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HEAT TRANSFER OF A PLATE IN A LIQUID FLOW

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Abstract—The paper presents results of the experimental investigation of heat transfer of a plate in a flow of air, water and transformer oil at different directions of heat flow over the range of Re_f numbers from 2×10^4 to 3×10^7 and that of Pr_f—from 0·701 to 380. Formulae were obtained to calculate heat transfer of a plate in a liquid flow.

Résumé—Cet article présente les résultats d'une recherche expérimentale sur la transmission de chaleur d'une plaque dans un écoulement d'air, d'eau et d'huile de transformateur, pour différentes directions du flux de chaleur et des domaines de nombres de Reynolds compris entre 2×10^4 et 3×10^7 et de nombres de Prandtl de 0,701 à 380. Des formules ont été obtenues pour calculer la transmission de chaleur d'une plaque dans un écoulement liquide.

Zusammenfassung—Es werden Versuchsergebnisse mitgeteilt für den Wärmeübergang an einer Platte bei Anströmung mit Luft, Wasser und Transformatorenöl. Die Untersuchungen wurden für verschiedene Wärmestromrichtungen durchgeführt in einem Bereich der Re_f-Zahlen von 2×10^4 bis 3×10^7 und der Pr_f-Zahlen von 0,701 bis 380. Die ermittelten Gleichungen erlauben die Berechnung des Wärmeübergangs an angeströmten Platten.

Аннотация—Представлены результаты экспериментального исследования теплообмена пластины в потоке воздуха, воды и трансформаторного масла при различных направлениях теплового потока в интервале чисел Re_f от 2×10^4 до 3×10^7 и Pr_f от 0,701 до 380. Получены формулы для расчёта теплообмена пластины в потоке жидкости.

NOMENCLATURE

l_0, length of the heated or cooled portion of the plate;
l, complete length of the plate with tip;
t_f, temperature of the liquid outside boundary layer;
t_w, wall temperature;
α, heat transfer coefficient;
w, liquid flow rate;
λ, thermal conductivity;
ν, coefficient of kinematic viscosity;
μ, coefficient of viscosity;
g, gravity acceleration;
c_p, heat capacity;
Nu_{f0}, Nusselt number $(\alpha l_0)/\lambda_f$;
Re_{f0} Reynolds number $(wl_0)/\nu_f$;
Re_f, Reynolds number $(wl)/\nu_f$;
Pr, Prandtl number $(c_p \mu g)/\lambda$.

Subscripts
f, liquid;
w, wall.

THE present paper contains results of the experimental investigation of heat transfer of a plate in a flow of a drop liquid at a turbulent boundary layer. In the literature there are data only on heat transfer of a plate in an air flow [1–5].

Experiments were carried out with air, water and transformer oil in hydrodynamic contours, the main scheme of which has been described before [6, 7]. A working liquid was fed by a pump with the efficiency of 200 m³/h from a tank with a capacity of 2 m³, to a tank with a lattice of longitudinal tubes which served to level the flow. The liquid from the tank entered an experimental channel portion of rectangular section through a smoothly contracting entrance, then it interflowed again into the tank through a steel tube 100 mm in diameter, on the straight portion of which there was a normal diaphragm which served to measure the liquid rate. In experiments with air the pump was replaced by a fan.

Electric heaters of plates were fed by direct current. Plates 50 mm wide were set into the channel of rectangular section 100 × 50 mm and plates 100 mm wide into the channel of 100 × 200 mm section. While determining the velocity in the channel the decrease of the channel section on account of the plate was taken into consideration.

The velocity of air changed from 7 to 70 m/sec, of water from 0·2 to 30·2 m/sec and that of transformer oil from 0·5 to 25·8 m/sec. High flow velocities were obtained by reducing channel height to 40 mm by uniformly graded inserts.

Four plates with water- and electric-calorimeters were applied in experiments. Dimensions of plates with the water calorimeters were 250 × 50 × 10 mm and 250 × 100 × 10 mm, those with electric-calorimeters 58 × 50 × 10 mm and 250 × 50 × 10 mm.

Plates 250 mm long had 23 thermocouples. The short electric plate had 12 thermocouples in its central portion. All the thermocouples were copper–constantan 0·15 mm in diameter. The average wall temperature was determined by graphic integration. The electromotive force of the thermocouples was measured by a potentiometer.

While carrying out experiments with the water plates, the water passing inside them was weighed and temperature change was measured by a pair of differential thermocouples with four junctions.

The electric heaters of the plates were fed by direct current supplied from a generator with an electronic voltage stabilizer. The voltage fall on the electric heaters was measured by the potentiometer through a voltage divider, and the current intensity by an ammeter of 0·5 grade.

Temperature of air ranged from 22° to 28°C, that of water from 12° to 90°C, that of transformer oil from 19° to 60°C. The wall temperature ranged from 10° to 107°C.

Limits of the Reynolds numbers change were from 2×10^4 to 3×10^7. An upper limit was obtained for the complete length of the plate (0·5 m).

In experiments the value of the criterion Pr_f varied from 0·701 to 380.

In order to find the influence of a length of non-heated initial portion upon heat transfer, Turbonit tips were made for each plate 50 mm wide. For plates 250 mm long the tips were made so that the length ratio of the heated portion l_0 (m) to the complete plate length l (m) was equal to 0·5, 0·6, 0·7 and 0·8.

For short plates the tips were made with ratios 0·11, 0·2, 0·3, 0·4 and 0·5. For this plate the tip with the ratio 0·5 (in contrast to all the others made with a semi-circular front edge) was made with a sharp edge, the thickness of which increased smoothly.

Physical parameters of air and water were taken according to the literary data [8]. Physical parameters of transformer oil were determined experimentally.

When primarily treating experimental data, criteria Nu_f, Re_f and Pr_f were determined. Physical parameters referred to the temperature of the liquid outside the boundary layer.

At first the experimental data were presented for plates with the ratio $l_0/l = 1$. The dependence of Nu_{f0} upon Re_{f0} determines the value of exponent at the Re_{f0} criterion equal to $n = 0{\cdot}8$.

Later on the treatment of the experimental data came to the determination of an exponent m at the criterion Pr_f. In a number of works on heat transfer [7–9] it was determined that the value of $m = 0{\cdot}25$ is a good one, where Pr_f is taken by the temperature of a liquid t_f, and Pr_w by that of a wall t_w.

In Fig. 1 the experimental data are given in the form of the dependence:

$$Nu_{f0}\, Re_{f0}^{-0\cdot 8}\, [Pr_f/Pr_w]^{-0\cdot 25} = f(Pr_f). \qquad (1)$$

It is seen from the diagram that all the points corresponding to heat transfer of the plate at its heating and cooling lie on a straight line with the exponent $m = 0{\cdot}43$. The inapplicability of the exponent $m = 0{\cdot}33$ is proved by a dashed straight line.

As a result of the further treatment of the experimental data on heat transfer of the plate, the following dependence was obtained:

$$Nu_{f0} = 0{\cdot}037\, Re_{f0}^{0\cdot 8}\, Pr_f^{0\cdot 43}\, [Pr_f/Pr_w]^{0\cdot 25}. \qquad (2)$$

Data obtained on the plates with tips (Fig. 2) are described by the following dependence:

$$Nu_{f0} = 0{\cdot}037\, Re_f^{0\cdot 8}\, Pr_f^{0\cdot 43}\, [Pr_f/Pr_w]^{0\cdot 25}\, [l_0/l]^{0\cdot 8} \qquad (3)$$

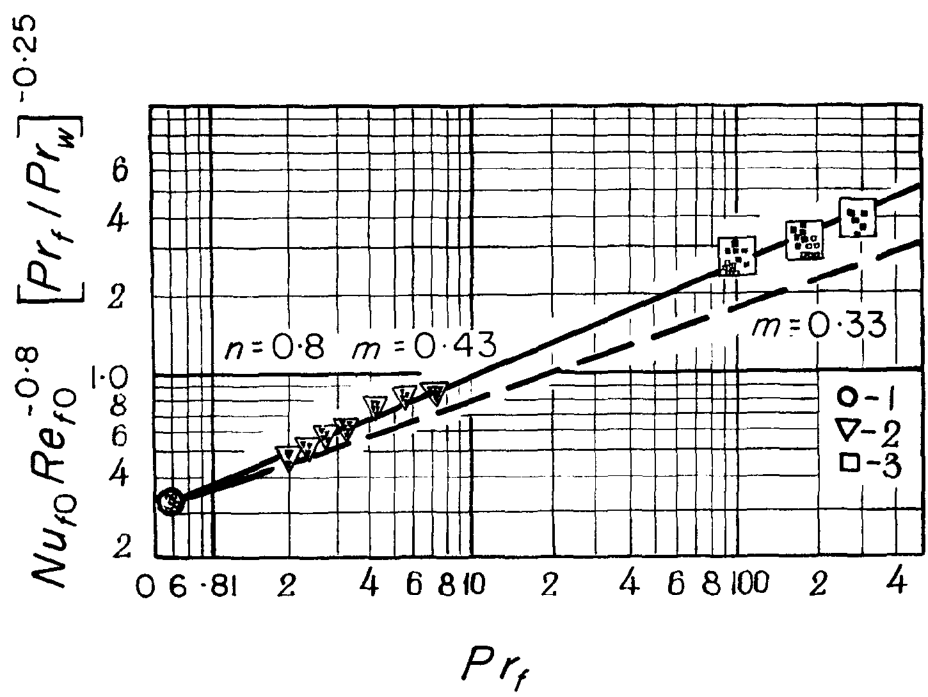

FIG. 1. Determination of exponent at Prandtl criterion. 1—air, 2—water, 3—transformer oil.

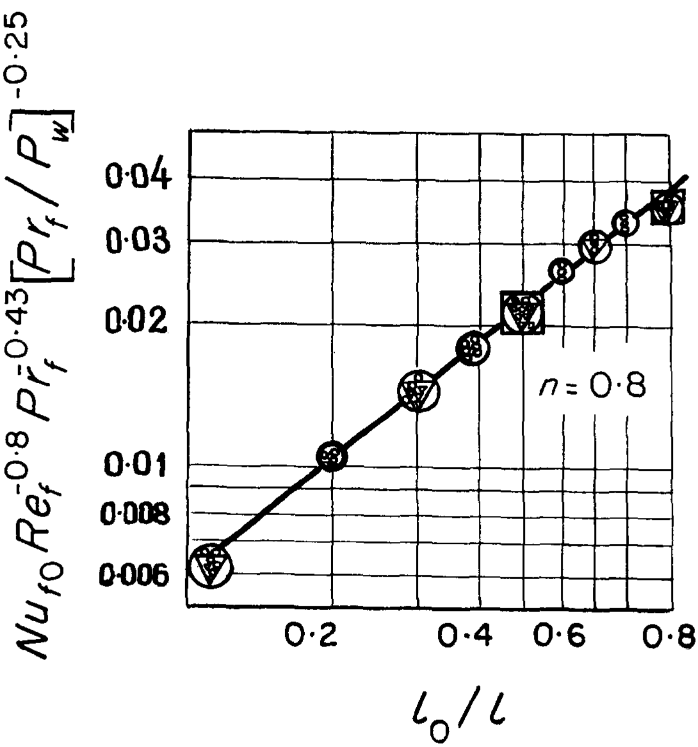

FIG. 2. Dependence of heat transfer from length of non-heated initial portion. See symbols in Fig. 1.

where Nu_{f0} refers to a heated or cooled portion of the plate l_0, and Re_f to the complete length l, or upon reduction:

$$Nu_{f0} = 0{\cdot}037\, Re_{f0}^{0{\cdot}8}\, Pr_f^{0{\cdot}43}\, [Pr_f/Pr_w]^{0{\cdot}25} \quad (4)$$

where Re_{f0} refers to the heated length of the plate l_0. The formulae (4) obtained differs in no way from dependence (2) for plates without non-heated tips. Therefore, it is possible to draw the conclusion that heat transfer of the plate does not depend upon the length of the initial non-heated tip and in calculations both Nu_{f0} and Re_{f0} should refer only to the length taking part in heat transfer.

The experimental data of the final treatment are given in Fig. 3 in the form of the dependence:

$$Nu_{f0}\, Pr_f^{-0{\cdot}43}\, [Pr_f/Pr_w]^{-0{\cdot}25} = f(Re_{f0}). \quad (5)$$

At $Re_f > 1{\cdot}4 \times 10^7$ the upper points are given in the form of the dependence:

$$Nu_{f0}\, Pr_f^{-0{\cdot}43}\, [Pr_f/Pr_w]^{-0{\cdot}25}\, [l_0/l]^{-0{\cdot}8} = f(Re_f) \quad (6)$$

as proof of the identicality of equations (3) and (4).

All the points in the range of the Re_{f0} numbers from 5×10^5 to 3×10^7 lie rather well on a straight line. Points pertaining to the plate with a sharp front edge of the tip lie here as well.

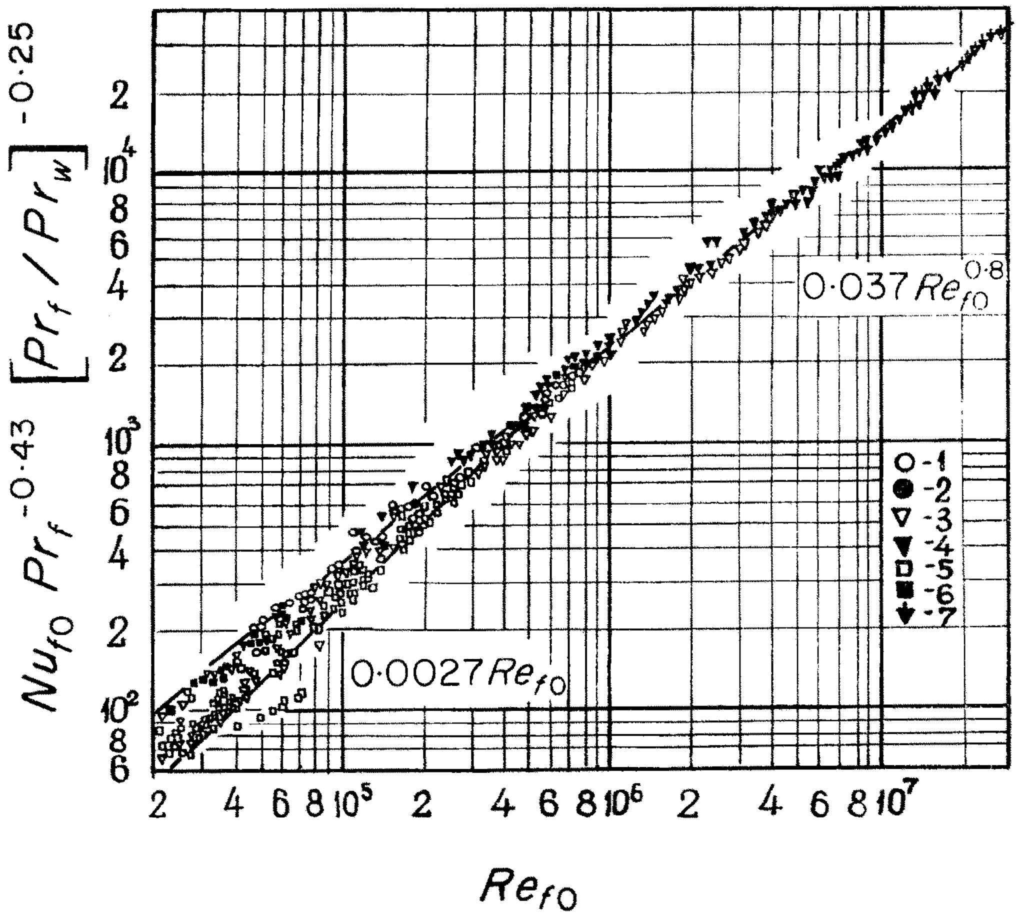

FIG. 3. Experimental data. 1—air heating, 2—air cooling, 3—water heating, 4—water cooling, 5—transformer oil heating, 6—transformer oil cooling, 7—water cooling, equation (7).

In the transient regime from a turbulent to a laminar boundary layer (Re_{f0} from 2×10^4 to 5×10^5) the experimental points lie between straight lines corresponding to equation (2) and the equation:

$$Nu_{f0} = 0{\cdot}0027\, Re_{f0}\, Pr_f^{0{\cdot}43}\, [Pr_f/Pr_w]^{0{\cdot}25} \quad (7)$$

depending on the intensity of turbulization on the surface of the plate.

Equation (7) shows that for some cases heat transfer in the transient region does not depend on the length of the plate.

For air ($Pr_f = 0{\cdot}702$) equation (4) is simplified and takes the following form:

$$Nu_{f0} = 0{\cdot}032\, Re_{f0}^{0{\cdot}8} \quad (8)$$

that agrees well with experimental data on heat transfer of a plate in a subsonic turbulent air flow [5].

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