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THE OPERATION OF COMPLEX MECHANICAL SYSTEM IN MOTOR TRANSPORT

The paper considers the operation of the fan as heat pump. Proceeding from the analysis of general scheme of fan operation transformation factor is determined. In the process of fan blades interaction with the environment the following problems are considered: impact mechanism of separate molecules of air, emerging centrifugal forms and hydrodynamic forces, caused by Bernoulli law. It was established that the power, consumed by the fan, depends on rotation frequency not on cubic power in 3/2 power with further transition into linear coupling.

Key words: *fan, heat pump, environment, laminar flow, continuous flow, energy system, cluster.*

Introduction

Nowadays the reasons of energy crisis are limited natural hydrocarbon fuels (peat, coal, oil, gas) and prices growing for these types of fuel. Many attempts are made to find the way out. Special attention is paid to methods of obtaining maximum conversion factor of one type of fuel into another. Researches aimed at usage of low-potential heat with application of heat of the environment applying heat pumps are carried out in this sphere.

Automobile as any other transport vehicle, moving in Earth atmosphere must be considered as complex energy system of open type. During the process of interaction of moving transport vehicle with the environment either energy transfer from moving object to the environment may occur, or vice-versa – environment transfers its own energy to moving object.

During movement of the transport vehicle its interaction with the air environment takes place. Fan is a connecting link for energy transfer «moving object – environment» or «environment – moving object»:

Therefore it is necessary to find out:

what interactions appear during the process of flow formation by the fan;

to determine the conditions when the fan passes into heat pump operation mode

to elaborate algorithm and programme for computer simulation of the fan operation as heat pump

Publications survey

Nowadays practically revolutionary situation has appeared in power engineering when intensive searches for new methods of energy obtaining and conversion started [3]. Conditions when complex system becomes open are realized during the heat pumps operation. In [4] it is shown that while operation of heat pump the environment is an active medium. Let us consider fan operation as open system, used for cooling different heating elements in complex power system.

Main part

Let us consider the interaction of air flow with the blades of the fan. We will present the blades of the fan in the form of one fourth of ellipsoid surface with large half-axle a and minor half-axle b. Large half-axle with radius r_0 composes angle α. Axis X is directed along half-axle a, and axis Y – along half-axle b. Start of counting we will locate at distance r_0 from rotation axis.

In such arrangement, as shown in Fig. 1, air will be drawn from the environment into vacuum zone with sound velocity

$$\bar{v} = \sqrt{\kappa \frac{P}{\rho}}, \tag{1}$$

where κ – is relation of heat capacities at constant pressure and constant volume, P – is the pressure in the environment ρ – is air density.

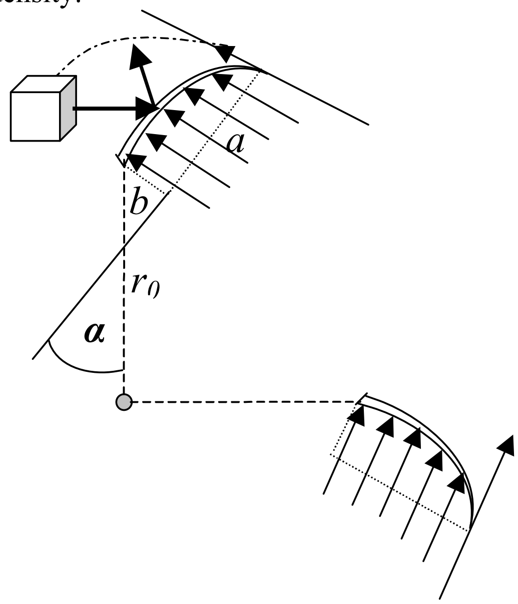

Fig. 1. Blades profile and their arrangement

At sound velocity $\bar{v}$, each module of air will collide with clusters, formed by crystal state of the substance, blades of the fan are made of. Share of energy, that will be transformed, in case of resilient interaction, form the molecule of air to the cluster of fan blade, taking into account connection energy, in first approximation is [6]:

$$\Theta = \frac{8Mm_a}{(2M + m_a)^2}, \tag{2}$$

where M – is mass of cluster.

Each cluster takes the impacts of air molecules, the flux of which is formed in preset direction with sound velocity. In this case, conventional convective heat exchange is realized. Air, reflected from the blade is cooled to the value

$$\Delta T = T_\infty - \Theta \frac{m_a \bar{v}^2}{2k_B}. \tag{3}$$

Here T_∞ – is the temperature of ambient air.

It is important to define, under what angle fan blades should be placed to provide air cooling by total interacting plane of the blade, and such cooling will create maximum increase of the moment at rotation axle of the fan.

Approximate scheme of fan blade flow depending on rotation direction is shown in Fig. 2.

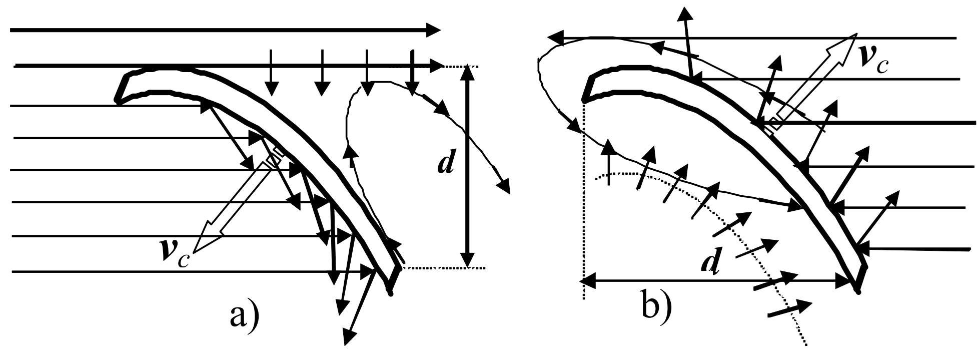

Fig. 2. Flow scheme of fan blade while its rotation:
a) in the direction of concave side and b) in the direction of convex side

When fan blades move by their concave side, they seem to capture the flow (Fig. 2. *a*).

The character of air molecules interaction while fan rotation in the direction of concave surface of the blade is shown if Fig 3. Direction of rotation is shown by the arrow. For concave surface at x distance along large half-axle the impact of molecules with the surface occurs under δ angle.

It follows from Fig. 3, that

$$\delta = \pi / 2 - (\alpha - \varphi);$$
$$\delta' = \alpha - \varphi, \tag{4}$$

and normal and tangential velocities equal correspondingly:

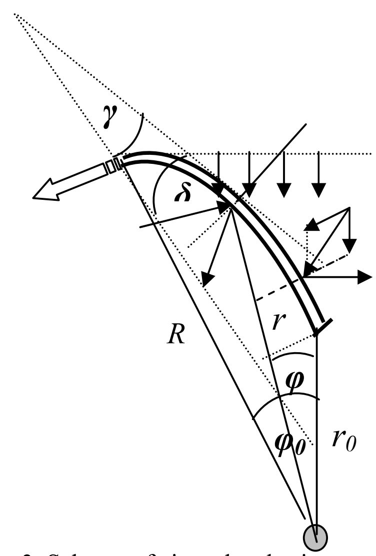

Fig. 3. Scheme of air molecules interaction
with fan blade while concave side rotation

$$v_n(x) = 2\pi rn\cos(\delta');$$
$$v_\tau(x) = 2\pi rn\sin(\delta'). \tag{5}$$

Force of action on dx element is defined by three components: impact of air molecules of normal components, centrifugal influence of tangential components and action of Bernoulli's law as a result of tangential motion of air along concave surface, Only the impact of air molecules should be overcome, and the energy must be spent on formation of air flow over the balance

If axle Z is directed along the blade by radius r_0, then, air mass during time dt starts to interact with width element of the blade dl of the following value :

$$dm = \rho_0 dldz \sin(\delta') v_B dt = 2\pi rn\rho_0 dxdzdt \frac{\sin(\delta')}{\cos(\gamma)} \tag{6}$$

Here: $dl = \sqrt{dx^2 + dy^2} = dx / \cos(\gamma)$, and angle γ is determined by the derivative from ellipsoid curve at a distance x along large half-axle of ellipse.

Time $dt = dl / v_\tau = dx / [2\pi rn \cos(\gamma)\sin(\delta')]$.

Taking into account (5) and (6) all three forces influencing the element of blade width *dl,* are perpendecular to the radius of fan rotation. The fan must overcame all these three forces, and they are equal:

$$\begin{aligned} dF_{spec} &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin(\delta')\cos^2(\delta')}{\cos(\gamma)}; \\ dF_C &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^2(\delta')\cos(\delta')}{\cos^2(\gamma)} \frac{dx}{r_{cur}}; \\ dF_B &= 2\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^3(\delta')}{\cos(\gamma)}. \end{aligned} \tag{7}$$

Here: $dl = \sqrt{dx^2 + dy^2} = dx / \cos(\gamma)$, and angle γ is determined by the derivative from ellipsoid curve at a distance x along large half-axle of ellipse.

Time $dt = dl / v_\tau = dx / [2\pi rn \cos(\gamma)\sin(\delta')]$.

Taking into account (5) and (6), all three forces influencing the element of blade width *dl,* are perpendicular to the radius of fan rotation. The fan must overcame all these three forces, and they are equal:

$$\begin{aligned} dF_{spec} &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin(\delta')\cos^2(\delta')}{\cos(\gamma)}; \\ dF_C &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^2(\delta')\cos(\delta')}{\cos^2(\gamma)} \frac{dx}{r_{cur}}; \\ dF_B &= 2\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^3(\delta')}{\cos(\gamma)}. \end{aligned} \tag{7}$$

Here r – is the radius of blade element form rotation axis equals:

$$r = \sqrt{[r_0 + c\cos(\alpha + arctg(b/a) - c\cos(\alpha + arctg(y(x)/(a-x))]^2 + c^2 \sin^2(\alpha + arctg(y(x)/(a-x))}$$

And in its turn $c = \sqrt{a^2 + b^2}$,

α – is the angle less than 45^0 of blade setting on the axle of fan rotation; $r_{cur.}$ – is radius of curvature of ellipsoid surface at a distance x along large half-axle *a,* determined from the equality of the derivative for ellipse and circumference

It follows that,

$$r_{cur} = \sqrt{a^4 / b^2 + (a^2 / b^2 - 1)x^2} . \tag{8}$$

The resultant force is double integral of the form

$$F_{con} = -\int_0^a \int_0^h (dF_{spec} + dF_C + dF_B) \frac{dx}{a} \frac{dz}{h} , \tag{9}$$

And resultant moment of forces:

$$M_{con} = -\int_0^a \int_0^h (dF_{spec} + dF_C + dF_B) r \frac{dx}{a} \frac{dz}{h}. \quad (10)$$

Temperature increase of the air as a result of impact action of fan blades occurs maximum at

$$\Delta T = \frac{m_a 4\pi^2 R^2 n^2}{6k_B}. \quad (11)$$

If R = 0,1 m and n = 100 Hz $\Delta T \sim 1{,}7$ K. Such temperature change of the flow can be neglected.

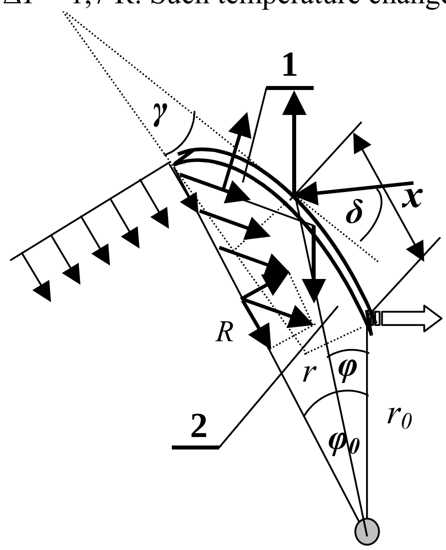

Fig. 4. Scheme of air molecules interaction with fan blade while convex side rotation

If the fan rotates in the direction of convex surface (Fig. 2 B) only one force counteracts motion, and the rest of forces that emerges as a result of fan rotation is directed in rotation direction. That is why energy consumption at the preset speed is drastically reduced especially if rotation speed of the fan increases.

The character of air molecules interaction while fan rotation in the direction of convex surface of the blade is shown in Fig 4.

. The direction of rotation is shown by the arrow. For convex surface at distance x along large half axle the impact of molecules against the surface occurs under the angle δ.

It follows from Fig. 4 that

$$\delta = \pi/2 - (\gamma + \varphi_0 - \varphi); \\ \delta' = \gamma + \varphi_0 - \varphi \quad , \quad (12)$$

normal and tangential speeds equal, correspondingly:

$$v_n(x) = 2\pi rn\cos(\delta'); \\ v_\tau(x) = 2\pi rn\sin(\delta'). \quad (13)$$

The force of impact on element dx is determined by three components : impact action of air molecules of normal component, centrifugal action of tangential component and the action of Bernoulli law due to tangential motion of the air along convex surface . Only impact action of air molecules must be overcome.

If axis Z is directed along the blade , then the air mass during time dt will start to interact with the element of blade width dl нас of the following value:

$$dm = \rho_0 dldz \sin(\delta')v_B dt = 2\pi rn\rho_0 dxdzdt \frac{\sin(\delta')}{\cos(\gamma)}. \tag{14}$$

Here $dl = \sqrt{dx^2 + dy^2} = dx/\cos(\gamma)$, and angle γ is determined by means of derivative of ellipsoid curve at the distance x along large half axle of the ellipse. Time $dt = dl/v_\tau = dx/[2\pi rn\cos(\gamma)\sin(\delta')]$.

Taking into account (13) and (14), all three forces ,acting on blade length element dl perpendicularly to fan rotation radius equal:

$$\begin{aligned} dF_{spec} &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^2(\delta')\cos(\delta')}{\cos(\gamma)}; \\ dF_C &= 4\pi^2 r^2 n^2 \rho_0 dxdz \frac{\sin^3(\delta')}{\cos^2(\gamma)} \frac{dx}{r_{cur}}; \\ dF_B &= 2\pi^2 r^2 n^3 \rho_0 dxdz \frac{\sin^3(\delta')}{\cos(\gamma)}. \end{aligned} \tag{15}$$

Resulting force represents double integral

$$F_{con} = \int_0^a \int_0^h (-dF_{spec} + dF_C + dF_B)\frac{dx}{a}\frac{dz}{h}, \tag{16}$$

And resultant moment of forces:

$$M_{con} = \int_0^a \int_0^h (-dF_{spec} + dF_C + dF_B) r \frac{dx}{a}\frac{dz}{h}. \tag{17}$$

Temperature increase of air due to the impact of fan blade will occur in accordance with (11) maximum on $\Delta T \sim 1{,}7$ K. Such variation of flow temperature can be neglected. Behind the concave side of fan blade only continuous flow emerges and interaction with the environment is rather complex process. Vacuum zone behind continuous flow is filled with the air in mutually perpendicular directions, as it is shown in Fig. 4, along the radius of rotation and perpendicularly to this radius of rotation, taking into account linear velocity of blade rotation. Angle, under which air flow is propagated, is determined by (34).

Proceeding form Fig. 4, filling of vacuum zone occurs in two different zones differently. Separation of the first and second zones, depending on rotation rate of the fan takes place at the distance $x_{cur.,1}$ and is defined by means of solution of non-linear equation:

$$arctg\left(\frac{b\sqrt{1-(a-x_{кр.,1})^2/a^2}}{(a-x_{кр.,1})}\right) = arctg\left(\frac{c\sin(\alpha + arctg(b/a))}{r_0 + c\cos(\alpha + arctg(b/a))}\right) + arctg\left(\frac{\bar{v} - 2\pi rn}{\bar{v}}\right) - \alpha. \tag{18}$$

Exact values, depending on fan rotation frequency are given in Table 1. The obtained values $x_{cur.1,}$ for the second zone is upper limit of integration.

In the first zone two flows with mutually opposite motion are met. As a result, hydrodynamic pressure equal $0{,}5\rho\bar{v}^2$=0,76 atm appears. In external side on allocated element of the surface the air moves with the speed

$$v_\tau = 2\pi rn\sin(\gamma + \varphi_0 - \varphi) \tag{19}$$

and creates hydrodynamic pressure $0{,}5\rho v_\tau^2$. The difference of these pressures determines the resultant moment and power correspondingly

$$N = \int_{x_{cur1}}^{a} \pi n \rho(\bar{v}^2 - v_\tau^2) r \frac{\cos(\gamma + \varphi_0 - \varphi)}{\cos(\gamma)} h dx \qquad (20)$$

In the second zone air molecules bombard the internal surface at the distance x along large half-axle a under the angle δ'', that equals:

$$\delta'' = \beta - \gamma; \quad \delta''' = \beta + \varphi_0 - \varphi - arctg\left(\frac{b\sqrt{1 - x^2 / a^2}}{a - x}\right). \qquad (21)$$

Normal and tangent speed of impact of air molecules against concave surface of fan blade are determined as:

$$v_n = \bar{v}\sin(\delta''); \quad v_\tau = \bar{v}\cos(\delta''). \qquad (22)$$

The mass acts on length element of ellipsoid surface of the blade dl

$$\Delta m = \rho dl dz \bar{v} \sin(\delta'') dt, \qquad (23)$$

where $dt = dl / v_\tau = dl / \bar{v}\cos(\delta'')$.

Proceeding from (21) – (23) impact forces on length element are expressed as:

$$\begin{aligned} \Delta F_{spec} &= \rho dx dz \bar{v}^2 \frac{\sin^2(\delta'')\cos(\delta''')}{\cos(\gamma)}; \\ \Delta F_C &= \rho dx^2 dz \bar{v}^2 \sin(\delta'')\cos(\delta'')\cos(\delta''') / [\cos^2(\gamma) r_{cur}]; \\ \Delta F_B &= \rho dx dz \bar{v}^2 \cos^2(\delta'') cos(\delta''') / \cos(\gamma). \end{aligned} \qquad (24)$$

The resultant force is perpendicular to rotation radius

$$F_{res.} = \int_0^{x_{cur}} \int_0^h (\Delta F_{spec} + \Delta F + \Delta F) \frac{dx dz}{ah}, \qquad (25)$$

And moment of force :

$$M_{res2} = \int_0^{x_{cur}} \int_0^h (\Delta F_{spec} + \Delta F + \Delta F) r \frac{dx dz}{ah}. \qquad (26)$$

Power corresponds to such moment of force:

$$N_2 = 2\pi n M_{res2}. \qquad (27)$$

Air flow, rejected by the fan, is cooled on average, by:

$$\Delta T = \int_0^{x_{cur}} \frac{\Theta m_a (\bar{v} - 2\pi r n)^2}{2k_B} \frac{dx}{a} \qquad (28)$$

The time of complete filling of vacuum zone in continuous flow:

$$t_{fil.} = \frac{c\, cos(\alpha + \eta)}{\bar{v}}, \qquad (29)$$

where angle $\eta = arctg(b/a)$; $R = \sqrt{[r_0 + c\cos(\alpha + \eta)]^2 + c^2 \sin^2(\alpha + \eta)}$ – is radius of rejected surface by the blades and r_0 – is radius of fan circle.

During time $t_{fil.}$ the blade of the fan will shift by the angle

$$\varphi_0 = 2\pi n t_{fil.}. \qquad (30)$$

Here n – is the frequency of fan rotation.

At the set speed of fan rotation during time t the blade will shift at the angle φ. If angle φ is less than angle φ_0, then continuous flow is created at a certain distance x from the edge of the blade. This distance can be found by means of solution of non-linear equation:

$$\frac{1}{2\pi n} arctg\left(\frac{c\, sin(\alpha+\eta) - c_1\, sin(\alpha+\eta')}{r_0 + c\, cos(\alpha+\eta) - c_1\, cos(\alpha+\eta')} \right) = t_{fil.}, \tag{31}$$

where $c_1 = \sqrt{x^2 + b^2(1 - x^2/a^2)}$ і $\eta' = arctg\left(b\sqrt{1 - x^2/a^2}\,/(a-x)\right)$.

Let us carry out computations for fan blades, made of aluminum in the form of ellipsoidal surface, dimensions of large half-axle being a = 5 cm, small half-axle b = 2 cm and radius of the circle r_0 = 5 cm. The radius of the surface at the angle of inclination of large half-axle relatively rotation radius $\alpha = 32^0$ equals 9,265 cm.

Aluminum cluster is a simple cubic structure, consisting of seven tree-atom molecules Al_3, that corresponds to facet-centered structure of aluminum crystal. That is why the mass of aluminum cluster equals $21 m_a m_0 = 21 \cdot 26{,}98 \cdot 1{,}66 \cdot 10^{-27} = 9{,}41 \cdot 10^{-24}$ kg (m_a – is atomic weight of aluminum, and m_0 – is the mass of one unit of atomic weight. At elastic collision of air molecules with aluminum cluster the share of transferred energy equals $\Theta = 0{,}097$.

Zone of continuous flow is formed behind the convex part of fan blade. Completely the zone of continuous flow is formed during the time, defined by the equation (29). It equals $9{,}2 \cdot 10^{-5}$ sec. Critical rotation frequency 844 Hz corresponds to this time. Fan blades must rotate with supersonic speed, completely continuous flow to be created behind the fan. Inn case of subsonic speeds of rotation continuous flow will be created, but only in small area. This area is determined by means of solution of non-linear equation (31). Table 1 contains distances at which continuous flow emerges at various rotation speeds.

Table 1

Location of the point of flow breakdown at large half-axle depending on rotation frequency

Parameters	Rotation frequency, Hz							
	30	50	60	75	100	200	300	400
$\varphi_{0,}$ degree.	1,00	1,66	2,00	2,49	3,33	6,65	9,98	13,30
X_{cur}, cm	0,92	1,01	1,06	1,12	1,23	1,66	2,12	2,63
X_{cur1}, cm	2,95	2,84	2,79	2,70	2,55	1,84	0,97	0

It follows form Table 1, that at small rotation speeds continuous flow is created in the proximity of axle part of the blade. Laminar flow is performed before the point of breakdown. Flow speed is stipulated only by rotation speed of the fan. In this case impact mechanism of interaction is absent. Only centrifugal forces and forces, emerging as a result of pressure reduction in accordance with Bernoulli law are realized. These forces, acting on blade length element dl equal:

$$\begin{aligned} \Delta F_C &= 2\rho\pi^2 r^2 n^2 (R-r)(\varphi_0 - \varphi)dxdz \frac{cos(\delta)}{cos(\gamma)} \frac{1}{r_{cur.}}; \\ \Delta F_B &= 2\rho\pi^2 r^2 n^2 (R-r)(\varphi_0 - \varphi)dxz \frac{cos(\delta)}{cos(\gamma)} \end{aligned}, \tag{32}$$

where r – is radius of point x rotation on large half-axle a, φ_0 – is the angle, overlapped along the are of continuous surface, angle $\delta = \alpha + \varphi_0 - \varphi$. These forces create rotation moment, opposite to rotation direction of the fan, that equals:

$$M = \int_{x_{cur}}^{a} -(\Delta F_C + \Delta F_B) r \frac{dx}{a}. \tag{33}$$

Vacuum, created in continuous flow is filled with the air in mutually perpendicular directions, as it is shown in Fig. 4, along the rotation radius and perpendicularly to rotation radius, taking into account linear rotation speed of the blade. Angle, under which air flow propagates, equals:

$$\beta = arctg\left(\frac{\bar{v} - 2\pi rn}{\bar{v}}\right) \quad (34)$$

Air molecules bombard external surface at the distance x along large half-axle a, under the angle that equals:

$$\delta = \pi / 2 - \delta'; \ \delta' = (\alpha + \beta - \varphi) \,. \quad (35)$$

Normal and tangential speeds of air molecules impact against concave surface of fan blade equal:

$$v_n = \bar{v}\sin(\delta'); \quad v_\tau = \bar{v}\cos(\delta') \,. \quad (36)$$

Mass acts on the element of ellipsoid surface length dl of the blade

$$\Delta m = \rho dldz\bar{v}\cos(\delta')dt \,, \quad (37)$$

where $dt = dl / v_\tau = dl / \bar{v}\cos(\delta')$.

Proceeding from (34) – (37) forces of action on length element will have the following expression:

$$\begin{aligned} &\Delta F_{spec.} = \rho dxdz\bar{v}^2 \frac{sin(\delta')cos^2(\delta')}{cos(\gamma)}; \\ &\Delta F_C = \rho dx^2 dz\bar{v}^2 \, sin^2(\delta')cos(\delta')/[cos^2(\gamma)r_{кр.}]; \\ &\Delta F_B = \rho dxdz\bar{v}^2 \, sin^3(\delta')/cos(\gamma). \end{aligned} \quad (38)$$

The resulting force is perpendicular to rotation radius

$$F_{res} = \int_0^{x_{cur}}\int_0^h (\Delta F_{spec} - \Delta F - \Delta F)\frac{dxdz}{ah} \,, \quad (39)$$

and moment of force:

$$M_{res} = \int_0^{x_{cur}}\int_0^h (\Delta F_{spec} - \Delta F - \Delta F) r \frac{dxdz}{ah} \quad (40)$$

Power, consumed by the fan, in accordance with (40) equals:

$$N_1 = 2\pi n M_{res} \,. \quad (41)$$

Power, consumed by the fan, depending on the frequency of rotation, in accordance with general definition, must depend proportionally to the third power of rotation frequency. In reality, this dependence is proportional approximately 3/2 and it decreases with the rotation speed increase and changes into linear dependence. This is the result of the impact of numerous forces on the blades of fan. These forces emerge as a result of their interaction with the environment. Consumption power slightly reduces with the increase of fan stages.

The fan rejects the air perpendicularly to the plane of the rotation. Each blade of the fan forms the speed of air stream rate:

$$\dot{Q} = \int_0^a (\bar{v} - 2\pi rn)(1 - \sqrt{\Theta})\frac{dx}{a} \,. \quad (42)$$

With the increase of the rotation rate , the speed of rejected air drops almost according to linear law. Maximum rate of rejected air occurs at small rates of fan rotation, that is why, systems, operating in fan mode, function at small rates of their rotation. If such systems are used as vortex thermal pump, then the efficiency of their application

$$\eta = \frac{\dot{Q}^3 + 2\dot{Q}R_{\Gamma}\Delta T / m_a}{\bar{v}^3} \ . \qquad (43)$$

Here, R_{Γ} = 8,3144 J/m,·K – universal gas constant.

At rotation rate 10 Hz transformation factor is 2,10% and at 100 Hz – it is 1,36%. At such transformation factors, it is not expedient to use the fan as heat pump. That is why, fans in automobiles are widely used for cooling the body of operating internal combustion engine.

Conclusions

General scheme of fan operation is developed, method of transformation factor of such an open system determination is substantiated. Types of interactions emerging in the process of air stream formation, have been revealed. Conditions when the fan switches to heat pump mode operation have been determined. Algorithm and programming tools required for modeling of fan operation as heat pump have been elaborated.

REFERENCES

1. Гречихин Л. И. Аэродинамика малоразмерного БЛА / Л. И. Гречихин, Д. А. Сахарук, А. Б. Сивашко // Proceedings 4th International Conference on SAUAV-2010. – 2010. – P. 39.

2. Гацукевич А. С. Работа турбин в качестве теплового насоса // А. С. Гацукевич, Л. И. Гречихин Гражданская авиация XX1 век: Сб. материалов 1 Международной молодежной научной конференции 23 – 24 апреля 2009 г. – Ульяновск: УВАУ ГА – 2009 – С. 9 – 10.

3. Гречихин Л. И. Современная энергетика. Пути и методы развития и применение на транспорте / Л. И. Гречихин, Куць Н. // Наукові нотатки. – 2010. – Вып. 28 (май 2010) – С. 162 – 165.

4. Гречихин Л. И. Получение и преобразование энергии в открытых системах / Л. И. Гречихин // Энергетика. – 2004. – № 4. – С. 76 – 81.

5. Плешивцев Н. В. Физика воздействия ионных пучков на материалы / Н. В. Плешивцев, А. И. Бажин – М.: Вузовская книга, 1998. – 392 с.

6. Стасенко А. Л. Физические основы полета / А. Л. Стасенко – М.: Бюро квантум, 2005. – 256 с.

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