HEAT TRANSFER IN THE FLOW OF LOW-DENSITY AIR IN NARROW CHANNELS

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Results are given from measurements on air flow in narrow channels; relationships in dimensionless terms are derived for the heat transfer over a wide range in speed (1-120 m/sec) and in pressure $(1 \cdot 10^5 > P > 1.33 \cdot 10^3)$ N/m^2.

There are many studies on heat transfer in channels with forced motion of liquid, and well-known relationships in dimensionless terms have been proposed for the heat-transfer coefficient [1-4]. However, many current heat-exchanger systems operate in the transition flow region, and there is a lack of satisfactory evidence for designing such devices; the discrepancies between formulas may be as large as 250% [4].

We have sought to derive reliable experimental evidence on heat transfer for air over a wide range of speeds and pressures in technically smooth small-diameter tubes; here we give results for force-fed air in copper tubes with internal diameters of 1.5, 3, 4, and 6 mm.

The tests were done with the apparatus shown in Fig. 1.

The air was taken from the atmosphere via the vacuum pump 1; it was cleaned from dust by the filter 5 and heated to a set temperature by an electrical heater 4 before passing to the heat exchanger; the test

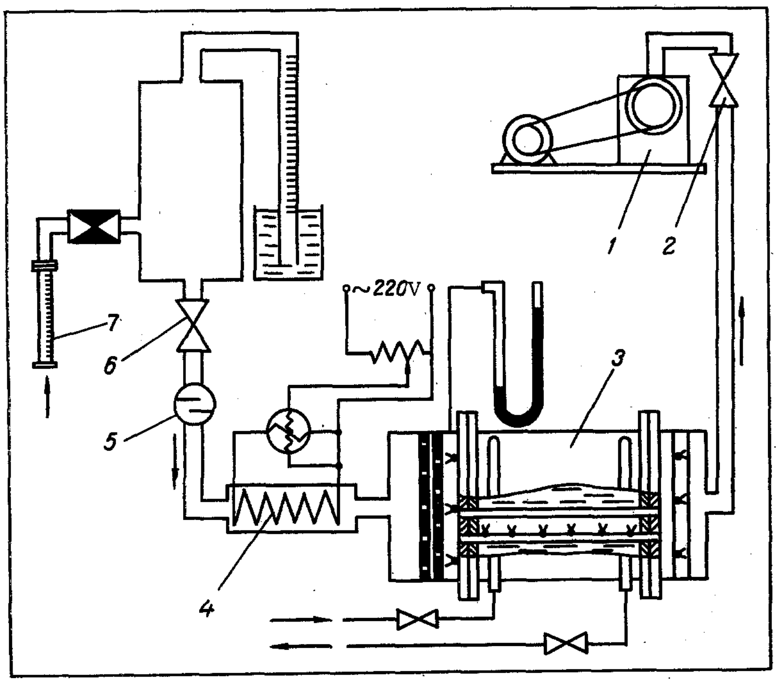

Fig. 1. The apparatus.

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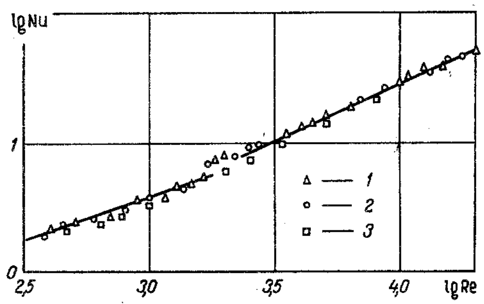

Fig.2. Generalized relationship Nu = f(Re) for heat transfer in narrow channels: 1) d = 4 mm, l/d = 95; 2) d = 3 mm, l/d = 105; 3) d = 1.5 mm, l/d = 210.

system 3 was a set of 6 thin-walled copper tubes fixed at the ends into Tufnol plates. The tubes had sharp edges at the inlet end, and there was no hydrodynamic stabilization region, i.e., the conditions were approximately as in a heat-transfer apparatus of this type. The tubes were cooled by surrounding them with a steel jacket through which flowed water at constant speed and temperature. In all the tests, the tube wall temperature was practically constant, i.e., we had the boundary condition t_W = const. At the inlet and outlet from the exchanger there were mixers that provided good mixing of the air before measurements were made with the thermocouple and uniform distribution of the air flow over the cross section of the exchanger. We used three copper–constantan thermocouples at inlet and outlet to measure the enthalpy mean temperature of the air. The temperature of the tube wall was measured at points along the length by copper–constantan couples attached near the internal surface of the tube.

The emfs of the thermocouples were measured by an M25 galvanometer; the bridge circuit was balanced by means of a low-resistance PMS-48 potentiometer.

The air flow rate and pressure at the inlet were measured by the valve 2 and needle valve 6, the pressure being monitored by a U-tube mercury manometer.

The air flow rate was monitored by one or two parallel rotameters 7, or volumetrically at low rates [5].

When the latter method was used, the flow rate was calculated from

$$V_1 = \frac{cn}{\Delta\tau}\left\{1 + \frac{\gamma_0}{\gamma_m}\cdot\frac{129.1\cdot 10^3\left(\frac{l}{N}n + h_2\right)}{P_0}\left[\frac{V_0}{cn} - 1\right]\right\}.$$

The volume flow rate, as referred to conditions at the inlet, was determined from

$$V_2 = V_1\frac{P_0}{P_p}\cdot\frac{T_p}{T_0}.$$

We did 7 series of experiments at different relative channel lengths: l/d = 40; 75; 95; 145; 200. In each series we did 25-30 tests at different values of Re and constant air temperature and pressure at the inlet. We also performed tests on the effect of free convection on the heat transfer with air flowing at an inlet temperature in the range 30-100°C, and we also did some tests at reduced pressures in the range Re = 500-1500 and pressures of $(0.133\text{-}10)\cdot 10^4$ N/m^2.

The heat transferred to the exchanger was determined from the enthalpy change between inlet and outlet:

$$Q = Gc_p\,\Delta t.$$

The results for each series were presented as dimensionless relationships of the form $Nu = c\cdot Re^n$; in calculating the mean heat-transfer coefficient for a given channel length, the temperature difference between the air and the internal surface of the tube was taken as the mean of the logarithmic values. The physical quantities appearing in the above dimensionless quantities were determined from the mean air temperature in the pipes.

The heat-transfer coefficient was determined in this way with a coefficient of variation not exceeding ±5%.

We found that the power n in the above relationship had one value for values of Re < 1700 and another for Re > 2250. We found also that c increased in the equation $Nu = c\cdot Re^n$ as the channels became shorter, i.e., the lines in logarithmic coordinates were parallel straight ones. If the pipe length was more than 100 diameters, the results were represented to ±3% by the following:

for Re < 1700

$$Nu = 0.08\,Re^{0.56};\qquad(1)$$

for Re > 2250

$$\mathrm{Nu} = 0.0117\,\mathrm{Re}^{0.86}. \tag{2}$$

The results gave the mean heat-transfer coefficients along the pipe lengths. To calculate the transfer for channels of length less than 100 diameters we had the following empirical relationships:

for Re < 1700 and 100 > l/d > 40

$$\mathrm{Nu} = \left[0.08 + \left(100 - \frac{l}{d}\right) 3.9 \cdot 10^{-4}\right] \mathrm{Re}^{0.56};$$

for Re > 2250 and l/d > 40

$$\mathrm{Nu} = \left[\frac{11.7}{\left(\frac{l}{d} - 40\right)^{0.7}} + 9.5\right] \cdot 10^{-3}\,\mathrm{Re}^{0.86}.$$

Figure 2 shows that there is a marked change in the coefficient between Re of 1700 and 2250, which indicates a change in the flow conditions; in this transition region, the laminar flow becomes unstable and the turbulence increases along the pipe. For Re above 2250, there is fully developed turbulence. The transition region is comparatively small because the developed turbulence sets in comparatively rapidly along these pipes in the absence of hydrodynamic stabilization at the inlet. These conclusions are confirmed to some extent by [6], in which it was shown that an equation characteristic of developed turbulence applies when there is increased initial turbulence in parts of the pipe more than 20 diameters away from the inlet.

We found no effect from free convection on the heat transfer for air flowing in these pipes.

The low-pressure experiments confirmed that the heat-transfer coefficient was independent of the pressure within the above range, i.e., one can use the above relationships to calculate the heat transfer.

The results represented by (1) may be compared with values calculated from a standard formula from the laminar region [1], which shows that for Re small the heat-transfer coefficients calculated from (1) are substantially less than those given by the formula of [1].

This difference may be as much as 20%; we obtain lower values for small Reynolds numbers on account of degeneration of the natural convection in narrow pipes ($Gr < 1 \cdot 10^3$).

There is less difference between our experiments and the values from the formula of [1] at larger Re, and when Re = 500, the two sets of values coincide.

In the turbulent region (Re > 2250), our measured values are considerably higher than those calculated from [1], the difference rising to as much as 50%.

We may compare (2) with the relationships of [7] for the transition region, which shows that the values from (2) are higher by about 15%.

For some part of the region (Re = 2250-32,000) there is a range where the turbulent flow is not yet fully established.

NOTATION

V	is the volume flow rate of air;
N	is the total number of buret divisions;
P_0	is the pressure in measuring tank;
l	is the length of measuring section of buret;
$\Delta\tau$	is the time of oil column rise to the height h_1;
n	is the number of buret division corresponding to h_1;
γ_o, γ_m	are the specific weights of oil and mercury;
c	is the scale division of buret;
h_2	is the height of oil drop in measuring cylinder;
V_0	is the total volume of system from needle throttle to heat exchanger inlet;
P_p	is the pressure at heat exchanger inlet;
T_p, T_0	are the temperature at heat exchanger inlet and of surrounding air;
G	is the air flow rate in mass terms;
c_p	is the mean specific heat of air;

Δt is the air temperature variation over measuring section;
Nu, Re are the Nusselt and Reynolds numbers;
l, d are the length and diameter of channel.

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