OFF- DESIGN PERFORMANCE PREDICTION FOR CRYOGENIC SMALL SCALE AXIAL TURBINE USING CFD SIMULATION

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Abstract- The Cryogen based Energy Storage (CES) technology which uses liquid air/nitrogen as an energy carrier has attracted lots of attention recently due to its higher energy density compared to other thermal energy storage technologies. This stored liquid can then be expanded through a Rankine cycle to convert the stored energy to work. Although higher ideal cycle efficiencies can be achieved with this configuration, the effect of the real turbine efficiency can be significant on the overall cycle efficiency. Therefore, it is important to predict the performance of the turbine at cycle operating conditions different from the turbine design operating point. In this work the Mean line method and ANSYS CFD were used to develop a small scale cryogen turbine and predict its performance at different operating conditions using Nitrogen as the working fluid. Results showed that the inlet pressure has the highest impact on the turbine performance as it shifts from the design operating point.

Keywords- Nitrogen ,Cryogenic Axial Turbo-Expander, mean line , CDF Analysis .

I. INTRODUCTION

Liquid air and liquid nitrogen when used as cryogen energy carriers are different to other conventional heat storage media. The energy storage in a cryogen happens through decreasing the cryogen internal energy while increasing its exergy [1-2]. As for energy density, cryogens have shown higher energy density than other thermal energy storage media. Also with their low critical temperatures cryogen are efficient working fluids for recovering low grade heat, thus leading to higher overall cycle efficiencies [1].The stored cryogen liquid can then be expanded through a turbine to convert the stored energy to work [3]. There are several types of cryogenic process plants, like air separation units, helium and hydrogen liquefiers, low temperature refrigerators, and cryogen based Energy Storage (CES) systems [4]. Almost every cryogenic system needs many components like compressor, heat exchanger, expansion turbine, instrumentation, vacuum vessel etc. [5-6]. The expansion turbine constitutes the most critical component of these cycles and its performance can significantly affects the overall cycle efficiency [7]. All cryogenic process plants run under varying operating conditions, and for each plant setting, the turbine inlet temperature, inlet pressure and flow rate will vary, leading to significant changes in turbine performance. Therefore, in order to predict the overall performance of any plant under various operating conditions, it is necessary to calculate the turbine inlet conditions corresponding the cycle operating conditions and to predict the performance of the turbine under such inlet conditions. This requires the study of the performance of the turbine at conditions away from its design point [7].

In this work the Mean line method and ANSYS CFD were used to develop a small scale cryogenic axial turbine and predict its performance at different operating conditions using Nitrogen as the working fluid. Operating parameters like inlet temperature, inlet pressure, mass flow rate and rotational speed were investigated.

II. MEAN LINE METHOD

This method simplifiesthe axial turbine by considering the change in the flow along a mean radius through the turbine with span wise variationsare neglected. In this analysis, the design of the cryogenic small scale axial turbine depends on theblade geometry and operation conditions. This approach is suitable for generating an initial design that can be further improved through 3D CFD analysis. Figure 1 shows the flowchart of the algorithm developed using the Engineering Equations Solver programme (EES).This algorithm is based on inlet conditions data and three estimated parameters. Mach number at stator outlet, swirl velocity at rotor inlet (initially estimated equal to blade velocity) and the outlet rotor temperature are estimated and continuously updated by three internal loops. The efficiency, power and mass flow rate are then calculated [8-9].

III. CFD MODEL

Figure 2 shows the flow chart for the CFD analysis process using ANSYS CFX 15.0 which solves 3D compressible, viscous Navier-Stokes equations.The analysis for cryogenic turbo expander can be performed by three main steps. Blade generation is used to create turbine blade using the shroud, hub and blade angles data generated by the mean line approach. Turbo mesh module was then used to create the mesh structure. Finally, CFX solver was used to input boundary conditions describing the flow and specify the correlations and physical parameters needed for solving the case.

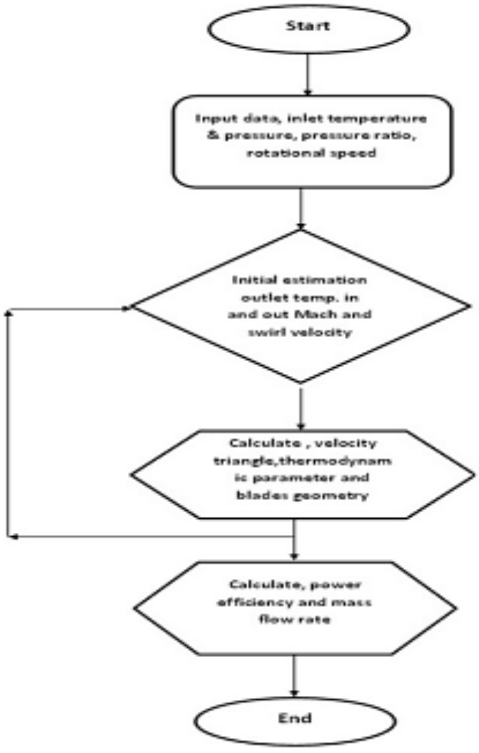


Figure 1 Preliminary design code flowchart

ANSYS TurboGrid module is used to generate the mesh structure where the Global size factor ATM topology method to determine the mesh density. In this work, the node count for the mesh used is 292109. Figure 3 shows the mesh configuration used in this work where O-type grid was used around blade and H-type grid for main gas flow path.

The CFX solver boundary condition have been defined by total pressure and total temperature at the stator passage inlet and mass flow rate at rotor passage outlet. No slip

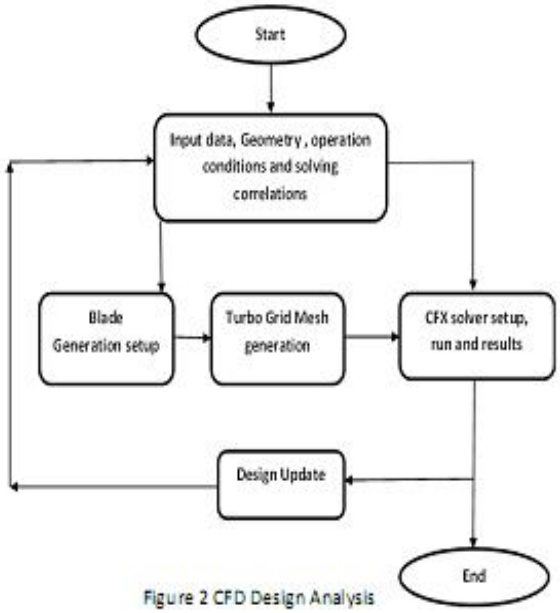


Figure 2 CFD Design Analysis Flowchart

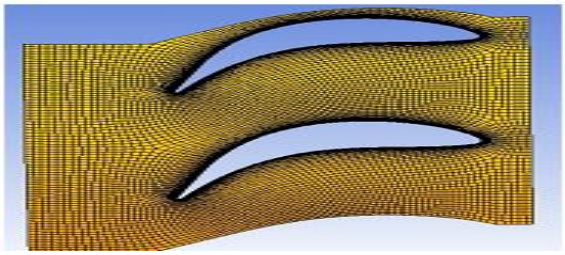


Figure 3. Mesh size and structure

boundary and periodic conditions have been selected to determine flow direction. The Frozen rotor model has been selected to model the interface between the stator outletand rotor inlet domains. In the Frozen rotor model the absolute parameters of the flow field were taken at one fixed rotor location. Theturbulence model is used to evaluated the flow separation from blade surface. In this study the steady state and shear stress transportation (SST) turbulent model have been used [10].

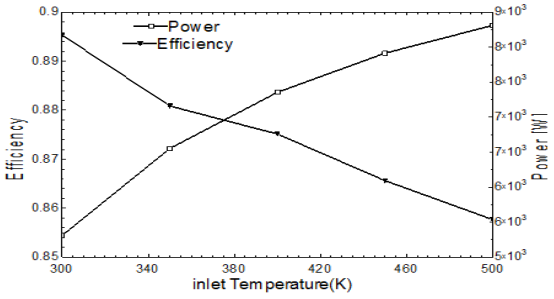


Figure 4 effect of inlet temperature on Power and Efficiency

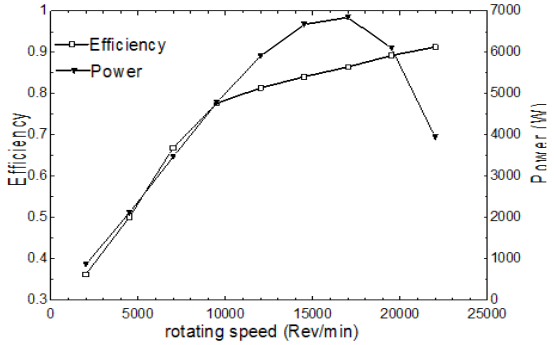


Figure 5. Effect of rotating speed on power and efficiency

RESULTS AND DISCUSSION

By following the design procedure outlined in figure 1, figures 4-5 show theeffect of varying total inlet temperature and rotational speed on the turbine efficiency and power output. Figure 4 show that as the inlet temperature increases, the power output increases while the efficiency decreases. In this case, a temperature of 300K was selected since it gave maximum efficiency of 89.5% with power output of 6kW. Figure 5 shows that as the rotational speed increases, both efficiency and power increases but the power reaches a maximum value at 16000RPM. A rotational speed of 20000 was selected as it produces high efficiency at the required power output.

Table 1. Operation condition for design point

Parameter	Unit	Value
Inlet total pressure	Kpa	300
Inlet total Temperature	K	300
pressure ratio	—	1.1
Tip diameter	mm	100
Hup diameter	mm	60
Blad hight	mm	20
Rotational Speed	Rev/min	20000
stator outlet Mach	—	0.3
stator outlet angle	degree	-15
Gas Constant	—	296.8

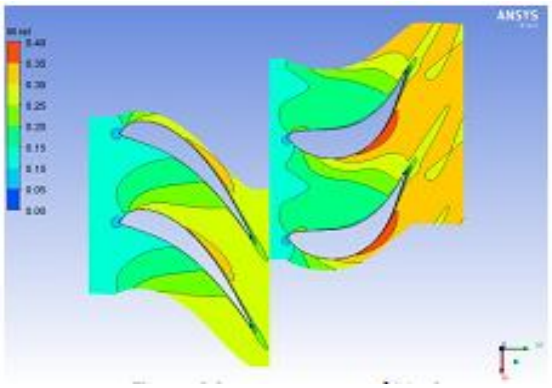


Figure 6.Stage contours of Mrel at 50% span

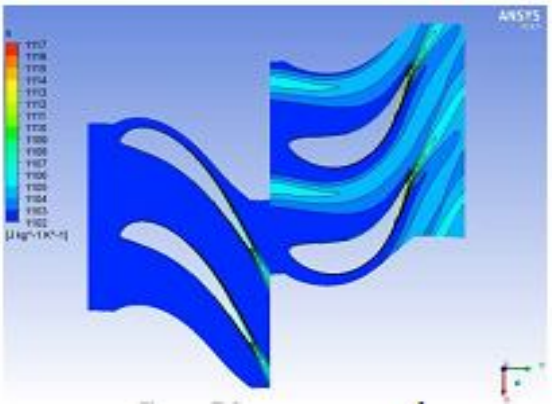


Figure 7.Stage contours of entropy at 50% span

was observed to that of the inlet temperature

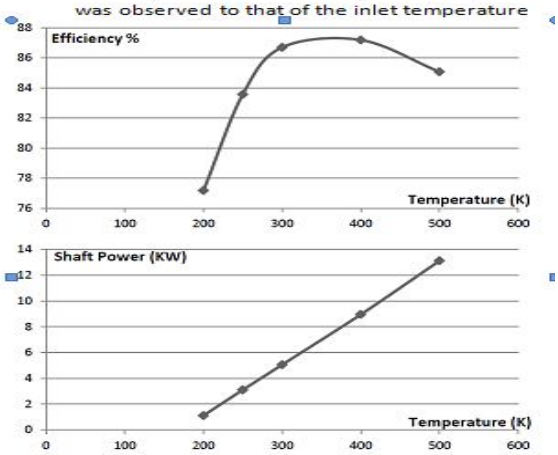


Figure 8.Effect of the Inlet temperature on the shaft power and efficiency

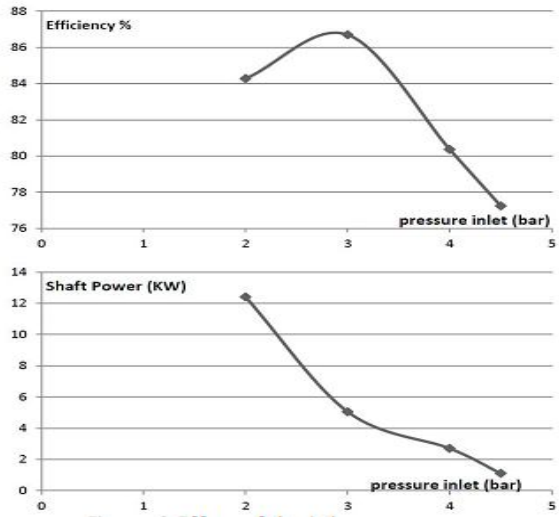


Figure 9.Effect of the inlet pressure on the shaft power and efficiency

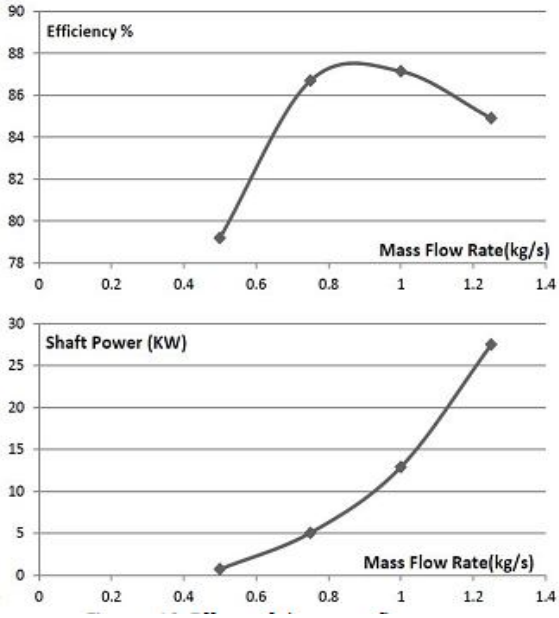


Figure 10.Effect of the mass flow rate on the shaft power and efficiency

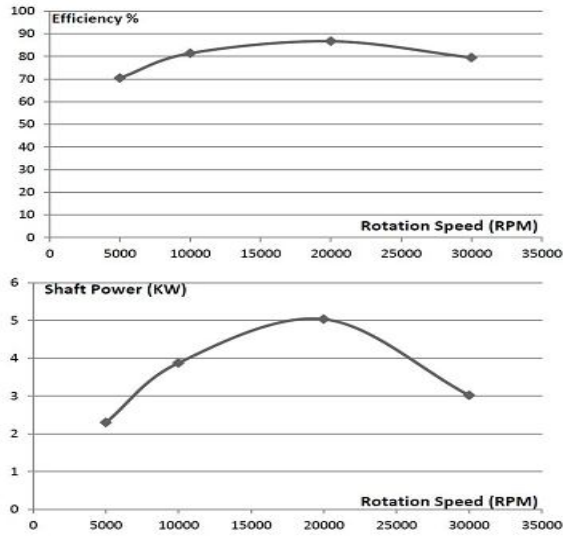


Figure 11.Effect of the rotational speed on the shaft power and efficiency

Table 1 summarises the output from the mean line approach in terms of inlet conditions and turbine initial geometry. Such conditions were used as input to ANSYS CFX software to carry out CFD simulation and achieve the turbine design point withsmoother stator and rotor velocity profile and produce power output with maximum efficiency. Figure 6 shows the Mach number contour in the blade mid span where subsonic flow is evident and no separation as shown in the entropy contours depicted in figure 7. The CFD simulation has been used to investigate the off design operating conditions in terms of changing the inlet temperature, inlet pressure, rotational speed and mass flow arte on the turbine efficiency and power output. Figure 8 shows the effect of varying the total inlet temperature on the power and efficiency. It can be seen that the power increasesas temperature increases while the efficiency increases to maximum value (at the design point of 300K)and then decreases. For inlet temperature ranging from 300K to 400 K, the turbine efficiency remains close to the maximum. Figure 9.show the effect for total inlet pressure variation on the power and efficiency. It is clear from this figure that the design point is at inlet pressure of 3bar where maximum efficiency is achieved. Also, the performance decreases significantly with the increase in the inlet pressure immediately after the design point. Figure 10 shows the effect for mass flow rate variation on the turbine power and efficiency. Similar response was observed to that of the inlet temperature where the output increases as the mass flow rate increases while the efficiency increases to a maximum value and then decreases. Figure 11 shows the effect forrotational speed variation on the power and total to total efficiency. It is clear that the effect of rotational speed on the efficiency is limited while its effect on the power output is more significant

CONCLUSIONS

The Cryogenic Energy Storage (CES) technology which uses liquid air/nitrogen as an energy carrier has higher energy density compared to other thermal energy storage technologies. The energy storage in a cryogen happens through decreasing the cryogen internal energy while increasing its exergy. The expansion turbine constitutes the most critical component of the cryogenic system and its performance can significantly affects the overall cycle efficiency. Cryogenic systems can run under various operating conditions leading to various turbine inlet conditions away from its design point, thus significantly affecting the cycle efficiency.

In this work the Mean line method and ANSYS CFD were used to develop a small scale cryogenic axial turbine and predict its performance at different operating conditions in terms of inlet temperature, inlet pressure, rotational speed, and Nitrogen mass flow rate. Results showed that the inlet pressure has the highest impact on the turbine performance, where power output and turbine efficiency went through significant reductions as the inlet pressure shifted away from the design operating point. Also, the off-design operating range that produced limited reduction of the efficiency is inlet temperature ranging from 300K to 400K, mass flow rate between 0.7 to 1kg/s and rotational speed between 10000RPM to 25000RPM.

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