HEAT TRANSFER FROM A HORIZONTAL CYLINDER UNDER MIXED CONVECTION CONDITIONS

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An investigation has been made of special features of heat transfer from horizontal wires under combined forced and free convection. It is shown that in counterflow, in contrast with auxiliary flow, the dependence of $Nu(Re)_{Ra=const}$ has a minimum. Near the minimum in the range $0.15 < Re^2/Ra\sqrt{Re} < 1.5$ there is a region where the heat transfer conditions are oscillatory.

Heat transfer in transverse flow over a cylinder at low Re, i.e., in the region where the free convection effect is appreciable, is an important problem, both theoretical and practical, and its solution requires the development of measuring devices with sensors in the form of heated wires [1, 2]. Study of this problem is presently incomplete, and is at the stage of accumulation of individual facts and correlations [3, 4].

The authors have attempted an experimental investigation of special features of heat transfer under mixed convection conditions with transverse flow over a horizontal cylinder as a function of the direction of forced flow.

A qualitative analysis of the heat transfer process under these conditions suggests that one can identify two specific physical mechanisms. The first is the addition of free convection to the forced convection, and this is independent of the direction of the forced motion. The effect is associated with reduction of the size of the zone in which the total temperature drop is concentrated as Re number increases, resulting in a decrease in the absolute value of the free-convective component in the heat transfer. The second mechanism is a change in the heat transfer because of geometric addition of the forced and free velocities of motion. One would expect the first mechanism to show up in the auxiliary flow. It should manifest itself in the dependence $Nu(Re)_{Ra=const}$ in the low Re region being substantially weaker than indicated by calculation, obtained by simple summation of the free convection and forced convection components, without allowing for interaction. The action of the second mechanism should be more pronounced in counterflow: in this case one would expect a region to appear near zero Re in which the values of Nu decrease with increase of Re, i.e., the correlation Nu(Re) for fixed Ra should have a characteristic minimum. Experimental studies of these expected features of heat transfer were the objective of the present investigation.

A study was made of heat transfer from a cylindrical sensor of length 9.4 cm, made up of platinum wire of three diameters: $0.5 \cdot 10^{-2}$ cm, $1 \cdot 10^{-2}$ cm, $2 \cdot 10^{-2}$ cm. The sensor was located in a vertical channel of rectangular cross section with a side ratio of 10/1. It was fixed along the major axis of the channel by means of a special element which allowed choice of the temperature deformation of the sensor and kept the wire straight.

Tests were carried out in high-purity nitrogen at atmospheric pressure. A system of two gas-reducing valves in series and a fine control valve was used for smooth variation and maintenance of the nitrogen flow in the channel. The gas velocity in the channel was measured by means of a liquid rheometer. The flow temperature was held constant and equal to room temperature in all the tests. The sensor was heated by a dc current supplied from a stabilized source. The electrical resistance of the sensor (and this means its temperature) and also the Joule heating were measured and recorded by a measurement system

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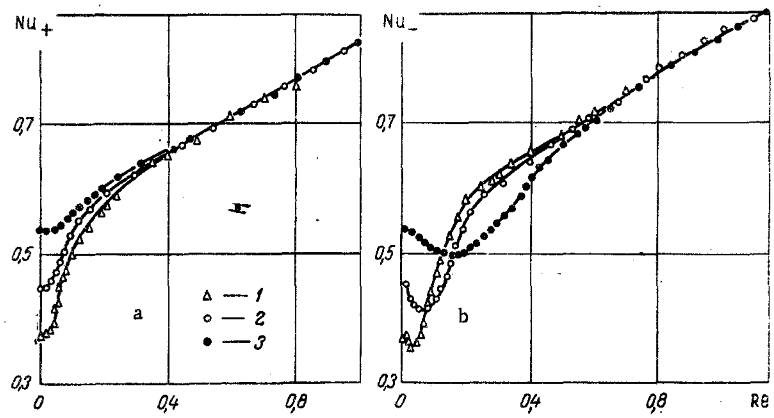

Fig. 1. Nu as a function of Re for fixed value of Ra: a) auxiliary flow Nu_+; b) counterflow Nu_-; Ra: 1) $4.3 \cdot 10^{-4}$; 2) $4.25 \cdot 10^{-3}$; 3) $4.52 \cdot 10^{-2}$.

described in [2]. The accuracy of sensor temperature measurement was 0.5°C, and that for measurement of Joule power was ~0.1%. From these measurements one could calculate the coefficient of heat transfer from the sensor to the gas stream. The channel length was chosen to avoid perturbations from the inlet and exit flow. There were no turbulent fluctuations in the flow: the channel Re number did not exceed 200.

Figure 1a, b shows the variation of Nu(Re) for fixed value of Ra: a is the case of ascending motion of forced flow (the Nusselt number is denoted by Nu_+), and b is for descending motion of the forced flow (the Nusselt number is Nu_-). Each curve was obtained by varying the velocity of the oncoming stream with unchanged sensor temperature and diameter. Figure 1a, b shows data obtained in tests with sensor temperature 150°C. It can be seen that the heat transfer correlations with auxiliary motion and in counterflow are substantially different: in the low Re region the $Nu_+(Re)$ dependence is a monotonically increasing function with a characteristic S-shape, while the $Nu_-(Re)$ dependence is a function with a sharply pronounced minimum. Thus, the qualitative nature of the dependence obtained corresponds to the expected influence of the above physical circumstances on the heat transfer.

It is clear that for combined forced and free convection the total heat transfer law is given by a function which is some combination of the Re and Ra parameters. We obtain the form of this combination from analysis of the position of the minima on the curves of $Nu_-(Re)_{Ra=const}$ (Fig. 1b).

If one assumes that the position of the minimum corresponds uniquely to a definite value of the combination of type $Re^m Ra^n$, one can easily determine the ratio m/n from the data of two curves. Calculation of this ratio for different pairs of curves (Fig. 1b) gave a value close to −5/2.

It turned out that all the experimental data obtained when one uses as an argument the parameter combination $Re^2\sqrt{Re}/Ra$ thus evaluated are described very satisfactorily by general laws. These laws for the auxiliary flow case are:

$$\frac{Nu_-}{Nu_0} = 1 + 0.16A^{2/5} \quad \text{for } 0{,}1 < A < 20; \tag{1}$$

$$\frac{Nu_-}{Nu_0} = 1 + 0.28A^{2/3} \quad \text{for } 0 < A < 0{,}1. \tag{2}$$

For the counterflow case the heat transfer law can be expressed as the function $(Nu_+ - Nu_-)/Nu_0$, which has the form

$$\frac{Nu_+ - Nu_-}{Nu_0} = \frac{0.15}{A^{0,17}} \exp\left[-0.22 \ln^2 A\right] \quad \text{for } 0 < A < 20, \tag{3}$$

where Nu_0 is the value of Nu for Re = 0; $A = Re^2\sqrt{Re}/Ra$.

The validity of the relations obtained begins to break down appreciably for values of the group $Re^2\sqrt{Re}/Ra = A$ larger than 20, when the effect of free convection is very small. Then the heat transmission is given by the well-known correlations for forced motion [5].

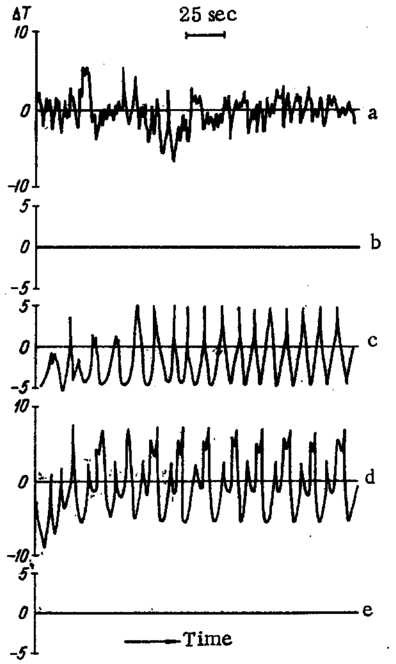

Fig. 2. Typical sensor temperature records ($\varnothing = 2 \cdot 10^{-2}$ cm) for T = 150°C and different blowing velocities v: a) v = 0; b) 1.3; c) 1.7; d) 2.5; e) 3 cm /sec.

It was observed during the investigation of heat transfer in the counterflow case that in the region of the minimum, approximately in the range $0.15 < A < 1.5$, there is a region where the heat transfer process is not steady, and regular oscillations of the sensor temperature occurred. Figure 1b gives values of Nu in this region, calculated from the mean heat transfer coefficients. The same is true of Eq. (3). By way of illustration Fig. 2 shows typical temperature records for the sensor, obtained during investigation of heat transfer on a sensor of diameter $2 \cdot 10^{-2}$ cm, with a mean temperature of 150°C. With no forced motion (Fig. 2a) the record has a fluctuating nature. The fluctuations are irregular in amplitude and frequency, due to the turbulence in the free convection motion. As the velocity of forced flow increases the free convection appears to be "blown away" and the amplitude of fluctuation decreases. For a flow speed of ≈1 cm/sec the fluctuations became quite noticeable (Fig. 2b). For further increase in velocity, and when the above-mentioned region of oscillatory conditions was encountered, the sensor temperature fluctuations again appeared, but these fluctuations differed now in that they were strictly regular both in amplitude and in frequency (Fig. 2c). The regular oscillations were maintained right up to a speed of ~2.5 cm/sec; their frequency remained approximately unchanged, but the amplitude and the shape of the oscillations showed some variation (Fig. 2d). Further increase in the flow velocity led to the oscillatory regime suddenly vanishing (Fig. 2e) and oscillations of this kind no longer occurred.

It should be noted that if one comes from the low speed region to the high speed region (>2.5 cm/sec), the above regimes are repeated.

The oscillatory conditions exist only in the counterflow case, and do not occur in the auxiliary flow case, for which one always obtains a regime similar to Fig. 2b.

The mechanism for excitation of oscillatory instability is a rather complex phenomenon requiring special investigation. It can obviously be explored by analysis of the frequency and amplitude characteristics of the temperature records, during study of the role played by thermal and hydrodynamic factors, and this might be accomplished by tests with automatic stabilization of sensor temperature. This is outside the scope of the present work at this stage of the investigation. We shall make only one comment relevant to this mechanism: one can assume that the oscillatory condition is excited when the typical velocity of free-convection motion becomes comparable with the counterflow velocity of the forced flow. This circumstance can lead to periodic breakdown and subsequent reestablishment of the thermal boundary layer around a cylindrical sensor (it is known that the outer problem of heat conduction for a cylinder does not have a stationary solution), and this results in the appearance of the observed temperature oscillations.

NOTATION

Re is the Reynolds number;
Ra is the Rayleigh number;
Nu_0 is the Nusselt number for natural convection heat transfer mechanism;
Nu_+ is the Nusselt number for the auxiliary flow case;
Nu_- is the Nusselt number for the counterflow case.

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