EXPERIMENTAL STUDY OF THE HEAT TRANSFER DURING A LAMINAR FLOW OF NON-NEWTONIAN FLUIDS THROUGH PIPES

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Results are shown of an experimental study concerning the heat transfer during a laminar flow of oils and non-Newtonain fluids, whereupon these results are compared with approximate theoretical calculations.

Calculation of the heat transfer which occurs during a laminar flow of non-Newtonian fluids through pipes is an important factor in many problems.

Published data on this subject, mainly theoretical data pertaining to the heat transfer in non-Newtonain fluids, have not yet been adequately verified by experiment and, as is well known, no test data at all are available on synthetic rubber in solution.

Here we will present the results of an experimental study concerning the heat transfer during a laminar flow of the following substances through circular pipes: mineral oils (grade MS machine oil, grade AK-10 automobile oil), aqueous solution of sodium–carboxymethycellulose (Na–CMC) in various concentrations, and benzene solutions of synthetic rubber (isoprene grade SRI).

The thermophysical and the rheological properties of these fluids are given in Table 1 and in Fig. 1.

The thermophysical properties of these fluids were determined with standard equipment according to known procedures [1]. The rheological properties of all solutions were determined with a model "Rotovisko" viscometer. As can be seen in Fig. 1, their behavior within the test range of shearing rates is adequately described by the rheological power-law equation

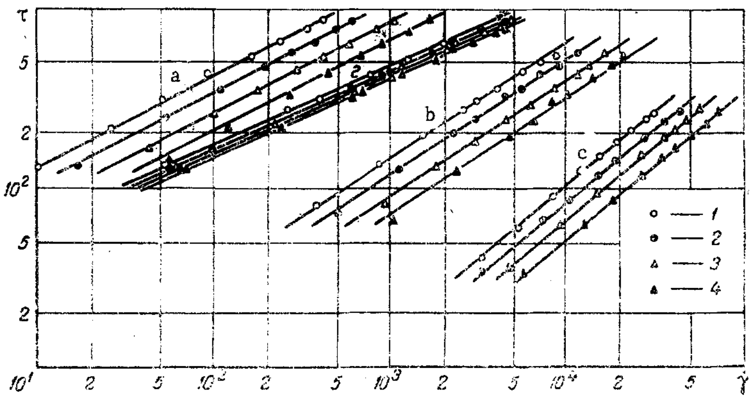

Fig. 1. Shearing stress τ (N/m^2) as a function of the shearing rate $\dot{\gamma}$ (1/sec) for (a) 10.5% aqueous solution of Na–CMC, (b) 6.2% aqueous solution of Na–CMC, (c) 2.5% aqueous solution of Na–CMC, (d) benzene solution of SRI: at the temperature of 20°C (1), 30°C (2), 40°C (3), 50°C (4).

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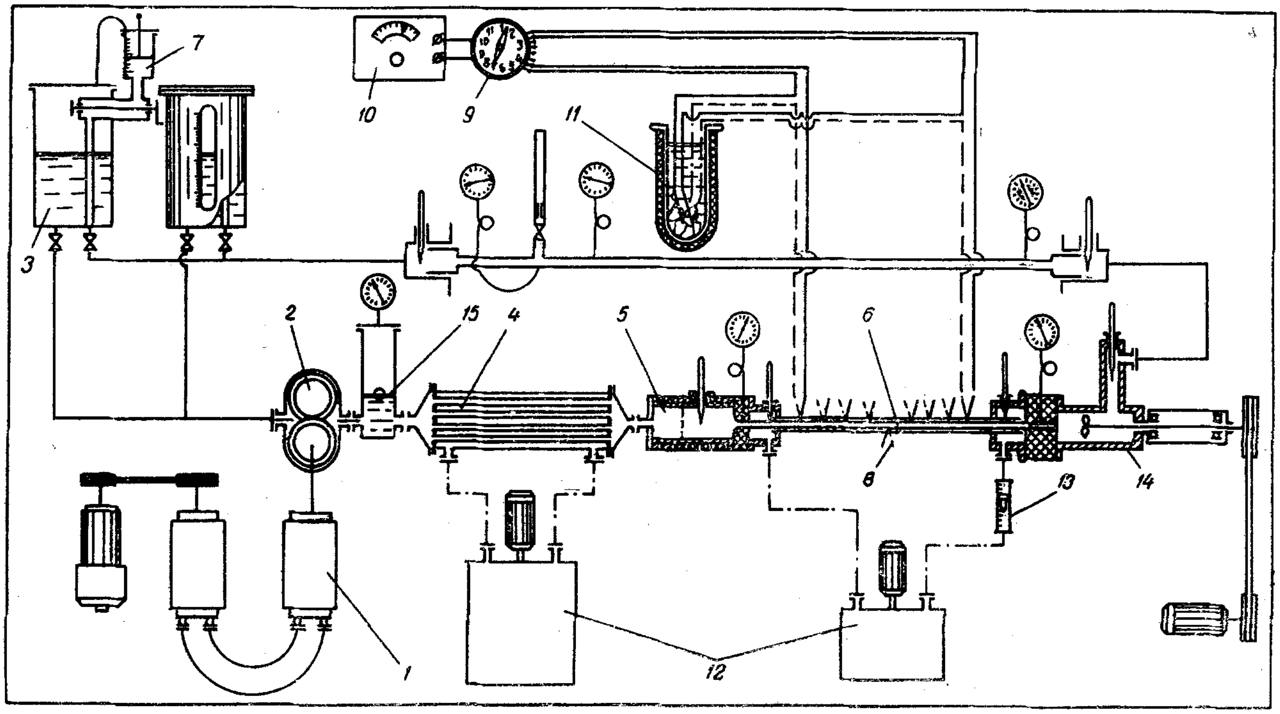

Fig. 2. Schematic diagram of the test apparatus: (1) hydraulic drive, (2) gear pump, (3) reservoir, (4) heat exchanger, (5) stabilizing chamber, (6) tabular heat exchanger, (7) measuring instrument, (8) thermocouple, (9) switch, (10) potentiometer, (11) Dewar flask, (12) thermostat, (13) rotameter, (14) mixing chamber, (15) standpipe.

$$\tau = K\dot{\gamma}^n. \tag{1}$$

Exponent n, which characterizes the flow mode, depends in this case only on the polymer concentration, while the consistency factor K depends on both the concentration and the temperature.

The tests were performed on an apparatus shown in Fig. 2. The measuring unit consisted of a horizontal heat exchanger of the "pipe inside a pipe" construction. The essential component of this heat exchanger was a pipe of grade Kh18N9T steel, 1 or 2 m long and 16 mm in diameter, placed coaxially inside another pipe serving as the jacket. The test fluid was moving inside the inner pipe, while water flowing between both pipes served as either the heating or the cooling medium.

A gear-pump circulated the active fluid around the system: reservoir 3, standpipe 15, heat exchanger 4, stabilizing chamber 5, test pipe 6, mixing chamber 14, and back to the reservoir 3.

The flow rate of a test fluid was regulated smoothly by varying the gear-pump speed with a model URS-5 universal reducer 1 and was measured with the special instrument 7.

TABLE 1. Thermophysical and Rheological Properties of the Studied Fluids

Fluid	ρ, kg/m^3	$c_p \cdot 10^{-3}$, J/kg·°C	λ, W/m·°C	n
Machine oil MS	889	1,905	0,128	1
Automobile oil AK-10	912	1,890	0,139	1
2.5% aqueous solution of Na-CMC	995	4,187	0,582	0,835
6.2% aqueous solution of Na-CMC	1035	4,187	0,582	0,644
10.5% aqueous solution of Na-CMC	1055	4,187	0,582	0,511
14% benzene solution of SRI	740	1,718	0,116	0,450

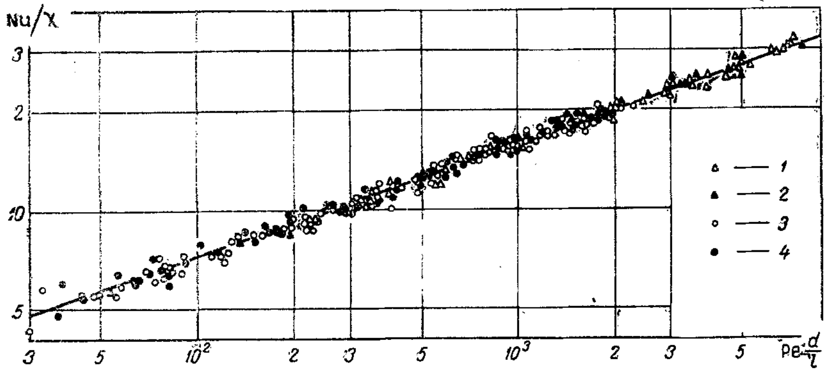

Fig. 3. Group $(\mathrm{Nu})\chi^{-1}$ as a function of group $(\mathrm{Pe})d/l$ for laminar flow in a pipe: grade MS machine oil (1), grade AK-10 automobile oil (2), aqueous solutions of Na–CMC (3), benzene solution of SRI (4).

The use of a low-rpm pump ensured sufficient stability of the test solutions over a length of time. The stability of their rheological properties was periodically checked with the "Rotovisko" viscometer.

The apparatus had been designed for operation in the heating and in the cooling mode, with the temperature of the fluid varying from 8 to 60°C and the temperature of the pipe wall within the test zone varying from 8 to 70°C. For cooling we used tap water, for heating we used hot water circulating through the thermostat 12. The flow rate of water was maintained constant by means of valves, was checked with the rotameter 13, and was measured by the weighing method.

The wall temperature along the test pipe was measured at nine points with Chromel–Copel thermocouples which had been mounted into the pipe wall. The thermocouple emfs were measured with a model PP potentiometer. The temperatures of the active fluid as well as of the water at the entrance and at the exit were measured with laboratory-type mercury thermometers within a 0.1°C precision and were checked with thermocouples.

The measurements in these tests were made under steady thermal and dynamic conditions. The conditions were considered steady as soon as after three to four measurements the instrument readings remained stable.

The mean value of the heat transfer coefficient was determined according to the formula

$$\alpha = \frac{Q}{F\delta T},$$

with Q denoting the thermal flux received by the active fluid and determined from the mass rate of water flow and the change in the water temperature, F denoting the inside surface area of the test pipe, and $\delta T = |T_m - T_w|$ denoting the temperature excess (its average value in most tests).

The results of the experiment are shown in Fig. 3. The straight line has been plotted according to the equation

$$\mathrm{Nu} = 1.55\chi \left(\mathrm{Pe}\frac{d}{l}\right)^{1/3}, \tag{2}$$

where

$$\chi = \left(\mathrm{Pe}\frac{d}{l}\right)^{m-\frac{1}{3}} \left(\frac{\nu_m}{\nu_w}\right)^{0,14}. \tag{3}$$

The values of exponent m were determined from the relation

$$m = 0{,}466 - \frac{0{,}138}{1 + 0{,}07\frac{1}{n}}. \tag{4}$$

As the reference we used the mean temperature of the fluid, and all dimensionless groups in the equation in [2] were defined in terms of this temperature.

According to Fig. 3, the test points for the Newtonian as well as for the non-Newtonian fluids fitted fairly well onto a straight line, which confirmed the validity of the equation in [2] for the given test range of variables. The maximum discrepancy between tested and calculated values was ±10%; the mean deviation was 5%.

The dissipation of mechanical energy affected the heat transfer only negligibly little even under the most unfavorable conditions in the fluid. The effect of an initial hydrodynamic stage on the heat transfer did not exceed 5%.

The results of this study confirm the correctness of the earlier proposed approximate equation in [2], where the effect of non-Newtonian properties on the heat transfer is accounted for by the exponent $m = f(n)$ or the $(Pe)d/l$ group.

NOTATION

T	is the temperature;
d, l	are the inside diameter and length of pipe respectively;
α, λ, a	are the heat transfer coefficient, thermal conductivity and thermal diffusivity respectively;
τ	is the shearing stress;
$\dot{\gamma}$	is the shearing rate;
K	is the consistency factor;
n	is the exponent characterizing the behavior of a fluid;
$\nu = 8K^{n-1}$	is the quantity proportional to the apparent viscosity;
u	is the velocity of fluid;
$Nu = \alpha d/\lambda$	is the Nusselt number;
$Pe = ud/a$	is the Peclet number;

Subscripts:

w refers to pipe wall;
m refers to the mean (temperature).

LITERATURE CITED

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