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The Design of the Scaled-down Experimental Device for Molten Salts

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Abstract - An intermediate heat transfer system (IHTS) with a molten salt working medium is one of the proposed concepts of the future DEMO fusion power plant. Molten salts are currently used for concentrating solar power plants, heat accumulation and energy storage, and in some chemical processes. Moreover, there are proposed as a coolant and fuel carrier in the future Generation IV fission nuclear power plants. Despite its current use in some fields, many questions remain unanswered. To study them, technically, organizationally, and financially demanding experimental devices are required. In order to avoid this demandingness, the possible use of scaled-down experimental devices is studied. Such an experimental device working with thermal oil at lower temperatures with similar behavior to molten salts called SHAKER is being built in the laboratories of the Faculty of Mechanical Engineering of Czech Technical University in Prague. The design of the afford mentioned scaled-down experimental device is presented in this paper.

***Keywords*:** scaled-down experiment, molten salts, thermal oil, fusion power plant, DEMO, intermediate heat transfer system

1. Introduction

The future demonstration fusion power plant DEMO [1], [2] is planned to operate in a "pulse-dwell" operation. Such a mode of operation will require balancing in order to deliver stable power to the power grid [3], [4]. One of the many proposed balancing systems is an intermediate heat transfer system (IHTS) with molten salt storage [5].

Molten salts are currently used in solar tower technologies and thermal energy storage technologies [6], in the chemical industry [7], and in metal extraction [8]. Moreover, molten salts are proposed as a coolant and a fuel carrier in future Generation IV molten salt reactors [9]. Despite the current use and the development status of molten salt technologies, there is more research and development needed before the application to the DEMO IHTS. Unfortunately, molten salt loops are technically, organizationally, and financially demanding experimental devices. Also, the safe and reliable operation of molten salt loops is challenging [10].

One of the ways how to lower the molten salt loops' demandingness is to use scaled-down experimental devices [11], [12]. One of the scaled-down experimental devices is DYNASTY – eDYNASTY experiment at Politecnico di Milano, Italy [13], [14], [15]. This experiment uses water as a working medium. Water has many advantages (simple to use, readily available, a lot of experience, etc.) and some disadvantages, mainly suboptimal scaling. Better scaling is provided by the use of thermal oils, e.g., experimental devices at the UC Berkeley [16], [17] and others [18], [19].

The main objective of this paper is to present the design of one such scaled-down experimental device, which will be later used to confirm the possibility of using such scaled-down models for cheaper and safer research and development of DEMO IHTS with molten salt storage and other applications.

2. Purpose

The experimental device, which is currently being built in the laboratories of the Faculty of Mechanical Engineering of Czech Technical University in Prague, is called SHAKER (Scaled-down tHermal oil – Ardent salt tricKle Experimental Research device). Its main purpose is to verify the possibility of using scaled-down models for the study of molten salt systems. Using a combination of this scaled-down experimental device, original molten salt experiments references, and CFD models of both scaled-down and original will significantly advance the field.

3. Design

The main idea of using scale-down models is to utilize suitable substitutional materials and apply the similarity theory. As mentioned in work by Bardet and Peterson [12], suitable substitutions for molten salts are thermal oils. When choosing the working fluid for SHAKER, numerous different thermal oils were considered. In the end, the Therminol D12 thermal oil was chosen. In the designing process, the focus was placed on the following variables:

1. thermal oil temperature,
2. velocity ratio,
3. piping diameter,
4. time scale,
5. temperature scale,
6. piping wall thickness.

These variables were set fixed based on the scaling of the dimensionless numbers in the afford-mentioned order.

This procedure resulted in the final design and dimensions of the SHAKER. Some details about the main dimensionless numbers used in the process are given in the following chapter. Chapter 3.2 describes the SHAKER basic design, including materials, dimensions, etc. Chapter 3.3 describes the instrumentation to be used, specifically temperature sensors and flow meters.

3.1 Scaling

For correctly chosen working parameters and correctly scaled-down dimensions, the characteristic dimensionless numbers can be matched well. There are many different dimensionless numbers, from which Prandtl number (Pr), Reynolds number (Re), Froude number (Fr), Strouhal number (Sr), and Rayleigh number (Ra) are the most impost for the study of natural convection. Prandtl number is the ratio of momentum diffusivity to thermal diffusivity, Reynolds number is the ratio of inertial and viscous forces, Froude number is the ratio of the flow inertia to gravity, Strouhal number describes oscillations, and Rayleigh number is associated with natural convection.

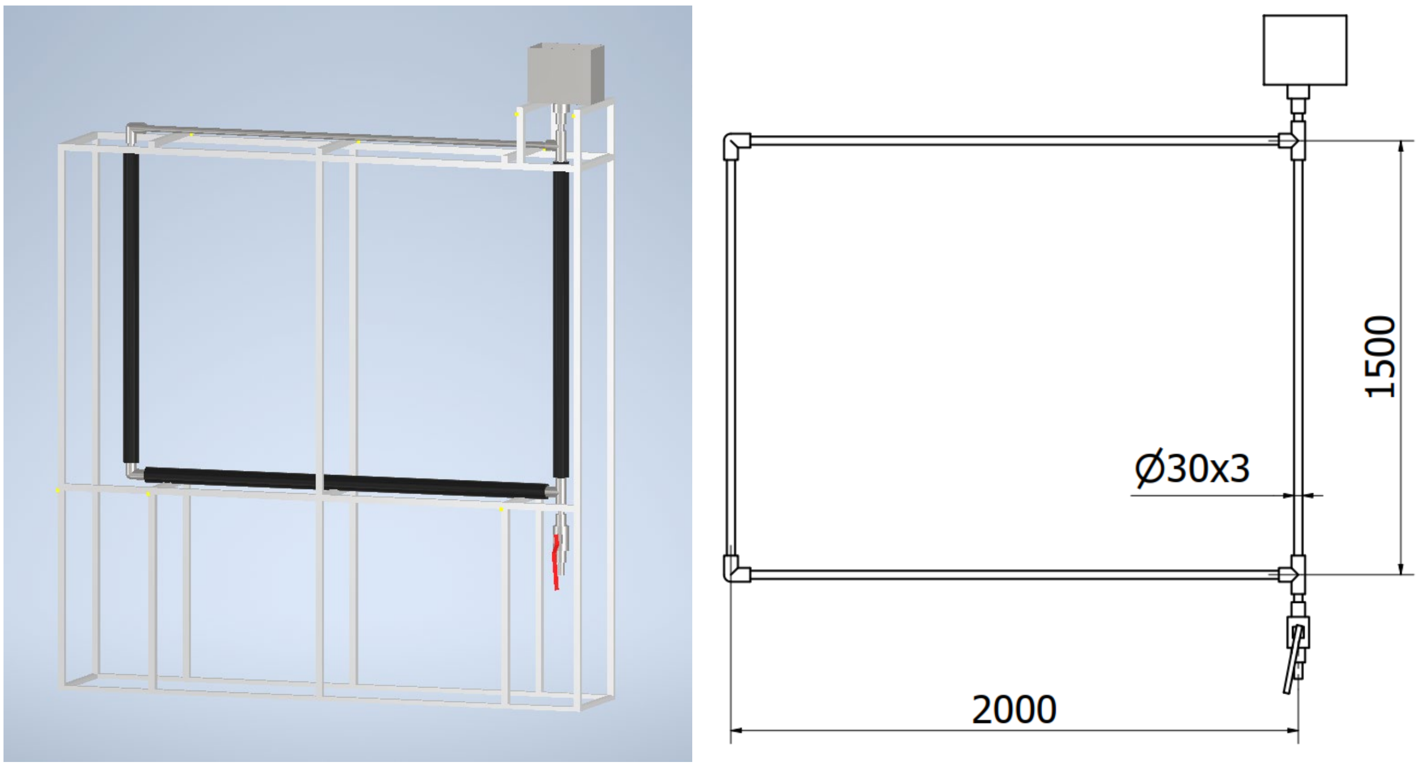
The ideal ratio of any of the above-mentioned dimensionless numbers of the scaled-down model, and the same dimensionless number of the original molten salt loop is one. Deviations from ideal dimensionless number scaling as well as basic working conditions are summarized in Table 1, where the subscript "M" stands for the model, i.e., the SHAKER, while "O" stands for the original.

Table 1: Scaling parameters and working conditions.

Parameter	$medium_O$	T_M [°C]	T_O [°C]	ΔPr [%]	ΔRe [%]	ΔFr [%]	ΔSr [%]	Δ (ß·ΔT) [%]
Solar salt	$NaNO_3$-KNO_3	105	300	0.124	0.495	0.511	0.195	0.427
FLiBe	LiF-BeF_2	65	700	0.030	0.835	1.010	0.238	0.040

3.2 Basic design

The SHAKER is a rectangular loop made out of stainless steel AISI 316L. The visualization of the SHAKER can be seen in Fig. 1 a). The design is based on the research needs, the laboratory capabilities, the common designs for molten salt loops and other experimental loops, the previously built experimental thermal oil loops mentioned above, and our experience.



a) b)

Fig. 1: a) a visualization of the SHAKER and b) the main dimensions of the SHAKER.

The SHAKER is designed as modular with natural or forced flow operation. The modularity allows using different experimental modules, such as a module for energy-balance-based flow measurements or a high cooling rate module.

The dimensions of the active part of the loop are approximately 2 m x 1.5 m (Fig. 1 b). The AISI 316 L stainless-steel pipes have an outer diameter of 30 mm and a wall thickness of 3 mm. The pipes are heated by electric resistive heating. The pipes with heating are then covered with the EPDM (ethylene propylene diene monomer rubber) synthetic rubber heat insulation.

The working fluid for the SHAKER is thermal oil Therminol D12. Therminol D-12 is a synthetic, non-toxic, liquid-phase heat transfer fluid ideally suited for applications that require efficient cooling and heating. Its common use includes the pharmaceutical and food industry [20]. As apparent from Table 1, Therminol D12 scales well to molten salts. The properties of the Therminol D12 at the temperature of 100 °C are shown in Table 2. In Table 2, r stands for Therminol D12 density, c_p for heat capacity, r· c_p is the product of density and heat capacity, n kinematic viscosity, l thermal conductivity, and b is coefficient of thermal expansion.

Table 2: The properties of Therminol D12 at the temperature of 100 °C.

Parameter	r	c_p	r· c_p	n	l	b
Unit	$kg·m^{-3}$	$kJ·kg^{-1}·K^{-1}$	$kJ·m^{-3}·K^{-1}$	$m^2·s^{-1}$	$W·m^{-1}·K^{-1}$	K^{-1}
Value	703.15	2.414	1698	$5.90·10^{-7}$	0.0966	0.00112

3.3 Instrumentation

The SHAKER will be equipped with multiple temperature sensors between the piping and the thermal insulation, some temperature sensors outside the thermal insulation, and possibly some temperature sensors penetrating the pipes and measuring the thermal oil temperature directly. The use of the pipes-penetrating temperature sensors is still an open question.

The flow measurement will be performed by a float flowmeter due to the very low mass flow rates when operated under natural circulation or a combination of ultrasonic and flow restriction flowmeters for forced flow operation.

4. Conclusion

The scaled-down experimental loop SHAKER is being built in the laboratories of the Faculty of Mechanical Engineering of Czech Technical University in Prague. The SHAKER is a rectangular experimental loop with thermal oil working fluid. The characteristic dimensionless numbers differ by about 1 % or less from the ideal scaling for FLiBe and solar salt.

When built and running, the experimental results will allow validation and verification of both the scaled-down thermal oil CFD models and the original molten salt CFD models. Moreover, the experimental results will be compared with CFD results. If the scalability of thermal oil experiments for molten salt application is confirmed, future cheaper, safer, and organizationally less demanding experiments might be used for research and development of DEMO IHTS with molten salt storage and other applications.

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References

[1] S. Ciattaglia, G. Federici, L. Barucca, A. Lampasi, S. Minucci and I. Moscato, "The European DEMO fusion reactor: Design status and challenges from balance of plant point of view: Design status and challenges from balance of plant point of view", in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2017, pp. 1-6.

[2] E. Bubelis, W. Hering and S. Perez-Martin, "Industry supported improved design of DEMO BoP for HCPB BB concept with energy storage system", *Fusion Engineering and Design*, vol. 146, pp. 2334-2337, 2019.

[3] E. Bubelis, W. Hering and S. Perez-Martin, "Conceptual designs of PHTS, ESS and PCS for DEMO BoP with helium cooled BB concept", *Fusion Engineering and Design*, vol. 136, pp. 367-371, 2018.

[4] J. Stepanek, S. Entler, J. Syblik, L. Vesely, V. Dostal and P. Zacha, "Comprehensive comparison of various working media and corresponding power cycle layouts for the helium-cooled DEMO reactor", *Fusion Engineering and Design*, vol. 166, 2021.

[5] M. Kovari and C. Howorth, "Molten salt energy storage for helium-cooled reactor: Report for TA WP13-DAS08-T03". European Fusion Development Agreement - Primary Heat Transfer System and Balance of Plant, 2013.

[6] S. Fereres, C. Prieto, P. Giménez-Gavarrell, A. Rodríguez, P. Sánchez-Jiménez and L. Pérez-Maqueda, "Molten carbonate salts for advanced solar thermal energy power plants: Cover gas effect on fluid thermal stability", *Solar Energy Materials and Solar Cells*, vol. 188, pp. 119-126, 2018.

[7] A. Misra, "Fluoride Salts as Phase Change Materials for Thermal Energy Storage in the Temperature Range 1000–1400 K: Thermal Analysis and Heat of Fusion Measurements", *Journal of The Electrochemical Society*, vol. 135, no. 4, pp. 850-854, 1988.

[8] D. Fray, "Emerging molten salt technologies for metals production", *JOM*, vol. 53, no. 10, pp. 27-31, 2001.

[9] J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J. Kloosterman, L. Luzzi, E. Merle-Lucotte, J. Uhlíř, R. Yoshioka and D. Zhimin, "The molten salt reactor (MSR) in generation IV: Overview and perspectives", *Progress in Nuclear Energy*, vol. 77, pp. 308-319, 2014.

[10] M. Cihlář, D. Procházková, P. Zácha, J. Prehradný, V. Dostál, M. Mareček and J. Uhlíř, "Causes of Failure of Experimental Molten Salt Research Device", in *Proceedings of 31st European Safety and Reliability Conference (ESREL2021)*, 2021, pp. 2638 - 2645.

[11] N. Zweibaum, E. Blandford, C. Gerardi and P. Peterson, "Scaling Methodology for Integral Effects Tests in Support of Fluoride Salt–Cooled High-Temperature Reactor Technology", *Nuclear Science and Engineering*, vol. 194, no. 8-9, pp. 793-811, 2020.

[12] P. Bardet and P. Peterson, "Options for Scaled Experiments for High Temperature Liquid Salt and Helium Fluid Mechanics and Convective Heat Transfer", *Nuclear Technology*, vol. 163, no. 3, pp. 344-357, 2017.

[13] A. Cammi and L. Luzzi, "Design report of the DYNASTY test facility with passive DHR system: SAMOFAR_WP3-D3.4". POLIMI, 2017.

[14] A. Cammi, L. Luzzi, C. Introini and S. Lorenzi, "Dynamics in natural circulation loop for internally heated molten salt: SAMOFAR_WP3-D3.2". POLIMI, 2019.

[15] A. Nalbandyan, A. Cammi, S. Lorenzi, E. Klinkby and B. Lauritzen, "Modelling and CFD analysis of the DYNASTY loop facility", vol. 8, 2022.

[16] L. Liu, P. Peterson, D. Zhang, I. Johnson, S. Qiu and G. Su, "Scaling and distortion analysis using a simple natural circulation loop for FHR development", *Applied Thermal Engineering*, vol. 168, 2020.

[17] C. Forsberg, P. Peterson, K. Sridharan, L. Hu, M. Fratoni and A. Kant Prinja, "Integrated FHR Technology Development: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics, Associated Benchmarking and Commercial Basis (MIT-ANP-TR-180)". 2018.

[18] B. Gajbhiye, S. C. S., C. Mathpati, A. Patwardhan, A. Borgohain and N. Maheshwari, "Pretest in forced circulation molten salt heat transfer loop: Studies with thermia-B", *Heat Transfer-Asian Research*, vol. 48, no. 8, pp. 4354-4372, 2019.

[19] Y. Shin, S. Seo, I. Kim and I. Bang, "Natural circulation with DOWTHERM RP and its MARS code implementation for molten salt-cooled reactors", *International Journal of Energy Research*, vol. 40, no. 8, pp. 1122-1133, 2016.

[20] Solutia, "Terminol D12 information bulletin". Solutia Europe S.A./N.V, Louvain-la-Neuve (Belgium).