EVALUATION OF BLADE CASCADE CHARACTERISTICS IN EXPERIMENTS CARIED OUT WITH HUMID AIR

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ABSTRACT

This contribution deals with methodology proposed for flow parameters evaluation on stators and linear cascades, for which the experiment proceeded with humid air. An aim of arranged methodology is correct computing of flow parameters of non-adiabatic flow in a blade cascade, where condensation appears.

INTRODUCTION

There is a number of assumptions ordinarily constituted at data evaluation leading to conclusion, that total temperature in an entry and an exit of the cascade are same. There is an arguable assumption, that is to say a negligible heat transfer from blades and other boundary walls into the flow. Of course this assumption is not applicable in all measurement cases. It is acceptable in situations, where facility temperature is stabilized in accordance with flow conditions. It is necessary to replenish all presented assumptions with a condition, that the parameters of dry air are further used for calculations of the cascade characteristics.

Data processed with mentioned assumptions are often presented with just air humidity and the temperature at the cascade inlet mentioned. As soon as the air is wet by an experiment, it is not possible to accept the assumption of adiabatic flow for high speed flow. It is because water contained in the air condensates, when temperature decreases sufficiently under dew point in a flow field. It causes condensation phenomena having impacts on the flow field. The non-adiabatic character mentioned therein before is a basic modification in comparison with the initial assumption, because the heat is released within the condensation and total temperature increases.

NOMENCLATURE

a .... [m/s] .... sonic velocity
E ... . mean reduced flow energy
F.... [m^2].......... outlet area
H ... . mean reduced enthalpy
i..... .... index variables
M .. .. Mach number
p .... [Pa] .... pressure
q .... local reduced flow density
Q ... . mean reduced mass flow
r .... [mm] .... radius
R ... [J/kg/K] ... universal gas constant
S.... .... mean reduced entropy
T ... [K] .... temperature
v .... [m/s] .... local velocity
V ... [m/s] .... mean velocity
α ... [°] .... yaw angle
β.... [°] .... pitch angle
ζ .... pressure loss coefficient
η.... .... energy loss coefficient
κ.... .... specific heats ratio
ρ .... [kg/m^3] ..... density

Subscripts
0 ....total condition
1 ....inlet condition
2 ....outlet condition
a ....axial
ha ......before heat addition
is ....isentropic
r ....radial
ref......reference condition
t ....tangencial
* ....critical condition

DATA REDUCTION

The methodology is designed for stator characteristics computation and is constituted by modification of one already used at VZLU (ref. 1). It's based on a fact that it is not possible to meet all physical conservation principles in determination of average flow parameters. Therefore suitable criteria were chosen. These criteria ensure that real and idealized averaged flow parameters have identical sum of enthalpy, entropy, energy and momentum in investigated area. System is completed with a law of mass conservation.

Reduced values are used in all equations. Parameters are reduced by the critical air velocity and density in reference condition that is computed from equation of state. There total temperature T_{01} and total pressure p_{01} at the inlet of cascade in the equation is used. These parameters vary slightly during the measurement that takes approximately an hour. Of course, proportionally to these changes absolute values of all parameters vary. This is the reason for using reduced values, whose variations are negligible. Pressure and temperature reference values are averaged from whole measurement and these values are used as constants for one regime.

Description of data reduction process will be described now.

At first, the mass flow in direction perpendicular to plane of traversing is computed

$$Q = \left(\frac{\rho \cdot V}{\rho_{01} \cdot a_*} \right)_a = \frac{1}{F} \cdot \iint_F \left(\frac{\rho_i \cdot v_i}{\rho_{01i} \cdot a_{i*}} \right)_a dF = \frac{1}{F} \cdot \iint_F q_i \; dF$$

where q_i is relative flow density in axial direction

$$q_i = \frac{\rho_i \cdot v_i}{\rho_{01i} \cdot a_{i*}} \cdot \sin\alpha_i \cdot \cos\beta_i \, .$$

Subsequently the flow energy

$$E = Q \cdot T_{02} = \frac{1}{F} \iint_F q_i \cdot T_{02i} \, dF \; ,$$

enthalpy

$$I = Q \cdot \left(c_p \cdot T_{02} - \frac{V_2^2}{2} \right) = \frac{1}{F} \iint_F q_i \left(c_p \cdot T_{02i} - \frac{v_{2i}^2}{2} \right) dF \, ,$$

entropy

$$S = Q \cdot \left(c_p \cdot \ln\frac{T_{02}}{T_{01}} - R \cdot \ln\frac{p_{02}}{p_{01}} \right) = \frac{1}{A} \iint_S q_i \cdot \left(c_p \cdot \ln\frac{T_{02i}}{T_{01i}} - R \cdot \ln\frac{p_{02i}}{p_{01i}} \right) dF \; ,$$

tangential momentum

$$H_t = Q \cdot \frac{V_2}{a_*} \cdot \sin\alpha_2 \cdot \cos\beta_2 = \frac{1}{F} \iint_F q_i \cdot \frac{v_{2i}}{a_{*i}} \cdot \sin\alpha_{2i} \cdot \cos\beta_{2i} \, dF \; ,$$

radial momentum

$$H_r = Q \cdot \frac{V_2}{a_*} \cdot \cos\beta_2 = \frac{1}{F} \iint_F q_{2i} \cdot \frac{v_{2i}}{a_{*i}} \cdot \cos\beta_{2i} \, dF \; ,$$

and axial momentum

$$H_a = Q \cdot \frac{V_2}{a_*} \cdot \cos\alpha_2 \cdot \cos\beta_2 = \frac{1}{F} \iint_F q_{2i} \cdot \frac{v_{2i}}{a_{*i}} \cdot \cos\alpha_{2i} \cdot \cos\beta_{2i} \, dF$$

can be computed.

Mean total temperature and mean velocity from system of equations are computed

$$T_{02} = \frac{E}{Q},$$

$$V_2 = \sqrt{2 \cdot \left(c_p \cdot T_{02} - \frac{I}{Q} \right)},$$

consecutively flow directions at the outlet of cascade (fig. 1) are evaluated

$$\alpha_2 = arctg\left(\frac{H_a}{H_t} \right) \; ; \; \beta_2 = arctg\left(\frac{H_r \cdot \cos\alpha_2}{H_t} \right).$$

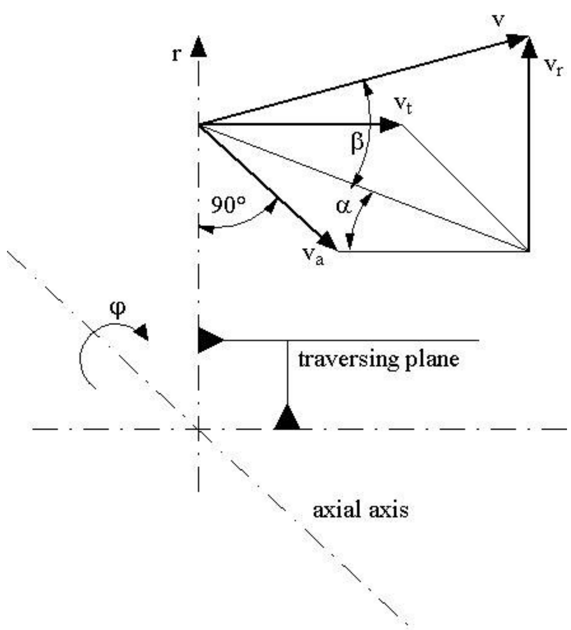

Fig. 1 Definition of flow angles

Pressure loss coefficient is defined as

$$\varsigma = \frac{p_{01} - p_{02}}{p_{01}},$$

where total pressure at the outlet is computed with

$$p_{02} = p_{01} \cdot \exp\left[\left(c_p \cdot \ln\frac{T_{02}}{T_{01}} - \frac{S}{Q} \right) / R \right].$$

To mean velocity V_2 corresponds

$$T_2 = T_{02} - \frac{V_2^2}{2 \cdot c_p}$$

and

$$p_2 = p_{02} \left(\frac{T_2}{T_{02}} \right)^{\frac{k}{k-1}} .$$

Polytropical change of state is used for next computations. Therefore polytropical exponent is determined for detected parameters

$$n = \frac{\log \frac{p_1}{p_2}}{\log \frac{\rho_1}{\rho_2}} .$$

This exponent that describes presented change is than used to compute balance of Newton's law of motion and energy with sense of loss is acquired.

$$e_L = \frac{V_1^2 - V_2^2}{2} - R \cdot T_1 \frac{n}{n-1} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] .$$

Coefficient of kinetic energy conversion can be than computed by

$$\eta = \frac{e_L}{\frac{V_2^2}{2} + e_L} .$$

HEAT ADDITION

A process for separation of loss caused by heat addition is described here. It is arranged for those cases, where change of flow energy is a negative process and one wants to know parameters without it.

A concept of adiabatic flow in the cascade with addition of heat in an area close to a traversing plane is used. So, it is possible to compute adiabatic parameters of flow with assumption of flow in a constant area duct with heat transfer without friction. Simple equations describing Rayleigh's curve are applied. The computation is done via critical ratios defined by following relations.

$$\frac{T_0}{T_0^*} = \frac{2 \cdot (\kappa + 1) \cdot M^2 \cdot \left(1 + \frac{\kappa - 1}{2} \cdot M^2 \right)}{\left(1 + \kappa \cdot M^2 \right)^2}$$

$$\frac{T}{T^*} = \frac{(\kappa + 1)^2 \cdot M^2}{\left(1 + \kappa \cdot M^2 \right)^2}$$

$$\frac{p_0}{p_0^*} = \frac{(\kappa+1)}{\left(1+\kappa\cdot M^2\right)^2}\left[\frac{2\cdot\left(1+\frac{\kappa-1}{2}\cdot M^2\right)}{\kappa+1}\right]^{\frac{\kappa}{\kappa-1}}$$

$$\frac{p}{p^*} = \frac{\kappa+1}{1+\kappa\cdot M^2}$$

Evaluation of parameters before heat addition is done with following procedure.
At first, total temperature ratio before heat addition is computed

$$\left(\frac{T_0}{T_0^*}\right)_{M2ha} = \left(\frac{T_0}{T_0^*}\right)_{M2}\frac{T_{01}}{T_{02}}$$

and Mach number of searched state is found:

$$M^*_{2ha} = 1 \pm \sqrt{1-\left(\frac{T_0}{T_0^*}\right)_{M2ha}} \qquad \text{and} \qquad M_{2ha} = \sqrt{\frac{M^*_{2ha}}{\kappa+1-\kappa\cdot M^*_{2ha}}} \quad ,$$

where positive sign in first equation is used for $M_2 > 1$.
All parameters for searched state are evaluated according to formula used for total pressure computation

$$p_{02ha} = p_{02}\cdot\frac{\left(p_0/p_{0*}\right)_{M2ha}}{\left(p_0/p_{0*}\right)_{M2}}$$

Then determination of loss coefficients can be done by the same procedure described before.

PHENOMENON OF CONDENSATION

The aim of this methodology is computation of stationary cascades, where the heat is evolved during condensation.

The condensation phenomenon is a complex process, that dramatically changes flow parameters. The first change, here solved, is non-adiabatic flow caused by heat released during condensation. It is possible to say, that amount of added heat is just a function of latent heat and amount of water condensed. Unfortunately, determination of condensed fraction is rather complicated, because condensation in high speed flows may run in 'shocks' with only fractional condensation, where maximum amount of heat released to flow is dependent on flow conditions before the shock. Moreover it is not a simple heat addition to flow in this case, but more influences are connected with this phenomenon. Finally a two phase flow constituted by mixture of air and water droplets or ice crystals after condensation occurs there.

At first, let's make assumption, that the fact of the two phase flow has negligible influence on results of data reduction computation and parameters of dry air can be further used. This assumption comes out from the fact, that fraction of condensed water (or ice) is small in this case in comparison with mass of air content.

Simple condensation process is used in the first approach of evolved heat computation. In this case, amount of condensed water is computed from known water content at the inlet and the state of saturation that corresponds to flow parameters at the outlet.

A condensation shock is also discussed. For this process, following computation of maximum temperature growth is used (ref. 2). It is presumed, that first condensation appears for 45 degrees super cooled vapor.

$$\Delta T_{shock} = T_{01}\cdot\frac{\left(M^2-1\right)^2}{M^2\cdot\left(M^2+\frac{2}{\kappa-1}\right)\cdot\left(\kappa^2-1\right)}$$

Then, temperature growth in one shock is equal or lower then this one. It means that only a fraction of the water vapor may be condensed**.** The remainder will continue as super cooled vapor until a next condensation shock occurs. But if the Mach number in stream is less than about 2, a second condensation shock may not occur. Computations made here are done with assumption of one condensation shock. With this, it's possible to evaluate total temperature at the outlet of the cascade and to determine characteristics of non-adiabatic flow with procedures described therein before.

EXPERIMENTAL RESULTS

Formation of this methodology is connected to experiments carried out in low pressure reversed flow wind tunnel and the turbine stator with following parameters was studied.

		Stator B2A
Chord	[mm]	76,4
Geometrical outlet angle	[°]	11,5
Hub diameter	[mm]	430
Blade height	[mm]	20
Outlet Mach number	[-]	2

Flow parameters in this experiment were observed with separated pressure probes (two directional probes and pitot-static probe – ∅ 1mm) and shielded thermocouple probe. The thermocouple probe was designed and used in order to verify assumption of adiabatic flow in the cascade. Air dryer of the facility didn't work properly, therefore relative humidity at the inlet of the stator was between 30 and 70% with total temperature approximately 30°C.

Regimes with higher total temperature at the outlet opposite to inlet were indicated, so properties of thermocouple probe were closely studied. Provided tests confirmed, that the probe gives acceptable results and watchfulness was finally put on the air humidity.

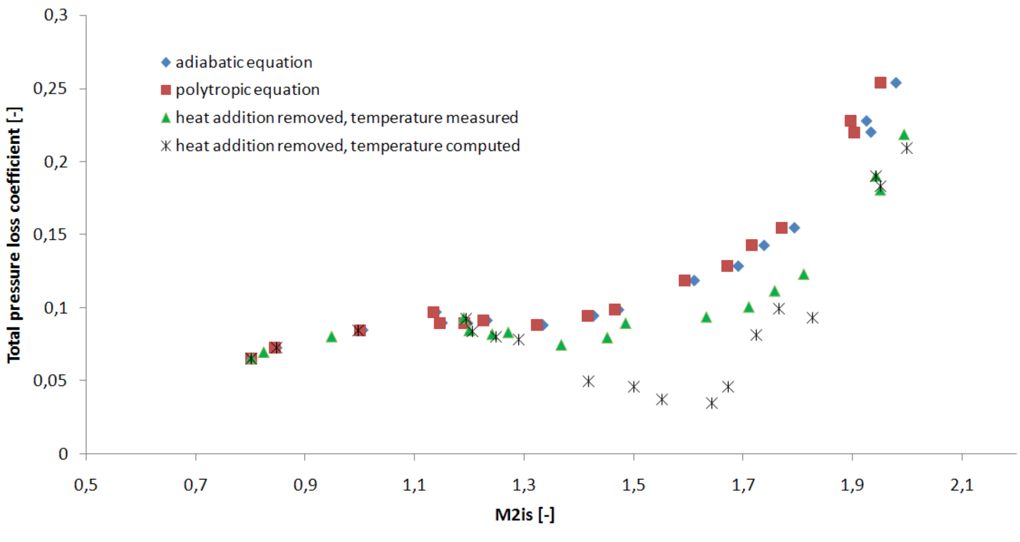

Fig. 2 Total pressure loss coefficient

Characteristics computation with presented methodology was done and comparison of obtained data is shown on fig. 2 and 3. The results obtained with different approaches are displayed in these diagrams. At first, data were evaluated with constant total temperature (signed as 'adiabatic'). Then data for measured total temperature at the outlet of cascade were computed (signed as 'polytropic') and finally remotion of added heat was done for total temperature measured and evaluated with assumption of single condensation shock.

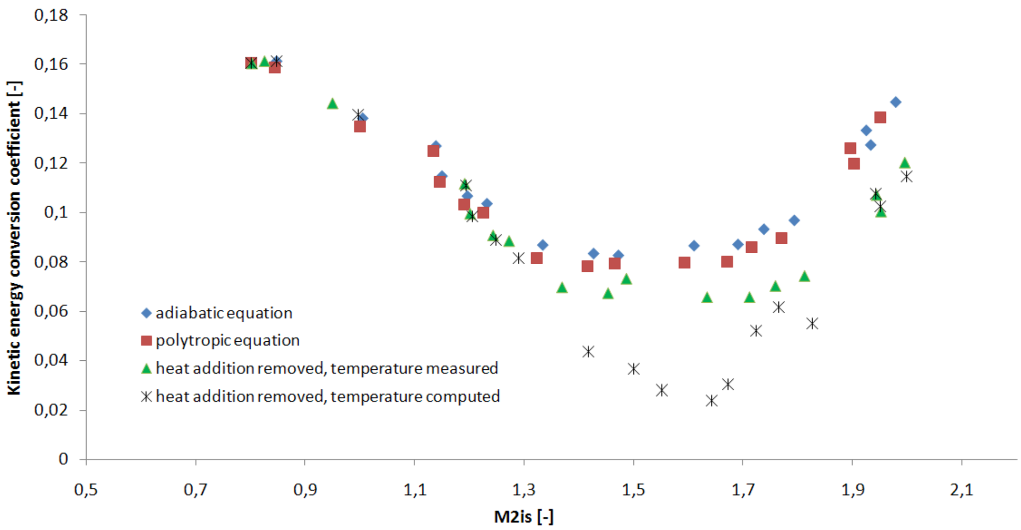

Fig. 3 Kinetic energy conversion coefficient

Total condensation was computed for high velocities (more then M≈1,4) with both types of temperature growth computation (fig. 5). It is acceptable solution, particularly in relation to flow parameters at the outlet of the cascade. In this point of view, using the thermocouple probe showed limitations of such instrument in this type of measurement. Difference between measured and calculated temperature growth was indicated, namely in the cases with high specific humidity. It's shown on fig. 4, where temperature growths in area of total condensation are presented. The pitot temperature is negligibly affected by condensation phenomenon, which is in accordance with experimental results (e.g. ref. 2). Possible explanation is that condensed water partially evaporates in front of pitot thermocouple probe and temperature decreases backward.

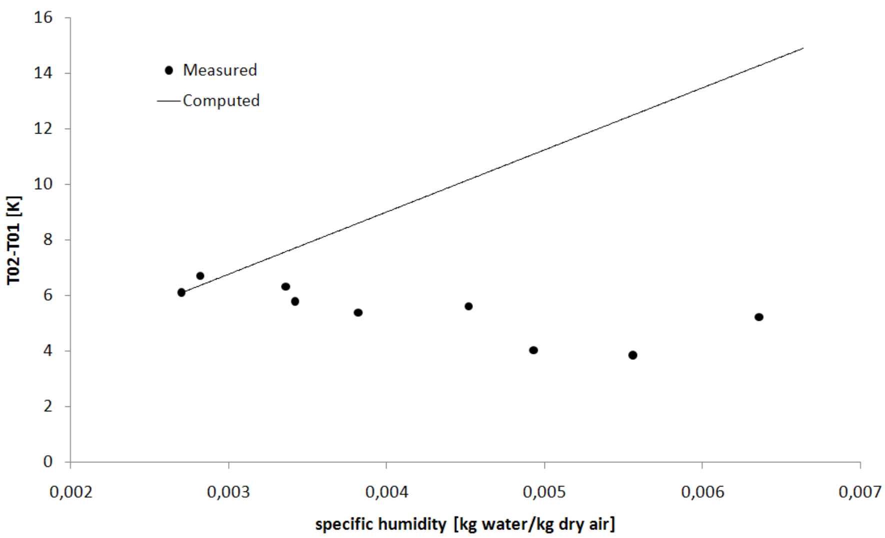

Fig. 4 Temperature growth as a function of specific air humidity

Comparison of measured and both computed temperature growths are displayed on fig. 5. Ratios of studied growths with maximum temperature growth are plotted on this diagram as a function of isentropic Mach number.

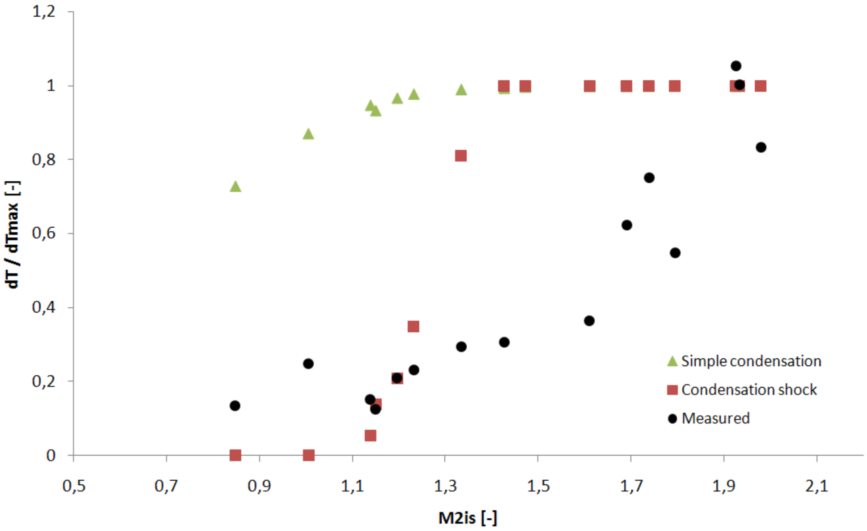

Fig. 5 Temperature growths related to maximum temperature evolving

CONCLUSION

The methodology proposed for evaluation of non-adiabatic flows was created and used for evaluation of experimental data acquired in the case of the turbine stator with maximum outlet velocity M=2. Designing of the methodology is by results obtained with shielded thermocouple probe that was experimentally used for the measurement. The probe indicated growth of total temperature in the cascade. Therefore results of experiment and temperature probe properties were thoughtfully studied and finally the condensation of water vapor was determined as the most probable temperature growth explanation. In accordance with expectation, regimes with affection of heat convection were simultaneously identified. This influence is perceptible in the cases of regimes measured in the beginning of experimental day, mostly when the facility was put out of operation for longer time. Regimes affected by heat convection are not presented in this contribution.

Analyzing of thermocouple probe measurement results showed, that the probe is not suitable for measurement of temperature growth that is connected with condensation phenomenon. It is caused by re-evaporation in front of the probe. It is in accordance with previously published results that this type of temperature probe is not usable to determine rate of condensation.

Assumption of total condensation of water contained in the air is possible to use, if the water vapor in stream is 45 degrees super cooled. A question of way of condensation remains in experiments, where is impossible to visualize flow field. The way of condensation is important from the point of view of new structures formation, because extra influences to flow are connected with it.

For further experiments it will be necessary to design probe suitable for temperature measurement in stream with condensed fraction, because it is important to get reliable data of flow parameters in conditions where condensation appears. Unfortunately, in case of this stator it is complicated with rather small height of blades.

Further experiments on the stator with dry air are required in order to verify process arranged for separation of heat addition loss.

ACKNOWLEDGMENTS

The support of this project from the Ministry of Education, Youth and Sports under the grant No MSM 0001066902 is gratefully acknowledged.

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