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GENERALIZED CORRELATIONS FOR HEAT TRANSFER DETERMINATION IN TURBINE CASCADES

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ABSTRACT

In developing new designs of steam and gas turbines, and when defining their flow part, it is necessary to perform a large number of various calculations. Among others, these include also the calculation of heat transfer between working fluid and blades of stator and rotor cascades (e.g. due to determining the efficiency of energy conversion i.e. losses in turbine stage, efficiency of the cooling systems of cooled stator and rotor blades, temperature fields i.e. state of temperature stresses and deformations of flow part elements, etc.). For these calculations it is necessary to know either the local or the average values of the convective heat transfer coefficients, depending on the accuracy of calculations.

In general, the convective heat transfer coefficients can be determined on the basis of experimentally obtained dependencies (correlations), then by analytical methods and at present by numerical methods as well. At subsonic flow of the working fluid the system of differential equations which describes the flow of working fluid in channels between blades allows separate calculation of real flow in cascade which provides the fields of velocity and pressure round the profile contour, and then determination of the heat transfer and losses based on calculation of the thermal and hydraulic boundary layers. However, even in this simple case of gradient flow around surface the calculation of boundary layer is accompanied by a series of difficulties and complexities. As the result of the present intensive progress in computers and information technology series commercial users' software for heat transfer calculation on turbine blades have been developed. It needs to be mentioned that with the aim of validating the accuracy of calculation results, these programs also require experimental checking. For these reasons the tendency is still that in the engineering practice the average convective heat transfer coefficients are calculated by using simple exponential equations obtained on the basis of experimental investigations, often without checking the possibility of their application in the individual case. Particularly, when high accuracy of calculations is not a requirement. Concretely, in calculating heat transfer in the flow part of steam and gas turbines this is indicated by the tendency to use the average value of convective heat transfer coefficients h_{av} in calculations, which can be determined by experimental dependencies of type $Nu_{av}=cRe^n$.

These correlations obtained under different conditions of experiments with various profiles cascades and in different ranges of Reynolds number change, are mutually distinguished by values of factor c and exponent n, so that calculations often give essentially different values. The differences in values of the exponent above Reynolds number indicate different lengths of the laminar, turbulent and transient boundary layers on the investigated blades, or the separation of the flow. Evidently, the character of the Nusselt number dependence is first of all determined by the flow characteristics around profiles. The variability of the factor c is caused by selection of characteristic quantities (dimension, temperature, velocity of the flow around profiles). Sometimes, the additional factors are introduced in correlations, which estimate the influence on the heat transfer of the cascade geometry and the flow conditions.

All the mentioned facts complicate practical usage of numerous correlations obtained on the basis of single experiments, and therefore in the work [Guzović, 1998] they have been first systematized and then the systematized correlations have been statistically analyzed. The obtained original generalized statistics correlations allow simpler and faster determination of the average convective heat transfer coefficients in turbo-machinery cascades, with accuracy acceptable for engineering applications. This paper presents both the results of the mentioned systematization and the original generalized statistics correlations.

CHARACTERISTICS OF EXPERIMENTAL INVESTIGATIONS AND SINGLE CORRELATIONS

The average value of convective heat transfer coefficients around profile contour is determined in a large number of experimental investigations. The majority of experiments was carried out on plane cascades (two-dimensional) which consisted of 3 to 7 real or model blades; the heat transfer was less often investigated on the annular cascades (three-dimensional) or on the segments of annular cascades. In literature therefore, there is a large number of correlations for calculating average heat transfer coefficients, proposed by different authors, with calculation results which may differ from one another even by 100%. This can be explained by non-satisfying of geometrical similarity in investigating profile cascades, by characteristics of development of boundary layers on profiles in cascades, by different experimental conditions (the level of turbulence, the value of temperature factor, etc.).

The experiments were performed both with direct (heat transfer from fluid to profile), and indirect (heat transfer from profile to fluid) direction of the heat flow. In the former case the blades are flowed around by hot gases and cooled on the inside by water or air; and in the latter case, the blades are flowed around by cold air and heated from the inside by steam, electric heater or have on the outer surface electric heaters in the form of a band, arranged along the profile contour.

The heat flux on the blade surfaces has been determined either on the basis of heater electric power (with electrical heating of blade), or on the basis of heat change of steam, water or air, which flow through the channels in the body of the blade thus heating or cooling it.

The values of heat transfer coefficients are determined according to the difference between the stagnation temperature of gas in the channel and the surface temperature at the corresponding point (in determining local values) or the average temperature around the profile contour (in determining average values).

The temperature of the blade outer surface is measured by thermocouples, whose hot end is located as close as possible to the surface. The average temperature of the blade surface is calculated as the mean arithmetic from measured values by thermocouples or is determined by integrating the measured temperature distribution.

In certain works heat transfer in the blade cascades was investigated by using the law of "transient regime" of blade heating. This method allows determination of the average heat transfer coefficients during experiment based on the measured difference of the blade temperature and the fluid flow temperature.

The experimental devices were in the majority of cases developed on the basis of recommendations used also in investigations of blade cascade aerodynamics (e.g. schemes of the flow input and output, arrangement of the measuring sections, etc.). The latest investigations of heat transfer are supplemented by investigations of aerodynamic characteristics of profiles and cascades.

The experimental investigations were performed on cascades which essentially differ from each other regarding geometrical and flow characteristics of profiles (impulse profiles, reaction profiles, dimensions), by cascade pitch, by angle of flow inlet, etc. The obtained maximum experimental values of Reynolds numbers are considerably lower than at the first stages of modern gas turbines (sometimes by one order of magnitude!). Therefore, direct usage of correlations on larger values of Reynolds number can cause error, whose magnitude depends on the flow characteristic around profiles in the cascade.

With steam and gas turbines with modest inlet temperatures of working fluid, the Reynolds number for blades is within the range from 10^5 to 10^6, while in gas turbines with high inlet temperatures it ranges from $7*10^6$ to $9*10^6$. The average values of heat transfer coefficient on profiles change thereby for the former from 200 to 1200 W/m^2K i.e. from 3000 to 5000 for the latter.

Characteristic dimensions, velocity and temperature, necessary for Nusselt and Reynolds number have been selected differently. It is e.g. the profile chord or the equivalent diameter of pipe, whose perimeter is equal to profile perimeter; then inlet velocity in cascade or outlet velocity from cascade or their mean-arithmetic value, etc. The mentioned facts are one of the causes of different absolute values of the factor c in equation $Nu_{p,av}=cRe^n$ (its magnitude changes in the range from 0,05 to 1,1). The exponent of Reynolds number varies in the range from 0,49 to 0,88, indicating different region of extension of laminar, transient and turbulent boundary layers on the investigated blades or the presence of separation of the boundary layer.

Absolute values of the temperature factor ψ (ratio of wall and flow temperature) in the experiments changes in the range from 0,65 to 1,25, and according to the results of the majority of experiments, it does not show any significant effect on the average value of Nusselt number (similar to the direction of the heat flux).

There are correlations which indirectly take into account the effect on the factor c and exponent n by the flow characteristics: by introducing the correction factor into the equation $Nu_{p,av}=cRe^n$, which depends on the geometrical characteristics of the inlet i.e. outlet cross-section of the channel between blades or of the channel between blades and cascade as a whole (e.g. profile angle deflection, profile thickness, profile pitch, temperature factor, Mach number, etc.); sometimes the correction factor with the exponent of Reynolds number (which also depends on the inlet and outlet angles of cross-section of the channel between blades) is also introduced in the equation. These correlations have often resulted from the analysis of experimental results of a larger number of authors, which significantly enhances their reliability. Also, these correlations can be applied in calculations of various blade types and the range of their possible application is significantly wider than in previously described correlations.

The heat transfer coefficients values on the blade leading edges of the stationary gas turbines reach 1000 to 2000 W/m^2K, and with turbo-jet engines 6000 to 10000 W/m^2K. For the leading edges the experimental data are generalized by dependencies of type $Nu_{1av}=cRe_1^n$, where the characteristic dimension and velocity are the diameter of leading edge and the flow velocity at inlet cross-section. Correlations proposed by various authors differ significantly both by the value of exponent of Reynolds number (0,5 to 0,7) and by the value of factor c: therefore, the values of heat transfer coefficients determined by various correlations differ 70 to 80%. This is connected with different conditions of flow around investigated blades, by the level of turbulence of the flow in front of the cascade and by boundaries of the leading edge surface, on which averaging (or measurement) of the heat transfer coefficient has been performed.

Values of heat transfer coefficients on the trailing edges of non-cooled blades of stationary gas turbines and of turbo-jet engines reach 1000 to 4000 W/m^2K. The existing experimental data on the trailing edges are also generalized by dependencies of type $Nu_{2av}=cRe_2^n$, where the characteristic dimension and velocity are diameter of trailing edge i.e. the flow velocity at outlet section. The exponent of Reynolds number in the obtained correlations has values from 0,4 to 0,93, which is related to different conditions of flow around this part of profile. Significant influence on the exponent is shown by the indefiniteness of boundaries of the trailing edge surface.

In the literature existing correlations for calculating the average convective heat transfer coefficient on the cylindrical wall of $Nu_{c,av}=cRe^n$ type channel, the value of factor c depends on the geometrical and flow characteristics of the cascades, and the exponent n is 0,5 or 0,8 depending on what flow regime prevails in the boundary layer on the cylindrical wall of channel: laminar or turbulent.

In the majority of research, primary attention was paid to the study of influences of the flow characteristics around profile on the average heat transfer in cascade (Reynolds number) and geometrical characteristics of cascade and profiles. Strictly speaking, these correlations are valid only for the flow of non-compressible fluid in the stationary cascades and at lower values of the heat flux. However, the gas flow in the flow part of high temperature cooled gas turbines is characterized by high velocities (Mach number Ma>0,8) i.e. by high Reynolds numbers, which disturb the "smoothness" of the flow around profiles (the surface roughness effect occurs) and by high heat flux which disturb the isothermal flow. At transfer from the stationary to the rotational cascades, the field of centrifugal forces which causes secondary flows is added to the flow of the working fluid. The secondary flows stipulate the phenomenon of Coriolis forces, which further change the flow character in the boundary layer of the rotating cascades. At the same time, the rotating cascade shows periodical non-stationary flows due to the edge traces of the upstream cascade and the related increased turbulence. The work [Guzović, 1998] from the available literature presents the influence of the incidence angle at variable working regime, of the flow turbulence, of the non-stationary temperature, of the flow compressibility, of the temperature factor and of the cascade rotation on the heat transfer, as well as the manner in which they are estimated.

All this complicates the practical usage of the collected experimental materials and requires strict matching of the geometrical and flow characteristics of the calculated cascade with those from the experiment on the basis of which the applied correlation is obtained.

Therefore, in order to simplify and accelerate determining of average heat transfer coefficients in engineering application, first numerous correlations from the available literature have been systematized, and then single systematized groups have been statistically analyzed in the work [Guzović, 1998]. The results of statistical analysis are the original generalized statistical correlations which replace a greater number of single correlations from literature, with the accuracy acceptable for engineering application.

SYSTEMATIZATION OF SINGLE CORRELATIONS

Single correlations from literature used to determine heat transfer in the blade cascades are systematized in five groups, and each group is presented in its corresponding table:

1st group: correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) along the whole profile (Table 1);

2nd group: correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) along the whole profile which estimate the influence of the cascade geometry and of flow characteristics on factor c and exponent n (Table 2);

3rd group: correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the leading edge of the profile (Table 3);

4th group: correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the trailing edge of the profile (Table 4);

5th group: correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the cylindrical wall of the channel between blades (Table 5).

The tables also present the characteristic quantities and the application ranges of the flow and heat transfer characteristics whose appliction is recommended. The work [Guzović, 1998] also describes in detail experimental devices and measurement techniques and mentions the remaining conditions in carrying out the experiments which in turn provide single correlations.

STATISTICAL ANALYSIS AND ORIGINAL GENERALIZED STATISTICAL CORRELATIONS

Groups of systematized correlations, i.e. the results of calculations of mean Nusselt numbers have been statistically analyzed, and the results are the original generalized statistical correlations of type $Nu_{av}=cRe^n$.

The statistical analysis is performed by means of a tabular calculator on a computer (method based on the least square method and dragging of exponential "trendline"). The obtained original generalized statistical correlations which replace a particular group of the systematized single correlations from the literature are presented in Table 6 (within brackets, next to equations are their related correlation factors). Table 6 also presents the characteristic quantities and the ranges of flow characteristic changes, recommended during their usage.

Due to identical calculations of Nusselt numbers according to systematized correlations in single groups, equal values of geometrical and flow characteristics (e.g. temperature factor, Mach number, turbulence ratio, profile relative deflection, flow relative deflection, etc.) have been inserted according to circumstances in them.

Here it should be commented on the characteristic quantities and selection of physical properties. Some of the correlations in Table 1 use as the characteristic dimension the profile chord b, others the hydraulic diameter D_{eq}. Sometimes, instead of the mean velocity w_{av} the inlet w_1 or outlet w_2 velocity from cascade is used as the characteristic velocity; similarly, physical properties are sometimes selected at inlet T_1 or outlet T_2 temperature instead of the average temperature $(T_w+T_{0f})/2$. Since in the majority of cases as the characteristic dimension appears the profile chord b, and on the other hand the hydraulic diameter D_{eq} is in value close to b, it is estimated that various characteristic dimensions would not significantly influence the accuracy of the original generalized statistical correlations. The same can be concluded both for the physical properties selected at inlet and outlet temperatures, in equal number of cases and for the inlet and outlet velocity as characteristic. Statistically, their influences will equalize because some give elevated values and others give lower values compared to the average ones.

The differences in correlations in Table 2 and Table 5 appear only in the selection of physical properties, and the previous conclusion is jointly the same. With correlations in Table 3 and Table 4 there are no differences regarding characteristic quantities.

Also, the work [Guzović, 1998] compares the calculation results obtained by the original general statistical correlations and by single correlations from literature.

Table 1 The single correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) along the whole profile

References	Correlations	Characteristics quantities				Application ranges		
		T	L	w	p (ρ)	$Re*10^{-5}$	Ma	ψ
[Jakob, 1960]	$Nu_{p,av} = 0{,}118 Re^{0,7} Pr^{1/3}$	-	$P/2$	-	-	-	-	-
[Jakob, 1960]	$Nu_{p,av} = 0{,}482 Re^{0,57} Pr^{1/3}$	-	$P/2$	-	-	-	-	-
[Andrews &Bradley, 1957]	$Nu_{p,av} = 0{,}756 Re^{0,49}$	$(T_w+T_0)/2$; T_w	b	w_2	ρ_{av}	0,4-5	0,1-1,0	0,9-0,5
[Andrews &Bradley, 1957]	$Nu_{p,av} = 0{,}169 Re^{0,66}$	$(T_w+T_0)/2$; T_w	b	w_2	ρ_{av}	0,4-5	0,1-1,0	0,9-0,5
[Smith, 1948]	$Nu_{p,av} = 0{,}045 Re^{0,77}$	T_{av}	D_{eq}	w_{av}	p_{av}	0,8-2	0,1	1,25
[Smith, 1948]	$Nu_{p,av} = 0{,}565 Re^{0,545}$	T_1	b	w_1	ρ_1	1,5-4	0,35	0,8
[Smith, 1948]	$Nu_{p,av} = 0{,}0205 Re^{0,88}$	$(T_w+T_0)/2$; T_w	b	w_1	p_{av}	0,4-2	-	1,2
[Ellenbrock, 1951]	$Nu_{p,av} = 0{,}053 Re^{0,49}$	$(T_w+T_{0f})/2$	D_{eq}	w_1	p_{av}	0,8-3,5	-	-
[Ainley, 1953]	$Nu_{p,av} = 0{,}1 Re^{0,68}$	$(T_w+T_{0f})/2$; T_w	b	w_2	p_{av}	0,7-1,5	0,6	0,8
[Knabe, 1966]	$Nu_{p,av} = 0{,}367 Re^{0,545}$	$(T_w+T_{0f})/2$; T_w	D_{eq}	w_{av}	p_{av}	0,2-0,7	0,25	0,93
[Wilson & Pope, 1954]	$Nu_{p,av} = 0{,}15 Re^{0,65}$	$(T_w+T_{0f})/2$; T_w	b	w_2	w_1	1,5-7	<0,25	1,05
[Karnozhickiy, 1963]	$Nu_{p,av} = 0{,}65 Re^{0,55}$	T_{0f}	b	w_1	ρ_1	0,4-5,4	<0,5	2-1,25
[Bodunov, 1961]	$Nu_{p,av} = 0{,}0646 Re^{0,73}$	T_{0f} ; T_1	b	w_1	p_{av}	1,5-5	<0,5	1,17
[Bodunov, 1961]	$Nu_{p,av} = 0{,}0913 Re^{0,7}$	T_{0f} ; T_1	b	w_1	p_{av}	1-4	<0,5	1,17
[Diban & Kurosh, 1971]	$Nu_{p,av} = 0{,}12 Re^{0,66}$	$(T_w+T_0)/2$	b	w_{av}	ρ_{av}	0,65-6	<0,5	1,15
[Diban & Kurosh, 1968]	$Nu_{p,av} = 0{,}0507 Re^{0,754}$	$(T_w+T_0)/2$	b	w_{av}	ρ_{av}	1-6	<0,5	1,15
[Diban & Kurosh, 1968]	$Nu_{p,av} = 0{,}128 Re^{0,66}$	$(T_w+T_0)/2$	b	w_{av}	ρ_{av}	0,8-5,5	<0,5	1,15
[Diban & Kurosh, 1968]	$Nu_{p,av} = 0{,}257 Re^{0,66}$	$(T_w+T_0)/2$	b	w_{av}	ρ_{av}	0,9-4,15	<0,5	1,15
[Kapinos & Slitenko, 1968]	$Nu_{p,av} = 0{,}166 Re^{0,68}$	T_{0f}	D_{eq}	w_{av}	ρ_{av}	0,4-11	0,5	1,2
[Halls, 1967]	$Nu_{p,av} = 0{,}235 Re^{0,64}$	-	-	-	-	-	-	-

Table 2 The single correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) along the whole profile which estimate the influence of the cascade geometry and of flow characteristics on factor c and exponent n

		Characteristics quantities				Application ranges		
References	Correlations	T	L	w	p (ρ)	$Re*10^{-5}$	Ma	ψ
[Bamet, 1953]	$Nu_{p,av} = 0{,}77\,Re^{0,545}$	T_1	b	w_1	ρ_1	1,08-3,2	0,6	1,2
[Lozickiy, 1960]	$Nu_{p,av} = 0{,}63\,Re^{0,55}$	T_1	b	w_1	ρ_1	0,7-3,75	0,3	0,98
[Walker & Markland, 1965]	$Nu_{p,av} = 0{,}235\,Re^{0,6}$	T_w; T_2	b	w_2	ρ_2	2-7	0,25	1,03
[Shtirlin, 1968]	$Nu_{p,av} = 0{,}4\,Re^{0,55}\,Ma_1^{0,77}$	T_1; T_w	b	w_1	ρ_1	1,5-4,4	1,2-2,0	0,65-0,83
[Diban & Glushchenko, 1973]	$Nu_{p,av} = 0{,}14\,Re^{0,65} * \left(\frac{Ma_2}{0{,}5}\right)^{-0,28}$	T_1	b	w_2	ρ_{av}	2,6-10,3	0,45-1,0	0,65-0,93
[Zhirickiy & Lokay, 1949]	$Nu_{p,av} = 0{,}14\,Re^{0,66}\,\psi^{0,5}\,\bar{t}^{\,0,12}$; $\bar{t} = t/b$	T_{av}	D_{eq}	w_{av}	ρ_{av}	0,7-3	<0,5	1,2
[Hodge, 1958]	$Nu_{p,av} = 0{,}051\,Re^{0,715}\,\psi^{-0,16}$	T_{av}	b	w_{av}	ρ_1	1,5-10	0,2-0,8	1,0-0,5
[Hodge, 1958]	$Nu_{p,av} = 1{,}12\,Re^{0,463}\,\psi^{-0,16}$	T_{av}	b	w_{av}	ρ_1	1,0-2,0	0,2-0,8	1,0-0,5
[Ivanov & Manushin, 1966]	$Nu_{p,av} = 0{,}085\,Re^{0,68}$	T_1;T_2	b	w_2	-	-	-	-
[Traupel, 1968]	$Nu_{p,av} = 0{,}05\,Re^{0,73}\,Pr^{1/3}$	T_{av}	b	w_1	-	-	-	-
[Traupel, 1968]	$Nu_{p,av} = 0{,}08\,Re^{0,73}\,Pr^{1/3}$	T_{av}	b	w_1	-	-	-	-
[Jakob, 1960]	$Nu_{p,av} = 0{,}10709\,Re^{0,7}$	T_{av}	D_{eq}	w_{av}	-	0,3-4,0	-	-
[Jakob, 1960]	$Nu_{p,av} = 0{,}07755\,Re^{0,7}$	T_{av}	D_{eq}	w_{av}	-	0,3-4,0	-	-
[Jakob, 1960]	$Nu_{p,av} = 0{,}4577\,Re^{0,57}\,Pr^{1/3}$	T_{av}	D_{eq}	w_{av}	-	0,7-2	-	-
[Jakob, 1960]	$Nu_{p,av} = 0{,}3383\,Re^{0,57}\,Pr^{1/3}$	T_{av}	D_{eq}	w_{av}	-	0,7-2	-	-
[Kapinos & Knabe, 1966] [Kapinos & Knabe, 1967]	$Nu_{p,av} = \left(0{,}0805\kappa^{-2,85} - 0{,}022\right) * Pr^{1/3} * Re^{0,74\kappa^{0,43}}$; $\kappa = \sin\beta_2/\sin\beta_1$	$0{,}5(T_w+T_f)$	D_{eq}	w_{av}	-	0,2-7,0	-	-
[Petrovskaya & Petrovskiy, 1971]	$Nu_{p,av} = \left(\frac{0{,}328}{\kappa} - 0{,}282\right) * Re^{0,736\kappa^{0,4}}$	T_{av}	D_{eq}	w_{av}	-	0,7-10	-	-
[Lokay, 1968]	$Nu_{p,av} = 0{,}206\,Re^{0,66}\,S_\Gamma^{-0,58}$; $S_\Gamma = \frac{\sin\beta_1'}{\sin\beta_2} * \sqrt{\frac{2B}{t\sin(\beta_1'+\beta_2)\cos\frac{\beta_1'-\beta_2}{2}} - 1}$	T_1	b	w_2	ρ_{av}	2,0-15,0	-	0,45-1,0
[Kapinos & Slitenko, 1981]	$Nu_{p,av} = 0{,}1015\,Re^{0,692}$	T_{av}	b	w_{av}	p_{av}	0,4-11,0	-	-

Table 3 The single correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the leading edge of the profile

References	Correlations	Characteristics quantities			Application ranges			
		T	L	w	Re_1	Ma	D_1/D_{max} (D_1/b)	ε_1 (ε_∞)
[Titov, 1987]	$Nu_{1av} = 0{,}936\varepsilon_1^{0{,}082} * \left(\frac{D_1}{D_{max}}\right)^{0{,}23} * Re_1^{0{,}5}$	T_1	D_1	w_1	$5{,}3*10^3$ - $3{,}5*10^4$	<0,45	0,17-0,64	2,2%-18,2% (1%-11%)
[Titov, 1987]	$Nu_{1av} = 0{,}994\varepsilon_\infty^{0{,}08} * \left(\frac{D_1}{D_{max}}\right)^{0{,}244} * Re_1^{0{,}5}$	T_1	D_1	w_1	$5{,}3*10^3$ - $3{,}5*10^4$	<0,45	0,17-0,64	2,2%-18,2% (1%-11%)
[Zhishina & Rost, 1979]	$Nu_{1av} = 1{,}02\,Re_1^{0{,}5}$	T_1	D_1	w_1	-	-	-	-
[Titov, 1987]	$Nu_{1av} = 1{,}01\varepsilon_1^{0{,}207} * \left(\frac{D_1}{b}\right)^{0{,}251} * Re_1^{0{,}5}$	T_1	D_1	w_1	$5{,}2*10^3$ - $2{,}5*10^5$	<0,71	(0,04-0,16)	0,7%-21% (0,6% -11%)
[Titov, 1987]	$Nu_{1av} = 1{,}538\varepsilon_\infty^{0{,}155} * \left(\frac{D_1}{b}\right)^{0{,}338} * Re_1^{0{,}5}$	T_1	D_1	w_1	$5{,}2*10^3$ - $2{,}5*10^5$	<0,71	(0,04-0,16)	1,7%-21% (0,6% -11%)
[Pochuev, 1975]	$Nu_{1av} = 0{,}23Re_1^{0{,}63}$	T_1	D_1	w_1	-	-	-	-
[Slitenko, 1968]	$Nu_{1av} = 0{,}138\,Re_1^{0{,}69}$	T_1	D_1	w_1	$4*10^3$-$1{,}3*10^5$	-	-	-
[Bodunov, 1961]	$Nu_{1av} = 0{,}265Re_1^{0{,}58}$	T_1	D_1	w_1	$4*10^3$-$1{,}3*10^5$	-	-	-

Table 4 The single correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the trailing edge of the profile

References	Correlations	Characteristics quantities			Application ranges	
		T	L	w	Re_2	ψ
[Diban & Glushchenko, 1973]	$Nu_{2av} = 6{,}15Re_2^{0{,}4}\left(\frac{T_w}{T_{0f}}\right)^{-0{,}5}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	0,7
[Diban & Glushchenko, 1973]	$Nu_{2av} = 4{,}01182\,Re_2^{0{,}4}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	2,35
[Diban & Glushchenko, 1973]	$Nu_{2av} = 0{,}535Re_2^{0{,}6}\left(\frac{T_w}{T_{0f}}\right)^{-0{,}5}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	0,7
[Diban & Glushchenko, 1973]	$Nu_{2av} = 0{,}3490Re_2^{0{,}4}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	2,35
[Pochuev & Shcherbakov, 1978]	$Nu_{2av} = 0{,}057\,Re_2^{0{,}71}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	-
[Pochuev & Shcherbakov, 1978]	$Nu_{2av} = 0{,}051Re_2^{0{,}73}$	T_2	D_2	w_2	10^5-$1{,}6*10^6$	-
[Slitenko, 1968]	$Nu_{2av} = 0{,}026Re_2^{0{,}69}$	T_2	D_2	w_2	$6*10^3$-$1{,}6*10^4$	-
[Bodunov, 1961]	$Nu_{2av} = 0{,}003Re_2^{0{,}93}$	T_2	D_2	w_2	$6*10^3$-$3*10^4$	-

Table 5 The single correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) on the cylindrical wall of the channel between blades

		Characteristics quantities				Application ranges	
References	Correlations	T	L	w	p	Re	Ma
[Kapinos & Slitenko, 1968]	$\mathrm{Nu}_{c,av}\ 1{,}59\,\mathrm{Re}^{0,5}$	T_{av}	b	w_{av}	p_{av}	$<3{,}3*10^5$	-
[Kapinos & Slitenko, 1968]	$\mathrm{Nu}_{c,av} = 0{,}038\,\mathrm{Re}^{0,8}$	T_{av}	b	w_{av}	p_{av}	$>4*10^5$	-
[Sidun, 1964]	$\mathrm{Nu}_{c,av} = \left(0{,}032 + 0{,}014\overline{\beta}\right) * \overline{t}^{\,-0,175}\,\mathrm{Re}^{0,8}$; $\overline{\beta} = \left(180^0 - \beta_1' - \beta_2'\right)/100$	T_{av}	b	w_{av}	p_{av}	$1{,}4*10^5$-$6*10^5$	-
[Bodunov & Lokay, 1974]	$\mathrm{Nu}_{c,av} = 0{,}032\left(1 + 0{,}7S_\Gamma^{-0,54}\right) ** \mathrm{Re}^{0,5}$	T_{av}	b	w_{av}	p_{av}	$1{,}5*10^5$-$2{,}5*10^5$	-
[Bodunov & Lokay, 1974]	$\mathrm{Nu}_{c,av} = 0{,}065S_\Gamma^{-0,54}\,\mathrm{Re}^{0,8}$	T_{av}	b	w_{av}	p_{av}	$1{,}5*10^5$-$2{,}5*10^5$	-
[Narezhniy, 1977]	$\mathrm{Nu}_{c,av} = 0{,}065S_\Gamma^{-0,54} * K_2^{-3,3}\,\mathrm{Re}^{0,8}$; $K_2 = 1 + \frac{\gamma - 1}{2}\mathrm{Ma}^2$	T_{av}	b	w_{av}	p_{av}	$4{,}8*10^5$-$2{,}4*10^6$	0,15-0,55
[Slitenko & Titov, 1985]	$\mathrm{Nu}_{c,av} = 0{,}278\overline{\beta}^{1,027}\overline{t}^{\,1,912} * \overline{\eta}^{-0,72}\,\mathrm{Re}^{0,5}$	T_{av}	b	w_{av}	p_{av}	$0{,}34*10^5$-$3{,}6*10^5$	-
[Slitenko & Titov, 1985]	$\mathrm{Nu}_{c,av} = 0{,}01451\overline{\beta}^{1,545}\overline{t}^{\,-0,208} * \overline{\eta}^{-0,7403}\,\mathrm{Re}^{0,8}$; $\overline{\eta} = \zeta / b$	T_{av}	b	w_{av}	p_{av}	$1{,}2*10^5$-$2{,}4*10^6$	-

Table 6 The original generalized statistical correlations for calculating the average Nusselt numbers (of the average heat transfer coefficients) in the turbine blade cascades

		Characteristics quantities				Application ranges			
Location of application	Correlations	T	L	w	$p(\rho)$	Re	Ma	ψ	ε_1
1) along the whole profile	$\mathrm{Nu}_{p,av}=0{,}123\mathrm{Re}^{0,6785}$; ($R^2$=0,8465)	$(T_w+T_{0f})/2$	b	w_{av}	p_{av} (ρ_{av})	$0{,}4*10^5$-$11*10^5$	0,1-1,0	0,5-2	-
2) along the whole profile with the influence of the cascade geometry and of flow characteristics on factor c and exponent n	$\mathrm{Nu}_{p,av}=0{,}1703\mathrm{Re}^{0,6382}$; ($R^2$=0,8571)	T_{av}	b	w_{av}	p_{av} (ρ_{av})	$0{,}2*10^5$ - $15*10^5$	0,2-0,8	0,65-1,2	-
3) at the leading edge of the profile	$\mathrm{Nu}_1=0{,}2893\mathrm{Re}_1^{0,5703}$; ($R^2$=0,6901)	T_1	D_1	w_1	-	$4*10^3$-$2{,}5*10^5$	<0,71	-	0,7% -21%
4) on the trailing edge of the profile	$\mathrm{Nu}_2=0{,}0021\mathrm{Re}_2^{0,9777}$; ($R^2$=0,9515)	T_2	D_2	w_1	-	$6*10^3$-$1{,}6*10^3$	-	0,7-2,35	-
5) on the cylindrical wall of the channel between blades	$\mathrm{Nu}_{c,av}=0{,}0837\mathrm{Re}^{0,7494}$; ($R^2$=0,8848)	T_{av}	b	w_{av}	(ρ_{av})	$3{,}4*10^4$ - $2{,}4*10^6$	0,15-0,55	-	-

CONCLUSION

The original generalized statistical correlations obtained by generalizing of a larger number of single correlations available in literature give, as the comparison shows, the accuracy of calculation results which is acceptable for engineering applications. These correlations can be applied in heat transfer calculations on various types of blades. The application scope of the original general statistical correlations is considerably greater than of any single correlation, because general correlation covers the ranges of geometrical and flow characteristics of all the single correlations. The finite estimation of the generalized correlations accuracy wiil give calculations of temperature fields i.e. temperature stresses. For these calculations the convective heat transfer coefficients (i.e. thermal boundary conditions) wiil determine by means of the generalized correlations, what it is the final aim.

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NOMENCLATURE

B - the cascade width;
P- the perimeter;
t - the cascade pitch;
$\beta(\beta')$ - the flow (profile) angle;
ε - the turbulence ratio;
ζ - the maximum deflection of the camber line;

SUBSCRIPTS

av - average;
c - on the cylindrical surface;
p - on the profile surface;