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# Radial Inflow Gas Turbine Flow Path Design

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**Abstract:-** A new method for radial inflow gas turbine flow paths design based on a unique integrated conceptual design environment AxSTREAM is presented in this paper. This integrated environment is a seamless and swift processing scheme that incorporates stages aerodynamic analysis and preliminary design/sizing based on the one dimensional method. The environment makes possible to find number of different designs with inverse task solver, basing on initially specified boundary conditions, closing conditions and design variables. Design space explorer provides easy and visual comparison for range of obtained design in customizable coordinate axes. Solution filtering on different parameters, such as meridional and axial dimensions, maximal blades weight, saving the time to choose from thousands obtained solutions the only one right design. Flexibility of presented approach allows to built-up complete gas turbine flow path from consequence of individual elements: stationary and rotating elements, ducts, heat exchangers, and analyze it in common environment. Complete control of all aspects of aerodynamic flow path quality, structural reliability, and integral performances on design and offdesign conditions is performing throughout all design process. This gives full interaction between user and system for immediate correction and enhancement of current design data using various optimization capabilities to feel the impact of changes on each design step. Integrated system AxSTREAM significantly shortening the design cycle time from initial machine concept to finalized design with all offdesign performances details. The design process is demonstrated for a 25kW radial inflow gas turbine.

**Keywords:-** Radial Inflow Turbine, Performance Maps, AxSTREAM

## I. INTRODUCTION

World's increasing demands in energy, as well as transportation market growth emerges gas turbine manufacturers to be proactive. They have to design machines, that satisfies today's requirements of highest efficiency (i.e. minimal fuel consumption), ability to operate in some certain range of conditions, weight restrictions. To be as much competitive as possible, design cycle shortening and intensifying is necessarily too. That's why question creation of new generation of gas turbine preliminary design environment raised up high last years. As it well-known, most of machine's geometrical properties selects on phase of preliminary design and remain almost unchangeable throughout next design phases, predefining its layout significantly. Therefore, preliminary design task is basis that should be selected very carefully. But from other side, it can be a number of different options that also can be found useful and need to be considered. This paper is describing theoretical backgrounds and internal structure of integrated gas turbine preliminary design system [1,2]. At the end process is demonstrated for 25kW radial inflow gas turbine with off design performance.

In recent years, methods for turbomachinery flow path design have greatly improved due to introduction of three dimensional (3D) viscous flow concepts. But one dimensional (1D) and two dimensional (2D) calculations are also beneficial, especially at the early stage of design. This paper describes the step in turbomachinery conceptual design, which uses 1D calculation [3].

Design of new turbomachinery is a long and complex process. It can be considered as a sequence of several steps.

They are:

- Preliminary design (sizing)
- Meanline and streamline flow path analysis
- Profiling and blade design
- Structure and model analysis
- Flow analysis

The design of radial turbines, begins with a design specification, and proceeds through preliminary design to blade design and finally analysis using increasingly sophisticated tools. A competitive product demands a high level of design optimization, and if this is to be done cost-effectively, an integrated design system is required to enable the designer to bring various design tools to bear at appropriate design points in the process. The design system must also allow the efficient transfer of information, because design is rarely a simple linear process, but almost always involves considerable iteration and development of design concepts in parallel [3,4]. A number of methods have been suggested for obtaining the overall dimensions of radial gas turbines; the most notable has been that presented by Rohlik[5] in the form of charts related to specific speed and defined slip as the ratio of the tangential velocity at the rotor inlet to the rotor tip speed. Benson[6,7] has analyzed the performance of radial turbines, the methods used in these analysis will be used for the development of the procedure for the prediction of the overall dimensions. Stanitz's [8] formula for the relationship between the slip factor and the number of blades for compressors will be used. The aggregate losses due to friction in the blade passages, clearance effects and disk friction are difficult to predict except on past experience. Benson [9] has made an extensive analysis of a number of radial turbines and has reported on a method for evaluating these losses from test data. The method of analysis developed by Benson to predict the performance characteristics of radial gas turbines is the basis of the design procedure. Baines [10,11] suggested an integrated approach to design a radial inflow turbine.

## II. REQUIREMENTS FOR GAS TURBINE INTEGRATED DESIGN ENVIRONMENT

Before design system creation is started, its developers have to outline obligatory requirements, which make such software concept satisfying end-users needs and meets modern turbomachinery design standards. Overview of different theoretical sources and a real design system, implemented in companies, are available in software to establish new design system requirements. Mainly, preliminary design system is integrated with aerodynamic performances analysis to perform study of designed machine and capabilities to alternate between created designs to make refinement, basing on design generated. Additional, but useful features of this system are design of repeating stages, capability to maintain specific design diameter, specification of stages reaction ranges for design, capability to stay in limited axial sizes ranges and weight ranges. One of the main requirements of such system is fast turnaround time with ability to create and consider extensive number of various designs, be able to find trade-off between existing constraints and required outputs. Machine’s various layout configurations and additional elements, such as ducts, exhaust diffusers, surge valves and others, can be used in gas turbine and effect its performances, thus taken into account as part of system design process.

### Radial Inflow Gas Turbine Design In Integrated Envinronment

Traditionally, for radial inflow turbine operation analysis for design and off-design points, the verification analysis problem has been performed in 1D formulations. In verification analysis of a radial inflow turbine, flow is treated as one-dimensional only [10]. Obviously, there is significant 3D flow in a radial inflow turbine. In contrast to 3D viscous flow calculations in a flow path, simplified 1D methods provide a close approximation for experimental data depending on the quality of empirical methods used to determine losses.

Integrated environment AxSTREAM was used to design radial inflow gas turbine by applying aerodynamic concept. An analysis based on AxSTREAM software requires numbers of internal iteration, but the designer will almost certainly have to repeat it a number of times with different starting parameters in order to achieve acceptable turbine geometry. The inlet total pressure can be specified initially. The exit pressure is set by ambient pressure to which turbine exhaust, so that the efficiency is eventually determined by the pressure ratio. Input data and parameters required for the analysis are given in Table 4.1.

**Table I:** Design point technical requirement and parameters

| Data | Unit | Min | Value | Max |
|---|---|---|---|---|
| Boundary conditions | | | | |
| inlet total pressure | bar | 2.8200 | 0.0000 | 2.8200 |
| inlet total temperature | K | 1200.0000 | 273.1500 | 1200.0000 |
| stat. pressure at outlet | bar | 1.1000 | 0.0000 | 1.1000 |
| mass flow rate | kg/s | 0.1028 | 0.0000 | 0.1028 |
| exit angle of inlet volute | deg | 90.0000 | 0.0000 | 90.0000 |
| shaft rotational speed | rpm | 150000.0000 | 0.0000 | 150000.0000 |
| Parameters | | | | |
| Stator outlet mean diameter | mm | 50.0000 | 0.0000 | 70.0000 |
| Rotor blade height ratio (LTE / LLE) | - | 2.5000 | 0.0000 | 5.0000 |
| Rotor diameter ratio m=D1/D2 | - | 2.0000 | 0.0000 | 2.2000 |
| Rotor LE height | mm | 5.0000 | 0.0000 | 6.0000 |
| hub reaction | - | 0.5000 | 0.0000 | 0.5500 |

### Empirical Models Applied for Design

The next empirical losses and deviation models were used for radial inflow turbine design and calculation procedure [4]:

• Radial turbine profile losses – by Craig & Cox

• Radial turbine deviation – by Stepanov

For this data, more than 150 design points were found by the software. Efficiency – flow rate coefficients and typical load diagrams are shown in Fig 1. Point color corresponds to efficiency level. The data point having maximum efficiency was selected for the design and analysis of turbine. Dimensions of turbine in maridional plane are shown in figure 3. Whereas figure 2 shows enthalpy- entropy diagram for 25 kW of radial inflow gas turbine.

## IV. RESULTS AND DISCUSSION

The design procedure provides an estimate of rotor dimension, from which the different ratios for turbine design can be calculated. The radius ratio of turbine hub to shroud at exit is 0.3099 by AxSTREAM. Baines [11] and Glassman [15] suggested this radius ratio is limited by crowding of the blades and it should be set as 0.3. The radius ratio of turbine shroud to tip is 0.6914. Rohlik[5] recommended that this ratio should not be exceed 0.7. The rotor tip width/tip diameter form AxSTREAM is 0.082. G. F. Hiett and I. H. Johnston [16] suggested that rotor tip width/tip diameter of 0.1 appears to be about optimum for maximum efficiency. This suggested that the turbine dimensional ratios calculated by AxSTREAM are very much nearer to the design ratios found in literature.

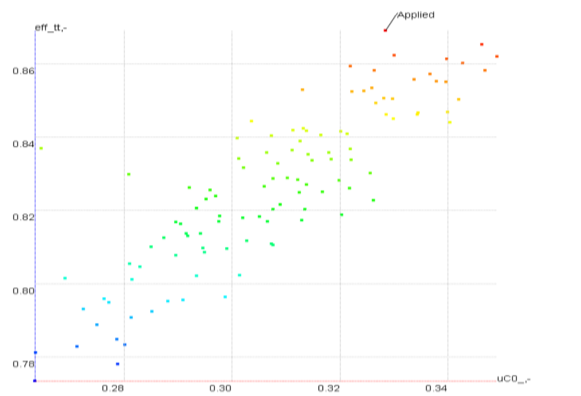


**Fig 1:** Estimated diagrams for radial inflow turbine efficiency

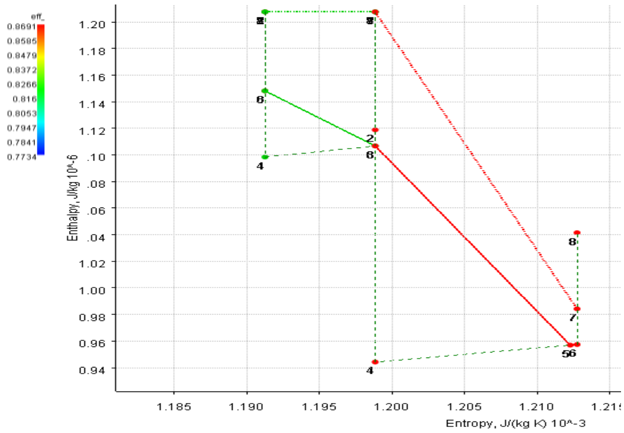


**Fig. 2:** Enthalpy- Entropy diagram

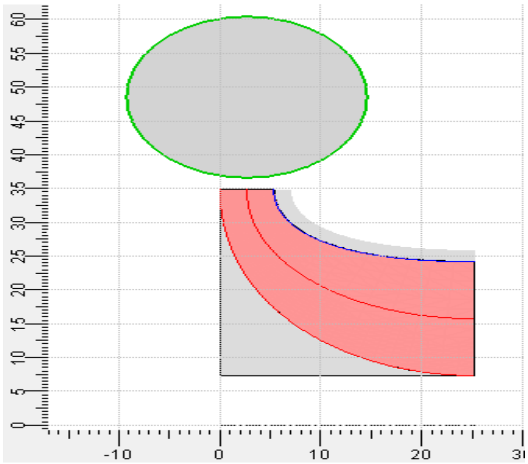


**Fig. 3 :** Dimension of turbine in maridional plane

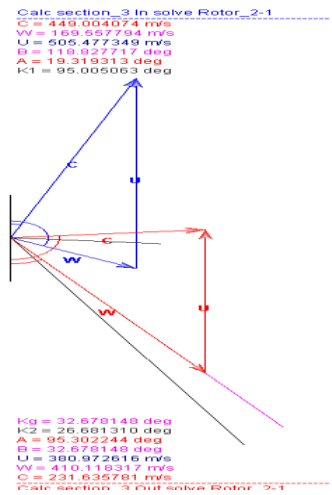


**Fig. 4:** Velocity triangle at inlet and exit

The blade speed is around 505m/s by meanline calculation, which is fairly high but should be acceptable for common rotor materials such as Kersit601, SS 304 or 316 at operating temperature. This will depend on the duty cycle and life requirements of radial turbine and a final decision must be made when structure analysis is carried out, but the value found here gives confidence that it is safe to proceed.

The rotor flow angle is -28˚, which give good incidence on to a radial inlet blade. This angle should be less than -40˚ suggested by Woolley and Hatton [12] and Yeo and Baines [17].

The flow coefficient of radial turbine by AxSTREAM is 0.396. This value should be in the range of 0.2 to 0.3 suggested by A. Whitfield and N.C. Baines [11]. So, further reduction in the loading coefficient is required. Since the power output and mass flow rate are fixed, this implies an increase in blade speed.
Other checks on the validity of the original assumptions can also be made before proceeding. The static pressure is 1.055 bar which is likely to be about the right level for exhausting to ambient pressure with some exhaust system loss. If the exit static pressure is appreciably higher or lower than ambient, corresponding adjustments to the inlet total pressure should be made and the procedure repeated.

## III. OFF-DESIGN PERFORMANCES STUDY FOR SYNTHESIZED MACHINE

**Off-design Study Theoretical Background**

Off-design conditions study and comparison of generated designs is additional point of interest. Off-design calculation requires only variation of boundary conditions: pressure, rotation speed and others for the fixed geometry in direct task. This makes no principal difference between direct task calculation on design and off-design modes in presented approach. As it was discussed above, specific empirical losses models can be applied in direct task for each machine. After applying proper loss models it’s possible to take into account variation of number of important effects, such as profile and secondary losses change depending on off-design conditions, deviation angle variation and calculate critical off-design incidence angles for radial inflow turbine for selected profile geometry. Maps are especially critical in case of turbine designs comparison, where they can have significant influence on design application. Other important question is correct operation ranges prediction. This problem also can be solved by application of real losses models and loss limits to calculation in direct task. Equation set solving results in some discrepancy accuracy on each step, and depending on selected accuracy limits and number of iteration steps performed, different accuracy could be obtained, that indicates stability of current calculated mode. Of course, question of proper loss models selection, as well as applying correct limits and scale coefficient, is crucial for correct operating range determination for each machine type, but it can be resolved to determine right models through model evaluation and comparison with experiment.

In recent years great attention has been paid to radial inflow turbines, especially in those applications where small turbomaehines are required. An investigation has therefore been carried out in order to obtain a method suitable to predict the off-design performances of such a turbomachine. An off-design performance of a radial-inflow turbine is presented by using software AxSTREAM. The software uses one/two-dimensional solution of flow conditions through the turbine passage. The loss model accounts for stator, rotor, incidence, and exit losses. Overall turbine geometry and design-point values of efficiency, pressure ratio, and mass flow are needed as input information. The output includes performance parameters for any number of given speeds over a range of turbine pressure ratio.

Rotational speed of the turbine has been varied between 1,00,000 to 2,00,000 rpm and static pressure varied between 1.0 to 1.2 bar. The results obtained are plotted in Figures 5 to 7 for 7 1D 7 calculation, which shows turbine maps, expressing pressure ratio, total to total efficiency and total to static efficiency as a function of turbine speed.

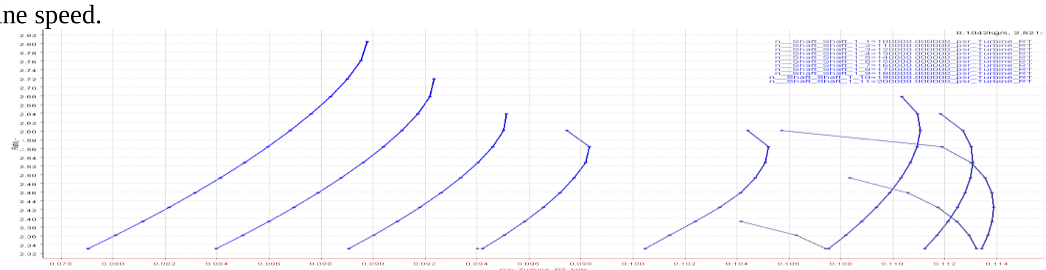

**Fig. 5**: Mass flow rate vs pressure ratio for variable speed (2D calculation)

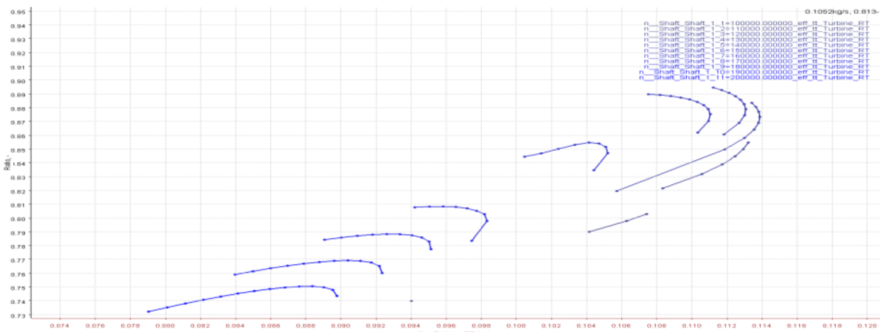

**Fig. 6**: Mass flow rate vs total to total efficiency for variable speed (2D calculation)

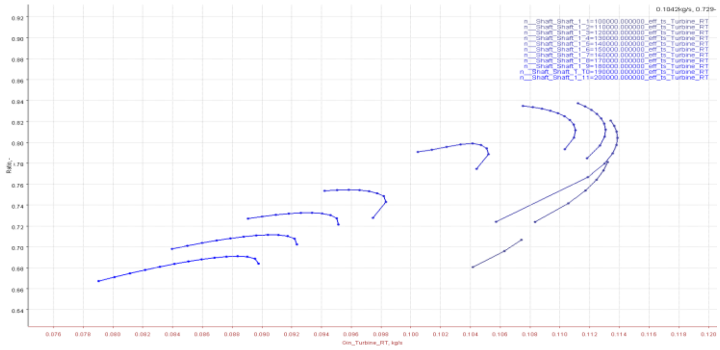

**Fig. 7**: Mass flow rate vs total to static efficiency for variable speed (2D calculation)

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