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REVIEW OF LOSS MODELS FOR HIGH PRESSURE TURBINES

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Abstract

This article presents a literature review about the physical analysis of the loss models, which are used in off-design procedure for high-pressure turbines.

A high-pressure turbine is designed to have maximum performance at design point. However, engines are operating in different conditions, and the comprehension of off-design conditions is very important. The loss mechanisms are very complex and predictions considering empirical methods are a good approach to have preliminary results. Based on these results, different researches have proposed theories about the loss mechanisms, and over the time, these models have been modified to describe better the phenomena involved between blades and flow. Once the physical mechanisms behind the loss models are known, it is possible to compare them and understand the reason why the results given for some methods present a higher agreement to experimental or numerical data.

In this framework, 2D numerical simulations of the flow around the blades of an axial high pressure turbine with different off design conditions have been realized, by using ANSYS FLUENT® code, to show the losses described by some of these models. Using these simulations a loss model has been selected and implemented in Matlab® to compare its results with the experimental data found in literature.

Keywords: *turbomachinery, gas turbines, high-pressure turbine, HPT, loss models*

1. Introduction

The procedure to design a high-pressure turbine involves different areas of engineering such as thermodynamics, aerodynamics, structure and material science. An iterative process is made to modify the results considering a better knowledge of the flow structure around the blades.

When choosing the gas path for a new turbine, several optimizations must be carried out by the designer in order to achieve maximum efficiency within constrains.

The material contained in [2] and [4] reflects among others current state of knowledge on the design of aviation turbine engines. The works [10, 12] present simplified methods for calculating turbine performance.

A tool to predict the losses in design and off-design conditions is a good way to have the preliminary results faster with relative accuracy.

This article describes firstly the flow field and loss mechanism in axial flow turbines considering the main types of losses. Then a brief explanation about some design and off-design loss models is explained. After a section describing a test case, which compares the results of these loss, models with experimental data and a simulation to show the flow field around the blades.

2. Flow Field and Loss Mechanisms in Axial Turbines

The flow around the turbine blade passage is a complex; this flow is characterized to be three-dimensional, viscous, and unsteady. Different types of flow regimes are present simultaneously. In the real flow case, the stress and strain, large pressure gradients, rotation, curvature, shock waves, boundary layer interactions, and heat transfer are phenomena, which occur during the flight. The geometry of the blades plays an important role when it comes about the behaviour of the phenomena cited above. Fig. 1 represents the flow structure in a turbine cascade.

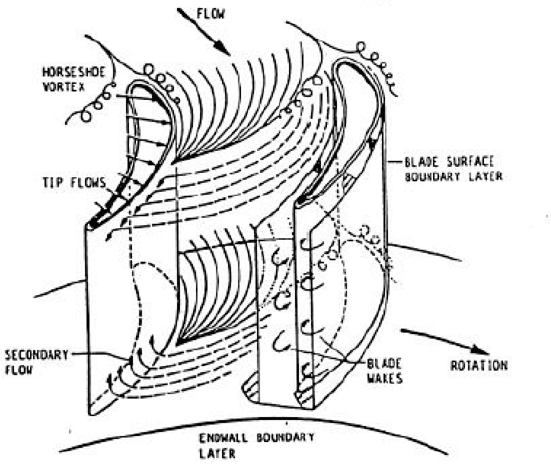

Fig. 1. Flow structure around a turbine cascade [7]

Different turbine design groups have their own system to choose and distribute total stage pressure drop between the rotor and the stator. These rules come from experience of blade testing and the amount of diffusion, which is permissible particularly for highly loaded blades. Locally on the suction surface of the blade, there could be a zone of an adverse pressure gradient depending on the turning and on the pitch of the blades. Thus, the boundary layer could grow rapidly or even separate in such a region affecting adversely the turbine efficiency. Fig. 2 illustrates the schematic of flow within the blade passage and the results of static pressure distribution on the blade surfaces are compared with the results of Fluent solver.

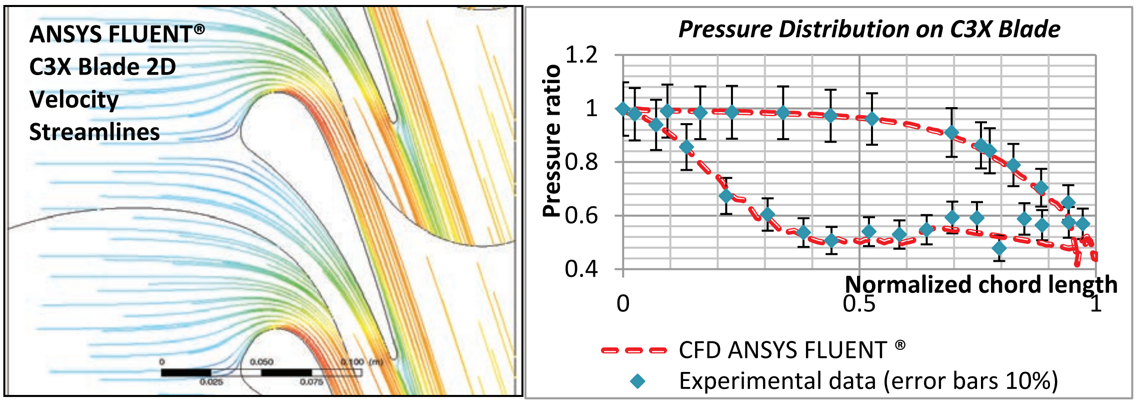

Fig. 2. Schematic diagram of flow through a turbine blade passage and pressure distribution around a turbine blade [Bugała, 2018], [15]

Flow through the rotor blades is related to the resistance and part of the kinetic energy is used to overcome it. The issue of determining the amount of losses generally comes down to determine the loss coefficient. The losses can be divided into different categories. The loss coefficient is a function of a number of variables, which depends on:

– outline of blade geometry (profile losses),
– the clearance between the blade tip and the casing (tip leakage),
– mixing between the secondary flow with the main flow (endwall losses),
– applied cooling (cooling losses),
– gap between the stator and rotor (non-uniform velocity distribution).

Determining the coefficient dependent on so many different factors is possible only on the experimental way but nowadays many loss prediction methods exist to predict losses in turbomachines.

Shock Loss

The shock loss is associated with the entropy creation, which occurs due to heat conduction, and high viscous normal stresses within the shock wave. Fig. 3 represents a typical contour of Pressure and Mach number around the blades. It is important to emphasize that the magnitude of the shock losses and the point where it happens across the airfoil may change varying the incoming flow.

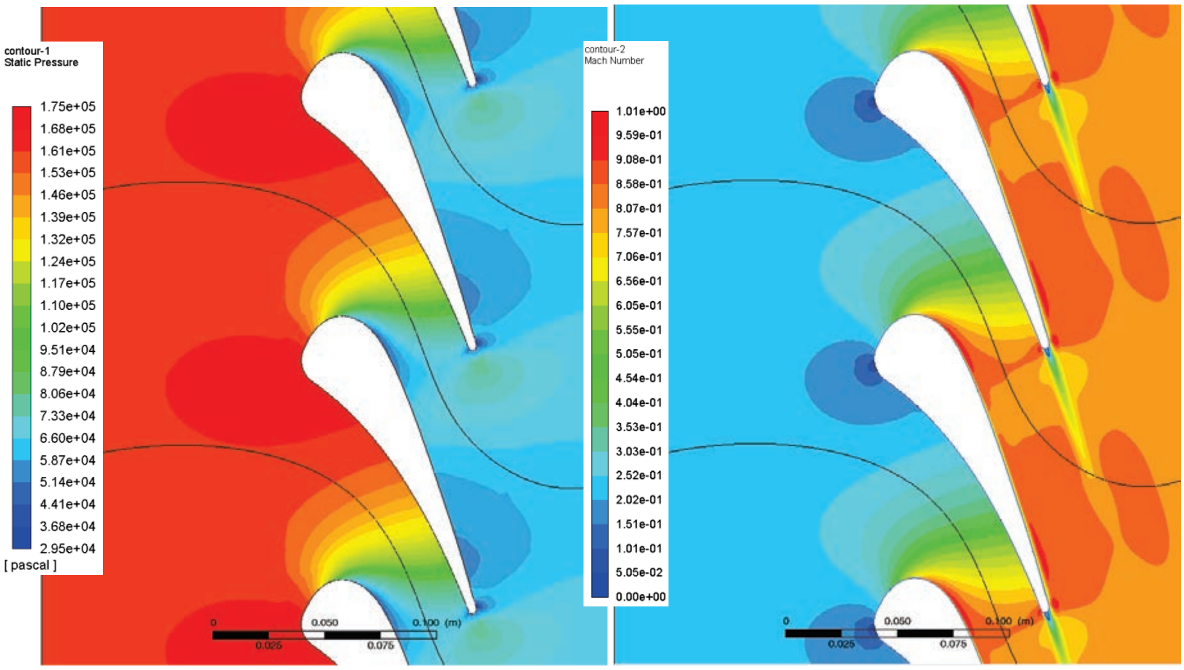

Fig. 3. Contours of Pressure and Mach number [Bugała, 2018]

Profile Losses

This loss happens due to the blade boundary layers on blade surfaces through viscous and turbulent dissipation [16]. The energy is transformed into heat within the boundary layer, therefore there is an increase in the entropy and it results in the stagnation pressure loss. Roughness of the blades surfaces, Reynolds number and the flow velocity are parameters that influence the magnitude of this loss.

Commonly the trailing edge loss is accounted for this type of loss, which occurs due to the finite thickness of the blade causing flow separation and shock expansion wave as a result of sharp corners.

Tip Leakage

This loss is caused by the clearance between the blade tip and the casing. It can be considered in different ways depending whether the blade is shrouded or unshrouded.

The loss happens because of the mixing of the leakage flow and the main flow, once they have different angles and velocities when mixing the flow generate the dissipation. The principal factor which influence this loss are the clearance size, cascade incidence and the pressure difference between the pressure surface and suction surface [3].

References [5, 14] are to the causes of the variability of the tip clearance of the rotor blades relative to the stationary walls of the casing, depending on the engine operation ranges and flight conditions of the aircraft.

Endwall Losses

This loss happens because of the mixing between the secondary flow with the main flow. It results in the formation of the secondary vortex and the counter vortex and the interaction among these vortices. These losses are lumped with the annulus wall boundary layer losses. The source of loss mechanisms is viscous and turbulent mixing and dissipation [16].

Cooling Losses

The gas turbine performance increases with increasing turbine inlet temperature. Nevertheless, this temperature is a design constrain, once the structural components have a restriction about the maximum temperature, because it can generate mechanical failure or even melt the turbine blades. Thus, cooling techniques should be implemented to maintain the blades at an acceptable temperature.

However, the cooling process generates aerodynamic losses increased profile losses as a result of thicker blade profiles from coolant holes, interaction of coolant film with the blade boundary layer, mixing losses between coolant and main flow and endwall losses. Currently, only the experimental tests are reliable to determine the aerodynamic performance.

3. Loss Models

Due to the complex flow and phenomena involved in the flow around a blade turbine an estimation of local losses is related with the solution of Navier-Stokes equations with a turbulence model. However, some authors have developed loss models to predict these losses. These losses are important to the preliminary design of the turbine considering both design and off-design points.

Ainley & Mathieson

Considering experimental data, Ainley & Mathieson developed a method to predict the losses through a turbine cascade. This method was widely used and can be used to predict the performance of an axial flow turbine over a wide part of operating range [1]. They assumed that the pressure loss coefficients are not influenced by the Mach number and the outlet angles from a blade row are not impacted by the flow incidence angle range [16].

The profile loss is a function of the inlet and outlet gas angles, trailing edge thickness, and chord. After knowing the stall incidence angle and the incidence angle, it is possible to predict the off-design profile loss coefficient. The secondary loss equation was derived from performance measurements and correlation given for profile loss [13]. This loss coefficient is predicted based on the blade loading considered as a main function of the blade turning. The tip leakage loss is function of blade loading, ratio tip clearance, and blade height. The total loss coefficient is the summation of these losses multiplied by a factor, which takes account for the trailing edge.

Dunham & Came

The previous method was improved by Dunham & Came; the development of the method is based on recent experimental data. They found that the Ainley & Mathieson method was not satisfactory for small turbines, thus they introduced some factors to correct the loss models [8].

The profile loss takes account for the coefficient found in the previous method taking into consideration the Mach number. The secondary loss model was corrected with the inclusion of a parameter, which is related, with the aspect ratio of the blade. The tip leakage loss coefficient is a power function of the tip clearance instead the linear function given by Ainley & Mathieson. The total loss has the influence of the Reynolds number on the profile and secondary loss.

Kacker & Okapuu

The loss model developed by [9] was based in both previous loss models. Considering experimental data, the introduction of compressibility and shock losses into the calculation of profile and secondary loss allowed better accuracy with these data. The data to predict profile loss coefficient given by the Ainley & Mathieson was based on experimental data at low velocity, and therefore could not predict well the behaviour of this loss in high Mach numbers. In order to correct it, a correction factor was introduced to determine this loss coefficient.

Kacker & Okapuu taking into consideration the influence of blade aspect ratio and the flow compressibility developed a new equation to predict the secondary loss coefficient. The trailing edge loss considers the pressure trailing edge loss coefficient is a function of outlet Mach number and energy trailing edge loss coefficient, the last is a main function of the ratio of trailing edge thickness to the throat distance of blade passage.

The tip leakage loss uses different equations whether the blade is shrouded or unshrouded. In total loss coefficient, the Reynolds number affects only the profile loss and the trailing edge loss is calculated separated from other losses.

Craig & Cox

The method developed by [6] is based on linear cascade tests on blading, on a number of turbine test results and on air tests of model cases. With their methodology, it is possible to predict the performance with high accuracy [7].

The profile loss consists of an incompressible profile multiplied by a factor with takes account for Reynolds number, incidence, and trailing edge, and there is a correction due to the Mach number. When it comes about the off-design, the profile loss coefficient is altered by a factor of incidence losses.

The secondary loss is a function of basic secondary loss flow, Reynolds number, and blade aspect ratio, because Craig & Cox using the experimental data from straight cascades that this type of loss did not need to be corrected for use in turbine stage calculation [16].

The tip leakage loss is calculated by the variation of the cascade efficiency due to the tip leakage loss and is a function of the leakage coefficient, ratio of the clearance to throat areas and the efficiency when the clearance is equals to zero. The annulus loss is important as a result of the interaction between two stages or between stator and rotor, the annulus loss coefficient is a function of geometry of the annulus wall. The total loss the simple summation of profile, secondary and annulus wall coefficients.

Moustapha

This loss model is used to predict the off-design conditions for profile and secondary losses.

The incidence losses are function of leading edge diameter, pitch; aspect ratio and channel convergence [11], where a factor takes account the variation of kinetic energy created by the off-design conditions.

The secondary loss would vary with the incidence, leading edge diameter, and blade turning.

It is important to emphasize that this model works only for off-design condition, and according to [16] the method developed by Kacker & Okapuu is used to calculate the losses at design point.

4. Computational Implementation and Results

The first methodology explained in this analysis was the model developed by Ainley & Mathieson. Loss coefficients determined by this method are an input to other loss models; therefore, it is important to validate this method.

Reference [1] there is a step-by-step calculation to predict the loss coefficients for stator and rotor row in a specific flight condition in both design and off-design points.

Following this procedure, it was possible to implement the loss model using Matlab and compare outcomes from the developed code and data provided by [1].

Tables 1 and 2 show the losses in both design and off-design conditions, respectively. Incidence angle was the parameter selected to determine if in a certain condition the flow is inside or not the design point. All the geometrical and flow information needed to obtain these values were presented.

Tab. 1. Stator Loss Coefficients from [1]

Profile Loss	Secondary and Leakage Los	Total Loss
0.0288	0.0295	0.0593

Tab. 2. Rotor Loss Coefficients from [1]

Incidence angle	Profile Loss	Secondary and Leakage Losses	Total Loss
-28.5	0.1739	0.1178	0.2800
-14.3	0.0853	0.1178	0.1950
-7.6	0.0565	0.1378	0.1767
0	0.406	0.1668	0.199
9.5	0.0821	0.2186	0.288
14.3	0.1820	0.2186	0.3845

It is important to emphasize that during the calculation performed in reference [1], some approximations were done, and it influenced the final loss coefficients. Outputs from Matlab have loss coefficients closer so Ainley & Mathieson and the off-design losses have a similar trend as shown in Tab. 2.

Tab. 3. Stator Loss Coefficients given by Matlab

Profile Loss	Secondary and Leakage Losses	Total Loss
0.0295	0.0301	0.595

Tab. 4. Rotor Loss Coefficients given by Matlab

Incidence angle	Profile Loss	Secondary and Leakage Losses	Total Loss
-28.5	0.1938	0.1241	0.3039
-14.3	0.0951	0.1241	0.2086
-7.6	0.0630	0.1429	0.1968
0	0.0421	0.1735	0.2061
9.5	0.1007	0.2254	0.3117
14.3	0.2430	0.2254	0.4477

Based on the geometrical and nominal flow parameters, which can be found in reference [16], Dunham & Came, Kacker & Okapuu and Mostapha & Kaker methods were chosen to compare the experimental data measured by probes at the Royal Institute of Technology and the outputs from Matlab code using the models cited.

Figure 4 exhibits the comparison between the experimental data and the loss coefficients obtained by the implementation of loss models considered for a stator row. All modes over predict loss coefficients and they have almost a constant line along the velocity ratio. Once the Ainley & Mathieson method uses data from turbines prior to 1950, and do not considered some effects, which were taken into account after deeper analysis over time, this method, is the most conservative in predicting the loss coefficients.

The outputs from Kacker & Okapuu and Moustapha & Kacker are equal because the Moustapha model is used just in case of off-design conditions, once the incidence angle is equal to zero, when considering design point conditions, the method developed by the first authors is used to predict the losses. In the Fig. 4 AMDC represents the results from Ainley & Mathienson and Duham & Came, K-O outputs from Kacker and Okapuu model and M-K the loss coefficients using Moustapha and Kacker model.

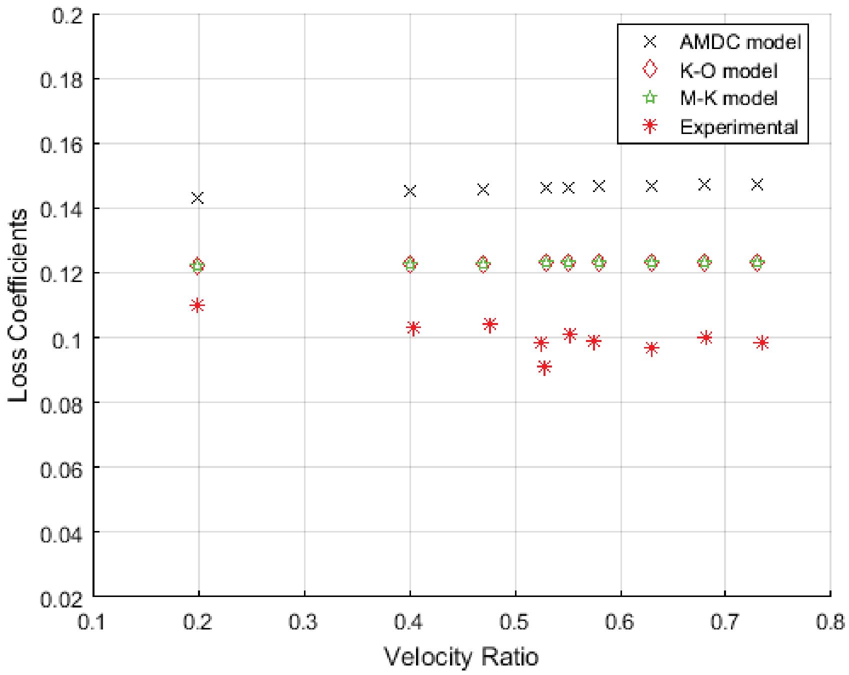

Fig. 4. Profile Loss coefficients over the stator row

5. Conclusions

Determining the loss coefficients in the first phases of an axial turbine project is an important tool to have an idea about the general engine behaviour. The development of a code which compares the loss coefficients using different models revels both design and off-design conditions.

Loss mechanisms, which are the source of the different types of losses, are important and show what are the main geometrical, flow and thermodynamics parameters that change in diverse circumstances.

Many authors developed different loss models to predict the loss coefficients in a considerable range. Based on the physics behind of each model, set of equations were developed as an attempt to meet experimental results.

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