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Knowledge Based Design of Axial Flow Compressor

Dinesh kumar.R*,Balaji.S**
*(Department of Aeronautical Engineering, Anna University, Chennai.)
** (Department of Aeronautical Engineering, Anna University, Chennai.)

ABSTRACT

In the aerospace industry with highly competitive market the time to design and delivery is shortening every day. Pressure on delivering robust product with cost economy is in demand in each development. Even though technology is older, it is new for each customer requirement and highly non-liner to fit one in another place. Gas turbine is considered one of a complex design in the aircraft system. It involves experts to be grouped with designers of various segments to arrive the best output. The time is crucial to achieve a best design and it needs knowledge automation incorporated with CAD/CAE tools. In the present work an innovative idea in the form of Knowledge Based Engineering for axial compressor is proposed, this includes the fundamental design of axial compressor integrated with artificial intelligence in the form of knowledge capturing and programmed with high level language (Visual Basis.Net) and embedded into CATIA v5. This KBE frame work eases out the design and modeling of axial compressor design and produces 3D modeling for further flow simulation with fluid dynamic in Ansys-Fluent. Most of the aerospace components are developed through simulation driven product development and in this case it is established for axial compressor.

Keywords – codes, Visual Basis net, model, compressor, single rotor

I. INTRODUCTION

An air compressor is a device that converts power (usually from an electric motor, a diesel engine or a gasoline engine) into kinetic energy by compressing and pressurizing air, which, on command, can be released in quick bursts.

Axial flow compressor: An axial compressor is a pressure producing machine. It is a rotating, airfoil-based compressor in which the working fluid principally flows parallel to the axis of rotation. This is in contrast with other rotating compressors such as centrifugal compressors, axial compressors and mixed-flow compressors where the air may enter axially but will have a significant radial component on exit. The energy level of air or gas flowing through it is increased by the action of the rotor blades which exert a torque on the fluid which is supplied by an electric motor or a steam or a gas turbine.

Axial flow compressors produce a continuous decelerating flow of compressed gas, and have the benefits of high efficiency and large mass flow rate, particularly in relation to their cross-section. They do, however, require several rows of airfoils to achieve large pressure rises making them complex and expensive relative to other designs (e.g. centrifugal compressors). Axial compressors are widely used in gas turbines such as jet engines, high speed ship engines, and small scale power stations. They are also used in industrial applications such as large volume air separation plants, blast furnace air, fluid catalytic cracking air, and propane dehydrogenation. Due to high performance, high reliability and flexible operation during the flight envelope, they are also used in aerospace engines.

Axial compressors consist of rotating and stationary components. A shaft drives a central drum, retained by bearings, which has a number of annular airfoil rows attached usually in pairs, one rotating and one stationary attached to a stationary tubular casing. A pair of rotating and stationary airfoils is called a stage. The rotating airfoils, also known as blades or rotors, accelerate the fluid. The stationary airfoils, also known as stators or vanes, convert the increased rotational kinetic energy into static pressure through diffusion and redirect the flow direction of the fluid, preparing it for the rotor blades of the next stage. The cross-sectional area between rotor drum and casing is reduced in the flow direction to maintain an optimum Mach number using variable geometry as the fluid is compressed.

The rotor reduces the relative kinetic head of the fluid and adds it to the absolute kinetic head of the fluid i.e., the impact of the rotor on the fluid particles increases its velocity (absolute) and thereby reduces the relative velocity between the luid and the rotor. In short, the rotor increases the absolute velocity of the fluid and the stator converts this into pressure rise. Designing the rotor passage with a diffusing capability can produce a pressure rise in addition to its normal functioning. This produces greater pressure rise per stage which constitutes a stator and a rotor together. This is the reaction principle in turbo machines. If 50% of the pressure rise in a stage is obtained at the rotor section, it is said to have a 50% reaction.

The airfoil profiles are optimized and matched for specific velocities and turning. Although compressors can be run at other conditions with different flows, speeds, or pressure ratios, this can result in an efficiency penalty or even a partial or complete breakdown in flow (known as compressor stall and pressure surge respectively). Thus, a practical limit on the number of stages, and the overall pressure ratio, comes from the interaction of the different stages when required to work away from the design conditions. These "off-design" conditions can be mitigated to a certain extent by providing some flexibility in the compressor. This is achieved normally through the use of adjustable stators or with valves that can bleed fluid from the main flow between stages (inter-stage bleed). Modern jet engines use a series of compressors, running at different speeds; to supply air at around 40:1 pressure ratio for combustion with sufficient flexibility for all flight conditions.

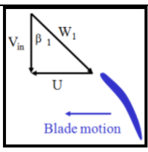
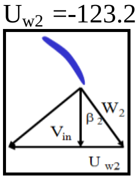
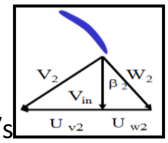
II. LITERATURE SURVEY

Majid Ahmadi, conducted research over "Aerodynamic Design of Turbo machinery Cascades Using A Finite Volume Method on Unstructured Meshes". National Science and Engineering Council, Canada. A recently developed aerodynamic inverse design method for turbo machinery cascades is presented and is implemented in a cell-vertex finite volume method on unstructured triangular meshes. In this design method, the mass-averaged swirl schedule and the blade thickness distribution are prescribed. The design method then provides the blade shape that would accomplish this loading by imposing the appropriate pressure jump across the blades and the flow tangency condition. The method is validated for a parabolic cascade. It is then used to design an impulse cascade and to redesign the ONERA cascade. A recently developed inverse design method for transonic cascade flows has been implemented using a cell-vertex finite volume Euler solver on unstructured triangular meshes. The design method has been validated and was demonstrated for the design of three different cascades. The usefulness of the method in re-moving shocks has also been demonstrated.

Ernesto Benini conducted research over "Three-Dimensional Multi-Objective Design Optimization of a Transonic Compressor Rotor", Journal of Propulsion And Power, Vol. 20, No. 3, May–June 2004. A method for transonic compressor multi-objective design optimization was developed and applied to the NASA rotor 37, a test case representative of complex three-dimensional viscous flow structures in transonic bladings. The optimization problem considered was to maximize the isentropic efficiency of the rotor and to maximize its pressure ratio at the design point, using a constraint on the mass flow rate. The three-dimensional Navier–Stokes code CFXTASCflow® was used for the aerodynamic analysis of blade designs. The capability of the code was validated by comparing the computed results to experimental data available in the open literature from probe traverses up and downstream of the rotor. A multi-objective evolutionary algorithm was used for handling the optimization problem that makes use of Pareto optimality concepts and implements a novel genetic diversity evaluation method to establish a criterion for fitness assignment. The optimal rotor configurations, which correspond to the maximum pressure ratio and maximum efficiency, were obtained and compared to the original design. A method for three-dimensional multi-objective optimization of a transonic rotor blade was developed and tested which was based on an evolutionary algorithm and a Navier–Stokes code. The method BENINI 565 was applied to the design optimization of NASA rotor 37 with the aim of achieving maximum efficiency and maximum pressure ratio with a constraint on the mass flow rate. The rotor blade was described using three profiles along the span, each of which was defined using parametric curves. The effect of blade lean was considered by changing the mutual tangential coordinates of the three profiles. The optimization run was carried out on a multi-processor computer and demonstrated that the overall adiabatic efficiency can be improved by approximately 1.5% (without changing the pressure ratio in a significant way) by giving the blade a proper lean toward the direction of rotation and by slightly changing the profile shape, especially toward the tip. This improvement followed from a drastic modification in the shock structure within the blade passage. The results also showed that the improvement in the overall efficiency, achieved in one operating point, is maintained at off-design conditions. The results also showed that the pressure ratio can be improved by about 5.5% by paying for a small efficiency drop (−0.8%). This was achieved by leaning the blade in the direction of rotation and by slightly increasing the profile curvature toward the rear to assure a subsonic diffusion. In this case, however, the presence of a shock wave, although less intense, accentuated the interaction between the shock and the boundary layer on the rear of the suction surface, a phenomenon that possibly determined a reduction in the operating range of the compressor.

III. KBE FRAME WORK AND DESIGN

The axial-flow compressor compresses its working fluid by first accelerating the fluid and then diffusing it to obtain a pressure increase. The fluid is accelerated by a row of rotating airfoils (blades) called the rotor, and then diffused in a row of stationary blades (stator). The diffusion in the stator converts the velocity increase gained in the rotor to a pressure increase. A compressor consists of several stages. One rotor and one stator make-up a stage, one additional row of fixed blades (Inlet Guide Vanes) is frequently used at the compressor inlet to ensure that the air enters the first stage rotors at the desired angle although the working fluid can be any compressible fluid , only air will be considered in design.

The relative speed of the rotor blade from the rotational velocity.	209.44 m/s 
The air to blade relative and the angle between the relative and actual air speed	$\beta_{1=}$ -50.934°
Calculate relative exit angle (β_2), then portion of the relative blade speed (U_{w2}). Calculate relative air speed (W_2)	$\beta_{2=}$- 35.93° U_{w2} =-123.214 m/s  W_2 =209.956 m/s
The portion of the relative blade speed associated with the actual air velocity (U_{v2}), and the actual air speed (V_2)	U_{v2} = -86.22 m/s V_2=190.617m/s 
The calculation to identify the Compressor Pressure Ratio (CPR).This can be found from the isentropic relationship	P_{o2}/P_{o1} $=(T_{o2}/T_{o1})^{(\gamma/(\gamma-1))}$ T_{o1} $=T_i + (V_{i2}/2Cp)$ =314.392 K
Specific work of the stage is calculated from the torque of the shaft, angular velocity of the blade, and mass flow rate of the air	W_{st} = 1.806e4 J/Kg T_{o2} $=T_{01} + (W_{st} / Cp)$ C_p =1004 m^2/s^2 K =332.38 K
Shaft Torque	T_{sh} =754.476 J Power=632.068 Kw
Compressor pressure ratio	1.215
Principle dimensions	Tip Radius (Rt) =0.2663 m Rr/ Rt =0.5 Root Radius (Rr) =0.13315 m Mean Radius =Rt + Rr / 2 = 0.199725 m Root Diameter = 532.6 mm Tip Diameter = 266.30 mm

Tip and Hub Radius

$R_t^2 = M / [\pi\rho Vi (1 – (rr^2 / rt^2))]$
$N = U / (2\pi R_t)$
U = 350 m/s
N = 8000
$R_t = U / 2\pi N$
$R_t^2 = 0.0532 / [1 - (rr^2 – rt^2))]$

For Hub to tip Ratio 0.3 to 0.7 tabulation is formed from the above relation the RPM can be modified to suit the required hub tip ratio.

Ratio	R_t (m)	U(m/s)	N (Rps)	N (Rpm)
0.30	0.2418	350.00	230.38	13823.06
0.35	0.2462	350.00	226.23	13573.98
0.40	0.2517	350.00	221.35	13280.77
0.45	0.2583	350.00	215.67	12940.44
0.50	0.2663	350.00	209.15	12549.15
0.55	0.2762	350.00	201.70	12101.96
0.60	0.2883	350.00	193.21	11592.41
0.65	0.3035	350.00	183.53	11011.83
0.70	0.3230	350.00	172.47	10348.29

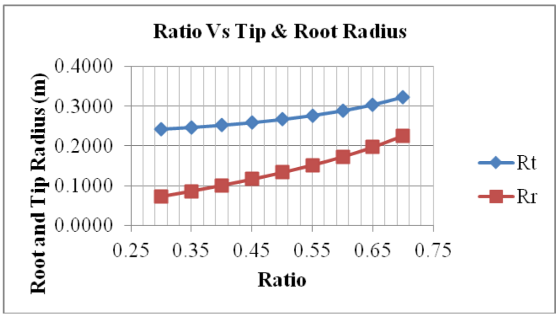


Fig. 1: Ratio Vs Tip & Root Radius

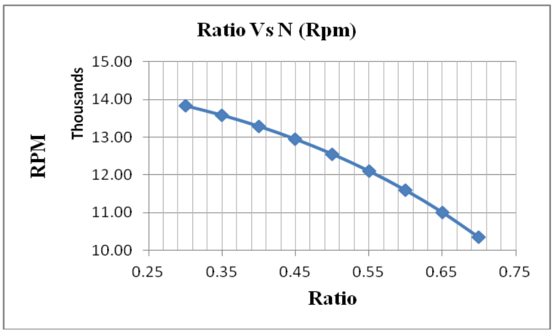


Fig.2: Ratio Vs RPM

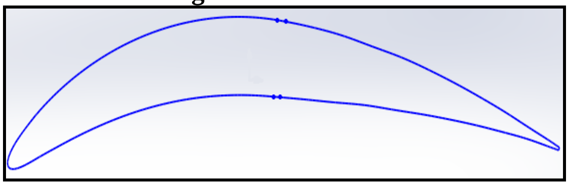


Fig. 3: NACA 63A010

Knowledge based engineering is a knowledge automation technique used widely for design automation. Complex design tasks which conceive lot of time in product development needs KBE tools to accelerate the design phase, which is term minimize the overall product development time. Each product have their own difficulties in development stage and engineering design principals lays foundation for proper product design, in such cases experience designer is the key for best results. Development of software programming helps us to create artificial intelligence integrated programs to represent the designer work and automates all possible works to greatly minimize time and accuracy. In system design where numerous branches integrates their design to get a final product (Ex. Aircraft design), complexity also in greater density, these type of constraints pushes the delivery of best product against time, but thanks to the development of computers and software to develop state of the art tools for knowledge automation, this could be from simple interest calculation to very complex space vehicle design, KBE already into action in almost all industries, for example Boeing uses CATIA for their entire product development, which greatly minimize time and human error. In this research work a KBE frame work is developed for design and modelling of single stage of an axial compressor is proposed and delivered, CATIA is extensively used in aviation industries and its automation tools like VBA, C++ are very much supportive in custom based designs and the same is utilized in this work to do the KBE frame work. The following are the steps involved in developing the KBE frame work for axial flow compressor

- GUI Design
- Input Verification
- Design Calculation
- Result Reporting
- Parametrical CAD model

Once valid design inputs are received then the program performs necessary design calculation to output designed values for compressor blade, the output report delivers all the design results. The following screen shows the codes that performs the necessary design calculations

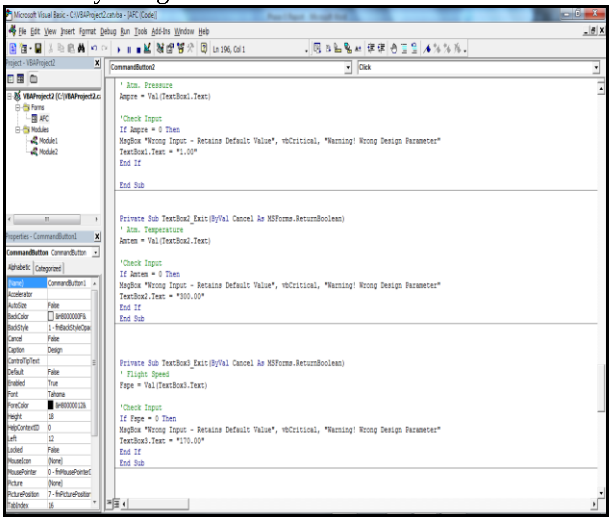


Fig.4: Code

IV. Result Reporting

Once the design calculation is over the results are written to files and delivered as report for further process

i. Parametric CAD Modelling

Parametric modeling uses parameters to define a model (dimensions, for example). Examples of parameters are: dimensions used to create model features, material density, formulas to describe swept features, imported data (that describe a reference surface, for example). The parameter may be modified later, and the model will update to reflect the modification. Typically, there is a relationship between parts, assemblies, and drawings. A part consists of multiple features, and an assembly consists of multiple parts. Drawings can be made from either parts or assemblies. Related to parameters, but slightly different are constraints. Constraints are relationships between entities that make up a particular shape. For a window, the sides might be defined as being parallel, and of the same length. Parametric modeling is obvious and intuitive. But for the first three decades of CAD this was not the case. Modification meant re-draw, or add a new cut or protrusion on top of old ones. Parametric modeling is very powerful, but requires more skill in model creation. A complicated model for an injection molded part may have a thousand features, and modifying an early feature may cause later features to fail. Skilfully created parametric models are easier to maintain and modify. Parametric modeling also lends itself to data re-use. A whole family of cap screws can be contained in one model, for example. The design results will update a parametric CATIA cad model to deliver the first stage of the compressor, which will be taken for flow and further design verification and enhancement works.

The parametric CAD model is very much user friendly and can be updated at any time and for any valid design output to provide faster, quicker and easier design results, the same will be exported is required format (STEP, IGES, etc.,) to perform flow simulation. Since the design, assembly and drafting are concurrently connected updates in design will simultaneously updates other relevant linked works (assembly, drafting, simulation, etc.)

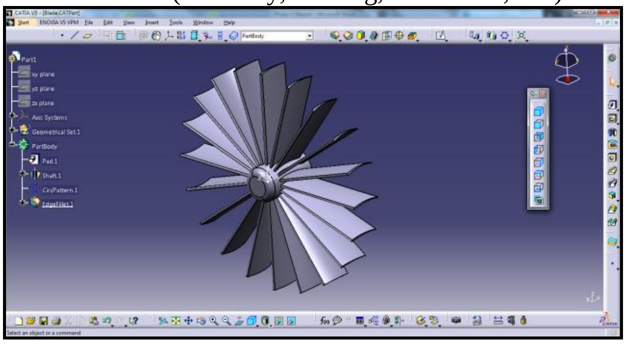


Fig.5: Parametric CAD Model

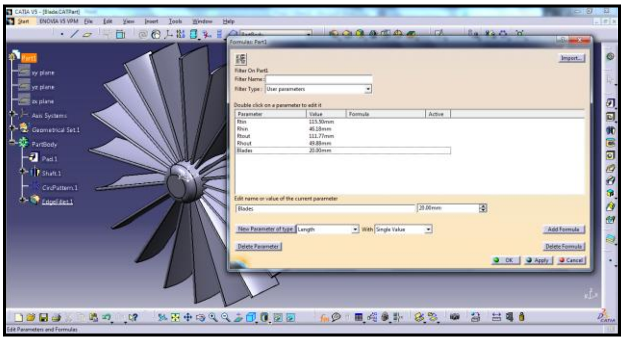
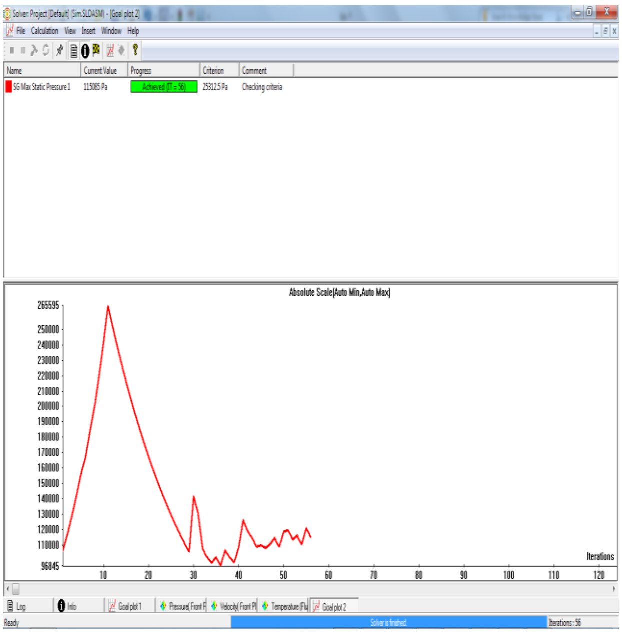


Fig.6: Linked Parameters

V. Simulation results



The benefit of COSMOS flow works is, the solver intelligently takes the iteration quantity which is not possible with Fluent and CFX

Fig.7: Convergence Plot

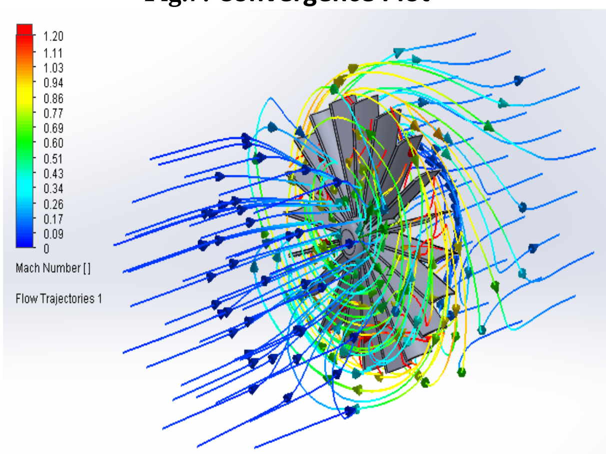


Fig.8: Flow Stream

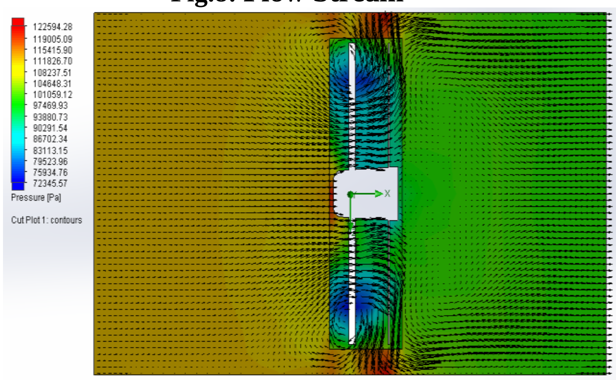


Fig.9: Pressure Plot

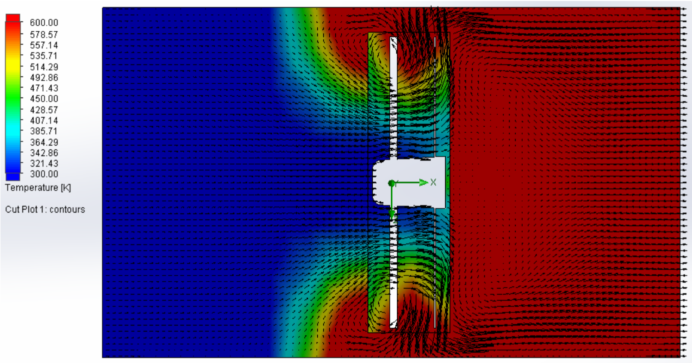


Fig.10: Temperature Plot

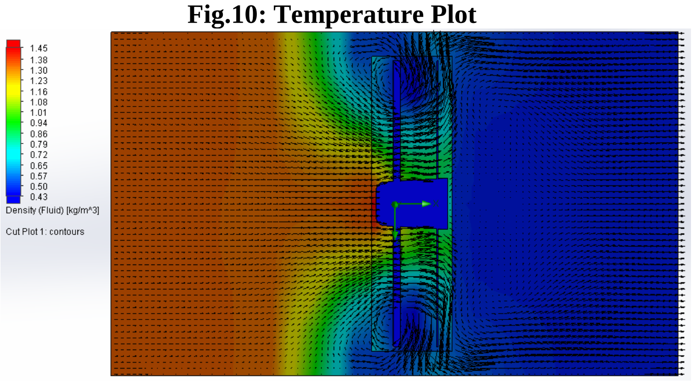


Fig.11: Density Plot

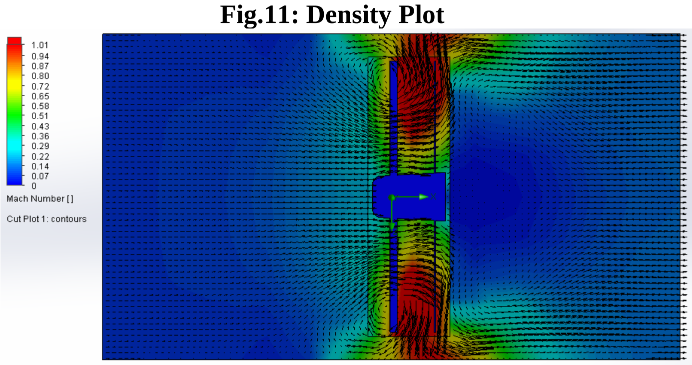


Fig.12: Mach plot

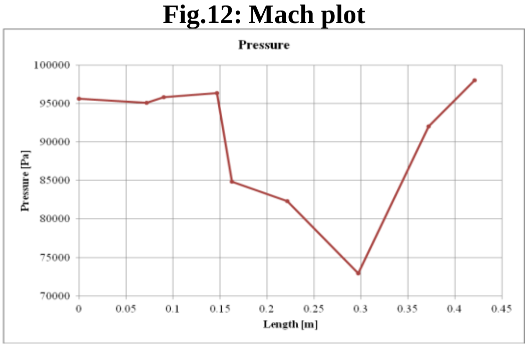


Fig.13: Pressure at Leading Edge

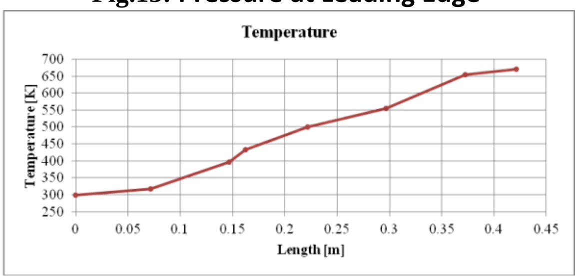


Fig.14: Temperture at Leading Edge

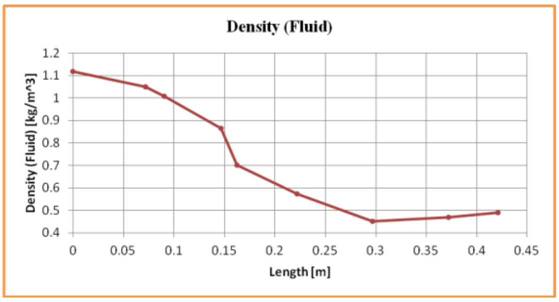


Fig.15: Density at Leading Edge

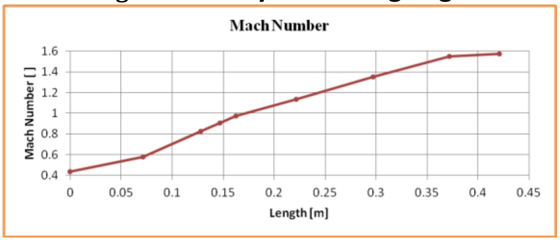


Fig.16: Mach at Leading Edge

VII. CONCLUSION

The knowledge based engineering frame work for axial flow compressor is done successfully. The initial phase of the work provides detailed literature review on concept of KBE technique, its methodologies and application, also delivers the problem in handling system and its sub design like aircraft engine, etc. reviews provides KBE techniques and tools used to develop it, design procedure of axial flow compressor also retrieved from books and journals. Methodology is formulated to carry out the work in systematic manner; the same is done to achieve the task. CATIA is a PLM tool used worldwide for end to end product development, here in this research work CATIA is used to design and model the first stage of axial flow compressor is performed using its automation tool VBA, it is an add-in product available with CATIA to develop KBE inside CATIA, even though CATIA has got dedicated KBE product like knowledge ware, it is always recommended to go with customized KBE frame work, which is very much reusable in the scalable version of the CATIA software. The flow simulation is a separate part from design and is presented to verify the design and enhance it further. Since the flow simulation requires parallel computing module and license to get more accurate design, which in terms require larger high density computational far field mesh, which is possible only by parallel modules of any CFD software (Fluent, CFX, STAR-CCM, etc.,), here a light meshed model is created with COSMOS flow simulation tool and verified the pressure difference, it produced a result with 93% accuracy (CPR designed 1.215, CFD result 1.135)

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