Journal of KONES Powertrain and Transport, Vol. 25, No. 2 2018

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2778

DEVIATION ANGLE MODELS IN OFF-DESIGN HIGH-PRESSURE TURBINES

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Abstract

In the article, a set of deviation angle models, which are used to predict the off-design performance high-pressure turbines, has been presented, basing on a literature study. The deviation angle is a deviation between the actual flow angle and the blade inclination angle. It is an essential parameter in turbine performance evaluation. This angle shall be obtained accurately in 1-D design and evaluation, so as to ensure the validity of blade profiling and calculation results. If deviation angle is ignored, the turbine will produce a lower change of tangential velocity, and consequently a lower torque, output work and enthalpy drop than intended by the designer. For this reason, the deviation angle model needs to be established. There exist a number of different deviation models, resulting in varying degrees of flow deviation when applied. In the article, correlations for gas outlet angle, dependent on the Mach number at outlet and determined by the blade loading towards the trailing edge has been presented. The main difficulty in establishing the deviation model is a continuity in defining the angle for all speed ranges (both subcritical and supercritical). Each of the models presented in the article deals with this problem in a different way. A few deviation models, briefly discussed in the article, are based on experimental data and one is based on analytical approach.

Keywords: *turbomachinery, gas turbines, high-pressure turbine, HPT, deviation angle*

1. Introduction

A cascade geometry is defined completely by the aerofoil specification, pitch-chord ratio and the chosen setting i.e. angle between chord line and meridional (stagger angle). Blade spacing is defined by two main parameters, the pitch, and the throat opening. The blade throat controls the mass flow passing by a turbine, and is very important specification in manufacturing drawings. The deviation angle is equal to the blade outlet angle minus the flow outlet angle. This is an essential parameter in turbine performance evaluation. Another important angle is the incidence angle. This parameter is important for turbine “off-design” performance calculations. The incidence angle is equal to the inlet flow angle minus the blade inlet angle. Cascade Geometry Nomenclature and other parameters are shown in Fig. 1.

2. Literature review

Deviation is mainly an inviscid phenomenon and is considered to be a natural consequence of circulation around an aerodynamically loaded blade alone. That causes the divergence of the streamlines from the suction surface in a diffusing flow. For highly loaded blades, this effect increases due to the rapidly growing boundary layer thickness.

A number of different deviation models exist there, resulting in varying degree of flow deviation when applied. The deviation is an essential parameter in turbine performance evaluation. This angle shall be obtained accurately in 1-D design and evaluation, so as to ensure the validity of blade profiling and calculation results. If deviation angle is ignored, the turbine will produce a lower change of tangential velocity, and consequently, a lower torque, output work and enthalpy

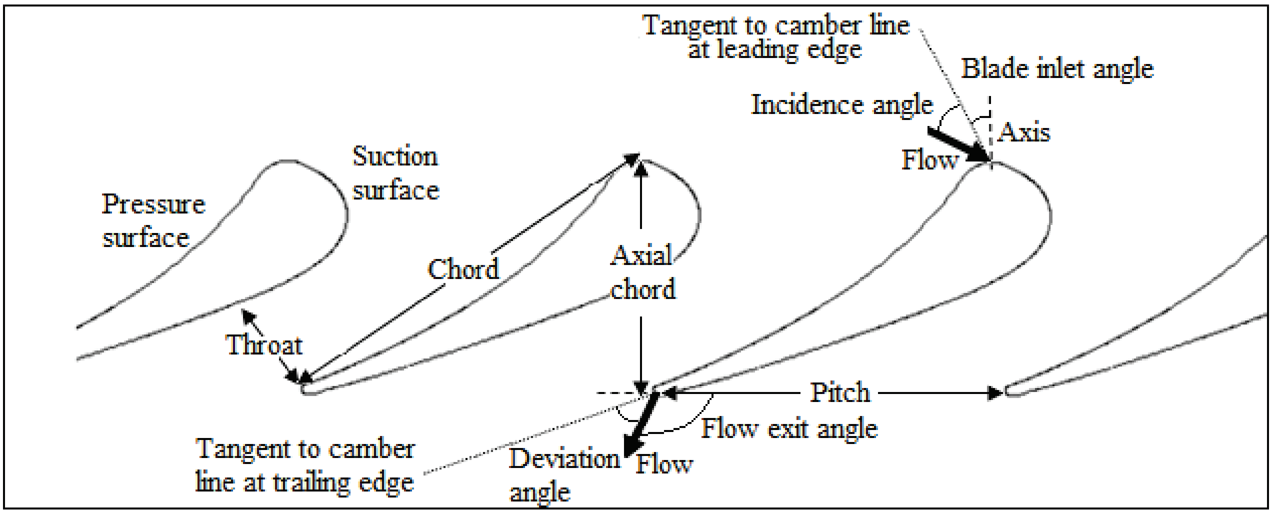

Fig. 1. Cascade Geometry Nomenclature [Bugała, 2018]

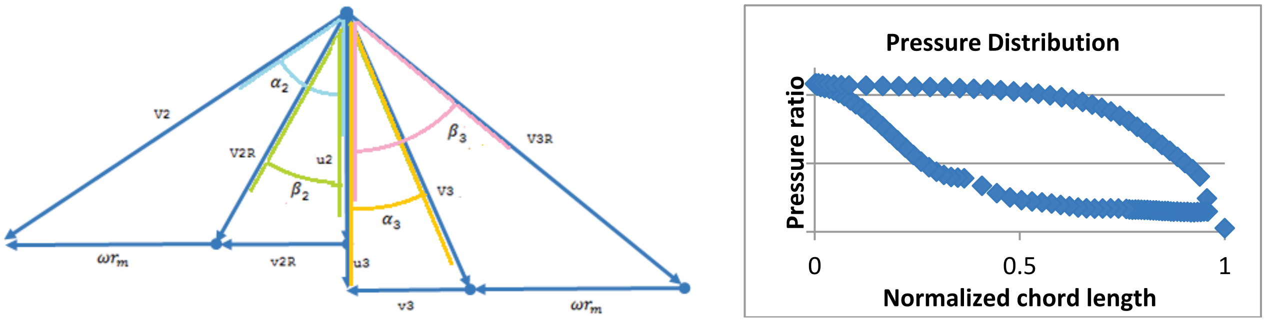

Fig. 2. Velocity triangles measured from axial direction for a typical one-stage turbine and pressure distribution on a turbine blade [Bugała, 2018]

drop, than intended by the designer. For this reason, the deviation angle model needs to be established.

Knowing the importance of being able to predict the deviation accurately, the author presents a set of deviation angle models, which are commonly used to analyse the off-design high-pressure turbines.

The first correlation described in this article has been defined by Ainley and Mathienson [1]. The correlation is based on the blade opening or throat. A set of analytic expressions for different Mach-number conditions is shown below. The correlation is based on flow outlet angle rather than deviation.

1. Predicted outlet angle for incompressible-fluid turbines, and for compressible-fluid turbines with throat Mach number up to 0.5:

$$|\alpha_{ex}|_{0<M_t<0,5} = \left[\frac{7}{6}\left\{\left|\cos^{-1}\left(\frac{o}{s}\right)\right| - 10^o\right\} + 4^o\left(\frac{s}{e}\right)\right], \tag{1}$$

2. Predicted outlet angle for turbines with sonic flow at the throat:

$$|\alpha_{ex}|_{M_t=1} = \left|\cos^{-1}\left(\frac{o}{s}\right)\right| - \left|\sin^{-1}\left(\frac{o}{s}\right)\right|\left(\frac{s}{e}\right)^{\left(1.786+4.128\left(\frac{s}{e}\right)\right)}, \tag{2}$$

3. Predicted outlet angle for throat Mach number between 0.5 and 1:

$$|\alpha_{ex}|_{0.5<M_t<1} = |\alpha_{ex}|_{0<M_t<0,5} - (2M_t - 1)\left(|\alpha_{ex}|_{0<M_t<0,5} - |\alpha_{ex}|_{M_t=1}\right), \tag{3}$$

where:

o – diameter of throat opening,

s – blade pitch,
e – radius of curvature of blade convex surface downstream of throat,
M_t – Mach number at throat.

The second correlation is the deviation model developed by Islam and Sjolander [5]. This model assumes that the deviation is determined by the blade loading towards the trailing edge. The correlation was based on experimental and numerical results obtained for turbine blades and reflected the recent improvements in turbine blade design. The resulting deviation correlation is shown in the article [5] and is given by the following equation:

$$\delta = \frac{(AVDR)^3 \left(\frac{s}{c}\right)^{1.1} (\alpha_1 + \beta_2)^{2.25}}{\xi^{1.45} \left(\frac{t_m}{c}\right)^{0.3} (22 + 0.22\beta_1^{1.64})}, \tag{4}$$

where:
δ – flow deviation (in degrees),
$AVDR$ – axial velocity density ratio,
$\frac{s}{c}$ – blade space-to-chord ratio,
α_1 – inlet flow angle (in degrees),
β_2 – outlet metal angle (in degrees),
ξ – stagger angle (in degrees),
$\frac{t_m}{c}$ – blade maximum thickness-to-chord ratio,
β_1 – inlet metal angle (in degrees).

The third method calculating the deviation angle is based on a simplified model of flow in oblique cut nozzle. The axis of the gas turbine nozzle is always inclined to the axis of the turbine. Therefore, on the outlet there is an oblique cut nozzle.

If the ambient pressure is established in the outlet section of the nozzle, the gas flow is influenced only by additional friction work. The direction of the gas stream in this part of the nozzle is consistent with the direction of the nozzle axis. This flow will have the character described above, until the critical pressure is reached. If the outlet pressure will drop below critical pressure, this decompression of the gas from the critical pressure will occur in the oblique cut nozzle. In this case, the inclined flow is limited only on one side by a wall, so it is subjected to one-sided pressure, which causes acceleration of the gas mass in the tangential direction.

Based on conservation laws, Traupel [12] derived the following simple method that allows an accurate prediction of the deviation angle for cascades. The gas flow from the oblique cut nozzle and the pressure distribution on the suction and pressure surface of a turbine cascade, are shown in Fig. 3. Exit flow angle is given by the following equation:

$$\beta_2 = arctan\left[\frac{a}{s}\frac{1}{cos\beta_a}\right], \tag{5}$$

where:
β_a – flow angle in throat,
a – throat opening,
s – blade pitch.

The deviation is obtained from the difference the camber angle at the trailing edge and the exit flow angle.

The last model is the extended Traupel model developed and described by Aronow [2]. This model is based on equations of momentum conservation and equation of continuity in the computational domain, including the throat and exit from the palisade. The function for exit angle includes the range of subcritical and supercritical values. Fig. 4 shows the subsonic deviation correlation.

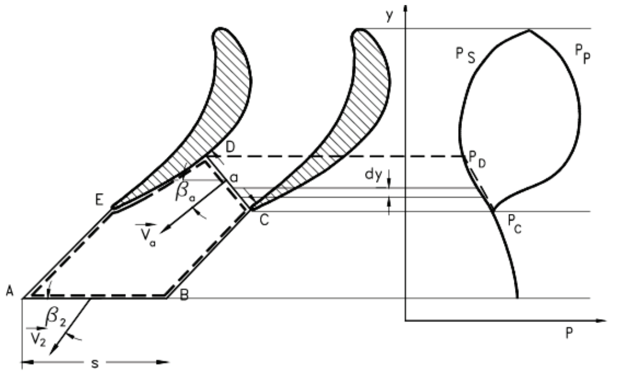

Fig. 3. The gas flow from the oblique cut nozzle and the pressure distribution on the suction and pressure surface of a turbine cascade [12]

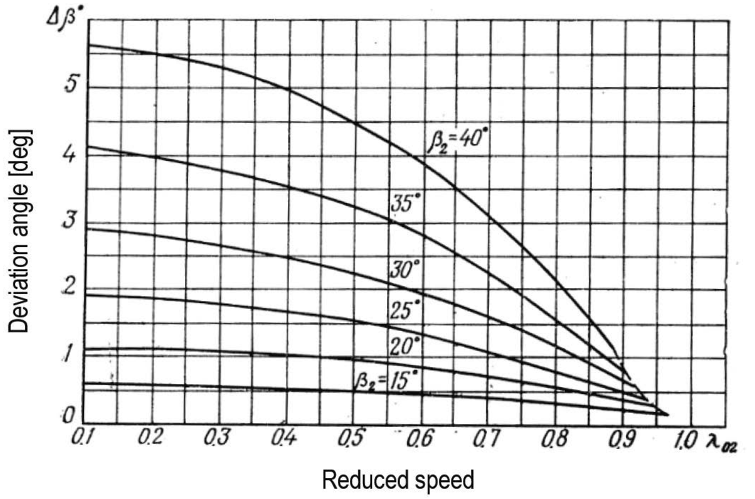

Fig. 4. Subsonic Deviation Correlation [9]

Exit flow angle can be obtained from:

$$\beta_2 = \arcsin\left[\frac{b}{t}cos\chi\frac{y\left(\lambda_{02}\psi_{pr}\frac{cos\beta_2}{cos\beta_n}\right)\pi(\lambda_{02}\frac{\psi_{pr}cos\beta_2}{\psi_{1-n}cos\beta_n})}{y(\lambda_{02}\psi_{pr})\pi(\lambda_{02})}\right], \tag{6}$$

where:

b – throat opening,
t – blade pitch,
$y(\lambda), \pi(\lambda)$ – gasodynamic functions of the reduced speed λ,
λ_{02} – reduced speed,
β_n – flow angle in throat,
ψ_{pr} – speed loss factors for palisades,
ψ_{1-n} – speed loss factors for the part of the palisade from the inlet to the throat.

This method of determination of the outlet angle from cascade was used in [11].

Figure 5 illustrates comparison of the experimentally determined angle of outflow from the stator with the results of calculations. It seems that the accuracy of this equation is quite sufficient for practical calculations. For subsonic flows, the exit angle varies very little with Mach number. For supersonic exit flows, that exit flow angle decreases. This is known as supersonic deviation.

This work is part of research on the topics related to the design and investigation of turbine engines provided by the Institute of Aviation. The material contained in [3] and [4] reflects among others current state of knowledge on the design of aviation turbine engines. The works [8, 10] present simplified methods for calculating turbine performance.

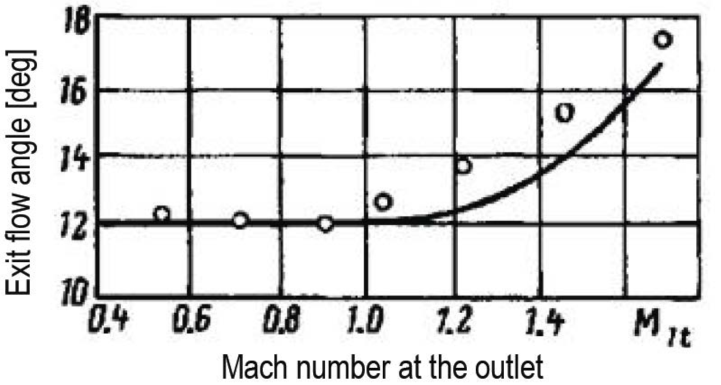

Fig. 5. Comparison of the experimentally determined angle of outflow from the stator (points) with the results of calculations (solid line) [2]

3. Conclusions

Design process of a turbine requires both engineering judgment and knowledge of typical design values. The aerodynamic design process is highly iterative, multidisciplinary and complex. Due to this, the modern gas turbine designers need a sophisticated design tools in terms of aerodynamics, mechanical properties and materials. The paper presents the literature review concerning deviation angle models. It is a significant parameter in the turbine design and performance evaluation. This angle shall be obtained accurately early in 1-D design and evaluation, so as to ensure the validity of blade profiling and calculation results. Unless deviation angle is included, the turbine will produce a lower torque, output work and enthalpy drop than planned by the designer. For this reason, the deviation angle model needs to be established.

Knowing the importance of being able to predict the deviation accurately, a set of deviation angle models, which are commonly used to analyse the off-design high-pressure turbines, has been selected and presented. Depending on the design requirements, the available models are based on the experimental or numerical results and the conservation laws. Those models are claimed to be of sufficient accuracy for practical calculations in works [1, 2, 5, 6, 7, 9, 11, 12].

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