Analysis of Number of Blades Effect on Performance of Rotor 37

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Abstract:- Number of blades is one of the major parameters affecting the performance and stability of compressors. The number of blades usually determined using blade spacing (the distance between two blades). This study has been devoted to estimating the change of performance parameters of rotor 37 as a result of number of blades change. The results of this study obtained using the CFD code "NUMECA Fine/Turbo". This CFD code is a steady, quasi-three-dimensional Reynolds Averaged Navier-Stokes (RANS) solver. Presented a comparison between three turbulence models (k-Epislon, Spalart-Allmaras and Blatwin-lomax) with experimental data. Spalart-Allmaras turbulence model is used mainly for calculations. The results are presented for three rotational speeds and three values of number of blades. Provided an analysis of number of blades effect on rotor pressure ratio, efficiency, loading coefficient and work. The obtained results verified using an existing experimental and published data.

Keywords:- *Number of Blades, Compressor, Rotor 37, Performance Parameters.*

I. INTRODUCTION

Compressor is essential component of gas turbine engines. However, compressor design can impose particularly difficult challenges, which results in significant changes of performance parameters, especially pressure ratio, efficiency and stability margin.

The design requirements of a compressor in general include high efficiency, high air flow rates and high pressure ratio per stage. The compressor must be designed to works satisfactory at various flight conditions and engine regimes. The modern gas turbine engines has a transonic compressor to obtain high pressure ratio with a minimum number of stages. The flow field that generates inside a transonic compressor rotor is extremely complex and presents many challenges to the compressor designers, because of complicated physical features such as shock waves, shock / boundary layer interaction, secondary flows, etc. including energy losses and efficiency reduction [1].

The change of blade geometric parameters of the compressor rotor leads to many design results, so focusing on this research area may help to develop new configurations with optimum performance parameters.

The number of blades is one of the important parameters affecting the compressor performance. The number of blades also is one of the influential parameters in flow analysis, and it directly related to the solidity (the ratio of the aerodynamic chord over the peripheral distance between two blades, also called the pitch). Actually, there is no general rules to guide the designer to define an optimum solidity in terms of loading or efficiency. The importance of developing a modern methodology to understand the effect of number of blades and solidity on compressors characteristics has also become one of the objective topics in the gas turbine design field.

II. BLADE GEOMETRIC PARAMETERS

A. Cascade Airfoil Nomenclature.

Figure 1 shows the cascade airfoil nomenclature and flow angles. Subscripts (i) and (e) are used for the inlet and exit states, respectively. At design, the incidence angle is nearly zero. The exit deviation can be determined by using Carter's rule [2]:

$$\delta_c = \frac{\gamma_i - \gamma_e}{4\sqrt{\sigma}} \quad (1)$$

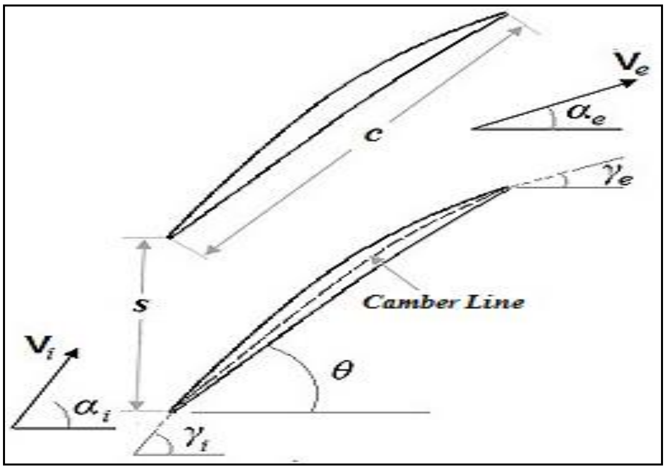

Fig 1 Cascade Airfoils Nomenclature.

c – blade chord;

s – blade spacing;

$\sigma = c/s$ = solidity;

θ – stagger angle;

V – absolute velocity;

α – absolute flow angle;

γ – airfoil angle;

$\alpha_i - \alpha_e$ = turning angle;

$\gamma_i - \gamma_e$ = airfoil chamber angle;

$\alpha_i - \gamma_i$ = incidence angle;

$\alpha_e - \gamma_e = \delta_c$ = exit deviation.

Losses in cascade airfoils are usually estimated in terms of total pressure drop divided by the dynamic pressure of the incoming flow. This ratio called the total pressure loss coefficient and defined as:

$$\phi_c = \frac{P_{t_i} - P_{t_e}}{\rho V_i^2 / (2 g_c)} \tag{2}$$

g_c - is a proportionality factor depends on the used units (for SI units $g_c = 1$).

The total pressure loss increases with Mach number and incidence angle.

B. Solidity and Number of blades.

The solidity must be selected in the basic design process of the compressor. However, there is no general rules to help the designer in this choice, because the impact of solidity on compressor performance has many approaches, and is not fully established.

For rotor or stator blade rows, the blade spacing (*s*) along the mean line is equal to the blade chord (*c*) divided by its solidity ($s = c/\sigma$). The number of blades is simply the circumference at the mean radius divided by the blade spacing:

$$N = \frac{2\,\pi\, r_m}{s} \tag{3}$$

III. ROTOR 37.

NACA Rotor 37 is one of the most used transonic compressor test case. Rotor 37 designed and tested by Reid and Moore at NASA Lewis, presently Glenn Research Center, is a low aspect ratio inlet stage for an eight-stage core compressor with a 20:1 pressure ratio. It was retested at NASA Glenn in isolation to avoid the interaction effects. As such the test case is ideal for code verification [3, 4].

Several numerical studies conducted for Rotor 37 using various CFD codes and verified using experimental data [3, 4, 5, and 6]. However, the rotor still presents a real challenge to 3D viscous flow solvers because the interaction between the shock waves and boundary layer is strong, and the effects of viscosity are dominant in determining the flow deviation and hence the pressure ratio.

In figures 2, 3 and 4 shown the geometric data, the 3D model and mesh grid of the rotor. Table 1 shows the basic design data of rotor 37.

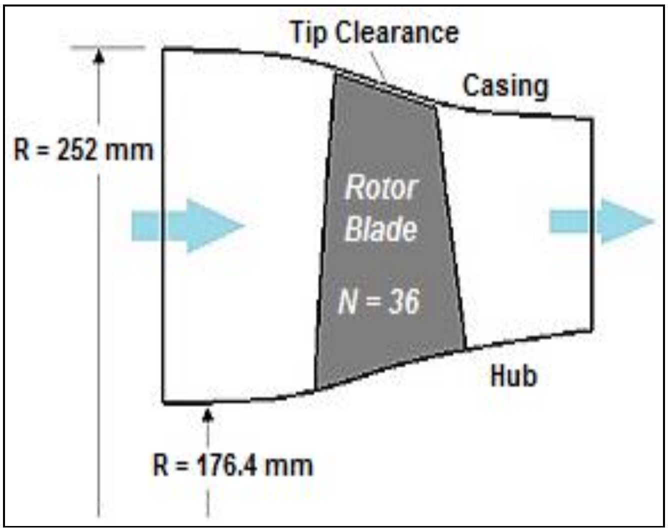

Fig 2 Geometric Data of the Rotor-37.

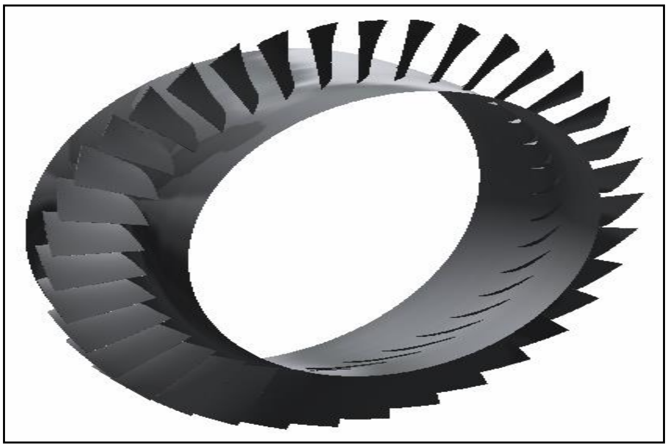
Fig 3 3D model of Rotor 37.

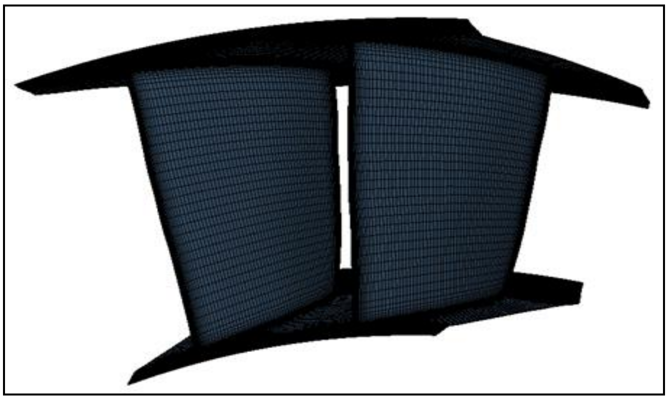
Fig 4 3D Mesh Grid of Rotor 37.

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Table 1 Main Design Data of Rotor 37.

Number of blades	36
Tip radius at leading edge	252 mm
Aspect ratio	1.19
Hub-tip radius ratio	0.7
Tip solidity	1.288
Tip clearance height	0.356 mm
Rotational speed	17188 rpm
Tip speed	454 m/s
Total pressure ratio	2.106
Mass flow (corrected)	20.19 kg/s
Chocked mass flow	20.93 kg/s
Blading Type	Multiple Circular Arc

IV. COMPRESSOR ROTOR CHARACTERISTICS

A. Rotor Performance Parameters.

In this study, the following performance parameters used for analysis:

- *Compressor Rotor Efficiency.*

Compressor rotor efficiency of an adiabatic compressor is defined as the ratio of the ideal work per unit mass to the actual work per unit mass between the same total pressures, or:

$$\eta = \frac{h_{t2s} - h_{t1}}{h_{t2} - h_{t1}} \tag{4}$$

Subscripts (1) and (2) are used for the inlet and exit states.

For a calorically perfect gas, this simplifies to:

$$\eta_s = \frac{T_{t2s} - T_{t1}}{T_{t2} - T_{t1}} = \frac{\left(p_{t2s}/p_{t1}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(T_{t2}/T_{t1}\right) - 1} \tag{5}$$

- *Rotor Pressure Ratio.*

The rotor pressure ratio can be determined as:

$$\pi = \frac{p_{t2}}{p_{t1}} = \left(1 + \eta_s \frac{\Delta T_t}{T_{t1}}\right)^{\frac{\gamma}{\gamma-1}} \tag{6}$$

- *Rotor Loading Coefficient.*

The ratio of the rotor work to blade speed squared is called "loading coefficient" and defined as:

$$\psi = \frac{g_c \Delta h_t}{U^2} = \frac{g_c \Delta h_t}{(\omega r)^2} \tag{7}$$

For a calorically perfect gas, the loading coefficient can be written as:

$$\psi = \frac{g_c c_p \Delta T_t}{U^2} = \frac{g_c c_p \left(T_{t2} - T_{t1}\right)}{(\omega r)^2} \tag{8}$$

Modern axial flow compressors used for aircraft engines have stage loading coefficients in the range of 0.3-0.35 at the mean radius.

- *Rotor Work.*

The rotor work output is given by:

$$W = \dot{m} c_p \left(T_{t2} - T_{t1}\right) \tag{9}$$

B. Corrected Quantities.

The characteristics of compressors usually presented by a plot called the compressor map. The data are presented in terms of corrected quantities that are related to the compressor performance and atmospheric conditions. Table 2 shows the corrected parameters.

Then

$$\dot{m}_{ci} = \frac{\dot{m}_i \sqrt{T_{ti}}}{p_{ti}} \frac{p_{ref}}{\sqrt{T_{ref}}} = \frac{p_{ref}}{\sqrt{T_{ref}}} A_i MFP(M_i) \tag{10}$$

Therefore, $\dot{m}_{ci} = f(M_i)$.

Thus, the corrected mass flow rate is directly proportional to Mach number at the defined section.

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Table 2 Corrected Parameters.

Parameter	Symbol	Corrected
Pressure	P_{t_i}	$\delta_t = \frac{p_{t_i}}{p_{ref}}, \quad p_{ref} = 101300 Pa$
Temperature	T_{t_i}	$\theta_t = \frac{T_{t_i}}{T_{ref}}, \quad T_{ref} = 288.2 K$
Rotational speed	N (RPM)	$N_c = \frac{N}{\sqrt{\theta_t}}$
Mass flow rate	$\dot{m}_i$	$\dot{m}_{c_i} = \frac{\dot{m}_i \sqrt{\theta_t}}{\delta_t}$

➢ *Calculation of Rotor-37 Characteristics.*

To assess the adequacy of calculations of Rotor-37 performance parameters, three turbulence models were used and compared with an existing experimental data. The results presented in figures 5and 6.

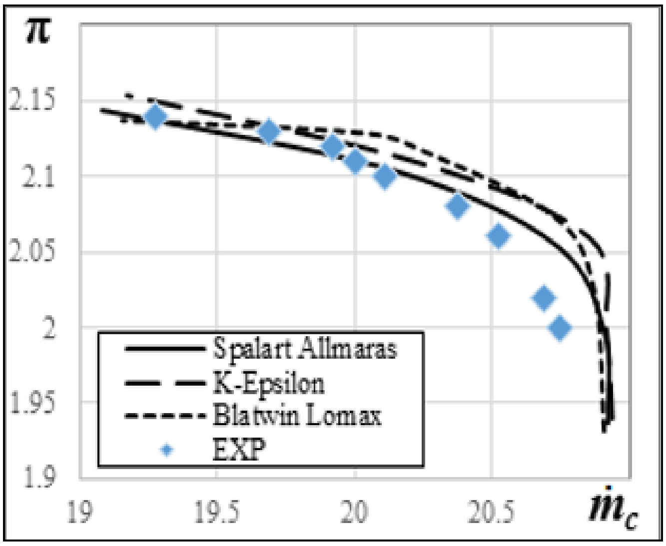

Fig 5 A Comparison of the Calculated Pressure ratio and mass Flow rate with the Experimental Data.

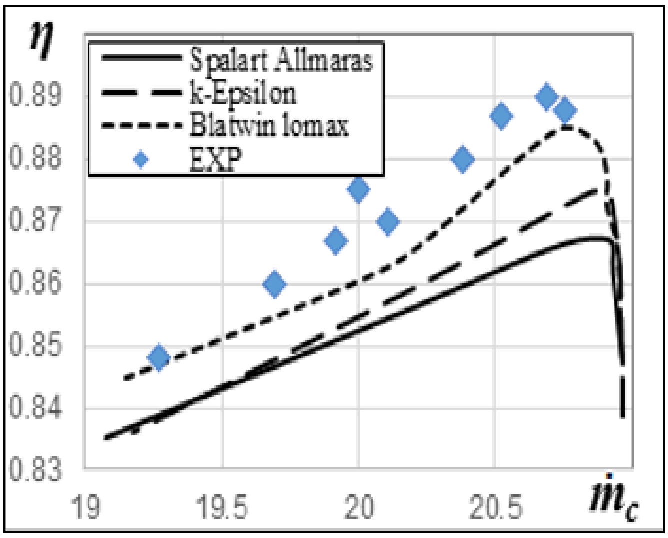

Fig 6 A Comparison of the Calculated Rotor Efficiency with the Experimental Data.

As seen from figures 5 and 6, the calculated results are qualitatively in a good agreement with the experimental data: the mass flow rate, the character of the pressure ratio and total efficiency curves. The curve of efficiency obtained using Blatwin-Lomax model is closer to experimental data, but Spalart-Allmaras model has the best agreement with experiment in the pressure ratio chart. The Spalart-Allmaras model used in this study because it has a better convergence with less cycles (iterations). From previous studies, Spalart-Allmaras model recommended for calculations related to a few axial compressor stages and isolated blade rows. However, the error of obtained results is less than 3%, which is acceptable for engineering applications. Thus, calculated results of Rotor-37 obtained in this study can be considered reliable.

➢ *The effect of Number of Blades on Performance Parameters of Rotor 37.*

To estimate the effect of number of blades on characteristics of rotor 37, a series of calculations performed for three values of number of blades (30, 36 and 42) , at three rotational speeds (17188 rpm (100%), 14609.8 rpm (85%) and 12031.6 rpm (70%)). The results of calculations presented in figures 7 and 8.

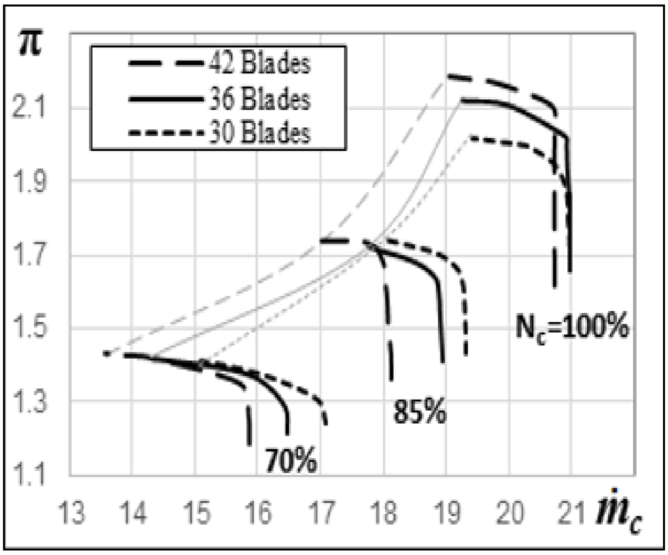

Fig 7 The effect of Number of Blades on the Rotor Pressure ratio and mass flow rate.

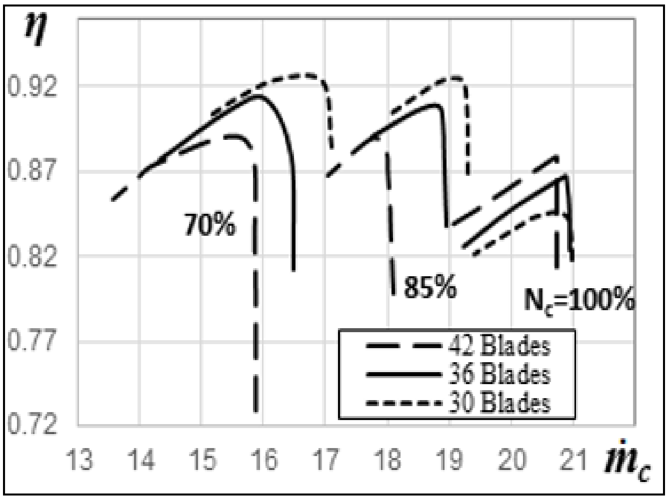

Fig 8 The effect of Number of Blades on the Rotor Efficiency.

As seen from figures 7 and 8, the increase of number of blades leads to a decrease in the maximum values of mass flow at all values of rotational speed. At lower values of rotation speed, the efficiency and pressure ratio are increase due to decreasing the number of blades, but at higher values of rotational speed, they increased by increasing the number of blades. These results suggested with the results of similar previous numerical studies [7, 8].

In figures 9 and 10 shown the change of the rotor loading coefficient and work with rotational speed due to number of blades change.

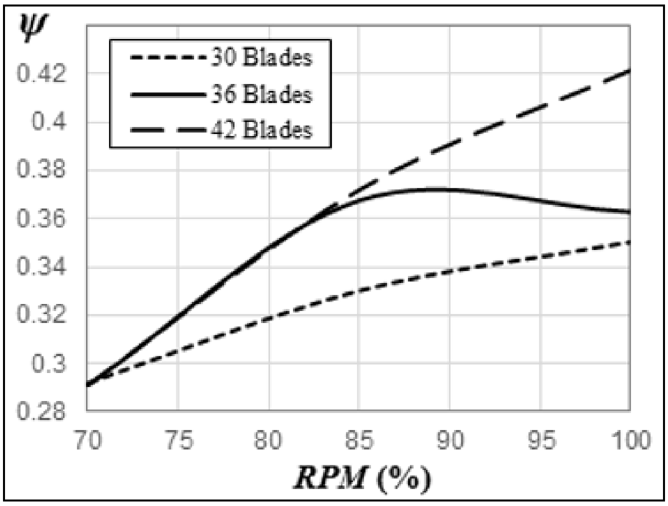

Fig 9 The effect of Number of Blades on Rotor Loading Coefficient.

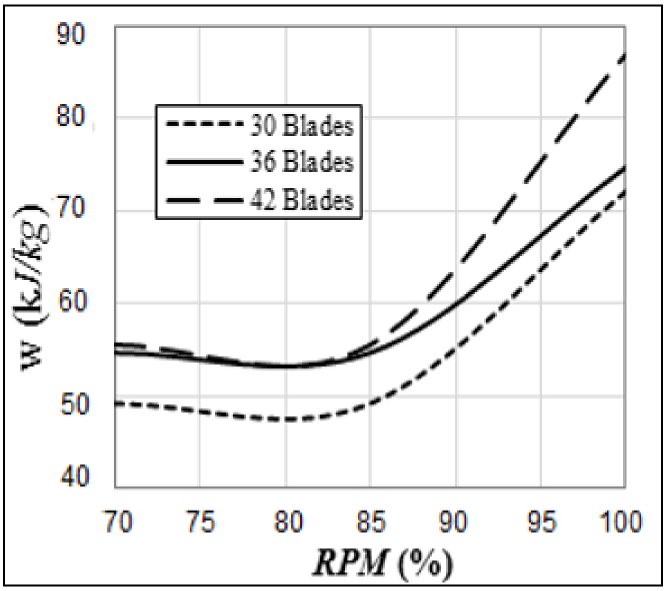

Fig 10 The effect of Number of Blades on Rotor Work.

Figures 9 and 10, show that, the number of blades increase leads to a clear increase in the rotor loading coefficient and work at the high rotational speeds, with a slight advantage when using 36 and 42 blades at lower speeds.

In figures 11, 12 and 13 shown the distribution of relative Mach number and velocity vectors at the blade tip (95% of the blade height) for various rotational speeds.

In figure 11, a shock wave appear when using 42 blades in low rotational speed (70%) in the middle of blade to blade passage, this leads to a decrease in efficiency. However, in the case of 30 blades there is no formation of shocks in the passage (due to the increase of passage area), thus the efficiency increases with less number of blades.

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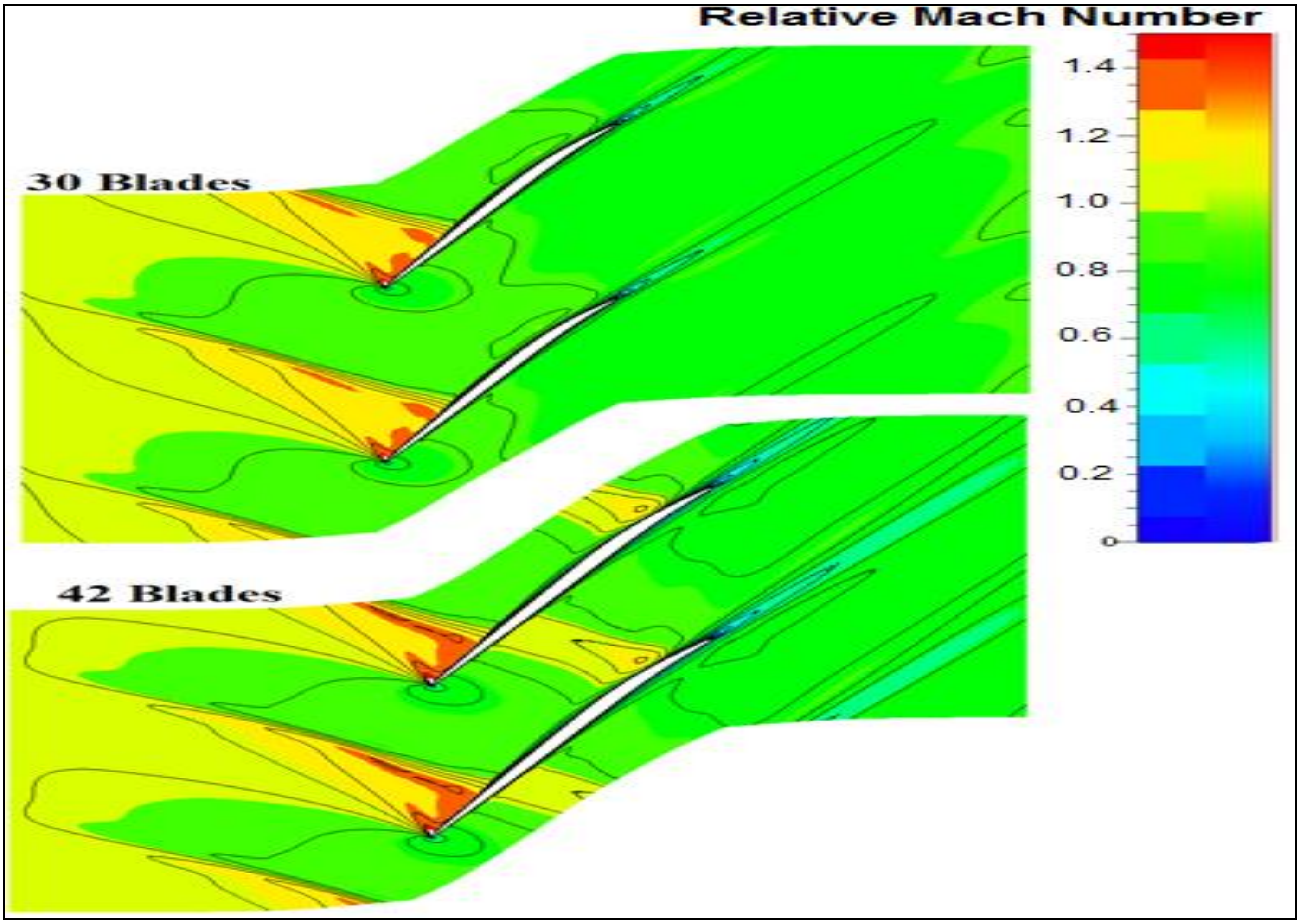

Fig 11 Distribution of Relative mach Number at 95% of Blade Height (Maximum Efficiency at N= 70%).

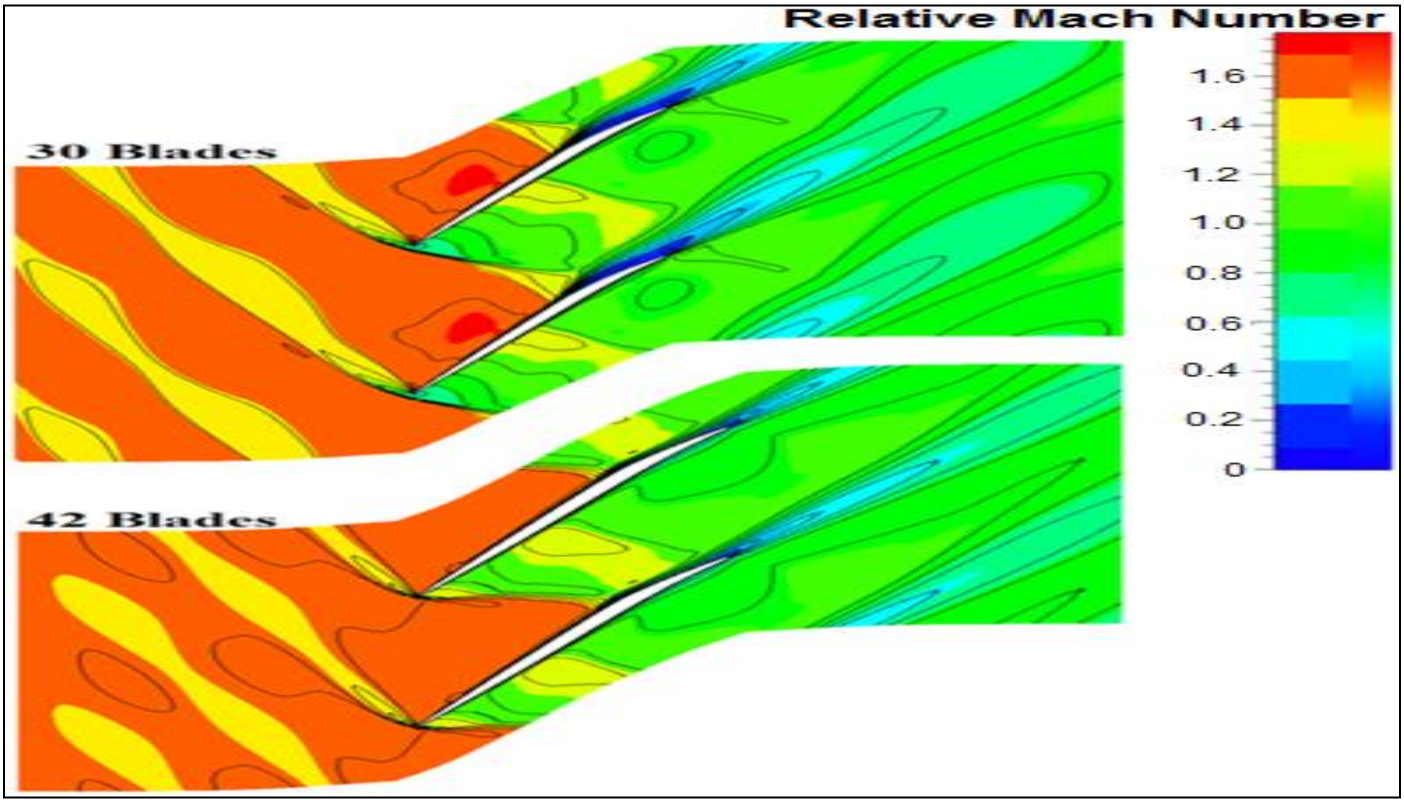

Fig 12 Distribution of Relative mach Number at 95% of Blade Height (Maximum Efficiency at N=100%).

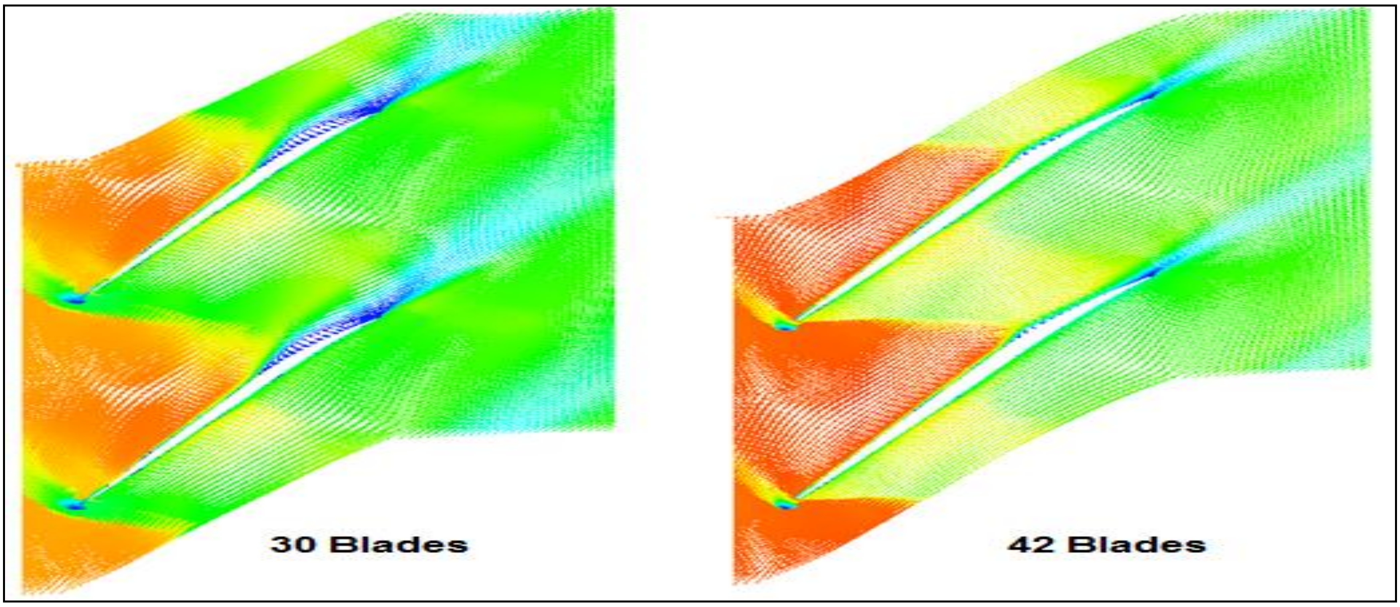

Fig 13 Distribution of Relative Velocity Vectors at 0.95% of Blade Height (Maximum Efficiency at N=100%).

From figures 12 and 13, it is evident that, due to spacing increase when using 30 blades at high values of the rotational speed, the flow separation occurs at the suction side and trailing edge, which may interacts with the generated shock waves at this section and decreases the rotor efficiency. When using 42 blades, fewer vortices formed due to the proximity of the blades to each other, thus give greater efficiency.

Figures 14, 15, 16 and 17 show the distribution of stage pressure ratio and efficiency along the radius (downstream of the rotor). The decrease of local values of pressure ratio and efficiency at high rotational speed when using less number of blades occurs at the tip sections as a result of leakage flow and vortex formation. At lower value of rotational speed, the highest values of pressure ratio and efficiency occur when using 30 blades due to the absence of oblique waves and flow separation, this consistent with the analysis of the previous task results. At the mean radius and hub section, the change of these parameters not significant.

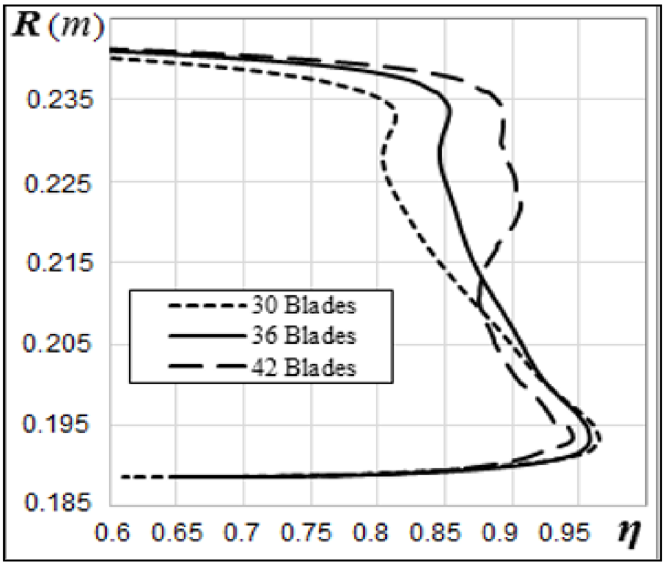

Fig 15 Distribution of Effeciency along the Radius at N=100%.

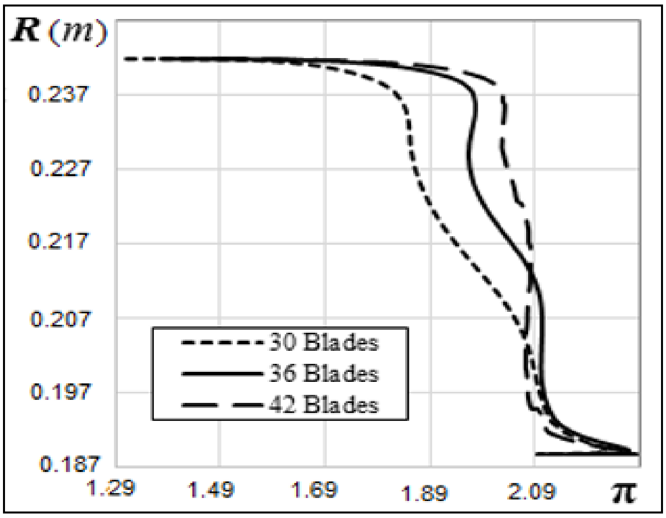

Fig 14 Distribution of Pressure Ratio along the Radius at N=100%.

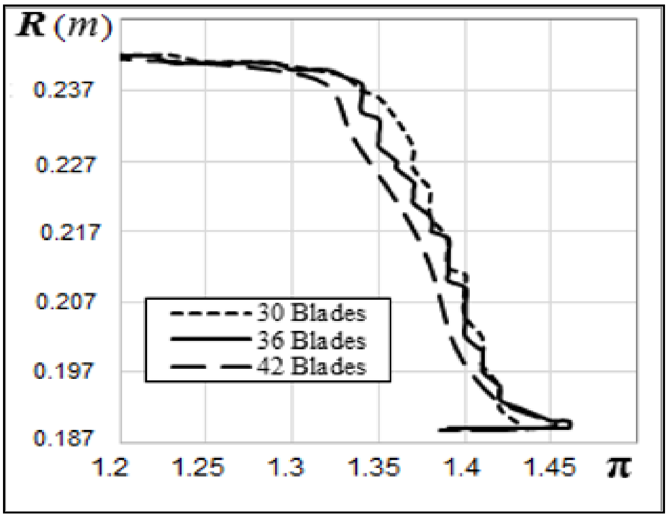

Fig 16 Distribution of Pressure Ratio along the Radius at N=70%.

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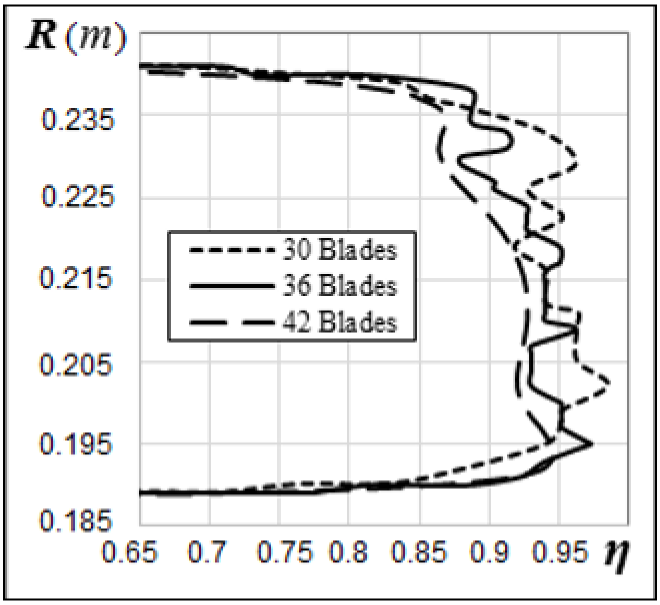

Fig 17 Distribution of Efficiency along the Radius at N=70%.

V. CONCLUSION

A numerical investigation of the number of blades effect on Rotor 37 characteristics has been presented. The 3D model and mesh grid of Rotor 37 are created. To assess the adequacy of calculations of Rotor 37 performance parameters, three turbulence models have been used and compared with an existing experimental data. The increase of number of blades leads to an increase of total pressure ratio, adiabatic efficiency, loading coefficient of the rotor at the high values of rotational speed. The decrease of number of blades leads to an increase of maximum efficiency and maximum mass flow rate at lower values of rotational speed. The use of 36 blades is more stable and reliable at different values of rotational speed, therefore it used in the designed rotor 37. The obtained results of this study suggested with previous similar studies.

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