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Application of Reynolds Analogy During Study of Heat Exchange of Symmetric Airfoil NASA-0021

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Abstract: This study presents the results of experimental and theoretical study of airfoil NASA-0021 heat exchange used as a cover blade and strokes of Darrieus rotor. Channels heat dissipation into the environment is defined as an internal hydrodynamics of channels of various forms as well as the external conditions of heat exchange.

Key words: Wind energy, NASA-0021, warm air, Reynolds number, heat exchange, heat transfer, heat dissipation, blade

INTRODUCTION

If to defer to the opinion of world experts in wind power it may be said that one of the important problems is icing of wind turbine blades during blizzard and frost.

Harsh winters are so peculiar to Nordic countries, create a very serious problem blades icing. As a result the capability of wind-driven power plant is lost. Due to the ice formation on the blades the aerodynamics of the blade is worsening and if the ice thickness exceeds a critical value you have to turn off over and over again. The Swedish statistical database of accidents contains overall 1337 records of such shutdown occurred between 1998 and 2003 as a result, in general, 161.523 h of downtime. About 92 accidents (7%) were due to the cold climate and as a result of 8022 h (5%) loss of production. Reports on low temperature downtime in a cold climate were 669 h (8%), although due to the cases of icing were 7353 (92%). Downtime is reported due to icing in Finland in the period from 1996-2001 were 1208/495/196/581/739 and 4230 h for the 19/21/29/38/61 and 61 turbines, respectively (Jasinski *et al*., 1998).

The variety of methods developed by experts in alternative energy resource and air flying machine is offered all over the world to solve this problem. Most of these methods have been taken from the aircraft industry and can be divided into two categories: active and passive. Passive methods are based on the physical properties of the blade for preventing ice accumulation while active methods based on external system applied to the blade. Two types of systems can be used to prevent icing in particular this is purging against icing and preventing icing. The first removes the ice from the surface after its formation, whereas the latter prevents early ice formation.

The methods of active protection for operation demand energy supply and include thermal, chemical and pneumatic methods and act as the systems for purging of ice or anti-ice (Laakso *et al*., 2003).

In this regard, in our opinion an absolute method of keeping the operating wind power unit is offered. This method uses self-ventilation of flowing elements of wind turbine by warm air which prevents wet snow accretion over the surface of machine and ice formation (Dalili *et al*., 2009).

Darrieus rotor turbine operates due to the occurrence of the lifting force on cover blades equidistant from a common axis. Stroke and cover blades are the channels in the form of symmetrical airfoil.

MATERIALS AND METHODS

Experimental part: Knowing the average expandable inner cavity speed of different forms and application it is possible to define heat transfer rate by experimental way. For this purpose an experimental stand has been prepared for study of heat exchange NASA-0021 airfoil with air flow leak at different speed and angle of attack. In other words, the heat transfer rate of symmetrical airfoil NASA-0021 (used as strokes and cover blades of wind turbine Darrieus) was determined when purging its internal cavity by heated air.

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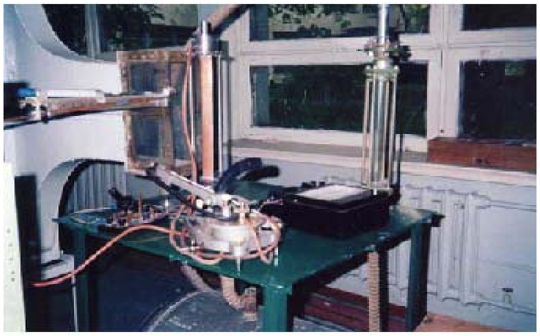

Fig. 1: Picture of the experimental unit

The installation consisted of experimental metal table on which study subject element of airfoil NASA-0021 was fixed (Fig. 1). Experimental table had a rotating mechanism on a horizontal surface allowing installing the wing element at any angle to the leaking air flow on it from the outlet of the wind tunnel.

Constructed experimental table was placed below the open operating site of the wind tunnel so as to provide air flow leakage only to the object under study. All measurements were made in an open operating site of wind tunnel with a rectangular output in front of which the element of airfoil to be studied is installed.

The heated air flowed through the inner cavity of airfoil element from muffle furnace at its four values of the flow (0.00103, 0.00153, 0.00203, 0,00253 m^3/sec). In order to determine heattransfer rate the heated air flow, the temperature difference between inlet and outlet of the wing cavity as well as the temperature of air stream flowing to the wing element from wind turbine with different speed ($4<U<36.67$M/C) and angle at various wing moves ($\varphi = 0°\div16°$) relative to flow direction were measured.

The experiment consisted of two large series of studies of heat exchange conformity with the environment of airfoil NASA-0021, heated inside by flowed warm air at four of its flows. In total more than 600 experiments were conducted 400 of which were processed (10 values of angle of attack (φ = 0°, ±4°, ±8°, ±12°, ±16°) where sign "+" is wing rotation relative to flow of wind tunnel at one way and sign "-" at another one). At nominal rotation of turbine Darrieus ($3.5\leq\chi\leq5.5$) angle of attack cannot exceed $\varphi = 16°$ under no position of cover blades (Eq. 1):

$$\mathrm{tg}\varphi = \frac{\sin\theta}{\chi+\cos\theta} \tag{1}$$

Under constant value of each of the mentioned angles of attack, measurements were made at 10 values of attack rate (V = 4, 8, 12, 16, 20, 24, 28, 32, 36 and 38 m/sec), however, at continuity of φ and V, warm air flow Q has changed four times. In each of 400 experiments the following were measured: warm air flow rate through the tested channel, its inlet T_0 and outlet T_1 temperature, flow temperature from wind tunnel T_∞ and barometric pressure P_{atm}. In both experiments, at $+\varphi$ as well as $-\varphi$ their arithmetic mean values were included in the process.

All this experimental data should be analyzed and organized, prepared to generalize for quantitative identification of conformity of specific channel heat dissipation under specific conditions the interaction with the environment. These laws of study of heat-mass exchange based on the theory of dimension and similarity of heat exchange process (Marchevskiy, 2008; Kirpichev *et al*., 1940) that allows to pass from a sample to a real object. Heat transfer from airfoil NASA-0021, heated inside by flowed warm air is described by Eq. 2 and 3:

$$q_{wv} = \alpha_{wv} F_{1v} (T - T_{wv}) \tag{2}$$

$$q_{wn} = \alpha_{wn} F_{2n} (T_{wn} - T_\infty) \tag{3}$$

Where:
v = Index refers to inner problem
n = Exterior and $q_1 = q_2$

Equation 2 and 3 are specific heat amount q_{wv} and q_{wn}, passed through unit area of blade surface, since, T, T_{wv}, T_{wn} function of $\bar{z}$ and differ from each other by a constant value. Total amount of heat released by blade into environment can be found by Eq. 2 and 3 through $\bar{z}$:

$$q_{wv} = \alpha_{wv} F_v \int_0^1 (T - T_{wv}) d\bar{z} = \alpha_{wv} F_v (T - T_{wv}) = q_1 = q_0$$
$$q_{wn} = \alpha_{wn} F_n (\bar{T}_w - \bar{T}_\infty) = q_2 = q_0 \tag{4}$$

Further, we will operate values of $\bar{T}$ and $\bar{T}_W$ in certain cases. If they are known then it is easy to determine T_{w0} and T_{w1}. Equation 2 and 3 do not allow finding values of three unknowns α_B, α_H, T_w. Therefore, these two equations must be supplemented by another equation or condition. Such a condition can be obtained if we use Reynolds analogy (Eq. 2), accepting as specified by Kirpichev *et al.* (1940), hypothesis of an immaterial impact of viscous sublayer during the turbulent flow over the plate. Then the expression (Eq. 2) takes the form:

$$q_{wn}(x) = \tau_{wn}(x)\, Cp \frac{T_w - T_\infty}{\mu_\infty} \tag{5}$$

Although, Reynolds analogy was developed for the case of longitudinal flow of smooth plate surface (exterior problem), it (the analogy) applicable to turbulent liquid flow in the channel (inner problem). The total amount of heat transferred from the channel is equal to friction stress at plane smooth wall and on the inner surface of the channel, relatively, denoted through τ_{wn} and τ_{wv}:

$$q_{wn} = \tau_{wv} Cp \frac{T - T_w}{\mu_{cp}} \quad (6)$$

Due to the flow without separation of airfoil NASA-0021 turbulent flow in a narrow range of angle of attack can be considered a process of heat exchange, subject to the dependence (Eq. 5) by directing the coordinate "x" along the perimeter of the wing:

$$q_{wn}(F) = \tau_{wv} Cp \frac{T_w - T_\infty}{v} \quad (7)$$

where, F = Wetted perimeter of airfoil. On the basis of equations $q_{wv} = q_{wn}$ as well as (Eq. 7) it can be written:

$$\frac{\tau v}{\mu_{cp}} = (T - T_w) = \frac{\tau n}{v}(T_w - T_\infty)\, q_1 = q_2 \quad (8)$$

where, indexes v and n represents values, related to the inner and exterior problems $\tau_{wv} = \tau_w = \tau_v$ and $\tau_{wn} = \tau_w(\Phi) = \tau_n$, respectively $q_{wv} = q_v$ and $q_{wn} = q_n$.

Since, $T(\overline{Z})$ and $T_w(\overline{Z})$, here, q_1 and q_2 specific heat amount per blade length unit. The total amount of heat released by the blade into the environment is found by integrating the last equation. As a result, we obtain:

$$\frac{\tau v}{\mu_{cp}} = (T - T_w) = \frac{\tau n}{v}(T_w - T_\infty)\, q_1 = q_2 \quad (9)$$

That allows to find $\overline{T}w$:

$$\overline{T}_w = \frac{T + \frac{\tau_n \mu_{cp}}{\tau_v V} T_\infty}{1 + \frac{\tau_n \mu_{cp}}{\tau_v V}} = \frac{\overline{T} + \Omega T_\infty}{1 + \Omega} \quad (10)$$

As shown by Kirpichev *et al.* (1940) at longitudinal flow of smooth plate for numbers Rex = u∞x/v to 107 (in this case, $Re_x = Re_v = V\Phi/v$) the following dependency is valid:

$$\tau n = 0.0296 Re_v^{-0.2} \rho V^2 \quad (11)$$

Under steady-state conditions the liquid pushing force is equal to the force of viscous resistance due to fluid friction on the walls of the channel, i.e.:

$$(P_1 - P_2)S = \tau_v F = \tau_v \Phi l \quad (12)$$

On the other hand:

$$\frac{P_1 - P_2}{l} = \frac{\zeta}{d}\frac{\rho u_{cp}^2}{2} = \frac{\zeta\Phi}{4S}\frac{\rho u_{cp}^2}{2} \quad (13)$$

We reduce Eq. 12 to the form:

$$\frac{P_1 - P_2}{l} = \frac{\tau_6 \Phi}{S} \quad (14)$$

Therefore, equating the left-hand sides (Eq. 13 and 14), we obtain:

$$\zeta = \frac{8\tau_v}{\rho u_{cp}^2} \text{ or } \tau_v = \frac{\zeta}{8}\rho u_{cp}^2 \quad (15)$$

where, ξ = In this case has formed into $\xi = 4.62Re^{-0.488}$. In the result we will have:

$$\frac{\tau_n}{\tau_v} = \frac{0.2368}{\zeta} Re_v^{-0.2}\ \rho V^2 = \frac{0.2368}{4.62} Re_v^{-0.2}\ Re_u^{0.488}\ \frac{V^2}{u_{cp}^2} \quad (16)$$

Let's reduce to the form:

$$\frac{u_{cp}}{V} = \frac{Re_u}{Re_v}\frac{\Phi}{d_э} \quad (17)$$

Therefore, model:

$$\Omega = \frac{\tau_n}{\tau_v}\frac{u_{cp}}{V} = 0.05126\frac{V}{u_{cp}} Re_v^{-0.2}$$
$$Re_u^{0.488} = 0.0128\frac{d_э^2}{S}\frac{Re_v^{0.8}}{Re_u^{0.512}} \quad (18)$$

Using the experimental data, the experimental values of the Nusselt number for the exterior problem ($Nu_n = \alpha_n\Phi/\lambda$) can be determine on the basis of Eq. 4:

$$\alpha_n = \frac{q0}{F_n(\overline{T}_w - T_\infty)}$$

where, $\overline{T}_W$ is determined from dependency Eq. 10 and 18. Therefore:

$$Nu_n = \frac{2q_0}{\lambda l} \frac{\left(1+0.5126\frac{VS}{Q}Re_v^{-0.2}\ Re_u^{0.488}\right)}{T_0+T_1-2T_\infty}$$

Due to parallel changes of T and T_w along the channel length, we will have $T-T_w = \bar{T}-\bar{T}_w = k$ where "k" constant value known in each experiment. This makes it possible to determine the temperature of the channel wall at its inlet t_{w0} and outlet T_{w1} by Eq. 19:

$$\left.\begin{aligned} T_{w0} &= \frac{T_0-T_1}{2}+\bar{T} \\ T_{w1} &= \bar{T}_w-\frac{T_0-T_1}{2} \end{aligned}\right\} \quad (19)$$

Theory of heat and mass exchange is based on the theory of dimensions and similarities (Kirpichev *et al*., 1940; Gukhman, 1973; Yershina and Manatbayev, 2006). Therefore, it is reasonable that to set a dependency criteria Nu_n from Re_V and Re_u where, $Nu_n = \alpha_n\Phi/\lambda$ determines heat dissipation from the side surface of airfoil element NASA-0021 external flow. For this purpose, we use Eq. 19, writing down as:

$$q_0 = q_2 = \alpha_n F\left(\bar{T}_w-T_\infty\right) = \frac{\lambda\Phi Re_u\left(T_0-T_1\right)}{4}$$

Or:

$$\alpha_n = \frac{\rho u_{cp} SCp\left(T_0-T_1\right)}{F\left(\bar{T}_w-T_\infty\right)} \quad (20)$$

Furthermore, it is implied from Eq. 10 and 18:

$$\bar{T}_w-T_\infty = \frac{1}{2}\frac{T_0+T_1-2T_\infty}{1+\Omega} \quad (21)$$

Taking into account that when $Pr\approx1$ $Cp = \lambda/\mu$ after little changes from Eq. 19-21, we shall get:

$$\begin{aligned} Nu_n &= \frac{\alpha_n\Phi}{\lambda} = \frac{T_0-T_1}{T_0-T_1-2T_\infty} \\ &\frac{\Phi Re_u+0.0128d_э\ Re_v^{0.8}\ Re_u^{0.488}}{21} \end{aligned} \quad (22)$$

Basically heat dissipation rate can be a function of temperature and Eq. 22 allows to determine criteria volume Nu_n for samples of experimental data in which T_0 and T_1 were measured. In field experiment during engineering analysis there are no such data. The problem consists in finding T_0, setting T_1, for example, outlet at the end of cover blades (Dalili *et al*., 2009), i.e., to find out what should be the temperature of the inlet channel, so that at the outlet the temperature will be at a desired level for thermal protection of a machine. It is not difficult to understand that value $\bar{T} = \frac{T_0-T_1}{T_0+T_1-2T_\infty}$ is determined by warm air flow conditions in the channel. Therefore, the value of T* was calculated by involving all the experimental data, the results of which are shown in Table 1.

Table 1: The value of T^* was calculated by involving all the experimental data

V	Q $m^3/sec\times10^3$	Re_u	T_0-T_1	$T_0+T_1-2T\infty$	$(T_0-T_1)/(T_0+T_1-2T\infty)$
4 m/sec					
1	103	3840	28.24	31.590	0.8940
2	153	5707	26.04	32.455	0.8300
3	203	7574	24.66	33.380	0.7357
4	253	9442	23.74	33.520	0.7081
8 m/sec					
1	103	3840	30.05	56.95	0.5276
2	153	5707	28.23	59.16	0.4770
3	203	7574	27.37	61.41	0.4456
4	253	9442	25.80	63.70	0.4050
12 m/sec					
1	103	3840	30.11	58.95	0.5108
2	153	5707	27.62	60.79	0.4543
3	203	7574	27.06	62.67	0.4318
4	253	9442	26.31	62.92	0.4182
16 m/sec					
1	103	3840	30.31	56.47	0.5367
2	153	5707	28.74	58.00	0.4955
3	203	7574	28.36	60.75	0.4668
4	253	9442	27.20	64.60	0.4210
20 m/sec					
1	103	3840	29.43	55.70	0.5284
2	153	5707	27.57	60.04	0.4592
3	203	7574	27.36	58.85	0.4649
4	253	9442	26.22	58.84	0.4457
24 m/sec					
1	103	3840	29.40	54.90	0.536
2	153	5707	28.60	55.30	0.517
3	203	7574	28.16	56.30	0.500
4	253	9442	27.83	61.10	0.455
28 m/sec					
1	103	3840	31.20	56.68	0.550
2	153	5707	29.93	57.80	0.518
3	203	7574	29.58	60.00	0.493
4	253	9442	26.94	61.00	0.442
32 m/sec					
1	103	3840	30.17	52.67	0.573
2	153	5707	28.76	54.00	0.533
3	203	7574	28.04	56.10	0.500
4	253	9442	27.96	60.00	0.466
36 m/sec					
1	103	3840	30.30	54.80	0.550
2	153	5707	27.79	56.72	0.490
3	203	7574	27.62	61.05	0.450
4	253	9442	27.26	63.78	0.430
38 m/sec					
1	103	3840	30.92	61.94	0.4992
2	153	5707	29.24	59.58	0.4908
3	203	7574	28.03	58.30	0.4808
4	253	9442	28.18	57.60	0.4893

As may be inferred from table 1, $\bar{T}^*$ at all values attack speed V differ from each other no more than 10-12% and only at V = 4 m/sec maximum difference may amount to 45%, although in all cases for small deviations from the growth of Q $\bar{T}^*$ is decreased. Therefore for engineering computation, it is recommended to take arithmetic mean value of $\bar{T}^*$ for each warm air flow which is

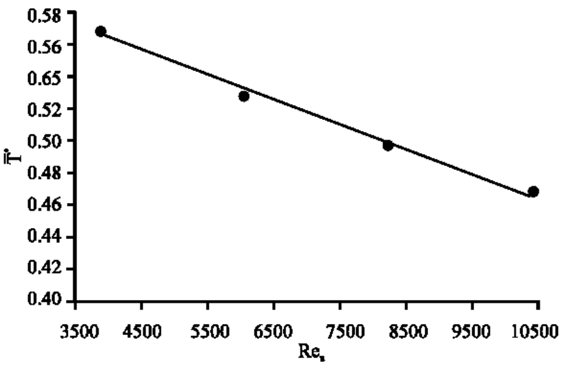

Fig. 2: Graph of variance of $\overline{T}^*$ from Re_u

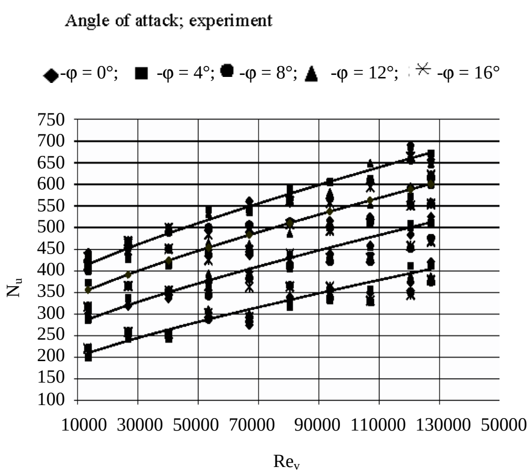

Fig. 3: Graphic display of Eq. 23 for all studies of channel heat exchange behavior with the form of airfoil NASA-0021; Warm air flow rate: 1-Q_1 = 0.00103 m^3/sec, 2-Q_2 = 0.00153 m^3/sec, 3-Q_3 = 0.00203 m^3/sec, 4-Q_4 = 0.00253 m^3/sec

shown as $\overline{T}^*$ (Table 1). Figure 2 shows a graph of variance of $\overline{T}^*$ from Re_u. This dependence has a linear character:

$$\frac{T_0-T_1}{T_0+T_1-2T_\infty} = 0.638-1.8\times10^{-5}\,Re_u \qquad (23)$$

By substituting Eq. 23 into 22, we finally obtain:

$$Nu_n = \left(0.32-9\times10^{-6}\,Re_u\right)\frac{Fre_u+0.0128d_э\,Re_v^{0.8}\;Re_u^{0.488}}{1} \qquad (24)$$

Figure 3 presents graphic display of Eq. 24 for all studies of channel heat exchange behavior with the form of airfoil NASA-0021 on the below described sample.

CONCLUSION

The obtained criteria dependence is valid for all cases of heat dissipation of airfoil NASA-0021 in incoming flow if its inner cavity through which the warm air flows, also has a form of NASA-0021. Herewith airfoil may be made of any material and has a certain wall thickness which should be considered as a flat plate of Δ thickness.

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