The Problem of Thermal Contact Resistance During Heat Transfer to Liquid Metals

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A comparison of the experimental data on the heat transfer of liquid metals with the theoretical data of Martinelly-Lyon [1,2] shows that most experiments [3-9] do not agree with theory or agree poorly. The theory has only been confirmed experimentally in [10-13]. The following feature is of interest. The theory is best confirmed by those experiments in which the heat exchangers were tubes of diameter 25, 30 and 40 mm and it is not confirmed by experiments using tubes with diameters less than 10 mm.

In the derivation of theoretical heat-exchange equations the temperature of the interface region between the liquid metal and the wall of the tube is assumed equal to the temperature of the outer surface of the liquid metal stream, which can obviously only be the case with an absolutely pure surface of heating. The difference between the experimental data and the theory is therefore usually explained by the contact thermal resistance at the boundary between the solid wall and the molten metal, which is not allowed for by the theory. Various hypotheses have been put forward on the nature of this resistance but as yet there has been no decided point of view.

If we assume that the Martinelly-Lyon theory is true with all its assumptions and the only reason for the discrepancies in the experimental data both among themselves and with the theoretical equation is the contact thermal resistance then, without making assumptions as to the nature of this additional resistance and without going more deeply into the problem as to whether the oxides are the only reason for its appearance, it should be mentioned that the fact of existence of a contact resistance leads to consequences which are interesting from a practical point of view although as yet little attention has been paid to these consequences. In fact, in such a case it should be assumed that the coefficient of heat transfer measured in the experiments is essentially a coefficient of heat transfer from the wall to the stream of coolant through a contact layer.

We will analyze the possible effect of the contact thermal resistance \( R' \) (in \( \text{m}^2 \text{hr} \cdot \text{C/kcal} \)) on the relationship of the coefficient of heat transfer \( \alpha \) measured in the experiments and the coefficient of heat transfer \( \alpha_0 \) calculated from theoretical formulas.

From the relationship

\[
\frac{1}{\alpha} = \frac{1}{\alpha_0} + R'
\]

we obtain

\[
\frac{\alpha}{\alpha_0} = \frac{Nu}{Nu_0} = \frac{1}{1 + R' \frac{\lambda_1}{d} Nu_0},
\]

where \( \alpha_0, Nu_0 \) are the coefficient of heat transfer and the Nusselt criterion, calculated according to the theoretical Martinelly-Lyon equation; \( \lambda_1 \) is the coefficient of thermal conductivity of the liquid metal; \( d \) is the internal diameter of the tube. If follows from relationship (2) that the results of experiments obtained on a tube of one diameter using a coolant of a certain degree of purity and represented in the form of the dependence Nu(Pe) cannot be recommended for calculating heat transfer in tubes of another diameter without knowing how \( R' \) depends on the diameter of the tube and the flow rate of the liquid metal.
In fact, writing the relationship (2) for tubes of a different diameter with a fixed value of the Pe number, we obtain

$$\frac{Nu_1}{Nu_0} = \frac{1 + R'_1 \frac{\lambda_1}{d} Nu_0}{1 + R'_2 \frac{\lambda_1}{d} Nu_0}.$$

Hence it can be seen that only in the case where the ratio of the Nu numbers is equal to unity can the experimentally obtained Nu be used in the calculation for another diameter and this in its turn is only possible when the contact thermal resistance is absent or changes so that the value \(R' \lambda_1/d\) remains constant for a constant value of Pe, i.e., \(R'\) changes in proportion to the diameter of the tube when Pe = const. However, as already mentioned, due to the lack of information on the nature of the contact resistance there is not yet any basis for assuming the same character of dependence of \(R'\) on the tube diameter.

If the contact resistance is only due to physical properties of the actual interface region, i.e., if for a certain degree of contamination of the coolant by oxides for a given all-liquid metal pair the value \(R'\) remains constant at different flow rates and is independent of the radius of curvature of the surface, then from the relationships (1) and (2) it follows that the best coincidence of the experimental data with the theory should occur when using tubes of a larger diameter. This feature is noticed when analyzing the results of the experiments.

Since the values of \(\alpha\) measured in experiments with the presence of thermal contact resistance in accordance with relationship (1) depend on the two values \(\alpha_0\) and \(R'\), each of which obey different laws of similarity, then for a reliable comparison of the experimental data obtained under various conditions with one another and with the results of theoretical solutions the criterial equation of heat exchange should contain a complex of determining values \((R' \lambda_1/d)\), considering the degree of the effect of contact resistance on the process of heat transfer (the contact criterion).

We will explain these ideas with an example. We will assume that in the turbulent flow of sodium in a 24-mm diameter tube \((Re > 10^4)\) an experimental curve of Nu(Pe) is obtained, 5% lower than the theoretical Martinelly-Lyon curve, i.e., \(Nu/Nu_0 \approx 0.95\). It is assumed that this accuracy points to good agreement with the theory since usually the error of the experiment is ±10%.

We will evaluate the thermal contact resistance. For example, for \(Pe = 200\) the value \(Nu = 8.73\) and for \(\tau = 240^\circ C\) the value \(\lambda = 68\) kcal/m·hr·°C. Substituting the values of \(Nu_0\) and \(\lambda_1\) in relationship (2) we obtain \(R' = 2.13 \times 10^{-6}\) m²·hr ·°C/kcal, which agrees well with the data of [10].

We will assume that the value \(R'\) is only determined by the physical properties of the interface region and is independent of the tube diameter and the conditions of motion of the coolant. Then for the same conditions and the same purity of the liquid sodium, but for a tube of diameter not 24 mm but 3 mm in accordance with relationship (2) we obtain \(Nu/Nu_0\) i.e., the lack of agreement with theory will be not 5 but 30%.

In the literature there are not experimental studies in which the purity of the liquid metal was kept constant and only the diameter of the tube was varied. It was therefore not possible to follow the dependence of \(R'\) on the diameter at constant rates and medium temperature of the coolant.

We will try to establish the character of the dependence of \(R'\) on the flow rate for a constant tube diameter, assuming that the Martinelly-Lyon theory is true and the difference between the experimental data and the theoretical data is only due to the presence of contact thermal resistance at the wall-liquid metal boundary.

For this purpose we will use the experimental data of [4] on the heat transfer of liquid sodium in a copper tube of 8.6 mm diameter at \(t_1 = 240^\circ C\). These data are satisfactorily approximated by the formula \(Nu = 5.9 + 0.015\text{-Pe}^{0.8}\), according to which in the range of numbers Pe = 200-1400 the ratio \(Nu/Nu_0 = 0.75\). Then for \(\lambda = 8.6\) kcal/m·°C·hr, \(R' = 2 \times 10^{-6}\) Nu ·°C/kcal. Since the experiments were carried out using a tube of one diameter, for the mean temperature of the coolant of 240°C and the same purity of liquid metal as in the experiment, it was possible to find the character of the dependence \(R' = \text{f}(\text{Pe})\).

*The possibility of a larger effect of the contact resistance in small diameter tubes was first mentioned by Poppendick [14].