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Investigation of the Dissipation and the Interference of Turbulent Spots

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Abstract

The present research is written by theoretical physicists in order to sort out conceptual results from the numerous experimental data which can be put into the basis of physical theory of the boundary layer. This possibility exists in the presented paper. It stands to reason omitted much of the information connected with the experimental methods in this case. However for high reliability the choice of experimental results was made with the help of the repetition principle of the experimental results in other authors work with the use of other experimental devices at different time and place. Generalization of kinetic ideas is discussed to describe a continuous system. An attempt is distribution function of pulsations. In particular, a sample of turbulent spots dissipation in the rarefied gas field is used to solve the problem. In this paper described the distribution of energy density fluctuations, the interference of two turbulent spots by direct simulation Monte-Carlo (DSMC) method.

Keywords

Turbulent Boundary Layer, Coherent Structure, Monte-Carlo Method, Computational Fluid Dynamics, Reynolds Number

1. Introduction

At the present time is obtained a tremendous quantity of data on the dynamics of a turbulent motion of incompressible fluid within the boundary layer at the plate, discovered in which are the structural elements of the interaction of the surface in flow with the flow itself. The experimental data are obtained by the different researchers, using the different methods, and these data reveal some general features of that interaction [1]. In a turbulent boundary layer, kinetic energy from the free-stream flow is converted into turbulent fluctuations and then dissipated into internal energy by viscous action [2]. Now is a proper time for the intensive theoretical comprehension of these results and for the construction on their basis of the global theories of turbulent motion. Listed below, in the most concise form, are the main results of the experimental research, and, in our opinion, these results might be actively used by the construction of mathematical models.

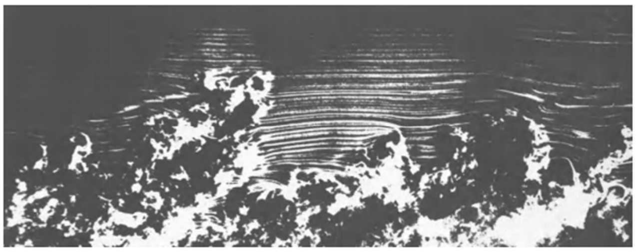

Fig. 1. *Boundary layer at the flat plate (from the album by Van Dyke).*

Experiments show the laminar flow loses stability and becomes turbulent at high values of Reynolds number. The first systematical experimental research of the transition of well-ordered laminar flow of the water to the chaotic turbulent flow motion in the circle pipes was fulfilled by O. Reynolds in 1883. In the album by Van Dyke shows boundary layer at the flat plate (fig. 1). The experiment showed that the transition occurs the at critical Reynolds number

$$\mathrm{Re}_{cr} = (U_\infty d / \nu)_{cr}$$

Reynolds supposed the transition is connected with the laminar ordered motion stability loss in the pipe. At present time there exist mathematical models for homogeneous and isotropic incompressible flows which can properly describe their physical properties. The transition at the flat plate arises in the same way. However adequate mathematical models do not exist in this case. The explanation of this fact is connected with high inhomogenity of the flow (mixing layer, jet, awake after body, boundary layer) and the extremely insufficient understanding of the phenomenon physics.

The submitted paper contains extensive experimental data base which allows us to give the deep physical interpretation to it and to introduce the main notion such as the organized structure. The state of turbulent boundary layer is substantially connected with organized structures: for example, the drag force decrease *oy* an aircraft by 10-15%, which is connected with structure control, gives us the economy of hundred billions dollars per year. We don't speak about the economic, the ecological and the social effect of more precise simulation of atmospheric motions, the weather forecast and the climate. It is convenient to divide the turbulent flow field into mean and pulsation parts to analyze the laws of its development: $u = \overline{u} + u'$, $v = \overline{v} + v'$, $p = \overline{p} + p'$ and so on.

$$\overline{u} = \frac{1}{\Delta\tau}\int u\, d\tau$$

O. Reynolds suggested that the chaotic turbulent motion belongs to the flow class described by Navier-Stokes equations.
The averaged Reynolds equations for a turbulent boundary layer look as follows:

$$\overline{u}\frac{\partial\overline{u}}{\partial x} + \overline{v}\frac{\partial\overline{v}}{\partial y} = -\frac{1}{\rho}\frac{\partial\overline{p}}{\partial x} + \nu\frac{\partial^2\overline{u}}{\partial y^2} - \frac{\partial\left(\overline{u'v'}\right)}{\partial y},$$

$$\frac{\partial\overline{u}}{\partial x} + \frac{\partial\overline{v}}{\partial y} = 0\,.$$

This system is unclosed since it contains the expression for the turbulent stress

$$\tau_T = -\rho\overline{u'v'}$$

which demands a piece of additional information for its definition by means of the mean flow parameters. Rigorous theory for the description of such relation does not exist and scientists use approximate phenomenological methods to define it.

Turbulent pulsations and their properties, physical characteristics and the process of its origin are of interest themselves. The extraction of deterministic peculiarities in turbulent chaos is one of the directions in the understanding of the turbulence essence and the construction of physical and mathematical models.

There are many surveys devoted to the structures in turbulent boundary layer. But these surveys are written as a rule by specialists-experimentalists as a rule and contain numerous details of measurements. They don't give us an opportunity to extract deep physical essence from these results. However one monograph of well-known specialists-experimentalist issued recently stands out against this background by Repic E.U., Sosedko U.P. [3].

The present survey is written by theoretical physicists in order to sort out conceptual results from the numerous experimental data which can be put into the basis of physical theory of the boundary layer. This possibility exists at present time in the authors' opinion. It stands to reason we omitted much of the information connected with the experimental methods in this case. However for high reliability the choice of experimental results was made with the help of the repetition principle of the experimental results in other authors' work with the use of other experimental devices at different time and place.

2. Description of Turbulent Flows: The Fluid Particles Model

By way of generalizing the application of kinetic models in mechanics of continuum, an attempt was made to describe turbulent flows and, in particular, the dissipation of a turbulent spot. Here, as in rarefied gas dynamics, the problem is solved in terms of the distribution function. However, the pulsation of the velocity of a fluid particle v is used as an argument rather than the molecular velocity x. It was Prandtl who first noticed a similarity between a rarefied gas and a turbulent fluid. In Yanitskii's model, each particle in a cell has a new property [4]. As before, a fluid particle is characterized by its physical coordinates and its velocity. For the distribution density of the particles, a kinetic equation is proposed that is similar to the model equation in rarefied gas dynamics. The main purpose of such a consideration is to retain the main principles of the direct statistical simulation [5-8]. To describe the turbulence, the following Onufriev kinetic equation is used:

$$\frac{\partial f}{\partial t} + \mathrm{v}\frac{\partial f}{\partial \mathrm{x}} - \frac{1}{2\tau_1}\frac{\partial}{\partial \mathrm{v}}\left(\mathrm{v}'f\right) = \frac{f_M - f}{\tau_2}$$

Here,

$$f_M = \left(\frac{3}{4\pi E}\right)^{3/2}\exp\left(-\frac{3\mathrm{v}'^2}{4E}\right)$$

is the normal distribution and E is the turbulent energy density. This equation is similar to the Krook model equation.
The simulation scheme is organized according to the same principles as in rarefied gas dynamics. Fluid particles in the cells are considered, and the process is split into three steps: the convective transport

$$\mathrm{v}\frac{\partial f}{\partial \mathrm{x}},$$

the turbulent dissipation of energy

$$-\frac{1}{2\tau_1}\frac{\partial}{\partial \mathrm{v}}\left(\mathrm{v}'f\right),$$

and the redistribution of energy

$$\frac{f_M - f}{\tau_2}.$$

We numerically solved the spot dissipation problem in which the energy is initially concentrated in the region of radius r_0, the characteristic radius of the spot is $r_*(t)$, and the density of the turbulent energy is $E_m(t)$ at the center of the spot. The initial data are as follows:

$$f(0,\mathrm{r},\mathrm{v}) = f_0(\mathrm{r},\mathrm{v}),\quad E_0(\mathrm{r}) = E_m^0 \exp\left(-\frac{\mathrm{r}^2}{\mathrm{r}_0^2}\right)$$

$$f_0(\mathrm{r},\mathrm{v}) = \left(\frac{3}{4\pi E_0}\right)^{3/2} \exp\left(-\frac{3\mathrm{v}'^2}{4E_0(\mathrm{r})}\right)$$

The numerical results are compared with the experimental ones ($r_* = r_*(t)/r_0$ and $E_m(t) = E/E_0$) (Fig. 2) [9].

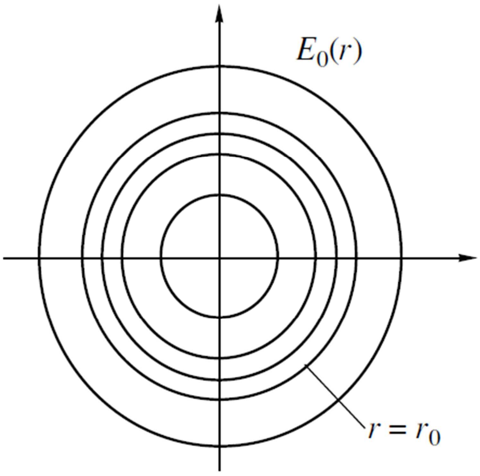

Fig. 2. Dissipation of the turbulent spot (the initial region).

The kinetic models of turbulence (Figs. 3-4) are more informative because they describe the pulsations at the level of the distribution function.

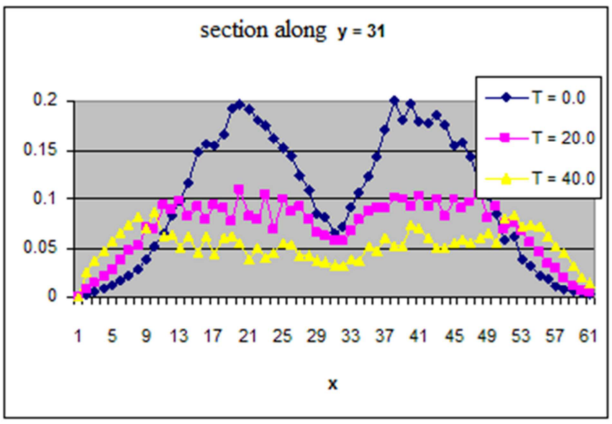

Fig. 3. Interaction of two turbulent spots (Distribution of Energy).

In the fig. 4 presented a plot of the logarithm of the ratio of energy in the center to its initial value on the time obtained from our experiment, as well as floor dependence obtained from laboratory experiments Naudasher [10].

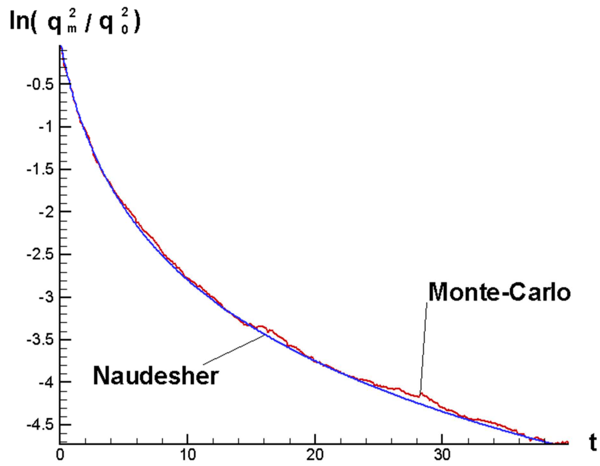

Fig. 4. The dependence of the energy in the center of the spot by the time.

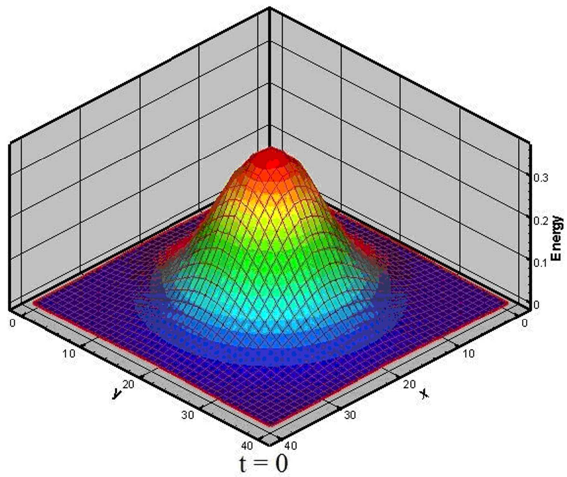

Fig. 5. The distribution of the specific energy in a turbulent spot (t = 0).

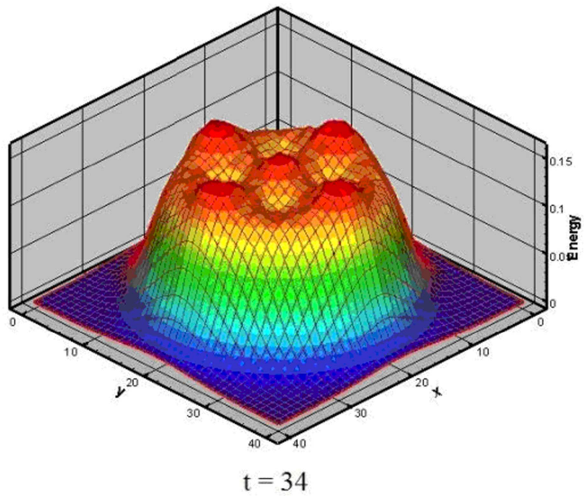

Fig. 6. The distribution of the specific energy in a turbulent spot (t = 34).

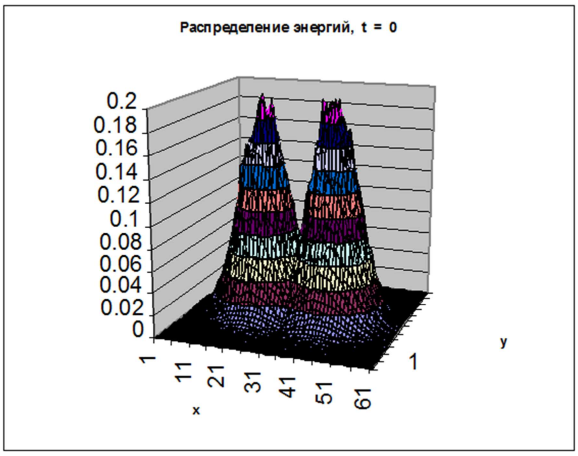

Fig. 7. The distribution of the turbulent energy of interacting spots at (t = 0).

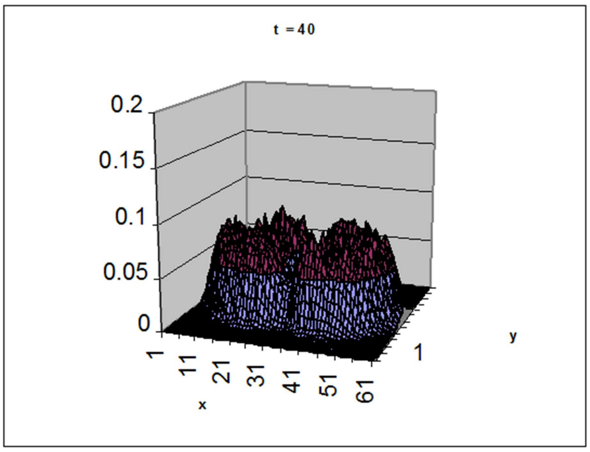

Fig. 8. The distribution of the turbulent energy of interacting spots at (t = 40).

In fig. 5 and 6 shows normalized curves of specific energy at time $t = 0$ and $t = 34$ [11-15]. It can be seen, there is a spread spots along the radius. This is due to a shift of fast particles from the center to the edges of the field. In fig. 7 and 8 shows the distribution of the turbulent energy of interacting spots ($t =$ 0 and 40) [11-15].

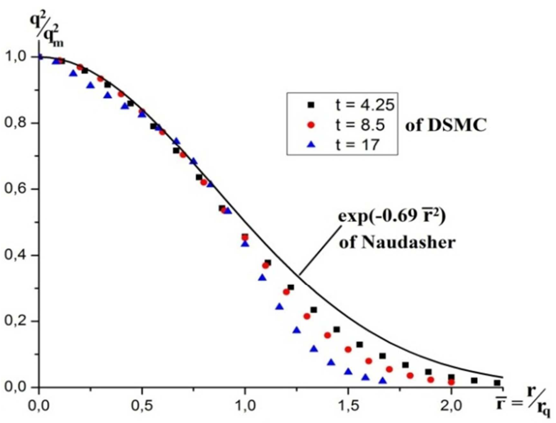

Fig. 9. The energy distribution of the relative radius of the spot.

In fig. 9 shows the distribution of energy distribution of the relative radius of two turbulent spots. From the calculation received energy distribution along the radius of the spot at the times t = 4.25, 8.5, 17 and compared with the experiment Naudasher.

3. Conclusions

The statistical modeling methods for turbulence flows are presented. Direct simulation Monte-Carlo methods are well proven to solve these problems in a rarefied gas. Such an approach to the description of turbulence seems to be promising because it makes it possible to take into account the large-scale turbulent process directly using the transport equation schemes and take into account the small-scale pulsations using the statistical simulation. The distribution of the specific energy and turbulent energy of interaction spots by Monte-Carlo method are described.

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