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Modelling and Analysis of a Divergent Exhaust Diffuser of a Gas Turbine Engine

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Abstract - *The main objective of this work is to create models of a Divergent exhaust diffuser of a gas turbine engine and analyse for a maximum value of Coefficient of pressure recovery (CPR). Efforts have been made to study various geometries of exhaust diffusers for its dimension parameters such as diffuser inlet diameter, divergent outlet diameter, diffuser outlet diameter and half cone angle. The Divergent exhaust diffusers are modelled for diffuser inlet diameter varying from 120 mm to 140 mm in steps of 5 mm, divergent outlet diameter = 252.25 mm, diffuser outlet diameter = 210.75 mm, half cone angle = 7° in Ansys workbench. Ansys Fluent is used to carry out Computational Fluid Dynamics (CFD) analysis and to study the static pressure and exit velocity using which the CPR is obtained for each case. Also, CPR values obtained from CFD analysis are compared with theoretical values using Continuity and Bernoulli's equations. Then, the case which gives the optimum value of CPR, will be chosen as the optimum geometry which gives best and efficient result, that leads to improve the performance of a Divergent exhaust diffuser and thereby the power and efficiency of a turbine.,*

Key Words: Computational Fluid Dynamics (CFD), Coefficient of pressure recovery (CPR), Divergent exhaust diffuser, Diffuser inlet diameter, Divergent outlet diameter and Half cone angle.

1. INTRODUCTION

In a gas turbine engine, the Divergent exhaust diffuser is a very important component. It is installed just after the low pressure turbine stage. The main function of a Divergent exhaust diffuser is to decrease the velocity and to increase the static pressure of the fluid discharging from the turbine. Hence, increasing the ratio of pressure in the turbine section thereby, improving the performance and efficiency of the turbine of a gas turbine engine. Generally, in the absence of a Divergent exhaust diffuser the fluid ejects more easily from the turbine. When the fluid is evicting from the turbine, the ambient pressure will try to reverse the fluid back into the turbine, resulting in a backflow condition. Due to this the performance of a turbine decreases. However, in the presence of a Divergent exhaust diffuser the backflow condition can be made absent. Because of this the work by the turbine will increase, thereby increasing the performance and efficiency of the turbine of a gas turbine engine. Also, by maintaining the design of a Divergent exhaust diffuser for a maximum Coefficient of pressure recovery (CPR) will increase the diffuser efficiency and in turn increase the turbine efficiency. The dimension parameters of an exhaust diffuser such as diffuser inlet diameter, divergent outlet diameter, diffuser outlet diameter and half cone angle affect the CPR. By many researchers' work has been done to obtain an optimum geometry of a Divergent exhaust diffuser.

Prashant Channaveere et.al [1], have performed Computational Fluid Dynamics (CFD) analysis on different geometries of a Divergent exhaust diffuser by varying the divergent outlet diameter from 237.25 mm to 252.25 mm in steps of 5 mm and all other dimensions were kept constant. They found that maximum CPR was obtained for 252.25 mm geometry. Hence, they considered 252.25 mm the optimum geometry which gave the efficient results when compared to other geometries. R Prakash et.al [2] and Dr. Basharat Salim [3], have conducted CFD analysis on different geometrical configurations of a Divergent exhaust diffuser for different half cone angle i.e. 5°, 7°, 10° and 12°, in which 7° Divergent exhaust diffuser was giving the best results. Vaddin Chetan et.al [4], have carried out numerical investigations to determine the static pressure, dynamic pressure and pressure recovery co-efficient by varying the area ratio and the divergence angle and by maintaining the constant length of the exhaust diffuser. Their results showed that the static pressure and pressure recovery co-efficient increases with increasing the divergence angle up to 11°, later further increase in the divergence angle decreases the pressure recovery co-efficient. Engr. Stephen Tambari et.al [5], have investigated the effects of Reynolds number and cone angle

(5°, 24° and 60°) on CPR. They found that the CPR is mainly effected by cone angle. The CPR versus Reynolds number plot is constant. Also, they verified the effects theoretically and experimentally. Venugopal M M et.al [6], have showed that if the performance of an exhaust diffuser is high then the power and efficiency of a turbine system can be enhanced.
Parameshwar Banakar et.al [7], have carried out analysis using 45° sector model of the diffuser mixer without struts and with struts considering the periodicity of geometry. An unstructured grid has been generated and simulation has been done using Ansys Fluent software. The analysis has been carried out with velocity components, total pressure and total temperature at inlet boundary conditions and a mass flow rate at the outlet.
Most of the researchers' work shows that design of a Divergent exhaust diffuser with divergent outlet diameter = 252.25 mm [1], half cone angle = 7° [2,3] will give maximum value of CPR. Also, there are works done on different models of Divergent exhaust diffuser by varying half cone angle (5° to 12°) [2-4] and divergent outlet diameter (from 237.25 mm to 252.25 mm) [1] but, there is less work done on diffuser inlet diameter.
So, in this work, main concentration is given on diffuser inlet diameter. Different 3D models with diffuser inlet diameter varying from 120 mm to 140 mm in steps of 5 mm, half cone angle = 7° and divergent outlet diameter = 252.25 mm are created and meshed using Ansys workbench. CFD analysis is carried on these meshed models using Ansys Fluent, to obtain the static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser. Using these values of static pressure and velocity, CPR is calculated. These results are validated with the theoretical calculations using basic equations [8]. The model which gives the maximum CPR is considered to be an optimized geometry of a Divergent exhaust diffuser.

2. BASIC EQUATIONS

The basic equations used to calculate CPR, by using CFD analysis results and by theoretically are:

Coefficient of pressure recovery (CPR) = $(P - P_i) / \frac{1}{2}\rho_i V_i^2$

Continuity equation $A_i V_i = AV$

Bernoulli's equation $P_i + \frac{1}{2}\rho V_i^2 = P + \frac{1}{2}\rho V^2$

Where,

P : static pressure at the point at which CPR is being evaluated

P_i : static pressure at the Divergent exhaust diffuser inlet

$\frac{1}{2}\rho_i V_i^2$: dynamic head available at the inlet of a Divergent exhaust diffuser, ρ_i value is taken from Table 2

V_i and V : velocities at the inlet and outlet of a Divergent exhaust diffuser

A_i and A: areas at the inlet and outlet of a Divergent exhaust Diffuser

3. MODELLING

The different sections in a Divergent exhaust diffuser are shown in Fig. 1

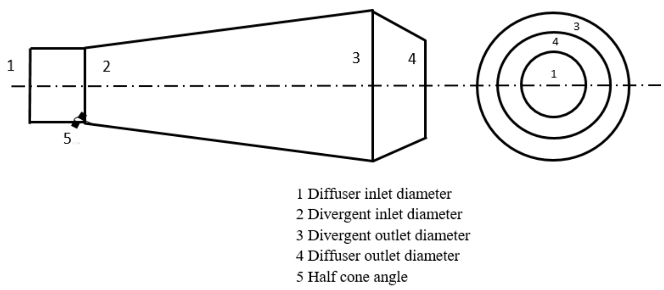

Fig -1: Sections in a Divergent exhaust diffuser

These are several parameters of an exhaust diffuser which affects the CPR value.
The modelling of a Divergent exhaust diffuser is done in Ansys workbench as shown in Fig. 2. The optimum dimensions for the Divergent exhaust diffuser are obtained from referring many researchers' work. The dimensions are tabulated in Table 1

Table -1: Dimensions of a Divergent exhaust diffuser

Parameter	Dimension
Divergent outlet diameter	252.25 mm
Diffuser outlet diameter	210.75 mm
Half cone angle	7°
Diffuser inlet diameter and Divergent inlet diameter	120 mm, 125 mm, 130 mm, 135 mm, and 140 mm

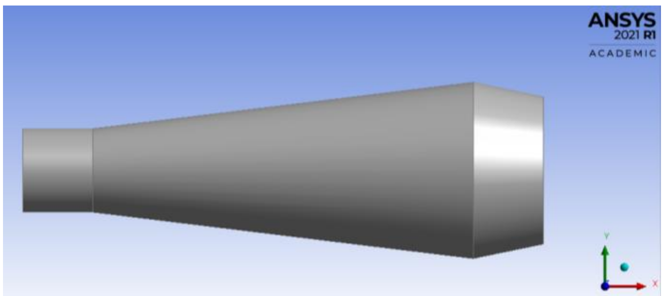

Fig -2: Divergent exhaust diffuser model

4. MESHING

Created 3D model is meshed using Ansys workbench. In order to improve solution accuracy, high resolution value of 7 is given to get a fine mesh. The meshed model of a Divergent exhaust diffuser is shown in Fig. 3. The meshed model will consist of different number of nodes and different number of elements. The meshed model will be divided into different sections such as inlet, outlet and walls.

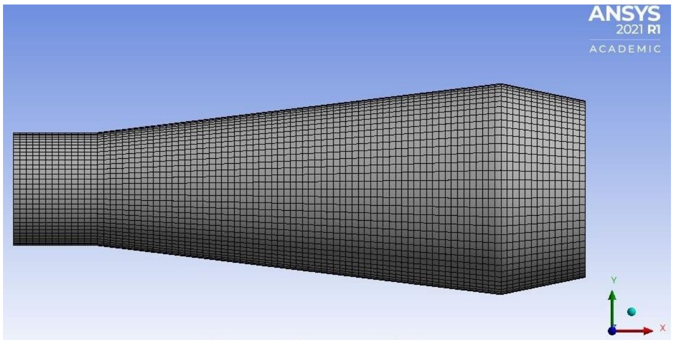

Fig -3: Meshed model of a Divergent exhaust diffuser

5. SETUP AND SOLUTION

The meshed 3D models will be assigned with input parameters and solved by using Ansys Fluent. The CFD input parameters are tabulated in Table 2.

Table -2: CFD input parameters

Parameter	Value
Solver	Double precision
Solver type	Pressure based
Velocity formulation	Absolute and steady
Viscous model	SST k-omega (2 eqn.)
Material	air Density 1.225 kg/m3 Viscosity 1.7894e-5 kg/m-s
Boundary conditions	**Inlet:** Velocity magnitude = 45m/s, Turbulence intensity = 2.5%, Hydraulic diameter = inlet diffuser diameter (i.e. from 120 mm to 140 mm depending on the model) **Outlet:** Pressure = 101325 Pa, Backflow hydraulic diameter = 210.75 mm Backflow turbulence intensity = 0 **Wall:** Stationary with specified shear condition. Roughness model = standard Roughness height and Roughness constant = 0
Solution methods	Coupled, Pressure = second order Momentum and Continuity equations = second order upwind.
Residual parameters	Continuity, velocity components = 1e-11 k and omega = 1 e-7
Solution initialization method	Standard
Initialization is computed from	Inlet of the Divergent exhaust diffuser
Number of iterations	3000

Similarly, the above procedure is followed for different 3D models of a Divergent exhaust diffuser.

In this work, the convergence of all the simulations is obtained at 150 to 900 iterations as in Fig. 4.

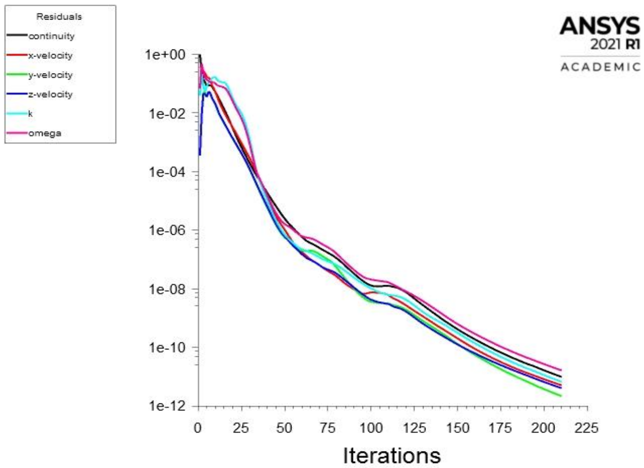

Fig -4: Convergence obtained during the simulation

6. RESULTS AND DISCUSSIONS

By analysing the different cases of Divergent exhaust diffuser in Ansys Fluent, static pressure contours, velocity contours and plots for a Divergent exhaust diffuser are obtained. These pressure and velocity contours is used to study the pressure static and velocity distribution along the length of a Divergent exhaust diffuser. From these values of static pressure and velocity the CPR is calculated.

<u>**Case 1:**</u> Divergent exhaust diffuser with diffuser inlet diameter = 120 mm

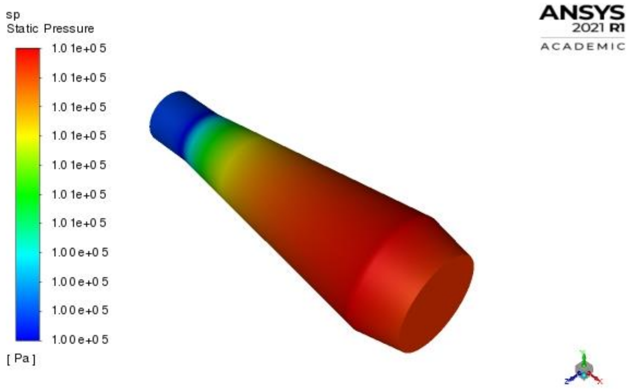

Fig -5: Contour of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 120 mm

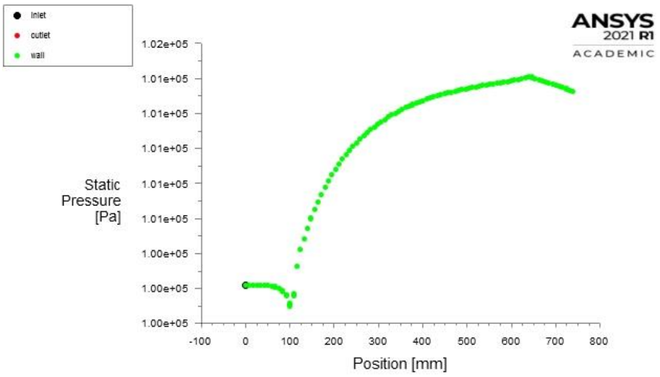

Fig -6: Deviation of static pressure for Divergent exhaust diffuser with diffuser inlet diameter =120 mm

It is seen in Figs. 5 and 6 that the variation of static pressure from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is gradually increasing. The static pressure value is minimum at the inlet which is 1.00e+05 Pa and gradually increases towards the outlet of a Divergent exhaust diffuser where it is maximum i.e. 1.01e+05 Pa, as the kinetic energy of the fluid gets converted to static pressure. But, from the divergent outlet to diffuser outlet it is decreasing as area is decreasing.

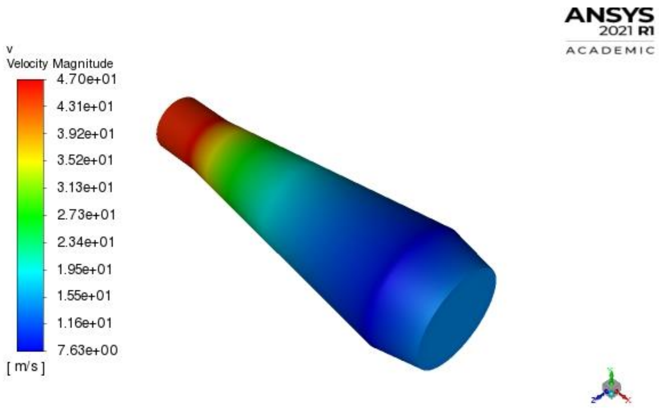

Fig -7: Contour of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 120 mm

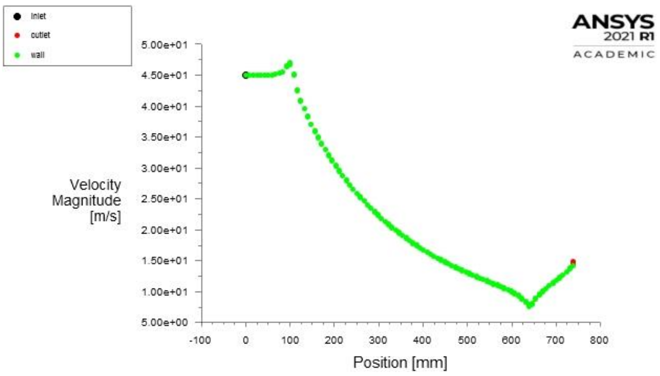

Fig -8: Deviation of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 120 mm

Figs. 7 and 8 shows that the variation of velocity magnitude from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is slowly decreasing. The velocity magnitude is more at inlet i.e. 4.5e+01 m/s and less at the outlet of a Divergent exhaust diffuser i.e. 1.48e+01 m/s. As it is known that the function of the diffuser is to decrease the velocity by increasing the static pressure i.e. changing kinetic energy to pressure. But, from the divergent outlet to diffuser outlet it is increasing as area is decreasing.

<u>Case 2:</u> Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

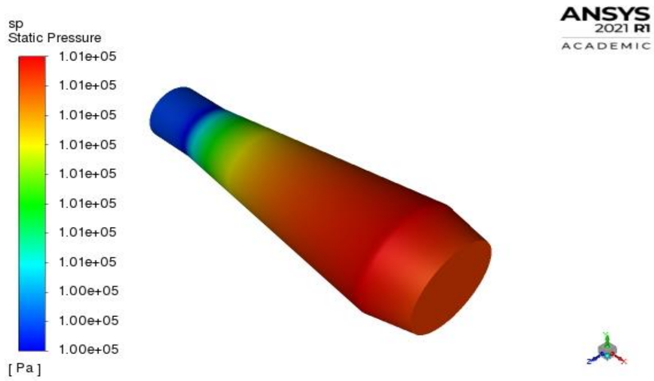

Fig -9: Contour of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

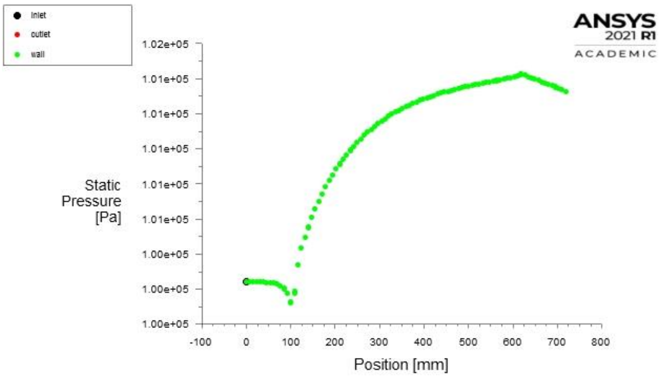

Fig -10: Deviation of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

It is seen in Figs. 9 and 10 that the variation of static pressure from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is gradually increasing. The static pressure value is minimum at the inlet which is 1.00e+05 Pa and gradually increases towards the outlet of a Divergent exhaust diffuser where it is maximum i.e. 1.01e+05 Pa, as the kinetic energy of the fluid gets converted to static pressure. But, from the divergent outlet to diffuser outlet it is decreasing as area is decreasing.

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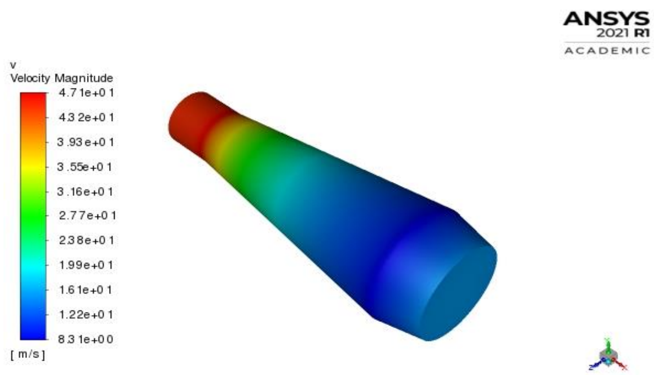

Fig -11: Contour of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

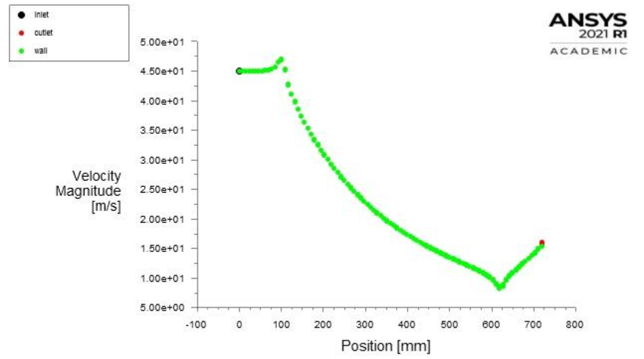

Fig -12: Deviation of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

Figs. 11 and 12 shows that the variation of velocity magnitude from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is slowly decreasing. The velocity magnitude is more at inlet i.e. 4.5e+01 m/s and less at the outlet of a Divergent exhaust diffuser i.e. 1.60e+01 m/s. As it is known that the function of the diffuser is to decrease the velocity by increasing the static pressure i.e. changing kinetic energy to pressure. But, from the divergent outlet to diffuser outlet it is increasing as area is decreasing.

Case 3: Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

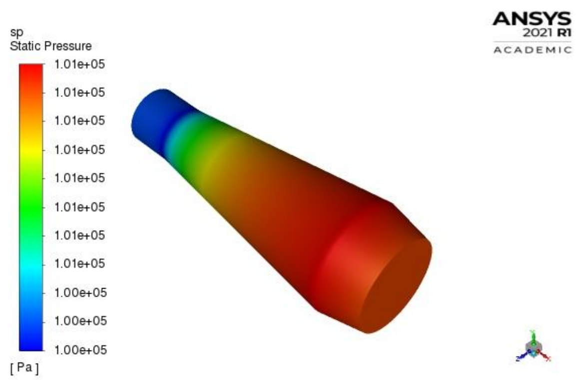

Fig -13: Contour of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

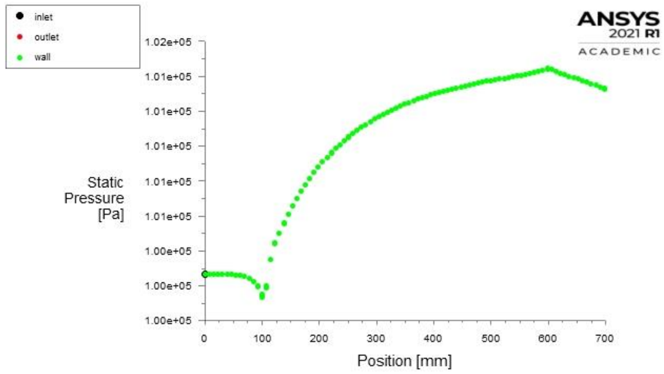

Fig -14: Deviation of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

It is seen in Figs. 13 and 14 that the variation of static pressure from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is gradually increasing. The static pressure value is minimum at the inlet which is 1.00e+05 Pa and gradually increases towards the outlet of a Divergent exhaust diffuser where it is maximum i.e. 1.01e+05 Pa, as the kinetic energy of the fluid gets converted to static pressure. But, from the divergent outlet to diffuser outlet it is decreasing as area is decreasing.

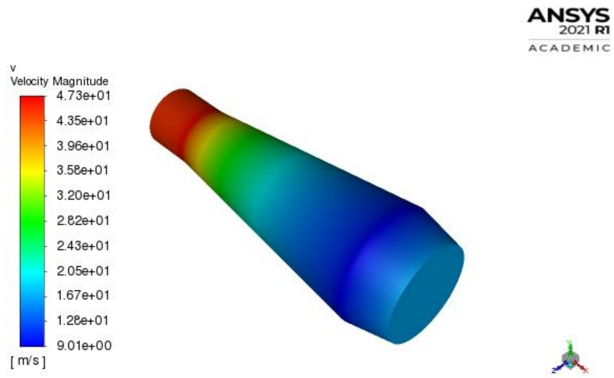

Fig -15: Contour of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

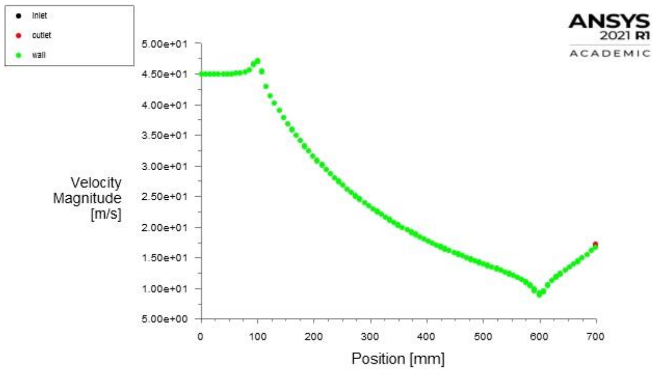

Fig -16: Deviation of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

Figs. 15 and 16 shows that the variation of velocity magnitude from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is slowly decreasing. The velocity magnitude is more at inlet i.e.

4.5e+01 m/s and less at the outlet of a Divergent exhaust diffuser i.e. 1.733e+01 m/s. As it is known that the function of the diffuser is to decrease the velocity by increasing the static pressure i.e. changing kinetic energy to pressure. But, from the divergent outlet to diffuser outlet it is increasing as area is decreasing.

Case 4: Divergent exhaust diffuser with diffuser inlet diameter = 135 mm

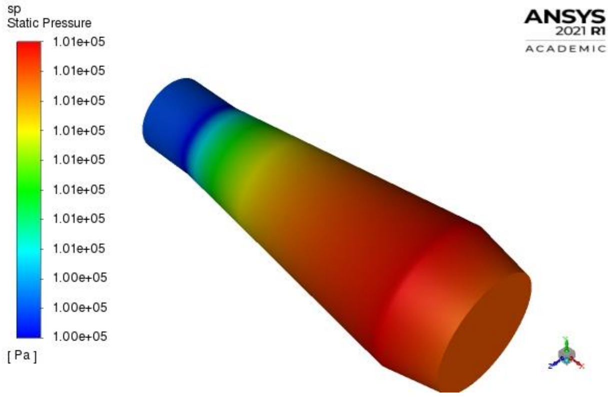

Fig -17: Contour of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 135 mm

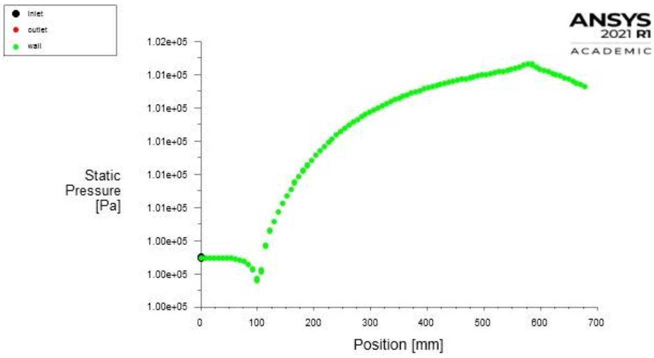

Fig -18: Deviation of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 135 mm

It is seen in Figs. 17 and 18 that the variation of static pressure from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is gradually increasing. The static pressure value is minimum at the inlet which is 1.00e+05 Pa and gradually increases towards the outlet of a Divergent exhaust diffuser where it is maximum i.e. 1.01e+05 Pa, as the kinetic energy of the fluid gets converted to static pressure. But, from the divergent outlet to diffuser outlet it is decreasing as area is decreasing.

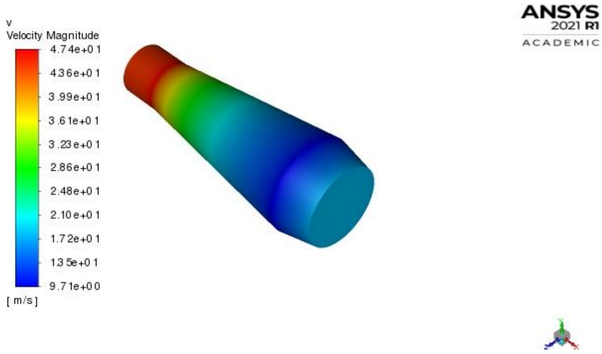

Fig -19: Contour of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 135 mm

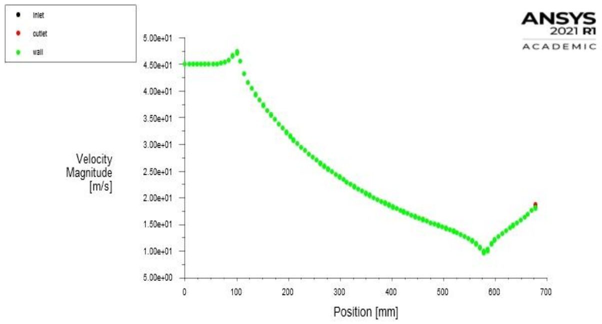

Fig -20: Deviation of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 135 mm

Figs. 19 and 20 shows that the variation of velocity magnitude from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is slowly decreasing. The velocity magnitude is more at inlet i.e. 4.5e+01 m/s and less at the outlet of a Divergent exhaust diffuser i.e. 1.8e+01 m/s. As it is known that the function of the diffuser is to decrease the velocity by increasing the static pressure i.e. changing kinetic energy to pressure. But, from the divergent outlet to diffuser outlet it is increasing as area is decreasing.

Case 5: Divergent exhaust diffuser with diffuser inlet diameter = 140 mm

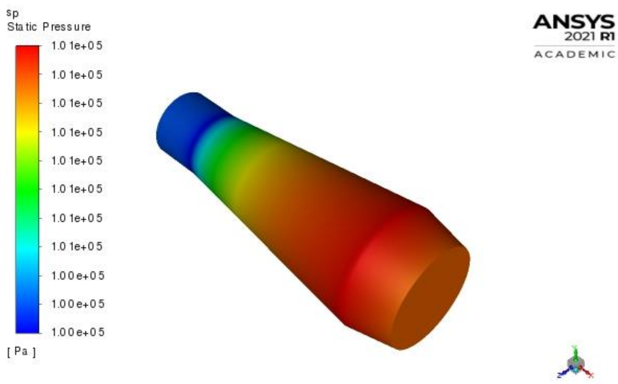

Fig -21: Contour of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 140 mm

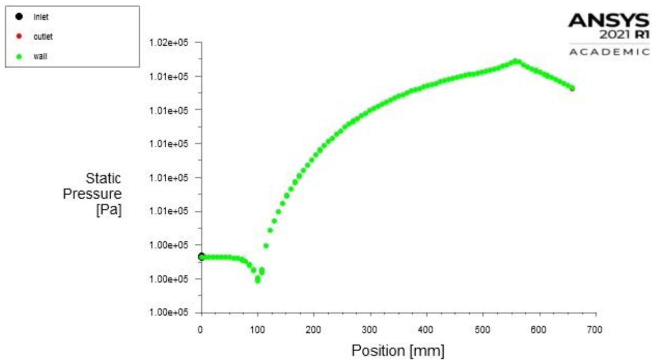

Fig -22: Deviation of static pressure for Divergent exhaust diffuser with diffuser inlet diameter = 140 mm

It is seen in Figs. 21 and 22 that the variation of static pressure from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is gradually increasing. The static pressure value is minimum at the inlet which is 1.00e+05 Pa and gradually increases towards the outlet of a Divergent exhaust diffuser where it is maximum i.e. 1.01e+05 Pa, as the kinetic energy of the fluid gets converted to static pressure. But, from the divergent outlet to diffuser outlet it is decreasing as area is decreasing.

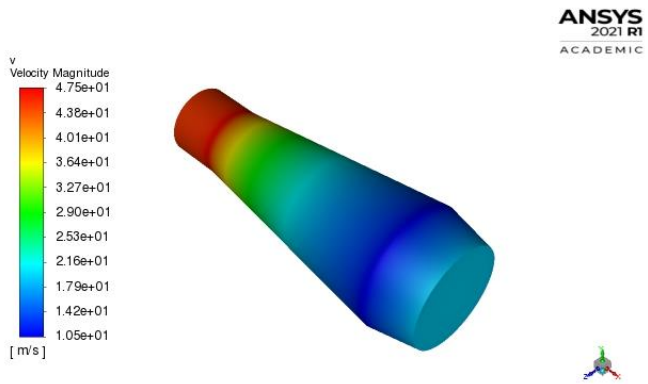

Fig -23: Contour of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 140 mm

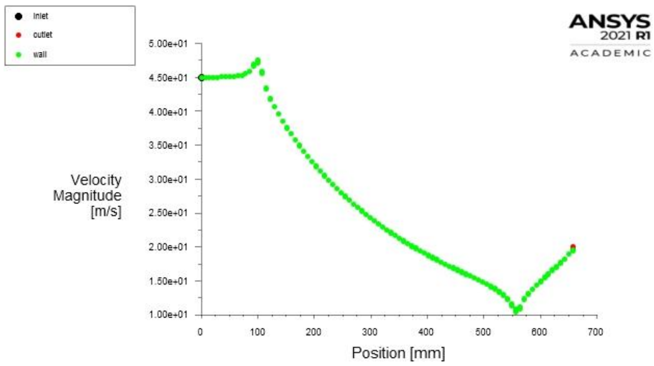

Fig -24: Deviation of velocity magnitude for Divergent exhaust diffuser with diffuser inlet diameter = 140 mm

Figs. 23 and 24 shows that the variation of velocity magnitude from divergent inlet to the divergent outlet along the length of a Divergent exhaust diffuser is slowly decreasing. The velocity magnitude is more at inlet i.e. 4.5e+01 m/s and less at the outlet of a Divergent exhaust diffuser i.e. 2.03e+01 m/s. As it is known that the function of the diffuser is to decrease the velocity by increasing the static pressure i.e. changing kinetic energy to pressure. But, from the divergent outlet to diffuser outlet it is increasing as area is decreasing.

The data obtained from CFD analysis for different cases of a Divergent exhaust diffuser are tabulated in the below Tables.

Table -3: Data obtained from CFD analysis of a Divergent exhaust diffuser with diffuser inlet diameter = 120 mm

Location	Static pressure (Pa)	Velocity (m/s)	CPR
Inlet	100220.5	45	
Outlet	101325	14.8268	0.8905

Table 3 shows the values obtained from CFD analysis for static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser with diffuser inlet diameter = 120 mm. It is found that the static pressure at the inlet is 100220.5 Pa and the velocity is decreased to 14.8268 m/s at the outlet. CPR obtained for these values of inlet, outlet static pressures and inlet velocity is 0.8905.

Table -4: Data obtained from CFD analysis of a Divergent exhaust diffuser with diffuser inlet diameter = 125 mm

Location	Static pressure (Pa)	Velocity (m/s)	CPR
Inlet	100243.7	45	
Outlet	101325	16.0516	0.8718

Table 4 shows the values obtained from CFD analysis for static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser with diffuser inlet diameter = 125 mm. It is found that the static pressure at the inlet is 100243.7 Pa and the velocity is decreased to 16.0516 m/s at the outlet. CPR obtained for these values of inlet, outlet static pressures and inlet velocity is 0.8718.

Table -5: Data obtained from CFD analysis of a Divergent exhaust diffuser with diffuser inlet diameter = 130 mm

Location	Static pressure (Pa)	Velocity (m/s)	CPR
Inlet	100269.9	45	
Outlet	101325	17.3284	0.8507

Table 5 shows the values obtained from CFD analysis for static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser with diffuser inlet diameter = 130 mm. It is found that the static pressure at the inlet is 100269.9 Pa and the velocity is decreased to 17.3284 m/s at the outlet. CPR obtained for these values of inlet, outlet static pressures and inlet velocity is 0.8507.

Table -6: Data obtained from CFD analysis of a Divergent exhaust diffuser with diffuser inlet diameter = 135 mm.

Location	Static pressure (Pa)	Velocity (m/s)	CPR
Inlet	100299.5	45	
Outlet	101325	18.6682	0.8268

Table 6 shows the values obtained from CFD analysis for static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser with diffuser inlet diameter = 135 mm. It is found that the static pressure at the inlet is 100299.5 Pa and the velocity is decreased to 18.6682 m/s at the outlet. CPR obtained for these values of inlet, outlet static pressures and inlet velocity is 0.8268.

Table -7: Data obtained from CFD analysis of a Divergent exhaust diffuser with diffuser inlet diameter = 140mm

Location	Static pressure (Pa)	Velocity (m/s)	CPR
Inlet	100332.5	45	
Outlet	101325	20.057	0.8002

Table 7 shows the values obtained from CFD analysis for static pressure and velocity at the inlet and outlet of a Divergent exhaust diffuser with diffuser inlet diameter = 140 mm. It is found that the static pressure at the inlet is 100332.5 Pa and the velocity is decreased to 20.057 m/s at the outlet. CPR obtained for these values of inlet, outlet static pressures and inlet velocity is 0.8002.

Finally, observing and studying the CFD analysis results for all the different cases of a Divergent exhaust diffuser, it can be considered that the best case is a Divergent exhaust diffuser with a diffuser inlet diameter = 120 mm. As this case gives the CPR = 0.8905 which is maximum when compared to all other cases.
These results are validated with the theoretical calculations using basic equations. The model which gives the maximum CPR is considered to be an optimized geometry of a Divergent exhaust diffuser.

Table -8: Validation of CPR value from result of CFD analysis with theoretical value for different models of a Divergent exhaust diffuser

Case No.	Inlet diffuser Dia (mm)	CFD analysis CPR	Theoretical calculated CPR	Difference CFD CPR - Theoretical CPR	% Difference Theoretical CPR with CFD CPR
1	120	0.8905	0.6758	0.2147	24.11
2	125	0.8718	0.6482	0.2236	25.65
3	130	0.8507	0.6195	0.2312	27.18
4	135	0.8268	0.5897	0.2371	28.68
5	140	0.8002	0.5587	0.2415	30.18

From Table 8, it is clear that the difference between CFD analysis CPR and theoretical calculated CPR is approximately 0.2.

7. CONCLUSIONS

From the work carried out in this paper the following conclusion are listed:

- Different 3D models of a Divergent exhaust diffusers with diffuser inlet diameter varying from 120 mm to 140 mm in steps of 5 mm, divergent outlet diameter = 252.25 mm, diffuser outlet diameter = 210.75 mm and half cone angle =7° are created in Ansys workbench.
- The created 3D models are meshed in Ansys workbench.
- CFD analysis is carried out on the different meshed models using Ansys Fluent.
- By using the data obtained from the CFD analysis, i.e. static pressure and velocity at the inlet and outlet of the Divergent exhaust diffuser the CPR is calculated for each model.
- The CPR value obtained through CFD analysis is validated with the theoretical calculation using basic equations.
- From both the results of CFD analysis and theoretical calculation, it is observed that Case 1 i.e. a Divergent exhaust diffuser with the diffuser inlet diameter = 120 mm, is giving the maximum CPR value when compared to all other cases i.e. CFD analysis CPR = 0.8905 and theoretical calculated CPR = 0.6758.

Finally, Case 1 can be considering the best and efficient result compared to all other geometries as, giving the optimum value of CPR, which leads to improve the performance of a Divergent exhaust diffuser and thereby, the power and efficiency of a turbine in a gas turbine engine.

Also, it will improve the result of a Divergent exhaust diffuser with diffuser inlet diameter = 135 mm.

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