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INVESTIGATION OF HEAT TRANSFER TO ORGANIC LIQUIDS

By

L. S. Sterman and V. V. Petukhov

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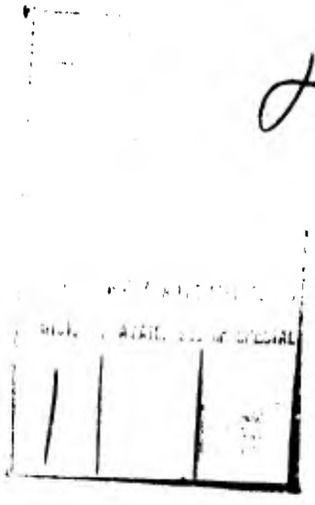

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INVESTIGATION OF HEAT TRANSFER TO ORGANIC LIQUIDS

By: L. S. Sterman and V. V. Petukhov

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ABSTRACT: The heat-transfer coefficients to monoisopropylbiphenyl and biphenyl during variations in the process parameters were determined, and the results were compared with theoretical equations of different types. These coefficients were determined during turbulent flow in tubes without a change in the state of aggregation of the organic fluids. The heat-transfer coefficients to monoisopropylbiphenyl were determined at heat fluxes of 200,000, 500,000, and 860,000 Kcal/m^2· hr and at circulation rates of 4, 6, 10 and 15 m/sec., and those to biphenyl were determined at a heat flux of 300,000 Kcal/m^2· hr and circulation rates of 4 and 6 m/sec. Under these conditions, the Reynolds number was found to fall within 25,00 - 420,000, and the heat-transfer coefficient varied from 3,000 to 18,000 Kcal/m^2· hr.°C.
Original article has: 7 figures and 5 formulas. English translation: 13 pages.

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

INVESTIGATION OF HEAT TRANSFER TO ORGANIC LIQUIDS

L. S. Sterman and V. V. Petukhov

In recent years increasing attention is being paid to organic heat-transfer agents. Physical and chemical properties of a number of organic heat-transfer agents have been studied quite completely [1]. At the same time, when carrying out calculations on heat transfer one encounters great difficulties, since the coefficients of heat transfer to organic liquids in the absence of change in the state of aggregation are usually relatively small and therefore for any significant heat flows large temperature drops are established between the wall and the liquid. Physical properties of the liquid under these conditions in the layer adjacent to the wall are noticeably changed and the coefficients of heat transfer cannot be determined without taking into account these changes.

A number of investigations have been conducted in the study of heat exchange with liquids with variable properties [2-7]. With a change of temperature for these liquids the viscosity is changed most strongly and therefore in a number of works the influence of exactly this constant is established. Thus, Sider and Teit [2], suggested calculating heat transfer of liquids with

variable properties by the equation

$$Nu = 0{,}027\, Re^{0.8} Pr^{0.43} \left(\frac{\mu_{ж}}{\mu_{ст}}\right)^{n}, \qquad (1)$$

where during the heating of the liquid the exponent n is equal 0.14.

Investigations of heat transfer to diphenyl, "Santowax"-R and "Santowax"-OM, (conducted by Silberberg and Huber [3]) showed that in the interval of change of Re from 20,000 to 300,000 formula (1) gives noticeable divergences of experimental and calculated data. At small values of Re (≤20,000) experimental data are less than the calculated (the divergence attains approximately 15%), and at large Re it is somewhat larger than the calculated (about ~7%), i.e., there is a dependence of Nu number on Re number which differs from the equation (1). The authors have offered a dependence with the form

$$Nu = 0{,}015 Re^{0.86} Pr^{0.27}, \qquad (2)$$

which generalizes the experimental data obtained by the authors with a precision of ±7.9%.

Attempts to evaluate the influence of not only the variable viscosity, but also the change of other physical constants were undertaken in work [4].

The dependence suggested by the author has the form

$$Nu = 0{,}021 Re^{0.8} Pr^{0.43} (Pr_{ж}/Pr_{ст})^{0.25}. \qquad (3)$$

Investigations of heat transfer to ditolylmethane (an organic liquid, similar in properties to "Dowtherm" [A] and diphenyl), conducted by Chechetkin and Kosterev [5], and also investigation of heat transfer to glycerine, conducted by Kosterin and Magomedov [6], showed that in the interval of Re numbers from 10^4 to 10^5 experimental data will agree well enough with dependence (3).

However, as is noted in the work of Petukhov and Kirillov [7], formula (3) corresponds more to the case of cooling. In the opinion of the authors, during heating the exponent at the ratio $Pr_{ж}/Pr_{ст}$ should be less.

In work [7] for calculation of the coefficient of heat transfer during variable properties of liquid dependence is offered in the form

$$Nu = \frac{0,125\,Re\,Pr\,\xi}{4,5\sqrt{\xi}\,(Pr^{2/3}-1,0)+1,07}\left(\frac{\mu_{ж}}{\mu_{ст}}\right)^{n}, \qquad (4)$$

where exponent n is equal to 0.11 in the case of heating the liquid and 0.25 for cooling, and ξ is calculated by equation

$$\frac{1}{\sqrt{\xi}} = 1,82\lg Re - 1,64. \qquad (5)$$

Calculations by the considered formulas lead not infrequently to noticeably divergent values of the Nu number. In connection with this, the goal of this work was experimental determination of coefficients of heat transfer to the flow of monoisonpopyldiphenyl and diphenyl during variation in wide limits of process parameters and comparison of results obtained with calculation equations of the different form.

In the experiments described rates of circulation were changed in the range from 4 to 15 m/s and the temperature difference from 13 to 150°C. Under these conditions the number Re was changed from 25,000 to 420,000, and the Pr number was from 5 to 36.

The experimental installation used in the experiments (Fig. 1) is a closed forced-circulation loop of liquid. The installation consists of the experimental section 1, heaters 2, and circulating pump 3 which are connected by pipes 57 × 3 mm of steel brand [1Kh18N9T] (1X18H9T). To the loop by a pipe with a diameter of 8 × 1 mm we connected a volume compensator 4, made from a pipe with an internal diameter of 195 mm. Pressure in the installation was created by nitrogen supplied from tank 8 to vessel 4.

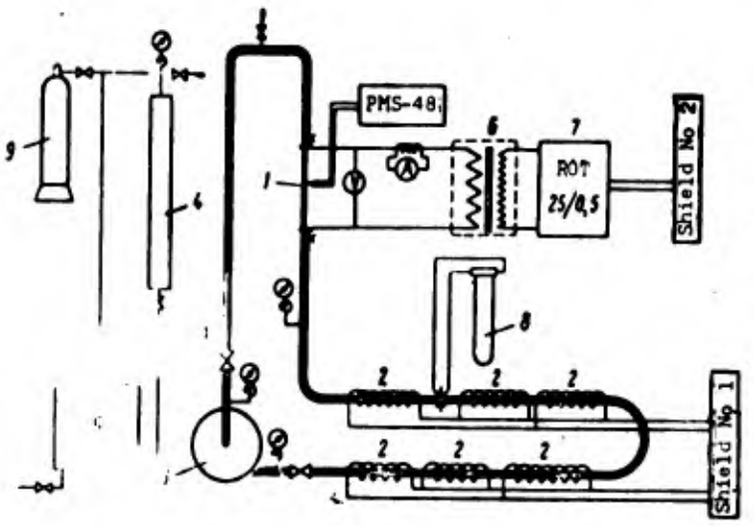

Fig. 1. Diagram of experimental installation: 1 – experimental section; 2 – electric heaters; 3 – circulating pump; 4 – volume compensator; 5 – tank for filling of circuit; 6 – transformer TPO-253; 7 – transformer ROT-25/0.5; 8 – flow meter washer with differential manometer Dt-50; 9 – nitrogen tank.

The level of liquid in vessel 4 was usually higher than the middle of the vessel, due to the fact that the nitrogen could not go into the loop directly or with the liquid in which it was dissolved.

To guarantee the possibility of working with diphenyl which has melting point higher than room temperature, the units and communicating lines of the loop were wound with electrical heaters made from nichrome wire. Part of the heaters (with power near 15 kW) were connected directly to a net with voltage of 220 V and part to the regulating transformer [ROT] (РОТ) 15/0.5, this permitted smoothly regulating the power of these heaters from 0 to 20 kW.

This heating was used for fusion of solid diphenyl (heating it up to the required temperature) and for compensation of thermal losses in the installation.

At different points of the circulation loop we established 22 Chromel-Copel thermocouples which were connected to a recording electron potentiometer [EPP-0.9] (ЭПП-0.9) and a millivoltmeter [MPP] (МПП). Control of temperature along the length of the circulation loop was necessary in order to guarantee uniform warm-up of the loop when starting the installation, and also to exclude the possibility of diphenyl congealing in separate sections of the loop during work.

We placed all manometers measuring pressure of liquid diphenyl and differential manometer [DT-50] (ДТ-50) measuring flow rate in a special cabinet. Upper and lower parts of the cabinet remained open. In the lower part we installed a heater with a power of 4 kW, which was connected to voltage regulator [RNO-250] (РНО-250). With the help of the heater we maintained a temperature around 80°C in the cabinet. All pulse tubes up to the cabinet were heated.

Temperature of the surface of the manometers was controlled and maintained in the range of 75-80°C.

The experimental section of the installation was prepared from a tube with a diameter of 12 × 1 mm made from brass of brand [L-62] (Л-62). The length of the tube during experiments with monoisopropyldiphenyl was 640, 880 and 920 mm, and during investigation of heat transfer to diphenyl it was 540 mm. Tube was warmed by alternating current, which was transmitted along its walls.

The general form and the lead-in unit of the thermocouple of the experimental section are shown in Fig. 2. Along the length of tube 4 we installed a series of Chromel-Copel thermocouples made from wire with a diameter 0.2 mm, which measured the temperature of the external wall of the tube. In experiments with monisopropyldiphernyl along the length of the tube we installed 11 thermocouples in one case and 17 in two others. During the installation of the 17 thermocouples we placed two at each of six marks (on opposite sides of the tube). During experiments on diphenyl we installed 11 thermocouples along the length of the tube.

During application of the tube made from brass an error in the determination of the temperature drop in the wall could not be reflected in any essential amount in the results of the experiment: a drop in the wall was found within the limits of 0.3-3.0°C and there was a drop between the wall and the liquid within the limits 13-150°C.

We measured the temperature of the liquid at the inlet and outlet of the experimental section also by Chromel-Copel thermocouples made from wire with a diameter of 0.2 mm. Hot junctions of these thermocouples were placed directly in the flow of the liquid at the center of the tube (Fig. 2).

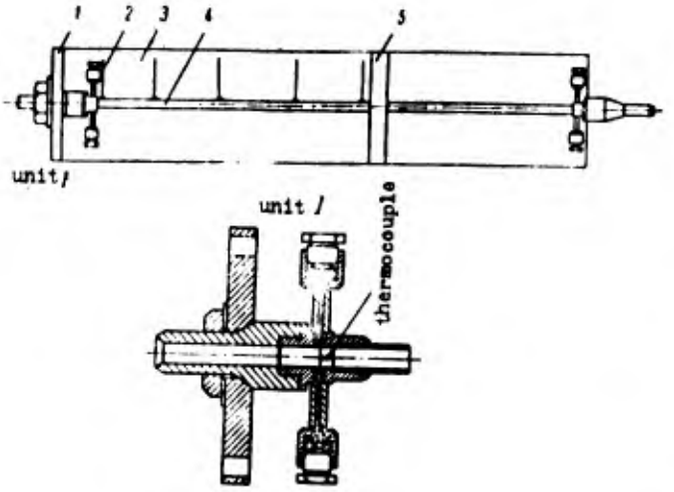

Fig. 2. Experimental section:
1 – current distributing flange;
2 – leads for measurement of voltage; 3 – insulation; 4 – experimental tube; 5 – movable current distributing flange.

We determined the temperature of liquid in a given section by its value at the inlet or outlet of the experimental portion and by the quantity of heat transmitted to portion before the section where the thermocouple was located or to the portion after this section.

For measurement of the thermal-EMF. We applied the null method. We determine the thermal-EMF with the help of a [PMS-48] (ПМС-48) low-resistance potentiometer, which allowed us to measure with an accuracy up to 1 μV.

The magnitude of heat flow was determined by input power. We measured the drop in voltage in the given portion by milliammeter [D-528] (Д-528) (which has an accuracy of the class 0.5) in series with which we connected a resistance box [KMS-6] (КМС-6). Such a circuit transformed the milliammeter into a multirange voltmeter with a lower limit of measurement of 0.5 V. The instrument was

preliminarily calibrated. The magnitude of the current flowing along the tube was measured by ammeter [ELA] (ЭЛА) which has accuracy of the class of 0.2.

The experiments for the determination of coefficients of heat transfer to monoisopropyldiphenyl and diphenyl during turbulent conditions of liquid flow in the pipes were conducted at circulation speeds of 4, 6, 10, and 15 m/sec. For every speed the values of the coefficient of heat transfer were determined at the specific heat flows of 200,000, 500,000 and 860,000 kcal/m^2·h. The temperature of the liquid at the inlet to the experimental portion in experiments with monoisoprophyldiphenyl varied in the interval from 70 to 280°C; during experiments on diphenyl the temperature was equal to 200°C.

The pressure in the experiments was so selected as to exclude the possibility of surface boiling of the liquid. Usually the temperature of the wall was lower than the temperature of saturation by not less than 20°C.

Experiments with monoisopropyldiphenyl were conducted on three experimental tubes differing only in length. On the tube with a length of 880 mm (88 d) the specific heat flows had values 200,000 and 500,000 kcal/m^2·h, and in experiments on the tube with a length of 640 mm (64 d) they were 500,000 and 860,000 kcal/m^2·h. On the tube with a length of 920 mm (92 d) we conducted experiments only during the heat flow of 500,00 kcal/m^2·h. The data obtained during the flow of 500,000 kcal/m^2·h coincided on all tubes.

Coefficients of heat transfer to diphenyl were obtained on a tube with a length of 540 mm (54 d) during a heat flow of 300,000 kcal/m^2·h. The data obtained in the investigation conducted by the authors agree satisfactorily with the experimental data for diphenyl

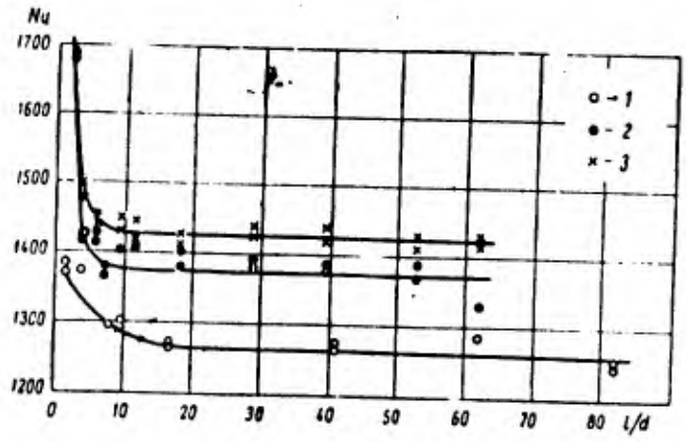

Fig. 3. Local values of the Nu number during different values of heat flow for the speed of liquid circulation 10.3 m/sec: 1 — q = 200,000 kcal/m^2·h; 2 — q = 500,000 kcal/m^2·h; 3 — q = 860,000 kcal/m^2·h.

obtained in the work [3].

In the experiments we determined local coefficients of heat transfer at different distances from the inlet section. The result obtained for monoisopropyldiphernyl are shown in Figs. 3 and 4.

In experiments on dispenyl the coefficient of heat transfer determined at a distance of 84 d and 92 d from the inlet section. Figure 3 compares the value of the Nu number for different values of magnitude of heat flow at a constant speed of liquid (10.3 m/s and a temperature of the liquid of 240°C and Fig. 4 compares the values of Nu for different values of circulation speed at the same temperature of the liquid and a heat flow of 500,000 kcal/m^2·h. As can be seen from Fig. 3 and 4, the Nu number and, consequently, the coefficient of heat transfer quickly decrease along the length of pipe according to the distance from the inlet and at the length $l > 15$-20 d they take on a constant value. Increase of heat flow leads to increase of intensity of heat exchange (during the constant value $t_{ж}$).

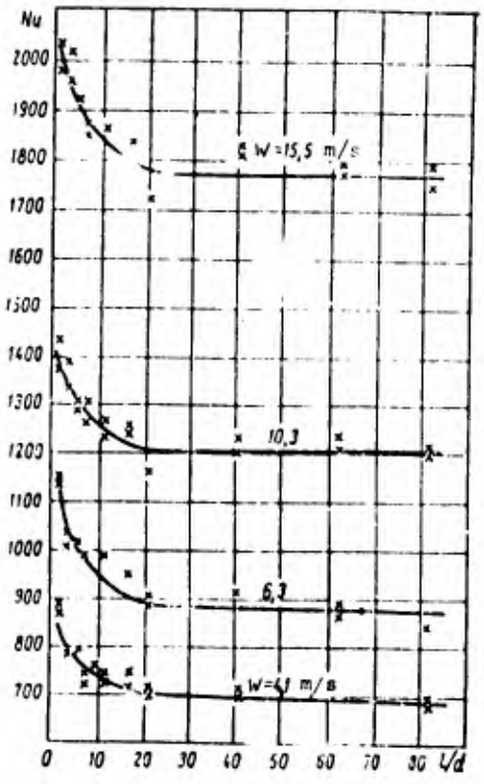

Fig. 4. Local values of the Nu number during different speeds of liquid circulation for the constant value of heat flow 500,000 kcal/m^2·h.

Comparison of obtained experimental data with magnitudes calculated by the formulas of different authors is shown in Fig. 5. For the comparison we took experimental data during $l > 50$ d, i.e., for the sections of the pipe where the influence of the inlet conditions is completely excluded. All thermophysical properties of monoisopropyldiphenyl used in the calculations were according to data of work [8], and for diphenyl they were according to data of work [3]. From Fig. 5 one may see that formulas (1) and (3) give smaller values for the coefficients of heat transfer as compared to the experiment. Analogous calculations conducted by the formula (2) showed that at values of Re numbers $>10^5$ during Pr numbers in the interval from 4 to 8 experimental data lie ~12% higher than the calculated and during $Re < 10^5$ and $Pr > 15$ the divergences already reach 60%. Best convergence between experimental and calculated data takes place during application of formula (4). However, even in this case the scattering is from +5 to -15%.

Experimental data of the present investigation were obtained during Pr from 6 to 36, when the Re number was changed from 25,000 to 420,000.

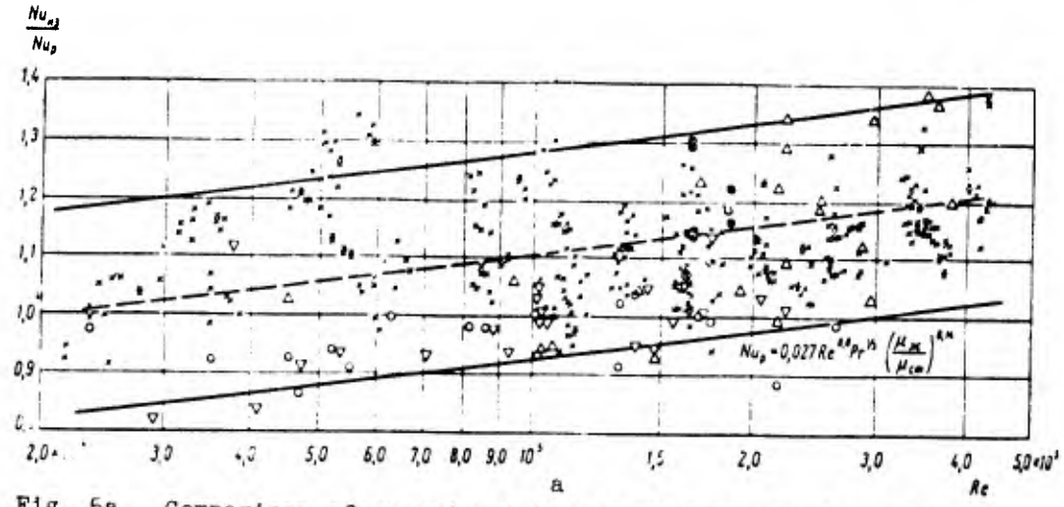

Fig. 5a. Comparison of experimental data with magnitudes calculated by the formula of Sider and Teit: 1 — monoisopropyldiphenyl (MEI); 2 — diphenyl (MEI); 3 — diphenyl [3]; 4 — "Santowax"-OM [3]; 5 — "Santowax"-R [3].

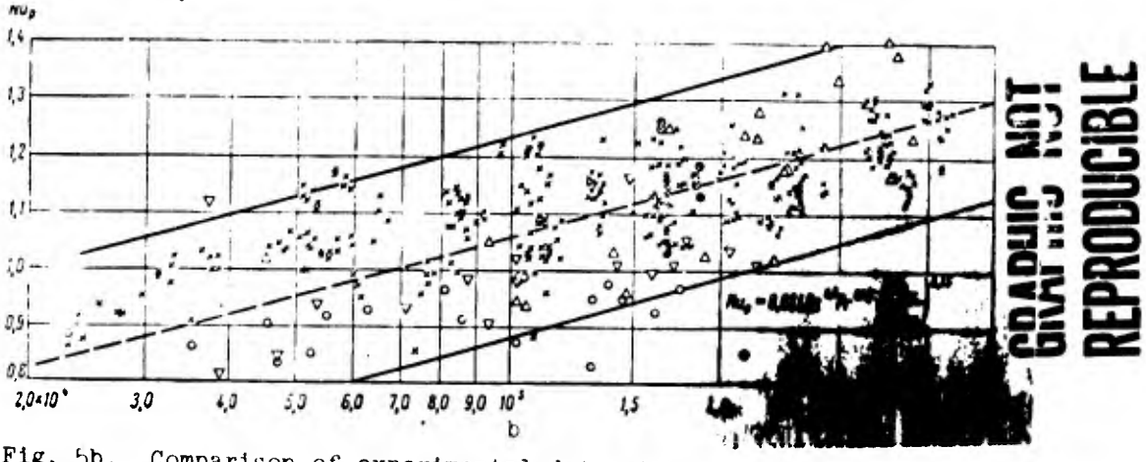

Fig. 5b. Comparison of experimental data with magnitudes calculated by the formula of Mikheyev: 1 — monoisopropyldiphenyl (MEI); 2 — diphenyl (MEI); 3 — diphenyl [3]; 4 — "Santowax"-OM [3]; 5 — "Santowax"-R [3].

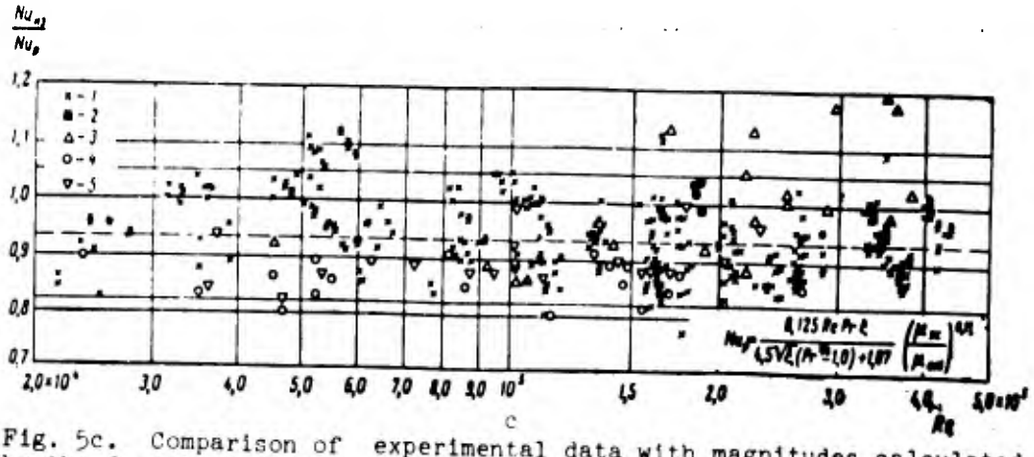

Fig. 5c. Comparison of experimental data with magnitudes calculated by the formula of Petukhov and Kirillov: 1 — monoisopropyldiphenyl (MEI); 2 — diphenyl (MEI); 3 — diphenyl [3]; 4 — "Santowax"-OM [3]; 5 — "Santowax"-R [3].

Figure 5 also gives a comparison of experimental data [3] obtained at 20,000 < Re < 270,000 and 4.8 < Pr < 10.6 with magnitudes calculated by the formulas of different authors. As can be seen from Fig. 5, experimental data on coefficients of heat transfer to "Santowax"-R and "Santowax"-OM are lower than values calculated by the formulas (1), (3), and (4), in the whole range of Re numbers (Re is changed from 20,000 to 250,000); they are higher than computed values determined by the formula (2).

Experimental data on diphenyl are higher than values calculated by the formulas (1), (2), (3) and (4).

Conclusions

1. We experimentally determined the values of coefficients of heat transfer during turbulent flow in pipes without a change in the state of aggregation of the organic liquids monoisopropyldiphenyl and diphenyl. Coefficients of heat transfer to monisopropyldiphenyl were determined during specific thermal flows of 200,000, 500,000 and 860,000 kcal/m^2·h and at circulation speeds of 4, 6, 10 and 15 m/s; with diphenyl the parameters were at a heat flow, 300,000 kcal/m^2·h; circulation speeds 4 and 6 m/s. Under these conditions the Re number was found within the limits of 25,000-420,000 and the coefficient of heat transfer had a value from 3,000 to 18,000 kcal/m^2·h·^{o}C.

2. The obtained experimental data were compared with magnitudes calculated by the formulas of Sider and Teit [2], Silberberg and Huber [3], Mikheyev [4] and Petukhov and Kirillov [7].

It was established that the best coincidence with experimental data occurred during calculation by the formula of Petukhov and Kirillov [7].

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