Journal of Physics: Conference Series **501** (2014) 012030 doi:10.1088/1742-6596/501/1/012030

Thermal-hydraulics of internally heated molten salts and application to the Molten Salt Fast Reactor

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Abstract. The Molten Salt Reactors (MSR) are an innovative kind of nuclear reactors and are presently considered in the framework of the Generation IV International Forum (GIF-IV) for their promising performances in terms of low resource utilization, waste minimization and enhanced safety. A unique feature of MSRs is that molten fluoride salts play the distinctive role of both fuel (heat source) and coolant. The presence of an internal heat generation perturbs the temperature field and consequences are to be expected on the heat transfer characteristics of the molten salts. In this paper, the problem of heat transfer for internally heated fluids in a straight circular channel is first faced on a theoretical ground. The effect of internal heat generation is demonstrated to be described by a corrective factor applied to traditional correlations for the Nusselt number. It is shown that the corrective factor can be fully characterized by making explicit the dependency on Reynolds and Prandtl numbers. On this basis, a preliminary correlation is proposed for the case of molten fluoride salts by interpolating the results provided by an analytic approach previously developed at the Politecnico di Milano. The experimental facility and the related measuring procedure for testing the proposed correlation are then presented. Finally, the developed correlation is used to carry out a parametric investigation on the effect of internal heat generation on the main out-of-core components of the Molten Salt Fast Reactor (MSFR), the reference circulating-fuel MSR design in the GIF-IV. The volumetric power determines higher temperatures at the channel wall, but the effect is significant only in case of large diameters and/or low velocities.

1. Introduction

In recent years, there has been a growing interest in the Molten Salt Reactor (MSR) technology, one of the six nuclear reactor concepts considered in the framework of the Generation IV International Forum as promising candidates for an increasingly sustainable, safe and secure nuclear energy production. A main and characterizing feature of MSRs is the dual role of the molten salts, acting as both fuel and coolant. This requires investigation in view of the little information available in the open literature regarding the thermal-hydraulics of internally heated fluids. Dedicated models and tools have been developed for specific applications like combustion processes (see e.g. [1]), but they are not directly applicable to the case of MSRs. Despite the scarcity of available data and theoretical studies, the presence of an internal heat generation perturbs the temperature field and consequences are to be expected on the thermal-hydraulics of MSRs. Among various aspects requiring investigation, the present paper focuses on the heat transfer phenomena occurring in molten salts flowing in forced convection in a channel.

Some preliminary studies on the subject are available in literature [2-4], but they are in most cases partial treatments and they do not lead to the proposal of correlations to be used for turbulent flows. Recently, a research activity on internally heated molten salts has been undertaken at the Politecnico Di Milano [5-7], focusing in particular on graphite-moderated MSR concepts. In the frame of such research activity, a new correlation has been proposed [5,6], giving a clear indication of the importance of internal heat generation in the heat transfer phenomena occurring in MSRs. As an example, figure 1 shows the Nusselt number in the core channels of the Molten Salt Breeder Reactor (MSBR) [8] as predicted by traditional correlations [9-13], as well as by the correlation proposed in [5]. A non-negligible difference is observed, especially for low Reynolds numbers. A drawback of the correlation proposed in [5,6] is that it has been obtained through interpolation of numerical/analytic results, without relying on a theoretical background and resulting in a complex functional form.

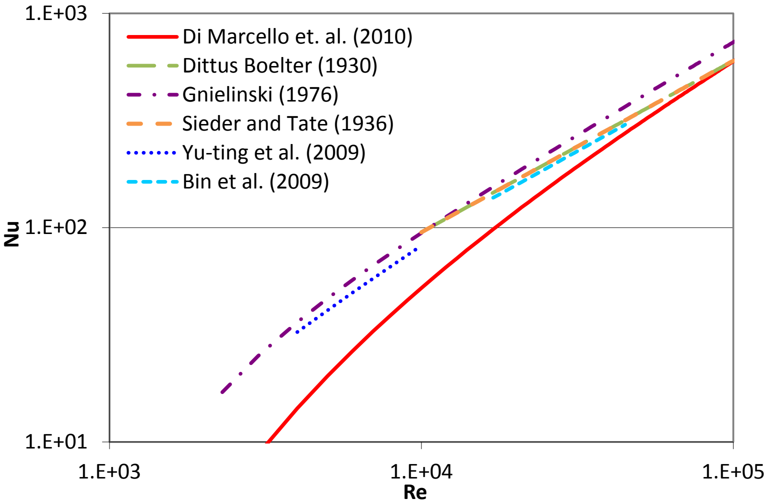

Figure 1. Nusselt number in the average core channel of the MSBR [5,9-13]

The paper is organized as follows. In Section 2, a heat transfer correlation is presented for evaluating the Nusselt number for the turbulent flow of internally heated molten salts in straight circular channels. Section 3 preliminarily discusses a possible experimental set-up that could be used to validate the results presented in Section 2. The proposed correlation is finally used in Section 4 to predict the effect of the internal heat generation on the out-of-core components of the Molten Salt Fast Reactor (MSFR), the reference circulating-fuel MSR design in the GIF-IV. Concluding remarks are provided in Section 5.

2. Heat transfer correlation

An accurate analytic treatment of the heat transfer for internally heated fluids has been developed in the past at the Politecnico di Milano [5-7]. Treatments of this kind, as well as dedicated CFD codes, can be used to investigate the details of heat transfer processes in many engineering applications. Nevertheless, when dealing with complex systems, computational requirements make often impractical the direct application of such techniques. In addition, simpler tools are needed to achieve first general information in preliminary design processes, as in the case of the MSFR out-of-core components. In these contexts, it can be useful to rely on the use of heat transfer correlations. The present section proposes a theoretical derivation of a correlation form for the Nusselt number in channels featured by internally heated fluids. A specific correlation is then obtained for the case of molten salts (Prandtl numbers approximately in the range $7.5<Pr<20$) through interpolation of data provided by the tool described in [5,6].

2.1. Derivation of a general correlation form

In this subsection, the problem of heat transfer in channels featured by internally heated fluids is treated theoretically, and a general form of the Nusselt number correlation is derived by means of the Π-theorem [14] and thanks to some physical considerations. In order to obtain such correlation, the field of investigation is restricted to a smooth channel with circular cross-section, average inlet fluid velocity u_{avg}, hydro-dynamically and thermally developed turbulent flow, uniform internal heat generation Q and constant (inward or outward) wall heat flux j_w. (figure 2).

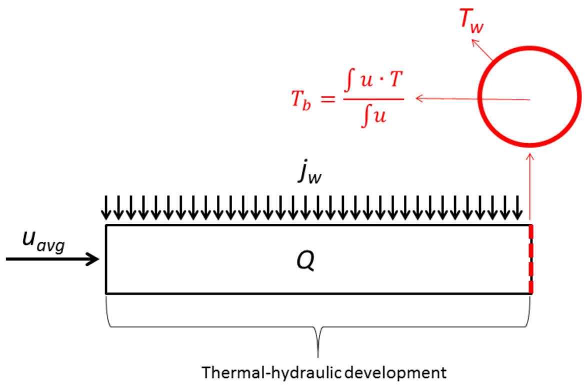

Figure 2. Schematic representation of the investigated heat transfer process

As a first step in the derivation of the heat transfer correlation, it should be recognized that the linearity (with respect to temperature) of the energy equation allows us to treat the physical situation here analysed as the superimposition of two simpler situations:

situation 1. A fluid flow without internal heat generation, but featured by constant wall heat flux j_w, which is the typical case considered by traditional heat transfer correlations;

situation 2. A fluid flowing in an adiabatic channel with volumetric heat generation Q.

Hence, it is possible to compute the temperature difference between wall (T_w) and bulk (T_b) temperatures as:

$$(T_w - T_b)_{Q+j_w} = (T_w - T_b)_Q + (T_w - T_b)_{j_w} \tag{1}$$

where the subscript $Q+j_w$ refers to the complete situation with both internal heat generation and wall heat flux, while the subscripts Q and j_w indicate that the temperature differences are computed in the simplified situation of internal heat generation alone (situation 2) and wall heat flux alone (situation 1), respectively. The presence of internal heating in situation 2 will result in a higher temperature at the channel wall, where the fluid is slower. In case of an inward wall heat flux the temperature difference $(T_w\text{-}T_b)_{Q+jw}$ will be increased compared to the classical one $(T_w\text{-}T_b)_{jw}$, thus suggesting a worsening of the heat transfer coefficient. In case of an outward heat flux, $(T_w\text{-}T_b)_{Q+jw}$ will instead be decreased (in absolute terms) and the heat transfer coefficient improved.

Introduction of Equation (1) in the definition of heat transfer coefficient leads to (j_w is assumed positive if entering the channel):

$$h_{Q+j_w} = \frac{j_w}{(T_w - T_b)_Q + (T_w - T_b)_{j_w}} = \frac{1}{\frac{(T_w - T_b)_Q}{j_w} + \frac{(T_w - T_b)_{j_w}}{j_w}} = \frac{1}{h_Q^{-1} + h_{j_w}^{-1}} \tag{2}$$

Attention must be paid to the term h_Q. Although similar to h_{jw} in its definition, it does not represent a heat transfer coefficient, since it includes in the same definition the temperatures of the situation 2 (with internal heat generation and with adiabatic walls) and the heat flux of situation 1 (without internal heat generation). It is now possible to rewrite the previous equation as:

$$Nu_{Q+j_w} = \frac{1}{Nu_Q^{-1} + Nu_{j_w}^{-1}} = Nu_{j_w} \frac{1}{1 + \frac{Nu_{j_w}}{Nu_Q}} \tag{3}$$

Equation (3) implies that the Nusselt number (*Nu*) in case of internally heated fluids and constant wall heat flux Nu_{Q+jw} can be computed by means of traditional correlations for the value of Nu_{jw} with the introduction of the corrective factor:

$$\zeta = \frac{1}{1+\frac{Nu_{j_w}}{Nu_Q}} = \frac{1}{1+\frac{h_{j_w}}{h_Q}} = \frac{1}{1+\sigma} \tag{4}$$

Assuming constant the properties of the fluid, it is possible to write:

$$\sigma = \sigma(c_p, \mu, \rho, k, D, u_{avg}, Q, j_w) \tag{5}$$

where c_p is the specific heat, μ the dynamic viscosity, ρ the density, k the thermal conductivity, and D the channel diameter. The assumption of constant physical properties is a typical one in the derivation of heat transfer correlations and it is often considered to be of second order importance [9]. However it should be kept in mind that the possibility exists to derive more accurate correlations by including a dependency upon the ratio of the viscosity evaluated at wall and bulk temperatures (see e.g. Ref. [13] for molten salts). Some of the dependencies in Equation (5) can be made explicit, thus reducing the experimental/computational efforts in the derivation of σ. Equations (2) and (4) yield:

$$\sigma = \frac{h_{j_w}}{h_Q} = \frac{h_{j_w}(T_w - T_b)_Q}{j_w} \tag{6}$$

The terms h_{jw} and $(T_w - T_b)_Q$ are independent of j_w. Moreover, the term $(T_w - T_b)_Q$ is directly proportional to Q - see for example [3]. It follows:

$$\sigma = \frac{Q}{j_w}\sigma'(c_P, \mu, \rho, k, D, u_{avg}) \tag{7}$$

Use of Π-theorem in the previous equation finally leads to:

$$\sigma = \frac{QD}{j_w}\varphi(Pr, Re) \tag{8}$$

Such useful result allows us to characterize the heat transfer in a channel with internal heat generation using only two parameters (Prandtl and Reynolds numbers), similarly to the case of a flow without heat generation. Clearly, this is also based on the assumption of constant physical properties (particularly for viscosity). The overall correlation for the Nusselt number in case of simultaneous wall heat flux and internal heat generation should then assume the form:

$$Nu_{Q+j_w} = \zeta Nu_{j_w} = \frac{1}{1+\sigma} Nu_{j_w} = \frac{1}{1+\frac{QD}{j_w}\varphi(Pr,Re)} Nu_{j_w} \tag{9}$$

Assuming as positive the function *φ(Pr,Re)* (see next subsection and Equation (12)), Equation (9) confirms that the Nusselt number in case of internally heated fluids is increased/decreased in case of outward/inward wall heat flux. The correction is higher when the Q/j_w ratio is higher, and when the channel diameter is increased. In case the wall heat flux is exiting the channel (j_w<0), Nu_{jw} may become negative for high values of the ratio QD/j_w. Physically, this means that the bulk temperature is lower than the wall temperature, although the heat is flowing out of the channel.

2.2. Data interpolation and application to molten salts

The results of the previous subsection can be used to derive Nusselt number correlations for internally heated fluids. In particular, if the correlations available in literature for Nu_{jw} are adopted, what is required is the derivation of the function *φ(Pr,Re).* In case of laminar flow, the function *φ(Pr,Re)* is constant and equal to 3/44 [3]. In case of turbulent flows, it can have a complex shape but, by restricting the field of application, it is reasonable to assume a simple dependency like:

$$\varphi(Pr, Re) = a_1 Pr^{a_2} Re^{a_3} \tag{10}$$

where a_1, a_2 and a_3 are constants to be determined. At this point, it is possible to evaluate the function φ and derive the constants a_1, a_2 and a_3. In particular, Equation (9) can be rearranged as:

$$\varphi(Pr,Re) = \frac{j_w}{QD}\left(\frac{Nu_{jw}}{Nu_{Q+jw}} - 1\right) \quad (11)$$

and the Nusselt numbers can be computed using the model described in [5,6]. Such model was shown able to reproduce the experimental data presently available with an accuracy comparable to the data uncertainties [5]. Comparison with the numerical results obtained using state-of-the-art CFD codes also showed an excellent agreement (within few percents) [6]. Computing φ for 100 different combinations of Prandtl and Reynolds numbers in the ranges $7.5<Pr<20$ and $10^4<Re<10^5$, and interpolating Equation (10) in the least square sense, the following correlation is obtained:

$$\varphi(Pr,Re) = 1.656 \cdot Pr^{-0.4} Re^{-0.5} \quad (12)$$

Equation (12) interpolates the results given by the model in [5,6] with an average error equal to 4.9% and a maximum error equal to 10.2% (figure 3). Such discrepancies can be considered acceptable for preliminary calculations. Extrapolation to Reynolds numbers as low as 2300 gives discrepancies of about 20%. Adopting Equation (12), the overall correlation for the Nusselt number in case of both internal heat generation and wall heat flux would be:

$$Nu_{Q+j_w} = \frac{1}{1+\frac{QD}{j_w}\varphi(Pr,Re)} Nu_{j_w} = \frac{1}{1+\frac{QD}{j_w}1.656 \cdot Pr^{-0.4} Re^{-0.5}} Nu_{j_w} \quad (13)$$

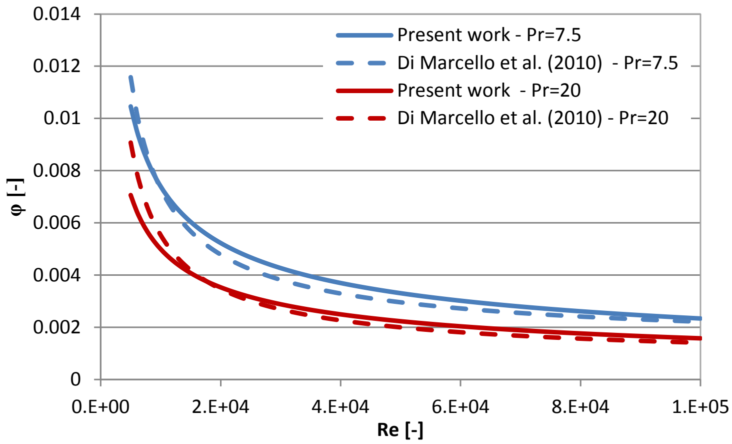

Figure 3. Prediction of the function φ according to di Marcello et al. [5] and using Equation (12)

3. Possible experimental set-up

With the objective of validating the correlation proposed (Equation (12)), the set-up of a proper experimental facility is necessary. Equations (6) and (8) can be rearranged as:

$$\varphi(Pr,Re) = Nu_{j_w} \frac{(T_w - T_b)_Q}{\frac{QD^2}{k}} \quad (14)$$

Assuming Nu_{jw} as known from available correlations (see e.g. [9-13]), what is necessary from an experimental point of view is the evaluation of the term $(T_w\text{-}T_b)_Q$. This requires a facility able to reproduce the condition of an internally heated, thermally and hydro-dynamically developed turbulent flow in a straight, circular and adiabatic channel. The experimental set-up must be suitable for measuring wall and bulk temperatures. Following the assumptions used to derive Equation (12), a uniform (and precisely-known) internal heat generation Q should be guaranteed. In addition, the definition of the dependency of φ upon Prandtl and Reynolds numbers requires the possibility to vary in a known way the fluid properties, as well as the possibility to vary and measure the fluid velocity.

A suitable starting point for the required experimental analyses is the facility adopted by Kinney and Sparrow [2]. This set-up was used to test water (close to room temperature and at atmospheric pressure), which could also be considered for the experimental set-up here under investigation. It would avoid high temperatures (and the related problems of structural materials and instrumentation)

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and use of toxic molten fluoride salts, while the Prandtl number typical of molten salts could be achieved by using thickening agents. However, attention should be paid to the possible non-Newtonian effects related to the use of thickening agents. In addition, it should be taken into account that simulation of molten salts using a different fluid with the same Prandtl number is theoretically possible only for constant fluid properties. A facility using water will then be useful to assess Equation (12), but it will be impossible to accurately determine additional correction factors allowing e.g. for the variation of viscosity with temperature.

A schematic view of the possible facility is shown in figure 4. A closed loop can be used, with a heat exchanger required for cooling the working fluid after it has been warmed in the test section. Such test section must be long enough to assure condition of full thermal and hydro-dynamic development. Kinney and Sparrow [2] adopted a test section length equal to 85 times its diameter, 40 of which for the sole hydraulic development. As a matter of fact, by analysing their results, it appears that the remaining 45 diameters for the thermal development can be reduced at least to 30 diameters (this reduces by 33% the total power required). Internal heating in the fluid can be obtained through Joule effect by forcing an electrical current to flow into it. This is possible by choosing an electrically insulating material (e.g., polyvinyl dichloride) for the channel wall in the test section, and by placing electrodes at the sides of it. In this way, the current is forced to flow longitudinally in the fluid. Adopting electricity to heat up the water also solves the problem of the knowledge of the volumetric power *Q*, which can easily be derived by measuring the electric current in the circuit and the voltage difference at the electrodes. Alternate current might help reducing problems of electrolysis, but further evaluations would be needed to exclude major problems in this sense, especially considering the presence of salting agents in the water and the high voltages required (see below). A cylindrical shell is posed outside the duct to reduce thermal losses towards the environment. In this shell, a certain amount of power is dispersed through electrical resistors in order to reach the desired adiabatic boundary condition at the pipe wall. Particular attention is necessary to well insulate the test section in critical zones such as contact points with the structure that supports the channel, near which the temperature field might be distorted by relatively high thermal losses. To overcome such difficulty, the arrangement illustrated in figure 4 can be adopted, where a single beam is used as supporting structure, with the test section connected to it through a silica aero gel support.

The velocity of the fluid can be varied by using an appropriate pump or valves, and it can be measured by means of standard techniques (e.g., Coriolis flow meter). As far as temperature measurements are concerned, for validating Equation (12) it is sufficient to measure wall and bulk temperatures just before the outlet of the heated section (but sufficiently distant from the last electrode, to avoid disturbances due to the distorted electric field). Wall temperature can be achieved using a thermocouple. In view of the electric field in the fluid, and in order to avoid flow disturbances, the thermocouple can be placed outside the channel, drilled partway in a shallow hole through the pipe wall. In fact, the adiabatic condition allows one to consider as approximately constant the temperature throughout the wall. The information about bulk temperatures can be gained using two mixing chambers before and after the test section, possibly compensating the obtained information considering the heat produced after the wall temperature measuring point. This suggests preliminary calculations to assess the electric field configuration and the resulting heating non-uniformity close to the electrodes. Voltage measurement should be taken to assess these calculations after the facility has been set up. A moving and electrically insulated thermocouple could also be placed inside the fluid and adopted to measure the entire radial temperature profile, which could be useful to validate CFD codes, as well as a redundant measurement for the bulk temperature (assuming as approximately known the velocity profile). As regards the irregular electric field close to the electrodes, the distorted heat generation is also expected to perturb the temperature profile, but according to Kinney and Sparrow, the effect of a small perturbation should propagate for a distance equal to 2-3 diameters at most. To confirm this, it is worth considering the use of thermocouples throughout the length of the heated section, at least at wall. This would also allow one to draw information about the thermal development of the fluid.

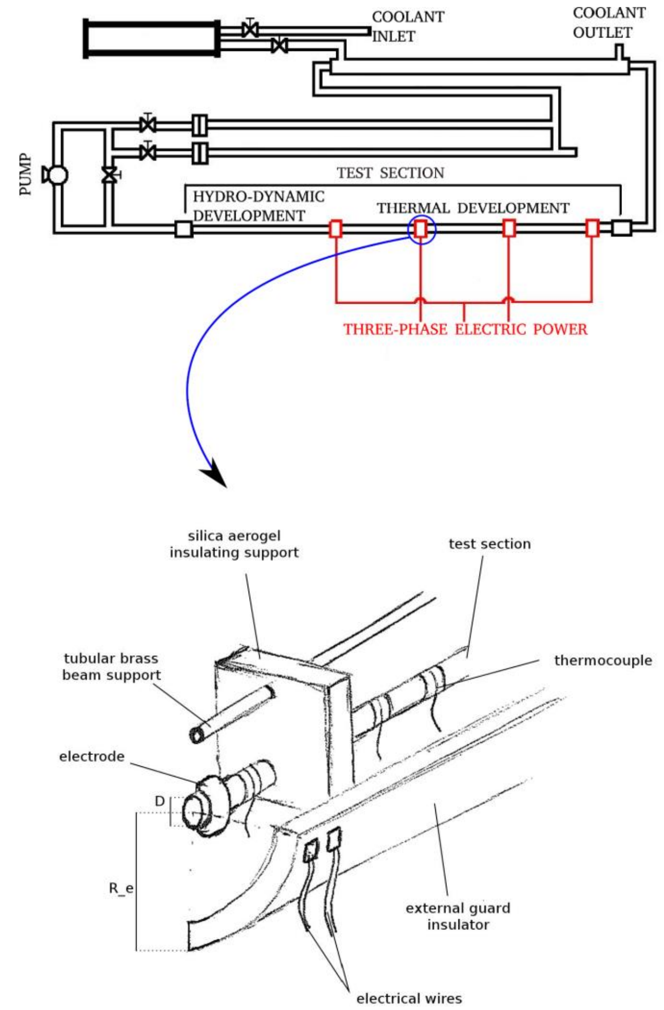

Figure 4. Schematic view of the possible experimental facility

A main difficulty about the experiment is related to the small magnitude of the temperature difference between wall and bulk temperatures. Equation (14) and use e.g. of the Dittus-Boelter correlation [9] for Nu_{jw} yield:

$$(T_w - T_b)_Q = \frac{QD^2\varphi(Pr,Re)}{kNu_{jw}} = \frac{QD^2}{k}\frac{1.656}{0.023}Re^{-1.3}Pr^{-0.8} \qquad (15)$$

Taking into account that the proportions of the tube are fixed because of the necessary thermal development of the flow, assuming a 30 diameter long heated section, and assuming the thermal conductivity of the water approximately equal to 0.6 W/(m·K) it is possible to write:

$$(T_w - T_b)_Q = \frac{Q_{tot}}{7.5\pi Dk}\frac{1.656}{0.023}Re^{-1.3}Pr^{-0.8} \cong 1.2[K\cdot m/(SV^2)]\,\sigma_e V^2 Re^{-1.3}Pr^{-0.8} \qquad (16)$$

where Q_{tot} is the total power in the heated section, V the effective phase voltage and σ_e the electric conductivity.

The temperature difference is then directly proportional to the Q_{tot}/D ratio, and to the product of the fluid electrical conductivity and the voltage. A minimum diameter of the tube equal to 2.54 cm (1 inch) has been assumed to make the dimensions of the thermocouples reasonably small compared to it. As concerns the electrical conductivity, use of salted water is necessary to have acceptable voltages. Kinney and Sparrow [2] used a 4 molal solution of NaCl in water. With a voltage of 400 V and a total power of 44 kW they were able to attain a $(T_w\text{-}T_b)_Q$ on the order of 1 K for Prandtl and Reynolds numbers equal to 4 and $8\cdot10^4$, respectively. In the present case, Prandtl and Reynolds numbers as high

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as 20 and 10^5, respectively, are to be investigated. This calls for a highly conductive fluid to keep as low as possible the necessary voltage. Use of NaCl limits the electrical conductivity to about 25 S/m, which has been considered too small for the purposes of the facility. A preliminary investigation allowed us to single out a 4 molal solution of KBr in water as a suitable candidate. KBr is in fact inexpensive and allows reaching a noteworthy 50 S/m electrical conductivity [17]. The effect of KBr addition on the Prandtl number of water is small and goes in the direction of slightly increasing it.

Assuming D=2.54 cm, σ_e=50 S/m, and using the properties of salted water [17], Equations (15) and (16) allow us to obtain power and voltage as a function of $(T_w\text{-}T_b)_Q$. Assuming the worst condition necessary to validate Equation (12) (i.e., Pr=20, Re=10^5), the data reported in figure 5 are obtained. It is clear that high voltages are required to achieve temperature differences above 1 K. For instance, if 1.5 K is considered an acceptable temperature difference to be measured (it caused a 5-10% scatter in the wall-to-bulk temperature difference data in Ref. [2]), 930 V would be required, with a notable total power equal to 260 kW. Velocities in the test section would be high (~10 m/s), while the temperature difference between inlet and outlet is not a concern, being on the order of 10 K.

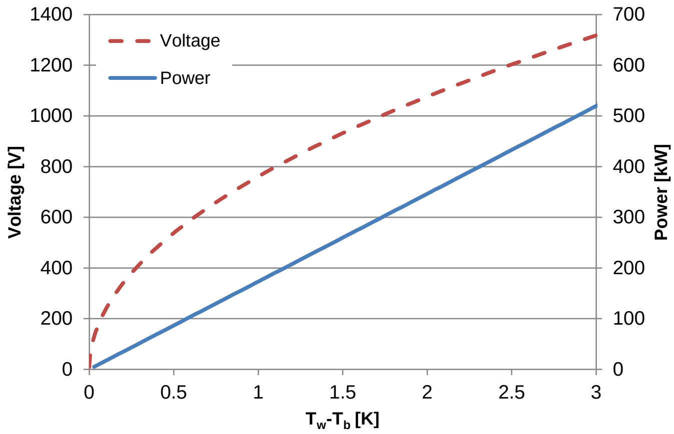

Figure 5. Voltage and power as a function of $(T_w\text{-}T_b)_Q$ – Pr=20, Re=10^5

4. Impact of the internal heat generation on the MSFR out-of-core components

The proposed correlation (Equation (12)) can be used to preliminarily investigate the impact of decay heat on the heat transfer processes in a number of MSFR out-of-core components, including pipes of the primary circuit, tubes of the heat exchanger, and channels of the salt reprocessing system (see e.g. [15,16] for the details about the MSFR design). As observed in subsection 2.1, the effect of the internal heat generation superimposes linearly with the effect of heat transfer at the channel wall. Independent of the wall heat flux, the effect of internal heat generation translates into a wall temperature increased by the term $(T_w\text{-}T_b)_Q$ (see Equation (1)), which can conveniently be used to assess the impact of internal heat generation on a generic component. To this purpose, Equations (6) and (8) can be rearranged to yield:

$$(T_w - T_b)_Q = \frac{QD^2\varphi(Pr,Re)}{kNu_{jw}(Pr,Re)} = \frac{QD^2\varphi(D,u_{avg})}{kNu_{jw}(D,u_{avg})} \qquad (17)$$

where the dependency on Re and Pr has been changed to a dependency on diameter and average velocity by using the MSFR salt properties (table 1).

Table 1. MSFR fuel salt properties [15]

Salt density [kg/m^3]	$4094\text{-}8.82\cdot10^{-1}\cdot(T[K]\text{-}1008)$
Salt specific heat [J/kg-K]	$-1111+2.78\cdot T[K]$
Salt thermal conductivity [W/m-K]	$0.928+8.397\cdot10^{-5}T[K]$
Salt kinematic viscosity [m^2/s]	$5.54\cdot10^{-8}\cdot\exp(3689/T[K])$

At this point, it is possible to evaluate the term $(T_w\text{-}T_b)_Q$ by using the correlation (12) for φ and suitable correlations for Nu_{jw}. As mentioned in subsection 2.2, Equation (12) is mainly valid for $10^4<Re<10^5$, but it can be extrapolated to Re=2300 with acceptable discrepancies. For Nu_{jw}, the Dittus-Boelter correlation [9] can be used for $Re>10^4$. For $2300<Re<10^4$, the Gnielinski correlation [10] gives instead more accurate results. For a laminar flow (Re<1000), Equation (14) becomes:

$$(T_w - T_b)_Q = \frac{QD^2\varphi(Pr,Re)}{kNu_{jw}(Pr,Re)} = \frac{QD^2 3/44}{k48/11} = \frac{QD^2 3}{k192} \quad (18)$$

The internal heat generation Q in the out-of-core components of the MSFR is determined by decay of actinides and fission products, which is on the order ~8 MW/m^3 [16]. Figure 6 shows the results of the numerical evaluation of equations (17) and (18). It only shows results for $Re<10^3$ and $2300<Re<10^4$. The scale of the colorbar has been limited to 120 K in the laminar region to allow a better visualization of results in the turbulent region. In fact, the term $(T_w\text{-}T_b)_Q$ would reach ~300 K at the right corner of the laminar region.

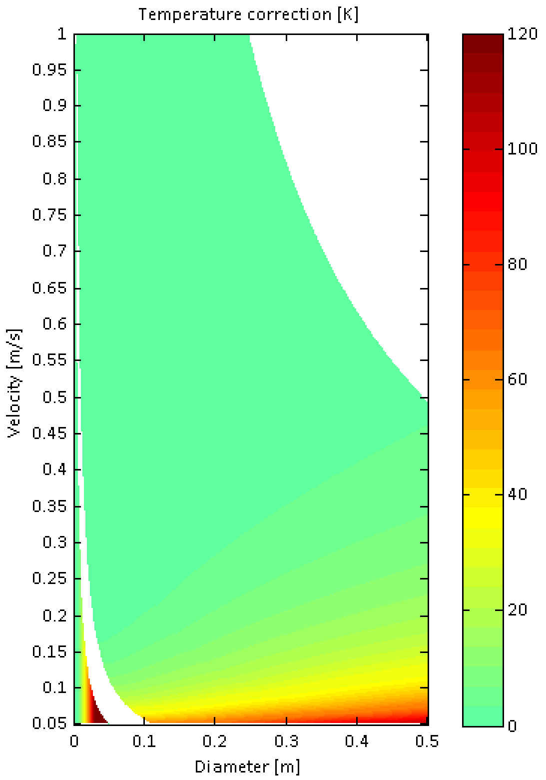

Figure 6. Increment of the wall-to-bulk temperature difference $(T_w\text{-}T_b)_Q$ due to the internal heat generation in the MSFR channels as a function of salt velocity and channel diameters

Figure 6 shows that the internal heat generation has an extremely limited impact on wall temperatures for high velocities. This excludes any significant effects on the pipes of the primary circuit and on the tubes of the heat exchangers, featuring velocities on the order of few meters per second [16]. However, the MSFR design includes a chemical system for fuel reprocessing, with reprocessing rates of the order of few litres or few tens of litres per day [16]. As an example, one can consider a channel used to transfer the fuel salt from the core to the reprocessing system. Adoption of a channel with 5 cm diameter and 5 cm/s of flow velocity would result in a reasonable salt extraction rate of 1 litre every 10 seconds. Considering a channel 2 m long, the internal heat generation would cause an acceptable increment of the bulk temperature of ~50 K, but the wall temperature close to the end of the channel would be approximately 300 K higher than the bulk one (as mentioned above).

5. Conclusions

The problem of heat transfer for internally heated fluids flowing in forced convection in a straight circular channel has been faced on a theoretical ground. After making the assumption of full thermal-hydraulic development of the flow, some physical considerations and application of the Π-theorem have made possible the achievement of a general form for a heat transfer correlation. It has been shown that the effect of internal heat generation can be described by means of a corrective factor to be applied to traditional correlations (e.g., the Dittus-Boelter or Gnielinski correlations) for the Nusselt number. The corrective factor has been demonstrated to be lower than one in case of inward wall heat flux, thus implying an overestimation of the heat transfer coefficient in case traditional correlations were used. In case of outward wall heat flux, the correction factor is instead generally higher than one. The possibility also exists of a negative heat transfer coefficient in case the wall heat flux is small compared to the internal heat generation. It has been shown that the corrective factor can be fully characterized by making explicit the dependency on just Reynolds and Prandtl numbers. On this basis, a preliminary correlation has been proposed for molten salts by interpolating the results provided by an analytic approach previously developed at the Politecnico di Milano.

A possible experimental facility for testing the proposed correlation has been discussed. In spite of some technical difficulty related to the achievement of internal heat generation through Joule effect, the facility appears feasible.

Finally, the developed correlation has been used to carry out a parametric investigation of the effect of decay heat on the out-of-core components of the reference Generation IV Molten Salt Reactor. The volumetric power determines higher temperatures at the channel wall, but the effect is significant only in case of large diameters and/or low velocities. This might be the case of the channels of the salt reprocessing system.

Acknowledgements

The authors acknowledge Mr. Manuele Aufiero (Politecnico di Milano), Mr. Jacopo De Amicis (Politecnico di Milano) and the experts from the SIET Laboratories (Piacenza, Italy) for their valuable suggestions about the presented experimental set-up.

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