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# TURBULENCE INTENSITY, TEMPERATURE AND CONCENTRATION OF ADMIXTURES IN A TURBULENT WAKE IMMEDIATELY BEHIND A PLATE PLACED ACROSS A FLOW

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**Abstract**—Results of experimental investigations are presented for the wake region behind a plate (placed across the flow) in immediate proximity to this plate and at short distances from it.

**Résumé**—Cet article présente les résultats d'expériences faites dans le sillage d'une plaque normale à un écoulement, immédiatement derrière la plaque et à une certaine distance.

**Zusammenfassung**—Es werden Versuchsergebnisse für die von Luft quer angeströmte Platte mitgeteilt, und zwar für den Bereich unmittelbar dahinter und in einiger Entfernung stromabwärts.

**Аннотация**—В статье приводятся результаты экспериментальных исследований в области аэродинамического следа за пластинкой (установленной поперек потока) в непосредственной близости за ней и при небольшом удалении.

## NOMENCLATURE

$d$, width of the plate;
$h^*$, dynamic pressure loss in mm of water column;
$u$, flow rate component (along axis $x$);
$t$, flow temperature in deg C;
$x, y, z$, co-ordinates;
$\bar{x} = x/d$, $\bar{y} = y/d$, relative longitudinal and transversal co-ordinates;
$\delta$, width of the wake;
$\epsilon$, dioxide gas volume concentration (per cent);
$\Pi$, temperature gauge reading;
$\theta$, excess temperature in deg C.

Flow parameters
0, at the wind tunnel inlet;
$m$, axis of the wake;
max, in undisturbed potential flow downstream of the aerodynamic body.

## 1. EXPERIMENTAL

INVESTIGATIONS were carried out in a flat wind tunnel. A flow velocity of up to 40 m/s on a plate was obtained with this wind tunnel.

Measurements of the intensity of turbulence were carried out by apparatus of the ETAM type operating on the principle of an electrothermoanemometer.

Pickups previously evaluated by a known flow velocity were used for determination of pulsation values.

A steel plate 10 mm wide and 1·5 mm thick placed across the flow was heated by electric current up to a temperature ~500°C for investigation of heat transfer in the region of a wake. Constant heat supply was ensured at the expense of heat transfer between the plate and the flow in the region of an aerodynamic wake.

High air heating in the region of the wake could lead to essential change of air density. The search for the influence of gas compressibility on transfer processes in the region of the wake was not considered to be a purpose of the investigation, therefore heating of air in the wake did not exceed 20°C.

In a flat-parallel flow, gas parameters along a plate (along the ordinate $z$) must preserve a constant value. However, intensive heat removal from the heated plate into cold lateral fins through which the current was supplied, led to the fact that flow temperature in the wake gradually decreased from the centre of the tube to the periphery and particularly sharply near the walls. In order to level the temperature field near the plate slots were cut in the bracing positions of the lateral fins which decreased essentially heat removal through lateral fins and temperature constancy was ensured in the centre of the tube on rather a greater distance along the co-ordinate $z$, i.e. the flow with all its parameters may be considered here to be flat-parallel.

Temperature measurement was made by two thermocouples (chromel–copel) the junction of which was 0·8 mm in diameter. Thermocouples were joined into a block for direct determination of the difference between the temperature $t$ at a measurement point and that of a running flow $t_0$ which changed somewhat—by 0·1°C—while testing. Chromel terminals of both thermocouples were joined together and the copel terminals were attached to a measuring galvanometer. One of the thermocouples was placed in the running flow, the other at the measurement point. Thermocurrents with a different direction were reciprocally neutralized. In a small temperature range the relation between the electromotive force generated in the junction, and the temperature may be considered to be linear and the same for both thermocouples. Therefore, it was assumed that the resultant current supplied to the galvanometer, and indications $\Pi$ were proportional to excessive temperature $\theta = t - t_0$.

In all cases with different errors of the indicator the calibration of the thermocouple block showed a linear dependence $\theta = k\Pi$.

Temperature fields were plotted graphically for each section (at a fixed distance from the plate $x = \text{const.}$) as follows: $\theta = \theta(y)$ where $y$ is the distance of the measurement point from the axis of the wake.

Calculation of flow velocity was carried out according to measurements, both of total and static pressures and direction streamlines at each point where temperature measurements were made.

To measure carbon dioxide gas concentration the plate placed in the flow was made with an internal hollow. On the rear part of the plate holes 0·3 mm were drilled in chess-board order. The carbon dioxide gas was supplied through lateral tubes from both sides to the internal hollow of the plate, and through the holes entered the zone of reverse flow motion and was drawn away by air currents to the edges of the plate. The rear part of the plate (with openings) was pasted with a triple layer of tape that decreased the outflow velocity of the carbon dioxide gas and reduced its deep penetration into the zone of reverse currents.

The carbon dioxide gas was supplied to the plate from bulbs with a liquefied industrial gas through two reducing valves placed in succession. Precise regulation of gas consumption was carried out by the second reducing valve. The consumption was controlled by the pressure drop on a throttle plate and maintained constant while testing. Gas concentration remained constant in the centre of the wind tunnel over rather a wide zone along the co-ordinate $z$.

The removal of gas samples was carried out by T-shaped pickups whose receiving part was installed in each measuring point along the streamline. The air was pumped out by a vacuum-pump from an air main between the pickup and aspirator, after this the gas sample entered the aspirator. The determination of the carbon dioxide gas percentage in the sample was carried out on the VTI indicator to within 0·05 per cent.

Results of concentration measurements as a percentage (by volume) of the carbon dioxide gas in the air, $\kappa$, were plotted graphically for each section as follows: $\kappa = \kappa(y)$.

Comparison of the fields of total and static pressures at plate heating and at supply of the carbon dioxide gas to the zone of reverse currents with fields of these parameters under conventional conditions (i.e. without plate heating and gas supply through it) showed that in all cases the difference did not exceed the precision of measurements (1 mm water column), consequently, neither flow heating, nor the introduction of admixtures into it noticeably influenced the structure of the turbulent wake behind the plate.

## 2. RESULTS OF MEASUREMENTS OF THE TURBULENCE INTENSITY

According to the results of measurements the turbulence intensity of the flow, $\epsilon$, (ratio of a pulsing velocity component to its averaged value) changed considerably both over the width of the wake and its length.

Since the change of all the flow parameters behind the plate is closely connected with the gasodynamic structure of the turbulent wake, it is necessary to distinguish the following flow regions downstream of the plate:

(a) The region of a potential flow between the boundary of the turbulent wake and a boundary layer on the wall of the wind tunnel. Turbulent pulsations of the flow generated by the plate do not penetrate into this region; here total pressure remains just the same as in the upstream flow and, consequently, the measured losses of the total pressure, $h^*$, remain constant and equal to those of $h_0^*$ at the inlet into the wind tunnel $|h^* = h_0^* = \text{const.}|$. In the region of the turbulent wake $h^* > h_0^*$ in contrast to that of the potential flow.

(b) The initial portion of the wake where boundary layers which left the edges of the plate have not yet managed to close up on the axis of the flow. Thus, in the initial portion of the wake it is necessary, in turn, to distinguish between two symmetrical regions of boundary layers and a core region of the reverse flow [2]. Moreover, because of values of the flow velocity in the initial portion, it is necessary to distinguish a region where the velocity component along the axis $x$ (an expense component of the velocity $u$) has just the same direction as the approaching flow ($u > 0$) and a zone of reverse currents where ($u < 0$).

(c) The main portion of the wake behind the section where boundary layers close up along the axis of the flow as a result of which the change of velocity and total pressure in the wake region acquires a monotonous character both along the axis of the flow and in the direction of $y$.

Dealing with a more detailed consideration of the wake structure it is also necessary to single out a transient portion in it (between the initial and main ones). However, in the present paper we are confining ourselves to the description of only the qualitative picture of variation of flow properties, we shall not, therefore, distinguish the transient portion from the main one.

As measurements showed (Fig. 1), the intensity of turbulence $\epsilon$ was very low ($<1$ per cent) in the potential flow. Here, its precise value was not measured because for measurement of such low qualities of $\epsilon$ it is necessary to work at rather high amplification coefficients, at which the apparatus was unsteady.

In the wake region the intensity of turbulence increased sharply, achieving the value of 60–70 per cent at a short distance from the plate, i.e. pulsations of flow velocity, generated by a

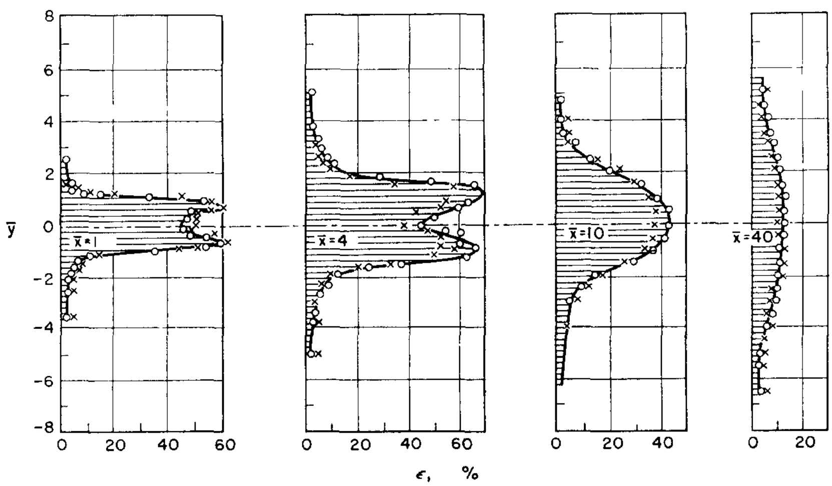


FIG. 1. Intensity of turbulence in different wake sections behind a plate $d = 40$ mm, ○—$u_0 = 38$ m/s, ×—$u_0 = 28$ m/s.

streamlined body, approached according to the order of magnitude the averaged value of the velocity.

In the initial portion of the wake region the intensity of turbulence increased while approaching the axis of the flow and achieved maximum, then it decreased noticeably immediately near the axis (in the core of the reverse flow), however, still preserving here rather high values (40–50 per cent). In all cases the maximum of $\epsilon$ coincided with a point where $u = 0$. In the main portion of the wake the variation of $\epsilon$ acquired a monotonous character with a very low maximum near the axis. While moving away from the plate, the turbulence generated by it attenuated gradually but rather slowly ($\epsilon$ decreased); and at a considerable distance from the plate it still differed noticeably from the turbulence in a potential flow.

In all cases the region of high turbulence coincided with the region where total pressure decreased in comparison with its value in the approaching flow (where $h^* > h_0^*$).

### 3. TEMPERATURE AND CONCENTRATION OF ADMIXTURES IN THE WAKE REGION

According to the results of measurements (Fig. 2), temperature in the whole region of potential flow was equal to that of the approaching flow ($\theta = 0$), i.e. heat spreading was limited by the region of the turbulent wake. From comparison of fields of temperature and total pressure it is seen (Fig. 3) that in all cases the region of temperature change coincided rather precisely with that of a total pressure change. At transition from the region of potential flow to that of the wake the flow temperature increased more sharply the closer the section was to the plate i.e. the thinner the boundary layer.

In the initial portion of the wake the temperature while approaching the axis of the wake, once it had achieved maximum, somewhat decreased. The temperature maximum corresponded here to the point where $u = 0$, i.e. temperature decrease occurred partially in the region of the boundary layer and partially in the region of the reverse flow core.

Such a character of the temperature change in the initial portion of the wake is closely connected with the existence of the zone of reverse currents downstream of the plate, as a result of which all the heat washed off by the flow from the front and back faces of the plate is carried away to its edges and thrown out into the flow by streams which leave the edges. In spite of a considerable temperature difference between heated streams and the approaching flow, practically all the heat carried away by the flow is distributed only in the boundary layer, since the intensity of turbulent exchange is considerably higher here than in the approaching undisturbed flow. Increase of wake width while

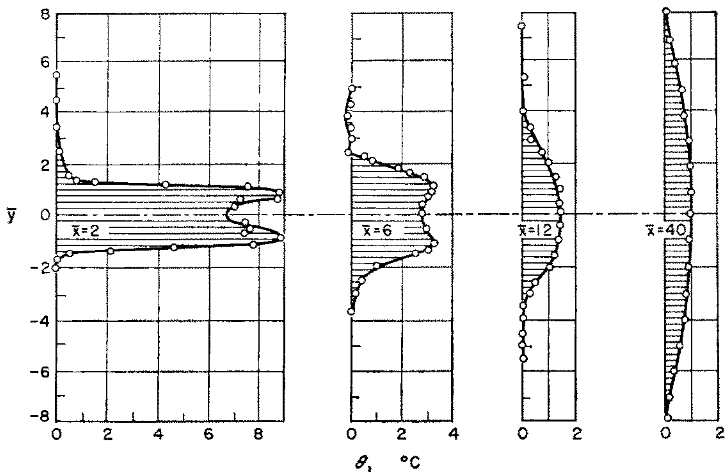


FIG. 2. Temperature change in different wake sections behind a plate $d = 10$ mm, $u_0 = 38$ m/s.

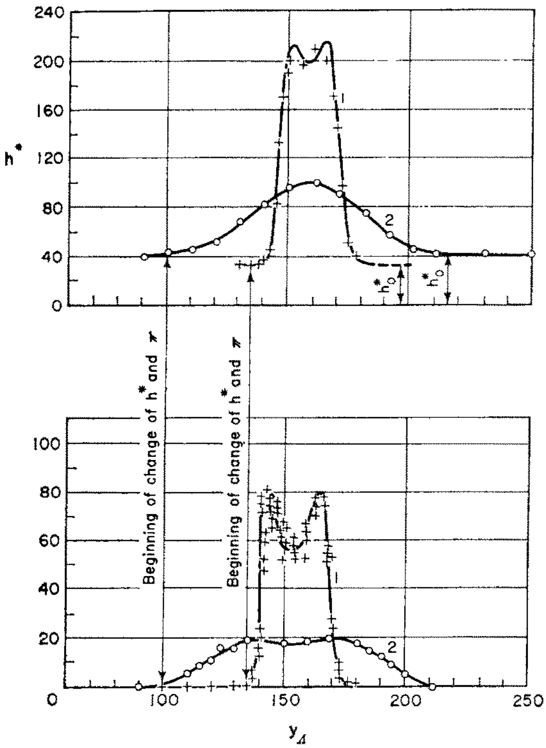


FIG. 3. Comparison of boundaries of a heat wake behind a plate $d = 10$ mm, $u_0 = 38$ m/s, $y$ is distance of measuring point from the fixed one in the flow, in mm; $h^*$-mm water column, $1-\bar{x} = 4$, $2-\bar{x} = 20$.

moving from the plate leads to decrease of the flow temperature in the boundary layer since the total heat remains constant, and the region of its distribution increases.

In the zone of reverse currents where $u < 0$, the flow is formed in each section by streams having come not from the plate but from the portions of the boundary layer being farther from the body than the mentioned section. These streams brought to each section lower temperatures than the maximum temperature of the flow in this section. With such a mechanism of heat exchange the lower temperature corresponds to the axis of the wake, since here the flow is formed by streams having come from the sections which are removed further from the body.

While moving away from the body the difference between the maximum temperature in a section and that along the axis must decrease.

All these peculiarities of temperature distribution in the initial portion of the wake conditioned by flow structure are confirmed by experimental data.

In the main portion of the wake the temperature along the axis is gradually levelled. At rather great distances from the body ($\bar{x} = x/d > 25$, where $d$ is the width of the plate) temperature profiles acquire a form with one maximum at the axis of the wake.

In well-known present works [3, 4, 5] on investigations of temperature fields in the region of a turbulent wake behind bluff bodies at great distances from them ($\bar{x} > 100$) it was determined that the ratio of the excess temperature $\theta$ in a measurement point to that of $\theta_m$ along the axis of the wake is a universal function of the dimensionless co-ordinate $\eta = y/\delta$ ($\delta$ is the width of the wake) for all sections, i.e. $\theta/\theta_m = f_T(\eta)$. It has also been determined that the analogous universal function $f(\eta)$ is valid for a velocity change in the region of the wake:

$$(u_{\max} - u)/(u_{\max} - u_m) = f(\eta).$$

Moreover, there is a ratio $f_T = \sqrt{f}$ between these functions for which a physical explanation has already been given in Taylor's works [6].

This fact facilitates a solution of the heat conductivity equation in the region of the wake and allows one to reduce rather simply a differential partial equation to an ordinary one, the solution of which is as follows:

$$\theta = \theta_m(x) \, . f_T(\eta).$$

As the results of the present work show, velocity fields preserve their universality at short distances from the plate. The universal function $f(\eta)$ is valid both for the whole wake region in its main portion and for the boundary layer in the initial portion of it.

At the same time, near the body the temperature profiles change qualitatively along the wake, and the similarity of temperature fields does not take place here, as a result of which the solution of the heat conductivity equation must have the most general form $\theta = \theta(x, y)$ and only at $x \to \infty$ does it take the form

$$\theta = \theta_m(x) . f_T(\eta).$$

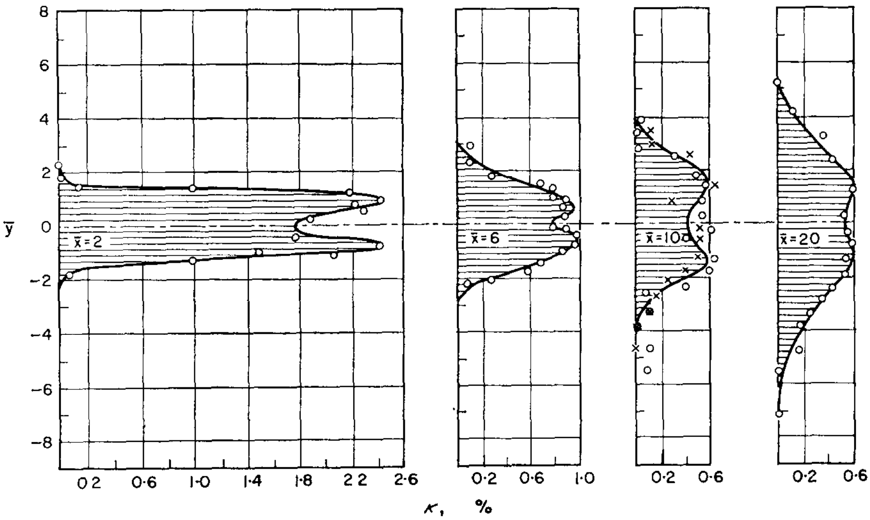


FIG. 4. Concentration change of carbon dioxide gas in different wake sections behind a plate $d = 10$ mm, $u_0 = 38$ m/s.

The results of measurements of concentrations of the carbon dioxide gas which was introduced into the zone of reverse currents behind the plate, are shown in Fig. 4.

All the mentioned peculiarities of temperature fields are also valid for concentration fields.

## 4. CONCLUSIONS

(1) The maximum speed pulsations immediately behind the plate reaches the values having the order of magnitude identical with that of averaged speed of flow.

(2) In the presence of slight turbulence in the approaching flow the heat and diffusion processes taking place behind the plate are restricted by the wake region.

(3) The similarity of temperature and concentration fields is absent immediately behind the aerodynamic body.

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