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Investigation the Design and Flow Analysis of Impeller for Centrifugal Compressor in Gas Turbine

[1]Charm Myae Zaw, [2]Myat Myat Soe

[1]Lecturer, Department of Mechanical Engineering, Mandalay Technological University, Mandalay, Myanmar
[2] Professor, Department of Mechanical Engineering, Mandalay Technological University, Mandalay, Myanmar
Email – [1]charmmyaezaw2013@gmail.com, [2]myatmyatsoe.mtu@gmail.com

Abstract: *This paper presents a case steady namely design of centrifugal air compressor impeller for gas turbine. The application data are obtained from 'Ywama Power Station'. Which are used to calculate parameters such as the specific speed, required shaft power, impeller dimension, number of blades. This paper contains a complete set of detail drawing for blade profile of impeller. The impeller design based on parameters flow analysis using air as the working fluid shows that a 0.162m diameter centrifugal compressor with a blade outlet width of 0.0021m gives a static pressure ratio of 4:1. In this design, the impeller blade has exit angle 65º with inlet blade angle 37.74º. So, this compressor is backward-curved blades. The number of blades having 19 equally spaced vanes with the profile is used to improve compressor efficiency.*

Key Words: *Centrifugal Compressor, Diameter, impeller, blade width, blade angle, number of blade, pressure ratio, efficiency*

1. INTRODUCTION:

A compressor is a piece of machinery that compresses a fluid, a liquid of a gas that flows in the compressor into greater pressure. During the past 30 years, the centrifugal compressor because of its simplicity and larger capacity/size ratio, compares to the reciprocating machines, became much more popular for use in process plants that were growing in size.

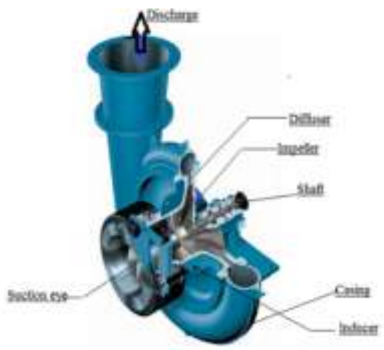

Fig.1.1 Typical Centrifugal Compressors

Centrifugal compressors are used in small gas turbine and are the driven units in most gas turbine compressor train. Centrifugal compressors range in size from pressure ratio of 1:3 per stage to as high as 12:1 on experimental models. Centrifugal compressors compress gas by means of blades on a rotating impeller which transfers rotary motion to the gas. Its impeller accelerates the flow by flinging it outward. This also increases the pressure. The pressure is increased further, and the flow is slowed when the flow meets the diffusers that ring the impeller.

Impeller is the most important part of the centrifugal compressor components because of the fact that its performance inadvertently determines the centrifugal compressor's performance. An impeller is essentially a disk-shaped structure with vanes that create the actual suction in a compressor. The impeller is always placed directly onto the shaft of the electric motor so that it spins at a very high speed. The effects of centrifugal force acting upon the spinning air within the impeller create the suction. As the impeller rotates, the spinning air moves outward away from the hub, creating a partial vacuum which causes more air to flow into the impeller. The most important impeller parameters can be grouped into three categories: Geometrical Parameters: tip diameter, hub diameter and tip width, Operating conditions: inlet total pressure, inlet total temperature and fluid density, Performance characteristics: mass flow parameter, pressure ratio and specific speed [1].

Fig.1.2. Impeller of centrifugal compressor

The impeller of centrifugal compressor is shown in Fig.1.2 and open impeller is consisted of two basic components. An inducer like an axial flow rotor and is the radial blade where energy is imparted by centrifugal force. Flow enters the impeller in the axial direction and leaves in the radial direction. The velocity variations from hub to shroud resulting from these changes in flow directions complicated the design procedure for centrifugal compressor.

2. SPECIFICAION DATA:

Inlet pressure, P_1	=	1030.766 kPa
Inlet temperature, T_1	=	380 K
Rated speed, N	=	45561 rpm
Outlet pressure, P_2	=	1799.6 kPa
Outlet temperature, T_2	=	448 K
Capacity, Q	=	0.1275 m^3/s
Air mass flow rate, m°	=	1.5907 kg/s

Centrifugal compressor with this specification has been installed on Ywama Power Station at Insein Township, Yangon, Myanmar.

3. METHOD:

The thermodynamics law fundamental to an understanding of compressor operation is the ideal gas law, which is expressed in equation from the follows;

$$Pv = ZRT \tag{1}$$

The general form of the thermodynamic head equation for a polytropic process is

$$H_p = ZRT_1 \frac{n}{n-1}\left[\left(r_p\right)^{\frac{n-1}{n}} - 1\right] \tag{2}$$

This equation drives from integrating the steady-state, steady flow work equation given by:

$$H_p = \int v dp \tag{3}$$

The polytropic process is of form:

$$Pv^n = \text{constant} \tag{4}$$

3.1 Impeller Inlet Dimension

Before the impeller dimensions can be fixed, the shaft must first be approximated. The shaft diameter based upon torque alone is given by the equation:

$$D_s = \sqrt[3]{\frac{16T}{\pi S_s}} \tag{5}$$

The eye diameter Do may be found from the continuity equation:

$$\frac{\pi}{4}D_o^2 - \frac{\pi}{4}D_h^2 = \frac{Q}{V_o}$$

$$D_o = \sqrt{\frac{4 \times Q}{\pi \times V_o} + D_h^2} \tag{6}$$

The mean diameter of the vane inlet is made slightly greater than the impeller eye diameter. Speed of sound of gas, a

$$a = \sqrt{k \times g \times R \times T_1} \tag{7}$$

The impeller inlet hub Mach number is 0.2 to 1 for compressible fluid. The value of Mach number is 0.3(assumed).

The impeller absolute velocity equation is

$$V_o = M \times a \tag{8}$$

The air enters the impeller eye to tip in the axial direction and prewhirl angle is zero, so that V_1=V_{f1} and is made slightly greater than V_o.

Impeller inlet width, b_1

$$b_1 = \frac{Q}{\pi \times V_1 \times D_1 \times \varepsilon_1} \tag{9}$$

Impeller inlet velocity, U_1

$$U_1 = \frac{\pi D_1 N}{60} \tag{10}$$

3.2 Impeller Outlet Dimension

Impeller Outlet diameter, D_2

$$D_2 = \frac{60 \times \sqrt{H_p \times g}}{\pi \times n \times \sqrt{K'}} \tag{11}$$

German turbo compressor practice indicated that with the specified by the meridional velocity ratio V_{f2}/V_{f1}, a value of about unity was desirable, but on larger compressor a value of about ½ appears to give satisfactory results. In this thesis, compressor size is small. Therefore

$$V_{f2} = Vf_1 \tag{12}$$

The outlet width is expressed by the following equation,

$$b_2 = \frac{Q}{\pi \times V_2 \times D_2 \times \varepsilon_2} \tag{13}$$

The outlet vane thickness factor ε_2 can be calculated with following equation;

$$\varepsilon_2 = \frac{\pi \times D_2 - \frac{z \times t}{\sin \beta_2}}{\pi \times D_2} \tag{14}$$

3.3 Number of blades

The greater the number of vanes, the smaller the slip, i.e. the more nearly $V_{\omega 2}$ approaches U_2. It is necessary in design to assume a value for the slip factor σ;

$$\sigma = \frac{V_{\omega 2}}{U_2}$$

To find the number of number of blades, the following equation is used.

$$\sigma = 1 - \frac{0.63\pi}{z} \tag{15}$$

3.4 Efficiency

The efficiency defined on the basic of this ideal work is the compressor efficiency. Compressor Efficiency, η_c

η_c = fluid power output / input power

Impeller Efficiency, η_i

$$\eta_i = 1\text{-}0.5\ (1\text{-}\eta_c) \tag{16}$$

Where,

H_p : polytropic head, k Nm / kg
D_s : shaft diameter, m
D_o : eye diameter, m
D_1 : inlet diameter, m
D_2 : outlet diameter, m
A : speed of sound, m/s
M : mach number
b : width, m
ε_1 : inlet vane thickness factor (0.8 to 0.9)
n : number of blades
σ : slip factor

4. VALUE OF MACH NUMBER:

The analytical design of impeller inlet result data are expressed by graphs. Fig.4.1, 4.2, 4.3 are used to check for assumed Mach number.

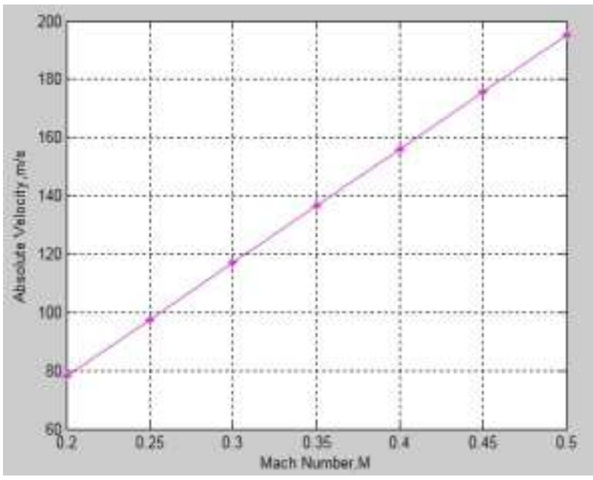

Fig.4.1 Mach number and Absolute velocity

The relation between the blade absolute velocity and Mach number are illustrated in Fig.4.1. This graph shows the larger the absolute velocity, the greater the Mach number.

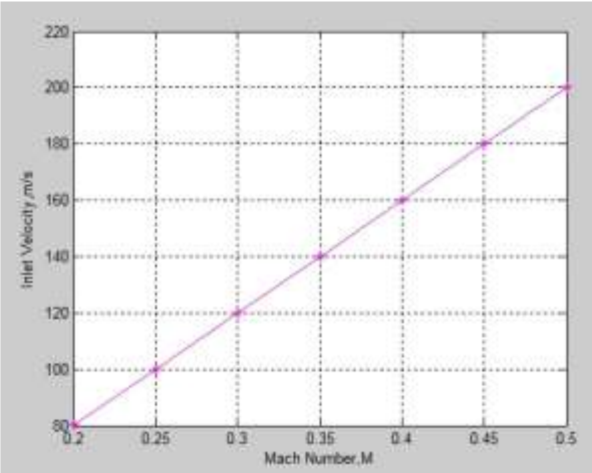

Fig.4.2 Mach number and Inlet Velocity

The relation between the inlet velocity and Mach number are illustrated in Fig.4.2. This graph shows the higher the inlet velocity, the larger the Mach number.

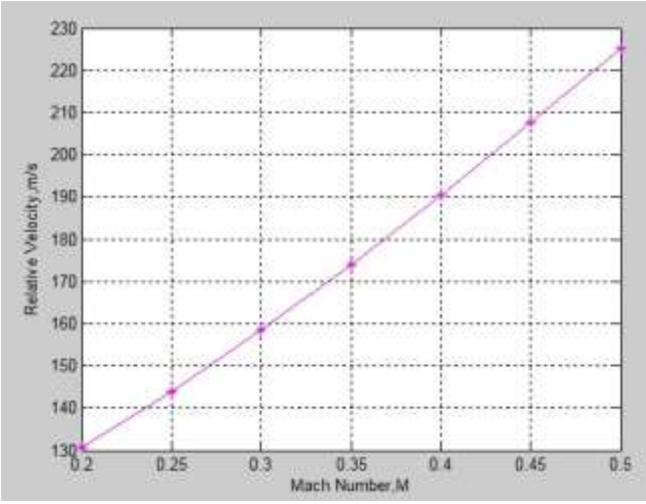

Fig.4.3 Mach number and Relative Velocity at Impeller Inlet

The relation between the relative velocity and Mach number are illustrated in Fig.4.3. This graph shows the greater the inlet relative velocity, the higher the Mach number.

Based on these conditions Mach number, M is 0.3, at that point of data is nearly equal to the actual velocity of the centrifugal compressor impeller inlet. Therefore, the design is satisfied for at that point of data.

5. VELOCITY TRIANGLE OF IMPELLER

Fig.5.1 shows inlet and outlet velocity triangle of centrifugal compressor impeller.

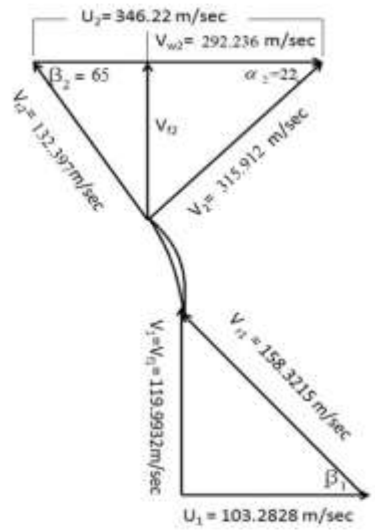

Fig.5.1 Inlet and outlet velocity triangle of impeller

Inlet blade angle, β_1

$$\beta_1 = \tan^{-1}\frac{V_1}{U_1} \tag{19}$$

Outlet blade angle, β_2

The compressor industry commonly uses a backward leading blade with angle, β_2 of between about 55-75 deg. The blade outlet angle of 65 deg is maximum power position.

Therefore, the maximum design condition the outlet blade angle, β_2 =65 deg

6. RESULT AND DISCUSSIONS:

6.1 Theoretical Results

Table 1. Calculated data of impeller

No.	Design Parameter	Symbol	Values	Units
1	Polytropic head	H_p	66.7	kNm/kg
2	Torque	T	32.577	N-m
3	Speed of sound	a	390.221	m/s
4	Mach number	M_1	0.3	-
5	Inlet velocity	U_1	103.283	m/s
6	Absolute velocity at inlet	V_1	119.993	m/s
7	Relative velocity at inlet	V_{r1}	158.322	m/s
8	Inlet blade angle	β_1	49	deg
9	Outlet velocity	U_2	346.22	m/s
10	Absolute velocity at outlet	V_2	315.912	m/s
11	Relative velocity at outlet	V_{r2}	132.397	m/s
12	outlet blade angle	β_2	65	deg
13	Outlet Mach no;	M_2	0.75	-
14	Impeller efficiency	η_i	93	%

Table 2. Comparison of calculated and existing data

No.	Design Parameter	Symbol	Unit	Calculated data	Actual data
1	Shaft diameter	D_s	m	0.0254	0.0254
2	Hub diameter	D_h	m	0.0286	0.028
3	Eye diameter	D_o	m	0.047	0.053
4	Inlet diameter	D_1	m	0.048	0.054
5	Outlet diameter	D_2	m	0.162	0.17
6	Inlet width	b_1	m	0.0093	0.0098
7	Outlet width	b_2	m	0.0021	0.0025
8	Number of vanes	z	-	19	19

In this paper, inlet and outlet diameters, blade width and number of blades are calculated for impeller design. According to the table 2, calculated data are approximately equal. But, number of impeller blade are the same.

6.2 Numerical Results

6.2.1 Velocity Distribution

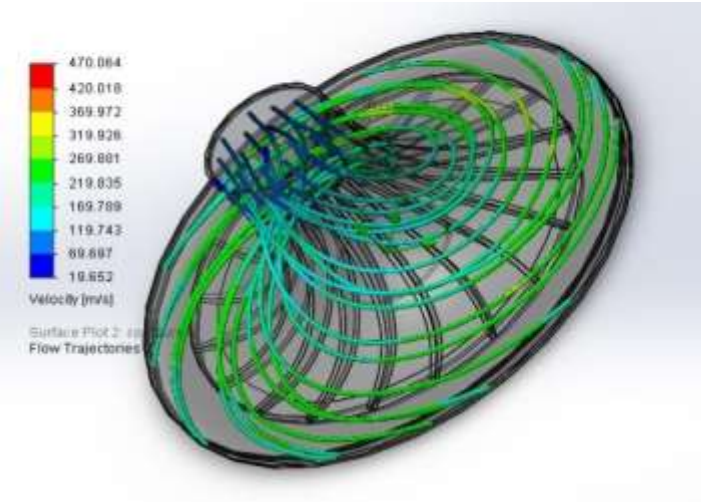

Fig.6.1 Velocity distribution of centrifugal compressor impeller (flow trajectories)

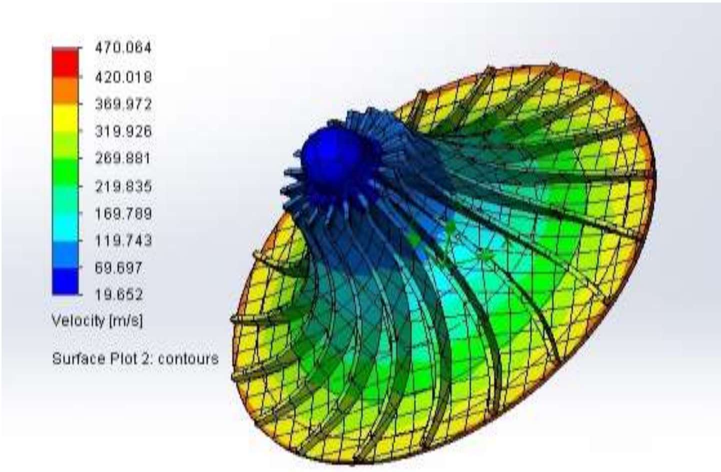

Fig.6.2 Velocity distribution of centrifugal compressor impeller (surface plots)

Fig.6.1 and 6.2 show the velocity distribution of centrifugal compressor impeller by using SolidWorks software. Mass flow rate and outlet pressure are input data for these flow simulations. The theoretical result of impeller inlet and outlet velocity V_1 and V_2 are nearly the same with numerical result.

6.2.2 Pressure Distribution

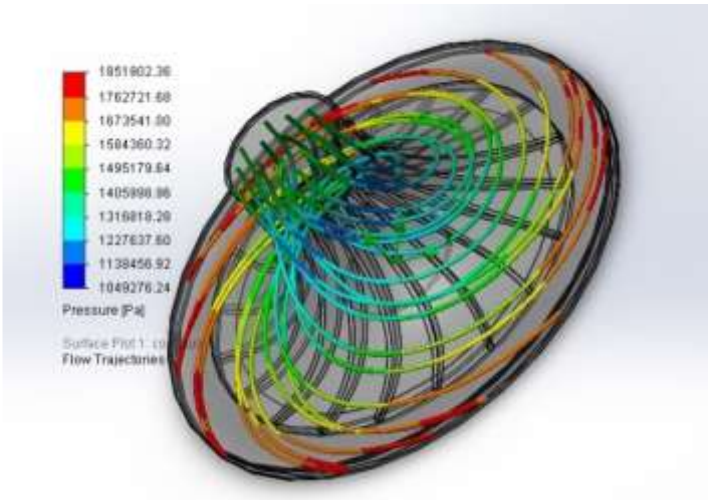

Fig.6.3 Pressure distribution of centrifugal compressor impeller (flow trajectories)

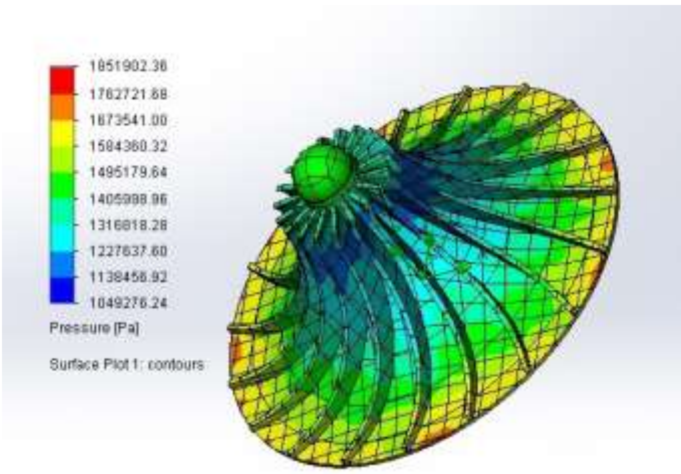

Fig.6.4 Pressure distribution of centrifugal compressor impeller (surface plots)

Fig.6.3 and 6.4 show the pressure distribution of centrifugal compressor impeller by using SolidWorks software. To run these flow simulations the input data are same with used at velocity distribution. The actual value of impeller inlet and outlet pressure are approximately equal with numerical value.

6.2.3 Meridional View of Backward-Curved Centrifugal Compressor Impeller Blade

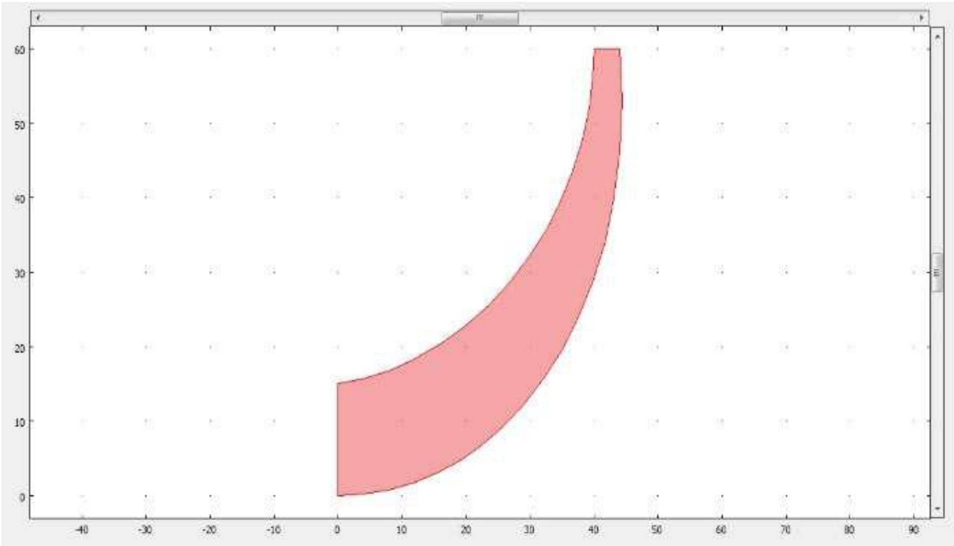

Fig.6.5 Meridional View of Impeller Blade

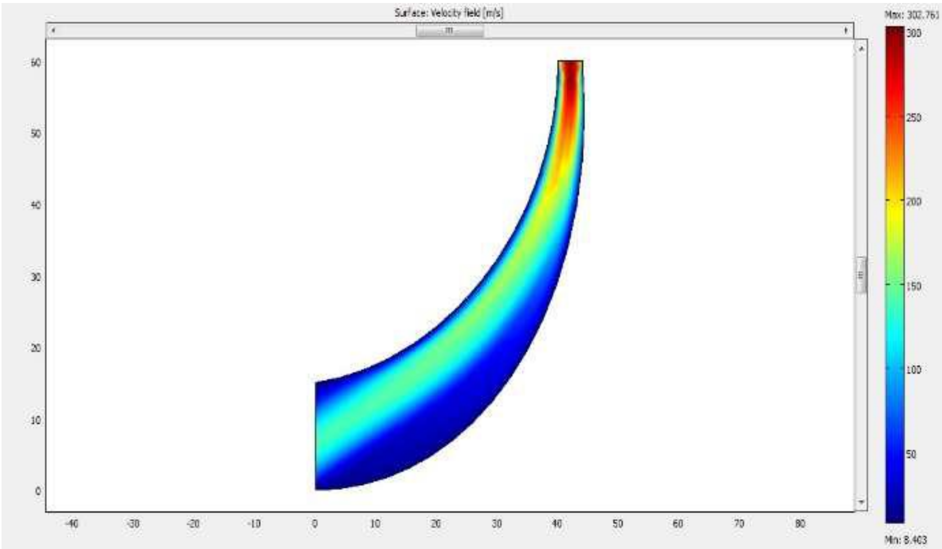

Fig.6.6 Velocity Distribution on Meridional Surface

Fig.6.6 shows the result of velocity distribution at the meridional surface of centrifugal compressor impeller blade. Inlet pressure and outlet velocity are input data for these flow simulations. The theoretical result of impeller inlet velocity V_1 is 119.993 m/s and outlet velocity V_2 is 315.912 m/s. The numerical result of inlet velocity is 125 m/s and outlet velocity are 302.761 m/s. So, theoretical result of impeller inlet and outlet velocity are slightly larger than the numerical result.

Fig.6.7 shows the result of pressure distribution at the meridional surface of centrifugal compressor impeller blade. To run these flow simulations the input data are same with used at velocity distribution. The specification data of inlet and outlet pressure are 1030.766 kPa and 1799.6 kPa. The numerical result of inlet pressure rate is 1050 kPa and outlet pressure rate is 1579.239 kPa. The existing value of impeller inlet and outlet pressure are slightly greater than the numerical research value.

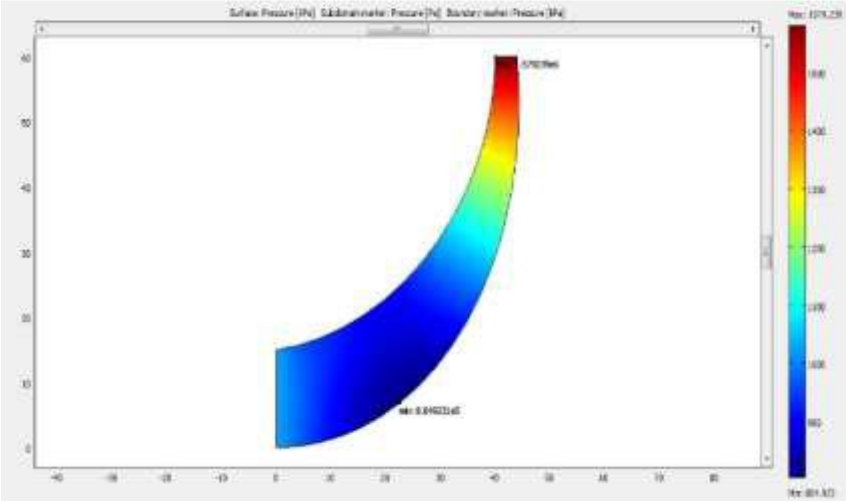

Fig.6.7 Pressure Distribution on Meridional Surface

7. CONCLUSION:

Centrifugal compressors are compressible flow machine. Centrifugal compressor from 'Ywama Power Station' is designed in this paper. This paper is attempted to design a single stage centrifugal compressor from 'Ywama Power Station'. The design of impeller in this paper is inlet and outlet diameter and number of blades and blade width. This paper describes the inlet and outlet velocity triangle. And this research shows the pressure and velocity distribution by using SolidWorks software and COMSOL Multiphysics. This paper can also be improved to gain a better understanding of the relationship between velocities and blade shape by using suitable theory. Moreover, the design procedure is described in detail. And this can support the production of centrifugal compressor impeller.

8. ACKNOWLEDGMENT:

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