Heat Transfer Correlations for the Generation-IV Molten Salt Reactor

Fangyu DONG [1], Niccolò LE BRUN [2,*], Christos N. MARKIDES [3]

* Corresponding author: Email: niccolo.le-brun11@imperial.ac.uk
1 Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London UK

Abstract Molten salts are highly suitable heat transfer fluids for high temperature applications, such as next generation nuclear reactors but also concentrated solar power systems, owing to their stability and capacity to transfer heat safely at low pressures compared to, e.g. pressurised water. The design of relevant components and equipment, and the operation of these resulting plants depend crucially on reliable heat transfer descriptions, which have proven a challenge given the harsh conditions in which relevant data needs to be generated. Some experiments have been performed in the literature, nevertheless, the results have been associated with significant deviations from expectations (predictions) based on standard heat transfer correlations. In this paper we re-interpret such data from the literature based on revised knowledge of the thermal properties of these salts, and show that if this is done appropriately, standard correlations are indeed applicable to molten-salt flows with errors similar to those expected from such empirical approaches.

Keywords: Molten salt reactors, Molten salts, Heat transfer fluids, Heat transfer correlations

1. Introduction

Molten salt reactors (MSRs) are currently being considered as possible Generation-IV nuclear reactor options due to their inherent safety and potentially better economics [1]. Despite the great promise of MSRs, much research is still needed to examine their viability and operability. Of primary importance is the rigorous evaluation of the applicability of standard thermohydraulic correlations to molten salt flows, such the Dittus-Boelter correlation:

$$Nu = 0.023 Re^{0.8} Pr^{n} \tag{1}$$

where n = 0.3 for cooling and n = 0.4 for heating.

Critically assessing the validity of such heat transfer correlations is paramount to obtaining accurate values of the heat transfer coefficient to be used in the thermohydraulic design of MSRs. A wide range of experiments was therefore conducted in the past to investigate standard heat transfer correlations for different molten salt types. However, the lack of accurate knowledge of the thermal properties (particularly the thermal conductivity) led to inaccurate evaluations of the dimensionless numbers from the raw experimental data and, consequently, large deviations between different experimental studies [2], from which little confidence could be gained into the use of these correlations for design and operation purposes.

This present study proposes to review exhaustively and to reinterpret data generated in previous experimental studies concerned with the thermohydraulic performance of molten salts at elevated temperatures, in order to obtain revised information on the validity of standard thermohydraulic correlations. This analysis is conducted in light of recent progress in our knowledge of the thermal properties of molten salts, which can allow for a correct re-evaluation of the experimental data available in the literature [3,4].

2. Preliminary Results and Discussion

An extensive data gathering activity from a wide range of previous experimental studies regarding heat transfer correlations of molten-salt flows is currently being conducted, covering both different molten salt types and different flow regimes. In parallel to this exercise, the data is being reprocessed by applying recent and accurate values of the transport properties of molten salts in order to

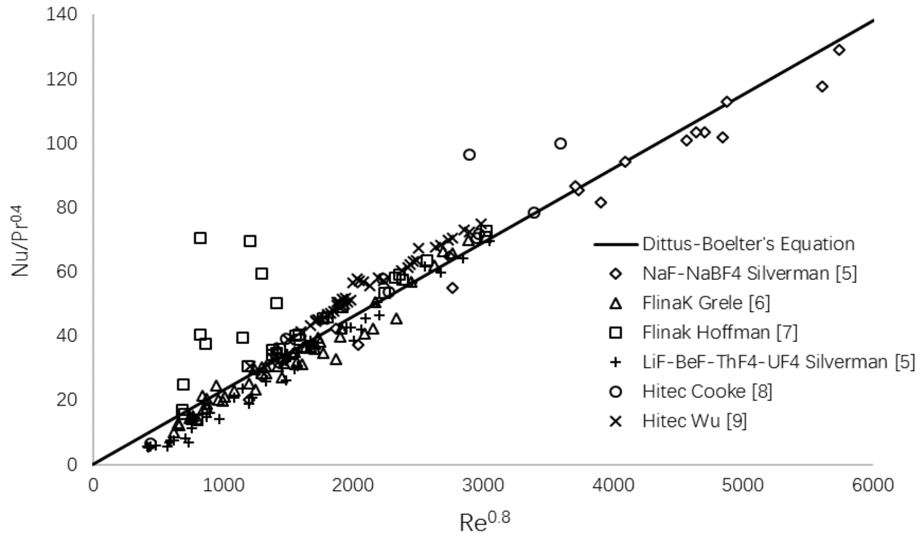

Figure 1. Comparison of the reprocessed experimental data and the Dittus-Boelter's equation.

obtain reliable values of the relevant non-dimensional numbers. In addition, the uncertainty (95% confidence interval) in the values of these dimensionless numbers is calculated by using the combined uncertainty approach. The results are being critically analysed and compared against standard heat transfer correlations to understand their validity and uncertainty.

Preliminary results from this effort are shown in Figure 1, which indicates that the reprocessed experimental data match well with the standard Dittus-Boelter's correlation, with some isolated exceptions. The original trend-line fitted by Grele [6] is approximately 40% lower than the Dittus-Boelter's equation but the deviation is less than 5% when using updated transport properties as is done in the present work. More experimental data will be analysed in the near future to ensure more accurate results and also to investigate other correlations suited for different flow regimes.

This work confirms that revised values of the dimensionless numbers calculated using correct transport property values are closer to the standard correlations than the original values, and therefore that the main disagreement in the literature on the efficacy of heat transfer correlations applied to molten-salt flows is down to an incorrect non-dimensionalisation due to incorrect thermophysical propriety values, rather than the correlations themselves.

References

1. Serp, J., Allibert, M., Beneš, O., Delpech, S., Feynberg, O., Ghetta, V., Heuer, D., Holcomb, D., Ignatiev, V., Kloosterman, J.L., Luzzi, L., 2014. The Molten Salt Reactor (MSR) in Generation IV: Overview and Perspectives. Progress in Nuclear Energy, 77, pp.308-319.

2. Ambrosek, J., Anderson, M., Sridharan, K., Allen, T., 2009. Current Status of Knowledge of the Fluoride Salt (FLiNaK) Heat Transfer. Nuclear Technology, 165(2), pp.166-173.

3. Le Brun, N., Markides, C.N., 2015. A Galinstan-Filled Capillary Probe for Thermal Conductivity Measurements and its Application to Molten Eutectic KNO_3–$NaNO_3$–NO_2 (HTS) up to 700 K. International Journal of Thermophysics, 36(10-11), pp. 3222-3238.

4. Jin, Y., Cheng, J., An, X., Su, T., Zhang, P., Li, Z., 2016. Accurate Viscosity Measurement of Nitrates/Nitrites Salts for Concentrated Solar Power. Solar Energy, 137, pp. 385-392.

5. Silverman, M.D., Huntley, W.R., Robertson, H.E., 1976. Heat Transfer Measurements in a Forced Convection Loop with Two Molten-Fluoride Salts: LiF-BeF_2-ThF_2-UF_4 and Eutectic $NaBF_4$-NaF (No. ORNL/TM-5335). Oak Ridge National Lab.

6. Grele, M.D., Gedeon, L., 1954. Forced-Convection Heat-Transfer Characteristics of Molten FLiNaK Flowing in an Inconel X System. National Advisory Committee for Aeronautics.

7. Hoffman, H.W., Lones, J., 1955. Fused Salt Heat Transfer. Part II. Forced Convection Heat Transfer in Circular Tubes Containing NaF-KF-LiF Eutectic (No. ORNL-1777). Oak Ridge National Lab.

8. Cooke, J.W., Cox, B.W., 1973. Forced-Convection Heat Transfer Measurements with a Molten Fluoride Salt Mixture Flowing in a Smooth Tube (No. ORNL/TM-4079). Oak Ridge National Lab.

9. Wu, Y.T., Chen, C., Liu, B., Ma, C.F., 2012. Investigation on Forced Convective Heat Transfer of Molten Salts in Circular Tubes. International Communications in Heat and Mass Transfer, 39(10), pp. 1550-1555.