HEAT TRANSFER FOR TRANSITIONAL, LONGITUDINAL FLOW OVER A TUBE BUNDLE

A. Ya. Inayatov

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Results are presented for an experimental investigation of heat transfer for longitudinal water flow at Re = 1000-12,000 over a staggered tube bundle consisting of 19 copper tubes with a relative spacing of s/d = 1.22. The experimental data obtained is compared with normative theoretical formulations due to Weisman and Mikheev.

Little attention has been given to heat transfer for laminar and transitional longitudinal water flow over a tube bundle. In particular, this flow regime is of practical interest in the computation of heat transfer for turbo power plant apparatus, for tubular boiler surfaces, for air furnaces and for the investigation of reactor consumption and output at nominal power level.

The theoretical investigation in [1] was devoted to the investigation of heat transfer in a tube bundle for laminar flow of the heat-transfer medium. Average Nusselt numbers, Nu = 4-11, were obtained for relative spacings of s/d = 1.1-1.5 for boundary conditions on the TVEL surface of t_W = const and q_W = const. However, the dependence of α on Re and Pr numbers and on temperature differential was not studied in [1].

The transitional flow regime is characterized by instability and the results of different experimental investigations differ markedly even for the same tubes [2]; reliable theoretical predictions do not exist. Treatment of tube bundles is even worse. Our work was conducted to eliminate this problem. The experimental apparatus and results of the study of α in turbulent flow are described in [3-5]. In assembling the apparatus for the present investigation the number of thermocouples was increased, their ohmic resistance was decreased and galvanometers, wattmeters, and current transformers were replaced by more accurate devices.

The water temperature at entrance and exit was measured with thermocouples mounted in copper-tipped capillaries. Stirrers were placed in front of the cases to mix the water. Eight, copper–constantan thermocouples were distributed along the surfaces of the center and edge tubes of the metering calorimeter; readings of these thermocouples were used to determine the integrated average temperature of the external tube surface. Thermoelectrodes on copper tubes were not protected by capillaries. Copper wires were forced into thermocouple channels after which the surface was smoothed and trimmed.

Water flow was regulated with a valve and measured with a double diaphragm (supply line diameter, D = 52 mm; primary diaphragm diameter, d = 16.4 mm; auxiliary diaphragm diameter, d' = 28.3 mm; spacing between diaphragms, a = 15 mm). The flow coefficient from [6] was α = 0.693 and from the results of calibration by measuring the water volume α = 0.720.

The thermocouple electromotive force was measured with a P 306 potentiometer with a GT-1 Hungarian reflecting galvanometer which facilitated measured accuracies to 0.0005 mV which corresponds to ~0.015°C. An M 195/1 galvanometer was used for control tests.

The ranges of the parameters investigated in the experiments conducted were as follows: w = 0.108-0.950 m/sec (critical value, 0.2); Re = 1000-12,000; Pr = 6.5-3.75; t_W = 30-70°C; t_f = 23-46°C; Δt = 4-30°C; α = 1163-5200 W/m^2·deg; and q = 18,600-35,000 W/m^2. The accuracy of the experiments was ±5%.

By generalizing tube heat-transfer data, Mikheev, [2], concluded that, to first approximation, the value of α for Re < 10,000 may be determined from its known formula for turbulent flow. In order to show the

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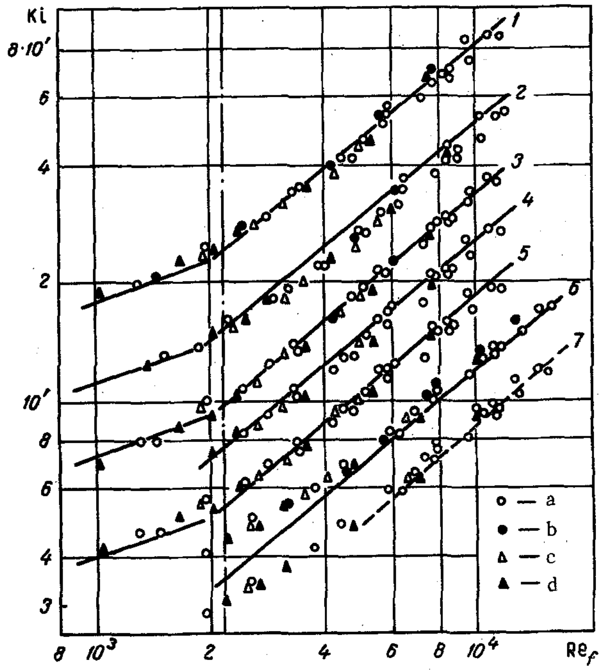

Fig. 1. Average heat transfer for longitudinal laminar and transitional flow of water over a tube bundle. a, b and c, d: M195/1 and GT-1 galvanometers, total and locally modelled bundle, respectively; 1) Weisman formula, [12], (d_h, t_f); 2) the same (d_h, t_m); 3) Mikheev formula, [2], (d_h, t_f); 4) normative method, [7] with correction due to Petukhov, [8], (d_h, t_f); 5) the same without correction (d_h, t_f); 6) normative method, thermal diameter is characteristic dimension (d_T, t_f); 7) the same corrected by the thermal factor c_t(d_T, t_f).

possibility of using known formulas for transitional flow, experimental heat-transfer data were compared with Mikheev's equations [2]; for $Re = 8 \cdot 10^3$–$2 \cdot 10^6$, $Pr = 0.7$–150,

$$Nu = 0.021\, Re^{0.8} Pr^{0.43} A, \quad (1)$$

VTI, TsKTI [7], $Re = 3 \cdot 10^3$–$7 \cdot 10^5$, $Pr = 0.7$–100,

$$Nu = 0.023\, Re^{0.8} Pr^{0.4} A, \quad (2)$$

and Weisman's [12], $Re = 25 \cdot 10^3$–10^6, $Pr = 1.75$–1.18 ($t_f = 100$–$150°C$),

$$Nu_m = c\, Re_m^{0.8} Pr_m^{1/3}, \quad (3)$$

where c = 0.026, s/d = 0.006; for s/d = 1.1-1.5 (for our staggered array, s/d = 1.22, c = 0.0257) and Petukhov's [8], $Re = 10^4$–10^6, $Pr = 0.7$–200,

$$Nu = \frac{0.125\xi\, Re Pr\, A}{4.5\sqrt{\xi}\,(Pr^{2/3} - 1) + 1.07}. \quad (4)$$

Values of the friction coefficient were computed from the Filonenko equation

$$\xi = (1.82\, \lg Re - 1.64)^{-2}. \quad (5)$$

Here $A = (Pr_f/Pr_w)^n$ is a coefficient which accounts for the effects of variable viscosity, i.e., the direction of heat flow.

For cooling of a fluid dropping in a tube, all authors [2, 8, 9, 10] give an identical correction factor, n = 0.25; for heating different values are given; Mikheev gives 0.25; Petukhov 0.11; Kutateladze 0.06. In accordance with the normative method $A = c_t = 0.7$ [7].

Experimental heat-transfer data for the transitional zone with Re = 2000-10,000, $K_i = cRe^{0.8}$, are compared with Eqs. (1), (2), and (3) in Fig. 1 on the basis of the relationship $K_i = f(Re)$. Laminar flow heat-transfer data for Re < 2000, $K_i = 0.15 Re^{0.33}$, are compared in Fig. 1 with Eq. (6) from [2] without account of the Grashof number

$$Nu = 0.15\, Re^{0.33} Pr^{0.43} (Pr/Pr_w)^{0.25}. \quad (6)$$

For convenience curves constructed from Eqs. (1), (2), and (3) and test data reduced for different characteristic dimensions and temperatures as well as with and without account of the effects of variable viscosity have been separated into seven groups by multiplying K_i by 2, 1.25, 1, 0.7, 0.5, 0.33, and 0.23.

The characteristic temperature for curve 2 is average temperature of the boundary layer $t_m = 0.5(t_f + t_w)$; for the remaining curves it is the average temperature of the fluid t_f.

The characteristic dimension for curves 6 and 7 is the thermal diameter d_T: for the remaining curves it is the hydraulic diameter d_h.

In the first and second groups the test data are compared with the Weisman formula where

$$Nu Pr^{-0.33} = K_1 = 0.0257\, Re^{0.8}, \quad Nu_m Pr_m^{-0.33} = K_2 = 0.0257\, Re_m^{0.8}.$$

In curve 1 the test data lie 5% below, and in 2, 10-12% below Eq. (3), which is only valid for fluid heating. In the third group experimental data are compared with the Mikheev formula where

$$Nu_f Pr_f^{-0.43} (Pr_f/Pr_w)^{-0.25} = K_3 = 0.021\, Re_f^{0.8}.$$

Experimental data in curve 3 for longitudinal, transitional water flow over a tube bundle ($s/d = 1.22$) are in good agreement with Eq. (1) which is valid for both fluid heating and cooling.

In the fourth, fifth, sixth, and seventh groups experimental data are compared with equations from the normative method VTI, TsKTI for different forms of the characteristic dimension and account for the direction of heat flow.

In 5, the characteristic dimension is the hydraulic diameter, d_h, where $NuPr^{-0.4} = K_5 = 0.023Re^{0.8}$. The experimental data are in excellent agreement with Eq. (2) which is valid only for fluid heating. On curve 4, $NuPr^{-0.4} (Pr_f/Pr_w)^{-0.11} = K_4 = 0.023 Re^{0.8}$ the experimental data which account for the effect of variable viscosity are 6% lower than Eq. (2). The correction $(Pr_f/Pr_w)^{0.11}$, valid for fluid heating, to the Petukhov equation (4), was applied, without any clarification, in the standards for thermal computation of boiler aggregates (1968) in the use of Eq. (2).

In 6 the characteristic dimension is the thermal diameter d_T, presented in [7], $NuPr^{-0.4} = K_6 = 0.023 Re^{0.8}$. The experimental data lie 5% above Eq. (2) and transition from laminar to turbulent flow occurs at $Re_{cr} = 5000$. The critical Reynolds number for the Weisman, Mikheev, and normative relationships is $Re_{cr} = 2000$-2300.

In 7, $NuPr^{-0.4} c_t = K_7 = 0.023 Re^{0.8}$, the experimental data which account for a temperature correction factor, $A = c_t = 0.7$, lie 30% below the normative equation.

Experimental data for the total and locally modelled bundle are presented in Fig. 1. This data is in satisfactory agreement. This also permits investigation of transitional flow heat transfer by heating only one tube in the bundle. This simplifies experimental procedure.

As may be seen from Fig. 1 (1 and 5) the rate corresponds to $Re^{0.75}$ as in Khobler [11], which stems from hydraulic theory of heat transfer (Prandtl analogy).

Generalization and analysis of the experimental data shows that, in the investigated range of $Pr = 3.75$-6.5, with increase in the level of m of the Prandtl criteria, the constant coefficient decreases; from Weisman, $m = 0.33$, $c = 0.0257$; from the normative method, $m = 0.4$, $c = 0.023$; from Mikheev, $m = 0.43$, $c = 0.021$. The product cPr^m computed from Eqs. (1), (2), and (3) for a temperature differential to $\Delta t = 30°C$ is in almost complete agreement with data to within the limits of experimental accuracy.

From Fig. 1 (curve 3) it is also evident that Eq. (6) may be used for approximate computation of the heat transfer for laminar, longitudinal flow over a tube bundle ($Re < 2000$).

Thus, it has been experimentally established that heat transfer for external, transitional, longitudinal flow over a tube bundle may be predicted by Eqs. (1), (2), and (3). The equations due to Weisman, Mikheev, and the normative method given almost identical values of the heat-transfer coefficient for fluid heating in the range $Re = 2000$-$10{,}000$. The validity of Eqs. (2) and (3) for fluid cooling still requires experimental verification. In Eqs. (1), (2), and (3) the characteristic dimension is the hydraulic diameter and the characteristic temperature is the average temperature of the flow.

NOTATION

- α is the mean heat-transfer coefficient;
- d_h is the hydraulic diameter of bundle;
- d_T is the thermal diameter;
- t_f is the mean temperature of liquid;
- t_m is the mean temperature of boundary layer;
- t_w is the mean temperature of tube wall surface;
- w is the velocity of liquid;
- q is the specific heat flux.

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