CONVECTIVE HEAT TRANSFER IN TRANSVERSE GAS FLOW OVER A CYLINDER

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A method is described for studying convective heat transfer in transverse flow over a wire, from the temperature dependence of the heat transfer coefficients. A formula has been obtained for calculating convective heat transfer in gas flow over a wire, for temperature differences up to 1000°C and Re values from 0.14 to 2.

The work described here was performed because of the requirements of the electro-thermograph method of investigating the kinetics of heterogeneous-catalytic reactions. The method and the results of chemical reactions have been described in detail in [1-3], and we shall mention the essential features only briefly here.

The method is based on measurement of the temperature of a wire of catalytic material washed transversely by a stream of reagents of given composition and speed. If we have information on heat transfer for the flow over the wire we can calculate the stationary rate of heat release or absorption in the reaction (depending on the sign of the heat reaction proceeding at the wire surface), and hence the reaction rate in the test conditions. The required temperature conditions for the surface reaction to proceed are set up by varying the electric current through the wire, thus simulating variation in gas stream temperature while keeping it unchanged in the tests. In the tests one measures and records the electrical resistance R (i.e., the temperature T) of the wire, and the electric current I passing through the wire. All the tests were done with platinum wire of diameter 0.1 mm.

Procedures have been proposed [3] in the development of the method for calculating the rate of heat release or absorption from the known experimental R, T(I) relations, knowing only the convective heat transfer.

Convective heat transfer in transverse flow over a cylinder has been the subject of a large number of papers [4-8]. The correlation used is

$$\mathrm{Nu} = C\,\mathrm{Re}^m\,\mathrm{Pr}^n \tag{1}$$

with C and m varying for different ranges of Re. These data were obtained with small degrees of overheat (e.g., of the order of 100°C in [4]). For large temperature heads a factor of the type $(T_W/T_\infty)l$ appears (discussed in [4] and other papers dealing in particular with theory of the hot wire anemometer and other sensors with a hot wire). We should mention that the formulas recommended in the above papers differ appreciably, particularly in the values of m (from 0.3 to 0.5) in the range of Re that interests us, i.e., less than 10. High accuracy in calculating the heat transfer coefficient is of primary importance for the thermographic method of studying chemical reactions.

We undertook investigations of the law of convective heat transfer in transverse flow over a wire, and here attention was focussed directly on the reacting element of the instrument in the method that was developed (the experimental equipment and the electrical details were described in [1, 3]).

The form of the law in question was established from analysis of the temperature dependence of the coefficients of convective heat transfer. These relations can easily be obtained for any gas, as follows.

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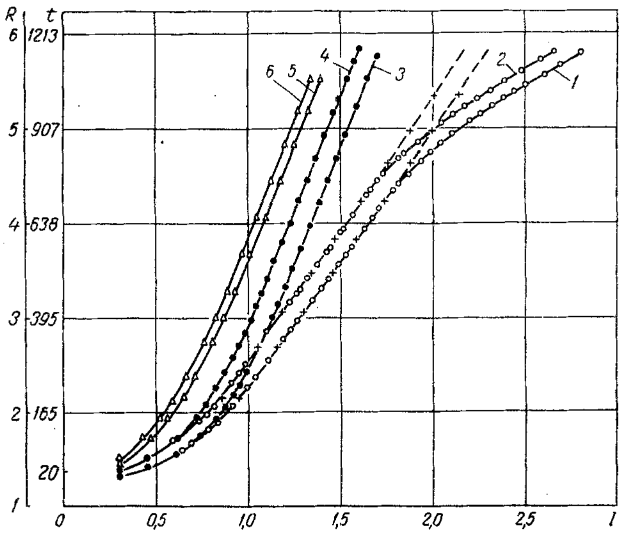

Fig. 1. Electrical resistance (or temperature) of the wire as a function of the current as obtained for different gas streams: 1, 2) in a stream of ammonia at speeds of 0.32 and 0.13 m/sec, respectively; the crosses indicate calculated values; 3, 4) in a stream of nitrogen (common grade) at speeds of 0.32 and 0.13 m/sec; 5, 6) in a stream of sulfurous anhydride at speeds of 0.15 and 0.075 m/sec (R in ohms, t in°C, I in A).

The dependence for R and T(I) was determined experimentally in streams of the test gas for any two blowing speeds. The difference in Joule heating at an arbitrary temperature (e.g., $T = T_0$) is expressed in terms of the heat transfer coefficients:

$$R_0\left(I_{20}^2 - I_{10}^2\right) = \left(\alpha_{20} - \alpha_{10}\right)\Delta T_0 S. \tag{2}$$

Here α_{20} and α_{10} are the coefficients for only the convective component of the heat transfer, since, by taking the difference, we automatically eliminate radiative heat transfer (subscripts 1 and 2 refer to the two blowing speeds). If the convective heat transfer is given by Eq. (1), then the difference in the Joule heating at the two different temperatures can be related to the ratio of the heat transfer coefficients at these temperatures, with other conditions being the same, i.e.,

$$\frac{R\left(I_2^2 - I_1^2\right)}{R_0\left(I_{20}^2 - I_{10}^2\right)} = \frac{\alpha}{\alpha_0} \cdot \frac{\Delta T}{\Delta T_0}, \tag{3}$$

since $(\alpha_2 - \alpha_1)/(\alpha_{20} - \alpha_{10}) \equiv \alpha_1/\alpha_{10} \equiv \alpha_2/\alpha_{20}$. Expressing the heat transfer coefficients in terms of the thermophysical characteristics, we obtain

$$\frac{R\left(I_2^2 - I_1^2\right)}{R_0\left(I_{20}^2 - I_{10}^2\right)} = \frac{\Delta T}{\Delta T_0} \cdot \frac{\lambda}{\lambda_0}\left(\frac{\nu_0}{\nu}\right)^m\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_0}\right)^n, \tag{4}$$

where λ, ν, Pr are the thermal conductivity, the kinematic viscosity, and the Prandtl number at the mean temperature of the boundary layer (such averaging is physically valid, since the temperature dependence of these characteristics is almost linear; in addition, the correlation of the results obtained, given below, confirms the correctness of the averaging). The reduction of the test data in accordance with Eq. (4) (calculation of the left side) and comparison of the results with those for the right side, should first confirm that it is possible to describe convective heating by an expression of the form of Eq. (1), and secondly, allows determination of the value of m (there are no particular discrepancies with regard to n in the literature; moreover, it has a very weak effect in the calculation of heat transfer coefficients for gases). We again note that the tests are done at arbitrary flow speeds, as can be seen from Eq. (4).*

*This can be important from the viewpoint that the experimental equipment and the method described for treating Eq. (4) can be the basis for a thermographic method of measuring the temperature dependence of the thermal conductivity or the viscosity of the gas blowing over the wire.

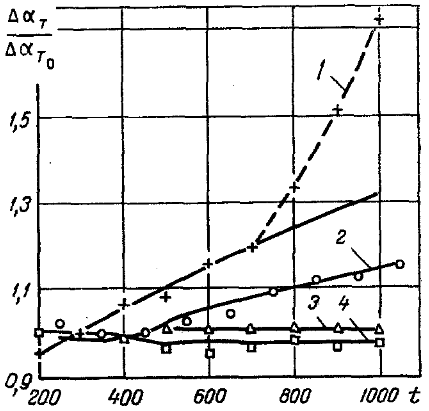

Fig. 2

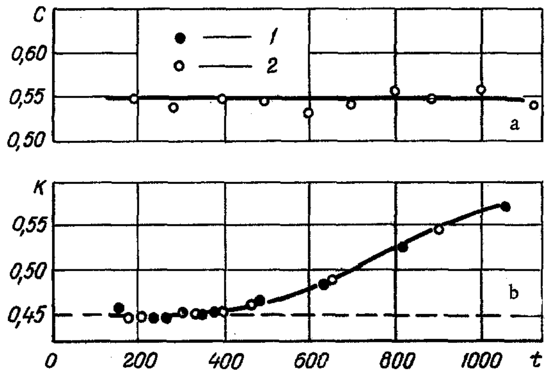

Fig. 3

Fig. 2. Dependence of the convective heat transfer coefficients (differences in the coefficients) in flow over a wire on the wire temperature, in streams of various gases: the points are the measured results: stream of 1) ammonia; 2) sulfurous anhydride; 3) argon; 4) common grade nitrogen; the full lines show the results of calculations as per Eq. (4) using the value $m = 1/2$.

Fig. 3. Dependence of the factors C (a) and K (b) in the correlation $Nu = K + C\,Re^{1/2}\,Pr^{1/3}$ on temperature, obtained from heat transfer studies in a stream of common grade nitrogen; 1) flow speed 0.32 m/sec; 2) 0.13 m/sec.

The measurements and calculations in accordance with Eq. (4) were made for the wire washed by streams of sulfurous gas, common grade nitrogen, ammonia, and argon. The primary experimental data are shown in Fig. 1 (the argon data are omitted to avoid complicating the figure). The Re variation in all the tests was limited to the range 0.14 to 2, approximately. It can be seen from Fig. 2 that the results of calculating the dependence of heat transfer coefficient on wire temperature using $m = 1/2$ and $n = 1/3$ are in very good agreement with the measurements of the dependence as per Eq. (4), for all the gases and over a wide temperature range (the thermophysical properties of the gases were taken from [10]).

Thus, we can evidently assert with confidence that in the test range of Re one does not need to introduce a temperature factor into the correlation, and that the exponent of Re in the convective heat transfer relation is 0.5 (it should be noted that this method is very sensitive to the value of m).

The value of C in the convective heat transfer correlation and its dependence on temperature can be obtained by processing the experimental data as per Eq. (2), i.e.:

$$C(T) = \frac{(I_2^2 - I_1^2)\,R}{\Delta TS\,\dfrac{\lambda}{\nu^{1/2}}\,\mathrm{Pr}^{1/3}\,\dfrac{v_2^{1/2} - v_1^{1/2}}{d^{1/2}}}, \tag{5}$$

where v is the local speed of the incident stream at the wire. Figure 3a shows the results of such data processing for nitrogen. The coefficient C does not depend on temperature up to 1100°C (which corresponds to a variation of Re from 0.14 to 1.5), and is 0.55.

It is clear that analogous results could be obtained, not only when the convective heat transfer law is written as in Eq. (1), but also in a two-term form: $Nu = K + 0.55\,Re^{1/2} \times Pr^{1/3}$, where K is a constant. Thus, we must check into the existence of a free term in the correlation. To do this, we go back to the R, T(I) curves, calculate K and construct its temperature dependence:

$$K(T) = \frac{d}{\lambda} \cdot \frac{RI^2}{\Delta TS} - 0.55\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}. \tag{6}$$

The results of calculating K in the example of heat transfer in an argon stream are presented in Fig. 3b. It can be seen that K is constant at the value 0.45 from 100 to 450°C (corresponding to an Re variation from 0.4 to 1.5). With further increase of temperature K increases, and this is associated with the increasing contribution of radiation to the heat transfer. Evidently, one could easily calculate the radiative heat transfer coefficient from the data of Fig. 3b, and we have determined that under the test conditions radiation made up about 14% of the total heat flux at 1000°C.

Thus, analysis of the temperature dependence of the heat transfer coefficient yields values in turn of all the constants in the convective heat transfer law, described by the correlation $Nu = 0.45 + 0.55\ Re^{1/2}\ Pr^{1/3}$. Using the law obtained and the experimental R(I) curves for nitrogen we calculated the R(I) curves that would be obtained in a stream of "inert" ammonia, if ammonia did not decompose endothermically on platinum (see Fig. 1). The results of the calculation were also confirmed by a check with Eq. (4). It can be seen that, beginning at a temperature of ~700°C, the curves for "inert" and "active" ammonia diverge, i.e., the heat absorption in the reaction becomes appreciable. This is reflected in the slope of the experimental temperature dependence of the difference in the heat transfer coefficients from their calculated values (see Fig. 2). These data were used to calculate the kinetic constants for the decomposition of ammonia on platinum, and they agreed with those given in [3].

Finally we comment on the approximation to the data of Hilpert [4] for air at small temperature differences (~100°C), made by Eckert and Soehngen [9]. They showed that in the range $1 < Re < 4000$ these results could be described very well by a two-term law $Nu = 0.43 + 0.48\ Re^{1/2}$. This formula is close to that obtained in the present paper for $0.14 < Re < 2$ at large temperature differences (up to 1000°C). This agreement between results of investigations conducted under different conditions allows us to hypothesize that the above form of the convective heat transfer law is possibly a general law in a very wide range of Re, at both small and large temperature differences. The appearance of a temperature factor when processing the results of investigations of convective heat transfer at large temperature differences, using a one-term approximation, probably stems from an attempt to describe the observed more rapid increase of the heat transfer coefficient with temperature associated with the existence of a free term in the convective heat transfer law. Moreover, both terms in the two-term form of the law have physical meaning (the first reflects the role of heat conduction, and the second reflects the role of convective transfer in a laminar boundary layer), whereas one can scarcely ascribe physical meaning to the temperature factor in the one-term law. Naturally, the conclusions drawn here require careful checking.

It should be noted that the annular location of the wire in the experimental situation is responsible for some uncertainty in calculating the local flow speed. Therefore the constants K and C could be somewhat refined in a more correct geometrical arrangement. However, this factor cannot affect the value of the exponent m, which is obtained without using the flow speed.

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