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Experimental Investigation and CFD Validation of Transient Molten Salt Melting in a Freeze Plug

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Abstract—

Molten Salt Reactors (MSRs) are among the promising Generation-IV nuclear reactor concepts due to their inherent safety characteristics, high thermal efficiency, and capability for passive safety operation. One of the important passive safety components in MSRs is the freeze plug system, which is designed to melt intentionally during abnormal operating conditions and allow the molten salt to drain into passively cooled dump tanks. Accurate prediction of freeze plug melting behavior is essential for ensuring reliable reactor safety performances. In the present study, an experimental investigation and Computational Fluid Dynamics (CFD) validation of transient molten salt melting in a freeze plug are carried out to analyze the thermal and phase change behavior of the system.

Experimental investigations were performed under controlled heating conditions to study the transient melting characteristics of molten salt within the freeze plug configuration. Temperature variation and melting progression were monitored to evaluate the thermal response during the phase transition process. A CFD-based transient numerical model incorporating solidification and melting physics was subsequently developed to simulate the melting behavior of the molten salt.

The numerical predictions were validated against the experimental observations through comparison of thermal response and melting characteristics. The results demonstrated good agreement between the experimental and numerical analyses, indicating the capability of the CFD model to accurately predict transient melting behavior in freeze plug systems. The validated computational model developed in the present work can further be utilized for predictive thermal analysis and future design assessment of molten salt freeze plug configurations. The study contributes toward the development of experimentally validated CFD methodologies for phase change analysis in molten salt thermal systems.

- **Keywords—**Molten Salt,Freeze Plug,Phase Change Heat Transfer,Transient CFD Analysis

I. INTRODUCTION

Molten salt systems are increasingly being utilized in advanced thermal engineering applications such as nuclear reactors, concentrated solar power plants, and high-temperature thermal energy storage systems due to their excellent thermophysical properties, high thermal stability, and efficient heat transfer capability [1], [2]. The safe and reliable operation of such systems requires effective passive safety mechanisms capable of operating under transient thermal conditions. Among the various safety approaches, freeze plugs are widely employed as passive thermal safety components for controlled drainage and emergency protection in molten salt systems [3].

A freeze plug typically consists of a deliberately solidified section of molten salt maintained under controlled cooling conditions. During abnormal operating or overheating conditions, the solidified plug melts automatically, allowing the molten salt to drain safely from the system. Therefore, accurate prediction of the transient melting behavior of freeze plugs is essential for evaluating system safety, operational reliability, and thermal response characteristics [4]. However, the melting process inside a freeze plug involves complex coupled phenomena including transient heat transfer, phase change, conduction, and buoyancy-driven natural convection, making the prediction of melting dynamics significantly challenging [5].

Experimental investigations provide important insight into the thermal response and melting progression of freeze plug systems under transient heating conditions. At the same time, Computational Fluid Dynamics (CFD) has emerged as an efficient numerical tool for analyzing phase change and thermal transport phenomena in molten salt applications [6]. Numerical techniques based on solidification and melting models enable prediction of temperature distribution, melt fraction evolution, and transient melting behavior within thermal systems. Nevertheless, accurate numerical prediction of molten salt melting requires proper validation against experimental observations because of the complex thermo-fluid interactions occurring during the phase transition process [7].

Therefore, the present study focuses on the experimental investigation and CFD validation of transient molten salt melting in a freeze plug system. Experimental observations are utilized to evaluate the accuracy of the developed transient CFD model through comparison of temperature evolution and melting characteristics. The validated numerical model developed in this work can further be extended for predictive analysis of melting behavior and melting time in different freeze plug configurations under varying thermal conditions, thereby reducing the need for repeated experimental investigations and supporting future freeze plug design and thermal safety assessment.

II. LITERATURE REVIEW

Molten Salt Reactors (MSRs) are considered promising Generation-IV reactor systems because of their high thermal efficiency and inherent passive safety characteristics. One of the major safety features in MSRs is the freeze plug system, which enables automatic draining of molten salt into subcritical storage tanks during emergency conditions. The melting and solidification behavior of freeze plugs is strongly governed by thermal gradients, phase change phenomena, material properties, and surrounding boundary conditions.

Over the years, several experimental and numerical studies have been conducted to improve freeze plug design and predict transient melting behavior. Early investigations mainly focused on experimental feasibility, while recent studies have increasingly adopted CFD methods for phase change analysis.

Ref	Authors / Year	Study Focus	Methodology	Findings
[1]	F. van Tuyl (2016)	Safety plug design for MSFR	Design and thermal analysis	Proposed improved freeze plug configuration for passive safety operation
[2]	Chisholm et al. (2020)	Freeze valve system reliability	Review and operational analysis	Discussed design, operating experience, and reliability of freeze valve systems
[3]	A. Makkinje (2017)	Freeze plug grate design	Numerical and design analysis	Investigated geometric optimization of freeze plug grate systems
[4]	P. Swaroop (2015)	Freeze plug design for MSR	Thermal and transient analysis	Studied melting response and passive safety requirements
[5]	ORNL (1962)	Development of freeze plug for MSRE	Experimental investigation	Established feasibility of freeze plug systems and identified effects of plug geometry and cooling
[6]	Serp et al.	MSR overview and perspectives	Review study	Summarized MSR concepts, safety systems, and future prospects
[7]	Ho et al. (2013)	Molten salt reactors	Review and material discussion	Discussed reactor concepts, materials, and operational characteristics
[8]	Ho et al.	Molten-Salt Fast Reactors	Technical overview	Presented MSFR concepts and passive safety features
[9]	Gérardin et al.	Design evolution of MSFR	Reactor design analysis	Discussed improvements in MSFR safety and system configuration
[12]	Kahraman et al.	Freeze valve melting and solidification	Coupled experimental and numerical study	Validated transient melting behavior using experiments and simulations
[15]	Sohal et al. (2010)	Thermophysical properties of molten salts	Property database development	Compiled engineering database for molten salt properties

III. METHODOLOGY

Material selection

Molten salt systems were considered in the current analysis. Selection of the HITEC salt for experimental analysis was based on its lower melting point and better handling properties. In order to evaluate the usefulness of the new method to next generation molten salt reactors (MSRs), predictions of the heat transfer process during melting of the freeze plug were made by means of a numerical analysis using the FLiNaK molten salt. FLiNaK molten salt is known as one of the candidate coolants and fuels for future MSRs.

The thermophysical properties of HITEC and FLiNaK salts used in the present study are summarized in Tables 1 and 2, respectively.

Property	**Value**
Density (kg/m(^3))	1930
Specific heat (J/kg·K)	1560
Thermal conductivity (W/m·K)	0.55
Viscosity (kg/m·s)	0.0015
Latent heat (J/kg)	80,000
Solidus temperature (K)	421
Liquidus temperature (K)	421.5

Table 1: Thermophysical properties of HITEC salt [15].

Property	**Value**
Density (kg/m(^3))	2020
Specific heat (J/kg·K)	1882.8
Thermal conductivity (W/m·K)	0.92
Viscosity (kg/m·s)	0.0029
Latent heat (J/kg)	454,000
Solidus temperature (K)	727.15
Liquidus temperature (K)	728.15

Table 2: Thermophysical properties of FLiNaK salt [15].

Experimental Setup

The experimental investigations were carried out at the Reactor Engineering Division (RED), Bhabha Atomic Research Centre (BARC), Mumbai. A laboratory-scale freeze plug facility was developed to investigate the transient melting behavior of molten salt under controlled thermal conditions.

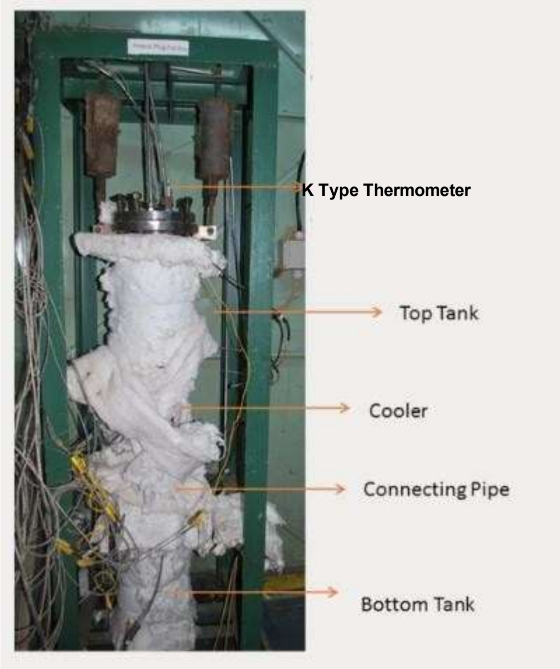

Figure 1:Experimental Setup

The experimental setup consisted of upper and lower molten salt reservoirs connected through a vertical pipe section incorporating the freeze plug region. HITEC salt was used as the working fluid throughout the experiments. The loop was fabricated using SS 316 piping and vessels to withstand elevated operating temperatures and molten salt exposure. An external air-cooling system was integrated around the freeze plug section to maintain the plug in a frozen state during normal operation.

Heating of the molten salt was achieved using mineral insulated (MI) surface heaters installed on both reservoirs, while controlled cooling was provided through a jacketed cooler surrounding the freeze plug region. Multiple K-type thermocouples were positioned throughout the freeze plug assembly, connecting pipe, and tank sections to monitor transient temperature evolution during the melting process.

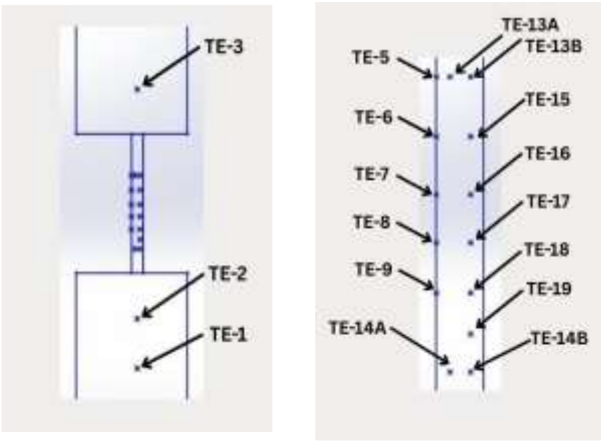

Figure 2: Thermocouple Location

*TE =Tempearture Element

The experimental procedure involved initially operating the cooling system to establish a stable frozen plug within the connecting section. Subsequently, the cooling system was deactivated to initiate melting of the freeze plug. Transient temperature measurements recorded during the melting process were later used for validation of the numerical model developed for the CFD analysis.

The principal operating parameters of the experimental setup are summarized in Table 3

Working fluid	HITEC salt
Line size	1” Sch 80
Loop material	SS 316
Design pressure	2.5 bar(g)
Coolant inventory	6.3 kg
Total heater power	2.5 kW
Design temperature	450 °C
Loop height	1.3 m

Table 3: Experimental setup parameters.

Pilot Experiment

In order to establish the accuracy of numerical methodologies via pilot experiments prior to the principal simulations, the thermal response of a shell structure using ANSYS Fluent's Shell Conduction model was validated against an explicitly defined solid shell structure, modelled under identical boundary conditions. The overall temperature response of both models were nearly identical, thus strongly suggesting the appropriateness of using the ANSYS Shell Conduction Model for all subsequent simulations whilst providing a significant reduction in computational cost.

A mesh independence study was performed using three systematically refined mesh configurations, with the contribution to grid convergence being evaluated using the Richardson's Extrapolation Method and the Grid Convergence Index (GCI) Method [16]. All test meshes demonstrated asymptotic convergence through GCI values of fine test meshes being less than 0.33%, indicating that the associated discretization error is negligible. Due to both results of convergence analysis and computational efficiency, a mesh size of 0.15 mm was implemented for all simulations.

Numerical Setup

Numerical Methodology

A three-dimensional transient CFD model was developed in ANSYS Fluent to investigate the melting behavior of the freeze plug system. The numerical model was based on the experimental configuration developed at the Reactor Engineering Division (RED), Bhabha Atomic Research Centre (BARC), Mumbai, and was used for both validation and predictive analysis.

Geometry and Computational Domain

The computational domain consisted of upper and lower molten salt reservoirs connected through a vertical pipe section incorporating the freeze plug region. Separate numerical configurations were developed for Freeze Plug 1 and Freeze Plug 2 to investigate both experimentally validated and reactor-relevant operating conditions.

Mesh Generation

The computational domain was discretized using a structured hexahedral-dominant mesh with local refinement applied in the freeze plug region to accurately capture steep. Thermal gradients and phase change behavior near the solid–liquid interface. A mesh independence study was performed to ensure numerical accuracy and solution stability.

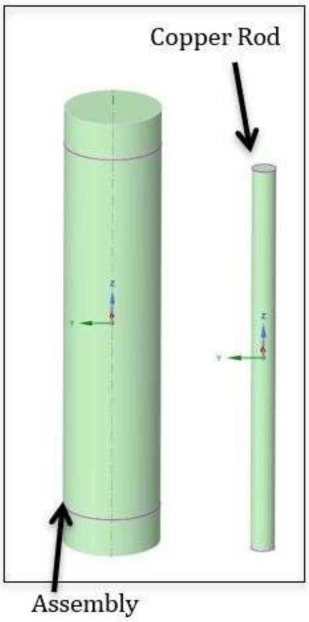

Figure 3:Freeze Plug 1: Geometry

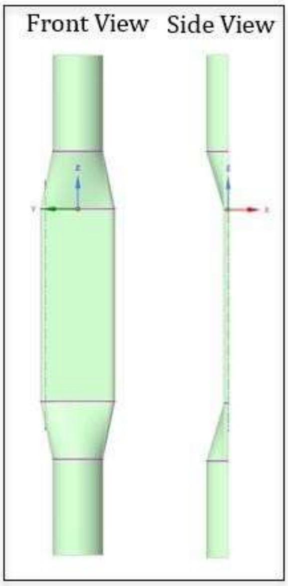

Figure 4:Freeze Plug 2: Geometry

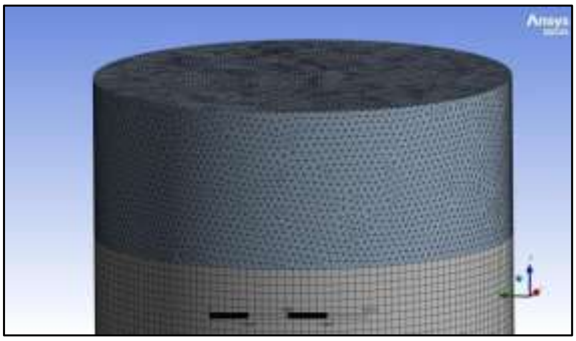

Figure 5:External Meshing

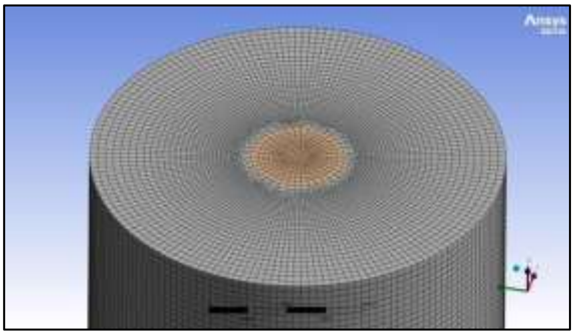

Figure 6:Internal Meshing

Simulations were performed using a pressure-based transient solver. The governing equations of mass, momentum, and energy conservation were solved simultaneously using the finite volume method.

Melting and solidification were modeled using the enthalpy–porosity approach available in ANSYS Fluent. In this method, the mushy zone is treated as a porous medium with permeability dependent on the local liquid fraction. As melting progresses, resistance to fluid motion within the mushy region decreases, allowing continuous transition between solid and liquid phases.

The energy equation included both sensible and latent heat transfer effects to accurately predict the transient melting process. Pressure–velocity coupling was achieved using the SIMPLE algorithm, while second-order discretization schemes were employed for momentum and energy equations. Gravity was enabled in the vertical direction to account for buoyancy-driven natural convection during melting.

Initial and Boundary Conditions

For Freeze Plug 1, the initial temperature distribution was obtained directly from experimentally measured thermocouple data. To achieve smooth spatial variation within the computational domain, the measured temperatures were fitted to continuous temperature profiles before implementation into the numerical model. Based on the resulting thermal distribution, approximately 70% of the freeze plug volume was initially in the solid phase for Case 1, while approximately 75% remained solid for Case 2.

The boundary conditions for Cases 1 and 2 were developed using experimentally measured temperatures at the initiation of melting. Constant temperature boundary conditions were applied to the upper and lower reservoir sections. Heat losses from the freeze plug surface were represented using an equivalent heat transfer coefficient accounting for the combined effects of natural convection and radiation heat transfer. Conjugate heat transfer was imposed at the copper–salt interface to accurately model thermal interaction between the solid copper insert and molten salt domain. The remaining external surfaces were considered adiabatic to isolate the effect of imposed thermal gradients.

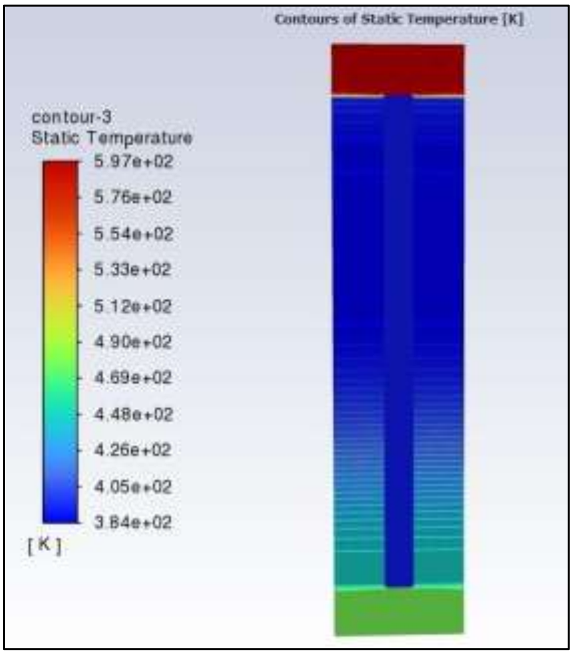

Figure 7:Initial Temperature Contour (Case 2)

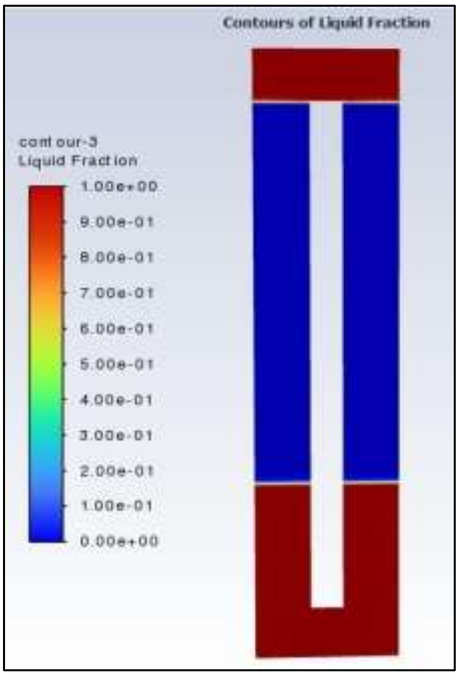

Figure 8:Initial Liquid Fraction (Case 2)

For Freeze Plug 2, a predictive analysis representative of advanced molten salt reactor operating conditions was performed using

FLiNaK molten salt. The upper and lower pipe sections were maintained at approximately 730 K to establish fully molten conditions, while the freeze plug region was initialized at approximately 573 K to maintain a distinct solidified zone. Constant temperature boundary conditions representing reactor operating conditions were applied to the surrounding wall regions and freeze plug neck section.

Solver Settings and Monitoring

Transient simulations were performed using a time step size of 0.5 s. Strict convergence criteria of (10e-8) were maintained for all governing equations to ensure numerical stability and solution accuracy during phase change calculations.

Temperature monitoring locations within the computational domain were defined corresponding to the experimental thermocouple positions for validation purposes. In Freeze Plug 2, additional monitoring points were positioned along the axial direction of the freeze plug to evaluate thermal gradients, liquid fraction evolution, and melting front progression during the simulation.

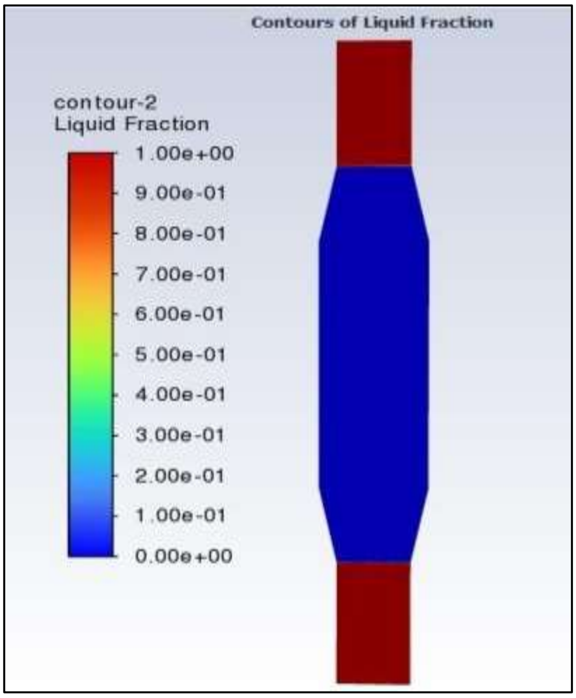

Figure 9:Initial Liquid Fraction (freeze plug 2)

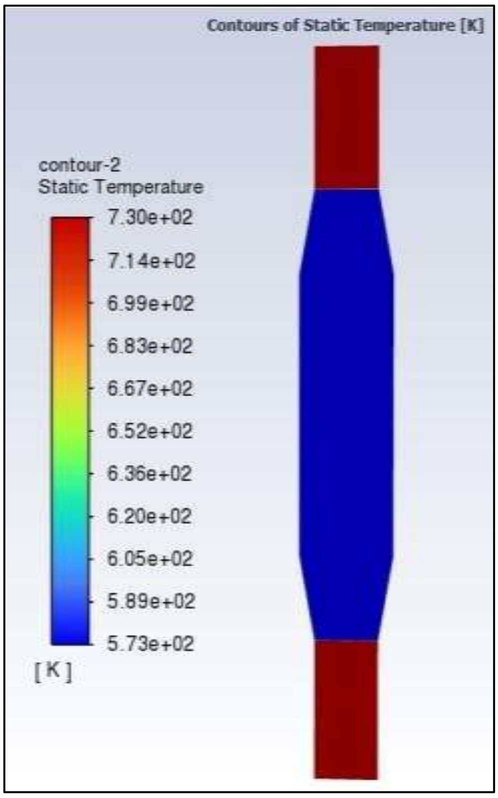

Figure 10:Initial Temperature Contour (freeze plug 2)

Set Up Validation

The numerical model was validated against experimentally measured transient temperature data obtained from thermocouples positioned throughout the freeze plug assembly. Good agreement between experimental and numerical results confirmed the capability of the developed CFD methodology to predict freeze plug melting behavior under both laboratory-scale and reactor-relevant operating conditions.

V. RESULTS AND DISCUSSION

Validation of Numerical Model

Experimental temperature measurements from the HITEC molten salt freeze plug system were used to validate the CFD model developed using the enthalpy–porosity method in ANSYS Fluent. The predicted temperature histories showed good agreement with thermocouple measurements throughout the transient melting

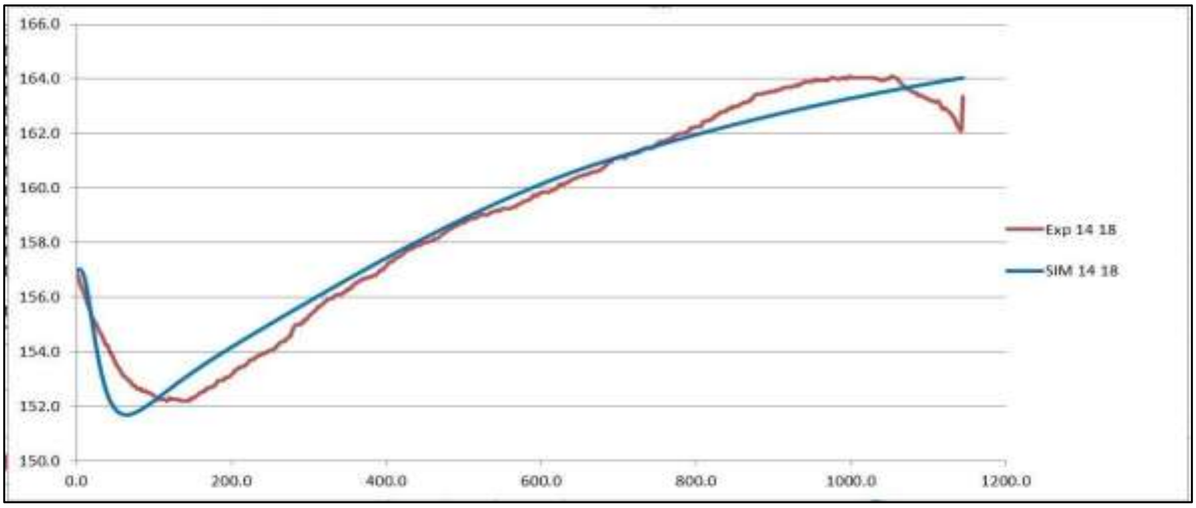

Figure 11: Comparison of experimental and numerical average temperature response for thermocouples TE-14 and TE-18 during transient melting of Freeze Plug 1 (Case 1）

process, confirming the capability of the numerical model to capture phase change behaviour and thermal evolution accurately.

For Freeze Plug 1, the experimentally observed melting times were approximately 1144 s for Case 1 and 682 s for Case 2. In both cases, the numerical model successfully reproduced the initial transient temperature decrease caused by internal thermal redistribution immediately after cooling removal, followed by gradual reheating due to heat transfer from surrounding molten salt and heated walls.

For Case 1, thermocouples TE-14 and TE-18 showed close agreement between experimental and numerical results, with overall deviation remaining below 2%.

Similarly, for Case 2, comparisons at thermocouple pairs TE-14 & TE-19, TE-14 & TE-16, and TE-15 & TE-16 showed deviations below 1.5%. Minor discrepancies were attributed to thermocouple response delay, unavoidable ambient heat losses, and simplifications adopted in the computational model.

Liquid fraction and temperature contours further confirmed that melting initiated near the heated wall regions and gradually progressed toward the colder core. At later stages, most regions approached fully molten conditions while limited solidified zones remained near the central core because of continued latent heat absorption. Overall, the close agreement between experimental observations and CFD predictions demonstrates that the developed numerical methodology provides a reliable framework for analysing transient melting behaviour in freeze plug systems.

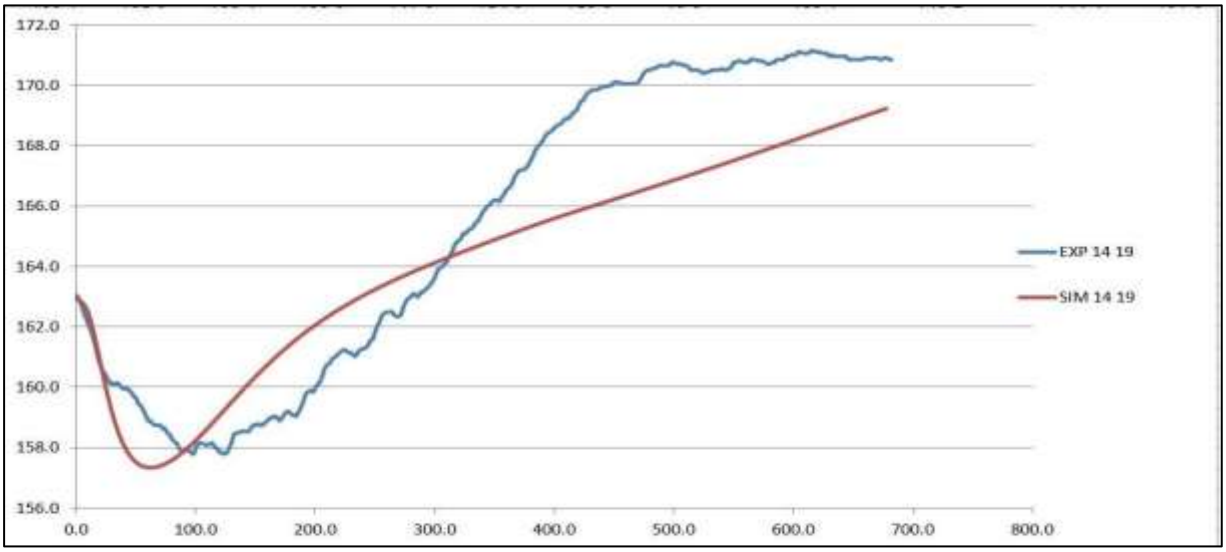

Figure 12: Comparison of experimental and numerical average temperature response for thermocouples TE-14 and TE-19 during transient melting of Freeze Plug 1 (Case 2).

Freeze Plug 1: Experimental Validation

The transient melting behaviour of Freeze Plug 1 was investigated experimentally and numerically using HITEC molten salt. The CFD model accurately captured the thermal evolution and melt front progression during both experimental cases.

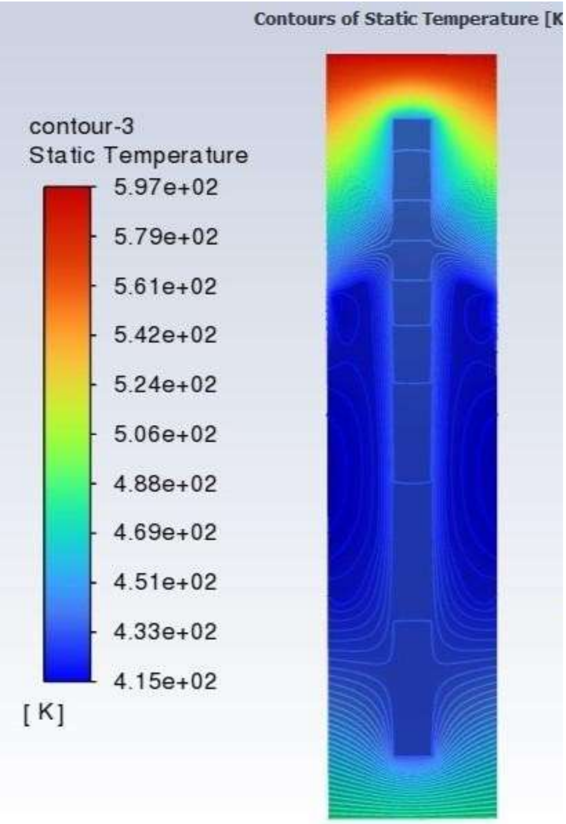

Figure 13:Temperature Contour at 682 s (Case 2)

In Case 1, the freeze plug melted completely in approximately 1144 s. The temperature initially decreased from nearly 157 degrees Celsius because colder regions within the plugcontinued absorbing heat after cooling removal. Subsequently, gradual reheating occurred due to heat transfer from the surrounding molten salt and pipe walls. Experimental and numerical temperature profiles showed excellent agreement, with deviations generally below 2%.

In Case 2, complete melting occurred faster, at approximately 682 s, because of reduced thermal resistance and modified thermal conditions. Similar transient behaviour was observed, consisting of initial cooling followed by steady reheating. Numerical predictions closely matched experimental measurements at all thermocouple locations, with deviations remaining within acceptable engineering limits.

Liquid fraction contours for both cases showed that melting progressed non-uniformly from the heated wall regions toward the colder central core. Temperature contours also confirmed that wall-adjacent regions experienced higher temperatures, while the core remained comparatively cooler because a significant portion of thermal energy was consumed as latent heat during phase transition.

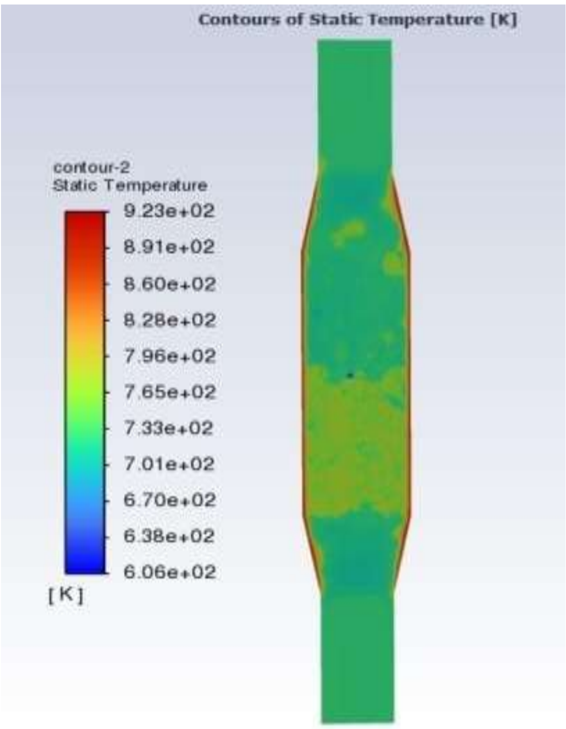

Figure 15: Temperature Contour at 280 s (freeze plug 2)

Predictive Analysis of Freeze Plug 2

Following validation, predictive simulations were performed for Freeze Plug 2 using FLiNaK molten salt under reactor-relevant operating conditions. Compared to Freeze Plug 1, substantially faster melting behaviour was observed because of higher operating temperatures and stronger thermal gradients.

Monitoring points located near heated boundaries exhibited early temperature rise, while points within the colder solidified core remained nearly constant during the initial stages because supplied thermal energy was primarily consumed in latent heat absorption. Melting progressed both radially and axially, and complete melt-through occurred at approximately 140 s.

Temperature contours indicated that heat transfer occurred predominantly from the heated walls toward the freeze plug centre. Near the final stages of melting, a sudden temperature rise was observed at several monitoring points after local phase change completion, indicating the transition from latent heat absorption to sensible heating.

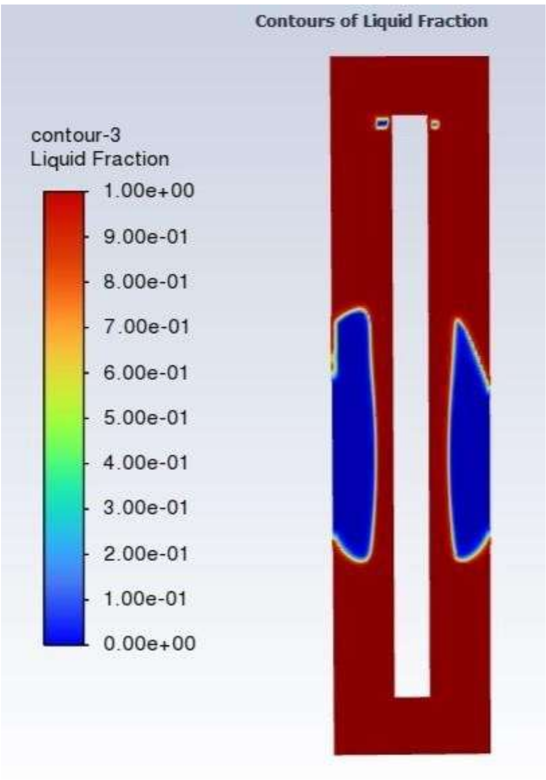

Figure 14:Liquid Fraction at 682 s (Case 2)

Discussion

The results demonstrate that the developed CFD model successfully predicts transient melting behaviour in freeze plug systems under both experimentally validated and reactor-relevant conditions. The enthalpy–porosity approach accurately captured the initial cooling stage, gradual reheating, melt front progression, and final melt-through process.

The melting behaviour was governed mainly by transient heat conduction and latent heat absorption. During the early stages, most supplied thermal energy was consumed in

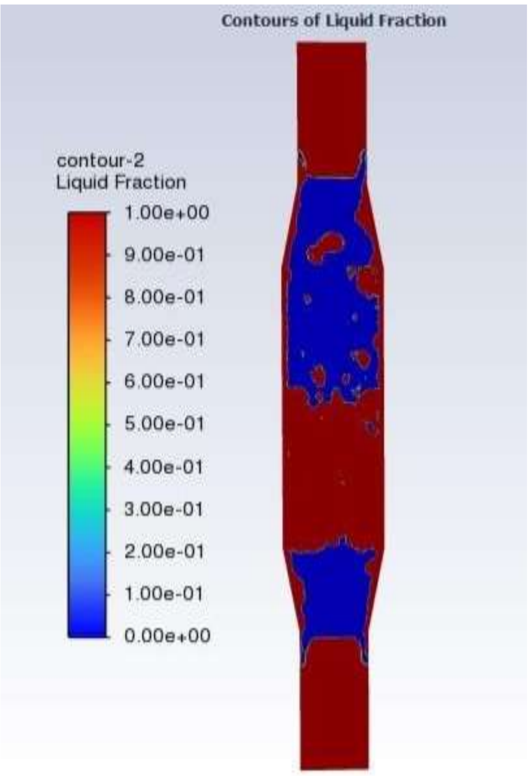

Figure 15: Liquid Fraction Contour at 280 s

overcoming latent heat of fusion, resulting in relatively slow temperature rise. After local melting completion, sensible heating dominated and temperatures increased rapidly.

The results also showed strongly non-uniform melting behaviour, where regions near heated boundaries melted earlier because of stronger thermal gradients, while the colder core melted more slowly because of higher thermal inertia and continuous latent heat requirements.

Comparison between Freeze Plug 1 and Freeze Plug 2 highlighted the strong influence of molten salt properties, thermal boundary conditions, and operating temperature on melting response time. While Freeze Plug 1 required several hundred seconds for complete melting, the FLiNaK-based Freeze Plug 2 melted completely within approximately 140 s.

Overall, the close agreement between experimental measurements and CFD predictions confirms that the developed numerical methodology can serve as a reliable tool for future analysis and design of freeze plug-based passive safety systems for molten salt reactor applications.

Engineering Implications

The findings of this study support the conclusion that freeze plug performance is strongly affected by boundary conditions imposed by thermal conductivity; thermophysical properties of molten salts; and starting thermal distributions.

Additionally, the computational fluid dynamics (CFD) framework validated all physics involved in capturing the interdependent relationships between heat transfer and phase change. Therefore, the CFD validation provides a novel and robust tool to analyze passive safety systems of molten-salt reactors.

Furthermore, results from the prediction of FLiNaK freeze plug performance indicate that selecting an appropriate material and utilizing a suitable thermodynamic design could effectively reduce the freeze plug melting response time. These findings have profound implications for the design of emergency drainage systems to provide the reactor with rapid, predictable melt-through to ensure safety.

Table 4:Quantitative comparison between experimental and numerical results

Parameter	Experiment	Simulation	Deviation
Initial average temperature (TE-14 & TE-18)	156.9◦C	157.0◦C	< 0. 1%
Minimum average temperature	152.2◦C	151.7◦C	0.30%
Average heating rate (150–700 s)	0.016 ◦C/s	0.017 ◦C/s	6.00%
Final average temperature	163.5–164.0◦C	164.0◦C	< 0. 6%
Initial TE-18 temperature	140.0◦C	140.0◦C	< 0. 1%
Minimum TE-18 temperature	134.7◦C	135.4◦C	< 0. 6%
TE-18 heating rate (150–1000 s)	0.019 ◦C/s	0.014 ◦C/s	26.00%
Final TE-18 temperature	151.0◦C	147.5◦C	~2.0%

VI. CONCLUSION

A combined numerical and experimental investigation was performed to evaluate the transient melting characteristics associated with freeze plug systems used as passive safety devices in molten salt reactors. In this study laboratory experiments utilizing HITEC molten salt were performed to obtain temperature evolution data as the plug was melting. Additionally, a 3D CFD model was developed using the enthalpy-porosity method to simulate the phase change behavior of the freeze plug.

The results obtained from the numerical model compared well with the temperature measurements from the experimental work, as the majority of the 2% deviation occurred in areas of rapidly changing temperature. The results also indicated that the melting process within a freeze plug is characterized by transient heat conduction, local latent heat absorbance, and gradual progression of the melt front.

Prior to the sustained heating and melting of the freeze plug, an initial cooling stage due to thermal redistribution was identified.

The results of a numerical investigation of an FLiNaK freeze plug melting showed that melting occurred at a more rapid rate at elevated thermal conditions compared to normal operating conditions; complete melting occurred within 140 seconds, demonstrating the effect that thermal boundary conditions and molten salts have on the passive safety response time.

It was concluded that CFD simulations combined with experimental verification will provide an effective and efficient means of designing freeze plugs, evaluating the safety of freeze plugs, and optimizing freeze plug performance in future molten salt reactors.

VII. FUTURE SCOPE

Future studies will build upon the existing methodology developed in this study to include assessing molten salt flow due to a gravity-driven condition after a freeze plug fails, as well as the drainage behavior of post-melting materials in addition to the melting behavior of materials.

By coupling the melting and discharging processes, it is hoped that a more complete evaluation of how well a passive safety system works will be produced.

Other areas identified for improvement include considering physical properties that are dependent on temperature, accounts of how radiation affects heat transport, and enhanced modelling of turbulence where appropriate. Additional understanding of the evolving melt front can also be achieved through the use of experimental techniques such as infrared thermography, ultrasonic sensors, and/or the use of a denser temperature measurement system.

In addition, the use of parametric studies of freeze plug geometry, cooling configuration (method of cooling), and other types of molten salts, will improve the development of an optimal plan for design. These studies include those that evaluate the long-term performance of materials exposed to repeated freeze-thaw cycles and how these conditions affect the integrity and durability of structures designed to function in a reactor environment.

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