flow regime characteristics. The enduring interest in MSRs has spurred the development of various fluoride salt test loops, including the FLiNaK salt test loop [42] and Liquid Salt Test Loop [43]. Yet, published test results on the overall heat transfer performance of SSHX remain scarce. Simulation studies utilizing Computational Fluid Dynamics (CFD) methods have simulated the fluoride SSHX [44] and air-cooled fluoride salt heat exchanger (ASHX) [45], offering predictive frameworks. Furthermore, while machine learning integration presents novel optimization avenues [37,46], the scarcity of experimental SSHX data—critical for validating efficiency and passive safety systems—highlights the necessity for performance testing under MSR-relevant conditions.

The present investigation bridges these knowledge gaps by designing and testing a novel shell-and-tube SSHX with integrated drainage ports in baffles, aiming to eliminate salt retention while maintaining thermal performance. The overall heat transfer was derived from experimental measurements and empirical calculations. Moreover, modified convective heat transfer correlations were proposed for fluoride salt flow, encompassing both internal tube flow and external flow across tube bundles with baffles featuring drainage ports. Comparisons were also made against established classical solutions.

2.1 Heat Exchanger Description

The tested SSHX, shown in Fig. 1 [Figure 1: see original paper], features a horizontal shell-and-tube configuration with 14 single-segmental baffles. Each baffle is modified with a triangular drainage port (12 mm height) at its lowest position to enable gravity-driven molten salt evacuation during shutdown, thereby eliminating residual salt accumulation and mitigating freeze-blockage risks. The tube bundle consists of 18 U-tubes (Φ13.72$×$1.65 mm, GH3535 alloy) arranged in a 30° triangular pitch (tube spacing P_t = 20 mm). The baffles are configured with 25% cuts, within the recommended practical range of 20% to 35% [47], and spaced at intervals of l_b = 120 mm, reinforced by 4 tie rods. The shell has an inner diameter D_{si} = 200 mm with a wall thickness of 5 mm, housing 1.8 m long U-tube straight sections.

The overall heat transfer coefficient (U) can be determined using Eq. (1) with the fouling thermal resistance neglected, considering the newly fabricated heat exchanger:

$$\frac{1}{U}=\frac{1}{h_i}+\frac{r_o\ln(r_o/r_i)}{k}+\frac{1}{h_o}$$

where Nu denotes Nusselt number (Nu), λ is the salt thermal conductivity, k stands for the thermal conductivity of the tube given in Table 1 [48], D is the tube diameter, and subscripts i and o represent the inside and outside of the tube, respectively.

For fluoride salt flow in U-tubes with 180° bends, the modified Dittus-Boelter equation [49] was used for initial prediction, as given in Eq. (2):

$$Nu=0.023Re^{0.8}Pr^{n}\phi$$

for 0.7 < Pr < 120 and Re > 2300. Where n = 0.4 for heating and 0.3 for cooling. Re and Pr stand for the Reynolds number (Re) and Prandtl number (Pr) respectively. ϕ denotes the correction factor, given by:

$$\phi=1-6\times10^{5}Re^{-1.8}$$

for 2300 < Re.

The Kern correlation [50], a widely accepted empirical model for shell-side heat transfer in staggered tube bundles with segmental baffles, was adopted for preliminary design of the SSHX, as shown in Eq. (4):

$$Nu = 0.36Re^{0.55}Pr^{1/3}\phi_s$$

for 2000 < Re < 10^6. Where subscripts m and w represent the mean temperature and the tube wall surface temperature, respectively.

Here, , and v stand for the density, viscosity and velocity of the molten salt, D__h represents the equivalent diameter, where D__h = D__i for the tube side, and D__h = D__{es} for the shell side. The velocity v can be defined as Eq. (7):

$$v = \frac{V}{A}$$

where V is the volume flow rate, A represents A__c of the all cross-sectional area of the tube bundle in the tube side and A__s of the maximum cross sectional area through which salt flows between tubes on the shell side.

2.2 Experimental Facility

The heat transfer performance of the SSHX was tested in the Scaled Simulation Fluoride Salt-cooled Reactor (SF0) facility described in our previous study [4], which simulates Thorium Molten Salt Reactor (TMSR) thermal-hydraulic conditions. The performance of key components and technical parameters (e.g., electric heater, molten salt pump capacity, and working fluid) are consistent with [4]. As illustrated in Fig. 3 [Figure 3: see original paper] [4], the primary circuit circulated molten salt through an electric heater and the SSHX, driven by a molten salt pump. The secondary circuit transferred heat from the SSHX to an ASHX via a secondary salt pump. The pipelines incorporated a 3-degree slope design to achieve passive molten salt drainage after shutdown, leveraging gravitational force for autonomous backflow to the storage tank. Key parameters, including molten salt flow rates (ultrasonic meters, \$±\$3% accuracy) and temperatures (K-type thermocouples, \$±\$0.4% uncertainty), were monitored at 10-second intervals.

2.3 Data Analysis

The tube-side (Q__i) and shell-side (Q__o) heat transfer rates were calculated using the energy balance method [4]. The logarithmic mean temperature difference correction factor (F) is determined by Eq. (9) [51]:

$$F = \frac{\sqrt{R^2+1}}{R-1} \ln\left(\frac{2-P(1+R-\sqrt{R^2+1})}{2-P(1+R+\sqrt{R^2+1})}\right)$$

where P = (T_i,in - T_i,out)/(T_i,in - T_o,in), R = (T_o,out - T_o,in)/(T_i,in - T_i,out), and f = (1+R^2)$^{0 \cdot 5}$. T stands for the temperature. Subscripts in and out represent the import and export, respectively.

The convective heat transfer coefficient inside the tube can be expressed by the algebraic correlation, given in Eq. (10):

$$h_i = \frac{Nu \cdot \lambda}{D_i}$$

By substituting Eq. (10) into Eq. (1), the overall heat transfer coefficient becomes:

$$\frac{1}{U} = \frac{D_o}{Nu\lambda_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o}$$

To isolate film heat transfer coefficients on both sides, the Wilson plot method [52] is applied to decouple these coefficients from the governing equation (Eq. 1). By maintaining a constant shell-side flow rate, the shell side film heat transfer coefficient can be treated as a constant. Consequently, Eq. (11) can be reformulated as a multidimensional linear equation:

$$\frac{1}{U} = a \cdot Re^{-n} + b$$

where a = (D_o)/(C λ_i) and b = (D_o ln(D_o/D_i))/(2k) + 1/h_o. The experimental data were fitted using the least squares method to obtain the optimal regression line. Through this analysis, the slope a, power n, and intercept b in Eq. (12) can be obtained. The empirical coefficients C and m in the heat transfer correlation can also be derived from Eq. (15) by fitting the experimental data. Additionally, based on these results, the Nu_o in Eq. (16) is redefined as Eq. (17).

3.1 Experimental Conditions and Results

The experiment was conducted in two phases under carefully controlled conditions. In the first phase, the primary circuit circulated molten salt at 597.7-648.7°C to transfer heat to the secondary loop, which operated at 564.1-578.6°C before rejecting heat to air. The second phase repeated this process with adjusted temperature ranges in both loops (primary: 581.3-633.3°C; secondary:

550.1-594.2°C). Throughout the experiment, the primary salt pump dynamically adjusted flow rates between 10.4-15.0 m^3/h, and the secondary pump operated steadily at ~20.4 m^3/h, while a blower continuously expelled heated air to maintain thermal equilibrium. Each test condition was maintained in thermal steady-state for over 1 hour, with temperature variations limited to $±$1°C and flow rate fluctuations below 3%. Complete experimental parameters are provided in Table 2 . After finishing the experiments, the system underwent natural cooling, and the molten salt was drained passively from the heat exchanger, thereby ensuring complete salt removal from both the tubes and shell.

3.2 Heat Transfer Rate

The experimental results, detailing the heat transfer rate and associated deviations, are presented in Fig. 4 [Figure 4: see original paper]. Quantitative analysis indicates that in the fluoride SSHX, the tube-side molten salt demonstrates slightly better heat transfer rates than the shell-side counterpart, with measured discrepancies confined within a narrow range of 2.2% to 7.2%. This systematic deviation may be attributed to parasitic heat losses to the ambient environment, which show temporal fluctuations between 13.3 kW and 19.8 kW as quantified in Fig. 4. It is worth noting that despite variations in operational conditions, the time-averaged heat leakage through the insulation layer remains stable at 16.6 kW. The observed asymmetry in thermal transport between tube-side and shell-side flows stems from fundamental differences in heat transfer pathways: tube-side thermal energy must be transmitted exclusively through the tube wall to reach the shell-side fluid, while a portion of the heat on the shell-side dissipates through the exchanger housing to the ambient atmosphere. This differential heat loss mechanism aligns rigorously with first law of thermodynamics principles governing energy conservation. Crucially, the relative constancy of heat leakage, despite increased heat transfer capacity, correlates with the minimal temperature variations observed on the shell. Additionally, measurement uncertainties in the temperature and flow rates of the molten salt, as well as deviations in their thermal properties, could also contribute to these deviations. Notably, the insulation system demonstrates remarkable temporal stability in heat loss characteristics, suggesting effective performance within the tested thermal load range.

3.3 Overall Heat Transfer Performance

In the experiment, the molten salt flow velocity inside the tube was varied from 1.88 m/s to 2.71 m/s, with the temperature variation detailed in Table 2. The corresponding Re ranged from 9133 to 14656, which indicates that the flow regime is mainly turbulent. The overall heat transfer coefficient measurements for the SSHX were first compared with empirical results on the basis of Nusselt analysis. Fig. 5 [Figure 5: see original paper] illustrates this comparison between the experimental results and empirical solutions. As evident from the figure, the empirical models employed to describe the heat transfer performance of the heat exchanger can be represented within -14% prediction error. The deviation between the empirical solutions and experimental results ranged from -13.2% to -8.3%. It was observed that the experimental data is greater than the empirical value, indicating that the empirical correlations underestimate the heat transfer performance. It can be seen in Fig. 5 that as the Re increases, the overall heat transfer coefficient shows an upward trend. This trend indicates that the tube side thermal resistance plays an important role in the overall heat transfer process.

3.4 Tube-Side Heat Transfer Performance

Fig. 6 [Figure 6: see original paper] illustrates the Wilson plot of the overall heat transfer coefficient as a function of the tube-side Re. By applying nonlinear regression to the experimental data, the coefficients in Eq. (12) were determined as a = 0.385446, n = 0.8 and b = 0.000261, respectively. Subsequently, the constants C = 0.0246 and m = 0.267 in Eq. (15) were derived. Consequently, the new heat transfer correlation for fluoride salt flow in U-tubes, initially defined by Eq. (10), is reformulated as Eq. (18):

$$Nu = 0.0246 Re^{0.8} Pr^{0.267}$$

The convective heat transfer data of the fluoride salt inside the tube are within the range of Re from 9133 to 14656 and Pr from 8.15 to 12.07, mainly in the turbulent flow regime.

The comparison between the new empirical correlation Eq. (18) and experimental results, as depicted in Fig. 7 [Figure 7: see original paper], reveals that the maximum deviation is confined to 5% for the majority of data points, with few exceptions. This indicates a high level of agreement between the empirical model and the experimental data.

Fig. 8 [Figure 8: see original paper] further compares the experimentally measured Nu as a function of Re with predictions from various classical empirical correlations, including the modified Dittus-Boelter equation (Eq. (2)), the Gnielinski equation (Eq. (19)) [53], and the modified Sieder-Tate equation (Eq. (20)) [49]:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

for $1.5 < Pr < 500$ and $3000 < Re < 10^6$.

$$Nu = 0.012(Re^{0.87} - 280)Pr^{0.4}\phi$$

for $0.7 < \mathrm{Pr} < 16700$ and $2300 < \mathrm{Re} < 10^6$, as well as high-viscosity fluid. Where the correction factor ϕ is given by Eq. (3).

As shown in Fig. 8, the values obtained by Eq. (19) are about 17% larger than the experimental data, and those from Eq. (20) exhibit an even more pronounced deviation of 25%. These indicate that fluoride salt cannot be treated as a high-viscosity fluid, and its flow behavior likely does not involve significant thermophysical property variations across the temperature range studied. In contrast, the comparison between Eq. (2) and the measurements reveals that the maximum deviation remains within \$±\$5.5% for the majority of data points. It demonstrates that the modified Dittus-Boelter equation still has strong predictive capability for fluoride salt heat transfer in tubular configurations, making it a suitable choice for engineering applications in this context.

3.5 Shell-Side Heat Transfer Performance

Since Eq. (2) has been rigorously validated for fluoride salt heat transfer in tubes, it can be substituted into Eq. (1) to derive an alternative solution, as presented in Eq. (21):

$$\frac{1}{U} = \frac{D_o}{Nu_i \lambda_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o}$$

Fig. 9 [Figure 9: see original paper] compares the values obtained from the two distinct approaches of Eqs. (17) and (21). As can be seen: (1) All Nu values are tightly clustered around 112, with a standard deviation of \$±\$9; (2) the results exhibit strong agreement, with deviations confined to within \$±\$6% for most data points, except for isolated outliers. This consistency not only validates the self-consistency of the analytical results but also reinforces the reliability of the methodology employed in this study.

Convective heat transfer data of the fluoride salt in shell-side flow across baffled tube bundles are within the range of Pr from 10.98 to 15.53 and Re from 3709 to 4815, which are constrained within relatively smaller bounds corresponding to changes in temperature with flow rate remaining unchanged as stated previously. Fig. 10 [Figure 10: see original paper] shows experimental Nu versus Re data compared with predictions from two traditional correlations: The Kern correlation (Eq. (4)) and the Donohue correlation (Eq. (22)) [49]:

$$Nu = 0.23 Re^{0.6} Pr^{1/3}$$

for 3 < Re < 2\$×10^{4}\$.

As illustrated in Fig. 10, compared to experimental results, the Kern correlation significantly underestimates the values with an average error of -23.6%, while the Donohue correlation amplifies this deviation, reaching -25.5%. The discrepancies may stem from the following factors: these methods assume idealized uniform flow and fail to account for the impact of the single segmental baffle with a salt drainage port on flow field modification and turbulence enhancement. These findings suggest that introducing a correction factor to address the observed discrepancies could be beneficial. The experimental data fitted to the form of the Kern equation are explicitly formulated in Eq. (23):

$$Nu = 0.36Re^{0.55}Pr^{1/3}\varepsilon$$

The least squares fitting of   to a curve results in   = 1.31.

The comparison between the modified Kern correlation (Eq. (23)) and experimental measurements, as illustrated in Fig. 10, demonstrates that errors predominantly range from -6.0% to 7.0%, with isolated cases reaching up to 10%. This indicates a strong concordance between the empirical model and experimental data, validating that the modified Kern correlation provides satisfactory predictive capability when compared with experimental observations.

It is noteworthy that the above results appear consistent with the conclusions of reference [54], where the correction factor is determined by the shell inner diameter (D_{si}), as listed in Table 3 . The findings reported in prior studies are derived from conventional baffle configurations in shell-and-tube heat exchangers, whereas the baffles in this study incorporate an innovative salt drainage port. The observed agreement between these results may imply that the small drainage port appears to have little impact on heat transfer. This may be attributed to the effect of the compact drainage port: although it induces localized flow diversion, it slightly improves the temperature distribution on the baffle surface. These competing mechanisms collectively result in a limited influence on overall heat transfer performance.

In the analysis of heat transfer, the uncertainty is evaluated by applying the Coleman and Steele method [55] alongside ASME standards [56]. It is estimated that the heat transfer rate uncertainty (δQ) is $±$5.9%, average heat transfer rate (Q) uncertainty $±$4.2%, overall heat transfer coefficient (U) uncertainty $±$4.3%, and Reynolds number (Re) uncertainty $±$3.7%, taking into account the uncertainties of flow rate, temperature and thermophysical properties of molten salt.

4. Conclusions

This study focused on experimentally evaluating the heat transfer performance of a novel shell-and-tube SSHX with baffles featuring a passive drainage port, aiming to overcome existing limitations in heat transfer efficiency and reliability. The key findings are as follows:

(a) Experimental overall heat transfer coefficients exceeded empirical predictions by 8.3%–13.2%, indicating underestimation by traditional models for convective heat transfer of fluoride salts.

(b) A new empirical correlation ($\mathrm{Nu}=0.0246\mathrm{Re}^{0}\cdot{}^{8}\mathrm{Pr}^{0}\cdot{}^{267}$, Re=9000~15000, Pr=8~12) for tube-side heat transfer was proposed, which demonstrated good agreement with experimental data, with a maximum deviation of 5%. This correlation can be used to predict the heat transfer performance of fluoride salt inside tubes in SSHXs.

(c) For shell-side heat transfer, a 31% correction factor (=1.31) applied to the Kern correlation reconciles predictions with experimental data (-6.0% to 7.0% error). This indicates that the modified Kern correlation provides satisfactory predictive capability for shell-side heat transfer in baffled tube bundles with drainage port.

(d) The modified Dittus-Boelter equation was found to have strong predictive capability for fluoride salt heat transfer in tubular configurations, with the maximum deviation confined to \$±\$5.5%. This suggests that the modified Dittus-Boelter equation remains a suitable choice for engineering applications in predicting the heat transfer performance of fluoride salt within tubes.

(e) The study also highlighted that the small salt drain port at the baffle edge has little impact on the overall heat transfer performance of the SSHXs.

Overall, this study successfully addresses a critical engineering challenge (molten salt freeze blockage risk) while preserving thermal efficiency by integrating structural innovation (compact drainage port) and model refinement (revised correlations). The research offers valuable experimental data and correlations for the design and optimization of SSHXs in MSR technology. Notably, the findings of this study seem to be primarily applicable to the particular experimental conditions tested. Although the Re range investigated is limited, the results demonstrate sufficiently robust to meet practical engineering applications. Future work will focus on validating the revised heat transfer correlation under broader experimental conditions, including extended Re ranges and varying salt temperatures.

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