# HEAT TRANSFER TO MERCURY IN LAMINAR AND TURBULENT PIPE FLOW

Ulrich GRIGULL

Institute of Technical Thermodynamics
Technical University Munich
Munich, Federal Republic of Germany

Herbert TRATZ

Institute of Technical Thermodynamics
Technical University Munich
Munich, Federal Republic of Germany

## Symbols

$D$ inside diameter of the test pipe

$F$ area

$J$ current

$L$ length of the testsection

$U$ voltage

$g$ gravitational acceleration

$q$ heat flux

$w$ local velocity

$\bar{w}$ mean velocity of a cross section

$\alpha$ heat-transfer coefficient

$\vartheta$ temperature

$\vartheta_c$ temperature in the centre

$\vartheta_m$ mean mixed temperature

$\vartheta_w$ wall temperature

$a=\lambda/c_p\varrho$ thermal diffusivity

$\beta$ coefficient of thermal expansion

$c_p$ specific heat at const.pressure

$\lambda$ thermal conductivity

$\eta$ viscosity

$\nu=\eta/\varrho$ kinematic viscosity

$\varrho$ density

$Nu=\alpha D/\lambda$ Nusselt number, calculated with the temperature difference between wall temperature and mean mixed temperature

$Nu_c$ Nusselt number, calculated with the temperature difference between wall and centre line

$Re=\bar{w}D/\nu$ Reynolds number

$Pr=\eta c_p/\lambda$ Prandtl number

$Pe=\bar{w}D/a = Re\cdot Pr$ Peclet number

$Gr=g\beta(\vartheta_w-\vartheta_c)D^3/\nu^2$ Grashof number

## Introduction

The object was to obtain the necessary data for the design of heat exchangers for use with liquid metals. A number of heat transfer measurements were made. The results obtained from these experiments gave lower heat transfer coefficients than expected, both for laminar and turbulent flow.

Particularly large deviations were found in the laminar region of pipe flow. In the case of the measurements of Johnson, Hartnett and Clabaugh [1], which were made with mercury and a lead-bismuth alloy, the exact theoretical solution would have given a Nusselt number of 4.36 for constant heat flux, independent of the value of the Reynolds number or the Peclet number. The experimental results, however, exhibited a considerable dependence.

A number of causes were assumed to be responsible for these deviations, among them the following:

Thermal contact resistance at the interface of the liquid metal and the pipe, due to an oxide layer, a gas film, impurities, or the effect of all three together.

Decrease in the thermal conductivity of the liquid metal by entrapped gas bubbles.

Longitudinal heat conduction in the fluid and in the pipe wall.

Influence of free convection on the heat transfer.

Abnormal hydrodynamic behaviour of the liquid metals could be eliminated as a possible cause after the authors had proved by experiment that mercury behaves hydrodynamically as a normal liquid [2].

Petukhov and Yushin [3] showed that the measurements made in the laminar region by Johnson and other workers were faulty. Their own measurements agreed very closely with theory. Unfortunately, the effect of longitudinal heat conduction could not be eliminated from these measurements due to the method used to obtain them. It was considered in the calculations, although simplifying assumptions had to be made. It appeared necessary, therefore, to make further measurements of heat transfer with liquid metals [4] in order to bring final clarification to questions still open in this field, particularly in the laminar region.

Measuring procedure and description of apparatus

The temperature profiles in fully developed laminar pipe flow with constant fluid properties and constant heat flux at the wall can be calculated exactly. It is found that the axial rise of all temperatures is linear.

This exact solution is particularly valuable, since this case can well be realized in measuring technique by electrical resistance heating. In consequence, it was used for the present measurements.

The Nusselt number is here defined by the expression

$$Nu = \frac{q\,D}{\lambda(\vartheta_w - \vartheta_m)} \qquad (1)$$

In this expression, $\vartheta_m$ is the mean mixed temperature of the fluid and $\vartheta_w$ the wall temperature at the same cross-section. The measurements of the mean mixed temperature in a mixing chamber would, however, have interrupted the linear temperature rise required by the theory. In the present investigations, therefore, the fluid temperature was measured at the pipe centre and the Nusselt number referred to the temperature difference between wall and centre. Because of easy handling and good knowledge of properties mercury was selected as the experimental fluid.

In order to eliminate all conceivable sources of error the apparatus was required to satisfy certain conditions. During the preliminary handling and in the apparatus itself the mercury was to come into contact only with such materials with which there would be absolutely no chemical reaction within the temperature range selected (25 - 100 °C). This condition was satisfied by plain low carbon steels, ferretic chromium steels and quartz glass. All seals had to be made without inserts of other materials, i.e. it was necessary to seal with steel against steel and with steel against quartz glass. Since these materials are resistant to mercury for longer periods only in the absence of oxygen, it had to be possible to evacuate the apparatus completely. It had further to be made vacuum tight for measurements without protective gas, since the vapour pressure of mercury at 25 °C amounts to only approximately $2.10^{-3}$ Torr. For measurements made with protective gas (in the present case argon) in order to study its effect on heat transfer, it had to be possible to fill the apparatus with such a gas during operation.The arrangement of the apparatus is shown schematically in Fig.1 .

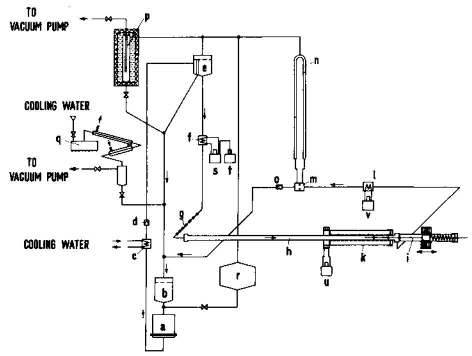


Fig.1 : a Helical induction pump, b Cooler, d Throttling valve, e Head tank, f Heat exchanger, g Heater, h Test pipe, i Thermocouple probe, k Compensating heater, l Cooler, m Orifice meter, n Manometer, o Control valve, p Condenser, q Distilling apparatus, r Sump tank, s,t,u and v Temperature controlled baths.

The helical induction pump a [5] moved the mercury from the reservoir b to the head tank e, any excess mercury being able to return directly to the reservoir by way of the overflow pipe. The remainder flowed through the heat exchanger f and the heater g to the test pipe h.

The heat exchanger f damped any possible temperature fluctuations. In the test pipe, the mercury first passed through the hydrodynamic smoothing section and then in the d.c. heated section through the thermal entrance section and the test section. At four points along the test section the wall temperature was measured with fixed thermocouples and the temperature of the fluid at the centre with a fixed thermocouple probe i. A large part of the test was carried out with a fixed thermocouple probe. Later it was replaced by the moveable thermocouple probe shown in Fig.1 , with which the fluid temperature was measured at four points opposite the wall-mounted thermocouples.

Behind the test pipe, the mercury flowed through the cooler $\ell$ , the orifice meter m and the control valve o, and back to the reservoir b. The orifice meter had three interchangeable orifice plates with different sizes of orifice which had previously been calibrated with mercury. In the cooler $\ell$ the mercury was cooled down to 25 $^{o}$C, the calibration temperature of the orifice meter.

The test pipe was a seamless drawn precision tube of ferritic chromium steel, 14.17 mm inside diameter and 16.20 mm outside diameter. The test section (Fig.2) was equipped with four thermocouples for measuring the wall temperature. Another four thermocouples were fitted into the two other parts of the test pipe (See Fig.2).

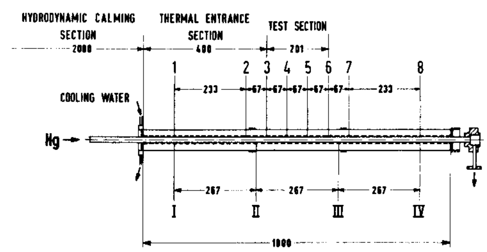


Fig.2: Test pipe with compensating heater, arrangement of the thermocouples.

At the points marked with Arabic numerals the electromotiv force is measured by the compensation method with a Diesselhorst compensator and at the other four points marked with Roman numerals with a millivoltmeter. The accuracy of this instrument was sufficient at these latter points, since these thermocouples served for balancing the compensating heater.

Scope of experiments

With the fixed thermocouple probe the heat transfer was measured within the temperature range of 30 - 85 $^{o}$C without and with argon as protective gas at position 6 (Fig.2) of the test section. The heat flux was only small to ensure that only small temperature differences occured in the mercury so that the temperature dependence of the fluid properties could be neglected. Furthermore, the same setup was used to study the effect of free convection on heat transfer the main interest being the set in of free convection. The measurements without and with protective gas were repeated as a check with the moveable thermocouple probe at positions 3, 4, 5 and 6 (Fig.2) of the test section and the set in of free convection was measured at position 3.

## Evaluation of test results

For the evaluation of the tests the values given by Lyon [6] for the density, the specific heat capacity and the viscosity of mercury and the values given by Vargaftic [7] for the thermal conductivity were used.

The coefficient of thermal expansion and the thermal conductivity of steel were determined by the authors own tests to an accuracy of 3 %.

The evaluation of the tests began with the calculation of the heat flux q from the electrical power input along the test section. The wall temperatures $\vartheta_w$ at the inside wall of the test pipe were then determined from the temperatures measured in the pipe wall. Their mean difference amounted to 6 % of the temperature difference between wall and centre. The temperature $\vartheta_c$ at the pipe centre was then calculated from the mean mixed fluid temperature in an area of 1 mm diameter measured with the 1 mm diameter probe. In the entire flow region, this correction amounted to approximately 0.02 % based on the temperature difference between wall and centre.

The desired Nusselt number $Nu_c$, based on the temperature difference between wall and pipe centre could then be calculated from the expression

$$Nu_c = \frac{q\,D}{\lambda(\vartheta_w - \vartheta_c)} = \frac{U\,J}{\pi\lambda L(\vartheta_w - \vartheta_c)} \qquad (2)$$

The corresponding Reynolds number or Peclet number was then obtained from the measured mass flow. All properties were based on the arithmetical mean temperature between wall and centre.

An estimate of the error in the Nusselt number gave a maximum possible error of 4 %, but on the assumption that the exact thermal conductivity value of mercury is known.

## Results of tests without protective gas

With the measuring procedure used, the rise of all temperatures, including the pipe wall temperature, in the fully developed flow is linear in the direction of flow. This rise could thus be calculated from the wall temperatures measured along the test section.

With this temperature rise, the power absorbed by the mercury along the test section was calculated and compared with the electrical power supplied. On average, the results agreed within approximately 2.3 %, only one result differing by 4.2 %. In the laminar region, the measured Nusselt number, calculated from expression (2) was compared with the corresponding theoretical value

$$Nu_{cth} = 16/6 = 2.666...$$

Both differed, on average, by approximately 1.7 %, only one result differing by a maximum of 4.1 %. As further check a comparison was made in the laminar region between the measured temperature difference between wall and pipe centre and the corresponding temperature difference obtained from the theoretical solution. The theoretical temperature difference was obtained from the expression

$$\Delta\vartheta_{cth} = (\vartheta_w - \vartheta_c)_{th} = \frac{3}{8}\frac{D}{\lambda}\, q \qquad (3)$$

where q is the heat flux calculated from the electrical power supplied. The comparison showed that they differ, on average, by approximately 1.8 %, only one result differing by a maximum of 4.3 %. The test results with the fixed and moveable thermocouple probes are shown in Fig.3. No systematic differences were found between the measurements obtained for the moveable probe and those for the fixed probe. (See Fig.3)

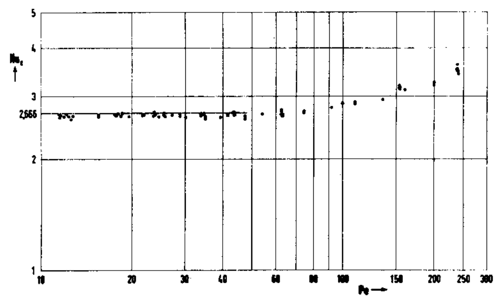

Fig.3: Nusselt number $Nu_c$ referred to the temperature difference between wall and centre line.

In order to compare the test results with those of other authors, the measured Nusselt numbers, which are based on the temperature difference between pipe wall and pipe centre, were converted into Nusselt numbers based on the difference between the pipe wall temperature and the mixed temperature of the fluid flow. The mixed temperature $\vartheta_m$ was calculated from the expression

$$\vartheta_m = \frac{\int_F \vartheta \; w \; dF}{\int_F w \; dF} \qquad (4)$$

The Nusselt numbers obtained from this expression are shown as small circles in Fig.4. For comparison, this figure also gives the results published by the following authors:

1-1 Styrikovic, Sorin, Semenovker [8, 9]; 2-2 Micheev, Voskresenskij, Fedynskij, Kondratev, Kalakuckaja, Petrov, et al. [10,11]; 3-3 Korneev [12]; 4-4 Englisch, Barret [13]; 5-5 Doody, Jounger [14]; 6-6 Bailey, Cope, Watson [15]; 7-7 Elser [16]; 8-8 Isakoff, Drew [17]; 9-9 Stromquist [18]; 10-10 and 11-11 Johnson, Clabaugh, Hartnett [19,1]; 12-12 Trefethen [20]; 13-13 Petukhov, Jushin [3].
The numbering in this summary is identical with that of Fig.4.

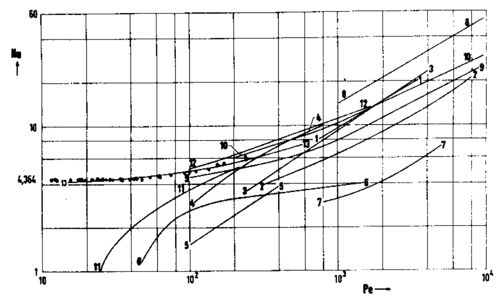

Fig.4: Heat transfer to mercury by pipe flow.

## Results of tests with protective gas

In the laminar region, measurement series were made with the fixed and the moveable probes, with the apparatus, which had previously been filled with mercury vapour, being filled with argon. For one part of the series the apparatus was filled with argon during operation and for another part while not in operation, i.e. with the test section empty. The heat transfer decreased only insignificantly. The Nusselt numbers were smaller than the theoretical value by not more than 6 % with a possible maximum measuring error of 4 %. It was assumed, however, that in the beginning, i.e. for the tests where the test section was empty, the gas could be displaced from the tube by the mercury.

## Results of tests on the beginning of mixed convection

As the governing temperature gradient between the pipe wall and the pipe centre becomes steeper, and thus the Grashof number becomes greater, an ever increasing free convection component is superimposed on the heat transfer by pure forced convection. The limit above which free convection affects heat transfer noticeably was determined in the laminar region both with the fixed and the moveable thermocouple probe at position 3 and 6 (Fig.2) of the test section. At a given Reynolds number the value of the Grashof number was indicated as limit value and entered in Fig.5 at which the measured Nusselt number $Nu_c$ exceeded the theoretical value of 2.666 for laminar flow. No difference was found between the measurements obtained with the two thermocouple probes, although the measurements with the fixed probe were made at position 6 (Fig.2) and those with the moveable probe at position 3.

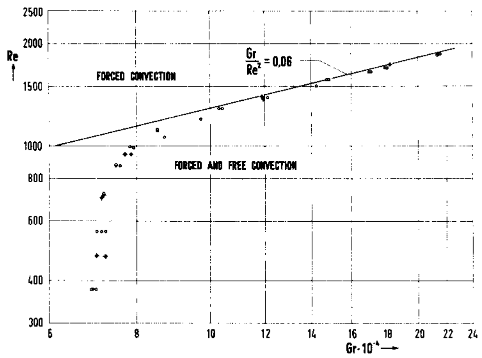


Fig.5: Boundary between pure forced and mixed convection; O Measurements with the fixed thermocouple probe; ⊕ Measurements with the moveable thermocouple probe.

The continuous straight line represents the theoretical limit found by Sparrow, Eichhorn and Gregg [21] between forced and mixed convection for boundary layer flow.

Conclusions drawn from test results

The measurements showed that the heat transfer to mercury takes place without any anomalies and that a comparison with the familiar results obtained by theoretical means is possible, provided that the assumptions on which the theory is based are taken into account for the test. No contact resistance affecting the heat transfer was observed at the interface of liquid metal and pipe. Even the gas film which was probably attached to the wall during the tests with protective gas failed to decrease the heat transfer significantly.

The tests showed, as did previous observations, that the heat transfer was increased, and not decreased, by free convection, as strangely enough was assumed by a number of authors. The only plausible explanation for the very small Nusselt numbers obtained by other authors at small Peclet numbers is likely to be provided by the longitudinal heat conduction in the fluid at the pipe wall. In the present measuring procedure the temperature difference, with which the Nusselt number $Nu_c$ is defined, is measured directly. Previous authors, however, determined only the fluid temperature in a mixing chamber behind the test section.

The total fluid temperature in the test section was then determined under the assumption that its variation between the beginning and the and of the heated pipe section is linear and that the inlet temperature of the fluid is equal to the temperature measured before the beginning of the hydrodynamic smoothing section. It is shown schematically in Fig. 6 that this assumption need not necessarily be correct.

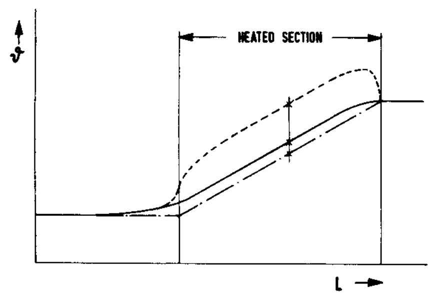


Fig. 6: Schematic diagram of temperature variation in pipe wall and in fluid.

The heavy continuos line represents the actual variation and the chain-dotted line the assumed variation of the mean mixed temperature of the fluid. The dashed line represents the measured actual variation of the wall temperature. It will be seen from Fig. 6 that temperature differences between wall and fluid, as determined by this process were too great and the resulting Nusselt numbers were inevitably too small. Petukhov and Yushin [3] take this into account for their measurements by a subsequent calculatory correction. With the test apparatus of Johnson et al. [1] an aluminium cylinder divided into 8 sections and carrying the heating wire was attached to the test pipe along the heated test section by the "Alumibond" casting process. Due to the high heat conductivity of the aluminium the wall temperature varied stepwise along the pipe upon heating and deviated the further from a linear variation the smaller the Peclet number was. Thus, the condition of constant heat flux was no longer satisfied. This method added to the errors depicted in Fig. 6 the error due to heating, which brought about the close relationship between the Nusselt number and the Peclet number in the laminar region. These errors became insignificant for Peclet numbers in excess of 300.

Summary

A pipe in a closed loop was heated with a constant heat flux. The heat transfer to mercury was measured with laminar and turbulent flow within a section where the hydrodynamic and thermal conditions has reached a steady state. In the loop, the mercury came into contact only with steel and quartz glass and was degassed continuously during the experiments. Under these conditions, the tests, which were carried out for Peclet numbers ranging from 11 to 250 at temperatures from 30 °C to 80 °C, showed that the heat transfer to mercury takes place in a perfectly normal manner. The results were capable of reproduction as often as desired. For laminar flow they differ by a maximum of 4 % from the theoretical value, which still lies within the measuring tolerance.

A gas film (argon in this case) which may have remained attached to the pipe wall during the measurements with protective gas did not appear to cause any perceptible increase in the thermal resistance. The limits of pure forced flow to mixed flow were determined by a series of tests performed for this particular purpose.

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