DEVIATION ANGLE IN TURBINE NOZZLE CASCADE WITH CONVERGENT MERIDIONAL SHAPE OF FLOW PATH

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ABSTRACT

This paper focuses on the subsonic deviation in axial and radial turbines while performing 1D/2D simulations.
Two turbines for which experimental data are available were considered in the article: axial (NASA Energy Efficient Engine) and radial (NASA CR-3514). According to the existing loss models, deviation angle in the stator cascade for considered flow parameters and blade designs should not exceed 0.2-0.3 degrees. However, experimental reports have shown the deviation angle of approximately 2 degrees.
Conducted additional CFD simulations have shown that the reason of such flow behavior is the convergence of the flow path meridional shape which is presented for both considered turbines.
Based on the three-dimensional flow analysis a technique for calculating the deviation angle, depending on the meridional shape of the turbine flow path was proposed and described in the paper. The values of deviation angle, calculated using proposed technique have met good agreement with experimental data.

1. INTRODUCTION

An axial or radial turbine is one of the key elements of the Organic Rankine Cycle. Correct prediction of its performance parameters leads to a more accurate efficiency estimation of the entire cycle.
In turn, the prediction of cascade outflow angle is an essential step in turbine performance analysis. It is a common practice to reference the discharge flow angle to the gauging angle by defining the deviation angle as (Aungier, 2006):

$$\delta = \alpha_1 - \alpha_g. \tag{1}$$

Usually, deviation angle for standard turbine cascades with subsonic flow is considered to be insignificant or isn't considered at all while performing 1D/2D simulations.
According to Ainley and Mathieson (1951) and Lee (1954) the deviation angle for subsonic flow should be evaluated taking into account the Mach number and the blade outflow gauging angle (see figure 1).

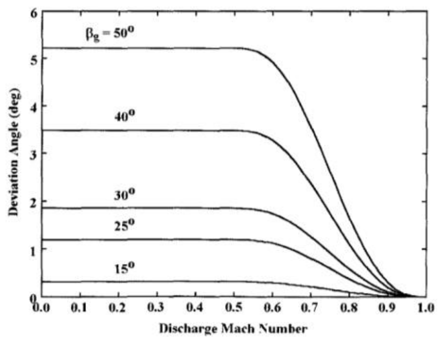

Figure 1: Deviation angle correlation for subsonic flow

Typically impulse turbines are designed with outflow angle from the nozzles to be in a range of 12-16° (from tangential acute) and Mach number > 0.6. For such applications according to figure 1 deviation angle should not exceed 0.2-0.3.
Shchegliaev (1976) proposed to define deviation angle when Mach number < 1 using equation:

$$\sin \alpha_1 = m \cdot \sin \alpha_g, \tag{2}$$

where $m \approx 1$ for modern aerodynamically efficient profiles. Thus, cascade outflow angle became equal to gauging angle and deviation angle is neglected.
Carter and Hughes (1950) were estimating deviation angle as a function of blade stagger angle, blade camber and the solidity of the blades. Originally this deviation model was developed for compressors but with specific settings may be also applied to turbine blades. Developed in 1950's using blade designs of that times may be not accurate for modern blades.
Islam and Sjolander (1999) have improved turbine deviation corrections based on Carter and Hughes model. They have found that the biggest influence on the turbine deviation have several factors: flow turning, pitch-to-chord ratio, inlet incidence angle, stagger angle and maximum thickness-to-chord ratio. Obtained correlation appears to have good agreement with database of measured values of turbine deviation angle.
It should be noted that none of the above-mentioned models takes into account the meridional shape of the turbine flow path. However, three-dimensional flow can have significant impact on the resulting cascade outflow angle. Current paper is focused on the development of the correction technique in which such effects are considered.

2. TURBINES UNDER CONSIDERATION AND INITIAL DEVIATION ANGLE PREDICTION

Two turbines for which experimental data are available were considered in this investigation: axial NASA Energy Efficient Engine (NASA CR-165149, 1979) and radial NASA TP-3514 (1995). Both turbines have common peculiarityof flow path shape, namely endwalls have convergent shape streamwise (see figure 2).

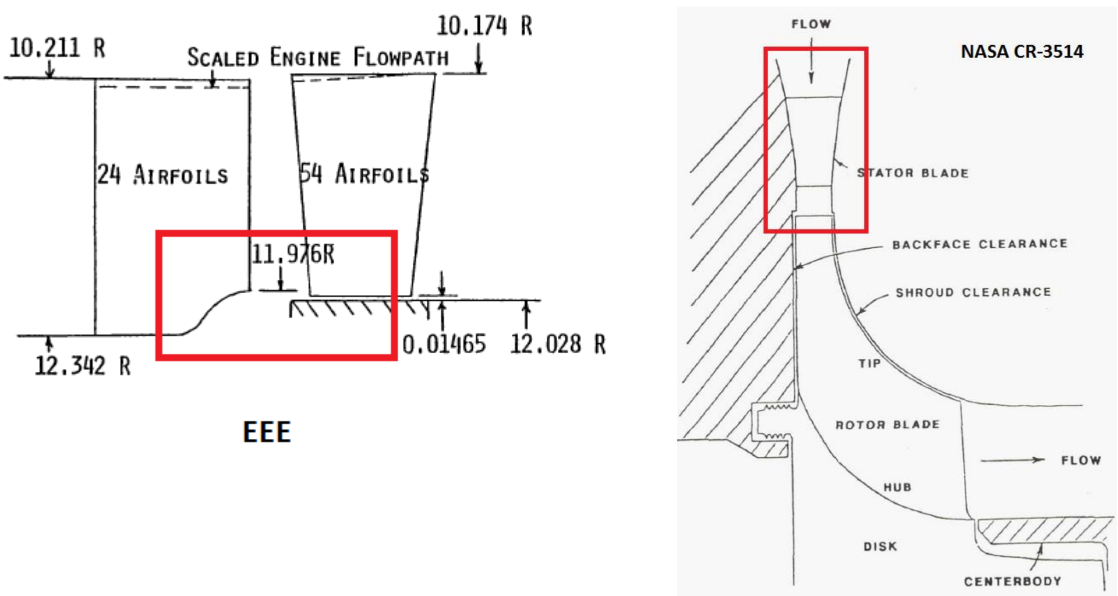

Figure 2: Considered turbines:
left – axial turbine NASA EEE; right – radial turbine NASA CR-3514

Experimental flow data for the considered turbines are given in table 1. According to the Ainley-Mathison and Lee deviation model (figure 1), the deviation angle for the nozzle vanes of the EEE axial turbine should be in a range of 0.1-0.3 degrees, while for radial turbine nozzles it should not exceed 0.1 degree. However, table 1 indicate that experimentally measured deviation angles have much higher values for both turbines.

Table 1: Measured and predicted deviation angle

	Experimental data				Ainley-Mathieson model
Parameter	**Gauging angle, deg**	**Mach number, –**	**Outflow angle, deg**	**Deviation angle, deg**	**Deviation angle, deg**
Axial turbine EEE	9.63	0.78	10.62	0.99	0.1-0.3
Radial turbine CR-3514	15.5	0.97	17.7	2.2	< 0.1

The nozzle deviation angle is not a problem by itself, since for most rotor blades is generally applicable to have inflow incidence up to 4 degrees. However, the deviation angle significantly affects on the massflow according to the methodology used in AxSTREAM® (Boiko and Govorushchenko, 1989). This becomes especially noticeable for nozzle vanes with relatively small gauging angles. For instance, the massflow rate for EEE axial turbine in the experimental report appeared to be almost 10 % higher than that calculated using meanline solver and the Ainley-Mathieson deviation model. This in turn, led to an underestimation of power, efficiency and other turbine performance parameters.

Since nozzle cascades of both turbines have a convergent endwalls, it can be assumed that this factor affects on the angle of deviation. To test this assumption, a series of 3D CFD simulations for the EEE turbine was carried out. At the first stage, the nozzle cascade was considered with parameters that exactly follow the experimental report (geometric and flow parameters). At the second stage, the nozzle shroud endwall was changed to ensure a constant height of the blade streamwise (figure 3). At the same time, the throat, the outlet cross section area and the gauging angle did not change, which makes it possible to compare the results of this calculation with the results obtained earlier (table 2).

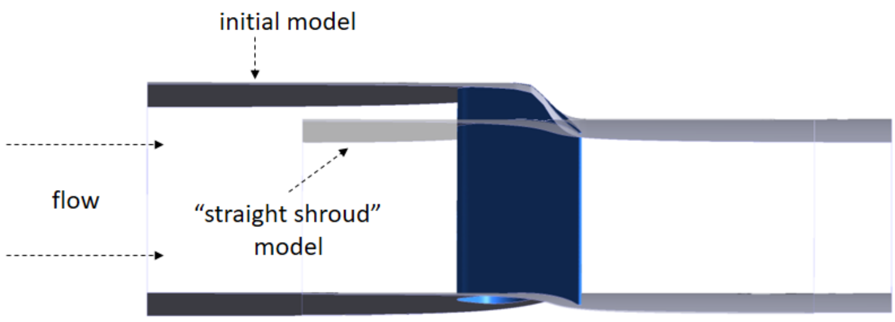

Figure 3: Nozzles for CFD simulations

Table 2: Massflow and deviation angle from CFD simulations

Parameter	**Inlet total pressure**	**Inlet total temperature**	**Outlet static pressure**	**Massflow**	**Gauging angle**	**Outflow angle**	**Deviation**
Initial simulation	3.96 bar	169.2° C	2.51 bar	10.25 kg/s	9.63 deg	10.43 deg	0.8 deg
Straight shroud				9.61 kg/s		9.69 deg	0.06 deg

Table 2 shows, that the deviation angle for the “straight shroud” model is 0.06 degrees, which corresponds to the predicted value according to the Ainley-Mathieson model (figure 1). However, the value of the deviation angle for the original model with curved shroud endwall is much higher and equal to 0.8 degrees. This leads to an increase in massflow by 6.7 %.
In this way, it was shown that the meridional shape of the turbine flow path significantly affects the deviation angle in the turbine cascades.

3. DEVIATION CORRECTION TECHNIQUE

The main factor influencing the stage massflow is the flow factor C_z/U. Since the blade circumferential velocity U is constant at fixed boundary conditions, the massflow change can occur only due to a change in the axial velocity component C_z. It also affects the cascade outflow angle, and hence the deviation angle (figure 4).

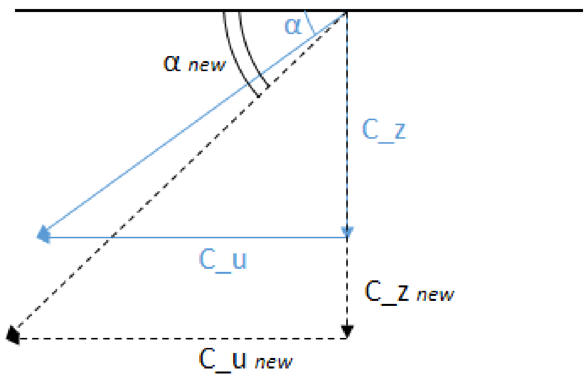

Figure 4: Velocity vector with changed axial velocity component

The developed correction technique assumes that the radial velocity component Cr appears in the flow due to the curved meridional shape of the flow path. At the same time, the real cascade cross section area decreases, which results in the changes of the axial velocity component. Figure 5 presents one of possible cases, when turbine hub is curved which leads to radial velocity component appearance near it. In general case both hub and shroud endwalls may have such shape, thus developed approach should be applicable for all cases.

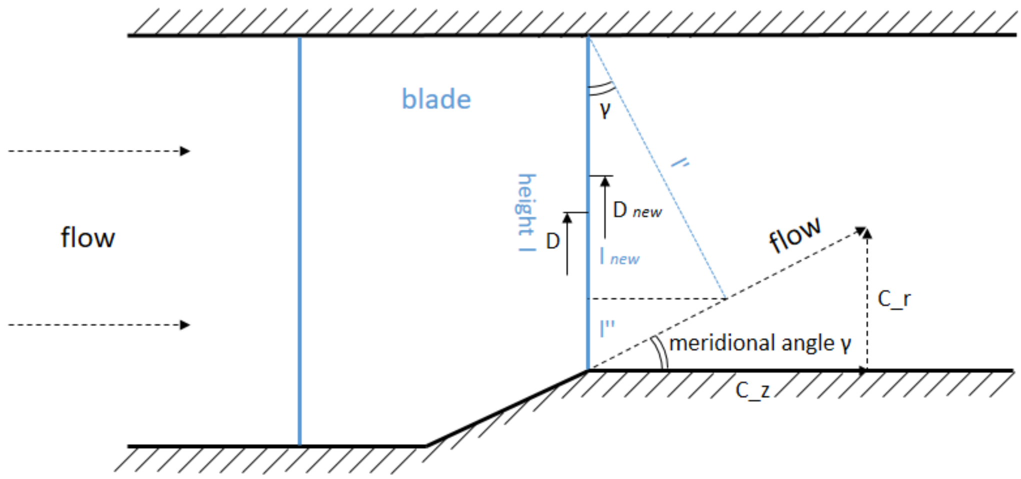

Figure 5: Illustration of correction technique

The new cascade cross section area (height) and the mean diameter can be found using below equations:

$$\gamma = \text{atan}\,(C_r/C_z); \tag{3}$$
$$l'' = l\cdot\sin^2\gamma; \tag{4}$$
$$l_{new} = l - l''_{hub} - l''_{shroud} = l\cdot[1 - \sin^2(\gamma_{hub}) - \sin^2(\gamma_{shroud})]; \tag{5}$$
$$D_{new} = D + l\,(\sin^2(\gamma_{hub}) - \sin^2(\gamma_{shroud})). \tag{6}$$

Continuity equation may applied for any turbine stage:

$$G\cdot v = F\cdot C_z. \tag{7}$$

Hence, a change in the axial velocity component can occur due to a change in the cascade cross section area or the massflow rate, or due to their joint changes. To solve this problem, it was divided into two phases. At the first phase, the flow deviation angle is defined. Assuming that the massflow doesn't changed in the cascade:

$$C_{z\_new} = G\,/\,(Pi\cdot D_{new}\cdot l_{new}\cdot\rho); \tag{8}$$
$$C_{u\_new} = (C_u\cdot D_{new})\,/\,D; \tag{9}$$
$$\alpha_{new} = \text{atan}\,(C_{z\_new}\,/\,C_{u\_new}); \tag{10}$$
$$\delta = \alpha_{new} - \alpha_g. \tag{11}$$

When the deviation angle is defined, 1D/2D simulations should be repeated (phase 2). Using the initial stage parameters, a new value of massflow rate and other performance parameters can be found.
For radial turbine stage, a similar approach can be applied. The difference is that the meridional angle γ is defined as the average inclination angle of the flow path, using the inlet and outlet diameters and the channel length of particular cascade.
Developed deviation correction technique was implemented in the AxSTREAM® throughflow solver (Moroz et al., 2005). Using this solver, streamline simulations for both considered in this paper turbines were carried out. The results of these simulations compared with experimental data and initial predictions are presented in table 3.
Developed deviation correction technique predicts the deviation angle and the turbine massflow with much higher level of accuracy. The massflow difference with experimental data doesn't exceed 2 %, while the difference with CFD simulations is almost absent.

Table 3: Deviation before and after correction

	Experimental data		**CFD simulations**		**1D/2D before corrections**		**AxSTREAM® 1D/2D after corrections**	
Parameter	Deviation angle, deg	Massflow, kg/s	Deviation angle, deg	Massflow, kg/s	Deviation angle, deg	Massflow, kg/s	Deviation angle, deg	Massflow, kg/s
EEE axial	0.99	10.49	0.8	10.25	0.05	9.51	0.79	10.28
CR-3514 radial	2.2	2.71	1.92	2.64	0.002	2.43	1.87	2.72

4. CONCLUSIONS

- Two turbines for which experimental data are available were considered in the article: axial (NASA Energy Efficient Engine) and radial (NASA CR-3514). According to experimental reports, deviation angles are significantly higher than that predicted by existing deviation models.
- The common feature of both turbines is the convergent meridional shape of the flow path. It was assumed that such feature may be the main reason of inconsistent deviation. CFD simulations have proved this statement.

- The new deviation correction technique which takes into account meridional shape of the flow path was developed. Correction technique is based on assumption that the real cascade cross section area is changed due to appearance of radial velocity component.
- Developed deviation correction technique was implemented in the AxSTREAM® throughflow solver. Streamline simulations of the considered turbines have shown that proposed correction technique predicts the deviation angle and the turbine massflow with much higher level of accuracy.

5. FUTURE WORK

In current paper the only designs where turbine flow path has convergent shape are considered. In the future, our plans are to consider how different flow path shapes affects on the deviation angle. If necessary, developed correction technique would be refined.
Also, due to experimental data availability, the developed technique was verified only for subsonic flow velocities. The future development plan includes investigations of the flow behavior in similar channel shapes at supersonic velocities.

NOMENCLATURE

α_1	cascade outflow angle	(degrees)
α_g, β_g	nozzle gauging angle and blade gauging angle	(degrees)
γ	meridional flow angle	(degrees)
δ	flow deviation angle	(degrees)
ρ	density	(kg/m^3)
C_r	radial velocity component	(m/s)
C_u	circumferential velocity component	(m/s)
C_z	axial velocity component	(m/s)
D	mean diameter	(m)
EEE	NASA Energy Efficient Engine	(–)
F	cross section area	(m^2)
G	massflow	(kg/s)
l	height	(m)
v	specific volume	(m^3/kg)

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