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LENGTHWISE FINNING SURFACE AS THE METHOD OF INFLUENCE ON THE FLOW SEPARATION IN DIFFUSERS

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Abstract. The paper deals with the analysis of power factors acting within the boundary layer for different types of flow: convergent, gradientless and diffuser. Based on the considered formation mechanism of boundary layer separation, a hypothesis about the possible influence on structure and character of a separated flow by changing the gradient of the tangential stresses in the boundary layer was proposed. This impact is proposed to realize by means of the longitudinal finning of diffuser. Verification of the concept is performed on the basis of numerical flow investigation and available experimental data.

MSC 2010: *97M50*
Keywords: *diffuser, longitudinal pressure gradient, friction tension, velocity, finned surface, boundary layer, inertial force, flow separation*

1. Introduction

Despite the great achievements of modern fluid and gas dynamics there is still a number of unsolved problems. The occurence of flow separation from streamlined surface is among them.

The phenomenon of flow separation is observed in many technical devices. It presence leads to a decrease in efficiency of industrial equipment and can have extremely negative impact on its performance [1-3]. The hydraulic resistance increasing, non-recoverable energy losses, considerable acoustic vibration are the small part of all possible adverse consequences of the flow separation [4-7]. So a developing of methods to prevent flow separation in industrial units is a great importance [9, 10].

Generaly the flow separation is described as a kind of critical change of the flow pattern [11-13]. When the flow separation happens, the steady flow turns into unsteady [14, 15].

A lot of scientific works are devoted to the investigation of different aspects of the flow separation problem. Many scientists cosidered mechanism of the flow separation in diffusers.

Törnblom carried out variety of numerical and experimental studies of flat diffusers. In his article [16] extensive data describing flow behavior in flat diffuser channels are provided. Some characteristics of the diffusers with a different opening angle are also presented in Chandavari and Palekar [17].

Symetric conical diffusers are adequately considered by Lenarcic et al. [18]. Authors do not only give the different flow regimes calculations results, but also offer the some optimization methods for diffuser and exit chamber design. Some other ways of diffuser's modernisation were proposed by by Singh et al. [19].

Problem of the flow separation from streamlined surface is widely reported in many Zaryankin works [20]. Author developed his own method to prevent flow separation occurence in different kind of industrial devices. Application of longititude finning of various configuration is the main concept of this method.

This article presents the results of the fins installation impact investigation to the flow separation in different diffuser channels: in the flat asymmetrical diffusers and wide-angle conical diffusers (in the absence of swirling flow on diffuser inlet).

2. The theoretical description of flow separation phenomenon

2.1. The existing view on the separation mechanism

The classic interpretation of the boundary layer separation mechanism from the streamlined surfaces in the diffuser flow` region is based essentially on the analogy of solid body that rises in the mountain. In this case, the inertial forces, the frictional forces and the force of gravity, forwarded in the opposite direction of movement, are affected on the moving body; in any fixed position, the velocity of all points of the body remains constant, and the friction forces act only on the contact surface.

The situation changed significantly when we considered moving liquids and gases. The speed and the tension of friction change, when distance from a streamlined surface in the cross section of the boundary layer, and the nature of these changes is determined by the sign of the current longitudinal pressure gradient.

Thus, the existing view on the boundary layer separation reasons does not consider changing all of the existing force factors and does not explain how to control a flow separation near the diffuser wall, where the pressure difference acting against the flow motion in the near-wall region is always more than the amount of moving fluid kinetic energy.

2.2. The analysis of force factors that determine flow nature within the boundary layer

Let us analyse the force factors that define the fluid behaviour within the boundary layer on the basis of averaged Prandtl equations for the two-dimensional flow [18]:

$$\rho\left(u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}\right)=-\frac{dp}{dx}+\frac{\partial \tau}{\partial y}, \tag{1}$$

$$\frac{\partial p}{\partial y}=0, \tag{2}$$

where: u and v - projection of a velocity vector $\vec{c}$ into coordinate axes; $\tau=\tau_M+\tau_T$ - total shear stress within the boundary layer consisting of molecular shear stress $\tau_M=\mu\frac{\partial u}{\partial y}$ (μ - viscosity coefficient) and turbulent shear stress τ_T.

As defined, on the external border of the boundary layer $\frac{\partial \tau}{\partial y}=0$. Thus, the Eq. (1) goes over into Euler equations for the two-dimensional flow of the ideal fluid. Further, from Eq. (1) (on the streamlined surface) follows next:

$$\frac{dp}{dx}=\left.\frac{\partial \tau}{\partial y}\right|_{y=0}. \tag{3}$$

In other words, the sign of longitudinal pressure gradient $\frac{dp}{dx}$ is the same as the sign of transverse gradient of the wall shear stress.

This condition is very important in the analysis of changes that occur within the boundary layer. Especially, in section where flow separation from occurs.

At multiplication of Eq. (1) by the elementary fluid volume $dV=dxdydz$, we obtain balance equation of all forces acting on an elementary fluid particle moving within the boundary layer:

$$dF_p=dF_\tau-dF_u. \tag{4}$$

Here, external force $dF_p=\frac{dp}{dx}dxdydz$ due to longitudinal pressure gradient is balanced by shear forces $dF_\tau=\frac{\partial \tau}{\partial y}dxdydz$ and inertial forces $dF_u=\rho\left(u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}\right)dxdydz.$

If the force dF_p, according to Prandtl's second equation, does not change in the cross section of the boundary layer, then the values dF_τ and dF_u are always changing in such a way that their algebraic sum had remained constant in any cross section of the boundary layer and equal to the external force dF_p. Accordingly, fluid motion along the streamlined surface is unseparated until the specified condition is fulfilled, i.e., until the diagram deformation of the force distribution dF_τ

and dF_u under the influence of external (in this case geometric) forces provides compensation of the force dF_p.

The qualitative change of the distribution diagram of the shear stresses and transverse gradient for convergent $\left(\frac{dp}{dx} < 0\right)$, gradientless $\left(\frac{dp}{dx} = 0\right)$ and diffuser $\left(\frac{dp}{dx} > 0\right)$ flows are shown in Figures 1 and 2.

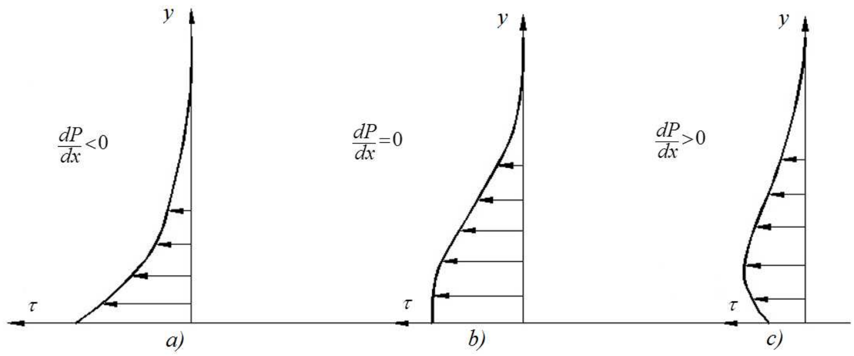

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Fig. 1. Diagrams of the shear stress distribution within boundary layer for different flow types: a) convergent flow, b) gradientless flow, c) diffuser flow

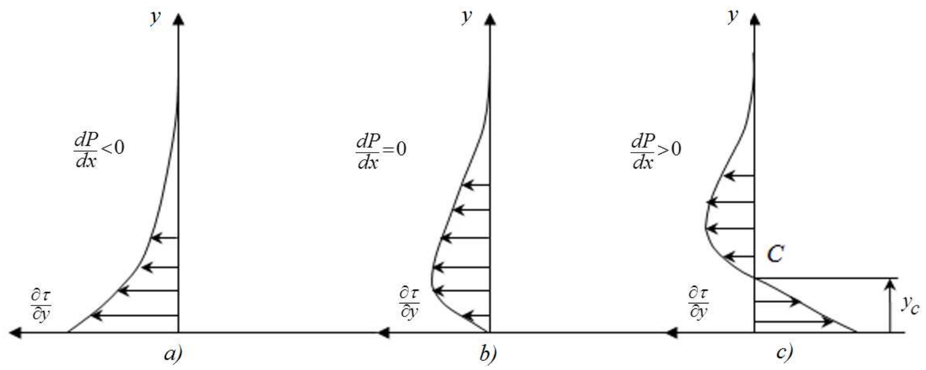

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Fig. 2. Diagrams of the transverse shear stress gradient distribution within the boundary layer for different flow types: a) convergent flow, b) gradientless flow, c) diffuser flow

According to Figure 2c shear forces in the diffuser flow region at distance $y < y_c$ are oriented in the same direction as the moving fluid. In other words, at this distance the overlying layers drag the underlying (stopped) fluid layers, hence, providing the principal possibility of unseparated flow at a positive pressure gradient.

The fact that determines the possibility of liquids and gases movement in the diffuser areas was first pointed out by Prandtl [21].

If we add up the distribution of all forces acting within boundary layer, then for the unseparated flow the balance of stress factors given by Eq. (4) must be fulfilled.

Distance from wall y_c at which a positive value of transverse shear stress gradient (shear force dF_τ) depends directly on a value of the positive pressure gradient $\frac{dp}{dx}$. The greater the longitudinal pressure gradient $\frac{dp}{dx}$, the greater the value of the coordinate y_c. In other words, value y_c determines the response level of the moving fluid medium to the external (in this case geometric) influence determined by the pressure gradient $\frac{dp}{dx}$.

However, the possibility of a flow response to external influence has certain limits, which, if exceeded, cause a flow separation from the streamlined surface.

There are two necessary conditions of boundary layer separation beginning: shear stress on the wall $(\tau_w = 0)$ and the transverse velocity gradient $\left(\frac{\partial u}{\partial y} = 0\right)$ in the separation point should be equal to zero. In addition, $\left.\frac{\partial \tau}{\partial y}\right|_{y=0} = 0$ is a sufficient condition for the flow separation.

The transition from an unseparated to a separated flow occurs as a result of impossibility of performance in a channel cross section of the main boundary condition $\frac{dp}{dx} = \left.\frac{\partial \tau}{\partial y}\right|_{y=0}$.

It should be noted that when the flow separation from a streamlined surface occurs, the longitudinal pressure gradient equals zero $\left(\frac{dp}{dx} = 0\right)$. The observed irreversible motion of the fluid is not due to the differential pressure, but due to the insectarium effect of a separated flow.

Thus, the flow separation from the streamlined surface is its crisis condition in which all possible structural changes in the boundary layer providing the possibility of the fluid flow against a positive pressure gradient defined by the geometrical shape of the channel or the geometrical shape of the streamlined body are completely exhausted.

3. Numerical and experimental investigation of the finning diffusers

3.1. Numerical study

Investigation of the longitudinal fining efficiency for flow characteristics improvement in the diffuser channels has been made for flat and wide-angle conical diffusers.

Flat asymmetrical diffusers with different opening angles and the various design options and fins layouts was studied numerically by mathematical modeling methods. Main geometric parameters of investigated models are presented in Figure 3 and Table 1.

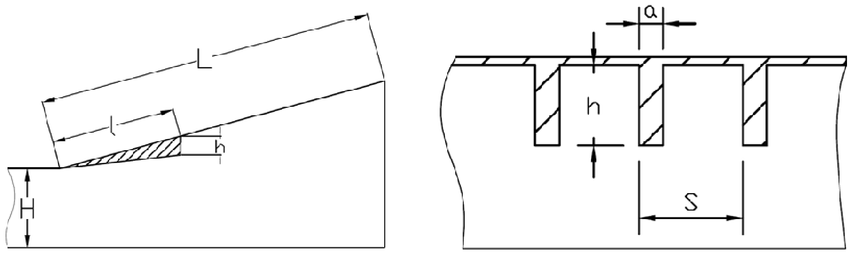

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Fig. 3. Main geometric parameters of flat finned diffuser ($\alpha = 15°$)

Table 1

Main geometric parameters of flat finned diffuser (α = 15°)

Parameter	Model A	Model B	Model C
Fin max height *h* [mm]	5	5	8
Fin width *a* [mm]	1.5	1.5	1.5
Finning step *S* [mm]	6.5	6.5	6.5
Fin length *l* [mm]	170	100	270
Diffuser up wall length *L* [mm]	270	270	270
Diffuser inlet height *H* [mm]	60	60	60

Example of computational mesh used in numerical study is shown in Figure 4. Mesh is unstructured; average mesh size: 2-3 million cells. The boundary layer volume composed by prismatic elements (number of prismatic layers: 13-15). Suggested flow separation area, fins' surface and space between fins were solved more detail to obtain stable and accurate solution.

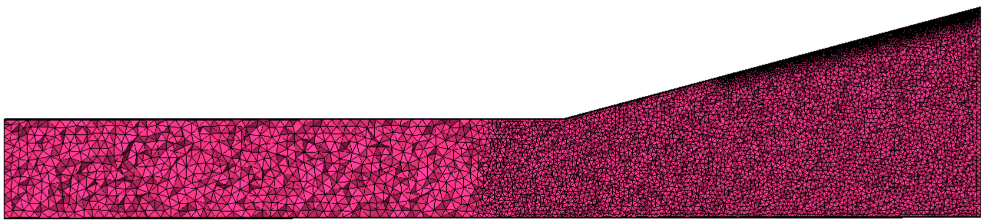

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Fig. 4. Computational mesh of flat finned diffuser ($\alpha = 15°$)

The flat diffuser flow simulation was carried out using software package ANSYS CFX. Boundary conditions are following. In model inlet there was a developed velocity profile, obtained by solving the problem of fluid flow in a long channel of rectangular section with ratio $L/d > 50$. In outlet there is static pressure value. Model's walls were defined variously depending on their geometric location.

The used turbulence model - k-omega. Problem was solved without taking into account time factor (steady-state type).

As shown by the results of the numerical experiment (Fig. 5), the longitudinal fins have a significant positive effect on the flow structure.

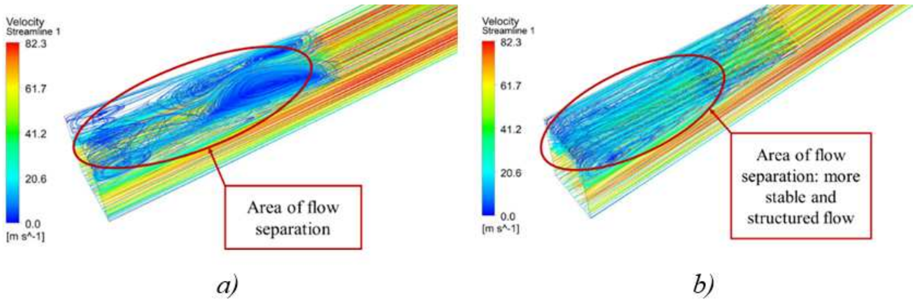

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Fig. 5. Streamlines in the diffuser according to the results of flow simulation diffuser: a) without finning ($\alpha = 15°$), b) finned diffuser ($\alpha = 15°$)

For diffusers with a small opening angle ($\alpha < 15°$) installation of the fins contributes to lower losses of energy flow; for wide-angle diffusers there was a slight increase in the pressure recovery coefficient along the length of the diffuser. As for finning system geometric parameters, results for different fins configurations for flat diffuser with angle 15 deg are presented in Figure 6.

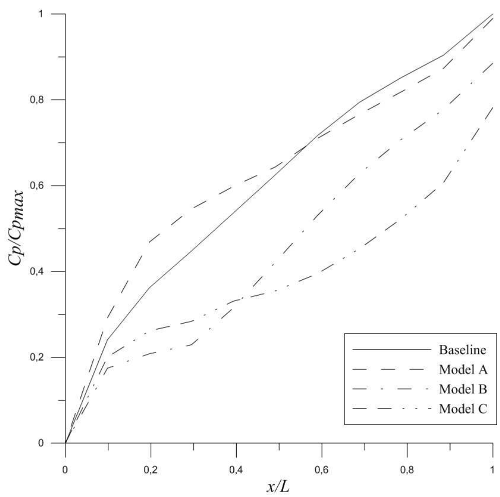

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Fig. 6. Relative pressure recovery coefficient distribution along flat diffuser for different finning models ($\alpha = 15°$)

A numerical study was also carried out for wide-angle conical diffusers. Main geometric characteristics of investigated models are given in Figure 7 and Table 2.

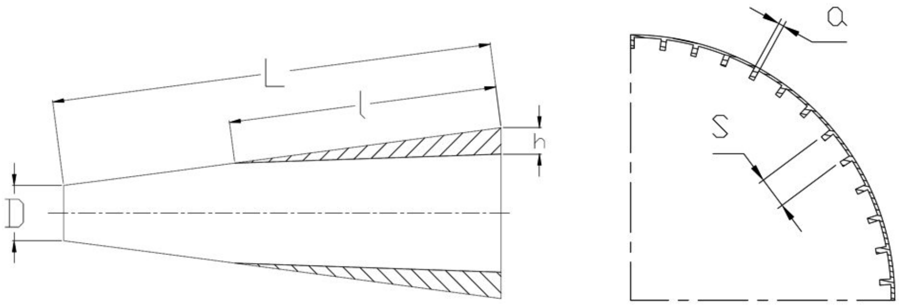

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Fig. 7. Main geometric parameters of conical finned diffuser ($\alpha = 15°$)

Table 2

Main geometric parameters of conical finned diffuser ($\alpha = 15°$)

Parameter	Model D	Model E	Model F
Fin max height *h* [mm]	2	2	15
Fin width *a* [mm]	0.5	1	0.5
Finning step *S* [mm]	6.5	6.5	6.5
Fin length *l* [mm]	140	140	220
Diffuser up wall length *L* [mm]	240	240	240
Diffuser inlet height *D* [mm]	30	30	30

Computational meshes size was 2-3 million cells, number of prismatic layers: from 13 to 15. The mesh volume inside the diffuser, near the finned walls, were made more detailed (Fig. 8).

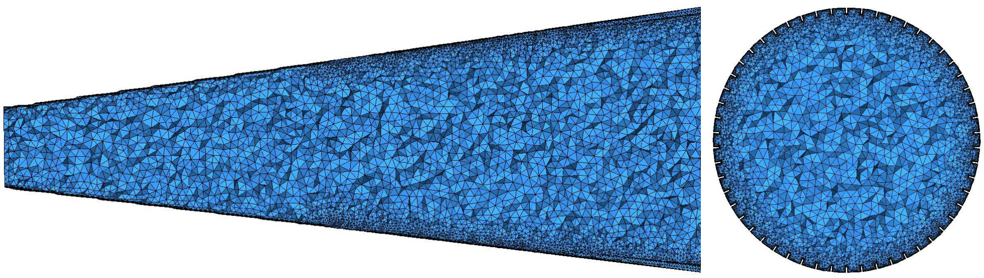

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Fig. 8. Computational mesh of conical finned diffuser ($\alpha = 15°$)

Non-uniform velocity profile, derived by simulation of the flow in cylindrical channel, was applied as boundary conditions at the diffuser inlet. At the outlet - static pressure. In addition, the stream outlet was carried out to special output camera mounted behind the diffuser. Wall models - smooth, adiabatic, no-slip.

The turbulence model used - k-omega. The problem was solved in a stationary conditions (steady-state type) using the software package ANSYS CFX.

The fins installation efficiency in the conical diffuser channels is the improvement of diffuser performance: more stable and structured flow. The modeling results for the conical diffuser with $\alpha = 15°$ are given in Figure 9.

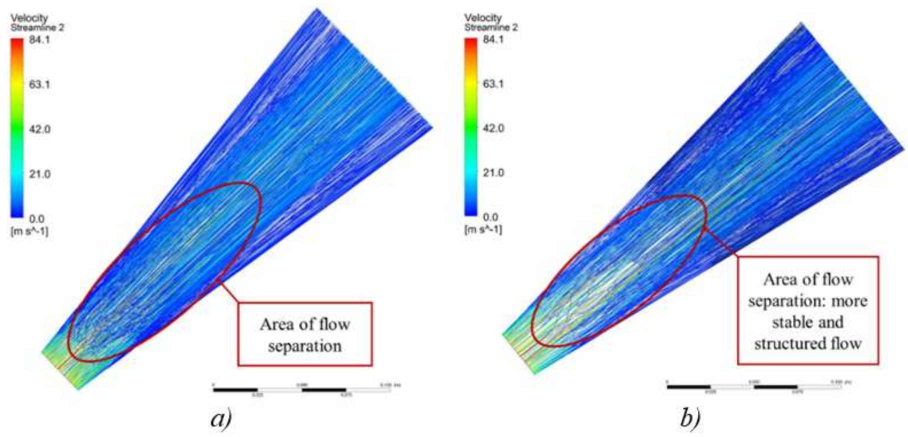

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Fig. 9. Streamlines in the diffuser according to the results of flow simulation: a) diffuser without finning ($\alpha = 15°$), b) finned diffuser ($\alpha = 15°$)

3.2. Experimental study

Experimental study was conducted for flat diffusers for the baseline (without finning) model and the model with longitudinal fins. The experimental unit used in the experiments are shown in Figure 10. Experimental unit contains the inlet channel and flat asymmetric diffuser, which formed by front, back and right-side lateral walls. Left-side lateral wall can be rotated to provide different diffuser opening angles. It also can be easily removed from the unit and replaced.

In the series of experimental tests oscillograms of the pressure pulsations on the walls of the flat diffuser with opening angle $\alpha = 15°$ (Fig. 11), in different sections during the flow in the absence of the fins (a) and with the installation of the trapezoidal fin (b) were obtained.

Source: *own development*

Fig. 10. The experimental unit for investigation of flat steel diffuser

A comparison of these waveforms shows multiple reducing of pressure pulsation amplitudes obtained by fins application. The fast of significant reduction of pressure pulsation leads to energy losses decreasing and improvement of diffuser efficiency.

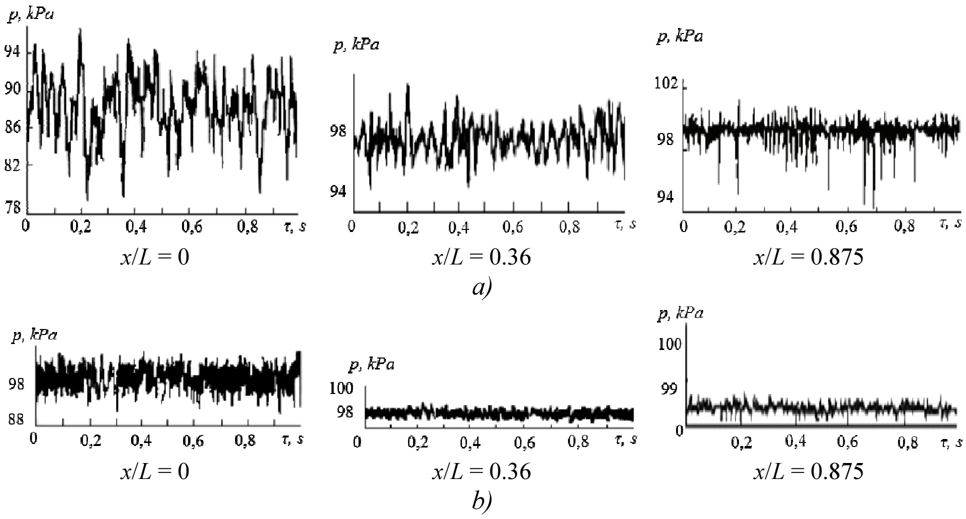

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Fig. 11. The oscillograms of pressure fluctuations on the diffuser wall along the length of the flat diffuser channel ($\alpha = 15°$) for the baseline diffuser (a) and the finning diffuser (b)

4. Conclusions

1. It is shown that the existing view on the separation mechanism requires clarification.

2. On the bases of considered force factors acting within boundary layer it is shown that the flow separation phenomenon is a crisis flow state, at which the moving fluid possibilities to respond to the inertial forces and friction forces plot deformations are completely exhausted.
3. It is justified that the boundary layer separation is largely depends on the transverse tension gradient of friction in the diffuser channel. Different geometric effects acting on this parameter give the opportunity to move a separation point location and change the whole character of the boundary layer separation phenomenon. Due to verify this theoretical hypothesis numerical and experimental investigations were carried out.

Nomenclature

A list of symbols

$\vec{c}$	velocity vector	u, υ, w	projections of the velocity vector to the coordinate axis
d	diameter	V	volume
F_P	force due to longitudinal pressure gradient	x, y, z	coordinate system
F_τ	friction force	α	diffuser opening angle
F_u	inertial force	μ	dynamic viscosity
L	length	τ	shear stress
p	pressure	τ_M	molecular friction tension
ρ	density	τ_T	turbulent shear stress

Abbreviations

CFD Computational Fluid Dynamics

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