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Air Pressure Force Acting on a Moving Plate

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A molecular kinetic model is developed for the gas-dynamic flow around a flat plate moving through the air at positive and negative angles of attack. It is shown that, at low velocities of the plate motion, the lift and the drag are determined by the gas-dynamics of the air flow in the rear region while at high velocities close to the speed of sound velocity the impact interaction between the plate and the molecules of the surrounding medium in the front region is of critical importance. No separated flow occurs behind the plate at low velocities. The conditions under which the drag and the lift of the plate reverse their directions are determined.

Key words: **gas-dynamic process, flow, plate, air resistance, molecular kinetic theory, lift force, drag force.**

Introduction

THE knowledge of the pressure force acting on a plate moving through the air serves as a basis for calculating such main characteristics of the aircraft wing as drag and lift. That is why the forces acting on the plate moving through the air attracted attention of numerous researchers who investigated the aerodynamics of various aircraft. Starting from the works of Newton and taking into account Bernoulli's principle, researchers finally arrived at a conclusion that lift and drag are determined as follows.

$$\bar{P}_y = C_y \frac{\rho v_a^2}{2} S; \quad \bar{P}_x = C_x \frac{\rho v_a^2}{2} S \qquad (1)$$

Here ρ is the ambient density; v_a is the speed of plate motion; S is the area of the plate, C_y and C_x, correspondingly, are the constants determining the lift and the drag of the plate moving through the air. A rather complicated mechanism of the interaction of the plate with the air it moves through lies in these constants which are determined experimentally for each specific case. In the end, various theories of aerodynamic flows around the bodies with complicated shapes were created to obtain C_y and C_x constants. Various physical models of aerodynamic flows around bodies were analyzed by Theodore von Kármán [1]. Fig.1 represents the results. When the air flows around the bodies with complicated shapes, a separated flow frequently develops. The separated flow is accompanied with vortex formation. Analyzing experimental data, Theodore von Kármán found out the conditions under which the vortices are formed and also described the nature of the vortices. For this reason, the train of vortices following a moving body was named "Kármán vortex street".

A more general approach to obtaining *Cy* and *Cx* constants under continual air flow around objects with taking into consideration separated flow was proposed by N.N.Simakov [2]. A complete analysis of the experimental data related to separated flow is described in [3]. The formation of separated flow with the use of molecular kinetic theory was studied in [4]. In the article [5], the molecular kinetic theory is used for the analysis of the working airscrew and it is shown that the airscrew is the heating pump. The molecular kinetic theory has also been used for the airscrew of the compound form with the Mobius surface and, as a result, optimum conditions of work [6] were established. The interesting results were obtained in grounding the separated flow behind a moving ball [7].

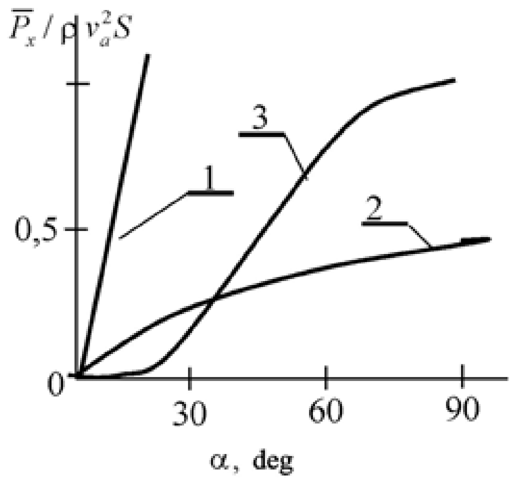

Figure 1. The dependence of C_x constant on the angle of attack: (1) Newton's corpuscular theory; (2) Rayleigh's theory, and (3) – circulation theory

However, no consistent theoretical analysis of flows around objects moving through the air with regard to a simpler case of a common flat plate with finite dimensions was presented. That is why the following goal was set: to study this simple case using the molecular kinetic theory and to clarify the aerodynamics of the flow about a flat plate. To reach the goal the following problems should be solved:

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- to study the flow around the flat plate with finite dimensions at a negative angle of attack;
- to study the flow around the flat plate with finite dimensions at a positive angle of attack;
- to perform a computer simulation of various types of motion of flat plates;
- to compare the theoretical results of the studies with experimental data.

Let us consider, one after another, these problems.

Negative angle of attack

Fig.2(a) shows the general diagram of the interaction between the air flow and the plate with the width *h* and the length *L* moving through the air. Relative to the plate, the velocities of air motion along the normal and along the surface in the front region are:

$$v_n = v_a \sin\alpha \text{ and } v_\tau = v_a \cos\alpha . \quad (1)$$

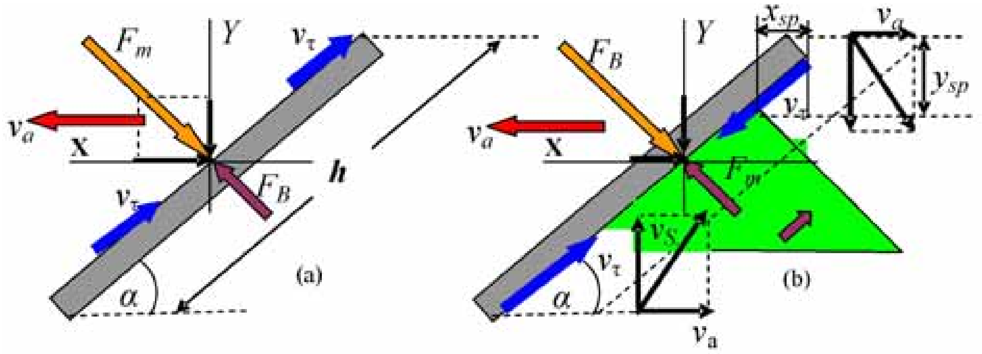

Figure 2. Interaction between the air flow and the plate moving through the air. Negative angle of attack: (a) front region and (b) rear region

The air mass preventing the plate motion in a unit of time *t* with the velocity of v_a, is determined as follows:

$$m = \rho_\infty h \sin\alpha \, L v_a t , \quad (2)$$

where: ρ_∞ is the density of the surrounding air.

The momentum gained by the air mass along the normal to the surface amounts to:

$$p = m v_a \sin\alpha = \rho_\infty h L v_a^2 \sin^2\alpha \ t . \quad (3)$$

Based on Newton's second law the following force acts on the moving plate along the normal to its surface:

$$F_{S,n} = \frac{dp}{dt} = \rho_\infty h L v_a^2 \sin^2\alpha. \quad (4)$$

In accordance with Bernoulli’s principle, the following gas dynamic force acting normal to the surface occurs:

$$F_{B,n} = \frac{\rho v_\tau^2}{2} S = \frac{1}{2}\rho v_a^2 \cos^2\alpha \, hL . \quad (5)$$

Hence, the resulting force acting upon the moving plate normal to its surface in the front region is as follows:

$$F_{n,res.} = F_{m,n} - F_{B,n} = \rho_\infty v_a^2 hL\left(\sin^2\alpha - 0,5\cos^2\alpha\right).. \quad (6)$$

There is vacuum space formed behind the rear side of the moving plate. The air flows which fill the area of rarefaction are mutually compensated at side walls while the air flows above and behind the plate are different. The resulting tangential velocity amounts to the following difference:

$$v_{\tau,res} = v_r\left[\sin(\alpha+\delta) - \sin(\alpha-\delta)\right], \quad (7)$$

where:

$$v_r = \sqrt{v_s^2 + v_a^2} \text{ and } \delta = arctng\left(\frac{v_a}{v_s}\right).$$

The above formula presents the velocity of the air flow which travels from the bottom upwards along the rear side of the plate and collides with the air flow which travels from the upper edge of the plate thus forming a tetrahedral cone possessing weak air flow travelling from the bottom upwards. Fig.2(b) shows the process of filling the vacuum space situated behind the rear side of the plate with the air. Based on the law of conservation of mass it follows that: the quantity of the air disturbed by the moving plate is equal to the mass of the air filling the vacuum space at all four sides. In accordance with the law of conservation of mass the following equation is realized:

$$\rho_\infty S_n v_a \Delta t \cong 4\rho\left(\frac{1}{2}x_{sp} y\right)L . \quad (8)$$

Here $\Delta t = y / v_s$.

It can be derived from (8) that:

$$x_{sp} = 0.5\frac{\rho_\infty}{\rho}\frac{h v_a \sin\alpha}{v_s} . \quad (9)$$

Here $v_s = \sqrt{\gamma k_B T / m_a}$ is the speed of sound, γ is the ratio of the specific heats at constant pressure and constant volume, k_B is the Boltzmann constant, and m_a is the average mass of air molecules. The air density within the vacuum space is:

$$\rho = \rho_\infty \exp\left(-\frac{m_a v_{\tau,res.}^2}{2k_B T}\right). \quad (10)$$

At the distance of $x_{sp.}$ the difference between the pressure in the vacuum space and the ambient pressure levels off and so the incoming flow of the ambient air ceases. Because of this a separated flow with reduced pressure is formed behind the plate; the pressure within the flow is determined by the following formula

$$P = P_\infty \exp\left(-m_a v_{n,res.}^2 / 2k_B T\right)$$

or

$$P = P_\infty - 0.5\rho v_{\tau,res.}^2 , \quad (11)$$

The vertex of the angle of the tetrahedral cone in the XY plane amounts to $\pi/2-\delta$. It follows herefrom that the vertex of the cone moves away from the plate as the motion velocity increases. If the plate moves at the speed of sound, the vertex of the cone amounts to the angle of $\pi/4$.

Up to the distance of $x_{sp.}$ the tangential velocity of filling the vacuum space is defined above by formula (7) while the normal velocity equals to:

$$v_{n,res.} = v_r\left[\cos(\alpha+\delta)+\cos(\alpha-\delta)\right] \quad .(12)$$

The air mass participating in filling the vacuum space and impacting the plate should be considered at three sides only, i.e. at left, right, and upper side of the plate. At the plate bottom side, the normal velocity of filling the vacuum space is less than that one at the upper region. As a result, the moment of force acts on the plate positioning it normal to the velocity of motion.

Assuming the force impacting the bottom part of the plate is negligibly small:

$$F'_{m,n} = \frac{d}{dt}\left(\frac{3}{4}m2v_{n,res.}\right) = \frac{3}{2}\rho_\infty hLv_{n,res.}v_a\sin\alpha \ . \quad (13)$$

This impact force reduces the drag of the moving plate while the force due to Bernoulli's principle, vice versa, increases the drag and is realized mainly at the bottom side only. Taking into account (7), the gas-dynamic force is equal to:

$$F'_{B,n}\,0.5\rho v^2_{\tau,res.}x_{sp}L/\cos\alpha \ . \quad (14)$$

The resulting force presents the difference as follows:

$$F'_{res.,n} = F'_{B,n} - F'_{m.,n} \ . \quad (15)$$

Along the X-axis, this force determines the drag of the plate moving through the air while along the *Y*-axis it determines the lift.

The air mass in the vacuum space is concentrated within the tetrahedral cone and is virtually motionless relative to the plate. Therefore it produces a gas-dynamic force due to the difference between the pressures at the front and rear walls of the moving plate. This force acting along the *X*-axis is:

$$F''_n = \left(P_\infty - P\right)\left(hL - 4x_{sp.}L/\cos\alpha\right) . \quad (16)$$

Here the pressure *P* is determined by formula (11).

Hence, the total force acting on the moving plate at the front and rear sides normal to its surface is as follows:

$$F_{n,tot.} = F_{n,res.} + F'_{res.,n} + F''_n \ . \quad (17)$$

Based on (17), the plate moving at a negative angle of attack experiences the drag:

$$\bar{P}_X = F_{n,tot.}\sin\alpha \quad (18)$$

and the lift:

$$\bar{P}_Y = F_{n,tot.}\cos\alpha \ . \quad (19)$$

After having divided the forces by $0.5\rho v_a^2 S$, we will get, correspondingly, the values of C_x and C_y.

Positive angle of attack

Fig.3(a) shows the diagram of the interaction between the air flow and the plate moving through the air at a positive angle of attack. The dimensions of the plate are: width *h* and length *L*.

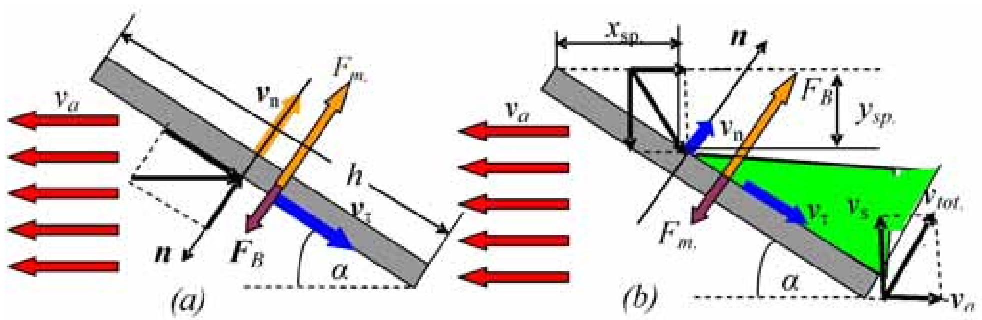

Figure 3. The diagram of the interaction between the air flow and the plate moving through the air. Positive angle of attack: (*a*) in the front plane and (*b*) in the rear plane

The velocities of the air motion along the normal and along the surface are:

$$v_n = v_a\sin\alpha \ \text{ and } \ v_\tau = v_a\cos\alpha \ . \quad (20)$$

The air mass preventing the plate motion in a unit of time *t* with the velocity of v_a, is determined as follows:

$$m = \rho_\infty S v_a t = \rho_\infty hL\sin\alpha\, v_a t \ . \quad (21)$$

The momentum gained by the air mass along the normal to the surface amounts to:

$$p = mv_a\sin\alpha = \rho_\infty hLv_a^2\sin^2\alpha\, t \ . \quad (22)$$

Based on Newton's second law the following force acts on the plate along the normal to its surface:

$$F_{m,n} = \frac{dp}{dt} = 2\rho_\infty hLv_a^2\sin^2\alpha . \quad (23)$$

In accordance with Bernoulli's principle, the following gas dynamic force acting normal to the surface occurs:

$$F_{B,n} = \frac{\rho_\infty v_\tau^2}{2}S = \frac{1}{2}\rho_\infty v_a^2\cos^2\alpha hL \ . \quad (24)$$

Hence, the resulting force acting upon the moving plate normal to its surface is as follows:

$$F_{n,tot.} = \rho v_a^2 hL\left(\sin^2\alpha - 0.5\cos^2\alpha\right) . \quad (25)$$

There is a separated flow formed behind the rear side of the moving plate with the pressure falling to the value of

$$P = P_\infty \exp\left(-m_a v_{\tau,tot}^2 / 2k_B T\right),$$

or

$$P = P_\infty - 0.5\rho v_{\tau,tot}^2 . \quad (26)$$

The occurred vacuum space is filled with air flow at the speed of sound. Fig.3(b) shows a case in point. On the basis of the law of conservation of mass, it follows that the quantity of the air disturbed by the moving plate is equal to the mass of the air filling the vacuum space at all four sides. Let us write down the law of conservation of mass for the case shown in Fig.3(b):

$$\rho_\infty S_n v_a \Delta t \cong 4\rho\left(\frac{1}{2} x_{sp.} y_{sp.}\right) L . \quad (27)$$

Here $\Delta t = y_{sp.} / v_{s.}$, and v_s presents the speed of sound. It follows from (27) that:

$$x_{sp.} = 0.5 \frac{\rho_\infty}{\rho} \frac{h v_a \sin\alpha}{v_s} . \quad (28)$$

At this distance $x_{cp.}$ (distance from the edge of the plate) the difference between the pressure behind the plate and the ambient pressure level off and so the incoming flow of the ambient air ceases. Because of this, a separated flow with reduced pressure, determined by formula (26), is formed behind the plate as a tetrahedral cone. However, the velocity which occurs at the moment of flow separation at the distance of $x_{cp.}$ along the X-axis should be used. The vertex of the angle of the tetrahedral cone in the XY plane amounts to $\pi / 2 - \delta$. It follows herefrom that the vertex of the cone moves away from the plate as the motion velocity increases. If the plate moves at the speed of sound, the vertex of the cone amounts to the angle of $\pi / 4$.

Air flow lags to some extent relative to the moving plate. Then the resulting velocity of filling the vacuum space in the rear region of the plate is determined as follows:

$$v_r = \sqrt{v_s^2 + v_a{}^2} . \quad (29)$$

Starting from the distance of $x_{sp.}$ the tangential and normal components of the velocity of filling the vacuum space become as follows:

$$v_{n,tot.} = v_{r.}\left[\cos(\alpha+\delta) + \cos(\alpha-\delta)\right];$$

$$v_{\tau,tot.} = v_r\left[\sin(\alpha+\delta) - \sin(\alpha-\delta)\right]. \quad (30)$$

The air mass participating in filling the vacuum space at all four sides of the plate:

$$m = \rho_\infty h \sin\alpha\, L v_a t . \quad (31)$$

This air mass impacts the plate as follows:

$$F'_{m,n} = \frac{3}{2}\rho_\infty h \sin\alpha\, L v_a v_{n,tot.} \quad (32)$$

and thus reduces the drag of the moving plate.

The presence of the tangential velocity of the air flow creates the force due to Bernoulli's principle:

$$F'_B = 0.5\rho v_{\tau,tot.}^2 x_{sp} L / \cos\alpha . \quad (33)$$

The resulting force is the difference:

$$F'_{n,tot} = F'_{B,n} - F'_{m,n} . \quad (34)$$

This force acting along the X-axis increases or decreases the drag, while acting along the Y-axis in a similar manner, it exerts influence upon the lift.

The air mass concentrated within the tetrahedral cone travels along the plate surface at a velocity of $v_{\tau,tot.}$ which is negligibly small. Therefore, it produces a gas-dynamic force due to the difference between the pressures at the front and rear walls of the moving plate. This force acting normal to the plate surface is:

$$F''_n = \left(P_\infty - P\right)\left(hl - 4x_{sp.} l / \cos\alpha\right). \quad (35)$$

The total force acting on the moving plate at the front and rear sides is as follows:

$$F_{n,tot.} = F_{n,res.} + F'_{res.,n} + F''_n . \quad (36)$$

Hence, the plate moving at a positive angle of attack experiences the drag:

$$\bar{P}_X = F_{n,tot.} \sin\alpha , \quad (37)$$

and the lift:

$$\bar{P}_Y = F_{n,tot.} \cos\alpha . \quad (38)$$

After having divided the forces by $0.5\rho v_a^2 S$ we will get, correspondingly, the values of C_x and C_y.

Computer simulation of various types of motions

The derived formulae describing the lift and the drag of flat plates were used to develop the computer software to simulate various types of motion of flat plates through the stationary atmosphere. The results of the simulation make it possible to analyze the interactions between the forces occurring in the surrounding atmosphere and the front and rear walls of the moving plate using the calculated values of the forces $E_{n,tot.}$, $F'_{n,tot.}$ and $F''_{n,tot.}$, shown in Table 1 depending on the velocity of the motion and the angle of attack.

It follows from Table 1 that at small angles of attack and at low velocities of the flat plate motion through the stationary atmosphere the drag and the lift are determined by the interactions realized in the rear region while at high velocities (close to the speed of sound) they are determined by the interactions realized in the front region.

In the rear region the area of a separated flow prevents the motion of the plate in all flight modes.

Table 1. Forces of the interaction between the flat plate and the surrounding medium in front and rear regions at negative angle of attack

Forces (N)	v = 5 m/s			v = 35 m/s			v = 125 m/s			v = 215 m/s		
	10°	35°	55°	10°	35°	55°	10°	35°	55°	10°	35°	55°
Fn,tot	-22	-0.35	24.5	-1077	-15.4	1200	-13743	-197	15300	-40680	-582	45300
F´n,tot	-0.35	-3.69	-5.4	24	47.2	-35.7	682	3300	3270	2600	17070	17070
F´´n,tot	85.8	58.67	28.6	4017	2553	1190	22950	15540	5720	35600	37200	20700

The results of the calculations of the drag and the lift depending on positive and negative angles of attack at some velocities of the plate motion are presented in Table 2.

The specific force characteristics of the drag and the lift for positive and negative angles of attack are presented in Figure 4.

Table 2. Dependence of the drag and the lift of plate with dimensions 1 x 1.5 m^2 on the angle of attack and the velocity of plate motion

Parameters	Velocity of Plate Motion (m/s)								
	5	35	65	95	125	155	185	215	245
$\alpha = \mp 10^o$									
P_x , N	11.0	515	1490	1720	1720	1420	739	-432	-2220
$P_{y,1}$, N	-62.5	-2910	-8470	-9710	-9720	-8050	-4190	2450	12600
$P_{y,2}$, N	62.5	2910	8470	9710	9720	8050	4190	-2450	-12600
$\alpha = \mp 35^o$									
P_x , N	31.4	1480	4510	8080	10700	15300	4140	-11900	-42200
$P_{y,1}$, N	-44.7	-2120	-6450	-11600	-15300	-14700	-5920	17000	60300
$P_{y,2}$, N	44.7	2120	6450	11600	15300	14700	5920	-17000	-60300
$\alpha = \mp 55^o$									
P_x , N	39.0	1980	6450	12800	19900	26900	32200	34100	30100
$P_{y,1}$, N	-27.5	-1390	-4510	-8900	-13900	-18800	-22600	-23900	-21100
$P_{y,2}$, N	27.5	1390	4510	8900	13900	18800	22600	23900	21100

Result analysis

1. At velocities of up to $83 \div 110$ m/c and angles of attack of up to 35^o the aerodynamics of the flat plate flight is determined, for the major part, by the interaction processes which occur in the rear region while at the velocities close to the speed of sound the aerodynamics is determined by the processes which occur in the front region. What this means is that small aircraft (Unmanned Aerial Vehicles, mini and micro aircraft) possess their own aerodynamics while large aircraft flying at speeds close to the speed of sound possess their own aerodynamics The first aerodynamics and the second one differ radically.
2. Starting from the speed of 200 m/s and up, at small angles of attack, the drag reverses its sign, i.e. the plate experiences acceleration but not drag. So, at the speed of 220 m/s and angles for up to 44^o the drag is negative featuring a maximum of 17400 N at the angle of attack of 33^o. Accordingly, at the speed of 260 m/s, the drag is negative for up to 51^o featuring a maximum of 64200 N at the angle of 36^o. The negative values of the drag at speeds of 215 m/s and 245 m/s are presented in Table 2. The reversion of the drag sign also means the reversion of the lift sign.

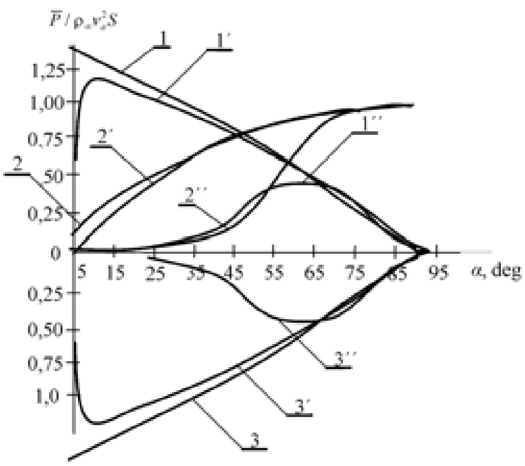

Figure 4. Dependences of Specific Force Constants on Angle of Attack at Various Velocities of Plate Motion**:** velocity is 5 m/s 1 - lift at a positive angle of attack; 2 - drag, and 3 - lift at a negative angle of attack; 1',2', 3′ accordingly for the velocity of 50 m/s, and 1",2",3" for the velocity of 180 m/s

This remarkable quality of flat plates which move through Earth's atmosphere at negative and positive angles of attack should be taken into account when designing various mechanical devices intended for aircraft wings and rudders.

Conclusions

1. The molecular kinetic theory is applied to ground the gas-dynamic flow around a flat plate when it moves through the stationary atmosphere at positive and negative angles of attack. As a result, it has been found out that the normal component of the velocity of the flow around the plate determines Newton's corpuscular theory while the tangential one determines d'Alembert-Euler continual theory with due regard to Bernoulli's principle.
2. It is shown that at low velocities of the plate motion the lift and the drag are determined by the gas-dynamics of the air flow in the rear region while at high speeds close to the speed of sound the impact interaction between the plate and the molecules of the surrounding medium in the front region is of critical importance.
3. The conditions under which the drag and the lift of the plate reverse their directions are determined. Such change in the direction is the cause of the reverse of wing flaps when they deflect for $30^o \div 45^o$ relative the velocity vector [4].

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Delovanje sile vazdušnog pritiska na pokretnu ploču

Razvijen je molekularno kinetički model gasodinamičkog opstrujavanja ravne ploče dok se kreće kroz vazduh pod pozitivnim i negativnim napadnim uglovima. Pokazano je da se pri niskim brzinama kretanja ploče sile uzgona i otpora određuju pomoću gasodinamike vazdušne struje iza ploče dok je pri većim brzinama koje se približavaju brzini zvuka interakcija ploče i molekula okolne sredine ispred ploče od većeg značaja. Pri niskim brzinama ne dolazi do razdvajanja struje iza ploče. Određeni su uslovi pod kojima dolazi do menjanja predznaka pravca uzgona i otpora ploče.

Ključne reči: **gasodinamički proces, opstrujavanje, ploča, otpor vazduha, molekularno kinetička teorija, sila uzgona, sile otpora.**

Сила давления воздуха на движущуюся плоскую пластину

Разработана молекулярно-кинетическая математическая модель газодинамического обтекания плоской пластины при ее движении с положительным и отрицательным углом атаки. Показано, что при малых скоростях движения пластины подъемная сила и лобовое сопротивление определяются газодинамикой течения воздуха в тыльной области, а при скоростях движения близких к скорости звука решающую роль выполняет ударное взаимодействие пластины с молекулами окружающей среды в передней области. При малых скоростях движения за пластиной срывное течение не возникает. Определены условия, когда происходит изменение направления действия лобового сопротивления и подъемной силы на пластину.

Ключевые слова: **газодинамика пластины, молекулярно-кинетическая теория, силовые постоянные.**

Action de la force de pression d'air sur la plaque en mouvement

On a développé un modèle cinétique moléculaire du courant gaz dynamique de la plaque plate en mouvement à travers l'air sous les angles d'attaque positives et négatives. On a démontré que les forces de poussée et les forces de résistance étaient déterminées par le gaz dynamique du courant d'air derrière la plaque lorsque la vitesse du mouvement de la plaque est petite. Quand les vitesses sont plus grandes et qu'elles s'approchent de la vitesse de son l'interaction de la plaque et des molécules du milieu ambiant devant la plaque est d'une plus grande importance. Lorsque les vitesses sont plus petites la séparation du courant derrière la plaque ne se produit pas. On a déterminé aussi les conditions sous lesquelles se produit le changement de l'indice de la direction de poussée et de la résistance de plaque.

Mots clés: **processus gaz dynamique, courant, plaque, résistance de l'air, théorie cinétique moléculaire, force de poussée, forces de résistance.**