Study on Heat Transfer Characteristics of Cooling Pipelines in Dual-Fluid Molten Salt Reactors

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Abstract

Abstract: The cooling circuit constitutes the core system for safe operation and energy conversion in nuclear reactors. Through the synergistic coordination of multiple critical functions, the cooling circuit becomes an indispensable "lifeline system" for the reactor. This study conducts a simulation investigation on the heat transfer characteristics of cooling pipelines in a two-fluid molten salt reactor under varying inlet temperatures and flow velocities. To this end, a heat transfer model for liquid fuel salt and chloride coolant is established based on the WISSR two-fluid molten salt reactor developed by the University of Michigan, and a three-dimensional model integrating the reactor core with cooling pipelines is designed. Due to the computational intensity of simulating the entire core, a partial core and pipeline section is selected for heat transfer simulation. Employing the thermophysical property calculation correlations for uranium-bearing fuel salt and coolant salt used in the WISSR reactor, the FLUENT model is utilized to compute the heat transfer characteristics between the two liquid molten salts during the exchange process. Finally, using the fuel power of the WISSR reactor as the simulation baseline, the heat transfer processes within the cooling circuit under different primary-side inlet parameters are investigated. The results demonstrate that: under identical conditions, the coolant outlet temperature follows a regular variation curve with increasing inlet temperature; as the primary-side inlet coolant salt temperature rises from 675°C to 745°C, the corresponding mean outlet temperature increases from 776.88°C to 852.94°C, thereby confirming the feasibility of achieving high coolant outlet temperatures (e.g., $ $800°C).

Full Text

Study on Heat Transfer Characteristics of the Cooling Circuit in a Dual-Fluid Molten Salt Reactor

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Abstract

The cooling circuit constitutes the core system for safe reactor operation and energy conversion, functioning as an indispensable "lifeline system" through the synergy of multiple critical functions. This study investigates the heat transfer characteristics of cooling pipelines in a dual-fluid molten salt reactor under varying inlet temperatures and flow velocities. Based on the WISSR dual-fluid molten salt reactor developed by the University of Michigan, we establish a heat exchange model for liquid fuel molten salt and chloride coolant, and design a simplified three-dimensional model integrating the reactor core with cooling pipelines. Due to the enormous computational demands of full-core simulation, we select a representative section of the core and piping for heat transfer analysis. Using physical property correlations for uranium-bearing fuel salt and coolant salt from the WISSR reactor, the FLUENT model is employed to calculate heat transfer characteristics between the two liquid salts. Finally, based on the WISSR reactor' s fuel power, we examine the heat transfer process within the cooling circuit under different primary-side inlet parameters. Results demonstrate that under identical conditions, the coolant outlet temperature exhibits a predictable trend with increasing inlet temperature. As the primary-side inlet coolant salt temperature rises from 675°C to 745°C, the corresponding mean outlet temperature increases from 776.88°C to 852.94°C, confirming the feasibility of achieving high coolant outlet temperatures (e.g., $ $800°C).

Keywords: dual-fluid reactor; heat transfer model; molten salt fast reactor; heat transfer performance

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Molten Salt Reactors (MSRs) represent an advanced reactor concept utilizing molten salts as both fuel carriers and coolants, where nuclear fuel dissolves in the molten salt to form liquid fuel, enabling fission reactions and heat transfer through salt circulation. Renowned for their excellent safety and economic characteristics, MSRs are a priority development among Generation IV advanced nuclear reactors [1]. Liquid-fuel MSRs employ molten salt as both fuel and coolant. Current mainstream designs typically use metal fluorides or chlorides as fuel carriers. Fluoride salts offer higher specific heat capacity and thermal conductivity, providing superior heat-carrying capability. Chloride salts feature high thermal expansion coefficients, strong natural circulation capability, high heavy metal solubility, and weaker neutron moderation, resulting in a harder neutron spectrum [2]. MSRs offer numerous advantages including high inherent safety, high fuel utilization, minimal nuclear waste generation, and enable thorium fuel cycles and nuclear waste transmutation, making them promising for nuclear power generation, waste management, and thorium resource utilization. Small Modular Molten Salt Reactors (SMRs) have attracted worldwide attention due to their high safety, versatile applications, flexible siting and installation, and modular design and production [3-5], leading to sustained development.

In recent years, extensive analytical and experimental research on MSRs has been conducted internationally, with significant design efforts undertaken by various countries. MSRs have garnered considerable attention in China, the United States, Russia, and other nations. In 2011, China launched the "Thorium-based Molten Salt Reactor Nuclear Energy System" (TMSR) program, led by the Chinese Academy of Sciences, aiming to achieve effective thorium resource utilization and nuclear hydrogen production [6]. The United States pioneered MSR research, beginning with the Aircraft Reactor Experiment (ARE) [7], and constructed the first high-temperature molten salt test reactor at Oak Ridge National Laboratory (ORNL) for the ARE program, marking the start of a long MSR development journey. After developing Hastelloy (nickel-chromium-molybdenum alloy) with molten salt corrosion resistance, the U.S. initiated the Molten Salt Reactor Experiment (MSRE) design in 1960, achieving a maximum coolant temperature of 663°C [8]. However, subsequent U.S. investment in MSR research declined significantly, forcing termination of many related programs. Research resumed after 2000, and in 2022, TerraPower partnered with Southern Company to plan construction of the world' s first critical fast-spectrum molten salt experimental reactor (MSFR) at Idaho National Laboratory [9].

The core advantage of Liquid-Fuel Molten Salt Reactors (LF-MSRs) lies in direct fuel dissolution in molten salt, enabling continuous online fuel processing and fission product removal without shutdown for refueling, thereby significantly improving fuel utilization and economics [10]. Additionally, liquid fuel provides inherent safety features such as negative temperature reactivity coefficients and atmospheric pressure operation, enabling automatic power regulation and eliminating core meltdown risks—challenges that solid fuels still face regarding shutdown refueling and potential safety limitations. Moreover, liquid-fuel reactor designs facilitate advanced fuel utilization modes like thorium-uranium cycles. Compared to conventional solid-fuel reactors, they eliminate fuel fabrication requirements and flexibly adapt to fast or thermal neutron spectra, making them highly promising candidates in Generation IV nuclear energy systems.

The Dual-Fluid Molten Salt Fast Reactor (DF-MSR) represents an innovative MSR design characterized by physically separating fuel salt and coolant salt into two independent circulation systems [11]. Fuel salt (typically containing fluorides of uranium, plutonium, or thorium) undergoes fission reactions in the core, releasing thermal energy, while coolant salt circulates independently to transfer heat from the core to heat exchangers for power generation or other applications.

In the dual-fluid MSR core designed by the University of Tennessee' s Nuclear Engineering Department, nuclear fuel consists of two separate salt streams circulating in the reactor core: one containing fissile uranium fuel salt, and the other containing blanket salt with fertile material. Fission neutrons can be captured by thorium atoms in the blanket salt, producing fissile uranium fuel through a series of decays. Recently, the University of Michigan combined the advantages of breeder-burner reactors and MSR technology to propose a dual-salt configuration molten salt reactor (WISSR) [12], which employs a novel reactor control method. Instead of using control rods to absorb neutrons entering and exiting the core, WISSR controls reactivity by moving liquid fuel into or out of the core. Fuel remains entirely within the reactor vessel except during refueling. Because the fuel is molten salt, it can be easily transferred through pipes connected to external equipment. The design incorporates numerous safety features, including large negative reactivity feedback coefficients, with coolant salt circulation through forced convection.

This study aims to construct a three-dimensional numerical model of the cooling circuit in a Dual-Fluid Molten Salt Reactor (DF-MSR) using Fluent software. Leveraging simulation data from the University of Michigan' s dual-salt configuration MSR, we investigate fluid flow and heat transfer characteristics in cooling tubes under high-temperature conditions, providing theoretical foundations and technical support for reactor thermal-hydraulic design optimization and safe operation. We quantify the impact of different operating conditions (e.g., inlet velocity, temperature gradients) on heat transfer efficiency, offering data support for reactor power enhancement and passive safety design.

1.1 Model Design

The WISSR reactor structure from the University of Michigan study mentioned above is shown in Figure 1 [Figure 1: see original paper]. Figure 2 [Figure 2: see original paper] presents a schematic of our independently designed partial core and cooling pipeline structure for the dual-fluid molten salt reactor. Given the complex structure of the actual steam generator, with a full-scale core diameter of 1.5 m and dense piping arrangements, this study focuses on molten coolant heat transfer issues. Complete full-scale simulation would require prohibitive computational resources. Therefore, to facilitate research while capturing the essential scientific problems, we simplified the number of pipes and selected a representative core section and piping arrangement as our research object, as shown in the figure. The total heat transfer section height is 1200 mm, with a heat transfer tube diameter of 8 mm. Coolant water enters from one side of the straight cooling tube, exchanges heat with liquid molten salt fuel in the annular space outside the tube, and exits from the other side. The structural material for the fuel container and cooling tubes is tentatively designated as SS-316H.

1.2 Mesh Generation

Using the numerical model established in this study, we investigate the coupled heat transfer characteristics between primary-side liquid metal and secondary-side water-steam in a liquid metal fast reactor helical coil steam generator. Referencing actual reactor operating conditions, mesh independence verification must be conducted prior to the main study. The geometric model is discretized using three-dimensional unstructured meshing with meshing software. The method adopts global mesh control. Mesh quality directly affects computational accuracy, requiring sufficient density in critical regions (such as near walls). The cooling tube walls, external molten fuel, and internal coolant fluid are refined to account for boundary layer thermal property gradients. A schematic of the mesh in selected regions is shown in the figure, with mesh quality above 0.9.

1.3 Simulation Method

1.3.1 Governing Equations The heat transfer and flow behavior of molten salt coolant can be described by the following fundamental governing equations:

1) **Mass Conservation Equation (Continuity Equation):**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

where ρ is molten salt density (kg/m^3) and $\mathbf{u}$ is velocity vector (m/s). This equation describes mass conservation of the molten salt.

2) **Momentum Conservation Equation (Navier-Stokes Equation):**

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f}$$

where p is pressure (Pa), ρ is molten salt density (kg/m^3), μ is molten salt dynamic viscosity (Pa·s), $\mathbf{u}$ is velocity vector (m/s), and $\mathbf{f}$ is external force (e.g., gravity). This equation describes the flow behavior of molten salt.

3) **Energy Conservation Equation:**

$$\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{u} T) = \nabla \cdot (k \nabla T) + Q$$

where c_p is molten salt specific heat capacity (J/(kg·K)), T is temperature (K), k is molten salt thermal conductivity (W/(m·K)), and Q is the heat source term (W/m^3) representing heat generated by nuclear reactions. This equation describes thermal energy transfer in molten salt.

1.3.2 Boundary Conditions To solve the above equations, reasonable boundary conditions must be defined: **Inlet boundary** specifies molten salt coolant inlet velocity and temperature using a velocity-inlet condition.

Outlet boundary is set as pressure-outlet. **Wall boundary** assumes no-slip conditions with specified wall temperature, heat flux, or energy source terms. All cooling tube inner/outer walls and fuel interfaces adopt coupled wall type, allowing heat transfer without mass transfer.

This study simulates the power density of the aforementioned BBMSR reactor [12], setting the energy source term in the fuel region to 80 MW/m^3. Fluent case convergence criteria combine residual curves with conservation of computed physical quantities. The residual convergence standard requires all variable residuals to drop below 10^{-3} (except energy), with energy residuals below 10^{-6}, at which point the solution is considered converged.

1.4 Physical and Chemical Properties of Molten Salt

This study selects a eutectic mixture of 55 mol% NaCl and 45 mol% $HMCl_3$ as fuel salt [13-15]. The heavy metal fuel consists of a mixture of depleted uranium and recycled TRU fuel from PWR spent fuel with 50 MWd/kg burnup after 10 years of cooling. The recycled TRU fuel comprises 20% U, 71% TRU, and 9% rare earth elements (by weight). Depleted uranium is mixed with recycled fuel to minimize TRU loading while achieving required neutronic performance. Depleted uranium is assumed to have 0.2% U-235 tail enrichment, with natural chlorine used. The structural material for fuel containers and coolant piping is tentatively designated as SS-316H.

This study considers a eutectic mixture of 15.11 mol% NaCl, 38.9 mol% KCl, and 45.98 mol% $MgCl_2$ (NaCl-KCl-$MgCl_2$) as molten salt coolant. NaCl-KCl-$MgCl_2$ salt melts at 675 K, helping reduce peak vessel wall and fuel salt temperatures. However, its higher viscosity significantly reduces Reynolds number and heat transfer coefficient. Under identical heat flux, the reduced heat transfer coefficient substantially increases temperature difference between coolant and wall.

Polynomial fits were performed for density, specific heat, thermal conductivity, and viscosity of coolant and fuel salts under reactor design conditions. The empirical property polynomials are presented in Table 1 and Table 2 .

Table 1 Coolant Salt Property Parameters

Physical Property	Empirical Correlation
Density ($kg \cdot m^{-3}$)	$\rho = 2112.8 - 0.56355T$
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	$C_p = 1438.0 - 0.5T$
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	$\lambda = 0.65322 - 0.00026T$
Viscosity ($Pa \cdot s$)	$\mu = 0.001$

Table 2 Fuel Salt Property Parameters

Physical Property	Empirical Correlation
Density ($kg \cdot m^{-3}$)	$\rho = 4206 - 0.8916T$
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	$C_p = 518.7$
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	$\lambda = 0.0005T - 0.169$
Viscosity ($Pa \cdot s$)	$\mu = 0.001$

2. Experimental Results and Analysis

Using the established numerical model, we investigate coupled heat transfer characteristics between the molten salt fuel system and cooling tubes in a liquid molten salt reactor. Multiple cases are set up to examine the influence of coolant inlet temperature and inlet flow velocity on coupled heat transfer in the reactor cooling system. Prior to the main study, mesh independence verification is conducted. Under identical conditions, the flow field distribution in the helical coil steam generator is calculated for several mesh node counts. Figure 4 [Figure 4: see original paper] shows the calculated coolant outlet temperature versus mesh node count.

The results indicate that when mesh count exceeds 15 million, computed results become essentially independent of mesh number. Therefore, balancing computational accuracy and efficiency, the model mesh node count is selected as 16.4 million (mesh density 0.001).

2.1 Heat Transfer Characteristics Analysis

2.1.1 Heat Transfer Analysis of Molten Salt at Different Flow Velocities Coolant inlet velocity is a primary parameter affecting heat transfer in cooling tubes. To investigate its impact on straight cooling tube performance, numerical simulations are conducted for inlet velocities ranging from 0.6 to 0.9 m/s. For comparative analysis, different inlet velocities are applied at the inlet while keeping all other parameters constant.

Figure 5 [Figure 5: see original paper] shows the temperature contour at the cooling tube outlet for an inlet temperature of 715 K and inlet velocity of 0.6 m/s. The uniform color distribution indicates small temperature gradients. The minimum outlet temperature is 802 K, while fluid near the tube wall reaches 887 K—higher than the central region. This demonstrates adequate heat exchange between coolant and tube wall. The pronounced temperature gradient results from combined effects of low fluid thermal conductivity and non-uniform velocity distribution. Near-wall fluid moves slowly with longer residence time, absorbing more heat, while central high-velocity fluid has shorter residence time and absorbs less heat.

Figure 6 [Figure 6: see original paper] presents temperature contours of coolant fluid at the cooling tube inlet and outlet. Figure 6(a) shows the inlet temperature contour, revealing significant temperature difference between coolant fluid and fuel molten salt. The cooling tube wall exhibits noticeable temperature rise due to direct contact with both coolant and fuel salt. Figure 6(b) shows the outlet fluid temperature contour. Due to laminar flow in the tube, a clear temperature difference exists. The central region at the coolant outlet shows minimal temperature rise, attributed to insufficient internal heat transfer influenced by coolant properties, tube heat transfer coefficient, and tube diameter. A clear flow boundary layer exists near the wall with significantly higher temperatures than the central region.

Heat transfer coefficient can be improved by selecting coolants with higher heat transfer coefficients, optimizing tube diameter, or using alternative tube materials.

2.1.2 Heat Transfer Efficiency at Different Inlet Flow Velocities Figure 7 [Figure 7: see original paper] shows that as primary-side inlet temperature increases, outlet temperatures rise accordingly across all three cases, following a consistent trend with similar overall heat transfer coefficient patterns. The outlet temperature variation curves are presented for inlet velocities of 0.6 m/s, 0.7 m/s, 0.8 m/s, and 0.9 m/s. At constant inlet temperature, higher inlet velocity results in lower outlet temperature, indicating reduced heat transfer between coolant and fuel. This occurs because increased flow velocity raises heat capacity flowrate, reduces fluid thermal residence time, and enhances turbulence, intensifying internal fluid disturbance and producing more uniform temperature distribution, thereby lowering overall outlet temperature.

2.2 Thermal Conductivity Variation During Cooling

Figure 8 [Figure 8: see original paper] shows the thermal conductivity contour of molten salt fuel during heat exchange. As indicated in Table 2, fuel thermal conductivity increases with temperature. At pipe junctions where coolant fails to adequately cool the region, higher temperatures result in higher thermal conductivity as visible in the figure. Areas near cooling tubes show lower temperatures due to more sufficient heat exchange. Heat transfer efficiency can be further improved by optimizing tube spacing.

Figure 9 [Figure 9: see original paper] displays the thermal conductivity contour of coolant fluid near the cooling tube wall during heat exchange. As shown in Table 1, coolant salt thermal conductivity decreases with increasing temperature. Before entering the cooling tube, the coolant maintains thermal conductivity at the set inlet temperature. Upon entering the tube, immediate heat exchange with fuel raises temperature and reduces thermal conductivity.

2.3 Density Analysis of Coolant Fluid During Heat Transfer

Figure 10 [Figure 10: see original paper] shows the density contour at the coolant outlet. The uniform color distribution indicates negligible density variation, consistent with the incompressible flow assumption. Any local deviations would require investigation for potential multiphase flow or temperature gradient effects.

2.4 Core Temperature Distribution

Figure 11 [Figure 11: see original paper] presents the overall temperature contour of molten salt fuel during cooling heat exchange. The figure clearly shows significantly reduced temperatures in regions where fuel salt contacts cooling tubes. Some fuel regions operate within normal temperature ranges for the given power level, while areas with higher fuel density exhibit elevated temperature zones. This occurs because coolant effectively absorbs heat only from fuel regions near tube walls. Core regions farther from cooling tubes reach maximum temperatures due to nuclear heat release, with pronounced radial and axial temperature gradients.

2.5 Velocity Field Analysis

Figure 12 [Figure 12: see original paper] shows the velocity trace contour of coolant fluid inside cooling tubes. The inlet effect is clearly visible at the entrance section. Due to fluid viscous forces, a flow boundary layer forms near the straight pipe wall. As fluid progresses through the pipe, boundary layer thickness gradually increases. After a certain distance, boundary layers developing from the wall periphery stabilize, establishing fully developed flow and laminar flow conditions. This confirms laminar flow regime in the tube. Figure 13 [Figure 13: see original paper] presents the velocity vector diagram of fluid in the cooling tube.

3. Conclusion

This study establishes a computational model for analyzing heat transfer in liquid metal dual-fluid molten salt fast reactors. Cooling heat transfer characteristics for a conceptual breeder molten salt reactor using independent molten salt coolant are analyzed, yielding the following conclusions: The Dual-Fluid Molten Salt Reactor (DF-MSR) design, featuring physical separation of fuel salt and coolant salt, indeed demonstrates feasibility for achieving high coolant outlet temperatures (e.g., $ 800°C).ThiscapabilitymakesDF − MSRhighlypromisingforhigh − temperaturehydrogenproductionandefficientpowergeneration.Selectingthermallystable, low− activationmoltensalts(suchasFLiBeorNaCl − KCl − MgCl_{2}$) allows independent optimization of thermal properties (e.g., specific heat capacity, thermal conductivity), overcoming traditional single-fluid temperature limitations. Stainless steel fuel chamber wall corrosion represents a clear challenge that may limit fuel chamber service life. Further research is needed to optimize the design, and multi-physics transient analysis should be conducted for anticipated accident scenarios.

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