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# REDUCTION OF THE AERODYNAMIC DRAG OF A MODEL USING A PLATE SET IN THE BOUNDARY LAYER

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*The article contains results of an experimental study of changes in the base pressure and the net drag of a three-dimensional model as a function of the position of a thin plate set in the boundary layer formed on the upper surface of the model.*

Methods of controlling aerodynamic drag are important for a wide range of objects, including transport facilities. The urgency of drag reduction of articulated vehicles and high-speed buses that carry a large part of freight and passengers is directly related to reduction of fuel consumption and, as a consequence, to reduction of environmental pollution with combustion products. Because of design features, these transportation facilities have a blunt stern. The aerodynamic drag of such bodies is largely determined by the base pressure. Studies of two-dimensional models show that the base pressure can be increased almost twofold by setting a separating plate [1] or by ejection of a jet from a slot formed in the base of the model [2, 3]. However, existing international standards of overall dimensions of transport facilities do not allow the first method to be used, while application of the second method requires substantial modification of the design. It is of interest to find a method of controlling aerodynamic drag that could be adapted quite easily to existing designs.

The flow around bodies with a blunt stern has much in common with separated flow behind a step, studies of which show that an action on the boundary layer before its separation changes the length of the separation zone, the value of the pressure gradient at the site of attachment of the separated flow to the plane, and the turbulence level of the shear layers [4-7]. Among a number of devices used for the action on the boundary layer, a thin plate set at the boundary of or inside the boundary layer has attracted the attention of many researchers [8-11]. It is found that under the action of the plate, changes in the structure of the boundary layer resulted in a 20% decrease in the friction coefficient. The level of the effect depended on the thickness and width of the plate and its coordinate inside the boundary layer. It can reasonably be suggested that separation of the modified boundary layer creates a near region of the wake with changed characteristics. Since the base pressure of a model is determined by the structure of the flow in direct contact with the base of the body [1-3], the goal of the present work is to investigate the dependence of the variation of the base pressure and the aerodynamic drag on the position of a plate set on the upper surface of the model.

**Experiment.** The studies were conducted in an open-jet wind tunnel of the closed type. The length of the working section is 2.6 m and its cross section is 1.5 × 1.2 m. The level of the turbulent flow is 0.2% in the working section that is free of the model.

A 1:20 model of an IVECO Euroclass HD-380 bus was chosen as the object of study (Fig. 1). The length of the model is $L = 0.6$ m, its height $H$ is 0.165, and its width is $B = 0.125$ m. The model was fixed on a rod that passed through a board that simulated the action of the earth. The gap of 10 mm between the surface of the board and the model was equivalent to the clearence of this type of bus. The other end of the rod was connected to an aerodynamic balance. This allowed us to measure directly the aerodynamic drag of the model. Over the contour of the model 20 holes were made along the symmetry line, and on the base of the model, along its height, 25 holes

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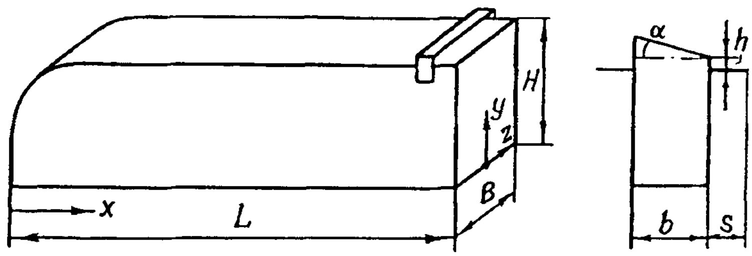



Fig. 1. Scheme of the model and location of the plate.

TABLE 1. Integral Parameters of the Boundary Layer on the Upper Surface of the Model at the Rear Edge as a Function of the Free-Stream Velocity

| $U_\infty$, m/sec | $\delta$, mm | $\delta_1$, mm | $\delta_2$, mm | $H_{12}$ |
|---|---|---|---|---|
| 15 | 14.33 | 2.125 | 1.532 | 1.387 |
| 20 | 13.27 | 2.123 | 1.512 | 1.404 |
| 25 | 12.62 | 2.119 | 1.495 | 1.417 |
| 30 | 11.54 | 1.837 | 1.31 | 1.403 |
| 35 | 11.80 | 1.928 | 1.366 | 1.412 |
| 40 | 11.73 | 1.97 | 1.38 | 1.428 |

were drilled (five rows of five holes in each) for measuring the pressure distribution. The holes were connected by pipes to a mechanism for pressure take-off located inside the model. This remote-controlled mechanism connected each hole to a differential pressure gauge located outside the wind tunnel. From the gauge, an electric signal was input to the digital converter of a personal computer. Each value of pressure was the result of 4-sec integration of a signal taken off with a frequency of 100 Hz. The base-averaged pressure coefficient, which characterized the base pressure of the model, was determined from the relation

$$(C_p)_b = (\Sigma\, C_{pi}\, F_i)/F_b\,,$$

where $C_{pi}$ are the values of the coefficient for a particular hole; $F_i$ is the area around the hole; $F_b$ is the area of the base of the model.

The dimensions of the plate were chosen in accordance with [9]. Its thickness and width were 0.5 mm and 20 mm, respectively. The leading edge of the plate was rounded and the rear edge was tapered. The plate was fixed on the sides of the model and could be moved along the upper surface with a step of 12 mm over a distance of 120 mm from the base of the model in the upstream direction.

**Results and Discussion.** The aerodynamic drag of bodies with a fixed position of separation of the boundary layer changes with increasing Reynolds number if before the time of separation a developed boundary layer has formed. In this case results of laboratory studies are also valid for higher Reynolds numbers. On the plate the transition from a laminar boundary layer to a turbulent one takes place at $\mathrm{Re}_{\delta_{cr}}$ calculated from the velocity of the free stream and the thickness of the boundary layer [12] determined from the velocity profile. The average velocity distribution from the upper surface of the model to the potential flow was measured with a Pitot tube 0.6 mm in diameter. The tube was fixed so that its intake port was located 15 mm ($x/l = 0.975$) from the base of the model in the upstream direction. The thickness of the boundary layer was found from the coordinate where the local velocity was 99% of the free-stream velocity. Measurements were taken at different free-stream velocities. The integral parameters of the boundary layer are given in Table 1.

As the potential-flow velocity grew, the thickness of the layer decreased to 11.5 mm ($U_\infty = 30$ m/sec), and then it remained almost unchanged. The Reynolds number calculated from the thickness of the boundary layer at $U_\infty = 15$ m/sec was $\mathrm{Re}_\delta = 143 \cdot 10^4 > \mathrm{Re}_{\delta_{cr}}$. Thus, a turbulent boundary layer was formed on the body. It is known [12] that the flow is separated from the surface if the shape factor $H_{12} \approx 1.8$. Data of Table 1 show that at all the

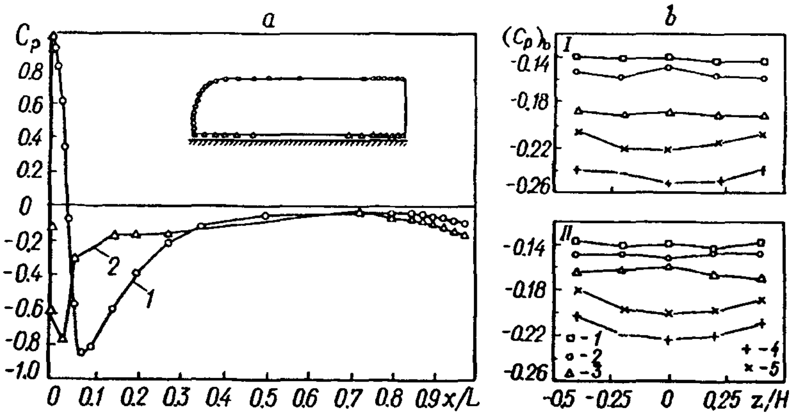



Fig. 2. Pressure-coefficient distribution over the contour (a) and the base of the model (b): a: 1) pressure distribution over the leading edge and upper surface of the model; 2) pressure distribution over the lower surface of the model; b: I) model without a plate; II) model with a plate, $\alpha = 4°$ [1) $y/H$ = 0.92, 2) 0.71, 3) 0.50, 4) 0.29, 5) 0.08].

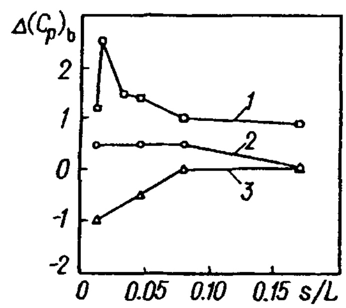



Fig. 3. Plot of the base pressure versus the position of the plate in the boundary layer versus the distance between its rear edge and the base of the model: 1) $h/\delta$ = 0.43, 2) 0.87, 3) 1.3. $(\Delta C_p)_b$, %.

studied velocities in front of the rear edge of the model the flow was continuous. Filament visualization of the flow confirmed this fact. The pressure distribution on the base and over the contour of the model was measured and the aerodynamic drag was determined at a potential-flow velocity $U_\infty$ = 30 m/sec (Re = $1.2 \cdot 10^6$) using the balance mechanism.

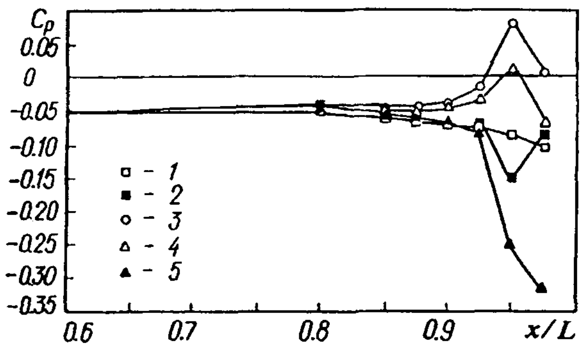
The pressure distribution over the contour of the reference model (without the plate) showed that a positive pressure coefficient $C_p$ was observed only near the stagnation point of the flow on the leading edge (Fig. 2a). The maximum base pressure was found in the upper part of the base (Fig. 2b, $y/H$ = 0.92). The pressure decreased toward the lower surface, reached a minimum at $y/H$ = 0.29, and then increased again. The averaged base-pressure coefficient $(C_p)_{b0} = -0.1846$ remained unchanged in the range of Reynolds numbers $0.8 \cdot 10^6 \le \mathrm{Re} \le 1.6 \cdot 10^6$.

The plate influenced the changes in the averaged pressure coefficient $(C_p)_b$ if it was located inside the boundary layer, i.e., in the case $h/\delta < 1$. The relative change in the averaged pressure coefficient was determined from the relation

$$\Delta (C_p)_b = 100\% \; [(C_p)_{b0}) - (C_p)_b]/(C_p)_{b0} \,.$$

The increment in the base pressure depended on both the position of the plate inside the boundary layer and the distance between the rear edge of the plate and the base of the model and was within 2.5% (Fig. 3).

In the boundary layer the static pressure changed only in the direct vicinity of the plate. In front of the edge it increased slightly, under the plate it decreased sharply, and it increased again behind the plate, so that the pressure coefficient measured in front of the edge of the base of the model was 14% higher than that for the reference model (Fig. 4).



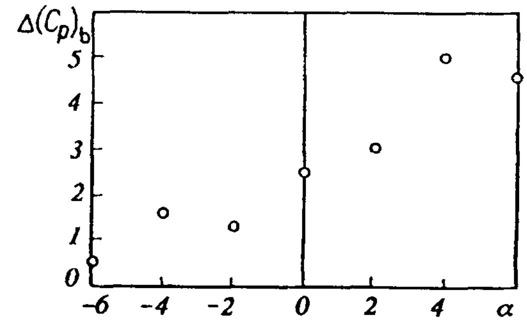




Fig. 4. Pressure distribution over the upper surface of the model in relation to the angle of attack of a plate with the coordinates $s/L = 0.017$, $h/\delta = 0.43$: 1) reference model, 2) plate at an angle $\alpha = 0^o$, 3) $4^o$, 4) $2^o$, 5) $-2$).

Fig. 5. Plot of the base pressure versus the angle of attack of the plate.

An increase in the angle of attack of the plate, fixed in the position $s/L = 0.017$, $h/\delta = 0.43$, to $\alpha = 4^o$ was accompanied by a 100% increase in the base pressure. A further change in the angle of attack ($\alpha = 6^o$) resulted in a decrease in the averaged pressure coefficient (Fig. 5). The increase in the base pressure is caused mainly by an increase in the pressure in the lower half of the base of the model. In the upper half, the change in the pressure was much less strongly expressed (see Fig. 2b). When the plate was set at negative angles of attack, the averaged base-pressure coefficient was much lower than $(C_p)_b$ obtained at a zero angle of attack of the plate (Fig. 5).

In the boundary layer, in front of the plate set at an angle $\alpha = -2^o$, the static-pressure distribution remained almost unchanged, but under and behind the plate the pressure decreased rapidly, reaching $(C_p)_b = -0.32$ in front of the edge of the base of the model (Fig. 4). At a positive angle of attack of the plate the pressure increased in front of it and a pressure peak appeared under the plate, whose value was $(C_p)_b = 0.018$ and $(C_p)_b = 0.085$ at $\alpha =$ 2 and $4^o$, respectively. At the rear edge of the plate, the pressure decreased but remained higher than it was behind the plate at $\alpha = 0^o$ by 15 and 100%, respectively, for 2 and $4^o$ (Fig. 4). The correlation between the growth of the pressure in front of the edge of separation and the increase in the averaged pressure observed for the plate with angles of attack $\alpha$ = 0, 2, and $4^o$ was absent at $\alpha = 6^o$. In this case, the base pressure decreased while in the boundary layer the pressure grew by more than an order of magnitude: $(C_p)_b = 0.0952$ in comparison with the previous angular position of the plate.

Reduction of the base drag of a model with a plate located inside the boundary layer does not guarantee net reduction of the drag of the model–plate system. The method of direct measurement of the net drag of a body using an aerodynamic balance excludes ambiguity of the treatment of the efficiency of using the plate. These measurements show a 1.5% reduction of the aerodynamic drag of the model–plate system when the plate is set at an angle of attack $\alpha = 4^o$.

**Conclusions.** The present studies show the efficiency of a thin plate set in front of the separation edge in the boundary layer, for control of the base pressure. With a constant coordinate of separation of the developed boundary layer from the upper surface of the model, the base pressure was observed to increase. The increment in the pressure depended on the position of the plate inside the boundary layer, the distance from the base of the model, and the angle of attack. A maximum increase in the averaged base-pressure coefficient of 5% was observed at the parameters $\alpha = 4^o$, $s/L = 0.17$, and $h/\delta = 0.43$. The aerodynamic drag of the model–plate system was reduced by 1.5% with optimum setting of the plate. However, the present data do not allow us to determine the mechanism of the action of the plate on the boundary layer or to find what kind of structural changes in this layer cause reduction of the base pressure and net drag of the body. Studies of the turbulence characteristics of the boundary layer and the flow adjacent to the base of the model are, therefore, of interest.

## NOTATION

$U$, average velocity, m/sec; $C_p(p_i - p_\infty)/0.5\rho U_\infty^2$, pressure coefficient; $p$, static pressure, Pa; $\rho$, air density, kg/m$^3$; $\mathrm{Re} = LU_\infty/\nu$, Reynolds number; $h$, distance between the surface of the model and the plate, mm; $b$, width of the plate, mm; $\alpha$, angle of attack of the plate; $\delta$, thickness of the boundary layer, mm; $\delta_1$, displacement thickness, mm; $\delta_2$, thickness of the momentum loss, mm; $H_{12} = \delta_1/\delta_2$, shape factor. Subscripts: $\infty$, referred to the potential flow; b, measured on the base of the model; $i$, referred to the running coordinate of the holes.

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