Transient Freezing of Molten Salt in Pipes: A Multi-Scale CFD and Lumped-Parameter Model Analysis

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Abstract

Molten salts are efficient heat-transfer and storage media widely used in advanced energy systems, including nuclear and concentrated solar power. Their high melting points, however, can induce transient pipeline freezing, impairing operational economy and compromising flow safety. This study employs an integrated multiscale CFD and lumped-parameter approach to systematically investigate the complex freezing process of molten salt in pipes and to quantify the effect of key boundary conditions. Under pumped-inlet conditions, the characteristic temperature and flow rate exhibit a distinct dynamic: an initial decrease, followed by recovery and stabilization, marking the transition from initial filling to steady flow. Excessively designed cooling systems can drive the heat removal rate beyond a safe threshold. The risk of pipe blockage rises substantially when the dimensionless freezing parameter $\theta \leq 1$. The model' s applicability is examined, and a parametric sensitivity analysis assesses the influence of inlet temperature, flow velocity, cooling intensity, pipe length, and wall thickness. This work provides a theoretical basis and safety-design guidelines for freeze-protection in molten salt cooling systems.

Full Text

Preamble

Transient Freezing of Molten Salt in Pipes: A Multi-Scale CFD and Lumped-Parameter Model Analysis∗ Hongxiang Yu,1, 2 Chong Zhou,1, 2, † Yao Fu,1, 2 Shangwu Wang,1, 2 Shuaiyu Xue,1, 2 and Hui Deng1, 2 1Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China 2University of Chinese Academy of Sciences, Beijing 100049, China Molten salts are efficient heat-transfer and storage media widely used in advanced energy

systems, including nuclear and concentrated solar power. Their high melting points, however, can induce transient pipeline freezing, impairing operational economy and compromising flow safety. This study employs an integrated multiscale CFD and lumped-parameter approach to systematically investigate the complex freezing process of molten salt in pipes and to quantify the effect of key boundary conditions. Under pumped-inlet conditions, the characteristic temperature and flow rate exhibit a distinct dynamic: an initial decrease, followed by recovery and stabilization, marking the transition from initial filling to steady flow. Excessively designed cooling systems can drive the heat removal rate beyond a safe threshold. The risk of pipe blockage rises substantially when the dimensionless freezing parameter $\theta \leq 1$. The model' s applicability is examined, and a parametric sensitivity analysis assesses the influence of inlet temperature, flow velocity, cooling intensity, pipe length, and wall thickness. This work provides a theoretical basis and safety-design guidelines for freeze-protection in molten salt cooling systems.

Keywords: Molten salt, Solidification/melting, Computational fluid dynamics (CFD), Cooling system design

INTRODUCTION

Molten salts are favored in advanced nuclear systems for their exceptional chemical stability and thermophysical per- formance at elevated temperatures [1], serving as primary heat-transfer and coolant media. In liquid-fueled molten salt reactors, they act as a solvent for nuclear fuel [2, 3], while in solid-fueled designs they function as the core coolant [4].

A defining characteristic of these salts, however, is their high solidification point. Although this permits system operation at atmospheric pressure, it concurrently introduces a substan- tial risk of flow blockage due to freezing during operational transients, such as startup, shutdown, and under postulated accident conditions [5]. Effectively mitigating this freezing risk is therefore a central challenge for ensuring system safety and reliability.

The integrity of coolant flow is a fundamental safety re- quirement for molten salt reactors. Research dating back to Yamamoto' s 1971 study on partial loop blockages under- scores the imperative of maintaining unimpeded flow channels [6]. Consequently, engineering designs universally in- corporate pipe insulation alongside active heating systems, to prevent freezing [7]. typically electrical trace heating, Despite these precautions, safety analyses for design-basis events including station blackout (SBO) or heater failure demonstrate that local solidification upon contact with colder structures remains plausible [8, 9]. This risk is accentuated during transient phases like initial system filling, cooldown, or passive decay heat removal.

It is particularly acute in fully passive safety systems such as the Direct Reactor Auxil- iary Cooling System (DRACS) [10], which depends entirely on buoyancy-driven natural circulation. The modest driving ∗ This work is finan-

cially supported by the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, under project "State Key Labora- tory of Thorium Energy (No. SYS-ZBS-202403)" † Corresponding author, zhouchong@sinap.ac.cn force in such systems is exquisitely sensitive to flow resis- tance. An excessively efficient heat exchanger can induce rapid cooling of the salt, potentially initiating localized freez- ing. This can disrupt the critical equilibrium between the buoyancy drive and flow resistance, leading to a loss of decay heat removal capability. Hence, quantifying a definitive ther- mal safety boundary to prevent overcooling is of paramount importance for reactor design.

Accurately defining this boundary requires a mechanis- tic understanding of the transient solidification process un- der flow conditions. This process constitutes a multiphysics problem, coupling multiphase flow, phase-change heat trans- fer, and porous media dynamics within a three-dimensional, unsteady framework. Early investigations, exemplified by the experimental work of Bergan et al. on solar salt sys- tems, provided valuable macroscopic observations of freez- ing but lacked resolution of local, transient phenomena [11].

While system-level codes are indispensable for integral safety analysis [12], they possess inherent limitations in capturing the localized, flow-dependent details of freeze-front propaga- tion. Computational Fluid Dynamics (CFD) has emerged as an indispensable tool for elucidating these micro-scale mech- anisms. CFD simulations enable detailed resolution of the solidification front evolution, flow channel occlusion within the mushy zone, and the consequent effects on system pres- sure drop and thermal hydraulics. For example, Lu et al. employed ANSYS Fluent simulations of a cold-fill scenario to derive a critical inlet temperature threshold for blockage prevention [13]. Subsequent studies have leveraged CFD to quantify the sensitivity of the freezing process to key param- eters (e.g., the mushy zone constant) and to calibrate mod- els against experimental data, thereby significantly enhancing predictive fidelity and validating CFD' s critical role in funda- mental research [14].

Nevertheless, the considerable computational expense of high-fidelity 3D CFD simulations precludes their direct use for rapid design iteration or real-time safety margin evalu- ation. This creates a compelling need for a rapid, physics-heat transfer coefficient outside the cold section is h0 with the surrounding temperature T∞.

The simulation employs KNO3-NaNO2-NaNO3 (Hitec, 53-40-7 wt%) molten salt. The thermophysical properties of the molten salt [16], air and steel [17], are detailed in Table 1 . The surface tension between molten salt and air $\sigma = 0.149 - 0.0000556\text{T N m}-1$ [1]. Gravity acceleration g is 9.81 m s−2.

B. Governing Equations The entire filling process involves multiphase flow and is simulated using the Volume of Fluid method [18]. This ap- proach tracks the interface between phases by solving the vol- ume fractions of different phases, constrained as follows: $\alpha\text{m} + \alpha\text{a} = 1$ where αm and αa denote the volume fractions of molten salt and air, respectively. The momentum and energy equations are shared among the phases, with material properties deter- mined by the volume-weighted average of each phase: x = αmxm + αaxa where x represents density (ρ), specific heat capacity (c), ther- mal conductivity (λ), or dynamic viscosity (µ).

The enthalpy-porosity technique is employed to simulate solid-liquid phase change phenomena [19, 20]. This tech- nique calculates the liquid fraction through enthalpy balance.

The total enthalpy H of the fluid is the sum of sensible enthalpy hsen and latent heat ΔH:

H = hsen + ΔH The sensible enthalpy hsen is the product of the specific heat and temperature which can be written as: hsen = cmT where cm is the specific heat capacity of molten salt.

The liquid fraction fl is expressed as: T − Ts Tl − Ts T < Ts , Ts < T < Tl T > Tl the region where fl ranges from 0 to 1 is termed the mushy zone, a semi-solid region in which the porosity decreases from 1 to 0 as the material solidifies.

The latent heat ΔH is calculated as the product of the liq- uid fraction fl and the latent heat of fusion Q: ΔH = flQ The energy equation is formulated as [21]: (ρH) + ∇ $\cdot$(ρvH) = ∇ $\cdot$($\lambda\nabla$T) + S Fig. 1 [Figure 1: see original paper]. Schematic view of simulation geometry and boundary con- ditions. informed prediction methodology that retains essential mech- anistic accuracy while offering computational efficiency, thereby bridging the gap between detailed simulation and en- gineering application. Foundational work in analogous ar- eas, such as the solidification risk model for lead-bismuth eu- tectic systems developed by Zeng et al., provides a valuable methodological reference [15].

Informed by high-fidelity CFD insights, the present study develops a rapid freezing cri- terion and associated safety boundary prediction framework that is both physically rigorous and practically applicable.

This tool is designed to support the design and safety anal- ysis of molten salt reactor coolant systems, with particular relevance to passive safety architectures, contributing to the advancement of inherently safe nuclear energy technology.

The paper is organized as follows. Section II details the numerical methodology, including the CFD model and its validation against experimental data. Section III presents simulation results, categorizes freezing scenarios, and ana- lyzes the blockage development process. Section IV derives an engineering-oriented freeze-plugging criterion from fun- damental energy principles, discusses its domain of applica- bility, and performs a comprehensive parametric sensitivity study. Concluding remarks are provided in Section V.

II. NUMERICAL METHODOLOGY A. Physical Model As depicted in Fig. 1, a three-dimensional geometric model of molten salt filling a cold pipe is constructed based on a Cartesian coordinate system. The model incorporates a fluid domain and a solid domain of specified thickness. The geometry is configured with reference to conventional pipe applicated in the design of salt/air heat exchangers in the DRACS. The horizontal steel pipe, featuring an inner radius R1 = 0.005 m and an outer radius R2 = 0.006 m, comprises an inlet section and a cold section with lengths Lin = 0.2 m and Lc = 1 m, respectively. The pressure difference at the pipeline inlet and outlet is P0. At t = 0, the molten salt ini- tiates the filling process with an initial temperature T0, the temperature of the inlet sec- tion is equal to T0 and the temper- ature of the cold section Tp is below the melting point of the molten salt. The outer wall temperature of the inlet section is maintained at the molten salt' s initial temperature T0 and the TABLE 1. Thermal properties of molten salt, air and steel in present simulation.

Molten salt 2293 − 0.7497T 5806 − 10.833T + 7.2413 × 10−3T 2 0.78 − 1.25 × 10−3T + 1.6 × 10−6T 2 0.4737 − 2.297 × 10−3T + 3.371 × 10−6T 2 − 2.019 × 10−9T 3 1.78 × 10−5 Steel Units: T (K), ρ (kg/m3), c [J/(kg·K)], λ [W/(m·K)], µ [kg/(m·s)], Q (J/kg); Ts and Tl are solidus and liquidus temperatures, respectively. where the phase related source S is: ($\rho\Delta$H) + ∇ ·(ρvΔH) The momentum equation is given by: (ρv) + ∇ ·(ρvv) = −∇P + ∇ ·(cid:2)µ(∇v + ∇vT)(cid:3) + ρg + A Here, g represents gravitational acceleration vector. A is the momentum sink term due to solidification expressed by the Carman-Kozeny equation, a well-known equation derived from the Darcy law [22]: (1 − fl)2 l + ϵ) Amushv where ϵ is a small constant (0.001) to prevent division by zero. Within the mushy zone, as the fluid solidifies, fl de- creases from 1 to 0, and the velocity approaches zero. The mushy zone constant Amush controls the rate of velocity re- duction during solidification; a higher value results in a more rapid decrease in velocity.

The governing equation in the steel pipe is: the solidification layer growth near the cold wall, the near- wall mesh was continuously refined, as shown in Fig. 2 [Figure 2: see original paper]. Four schemes were tested for mesh independence validation. The growth of the solidified layer brings additional flow resis- tance, affecting the transient flow process. The simulation results show that when the near-wall mesh thickness is refined to above 0.1 mm, the rate of change of flow distance over time is less than 5%. The global liquid fraction calculation results under different mesh schemes differed by less than 3%. Fi- nally, mesh3 was selected, its main flow domain element size was 0.5 mm, near-wall zone element size was 0.1 mm, total grid number was 460800. The time step Δt = 0.001 s was chosen, its related liquid fraction calculation results differed by less than 1% compared with Δt = 0.0005 s. = λst$ $2T C. Simulation Procedure and Model Verification The simulations were performed using the commercial software ANSYS FLUENT. The computational domain was discretized with finite volume grids, with all variables stored and calculated at the cell centers. A laminar flow model was applied. To enhance stability in simulating the complex tran- sient processes, the pressure-velocity coupling was resolved using the PISO algorithm, and the PRESTO scheme was em- ployed for pressure interpolation. Furthermore, a double- precision solver was utilized for solving the momentum and energy equations to improve the accuracy of the transient cal- culations.

A three-dimensional filling geometry model was estab- lished. To increase the stability of transient calculations, the mesh division was fully hexahedral structured. Considering Fig. 2. Schematic diagram of the mesh schemes.

The solid-liquid phase change was simulated using the enthalpy-porosity model which accounts for the latent heat and introduces a momentum damping effect within the mushy zone. The damping intensity is governed by the material-dependent mushy zone constant, Amush. To calibrate this key parameter, the numerical model was verified against the experimental data of Zhang et al. [16]. Fig. 3 [Figure 3: see original paper] compares the simulated penetration distances across a range of Amush val- ues with the experimental measurements. For Hitec salt, an Amush value of 5×104 yielded the optimal agreement. This good correspondence verifies the reliability of the present computational methodology for subsequent studies. in Fig. 5 Figure 5: see original paper-(d), the initial constant pressure difference is en- tirely converted into kinetic energy, driving molten salt into the empty pipe at a high initial flow rate. As filling progresses, the salt is cooled by the cold pipe wall. This results in a sig- nificant heat flux, causing the characteristic temperature to decrease while simultaneously heating the pipe wall. Con- currently, increasing flow resistance leads to a rapid decay in the mass flow rate. Once the molten salt front reaches the out- let, the continuous inflow of molten salt raises the character- istic temperature. The associated reduction in fluid viscosity lowers the frictional resistance, allowing the mass flow rate to recover. After approximately 30 s, the pipe wall temper- ature stabilizes under the specified heat transfer conditions, establishing a steady thermal gradient as the flow reaches an equilibrium state.

A lower inlet pressure differential results in a lower initial flow rate. For P0 = 108 Pa, a distinct behavior is observed when $16 < t < 30$ s, where the characteristic temperature within the one-meter pipe decreases to a level near the mushy zone. The local solidification that occurs introduces addi- tional flow resistance, causing the flow rate to stagnate at a persistently low value. Despite this significant flow attenu- ation, the molten salt ultimately maintains through-flow, and the system progresses to a final state of combined thermal and hydraulic equilibrium.

Initial Filling Stage: Freezing Blockage During Initial Flow Establishment The analysis in Section III indicates that an insufficient in- let pressure during the initial filling stage can readily induce freezing and blockage. This is conclusively demonstrated in Fig. 6 Figure 6: see original paper(a), where for P0 = 108 Pa, a reduction in the in- let temperature by 50 $\circ$C leads to complete freezing within the one-meter pipe. In contrast, Fig. 6(c)(c) shows that in- creasing the inlet pressure by 750 Pa enables the molten salt to traverse the entire pipe length and achieve thermal equilib- rium, even when the inlet temperature is reduced by 75 $\circ$C.

These results underscore that an adequate pressure head con- stitutes the primary and essential barrier for ensuring safe heat removal during this phase.

While sufficient upstream driving force allows the fluid to successfully fill the empty pipe, an excessively low inlet tem- perature will cause the salt to cool to its freezing point too rapidly, resulting in blockage. Fig. 6(b) presents results for different inlet temperatures, ranging from 425 K to 445 K, under an inlet pressure P0 = 458 Pa. Two distinct outcomes are identified: i) Complete freezing occurs at inlet tempera- tures T0 = 425 K, 430 K, characterized by the characteristic temperature falling below the mushy zone and the flow rate decaying to zero. ii) Conversely, complete through-flow oc- curs at T0 = 435 K, 445 K, where both parameters recover and stabilize. This identifies a critical inlet temperature for a given pipe geometry, below which freezing is inevitable dur- ing initial filling.

To provide clearer insight into the transient phase-change process, Fig. 7 [Figure 7: see original paper] presents liquid fraction contours for inlet tem- Fig. 3. Comparison of penetration distances between the experimen- tal data and the simulation results.

III. NUMERICAL RESULTS AND ANALYSIS The analysis in Section III focuses on the transient freez- ing of molten salt as it flows into a cold pipe. This process is governed by a critical positive feedback loop: the growth of a solid layer adjacent to the pipe wall increases the flow resis- tance, which reduces the flow rate and in turn accelerates fur- ther solidification, potentially culminating in complete flow blockage. To accurately simulate this coupled transient phe- nomenon, a pressure boundary condition that reflects actual pump characteristics is essential. This methodology is consistent with the approach of Lu et al. [13] and supported by Yu et al. [14] in their discussions on boundary condition as- sumptions for practical engineering scenarios.

A. Characteristics of Pressure-Driven Flow Regimes in Cold Fig. 4 [Figure 4: see original paper] illustrates the typical progression of a cold-pipe fill- ing process, which transitions from the initial filling stage to the establishment of thermal equilibrium under sustained flow. The temporal evolution of key parameters under differ- ent inlet pressures, P0, is detailed in Fig. 5. Here, the characteristic temperature is defined as the average temperature at the advancing flow front, representing the minimum stream- wise temperature; upon complete filling, it becomes equiva- lent to the average outlet temperature.

Fig. 4. Schematic diagram of the cold filling stages.

The general trends observed across different pressure con- ditions are similar. For the case with P0 = 860 Pa, shown (a) Mass flow (b) Characteristic temperature (c) Wall temperature (d) Wall heat flux Fig. 5. Variation of characteristic quantities during the filling process (T0 = 500 K, h0 = 20 W m−2 K−1). (a) Mass flow. (b) Characteristic temperature. (c) Wall temperature. (d) Wall heat flux. peratures of 425 K and 435 K, respectively. When the inlet temperature is below the critical value, as seen in Fig. 7(a), so- lidification initiates irregularly from the pipe wall and grows radially inward until the flow channel is completely occluded.

For the case with an inlet temperature above the critical value, shown in Fig. 7(b), solidification also begins at the cold wall.

However, influenced by gravity, the solid phase concentrates at the bottom of the pipe. This bottom layer is subsequently remelted by the continuous scouring action of the incoming hotter flow, after which the system stabilizes.

C. Steady-State Stage: Critical Freezing Under Fully-Developed Flow The analysis in this section extends the investigation to a fully developed, steady flow, examining the system' s re- sponse when the cooling intensity exceeds a critical limit.

This scenario is particularly pertinent for defining precise safety boundaries in the design of cooling systems intended for steady-state operation.

Fig. 8 [Figure 8: see original paper] presents the system' s response to different heat transfer coefficients applied after the flow is largely stabi- lized beyond 80 s. A baseline coefficient of 20 W m−2 K−1 was used prior to this time. For a heat transfer coefficient h0 = 100 W m−2 K−1, shown in Fig. 8(a), the character- (a) T0 = 425 K (a) P0 = 108 Pa (b) P0 = 458 Pa (b) T0 = 435 K Fig. 7. Contours of liquid fraction during filling processes (P0 =

458 Pa, H:L = 5:1). (a) T0 = 425 K. (b) T0 = 435 K.

(c) P0 = 860 Pa Fig. 6. Variation of mass flow (left) and characteristic temperature at different values of T0. (a) P0 = 108 Pa. (b) P0 = 458 Pa. (c) P0 = 860 Pa. istic temperature initially decreases and fluctuates near the mushy zone before eventually recovering. Correspondingly, the flow rate exhibits a distinct "concave profile" before re- turning to a stable value. In sharp contrast, for a coefficient h0 = 200 W m−2 K−1 shown in Fig. 8(b), both the character- istic temperature and mass flow rate undergo an irreversible and precipitous decay. As the temperature drops definitively below the mushy zone, complete freezing occurs within the pipe.

The underlying spatial progression of these freezing pro- cesses is visualized in Fig. 9 [Figure 9: see original paper]. For the case with h0 =

100 W m−2 K−1, depicted in Fig. 9(a), the enhanced cool-

ing disrupts the established thermal balance shortly after its application. Solidification initiates at the wall and, driven by gravity, accumulates predominantly at the pipe bottom (80 < t < 180 s). Subsequently, heat from the sustained inflow gradually remelts this solidified layer, allowing a new thermal equilibrium to be established (180 < t < 300 s).

For the case with h0 = 200 W m−2 K−1, shown in Fig. 9(b), solidification progresses more rapidly at the bottom. A dis- tinctive "air region" forms near the top of the outlet, and the cooling intensity reaches the critical threshold for global so- (a) h0 = 100 W m−2 K−1 (b) h0 = 200 W m−2 K−1 Fig. 8. Variation of mass flow (left) and characteristic temperature at different values of h0 (P0 = 458 Pa, T0 = 435 K). (a) h0 =

100 W m−2 K−1. (b) h0 = 200 W m−2 K−1.

lidification, resulting in complete blockage of the pipe by 300 Fig. 10 [Figure 10: see original paper]. Schematic of a control volume for flow and heat transfer in a pipe. Δhsen + Δhlat = −K(T (z) − T∞) ･πdo The left side is the fluid enthalpy drop. The right side represents heat dissipation to the environment at temperature T∞. The coefficient K is the overall heat transfer coefficient, based conservatively on the outer pipe area: (cid:18) 1 K = 1/ (cid:19) Here, λs is the pipe thermal conductivity. The terms hi and ho are the convective heat transfer coefficients on the fluid- pipe and environment-pipe interfaces, respectively.

When the outlet temperature satisfies Tout ≥ Tl, the en- thalpy drop is dominated by sensible heat. And Eq. (12) sim- plifies to: o ･ρlucl (cid:19) (cid:18) dT (z) = −K(T (z) − T∞) ･πdo Here ρl and cl are the fluid density and specific heat. The velocity u = dz/dt.

Rearranging Eq. (14) gives: T ′(z) + ρlucldo T (z) = ρlucldo The fluid temperature T (z) is subject to these boundary conditions:

T (z) = T0 T (z) = T∞ Solving Eq. (15) with conditions (16) and (17) yields:

T = T∞ + (T0 − T∞)e− 4K ρl ucl do This solution shows an exponential temperature decay along the pipe. Eq. (18) describes steady, fully-developed flow. For the short initial cold-filling process, assuming con- stant wall temperature (K = hi, T∞ = Tw) makes Eq. (18) consistent with the criterion from Zeng et al [15]. (a) h0 = 100 W m−2 K−1 (b) h0 = 200 W m−2 K−1 Fig. 9. Contours of liquid fraction during filling processes (P0 =

458 Pa, T0 = 435 K, H:L = 5:1). (a) h0 = 100 W m−2 K−1. (b)

h0 = 200 W m−2 K−1. IV. THEORETICAL MODEL AND DISCUSSION To prevent heat transfer failure from molten salt freezing in cold pipes, previous studies have proposed several opera- tional strategies. Yu et al. suggested using higher pump power to reduce the cooling duration [23]. A more conservative approach by Ben et al. advised maintaining the pipe wall tem- perature consistently above the salt' s melting point [10]. To advance beyond these general guidelines and establish quan- tifiable safety boundaries for system design, this section de- velops thermal equilibrium equations to establish a freezing risk assessment criterion and enables a quantitative sensitivity analysis of key parameters.

A. Thermal Equilibrium Model Formulation Section III established that freezing risk emerges when the characteristic temperature enters the mushy zone. A primary design objective is therefore to ensure the bulk outlet temper- ature remains above the liquidus temperature. Fig. 10 shows a schematic of a differential control volume for pipe flow. Here, dz and dt are infinitesimal length and time elements. The fluid temperature T is a function of axial distance z. The pipe inner and outer diameters are di and do.

An energy balance for the fluid control volume accounts for sensible and latent enthalpy changes:

When the fluid is in the mushy zone (Ts $<$ Tout $<$ Tl), latent heat dominates. Following the approach of Voller et al. [19], Eq. (12) becomes: o $\cdot\rho$lu Tl $-$ Ts dT (z) = $-$K(T (z) $-$ T∞) $\cdot\pi$do (19) The corresponding boundary conditions are:

T (z) = Tl T (z) = T∞ The solution is: T = T∞ + (Tl $-$ T∞)e$-$ 4K(Tl$-$Ts) ρl udoQ (z$-$zl) Within the mushy zone, velocity decays linearly:

T $-$ Ts Tl $-$ Ts T $<$ Ts $\cdot$u, Ts $<$ T $<$ Tl T $>$ Tl Liquid fraction follows a similar relation:

T $-$ Ts Tl $-$ Ts T $<$ Ts , Ts $<$ T $<$ Tl T $>$ Tl The total pressure drop combines frictional and mushy- zone contributions: ΔP = ΔPf +ΔPe = f $\cdot$+Amush$\cdot$ (1 $-$ fl)2 l + ϵ) $\cdot$u (25) Eqs. (18) through (25) form the governing system for steady-state pipe flow and heat transfer. Applying this model to Hitec salt with parameters T0 = 580 K, u = 0.05 m s$-$1, T∞ = 300 K yields the results in Fig. 11 [Figure 11: see original paper]. Although Eqs. (18) and (22) predict exponential decay, Fig. 11(a) shows a nearly linear temperature decrease over a short length. Latent heat release in the mushy zone slows the cooling rate. Fig. 11(b) shows that flow resistance rises sharply as solidification pro- gresses, leading to eventual blockage.

B. Dimensionless Analysis and Parametric Sensitivity The theoretical analysis in the previous section indicates that a drop in molten salt temperature into the mushy zone leads to a sharp increase in pressure drop, readily resulting in flow blockage. A conservative design approach, there- fore, prioritizes ensuring the fluid outlet temperature remains above this zone. Under this condition, the fluid temperature distribution follows Eq. (18), which can be expressed in a dimensionless form:

T $-$ T∞ Tl $-$ T∞ T0 $-$ T∞ Tl $-$ T∞ Here, the heat transfer surface area is A1 = πdol, and the fluid flow area is A2 = (1/4)πd2 i . Eq. (26) describes the cooling process of molten salt from a high inlet temperature towards the surrounding temperature, with the exponential decay term quantifying the cooling rate.

The onset of freezing risk occurs when the fluid temper- ature drops to the phase-change threshold, defined as T = Tf reeze, signifying that heat dissipation has reached a critical level. The corresponding critical dimensionless temperature

θcritical = Tf reeze − T∞ Tl − T∞ For Eq. (26), where Tf reeze = Tl, we obtain θcritical =

1. A dimensionless temperature $\theta \leq 1$ indicates the fluid

temperature has fallen below its liquid temperature, signaling a risk of freezing.

Based on Eq. (26), Fig. 12 [Figure 12: see original paper] reveals the sensitivity of the di- mensionless temperature θ to various influencing parameters.

The base case conditions for Hitec salt are: T_0 = 435 K, u = 0.2 m s^{-1}, l = 3 m, T_∞ = 300 K, ho = 20 W m^{-2} K^{-1}, hi = 217 W m^{-2} K^{-1} (Nu = 4), di = 10 mm, and dt = 1 mm.

Fig. 12(a) illustrates the influence of flow velocity u and pipe length l. The dimensionless temperature exhibits a neg- ative exponential relationship with the reciprocal of flow ve- locity. For $\theta > 1$, a steady flow equilibrium can always be es- tablished. However, when u < 0.05 m s^{-1} leading to $\theta < 1$, flow oscillations will develop irreversibly towards freezing.

For heat transfer pipes operating under low flow conditions, such as in natural circulation, the flow velocity is a critical parameter. Within a certain range, θ shows an approximately linear negative correlation with pipe length, indicating that excessively long heat exchanger tube bundles have a limited safe operating range for specific scenarios.

Fig. 12(b) shows the effects of inlet temperature T_0 and ambient temperature T_∞. The inlet temperature is the only variable demonstrating a significant positive correlation with θ, confirming that increasing the inlet temperature effectively reduces freezing risk. In contrast, the ambient temperature shows much lower sensitivity, with its positive correlation slope nearly 40 times smaller.

Fig. 12(c) presents the influence of the external and inter- nal convection coefficients, ho and hi. Overall, θ has a nega- tive exponential relationship with the external coefficient ho.

Within the plotted range, this appears nearly linear. When θ falls below 1, indicating freezing risk. This is particularly relevant for molten salt-to-air heat exchangers, where ho is a practically adjustable parameter that must not be "over- conservatively" specified. The internal coefficient hi, repre- senting the Nusselt number (Nu), has an extremely low sensi- tivity on θ, implying that for $\theta > 1$, the internal heat transfer does not govern the final flow state.

Finally, Fig. 12(d) examines the impact of inner diameter di and pipe thickness dt. For conventional pipe thicknesses (0.5 mm to 2 mm), the influence is negligible. Similar to flow velocity, a reduction in the inner diameter to 5 mm causes θ to begin following a distinct exponential decay. This obser- (a) Molten salt temperature (b) Pressure drop Fig. 11. Variations of molten salt temperature (a) and pressure drop (b) with the length of pipe. vation reiterates a crucial design consideration: key heat ex- change equipment in MSR decay heat removal systems, such as molten salt/air heat exchangers, often employ long, slender pipes operating for extended periods in environments below the salt' s melting point. If such systems must adapt to special operating modes like natural circulation, the associated reduc- tion in flow rate significantly increases freezing risk, making robust freeze-protection design paramount.

V. CONCLUSION This study employs a multi-scale methodology, integrating a three-dimensional Computational Fluid Dynamics (CFD) model with a lumped-parameter model, to investigate the so- lidification and melting behaviors of molten salt during its flow into horizontal cold pipes. The key conclusions are sum- marized as follows: • Model verification: solidification-melting. The system pressure balance calculation demonstrates that a mushy zone constant of Amush = 5 × 104 produces a simulated penetration distance in satisfactory agree- ment with the experimental results of Zhang et al. This calibrated parameter enables reliable calculation of the additional pressure drop within the Hitec salt mushy zone. • Filling dynamics and phase-change behavior of molten salt in a cold pipe. The simulations depict the complete process from initial flow to final freez- ing. Under pressure-driven conditions, the flow ve- locity responds transiently to the increasing pressure drop caused by solidification. Two regimes are identi- fied: i) Initial filling stage: Solidification initiates near the cold wall. A minimum inlet temperature T0 ex- ists; below this value, the bulk salt temperature drops into the mushy zone during filling, leading to com- plete blockage. ii) Steady-state stage: A sudden in- crease in cooling causes colder fluid to settle at the pipe bottom under gravity, where solid accumulates.

A critical external convection coefficient ho is identi- fied; when exceeded, the available pressure head can- not overcome the sharply rising flow resistance, result- ing in irreversible flow decay and eventual freezing. • Extended model for temperature evolution and freeze-protection criterion. Based on energy conservation, a model for temperature and pressure drop evo- lution is established. For the initial filling problem, the temperature profile aligns with the results of Zeng et al. Entry into the mushy zone induces a sharp pressure rise, indicating blockage risk. Therefore, a key design requirement is to keep the outlet temperature above the liquidus point. By defining a dimensionless tempera- ture θ as the ratio of dissipated to inlet heat, the safety criterion is expressed as θ > 1. • Parameter sensitivity ranking. The expression of θ shows that blockage risk depends on the inlet tem- perature T0, flow velocity, ambient temperature, inter- nal and external convection coefficients (hi, ho), pipe diameter, and wall thickness. Under passive, low- velocity operation of a molten salt/air heat exchanger, the following sensitivity order is observed: increasing T0 or reducing pipe length most significantly lowers risk; raising ambient temperature while reducing ho is also effective; hi and wall thickness exhibit low sensi- tivity. (a) u, l (b) T0, T∞ (c) ho, hi (d) di, dt Fig. 12. Variation of the dimensionless temperature θ under different conditions. (a) u, l. (b) T0, T∞. (c) ho, hi. (d) di, dt.

NOMENCLATURE Greek symbols General symbols pressure drop [Pa] frictional pressure drop [Pa] additional pressure drop [Pa] friction factor [-] pipe length [m] pipe inner diameter [mm] pipe outer diameter [mm] pipe thickness [mm] velocity [m • s−1] velocity vector [m • s−1] Reynolds number [-] Nusselt number [-] inner pipe radius [m] outer pipe radius [m] temperature [K] initial pipe temperature [K] characteristic temperature [K] surrounding temperature [K] time [s] ρ density [kg • m−3] σ surface tension [N • m−1] µ dynamic viscosity [Pa • s] λ thermal conductivity [W • m−1 • K−1] Amush mushy zone constant [-] liquid fraction [-] acceleration of gravity [m • s−2] latent heat of fusion [kJ • kg−1] specific heat capacity [J • kg−1 • K−1] convective heat transfer coefficient inside the pipe [W • m−2 • K−1] convective heat transfer coefficient outside the pipe [W • m−2 • K−1] Subscripts 0 initial condition in inlet pipe cold pipe m molten salt liquid s solid w wall a air st steel [1] G.J. Janz, Molten Salts Handbook. Academic Publisher, New York (1967) [2] Mei, M. D., Chen, X. W., Sun, S. D., Yan, R., Zou, Y., Design and flow field analysis for visualization experiment facility of pebble bed based on molten salt reactor. Nuclear Science and Techniques. 30(3), 51 (2019). doi: 10.1007/s41365-019-0574- [3] ZHANG, D., QIU, S., LIU, C., SU, G, Steady thermal hy- draulic analysis for a molten salt reactor. Nuclear Science and Techniques 19(3), 187–192 (2017). doi: 10.1016/S1001-8042(08)60048-2 [4] Ji, RM., Dai, Y., Zhu, GF. et al., Evaluation of the fraction of delayed photoneutrons for TMSR-SF1. NUCL SCI TECH 28. 135, (2017). doi: 10.1007/s41365-017-0285-9 [5] Wang, Y., Tian, J., Wang, SW. et al., Experimental study on the penetration characteristics of leaking molten salt in the thermal insulation layer of aluminum silicate fiber. NUCL SCI TECH. 55132(9), 92 (2021). doi: 10.1007/s41365-021-00935-6 [6] YAMAMOTO T, MITACHI K, IKEUCHI K, et al., Tran- sient Response of Small Molten Salt Reactor at Duct Blockage Accident. TRANSACTIONS OF THE JAPAN SOCIETY OF MECHANICAL ENGINEERS Series B 71(710), 2537–2544 (2005). doi: 10.1299/kikaib.71.2537 [7] ROSENTHAL M W, KASTEN P R, BRIGGS R B, Molten-Salt Reactors—History, Status, and Potential. Nu- clear Applications and Technology 8(2), 107–117 (1970). doi: 10.13182/NT70-A28619 [8] Xu, B., Zou, Y., Sun, Q., Yu, X., Accident analyses of sta- tion blackout for TMSR-SF2. Nuclear Techniques 40 44, 57–62 (2017). doi: 10.11889/j.0253-3219.2017.hjs.40.100601 [9] Wang, K., Wang, C. Q., Yang, Q., He, Z. Z., Wang, N. X., Uncertainty and sensibility analysis of loss-of-forced-cooling accidents for 150-MWt Molten Salt Reactors. Nuclear Science and Techniques 36(6), 111 (2025). doi: 10.1007/s41365-025- [10] N. Le Brun, G.F. Hewitt, C.N. Markides, Transient freezing of molten salts in pipe-flow systems: Application to the direct reactor auxiliary cooling system (DRACS). Applied Energy 186(1), 56–67 (2017). doi: 10.1016/j.apenergy.2016.09.099 [11] N.E. Bergan, External molten salt solar central receiver test.

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