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TURBULENT HEAT TRANSFER IN A FLOW OF LIQUID METALS

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Аннотация—Работа посвящена экспериментальному исследованию турбулентного переноса тепла в потоке жидких металлов.

Проведено одновременное измерение температурного поля в потоке и коэффициента теплоотдачи методами, учитывающими термическое контактное сопротивление на границе раздела фаз.

При этом удалось достаточно чётко разделить два явления, определяющих передачу тепла в жидких металлах: совместный молекулярный и турбулентный перенос тепла, описываемый полуэмпирической теорией теплообмена, и имеющее место в жидких металлах термическое контактное сопротивление на поверхости теплообмена, вызываемое выпаданием окислов жидких металлов в районе ламинарного подслоя и другими факторами.

Проведенные исследования показали, что при учёте термического контактного сопротивлония полученные экспериментальные данные хорощо совпадают с расчётными, основанными на полуэмпирической теории теплообмена.

NOMENCLATURE

r_0, tube radius;

$\xi = \frac{r}{r_0}$, relative co-ordinate of point;

ϵ_a, turbulent heat transfer coefficient;

ϵ_j, turbulent momentum transfer coefficient;

R_c, thermal contact resistance;

t_u, wall temperature;

q, local heat flow;

q_u, heat flow at wall;

λ, heat conductivity;

u, flow velocity at given point;

w, characteristic velocity.

In their present state of development, turbulent theories do not permit an analytical determination of turbulent heat transfer in a liquid flow. Semi-empirical heat transfer theories based on the analogy between heat and momentum transfer are therefore widely used. Using various assumptions, the authors calculated turbulent heat transfer, determined the temperature field in a liquid flow and the heat transfer coefficients. The validity of assumptions in semi-empirical theories may be verified by experiments on measurement of temperature fields in liquid metals. Because of the high thermal conductivity of liquid metals the main temperature drop is not just concentrated within the thin laminar sub-layer as in ordinary low heat-conducting fluids but it extends into the turbulent bulk flow. This allows sufficiently accurate experimental determination of temperature gradients across the section of a tube and reliable verification of assumptions for semi-empirical heat transfer theories.

Martinelli was the first to apply the theory of the hydrodynamic analogy to liquid metals taking account of molecular heat conduction in a turbulent main stream. The assumption was made in calculations that the ratio of turbulent heat and momentum transfer coefficients ($\epsilon = \epsilon_a/\epsilon_\nu$) does not depend on the radius and velocity of the flow. Lyon obtained the general equation for the heat transfer coefficient in a tube:

$$\frac{1}{\bar{Nu}} = 2\int_0^1 \frac{\int_0^1 \frac{u}{w}\,\xi \mathrm{d}\xi}{1 + \epsilon\frac{\epsilon_\nu}{\nu}p_\eta}\,\mathrm{d}\xi \qquad (1)$$

where

$$\xi = r/r_0.$$

Using Martinelli's main assumptions he presented the calculation results for $\epsilon = 1$ as a formula

$$Nu = 7 + 0{\cdot}025\, Pe^{0{\cdot}8}. \quad (2)$$

The majority of experimental data on heat transfer to liquid metals have been obtained under conditions where the percentage of oxides and purity of the heat transfer surface was not under control and is noticeably below the values calculated by formula (2). Before temperature fields were measured reliably in liquid metal flow, the opinion existed that the reason for divergence between experimental data and the Martinelli–Lyon theory lay in the non-validity of the assumption that $\epsilon = 1$. Using the high thermal conductivity of liquid metals as a basis, Voskresensky, Deissler *et al.* made an analytical attempt to take into account heat transfer by conduction from separate moles into the surrounding medium. The value of ϵ turned out to be noticeably less than unity. In determining ϵ Voskresensky, Likoudis and Touluk'yan tried to use experimental data on heat transfer to liquid metals; however the authors erroneously assumed that in these data there was no thermal contact resistance. This led to an unjustifiably low estimate of turbulent heat transfer and, consequently, of ϵ for liquid metals.

In our opinion, the thermal contact resistance on a heat transfer surface is one of the reasons for divergence between various experimental data and these data and formula (2). Apparently, the value of this resistance depends upon the kind and purity of the liquid metal, wall material and upon several other factors. For evaluating the role of the thermal contact resistance the heat transfer coefficient may be determined by two methods:

(1) by measuring and treating the temperature field in a flow of liquid metals,

(2) by measuring wall temperature and average temperature of the liquid metal.

On the basis of temperature fields measured in a liquid flow the turbulent heat transfer coefficient may also be determined and the value ϵ calculated for liquid metals and water.

This paper presents the results of experiments on determining the heat transfer coefficients and on measuring the temperature fields in a flow of different alkali and heavy liquid metals (sodium, mercury, etc.). The metals investigated are notable for rather a wide range of number $Pr = 0{\cdot}005$–$0{\cdot}05$. Several tests on measuring the temperature fields were carried out with water ($Pr \simeq 10$).

Experimental section I on which heat transfer to the alkali metals was investigated is horizontal. The block of a movable thermocouple was attached to the tube with a gliding fit and sealed with "sphere-in-cone connexion". The thermocouple, of an alundum wire (nichrome and constantan 0·2 mm in diameter) was inserted into a stainless capillary 0·8 × 0·15 mm in diameter. The end of the casing was sealed integrally with thermo-electrodes. The displacement of the thermocouple over the tube diameter was carried out using a joint protected by a bellows. The accuracy of displacement along the diameter was ensured by guides at the end of the thermocouple block. The location of the thermocouple in the tube was shown by a dial indicator. The calibration was carried out by a periscope РВП-457 to within 0·1 mm.

In the same section as the movable thermocouple, three nichrome–constantan thermocouples were attached to the wall of the tube. Their junctions were sealed to the wall of the tube. A heat flow was created by a nichrome heater made out of wire 3 mm in diameter and insulated from the wall by a uniform mica layer 0·4 mm in thickness. Radial heat leakage was measured and compensated for. Over the liquid metal velocity range investigated in section I the inertia forces exceeded gravitational ones.

Experimental section II on which experiments with heavy metals and water were carried out, was located vertically. The liquid flowed upwards. The temperature field was measured simultaneously with two movable thermocouples situated in one sonde; it ensured mutual control in the readings. The thermocouples were made of alundum thermo-electrode chromel–alumel wire 0·1 mm in diameter. The cover was 20 mm in thickness.

Two thermo-electrodes were placed in one capillary 0·5 × 0·1 mm in diameter in stainless

steel IXI8H9T. The end of the capillary was sealed together with the thermo-electrodes forming a hot junction of the thermocouple. In experiments with water the junction of the thermocouple 0·2 mm in diameter was open. The displacement of the thermocouples along the diameter was carried out by two reversible electric motors. The accuracy of displacement was secured by the guides. The location of the thermocouples in the tube was determined by a revolution counter within 0·01 mm. In the same section where the movable thermocouples travelled two other similar thermocouples were attached to the wall of the tube. Their junctions were sealed to the tube wall. The heat flow was created by an electric heater made out of nichrome band 6 × 0·2 mm in section and insulated from the tube with a uniform micalex layer 0·3 mm in thickness. Radial heat leakage was compensated for by an external heater. Main characteristics of the experimental sections are given in Table 1.

Table 1. *Leading particulars of experimental sections*

Name		Section I	Section II
Tube material			Steel IXI8H9T
External tube diameter (D) (mm)		42	34
Internal tube diameter (d, $2ra$) (mm)		31·1	29·3
Length of heat transfer section (mm)	l_h	1194	980
	l_h/d	38	34
Distance from beginning of heating section to thermocouples (mm)	l_{th}'	976	945
	l_{th}'/d	31	32
Distance from tube entry to thermocouples (mm)	l	1166	985
	l/d	37	34

When testing the average temperature of the liquid metal both the entrance to and exit from the experimental section were measured. All the thermocouples were graduated by calibration platinum platinum–rhodium thermocouples. The measurement of electric power was carried out by astatic wattmeters of the 0·2 and 0·5 grades. Liquid metal rate was measured by magnetic and restrictive flow meters. When testing the alkali metals they were subjected to continuous purification from oxides in a cold trap. Oxygen percentage was within the range of 0·02–0·05 per cent by weight. Heavy metals were not subjected to continuous purification. At the beginning of the experiment the oxygen percentage was $\sim 1 \times 10^{-3}$ per cent by weight and did not change during the experiment.

When measuring temperature fields in liquid flow, turbulent pulsations were found, the value of which attained ±20 per cent of the value of the total temperature. In experiments it was found that the amplitude and frequency of pulsations depended on the value of the heat flow, physical properties, liquid flow regime and dimensionless distance from the wall. In liquid metals where a temperature gradient change over the tube section occurs smoothly, maximum pulsations were observed approximately in the middle region between the centre and the wall of the tube. The maximum pulsations were observed near the wall in water which has a sharp temperature gradient in the layer near the wall.

Such a change of temperature pulsations over the tube radius qualitatively agrees with the hypothesis that the value of turbulent temperature pulsations is proportional to mixing length and temperature gradient. At the same time experiments showed that the temperature pulsations on the axis and near the wall of the tube were not equal to zero. Temperature pulsations were also observed in the tube wall itself but somewhat different from those in the liquid. The liquid temperature pulsations near the wall and temperature vibrations of the wall itself denote that the heat transfer process through the liquid layer near the wall and through the heat transfer surface is not, strictly speaking, stationary (steady).

Temperature measurement in the flow of liquid metal was carried out with the help of movable thermocouples fixed at nine to twelve points with respect to the tube radius. The movable thermocouples were differentially connected with the thermocouples fixed at the entrance to the section. For reliable determination of the average temperature values indications of all the thermocouples were recorded on

diagrams of self-balancing fast potentiometers ЭПП-09 with limits of scale 0–0·5 mV connected in series with the low-ohmic potentiometer. The readings of thermocouples recorded for 30 to 50 s were averaged in time and plotted on diagrams with co-ordinates $(t - t_{u_s})$, ξ.

The wall temperature required for calculating the heat transfer coefficient was determined by extrapolation of the temperature profile on the wall. The validity of extrapolation was verified by the boundary condition:

$$\left.\frac{dt_e}{dr}\right|_{r=r_0} = \frac{q_w}{\lambda_e}. \quad (3)$$

The average temperature of the liquid metal flow was calculated by the formula:

$$\bar{t}_e = \frac{\int_0^{r_0} ut_e r dr}{\int_0^r ur dr}. \quad (4)$$

In calculations the universal law of velocity distribution was used

$$u^+ = 5{\cdot}5 + 2{\cdot}5 \ln y^+. \quad (5)$$

The application of other equations of the velocity distribution in a tube slightly alters calculation values of the average temperature of a liquid metal.

It is interesting to note that the dimensionless radius where the local temperature of a liquid is equal to the average, is the same for all the liquid metals investigated and equal to 0·7–0·75. It agrees with the theory and the results of other experimental works.

The values of *Nu* obtained by working out the temperature fields measured in a flow of liquid metals agree well both amongst themselves and with earlier results obtained with alloys of sodium, potassium and mercury. The coincidence of experimental data with Lyon formula (2) over rather a wide range of $Pe = 100$–$12\,000$ is observed. It shows that the heat transfer process without accounting for surface phenomena at the "wall–liquid metal" boundary is described by a common critical ratio (2) both for alkali and heavy liquid metals.

However the coincidence between experimental data with formula (2) does not confirm the Lyon assumption that the ratio of turbulent heat and momentum transfer coefficients $\epsilon = \epsilon_a/\epsilon_\nu$ does not change over the tube section and is equal to unity at all *Pe* numbers. As the further calculation of the obtained data on temperature fields demonstrated the ratio of turbulent heat and momentum transfer coefficients does change over the tube radius and depends on *Pe*. In the region of small *Pe* numbers the relation ϵ is somewhat less than unity, but at great *Pe* numbers, slightly exceeds it.

In experiments the heat transfer coefficient was also determined by methods taking into account the thermal contact resistance on a heat transfer surface. Considerable errors appear when measuring the mean temperature drop between a liquid metal with high heat conductivity (alkali metals) and the wall of stainless steel to which the thermocouples were attached.

To confirm the obtained values of heat transfer coefficients taking account of the thermal contact resistance, the transient method of measuring was also used. Results of experiments treated in criterial form are given in Fig. 1. Experimental data for alkali metals agree satisfactorily with formula (2); for heavy liquid metals these data are considerably below this formula.

The coincidence of data on alkali metals obtained by different methods (with and without regard to the thermal contact resistance) shows the absence of the thermal contact resistance in experiments. This fact together with the results of the work carried out earlier on an alloy of sodium and potassium permits the conclusion that in some cases after thorough purification of alkali metals from oxides it is possible to avoid thermal contact resistance altogether. For heavy metals the difference in values of heat transfer coefficients obtained by different methods shows the presence of the thermal contact resistance on the wall–liquid metal boundary. Simultaneous measurement of the temperature distribution in the wall and in the flow of liquid metal enabled the calculation to be done of the thermal contact resistance of liquid metal flow down a stainless steel pipe (IX18H9T) (18% chrome steel). It was determined by the formula:

$$R_c = \frac{t_w^{II} - t_w^{I}}{q_w},$$

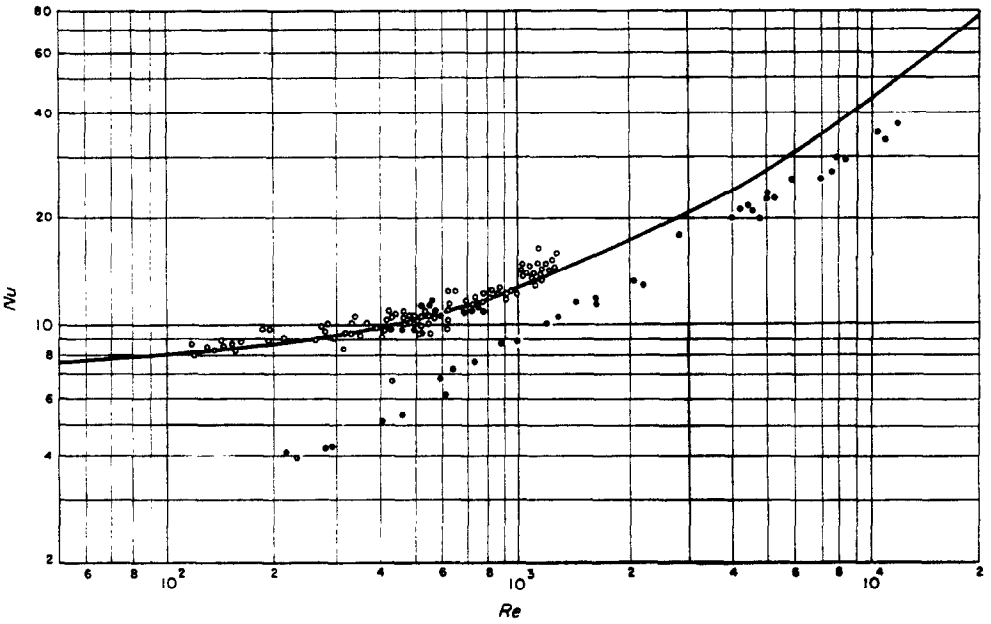

FIG. 1. Data on heat transfer to liquid metals obtained by methods taking into account thermal contact resistance.

Alkali metals:
◓ —stationary measurement method,
○ —non-stationary measurement method.
●◑ —Heavy metals,
—— —calculation curve by formula (2).

where t_w^{II} and t_w^{I} are found by two methods (from the wall side and liquid side). The results obtained are plotted in Fig. 2. Under these conditions of testing the value of the thermal contact resistance was not kept constant and depended on the liquid metal flow rate to the same degree as the thickness of a laminar sub-layer. Hence, we may assume that the thermal contact resistance is proportional to the thickness of the laminar sub-layer, and, consequently, to the tube diameter. This conclusion is confirmed by the fact that in criterial treatment the experimental data obtained on tubes with different diameters (9–30 mm) coincide. The values of the thermal contact resistance plotted in Fig. 2 may be presented in a dimensionless form:

$$\frac{R_c\lambda_e}{d} = 6 \times 10^{-3} + \frac{1300}{Re}. \qquad (6)$$

The given formula is not, apparently, a generalized relation for all the heavy liquid metals but is valid only for the specific conditions under which experiments were carried out.

The facts obtained allow to some extent clarification of the physical meaning of the thermal contact resistance in a flow of heavy liquid metal in tubes. The deposition of a film of liquid metal oxides in the region of the laminar sub-layer is one of the reasons for the appearance of thermal contact resistance. Therefore for constant temperature of the liquid metal and for constant percentage of oxides in it, the value of the thermal contact resistance depends mainly on the same factors as does the thickness of the laminar sub-layer (upon flow rate of the liquid metal and the tube diameter). Chemical analysis showed that, in fact, the concentration of oxides near the wall was one order greater than in the bulk flow of liquid metal. The mechanism of the thermal contact resistance may differ for different liquid metals as well as for various materials for the heat transferring surface.

A simultaneous change both of temperature

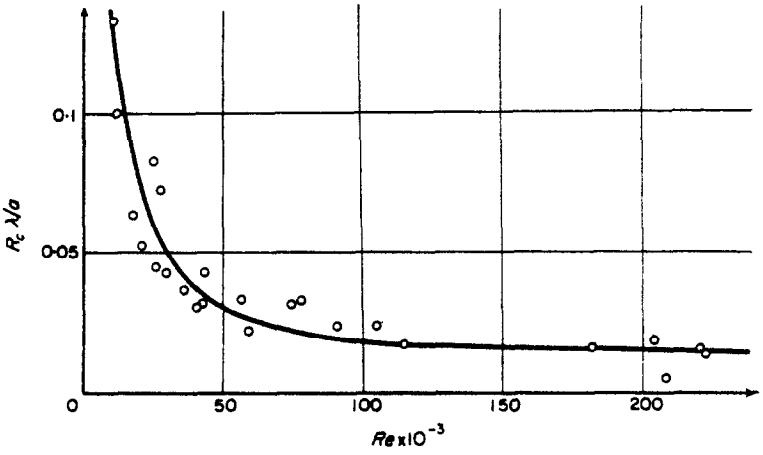

FIG. 2. Thermal contact resistance in a flow of heavy liquid metal in a tube of steel IXI8H9T.

fields in the flow and heat transfer coefficients carried out by methods taking into account the thermal contact resistance allowed a fairly definite distinction to be drawn between the two processes determining heat transfer to liquid metals. The first process, bound up with molecular and turbulent transfer of heat, may be described by semi-empirical heat exchange theories. Experiments have shown such heat transfer to be described to a first approximation by the Martinelli–Lyon theory. At present the second process caused by the thermal contact resistance on a heat transfer surface cannot be estimated theoretically.

Calculation from the temperature fields measured allowed the determination of turbulent heat transfer in liquid flow. The turbulent heat transfer coefficient was derived from the equation:

$$\epsilon_a = \frac{q/q_w}{\partial t/\partial \xi}\frac{r_0 q_w}{c_p \gamma} - a. \tag{7}$$

The ratio of local heat flux to the flow along the wall was obtained from the relations involving heat balance of an elementary liquid volume and from the application of the universal law of velocity distribution:

$$q/q_w = \frac{1}{\xi}\frac{u^*}{w}\left[(4{\cdot}25 + 2{\cdot}5 \ln y^+)\,\xi^2 - 2{\cdot}5\,(1-\xi^2)\ln\frac{r_0}{y}\right]. \tag{8}$$

Equation (8) is valid only for the turbulent mainflow, i.e. at $y^+ \geqslant 30$.

When dealing with experimental data the determination of local temperature gradients gives the greatest difficulty. For some experimental data the following formula describing the temperature field was chosen:

$$t - t_{u_s} = A\xi^2 + B\xi^3 + C\xi^4. \tag{9}$$

Coefficients in the series were determined by the method of least squares. The temperature gradient was determined by differentiation. The graphical differentiation of the temperature fields was carried out as well. Values of the temperature gradients obtained by analytical and graphical methods agreed well between themselves. The temperature gradients calculated by the graphical method were applied to determining ϵ_a by formula (7). In Fig. 3 the distribution of the turbulent heat transfer coefficient over the tube section is given. The coefficient ϵ_a increases both with *Re* and with distance from the wall. It should be noted that the coefficient ϵ_a is not equal to unity on the axis of the tube. However since there is considerable error when determining ϵ_a in the central region of the flow ($\xi < 0{\cdot}4$), it is difficult to speak of a precise value of this coefficient in the centre of the tube.

Heat transfer even to liquid metals possessing high heat conductivity is determined, to a

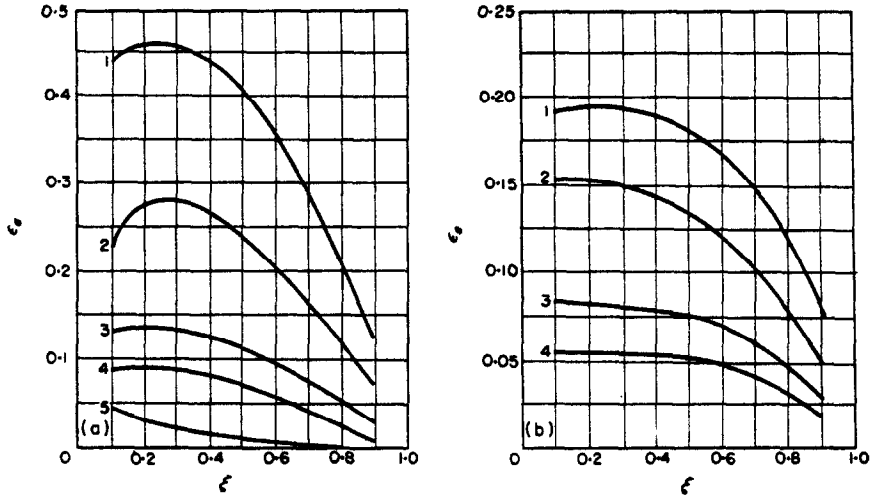

FIG. 3. Distribution of turbulent heat transfer coefficient over the tube sections at different *Re* numbers.

(a) heavy metal: $\lambda \cong 10$ kcal/m hr °C,
1—$Re = 200\,000$, 2—$Re = 120\,000$,
3—$Re = 60\,000$, 4—$Re = 38\,000$,
5—$Re = 121\,000$;

(b) alkali metal: $\lambda \cong 40$ kcal/m hr °C,
1—$Re = 24\,500$, 2—$Re = 16\,500$,
3—$Re = 11\,000$, 4—$Re = 7900$.

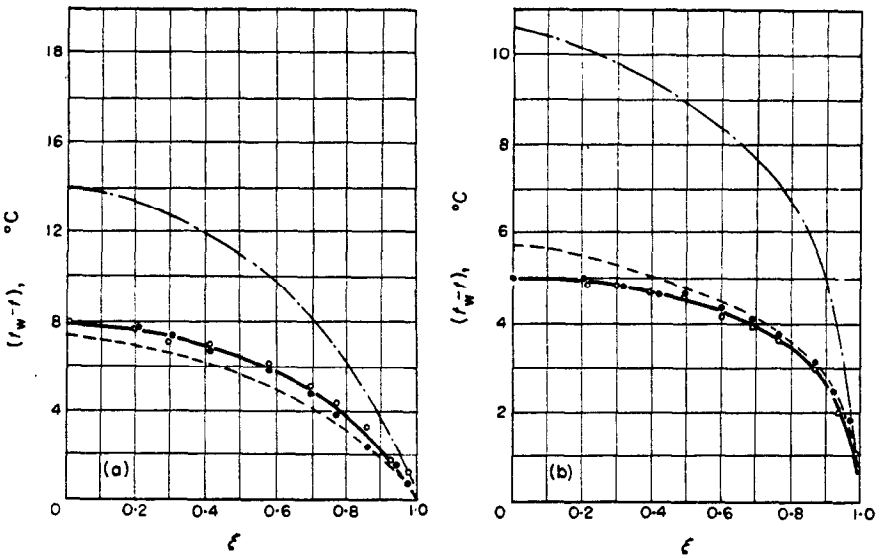

FIG. 4. Comparison between temperature fields determined experimentally in heavy liquid metal flow with calculated values.

(a) $Re = 26\,900$, $Pr = 0{\cdot}022$, $q = 18\,700$;
(b) $Re = 228\,000$, $Pr = 0{\cdot}022$, $q = 47\,600$.

——— curve averaging experimental points,
– – – – – curve calculated by the Lyon equation (1),
—·— curve calculated by the Voskresensky formula.

marked degree, by turbulent heat transfer. At large numbers of $Re \sim 200\,000$ such heat transfer plays the determining role. In his calculations Voskresensky overestimated the value of molecular heat transfer. Comparison between temperature fields determined experimentally and those calculated by the Lyon and Voskresensky theoretical relations leads to the same conclusion (Fig. 4). The temperature profile calculated by the Voskresensky theory lies considerably above the experimental points. The experimental data coincide with the temperature profile calculated from the Lyon ratio (1) more satisfactorily. At low numbers of $Re \sim 30\,000$ experimental points lie above and at large numbers of $Re \sim 200\,000$ below the Lyon curve.

Apparently, the assumption that $\epsilon = 1$ leads to overestimation of the turbulent heat transfer at low, and to underestimation at high numbers of *Re*. Such a character of change of ϵ depending on *Re* is quite understandable. Probably, at small *Re* numbers heat losses transferred by a mole due to high liquid heat conduction may be greater than momentum losses, i.e. ($\epsilon < 1$). With highly developed turbulent flow moles may appear whose momentum vanishes quicker than heat ($\epsilon > 1$). In Fig. 5 the dependence of ϵ on *Re* at $\xi = 0{\cdot}8$ is given for different liquids; liquid metals ($Pr \ll 1$) and water ($Pr \simeq 10$). The value ϵ_ν was calculated by the formula:

$$\epsilon_\nu = \frac{u^*(1 - y/r_0)}{2{\cdot}5} - \nu. \tag{10}$$

Within the accuracy of experiments we may assume that the *Pr* number hardly influences the coefficient ϵ. Probably, the mechanism of turbulent heat transfer for different liquids differs only slightly in the different cases and is mainly determined by the hydrodynamics of the flow. Experiments showed that the value ϵ changes with the increase in the distance from the wall, however, in the region which determines heat transfer ($\xi = 0{\cdot}5$–$0{\cdot}9$) this value appeared to be approximately constant.

Experimental values of the coefficient ϵ_ν were used for determining *Nu* by formula (1). The *Nu* numbers determined by this method are described by formula (2) satisfactorily and coincide well with the values obtained by calculating the average temperature drop from the temperature profile.

The investigation on temperature fields in a flow of liquid metals allows experimental determination to be done of the value of turbulent heat transfer coefficients and confirmation of the validity of assumptions of semi-empirical heat transfer theories, but we still are unable to improve on our knowledge of the heat transfer process itself. Apparently, only a thorough analysis of turbulent temperature and velocity pulsations will make it possible to develop a fundamental heat transfer theory.

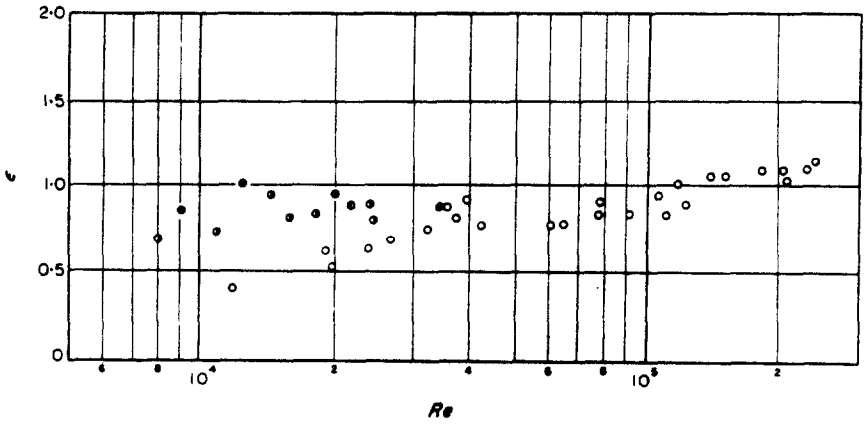

FIG. 5. Dependence of ϵ on *Re* at $\xi = 0{\cdot}8$ for different liquids ●—water ($Pr \sim 10$); ◑—alkali metal ($Pr \sim 0{\cdot}05$); ○—heavy metal ($Pr \sim 0{\cdot}02$).

Abstract—The present paper deals with experimental investigations into turbulent heat transfer in a flow of liquid metals.

Measurement of the temperature field in the flow as well as the heat transfer coefficient is carried out by methods which take the thermal contact resistance at an interface into consideration.

Two phenomena characterizing heat transfer in liquid metals are distinguished with sufficient accuracy, i.e. combined molecular and turbulent heat transfer, described by a half-empirical heat transfer theory, and the thermal contact resistance in liquid metals on a heat transfer surface, caused by the precipitation of liquid metal oxides in the region of a laminar sublayer and by a number of other factors.

The investigations show that the experimental data agrees well with calculated data based on the half-empirical heat transfer theory when the thermal contact resistance is taken into account.

Résumé—Cet article concerne des recherches expérimentales sur la transmission de chaleur turbulente dans un écoulement de métaux liquides.

Les mesures du champ de température dans l'écoulement et du coefficient de transmission de chaleur sont effectuées selon des méthodes qui tiennent compte de la résistance thermique de contact à l'interface.

Deux phénomènes caractéristiques de la transmission de chaleur dans les métaux liquides sont mis en évidence avec une préision suffisante: d'une part, la transmission de chaleur turbulente et moléculaire, décrite par une théorie semi-empirique de la transmission de chaleur et d'autre part, la résistance thermique de contact sur une surface d'échange due au dépôt d'oxyde métallique liquide dans la région de la sous couche laminaire et à d'autres facteurs.

Les recherches montrent que les données expérimentales sont en bon accord avec les résultats du calcul fait à partir de la théorie semi-empirique de transmission de chaleur, quand on tient compte de la résistance thermique de contact.

Zusammenfassung—Der Wärmeübergang bei turbulent strömenden flüssigen Metallen wurde experimentell untersucht.

Die Messung sowohl des Temperaturfeldes in der Strömung als auch des Wärmeübergangskoeffizienten erfolgte nach Methoden, die einen thermischen Kontaktwiderstand an den Berührungsflächen berücksichtigen.

Zwei charakteristische Erscheinungen des Wärmetransports in flüssigen Metallen zeichneten sich mit genügender Genauigkeit ab: nämlich, der kombiniert molekulare und turbulente Wärmetransport, der durch eine halbempirische Wärmetransporttheorie wiederzugeben ist und der thermische Kontaktwiderstand der flüssigen Metalle an der Wärmeübergangsfläche. Dieser Kontaktwiderstand tritt als Folge der Ausscheidung von Metalloxyden in einer laminaren Unterschicht und anderen Ursachen auf.

Die Untersuchungen zeigen gute Übereinstimmung zwischen experimentellen und gerechneten Werten. Letztere wurden mit Hilfe der halbempirischen Wärmetransporttheorie unter Berücksichtigung des thermischen Kontaktwiderstandes ermittelt.