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Olali N.V.
Niger Delta University

Olali M.O.
Niger Delta University

Orukari M.
Niger Delta University

Jumbo E.E.
Niger Delta University

A MODEL OF COMPRESSOR BLADES CONTAMINATION IN AVIATION GTE IN OPERATION

An important scientific problem, namely the development of a mathematical model of airborne gas turbine engine blades contamination in operation is solved in the paper. The mechanism of adhesion of dust particles to the blades of GTE is revealed, depending on their size and speed. The structural analysis of dust samples taken at different airfields, as well as deposits on the blades of motor compressors, has been carried out. As the angle of inclination of the surface decreases with respect to the axis of the flow, the marginal size of the area saturated with adhered particles decreases. As a result of consideration of the processes of mass transfer, adhesion and separation, it was concluded that the process of bladder contamination depends on many factors, and the maximum thickness of the layer of deposits is almost equal to the thickness of the boundary layer.

Key words: *aviation gas turbine engine, model, blade, pollution, adhesion, nature of the flow.*

Introduction. One of the defining conditions in solving the problem of maintaining gas-dynamic stability of compressors GTE in the conditions of operation is to maintain the technical state of the flow section of the engines at a given level with an increase in production.

Experience has shown that from all operational factors that pour into the state of the compressor flow section of GTE, only the effect of pollution can be with a greater or lesser effect eliminated due to the running of the washing of the flow section in operation.

Analysis of recent research and publications. In the practice of the leading airlines, the washing of the flow section of GTE has been widespread since the 70s of the XX century [3; 4]. The study of various methods for washing the flow section [5–7] shows that the most important issues are the justification of the frequency of washing and the effectiveness of detergents, the development of methods for introducing detergents into the flow section, reducing the complexity and time consuming for washing. Solving these issues requires a thorough analysis of the causes of pollution and their chemical composition.

Construction of a model of blades contamination. The condition of contamination of bodies in a polluted air stream is the excess of the forces of adhesion of particles of contamination to their surface over the separation forces. Adhesion of particles in the general case occurs under the influence of molecular, electric, Coulomb, capillary forces and frictional forces. Its size is influenced by the size, shape, chemical composition of particles, geometric and aerodynamic characteristics of the elements of the flow section, the material from which they are made, the state of their surface. The determinants in this case are the conditions for the particle's approach to the surface and the time of contact with it. Fastening of particles will depend on the peculiarities of the motion of particles near the surface, conditions that promote or prevent the contact of particles with the surface and adhesion to it, the physical and chemical parameters of the material of the surface and particles, the structure of the boundary layer, the interaction of particles settled in the dusty air stream and a number of others factors [3, p. 86]. At adhesion, the velocity of the particles at which adhesion occurs is of high importance. With regard to the compressor blades of GTE, these speeds can be determined by gas-dynamic calculation. Performed studies on the adhesion of particles from the air flow with a change in a wide range of values of the relative velocity of particles showed that the curves of the adhesion of particles to substrates from different materials have two transition points, in which the patterns of the number of particles adhering to the flow velocity change. The velocities corresponding to these points can be conventionally called the first and second critical velocities (Fig. 1).

The main factors affecting the content of particles are the size and velocity of the particles, as well as the elastic properties of the materials of the contacting bodies and the number of particles adhering from the material of the surface.

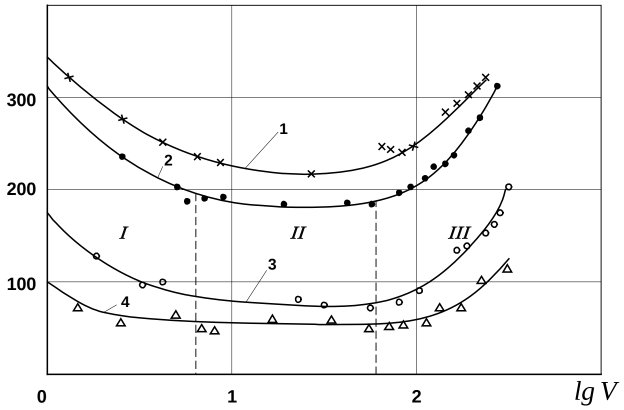

Fig. 1. Dependence of the number of particles that settled on the surface of the samples, on the velocity of particles (in m / s): 1 – duralumin; 2 – duralumin with an enamel coating; 3 – heat resistant laminate; 4 – steel

The smaller the number of the particles, which are fixed to the surface, the greater the value of the second critical velocity. The values of the first and second critical velocities depend on the material of the surface.

The condition for fixing particles can be represented as:

$$F_{\text{i}} + F_{\text{sa}} + F_{\text{f}} + P > F_{\text{er}} + F_{\text{ff}} ,$$

where F_i – force of inertia; F_{sa} – the strength of adhesion; F_f – friction force; P – force of gravity of a particle; F_{er} – the force of elastic repulsion; F_{ff} – frontal force.

The most intense contamination of the flow section occurs when the rotor runs out after stopping, the parking of aircrafts without covers and gas stubs in the conditions of a dusty atmosphere.

When considering the adhesion and rebound of particles, it is necessary to take into account the conditions of contact of particles with the surface when it is blown by dusty air flow. The F_{er} value is directly proportional to the square of the radius of the particles r_2^2, and the adhesion strength is proportional to r_2^{-1} [4, p. 212]. Then, the ratio of F_{sa} to F_{er} is proportional to r_2^{-3} and depends on the conditions of the flow of obstacles, and on the elastic properties of the surface. Under the same conditions of flow, the number of particles that settled N is proportional to the ratio of F_i/F_{er}. Since this ratio is strongly increased with a decrease in the radius of the particles, then, with decreasing r_2, the magnitude of N will increase as well. According to the observations [4, p. 214] particles up to 1 μm stick irrespectively the flow velocity.

The main value that characterizes the fixation of particles on the surface at a high speed of their flight, characteristic of the operating modes of GTE, which is hundreds of meters per second, is the depth of penetration. Depending on the ratio of the diameter of the particles and the depth of penetration, there can be two cases: the penetration depth H is less than or equal to the radius of the particles $H \leq r2$ and $H > r_2$. The depth of particle penetration is proportional to the particle's velocity, their size and density and inversely proportional to the mechanical strength of the surface.

Operational contamination of the aviation GTE blades.

The correctness of the above considerations is confirmed by the research. Structural analysis of dust samples taken at different airfields, as well as deposits on the blades of compressors of engines NK-8-2U, D-30 II and III series, D-36 showed that particles of dust up to 10 microns make up 8…11% of the volume, and the composition of deposits on the blades of compressors are the particles, which are not larger than 3...5 microns. It should also be noted that the number of pollutants on the titanium blades is greater than that of steel ones [3, p. 88; 5, p. 34].

The electrical component of the adhesive force for non-discharged particles can be determined from the expression:

$$F_{\text{e}} = 2\pi q^2 S ,$$

where S is the contact area; q is the specific charge of the layers of the double electric layer created on this contact area.

Experimental data [4, p. 312] show that because of this, total adhesion will mainly have an electrical nature and grow in proportion to the square of the radius. For particles of dielectrics (in the vast majority of cases pollution particles are dielectrics by their nature) contact with metal is accompanied by the creation of a double dielectric layer. In this case, in a medium that does not conduct a current (such kind of medium is usually gases), with any contact violations there is a non-equilibrium electrical component of adhesion, which can exceed a few times the equilibrium (electrostatic) component as it is inversely proportional to the square of the diameter of the particles d_2:

$$F_{\text{neq}} = q_0^2 / d_2^2 .$$

The full force of adhesion and the force to be overcome when the particles are separated from the surface, corresponding to the zero distance between them equals to

$$F_{ad} = -\frac{2\pi r_1 r_2}{r_1 + r_2}\left[\sigma_{12} - \sigma_{13} - \sigma_{23}\right] .$$

On the other hand,

$$F_{\mathrm{ad}} = F_{\mathrm{mol}} + F_{\mathrm{eq}} = F_{\mathrm{mol}} + F_{\mathrm{e}} + F_{\mathrm{neq}} = F_{\mathrm{vdw}} + F + F_{\mathrm{e}} + F_{\mathrm{neq}},$$

where F_{vdw} – van der Waals forces; F_{mol} – capillary forces that have a molecular nature; F_e is equilibrium and F_{neq} is the no equilibrium electrical component associated with the appearance of a double layer and the preliminary electrification of particles in the gas stream.

Assessment of particles adhesion to obstacles in the air flow. But before moving on to the study of the process of removing adherent particles from the upper surface separation, consider some of the quantitative relationships that allow us to estimate the adhesion of the particles to the obstacles in the air flow. It is necessary to take into account two circumstances:

- previously adherent particles;
- the fact that dusting occurs on all sections of the profile and on the height of the blades.

The adherent particle shields for other particles a part of the area that can be determined by the formula:

$$a = \pi d_2^2 / 2\sin\phi,$$

where φ is the angle of the flow and the surface encounter.

The area of the blade, which is occupied by adherent particles, equals:

$$S_p = \left(\frac{\pi d_2^2}{2S\sin\beta} - \sqrt{\frac{\pi d_2^2}{2S\sin\beta} - \frac{\pi d_2^4}{2S^2\sin\phi}} \right) \pi d_2^2 \, N_{\mathrm{p}} 100/4S,$$

where N_p is the number of adherent particles; S – surface area of the blade blown by the flow; β is the angle of the installation of blades in a grate.

With the decrease of the angle of inclination of the surface in relation to the axis of flow, the limiting size of the area saturated with adherent particles decreases. As the flow velocity increases, the previously described change of adhesion is observed due to their separation or penetration.

The nature of the deposition of contaminants is influenced by the state of the boundary layer, therefore it is necessary to link the process of mass transfer of pollution to the surface of the elements of the flow section with the phenomena occurring in the boundary layer. In accordance with the flow conditions for the laminar boundary layer, the resistance strength can be determined from the equation [4, p. 316].

$$F = 3\pi\mu V_2 d_2$$

and for the turbulent boundary layer [4, p. 318] of the equation:

$$F = \frac{19,8\rho^2 V_\infty^{1,44} d_2^{1,44} \nu^{0,54}}{x^{0,14}},$$

where $V_2 = \frac{V_\infty d_2}{28}$ is the velocity in the laminar layer at the height of the radius of the particles; V_∞ is the speed at the boundary of the laminar boundary layer, which equals to the free flow velocity; μ is dynamic viscosity; d_2 is a diameter of the particle; δ is thickness of the boundary layer; ρ is air density; ρ^2 is density of particles; ν is kinematic viscosity; x is a distance from the leading-edge profile.

The force of dynamic action is manifested by the impact of particles moving on adherent ones. As a result of adding this force to the aerodynamic the separation force increases. The larger the number of particles, the less the flow velocity required for the particles separation.

When the impact of particles reaches the adjuvant, the amount of motion equals to the pulse of force $F_d = F_1 + F_t$, which is spent not only on the deformation of the contact zone (under the action of force F1), but also on the separation of the adherent particle (under the action of Ft)

$$m_2 (V_1 - V_2) = F_{\mathrm{d}} \Delta t, \tag{1}$$

where m_2 is the mass of the particle; V_1 is particle velocity before impact; V_2 is a speed of rebound; Δt is time of impact.

For force F_1 equality $F_1 = F_d \sin\beta$, where β is the angle of particle contact with the surface.

Before separation, the particle can slide on the surface, with the condition of slipping $F_{\mathrm{sep}} \geq \mu F_{\mathrm{ad}}$, where $F_{\mathrm{sep}} = F_{\mathrm{d}} \cos\beta$, μ is a coefficient of friction; F_{ad} is the adhesion force (μ and F_{ad} can only be determined experimentally).

From [4, p. 320] the time of impact of particles in contact with the surface equals:

$$\Delta t = 6,11 \cdot 10^{-4} / V^{0,2}.$$

Then the equation of motion (1) will look like:

$$m_2 V^{0,2} (V_1 - V_2) = 6,11 \cdot 10^{-4} \left(F_{\mathrm{d}} \sin\beta + \mu F_{\mathrm{ad}} / cos\beta \right) k,$$

where k – coefficient, which takes into account energy losses in the contact zone deformation.

From equation (2) we can determine the force of dynamic action. The more particles carry the airflow and the larger their size, the stronger its effect on the adherent particles. In the case when the size of the grains flowing into the flow section of the working engine is 1 ... 2 orders of magnitude higher than the size of previously adherent particles, then the force Fls for a stream of this concentration is found to be higher by 1 ... 2 orders of magnitude.

At separation of particles two phenomena are distinguished, they are: erosion and denudation. Erosion is an autogenous separation of individual particles or a layer of dust. In this case, the adhesion force is greater than the force of autohesion (the forces of particle clustering with each other).

$$F_{\mathrm{ad}} > F_{\mathrm{autoh}},$$

where F_{ad} is the force of adhesion; F_{autoh} is the power of autohesion.

Denudation is an adhesive separation of the whole mass of adherent particles. In this case, the $F_{ad}<F_{ate}$. At denudation, the gap starts from the middle edge and the airborne dust cloud fills the entire blade channel. There is a class of pollution in which denudation of such particles does not occur (compact dust, gypsum, shale, carbonates). The layer of particles of the correct form tears off faster than of the wrong one. At an air flow velocity of about 30 m/s (which corresponds to the cold-scroll mode for fixed shoulder blades), after about 0.25 seconds, about 60% of adherent particles of the correct form and only 20% of irregular particles [4, p. 326] are cut off from the beginning of the air flow interaction. The speed of denudation can be estimated by the formula:

$$V_{\mathrm{denud}} = K_1 \left(F_{\mathrm{autoh}} \rho_2\right)^{0,5} + K_2 ,$$

where for the adherent layer of particles of the correct form $K_1 = 17,6$; $K_2 = 21.8$; but for the wrong one – $K_1 = 16,6$; $K_2 = 26.6$.

Studies conducted show that the time of denudation can be just a second. The time of erosion is much larger and in some cases is hundreds of seconds. The dependence of the wear of particles of pollution on the velocity of the airflow bears the character of raising to a power. The separation and wearing of dust particles depend on the magnitude and direction of the force applied to the particle. If the separation force is applied normally to the dusty surface, then the separation of the particles requires the condition $F_r>F_{ad}$. When the force is tangentially directed, the moment of forces $M_t = F_{t2}$ operates. The first stage of the separation process in this case will be rolling or sliding of the particle, that is, overcoming not only the forces of adhesion but also friction. Increasing the angle of the air flow and the dusty surface encountering increases the efficiency of dust separation.

When blowing compressed blades on, adherent particles are affected by the forces of adhesion of F_e, the mass of particles P, and the aerodynamic force of F_{aer}. The conditions for separation of particles can be represented by inequality:

$$F_{aer} \geq \mu F_{ad},$$

where μ is the coefficient of friction.

The aerodynamic force is basically the strength of the resistance, which can be determined by the formula:

$$F_{\mathrm{aer}} = F_{\mathrm{c}} = Cx \frac{\rho V^2}{2} S_2 ,$$

where C_x – coefficient of dynamic resistance of particles; ρ is air density; *V* is flow rate; S_2 is the area of the particle master cross-section.

The flow conditions of the particles in the stream and those, which are adherent to the blades are not identical. The rate in the non-excited flow is distributed more or less evenly. In the boundary layer, the flow rate varies from zero to a definite value. This change affects the aerodynamic force, since the coefficient C_x depends on the Reynolds number, which, in turn, depends on the flow velocity:

$$C_x = F\ (\mathrm{Re});\ \mathrm{Re} = F\ (V).$$

Thus, this parathion of the air flow by adherent particles is in separable linked with the structure of the boundary layer and the distribution of velocity in this layer. The nature of the action of the flow on the adherent particles can be determined from the number of Reynolds $\mathrm{Re} = \frac{d_2 V}{\nu}$ taking into account the diameter of the particles [6, p. 341]:

$\frac{d_2 V_{\mathrm{sep}}}{\nu} < 5$ laminar action;

$5 < \frac{d_2 V_{\mathrm{sep}}}{\nu} < 70$ laminar-turbulent action;

$\frac{d_2 V_{\mathrm{sep}}}{\nu} > 70$ turbulent action,

where d_2 is the diameter of the particles (the thickness of the deposit layer); V_{sep} is the rate of erosion or denudation (speed at the height of the radius of particles); *ν* is the kinematic viscosity of air.

The action of the flow on the adherent particles in the conditions of a laminar boundary gas and laminar sublayer has common and distinct patterns. The commonality is that there is a linear change in velocity in the thickness of the laminar layer and laminar sublayer. The difference is that the laminar boundary layer directly contacts an unexplained flow. With a turbulent boundary layer between the laminar sublayer and the non-excited stream there is a buffer layer and a turbulent core. These features affect the aerodynamic force.

When laminar mode is wrapped $C_x = \frac{24}{\mathrm{Re}}$. Taking into account the known equations for the master cross-section of the particle $S_2 = \frac{\pi d_2^2}{4}$ and the Reynolds number $\mathrm{Re} = \frac{d_2 V_2}{\nu}$, we find the following expression for the aerodynamic force, laying $V_2 = V_\infty \frac{d_2}{2\delta_{\mathrm{LPS}}}$ (the linear law of the velocity distribution in the boundary layer):

$$F_{\mathrm{aer}} = 3\pi\eta V_\infty d_2^2 / 2\delta_{\mathrm{LPS}} ,$$

where η is dynamic air viscosity; δ_{LPS} is the thickness of the laminar boundary layer.

The thickness of the laminar layer is the line at which the growth of aerodynamic force is observed. Therefore, in order to determine the particle separation conditions and the calculation of the aerodynamic force, it is necessary to know the thickness of the laminar layer, which depends on the speed of the unexcited flow V∞ and the distance x from the leading edge of the blade to the location of the adherent particles. The dependence of the thickness of the laminar boundary layer on V∞ and x is expressed by the Blasius formula:

$$\delta = 5,0\sqrt{\frac{\nu x}{V_\infty}}$$

Then $F_{aer\ LPS} = 0,94\rho d_2^2 V_\infty \left(\frac{\nu}{x}\right)^{0,5}$.

This formula can be used to determine the aerodynamic force required for the separation of adherent particles under the conditions of the laminar boundary layer. In the turbulent mode of flow around a dusty surface, the thickness of the laminar sublayer at the free flow of the surface can be determined by the formula [6, p. 344]:

$$\delta_{LTPS} = 33,3\nu \Big/ V^{0,857} \left(\frac{\nu}{y}\right)^{0,333} , \qquad (3)$$

where V is the flow velocity in the laminar sublayer at a height Y from the surface. The relationship between V and V is determined from the ratio $V/V_\infty = (Y/\delta_{\text{т}})^{0,143}$, where $\delta_{\text{т}}$ is the thickness of the turbulent boundary layer at a distance x from the leading edge.

Then we find from formula (3)

$$\delta_{LTPS} = 33,3\nu / V_\infty^{0,857}\, \delta_{\text{т}}^{0,143} . \qquad (4)$$

The thickness of the turbulent boundary layer is [7, p. 128]

$$\delta_{\text{т}} = 0,37x \left(V_\infty \frac{x}{\nu}\right)^{-0,2} = 0,37x^{0,8} \left(\frac{\nu}{V_\infty}\right)^{0,2} . \qquad (5)$$

Substituting (5) into (4), after transformations we obtain a semi-empirical formula for determining the thickness of the laminar sub layer in a turbulent flow mode:

$$\begin{aligned}\delta_{LTPS} &= 3,33\left(\frac{\nu}{V_\infty}\right)^{0,857} \left[0,37x^{0,8}\left(\frac{\nu}{V_\infty}\right)^{0,2}\right]^{0,143} = \\ &= 29,4x^{0,1}\left(\frac{\nu}{V_\infty}\right)^{0,9}\end{aligned} \qquad (6)$$

Where x is the distance from the leading edge; ν is kinematic air viscosity; V_∞ is the free flow rate.

To determine the aerodynamic force, it is first necessary to determine the coefficient C_x. For a turbulent boundary layer, the coefficient of resistance is approximated by the following expression [7, p. 130]:

$$C_x = \frac{22}{\mathrm{Re}^{0,7}} .$$

Then the aerodynamic force in the turbulent boundary layer can be determined from the expression [4, p. 331]:

$$F_{\mathrm{aerTPS}} = 2,75\pi\rho\nu^{0,7} d_2^{1,3} V_2^{1,3}; V_2 = V_\infty \left(\frac{d_2}{2\delta_{\text{т}}}\right)^{0,143}.$$

In turn $\delta_{\text{т}} = f(x)$ and $V_2 = V_\infty \left(\frac{d_2}{0,74x^{0,8}\nu^{0,2}}\right)^{0,143}.$

The final expression for

$$F_{\mathrm{aerTPS}} = 19,8\rho V_\infty^{1,36} d_2^{1,44} \nu^{0,54} / x^{0,14} .$$

The given expressions for calculating the aerodynamic force are not accurate, because they take into account the velocity distributions in the boundary layer.

Determination of the zones and thickness of pollutants on the compressor blades.

As a result of consideration of the processes of mass transfer, adhesion and separation, it can be concluded that the process of bladder contamination is practically impossible to calculate accurately; and it depends on many factors, and the maximum thickness of the bed of deposits is almost equal to the thickness of the boundary layer calculated for a given point of the surface to the distance from the leading edge and number Re for sand roughness or no excited flow.

Then the thickness of the blades of the compressor for normal operation can be expressed in the form of the equation:

$$\begin{aligned}\delta_3 &= \delta_{\text{ТПС}}\left[1 - \exp\left(-k_{\text{р}}\tau\right)\right]\sin\phi\sin\beta\Big|_{\beta_1}^{\beta_2} = \\ &= 0,37x^{0,8}\left(\frac{\nu}{V_\infty}\right)^{0,2}\left[1 - \exp\left(-k_{\text{р}}\tau\right)\right]\sin\phi\sin\beta\Bigg|_{\beta_1}^{\beta_2} .\end{aligned}$$

It follows from the formula that the thickness of the deposits increases along the blade cord in the direction of the flow and depends on the structural angles β_1 and β_2 of the inlet and outlet of the flow, as well as the mode of operation of the engine and the speed of flight. They all determine the angle of the profile φ. Therefore, the problem of determining the thickness of the layer of contamination for a free profile (isolated blade) can be reduced to the solution of the equation of the boundary layer. However, the feature of the flowing part of the compressor lies in the fact that the shoulder blades are a system of diffuser channels, which in a greater degree are prone to failure of the flow. The disruption of the flow occurs due to the features of the flow in the diffusers, the aerodynamic characteristics of the compressor profiles, the presence of flow unevenness and a number of other factors. In this process, contamination plays a role of the initiating factor. As a rule, the breakage zone is located behind the throat of the intrapulmonary canal on the back of the profile [7, p. 265].

The breaking area on the compressor blades has a clearly defined boundary, the location of which is a subject of calculation. In the range of numbers Re, in which modern engines operate, there are several characteristic zones on the surface of the blades [3, p. 97] (Fig. 2).

On the back of the shoulder blade is a small length-bearing zone lying near the entrance edge of the blade, with a laminar boundary layer, which ends with a zone of laminar separation. The length of the laminar zone in the range of numbers $Re = 10^4 \ldots 10^6$ is (0,003 ... 0,16) b, the zone of laminar separation is (0,02 ... 0,05) b, (where b is the profile chord). To calculate the maximum thickness of deposits in the laminar zone, we can use the Blasius equation, where Re is calculated by the velocity of the unexcited flow for the distance x from the leading-edge profile.

According to the zone of laminar separation, the zone of turbulent flow regime begins, where the thickness of the contaminants is determined by the thickness

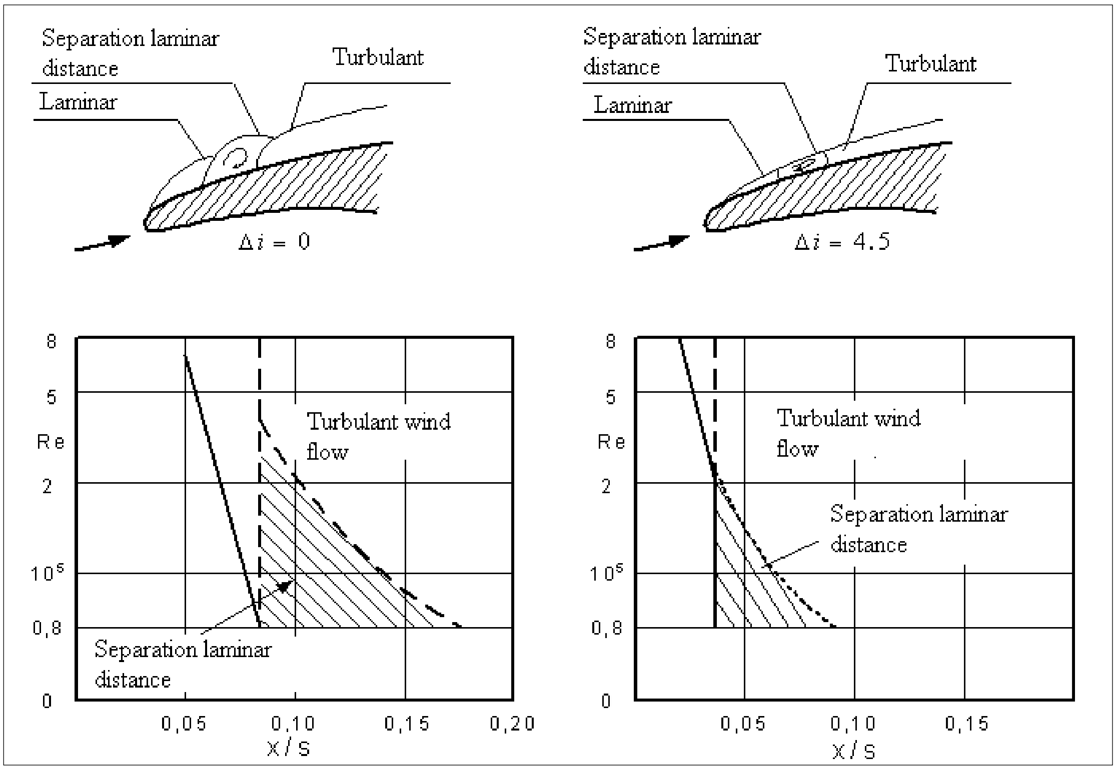

Fig. 2. The influence of the Reynolds number and the angle of attack on the flow regime in the boundary laye

of the laminar sublayer and the thickness of displacement and can be determined by the formula [5, p. 41]:

$$\delta_з = 29,4x^{0,1}\left(\frac{\nu}{V_\infty}\right)^{0,9}.$$

In the diffuser interblade vane channels, the laminar sublayer at a positive pressure gradient along the length of the channel rapidly loses its stability and is disconnected, therefore, quickly after the turbulent flow regime is established, the gap of the boundary layer passes and a significant part of the surface of the back of the blade operates under breakage conditions. The breaking of the boundary layer significantly changes the conditions of flow. By the point of separation, the boundary layer is characterized by two opposite flows: the outer has the direction of the core of the flow, the inner – the opposite. The boundary layer is twisted into a whirlwind. The appearance and wear of vortices is accompanied by the accumulation of slowed air and the formation of a stagnant zone. Due to the influence of vortices, the velocity of particles in this zone will be greater than the irregular flow, and the pressure is less.

Therefore, vertical resistance arises, which is accompanied by energy consumption and increased separation of the process of precipitation of particulate pollutants. The position of the point of separation of the boundary layer can be calculated by the formula [7, p. 218]:

$$x_{\text{sep}} = \frac{\delta^{**}\sqrt[5]{\operatorname{Re} x}}{K_1 K_2},$$

where $\delta^{**} = \delta_{\text{TPS}}\frac{n}{(n+1)(n+2)}$ is pulse loss thickness; n = 1.43 ... 2.5; K_1 = 0,36, K_2 = 0,147 ... 0,159 are the empirical coefficients; x_{sep} is the coordinate of the point of separation.

It is easy to show that the position of the point of separation in the peripheral part of the blades shifts back on the chord profile, so the width of the breakaway zone to the periphery decreases [7, p. 220]. In the separation zone, the thickness of the contaminants cannot be clearly calculated, but according to experimental data, it is found that it is equal to the thickness of the sublayer of the turbulent zone and significantly affects the amount of losses. On the concave part of the shoulder blade (trough), the turbulent boundary layer is installed directly behind the incoming edge of the shoulder blade and extends without interruption to the entire length of the shoulder blade. The thickness of the contaminants corresponds to the thickness of the laminar sublayer and the length of the chord may slightly increase (Fig. 3).

The given considerations require some adjustments. According to the data obtained by Trukkenbrodt, Glushvitts, Schmidtbauer and Parr [6, p. 154], the structure of the boundary layer on the shafts of movable (impellers) and

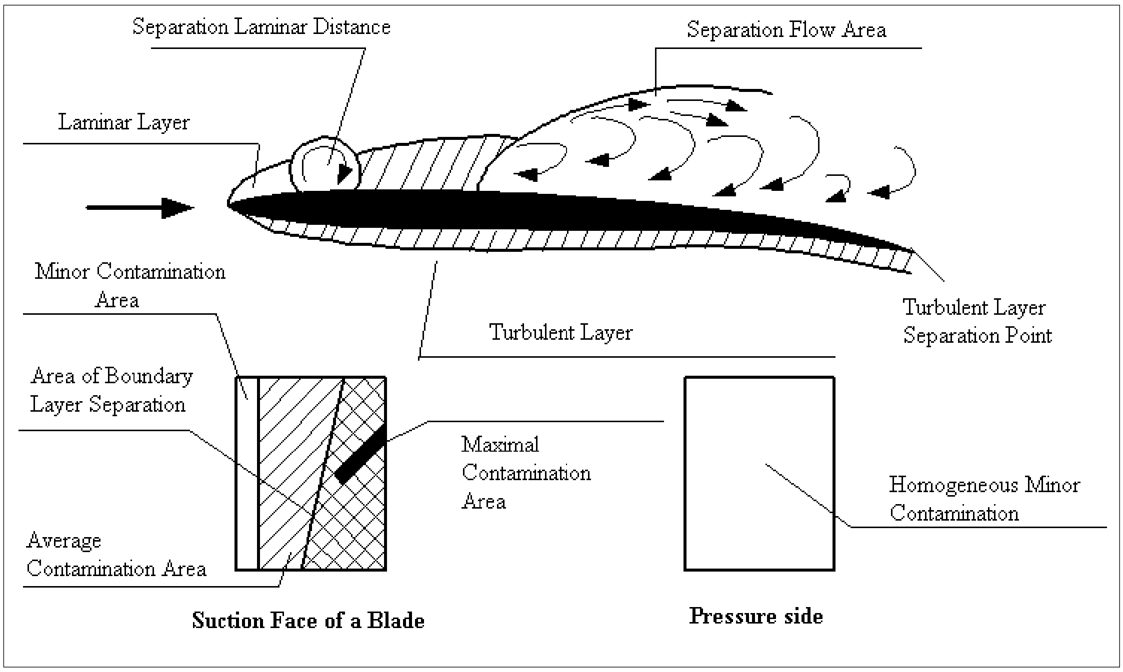

Fig. 3. Distribution of the boundary layer and the nature of pollution of the working blades of the compressor

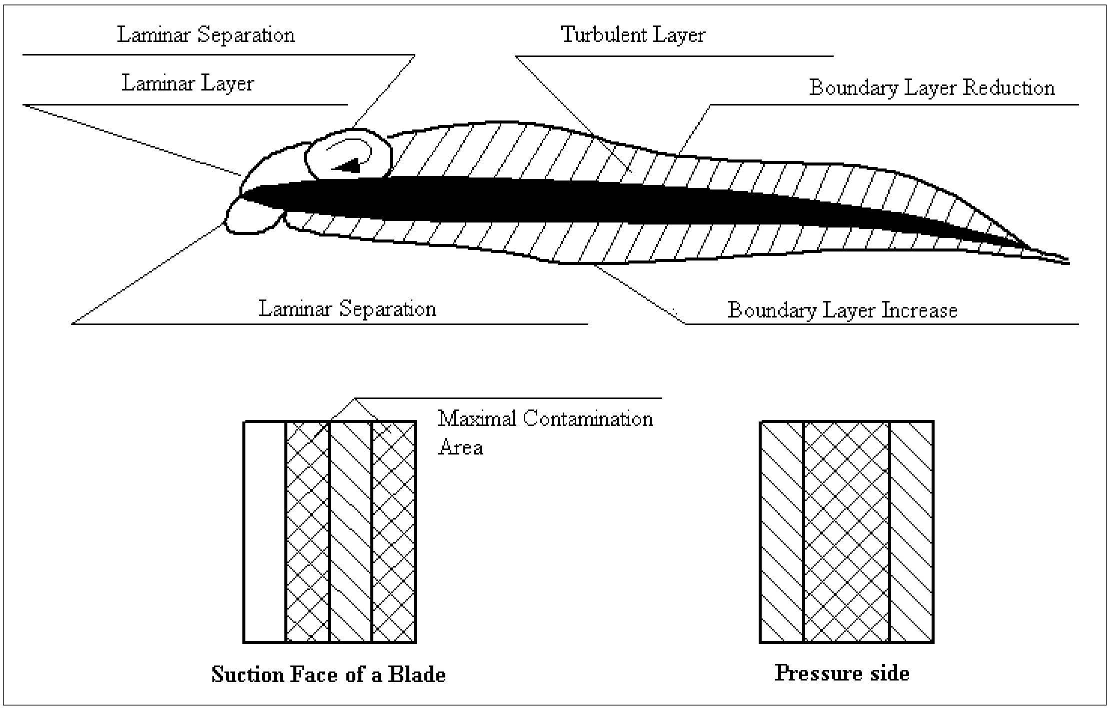

Fig. 4. Distribution of the boundary layer and the nature of the blades contamination of the compressor guiding apparatu

fixed (guiding apparatus) crowns differs, with its thickness for rotating blades strongly increases with increasing parameter $\lambda = \frac{\omega R}{V_\infty}$, where ω is an angular velocity; R is a radius; V_∞ is the axial velocity of the unexcited flow.

On the blades, which rotate, the boundary layer becomes thinner than with the flat flow of the same profile due to centrifugal forces, which also significantly affect the transition of the laminar form to the turbulent one. This conclusion is experimentally confirmed in [3, p. 99; 5, p. 341], where it is shown that on the blade, which rotates, the transition of the laminar form to the turbulent one, passes under other different conditions with a significantly smaller number of *Re* than on the fixed ones.

On the concave part of the stationary blades, the boundary layer is thicker, and the maximum thickness corresponds to the largest curvature of the profile. In this case, this parathion of flow on the back of the profile of the fixed blades of the guides is not observed. Accordingly, the deposition of pollution on the blades of the guides will be different from the deposits on mobile blades (Fig. 4).

Taking into account all of the above, it can be concluded that the thickness of the contamination layer stabilized on the blades of the compressors is equal to the thickness of the boundary layer, and the distribution of them on the profile of the blades corresponds to the presented picture of the flow. The dynamics of the growth of the thickness of pollution is determined by the value of the coefficient *Kr*, which is included in the index of power. The calculation of this coefficient is an extremely difficult task and for practical purposes *Kr* can be determined only experimentally.

Conclusion. The validity of the developed model of distribution of pollutants on the surface of blades is confirmed experimentally. Investigation of the fan blades, compressors of medium and high-pressure engines D-36, which were conducted in conditions of aircraft repair plant, showed that the contamination of the rotter blade, regardless of the work of the engines, received for repairing was in the accordance with the developed methodology.

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МОДЕЛЬ ЗАБРУДНЕННЯ ЛОПАТЕЙ КОМПРЕСОРІВ АВІАЦІЙНИХ ГТД В ЕКСПЛУАТАЦІЇ

У статті розв'язана важлива наукова проблема – розробка математичної моделі забруднення лопатей авіаційних газотурбінних двигунів у експлуатації. Розкрито механізм адгезії частинок пилу до лопатей ГТД залежно від їх розміру та швидкості. Проведено структурний аналіз проб пилу, які взяті на різних аеродромах, а також відкладень на лопатях компресорів двигунів. Зі зменшенням кута нахилу поверхні стосовно осі потоку граничний розмір площі, насиченої частинками, що прилипли, зменшується. У результаті розгляду процесів масопереносу, адгезії та відриву зроблено висновок, що процес забруднення лопатей залежить від багатьох факторів, а максимальна товщина шару відкладень майже дорівнює товщині граничного шару.

Ключові слова: *авіаційний газотурбінний двигун, модель, лопаті, забруднення, адгезія, характер течії.*

МОДЕЛЬ ЗАГРЯЗНЕНИЯ ЛОПАСТЕЙ КОМПРЕССОРОВ АВИАЦИОННЫХ ГТД В ЭКСПЛУАТАЦИИ

В статье решена важная научная проблема – разработана математическая модель загрязнения лопастей авиационных газотурбинных двигателей в эксплуатации. Раскрыт механизм адгезии частиц пыли к лопастям ГТД в зависимости от их размера и скорости. Проведен структурный анализ проб пыли, которые взяты на разных аэродромах, а также отложений на лопастях компрессоров двигателей. С уменьшением угла наклона поверхности по отношению к оси потока предельный размер площади, насыщенной прилипшими частицами, уменьшается. В результате рассмотрения процессов массопереноса, адгезии и отрыва сделан вывод, что процесс загрязнения лопастей зависит от многих факторов, а максимальная толщина слоя отложений почти равняется толщине предельного слоя.

Ключевые слова: *авиационный газотурбинный двигатель, модель, лопасть, загрязнение, адгезия, характер течения.*