DOI: https://doi.org/10.14311/TPFM.2025.019

MOLTEN SALT FREEZE VALVE OPERATION: EXPERIMENTAL STUDY

T. Korinek [1], M. C. Kahraman [2], J. Skarohlid [1], R. Skoda [1,3]

[1] **Department of Power Systems 4.0, Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague, Jugoslavskych partyzanu 1580/3, 160 00 Prague, Czech Republic**

[2] **Department of Energy Systems Engineering, Faculty of Engineering, Yalova University, Merkez, Yerleşkesi Çınarcık yolu üzeri, 772 00 Yalova, Türkiye**

[3] **Department of Power Engineering, Faculty of Electrical Engineering, University of West Bohemia, Univerzitni 26, 301 00 Pilsen, Czech Republic**

Abstract

A freeze valve is a unique device for pipe sealing in molten salt applications. The present study focuses on the experimental investigation of freeze valve operations, with particular interest in opening time for different variations in the geometry of the freeze valve. The geometry of the freeze valve was based on the design used in the Oak Ridge Molten Salt Reactor Experiment. The tested freeze valves varied on the thickness of the flattened part. An experimental apparatus was built to test the freeze valves. Good repeatability of experimental tests was achieved with a standard deviation less than 5 % of the opening time. Results from experiments indicated that a decrease in the flattened part thickness led to an increase in opening time.

Keywords: molten salt, freeze valve, experiment, hitec.

1 Introduction

Molten salts have a variety of applications, such as thermal storage [1], concentrated solar plant [2], and molten-salt nuclear reactors (MSR) [3]. The salts' high boiling point at atmospheric pressure does not require enormous pressure to operate at higher temperatures. However, molten salts are quite corrosive, and their relatively high melting temperature leads to a high demand on the performance of used components. Further, a relatively high melting point might lead to damage of moving components in the case of unintentional solidification. This significantly increases the requirements for safety, reliability, and maintenance of each component.

A relatively high melting point led to the development of a unique device called a freeze valve, which serves as a pipe sealing [4]. The freeze valve is based on active cooling of a specific part of the valve in order to form a frozen plug that seals the pipeline. When the cooling is switched off, the frozen plug melts, and the pipeline is unsealed. Heat for melting the frozen plug is either provided by an additional heater or in the case of a molten salt reactor, by decay heat from nuclear fuel.

The freeze valve was used as a passive safety feature in Oak Ridges Experimental Molten Salt Reactor (MSRE) [5, 6]. MSRE had nuclear fuel dissolved in a fluoride salt. The freeze valve served to ensure the safe shutdown of the reactor in case of a station blackout scenario (SBO). During SBO no electricity is supplied and cooling of the valve automatically shuts down, which leads to the melting of the frozen plug. After the frozen plug has been melted, the pipeline from the reactor to the dump tanks opens, and the fuel salt is safely transferred to the dump tanks, where the fuel salt is passively cooled.

The majority of recent studies focused on numerical simulations of freeze valves under various operating conditions [7, 8, 9, 10]. Apart from MSRE, several experimental studies were performed with molten salt freeze valves. Numerical and experimental work with FLiNaK salt revealed the influence of the flattened part length on the axial length of the salt plug [11]. The influence of the finned freeze valve on cooling performance was experimentally and numerically studied, revealing an effective operating temperate 530-600 °C [12]. Europen MSR design led to the development of two experimental facilities served for the testing of the freeze valve within the European project SAMOFAR [13], where a new freeze valve design was introduced. The new design of the freeze valve was an internally cooled copper disk surrounded by heating blocks and thermal insulation.

The present study focuses on experimental investigation of molten salt freeze operation; solidification and melting of frozen plug. The freeze valve was based on the MSRE freeze valve design and several geometry variants were tested on experimental apparatus in order to reveal behavior during the formation and melting of the frozen plug.

2 Experimental setup

Research on molten salt freeze valves was performed on an experimental stand specifically built for freeze valve testing. The experimental stand had several components, including a high-temperature furnace, salt cartridge, cooling blanket, tested freeze valve, heated pipelines, additional heating blocks, and nitrogen cover gas system. The experimental stand is shown in Fig. 1.

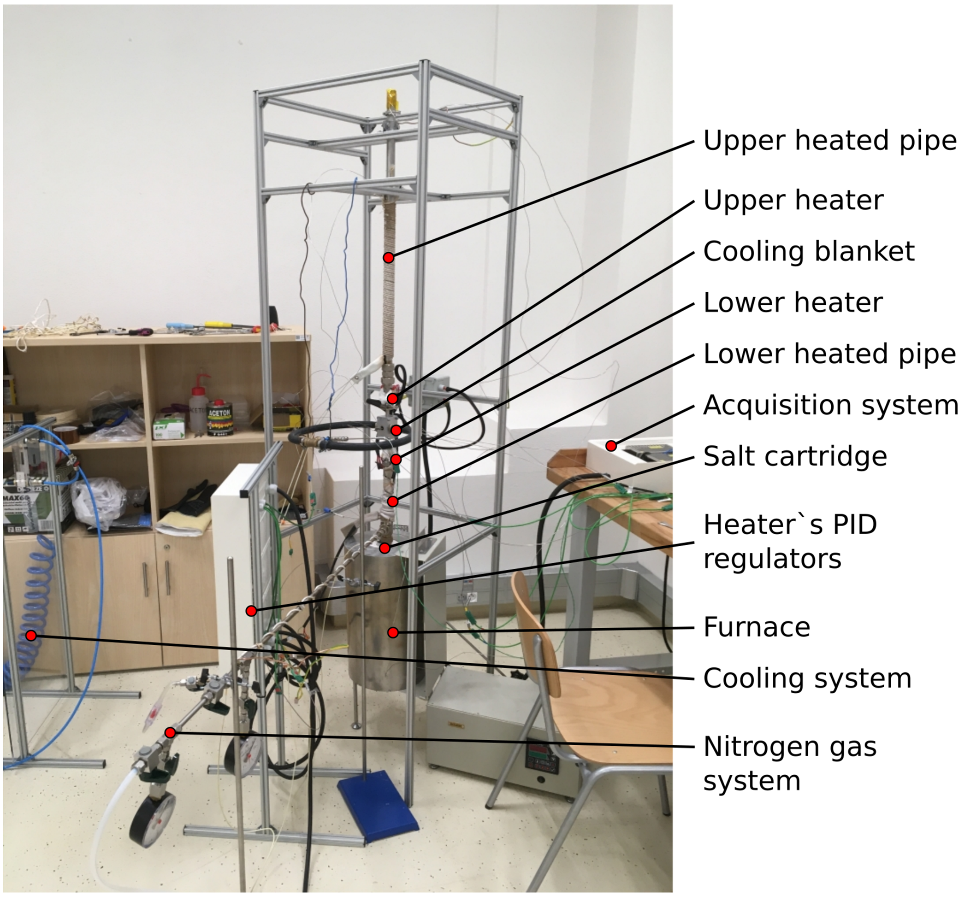

Figure 1: Experimental stand for molten salt freeze valve testing.

The freeze valve was based on the MSRE freeze valve design, a pipe with a flattened part that was externally cooled to form a frozen plug inside the pipe. The geometry of the tested freeze valve and position of thermocouples is shown in Fig. 2. Three geometry variants were tested, which varied with the thickness of the flattened part H. The geometry dimensions of the freeze valve variants are shown in Table 1.

Table 1: Dimensions of freeze valve variants

Variant name	D	L	H	W	l	T
FV-4.7	12 mm	250 mm	4.7 mm	16.3 mm	20 mm	10 mm
FV-6.3	12 mm	250 mm	6.3 mm	15.6 mm	20 mm	7 mm
FV-7.5	12 mm	250 mm	7.5 mm	15.0 mm	20 mm	7 mm

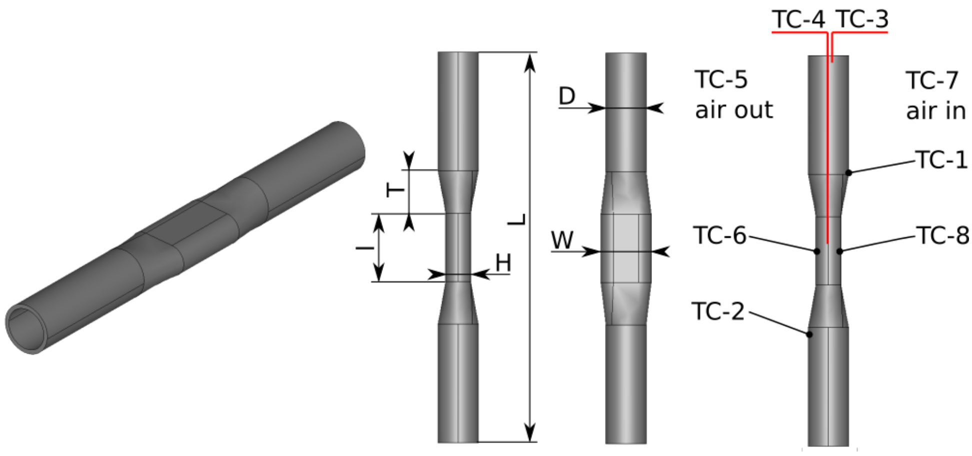

Figure 2: Freeze valve geometry and location of thermocouples.

The tests were performed with ternary nitrate salt mixture Hitec. The composition of the Hitec salt is 53 %wt KNO3, 40 % NaNO2 and 7 %wt NaNO3 and the thermophysical properties are shown in Table 2.

Table 2: Hitec salt properties.

Melting temperature	142 °C .
Density at 200 °C	2107 kg/m^3.
Heat Capacity at 200 °C	1560 J/kgK.
Thermal conductivity at 200 °C	0.38 W/mK.
Dynamic viscosity at 200 °C	3.17 mPas.

3 Test procedure

The experiments were carried out in two consecutive stages. In the first stage, molten salt was solidified inside the freeze valve from the frozen plug. The second stage involved the melting of the freeze plug due to heat from the heating system (heater blocks and heated pipes). All experiments were conducted in a similar laboratory setting with an initial temperature of 23°C. Start of the experiment was performed by setting furnace temperate t 300 °C to quickly achieve the melting temperate of test (142°C). To prevent sudden solidification of the molten salt in the testing section, the lower and upper pipes were heated to 235 °C, and the heating blocks placed in the vicinity of the cooling blanket were set to 235 °C. Rock wool insulation was applied to all pipes in the system to minimize heat loss. Four K-type thermocouple sensors were placed on the outer surface of the freeze valve, and two thermocouples were placed inside the freeze valve (in the middle and at the end of the freeze valve). In addition, two thermocouples were used to measure the inlet and outlet temperatures.

Before starting the experiment, the salt level in the reservoir and the integrity of all connections were checked. The heaters were then activated and adjusted to the specified temperatures. Additionally, the nitrogen gas system used for salt transfer from the cartridge to the testing section was equipped with tape heaters (set to 120 °C) to prevent solidification of the salt inside the cartridge.

After initial heating, the molten salt was pressurized in the reservoir and directed to the testing section. This pressurization process was repeated three times to ensure that the salt reached the plug region. The cooling system was then activated for 1,000 seconds with a flow rate of 300 liters per minute (LPM) to form the frozen plug inside the valve. Thermocouple readings were used to confirm the formation of a solid plug. A temperature peak was observed after a successful pressurization. Once the plug was formed, the experiment proceeded to the melting phase. This phase started with the deactivation of the cooling system. Partial melting of the plug was monitored through temperature variations, and the complete opening was confirmed by observing the flow of gravity-driven molten salt flow through the freeze valve region. The complete experimental procedure for freeze valve testing is depicted in Fig. 3.

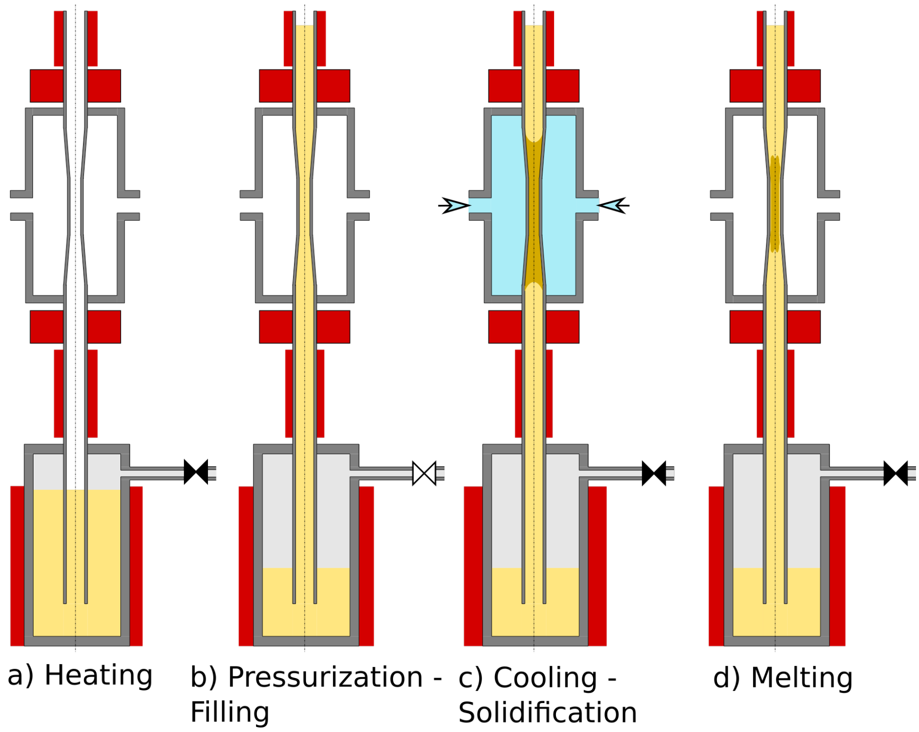

Figure 3: Procedure of freeze valve experimental testing.

4 Results

The timeline of the experiment is depicted in Fig. 4, where readings from eight thermocouples are shown. In order to prevent unintentional solidification during the salt transfer from the salt cartridge to the testing section, the pressurization/filling was started after the temperature in the testing section (from all six thermocouples) was higher than the salt melting temperature. This process took two hours. The successful transfer of the salt was evinced by temperature peaks with the following temperature increase in the testing section. The temperature increase was due to an increased heat transfer from heat convection. On the contrary, unsuccessful filling resulted in a temperature decrease in the test section. After successfully filling, the cooling was switched on, leading to a rapid temperature decrease and the formation of a frozen plug (salt solidification inside the freeze valve). The cooling was switched off after 1000 seconds, which resulted in an immediate increase in temperature on the outer surface of the freeze valve and inside the freeze valve. On the contrary, the temperature inside the pipe above the freeze valve was decreasing. This was caused by heat exchange between the cold region where the frozen plug was located and the hot region above the plug where the salt was still in liquid form. The melting of the frozen plug had three distinct phases. The first phase was a linear temperature increase in the test section until a temperature of 80 $^\circ$ C was reached. After that, the second phase started, which had a more rapid temperature increase due to an increased amount of liquid salt inside the freeze valve and better flow mixing between cold and hot regions. The second phase ended when the temperature inside the freeze valve reached the melting temperature. The third stage was a complete melting of the plug and opening of the freeze valve.

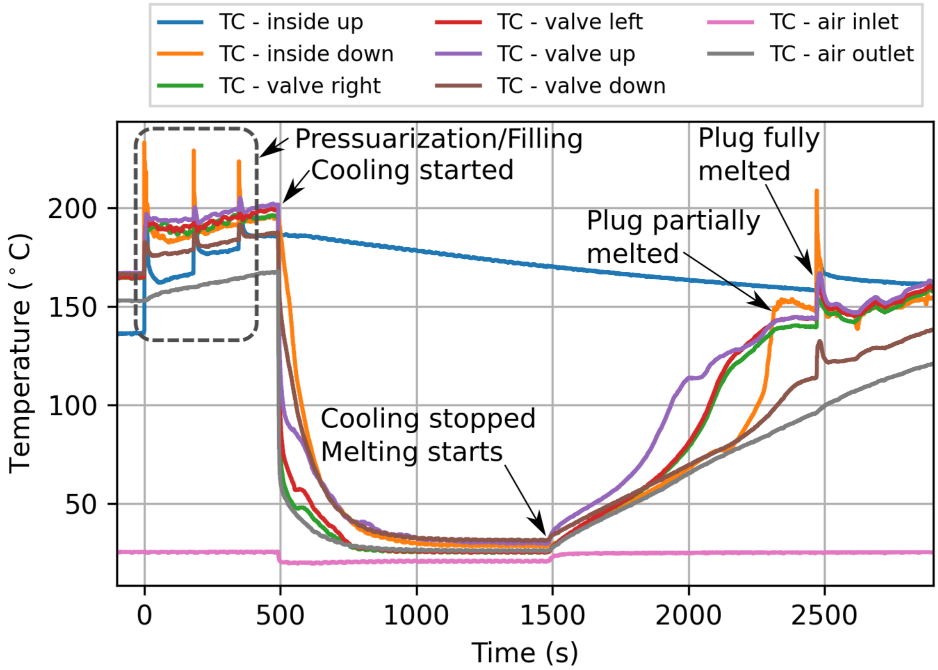

Figure 4: Temperature evolution during experimental procedure for the valve FV-6.3.

The solidification and melting process observed from the temperature sensor placed in the freeze valve is shown in Fig. 5 for each tested freeze valve geometry. The solidification process (formation of frozen plug) was almost identical for all tested geometries, and only a minor difference was observed during the first 100 seconds of the cooling process. However, the geometry significantly influenced the melting of the frozen plug. Previously described phases of plug melting were visible for all geometries, and temperatures depicting each phase remained the same, but the time to reach it differed. An increase in the thickness of the valve flattened part led to a decrease in the time of each melting phase. To conclude, a smaller thickness of the valve's flattened part results in a longer melting time (freeze valve opening time).

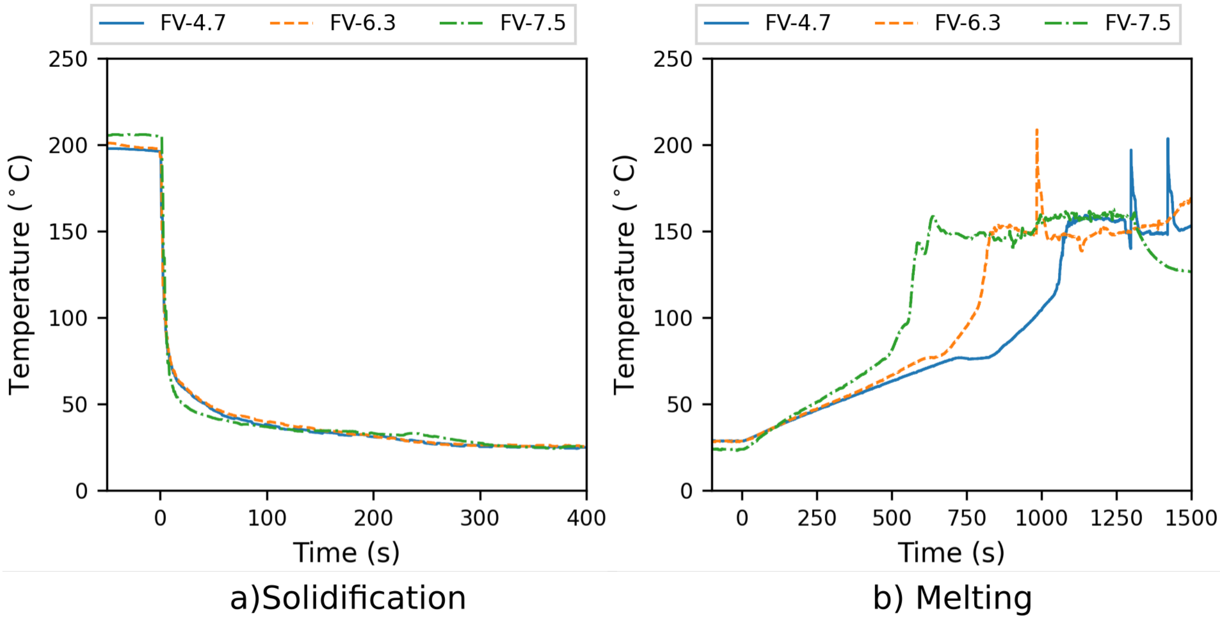

Figure 5: Solidification and melting process for different freeze valve geometry.

The difference in melting time could be caused by different cooling due to a different cooling performance. The decrease in the valve flattened part thickness led to an increase in the width of the flattened part, which resulted in a larger surface where heat transfer occurs. However, the smaller thickness leads to a smaller amount of salt in the freeze valve, and no significant difference in temperature was observed during the formation of the frozen plug. A difference in cooling performance could be observed from the temperature difference between the air inlet and the air outlet. Fig. 6 shows the air temperature difference for each tested geometry. The evolution of temperature difference is identical after the cooling started, even when the initial temperature difference (before cooling) was not identical. We assume that the amount of salt undergoing solidification was the same for all tested geometry. Thus, a small valve flattened part thickness led to a larger amount of frozen salt above and below the flattened part.

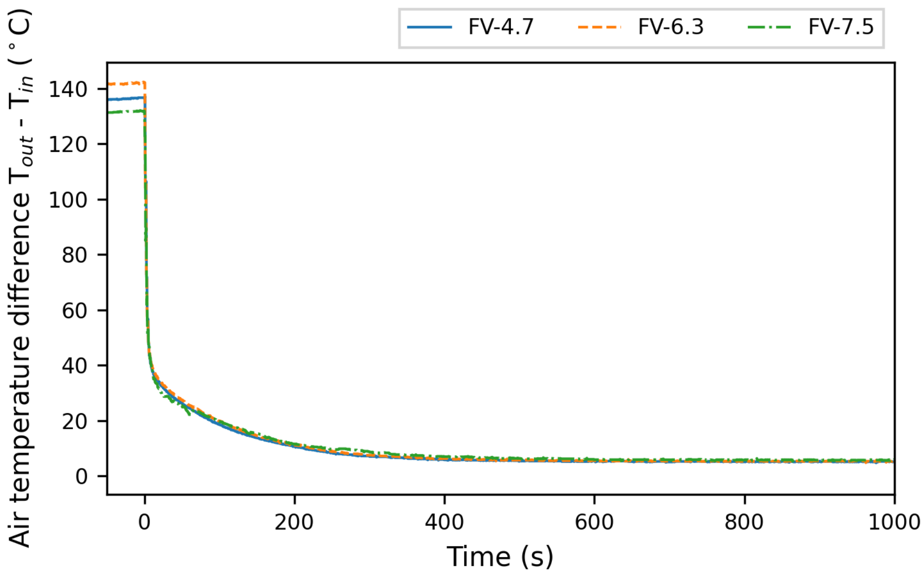

Figure 6: Comparison of cooling air temperature difference.

The melting time obtained from the experiments carried out is shown in Fig. 7 and Table 3. A smaller flattened part thickness resulted in a higher melting time and higher standard deviation.

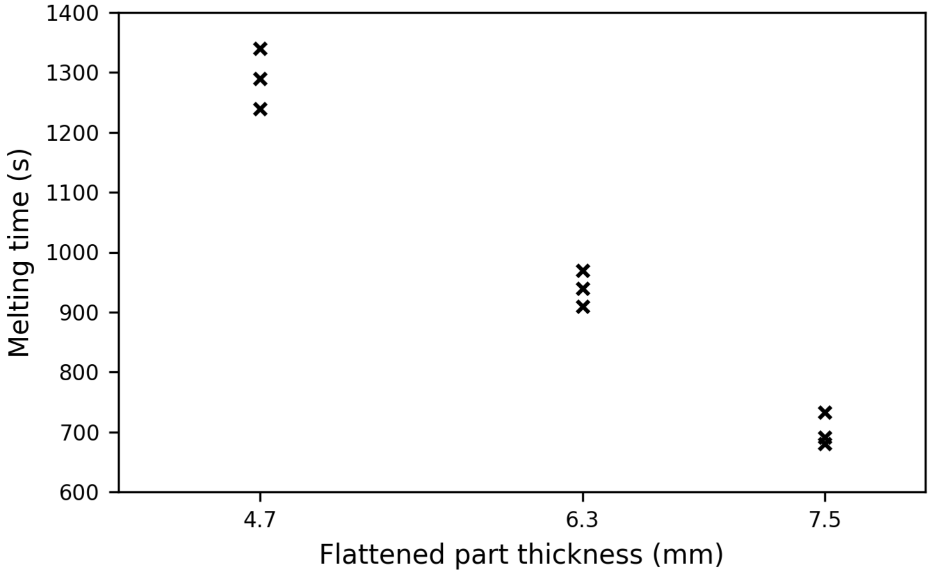

Figure 7: Comparison of melting times obtained from conducted experiments.

Table 3: Overview of melting times.

Geometry	Melting time
FV-4.7	1290±42
FV-6.3	940±25
FV-7.5	701±23

5 Conclusions

The experimental investigation of the operation of the molten salt freeze valve revealed critical insights into the behavior of the freeze valve geometries during the solidification and melting processes of molten salts. The study demonstrated that the thickness of the flattened part of the valve significantly affects the melting time, with thinner flattened parts resulting in longer melting times. This finding highlights the importance of geometry in optimizing valve performance for molten salt applications, where reliability and safety are the main concerns. The results contribute valuable data to the development of advanced molten salt systems, including nuclear reactors and thermal storage systems. Future studies could explore the integration of numerical models with experimental data to refine design parameters and further improve operational efficiency.

Acknowledgment

The financial support for the present project was provided by the Technological Agency of the Czech Republic grant no.TS01030136.

References

[1] Bauer, T., Odenthal, C. & Bonk, A.: Molten salt storage for power generation. *Chemie Ingenieur Technik*, vol. 93, no. 4, (2021): pp. 534–546.

[2] Zhang, H., Baeyens, J., Degrève, J. & Cacères, G.: Concentrated solar power plants: Review and design methodology. *Renewable Sustainable Energy Rev.*, vol. 22: (2013), pp. 466–481.

[3] Forsberg, C. W., Peterson, P. & Pickard, P.: Molten-salt-cooled advanced high-temperature reactor for production of hydrogen and electricity. *Nuclear Technology*, vol. 144, no. 3: (2003) pp. 289—302.

[4] Chisholm, B. M., Krahn, S. L. & Sowder, A. G.: A unique molten salt reactor feature - The freeze valve system: Design, operating experience, and reliability. *Nuclear Engineering and Design*, vol. 368: (2020) 110803.

[5] Richardson, M.: Development of freeze valve for use in the msre. *Oak Ridge National Laboratory Report*, ORNL-TM-128: (1962).

[6] Richardson, M.: Freeze valves, msre systems and components performance. *Oak Ridge National Laboratory Report*, ORNL-TM-3039, (1973): pp. 341–355.

[7] Tartaglia, D., Cammi, A., Introini, C. & Lorenzi, S.: Numerical modeling and simulation of melting phenomena for freeze valve analysis in molten salt reactors. *Nuclear Science and Engineering*, vol. 197, no. 12: (2023) pp. 3058–3081.

[8] Kahraman, M. C. & Lule, S. S.: Numerical investigation of behaviour of small modular molten salt reactor freeze plug under various reactor operating conditions. *Numerical Heat Transfer Applications*, vol. 85, no. 11: (2023) pp. 1–20.

[9] Pater, M., Kaaks, B., Lauritzen, B. & Lauthouwers, D.: A numerical benchmark for modelling phase change in molten salt reactors. *Annals of Nuclear Energy*, vol. 194: (2023) 110093.

[10] Pater, M., Bahl, Ch. R. H., Klinkby, E. B., Schofield, A. V. & Lauritzen, B.: Computational fluid dynamics model for a C-shaped sodium hydroxide freeze valve. *International Journal of Heat and Fluid Flow*, vol. 103: (2023) 109202.

[11] Li, Q., Tang, Z. & Fu, Y.: Preliminary Study of the Use of Freeze-Valves for a Passive Shutdown System in Molten Salt Reactors. In *Proceedings of the ASME/NRC 2014 12th Valves, Pumps, and Inservice Testing Symposium NRC2014*, Rockville, Maryland, USA, 2014.

[12] Jiang, X., Lu, H., Chen, Y., Fu, Y. & Wang, N.: Numerical and experimental investigation of a new conceptual fluoride salt freeze valve for thorium-based molten salt reactor. *Nuclear Science and Techniques*, vol. 31, no. 16, (2020).

[13] Giraud, J., Ghetta, V., Rubiolo, P. & Tano Retamales, M.: Development of a cold plug valve with fluoride salt. *EPJ Nuclear Science and Technologies*, vol. 5, no. 9, (2019).