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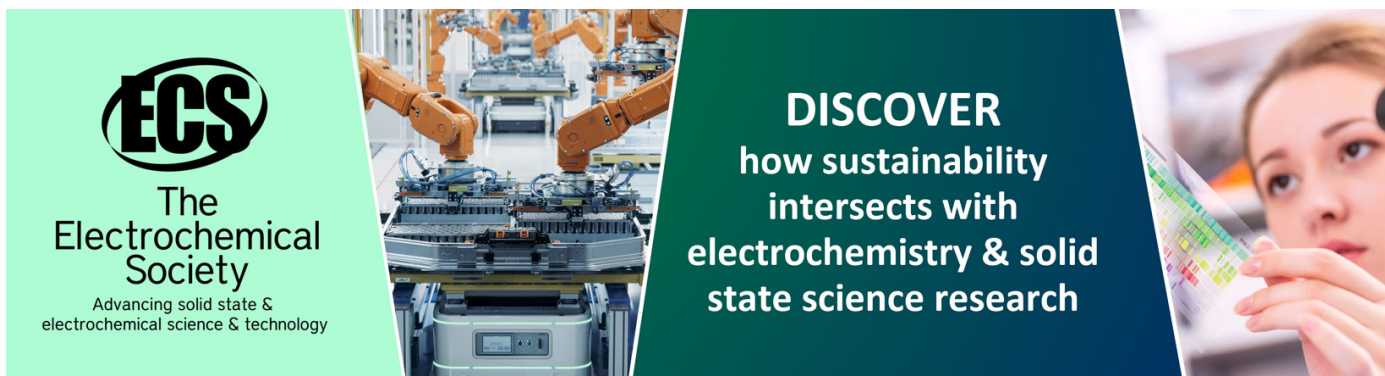
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The Gas Flow Characteristics of A Helicopter Engine Exhaust Duct Using CFD Analysis

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Abstract: In this project is the gas flow characteristic of a helicopter engine e xhaust and to derive an optimized geometry for the e xhaust duct with minimum pressure loss using CFD analysis. In this project, the variables to be analyzed are the in let static pressure, velocity and temperature of the e xhaust gas at the exit of the e xhaust duct. Cylindrical e xhaust ducts of various dimensions are modeled by changing the primary and secondary inlet area and the e xhaust geometry is optimized based on the CFD results. For the same optimized area of primary and secondary inlet, divergent e xhaust duct is modeled and analyzed for various divergent angles. Parametric studies were carried out for a better comparison between cylindrical and divergent ducts for the better thermal efficiency.

1. Introduction

A helicopter is a type of rotorcraft in which lift and thrust are complete by one or more engine driven rotors In difference with fixed wing aircraft. This allows the helicopter to take off and land vertically, to hover, and to fly forward, backward and laterally. These attributes consent helicopters to be recycled in jammed or isolated zones where fixed-wing aircraft would not be able to take off or land. The capability to efficiently hover for long periods of time allows a helicopter to accomplish tasks that fixed-wing aircraft and other forms of vertical takeoff and landing aircraft cannot execute. Rotary winged aircraft primarily utilize turboshaft engines in order to create the power required for flight. A turboshaft engine is a form of gas turbine which is enhanced to produce shaft power, rather than Jet thrust In standard, a turboshaft engine is similar to a turbojet with additional turbine increase to extract heat energy from the exhaust and change it into output shaft power. The engines and the attending accessories within the engine section need cooling in order to ensure that maximum component allowable limits are not exceeded.

1.1 CFD Approach:

Computational fluid dynamics is the branch of fluid dynamics that utilizations numerical strategies and calculations to examine the issues. It is a PC based instrument for reproduc ing the conduct of frameworks including liquid stream, heat exchange, and other related physical procedures. It works by explaining the conditions of liquid stream (in an exceptional structure) over a locale of enthusiasm, with determined conditions on the limit of that area.

1. The fluid continuum is discretized: i.e., field variables are approximated by their values at a finite number of nodes.
2. The equation of motions is discretized: i.e., approximated in terms of values at the nodes.
3. The system of Algebraic equations is solved to give values at the nodes.
4. The process of performing a single CFD simulation is divided into four modules:
 - a) Creating Geometry/Mesh
 - b) Defining Physics of the Model
 - c) Solving the CFD Problem



d) Visualizing the Results in the Post-processor

1.2 Modelling of a duct

In gas turbine applications, the engine, its enclosure and the exhaust system must be cooled to limit the temperatures. The limitation on temperature may be set by structural integrity, internal space ventilation, space saving or suppression of infrared signature. In many cases the cooling system are fully passive, i.e. without any external driving source. In case of Helicopters, the hot exhaust from the turbine may hit the structural components such as tail boom, tail rotors which causes structural integrity problems.

1.3 Exhaust System

Exhaust system is an integral part of an engine. The primary purpose of the exhaust system is to drive out the gases from the turbine to the atmosphere. In helicopters powered by the turbo shaft engine, exhaust duct reduces the velocity, dissipate the remaining thrust and provides cooling to the exhaust gases while the gases leaving through the exhaust system.

1.4 Exhaust Duct

Exhaust duct is the pipe where the exhaust gases are cooled and expelled out to the atmosphere. In helicopters the exhaust duct is not attached directly to the engine, there is a gap between the front edge of the duct and the rear-most portion of the engine nozzle. Exhaust cone is placed in the rear end of the turbine to collect and discharge gases from the turbine wheel. This helps in streamlining the gas flow from the turbine and also helps in reducing the static pressure of the hot gases at the entrance of the exhaust duct

Flow path of an exhaust system

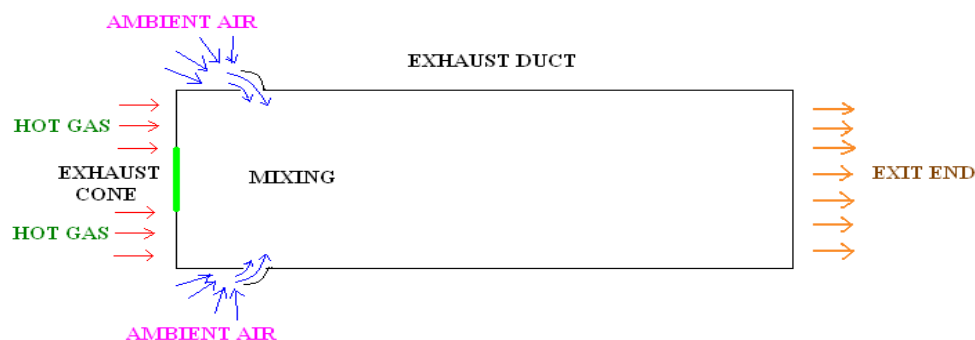


Figure 1. Schematic diagram of exhaust duct

The above figure shows the schematic diagram of the constant area exhaust duct. The rear end of the exhaust cone will be present at the centre of the duct inlet and the high temperature exhaust gas from the engine nozzle enters through the duct inlet. Due to the presence of the cone in the inlet area, the hot gas enters the duct at a high velocity thereby reducing the static pressure. Ambient air reaches the secondary inlet area through the cooling inlet..

In hover condition, this force draws the ambient air inside the duct. These two streams (hot gas and ambient air) travel in the duct and mix together. Due to this mixing of hot gas with ambient air, temperature of the exhaust gas will be reduced.

2. Design Parameters

The Design parameters are as follows

a) Duct Size

Diameter: The diameter of the duct should be optimum to accommodate the mass flow of gas passing through the duct. The diameter of the duct is chosen based on the existing helicopter exhaust design.

Length: The length of the duct plays an important role in the mixing and pressure rise of the gases. Depending upon the flow and other geometrical parameters there is an optimum length of the duct.

b) Duct shape

The duct shapes taken into analysis are

1. Cylindrical
2. Divergent

c) Secondary inlet area

The secondary inlet area should be chosen such that it should pave the way for the required amount of ambient air to enter into the exhaust duct for proper cooling of exhaust gases.

2.1 Initial parameters:

Geometry parameters

- Diameter of duct – 300 mm
- Length of duct – 600 mm

Flow parameters:

Hot Gas Properties

- Mass flow rate – 3 kg/s
- Temperature – 900 K

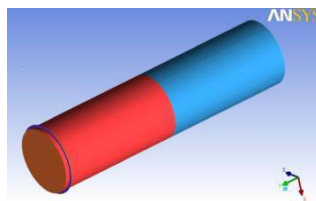
Hot Gas Composition (Mass Fraction)

- Nitrogen (N₂) – 0.75
- Oxygen (O₂) – 0.16
- Carbon-dioxide (CO₂) – 0.06
- Water Vapor (H₂O) – 0.025
- Carbon monoxide (CO) – 0.005

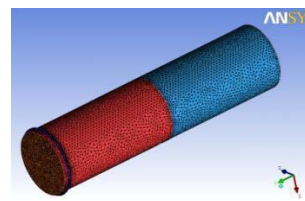
3. CFD Results

The model is designed in CATIA and imported to ICEM CFD.

CASE 1: Constant Area Duct with 11 mm Height Scoop (Hover at S.L)



a) Geometry



b) Mesh (unstructured mesh consisting of Tetrahedral, pyramid and prism elements)

Figure2. Geometry and Mesh model In Case-I

3.1 Boundary conditions

The various boundary conditions used for simulation are given below

a) Inlet

At this boundary, the following initial conditions are given.

Mass Flow Rate – 3 kg/s & Temperature – 900 K

b) Opening

Secondary inlet is given as OPENING boundary condition. In opening boundary condition, the fluid can both enter and leave the boundary.

At secondary inlet, the ISA conditions at sea level are given i.e.

Pressure – 1 atm & Temperature - 15°C = 288 K

c) Wall

On the solid surface, the fluid is assumed to stick to the wall by the action of viscosity. This is called no-slip condition and it requires that the solid and adjacent fluid surface do not have a velocity relative to each other. Hence the wall boundary conditions are given for the duct and the lip.

d) Outlet

At the outlet of the domain, the boundary condition is given as OUTLET. Here, the fluid can only leave the boundary. Fluid cannot enter through the boundary.

3.2 a) Post – processing result in Case-I

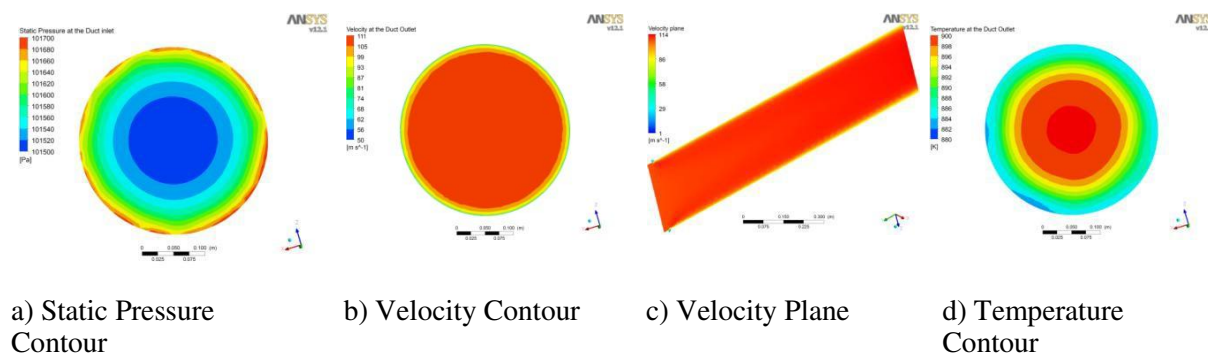


Figure 3. Static pressure, velocity and temperature counter in case-I

Here the static pressure varies from 101500 N/m^2 - 101700 N/m^2 and average static pressure - 101568 N/m^2 . The total temperature varies from 880 K – 900 K , average Temperature – 893 K

In this case (11 mm scoop height), the velocity and the temperature at the outlet section is higher and the static pressure at the inlet is higher than that of the ambient static pressure thus not satisfying the design requirement

CASE 2: Constant Area Duct with 25 mm Height Scoop (Hover at S.L)

The mesh type chosen is unstructured mesh consisting of Tetrahedral, pyramid and prism elements.

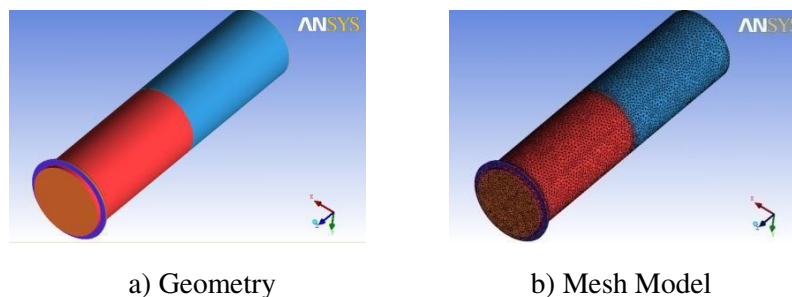


Figure 4. Geometry and Mesh model in case-II

The boundary conditions, material properties and the solver inputs are same as given for case 1.

b) Post processor Results in Case-2

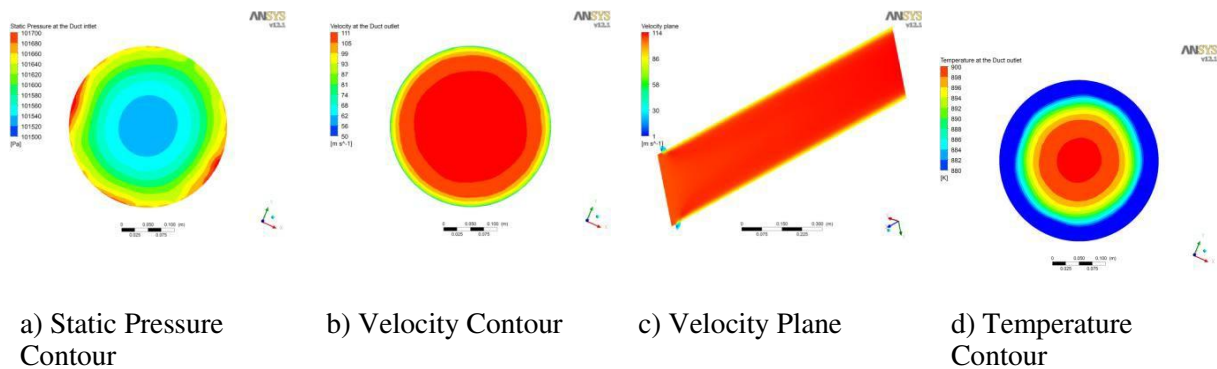


Figure 5. Static pressure, velocity and temperature counter in Case-II

It is observed that the static pressure varies from 101500 N/m^2 - 101700 N/m^2 & average static pressure is 101592 N/m^2 , velocity at the inlet is 108 m/s and the outlet average velocity 107 m/s . i.e. the velocity reduction is very less. The total temperature varies from 880 K - 900 K & Average Temperature - 886 K

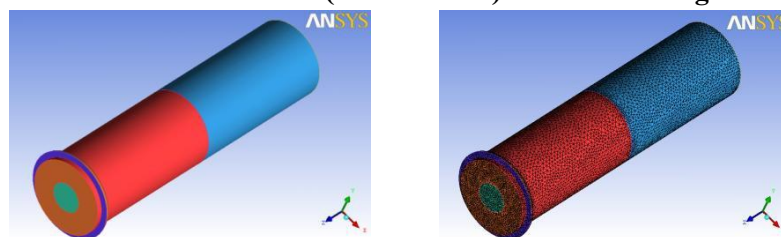
Comparison of the above two cases are given in the table below

Table1 . Comparison of flow properties in case-I & Case-II

Flow (→) properties	Static pressure (N/m^2)		Mass flow ratio (%)	Temperature at outlet (K)	Velocity (m/s)	
	Primary inlet	Secondary inlet			Inlet	Outlet
Cases (↓)						
Case 1 (11mm)	101568	101281.82	0.41	893	108	108
Case 2 (25 mm)	101592	101281.82	0.50	886	108	107

From the above table it is observed that in case 1, the velocity and the temperature at the outlet do not satisfy the design requirement. In case 2, the temperature is reduced a little. But the static pressure is increased instead of decreasing. If we increase the secondary inlet area further, the static pressure will further increase.

CASE 3: Constant Area Duct with Cone (Dia. 120 mm) and 25 mm height scoop (Hover at S.L)



a) Geometry

b) Mesh Model

Figure6. Geometry and Mesh model In case-III

c) Post – processor results case -3

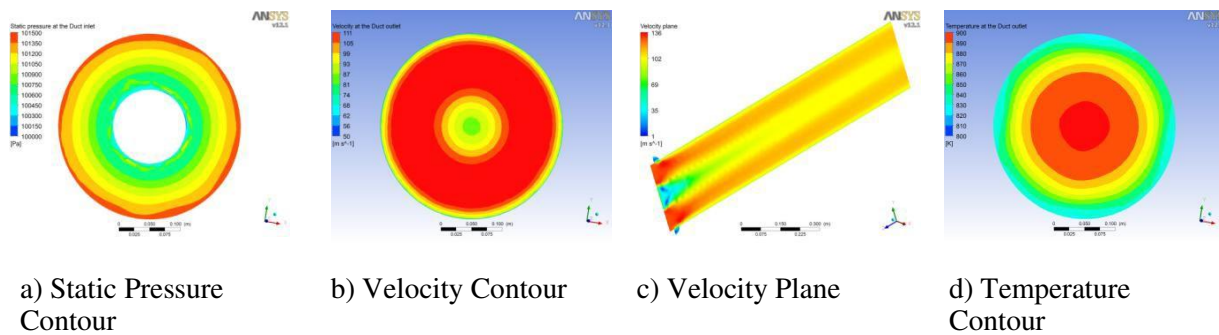


Figure 7. Static pressure, velocity and temperature counter in Case-III

- In this case the static pressure varies from 100000 N/m² to 101500 N/m² & average static pressure is 101035 N/m². The average velocity is reduced from 128 m/s to 109 m/s as the flow travels through the duct. The total temperature varies from 820 K to 900 K & the average Temperature is 872 K.

CASE 4: Constant Area Duct with Cone (Dia. 150 mm) and 25 mm Height Scoop (Hover at S.L)

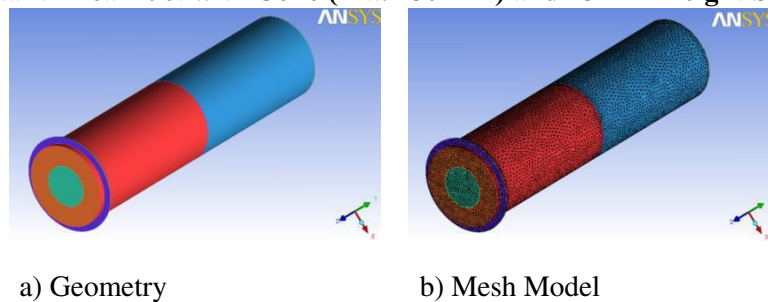


Figure 8. Geometry and Mesh model in case-IV

d) Post – processing result in case-4

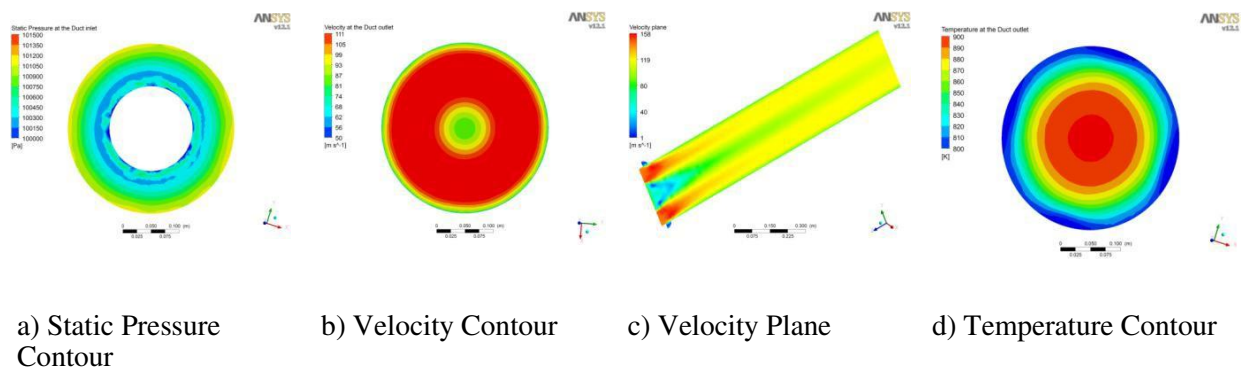


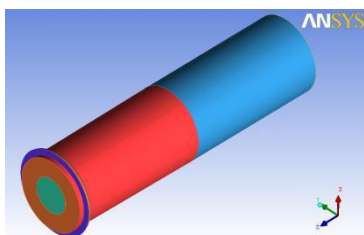
Figure 9. Static pressure, velocity and temperature counter in Case-IV

Table 2: Comparison of Flow parameters in case-III & IV

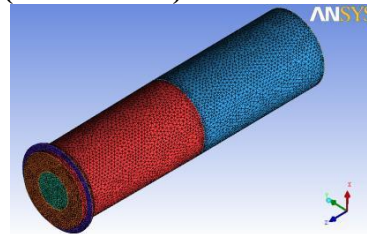
Flow (→)	Primary inlet	Mass flow	Temperature at	Velocity (m/s)
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properties	Static pressure (N/m ²)	ratio (%)	outlet (K)	Inlet	Outlet
Cases (↓)					
Case 3 (120 mm dia cone)	101035	4.3	872	128	109
Case 4 (150 mm dia cone)	100630	8.19	856	144	111

CASE 5: Divergent Duct with 0.5° Divergence Angle (Hover at S.L)



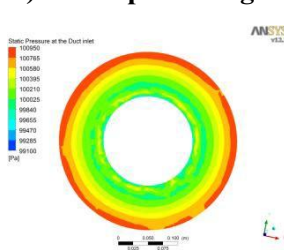
a) Geometry



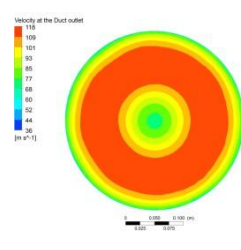
b) Mesh Model

Figure10. Geometry and Mesh model in case-V

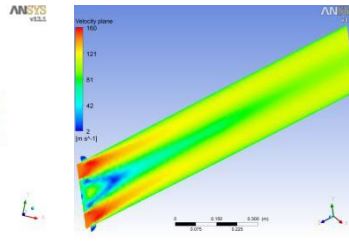
e) Post – processing result in Case-5



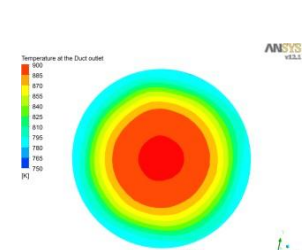
a) Static Pressure Contour



b) Velocity Contour



c) Velocity Plane

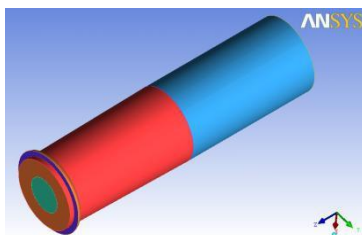


d) Temperature Contour

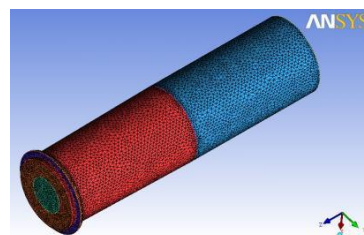
Figure11. Static pressure, velocity and temperature counter in Case-V

In this case, the inlet static pressure and the outlet temperature is reduced than the previous case (Cylindrical Duct). Also the velocity is reduced to 105 m/s. But this velocity reduction is not sufficient. We have to further reduce the velocity and hence we are increasing the divergence angle.

CASE 6: Divergent Duct with 1° Divergence Angle (Hover at S.L)

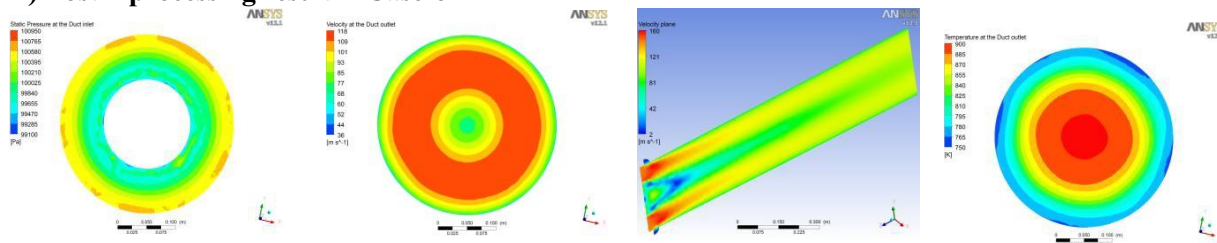


a) Geometry



b) Mesh Model

Figure12. Geometry and Mesh model in case-VI

f) Post – processing result in Case-6

a) Static Pressure Contour

b) Velocity Contour

c) Velocity Plane

d) Temperature Contour

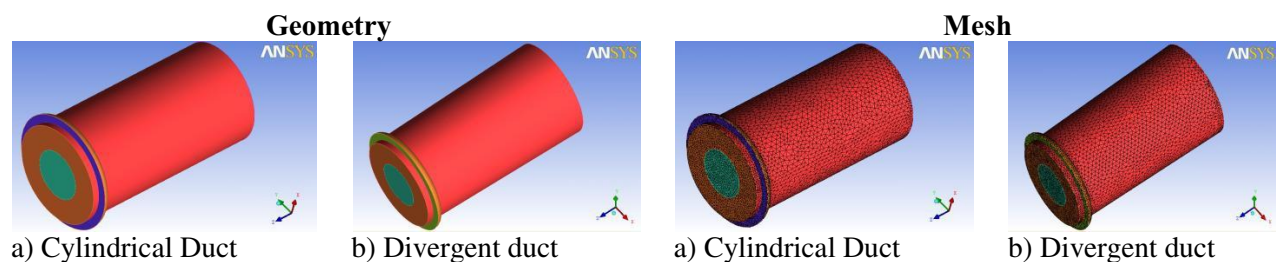
Figure 13. Static pressure, velocity and temperature counter in Case-VI**Table3.** Comparison between the two configurations (0.5° and 1° divergent duct)

Flow (→) properties	Primary inlet Static pressure (N/m ²)	Mass flow ratio (%)	Temperature at outlet (K)	Velocity (m/s)	
Cases (↓)				Inlet	Outlet
Case 5 (0.5 ° angle)	100398	10.03	848	144	105
Case 6 (1° angle)	100183	11.91	839	144	99

From the above table it is observed that Case 6 (1° divergent duct) is best suitable for our design requirement. If we further increase the divergence angle, there is a chance of reverse flow at the outlet. Thus the optimized angle is taken as 1° mm

4. Comparison of Cylindrical and Divergent Exhaust Duct with Domain (Hover Condition at S.L, ISA)

The optimized geometry of cylindrical and divergent duct is modelled using the CATIA and is imported to ICEM CFD

**Figure14.** Comparison of geometry and mesh model for cylindrical and Divergent Duct**g) Post – processing result Hover Condition at S.L, ISA**

Static Pressure Contours

Velocity Planes

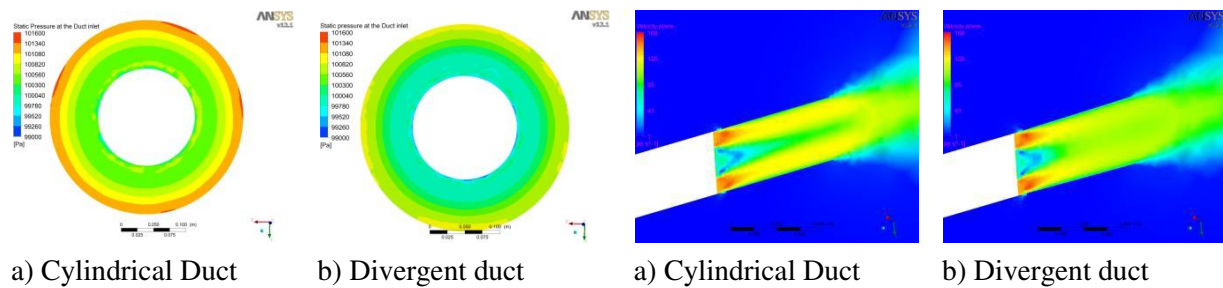


Figure15. Static Pressure and Velocity Planes of Cylindrical and divergent Duct

Table4. Static Pressure of the Cylindrical and Divergent Duct

Static Pressure (N/m ²)	Cylindrical	Divergent
Range	99520-101600	99000-101080
Average	100773	100302

From the above table it is observed that the static pressure in the divergent duct is less than the cylindrical duct and will suck more ambient air which will provide better efficiency for mixing.

Velocity contours

Temperature Contours

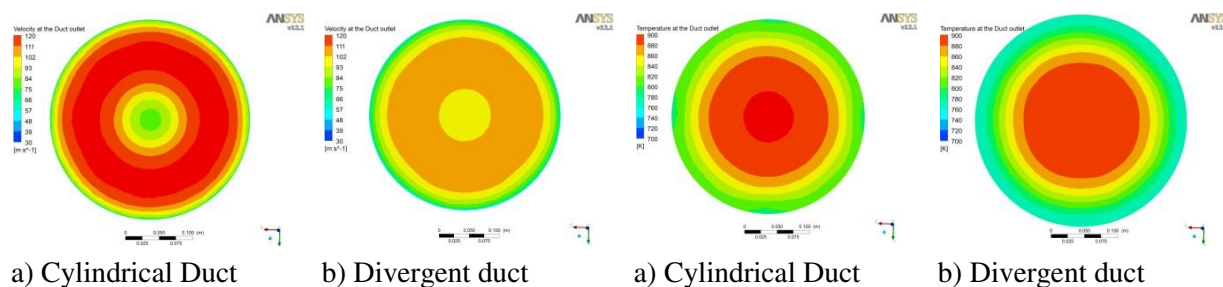


Figure16. Velocity and temperature contours comparison for Cylindrical and Divergent Duct

Table5 Velocity and temperature of the Cylindrical and Divergent Duct

	Velocity (m/s)			Temperature	
	Cylindrical	Divergent		Cylindrical	Divergent
Range	55 – 120	48 – 110	Range	800 – 900	760 – 900
Average	111	99	Average	859	838

5. Comparison of Cylindrical and Divergent Duct with Domain (Forward Flight Condition at S.L, ISA)

a) Boundary conditions

The boundary conditions are same as given for the hover condition except that the front surface of the domain is given as INLET condition and the air enter that surface at a velocity of 50 m/s.

Material properties and solver inputs are same as given for the hover conditions.

h) Post – processing result Forward Flight Condition at S.L, ISA

Static Pressure Contours

Velocity Planes

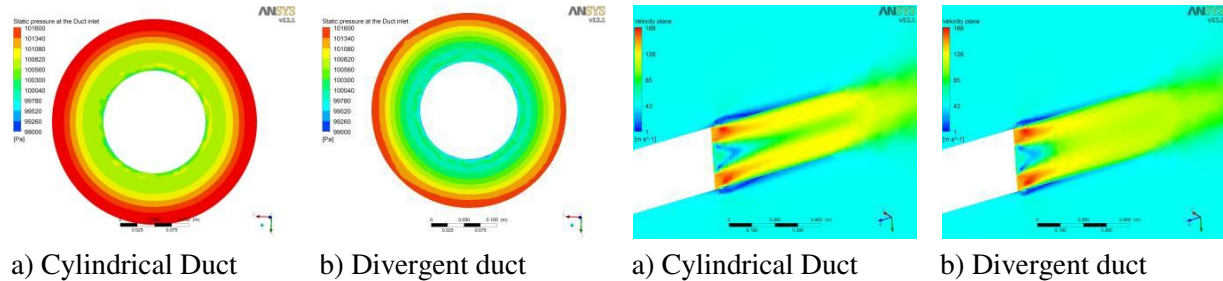


Figure17. Static Pressure and Velocity Planes of Cylindrical and divergent Duct at Forward Flight Condition

Table6 Static Pressure of the Cylindrical and Divergent Duct

Static Pressure (N/m ²)	Cylindrical	Divergent
Range	99780 - 101600	99260-101600
Average	101203	100678

From the above table, it is observed that reduction in the static pressure is more in the divergent duct than the cylindrical duct.

Velocity contours

Temperature Contours

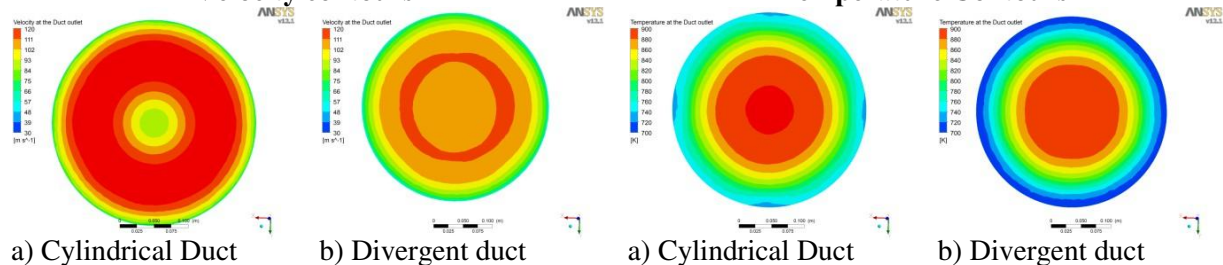


Figure18. Velocity and temperature contours comparison for Cylindrical and Divergent Duct Forward Flight Condition

Table7. Velocity and temperature of the Cylindrical and Divergent Duct Forward Flight Condition

Velocity (m/s)			Temperature		
	Cylindrical	Divergent		Cylindrical	Divergent
Range	57 - 120	48 - 120	Range	720 - 900	700 - 900
Average	113	101	Average	833	810

From the results, it is clear that the temperature reduction is more in the divergent duct only. This will help in increasing the life of the components

6.Results and Discussions

Inlet static pressure is inversely proportional to the mass flow rate of the secondary air entering the duct. This static pressure varies from the higher value at the duct surface to the lower

value near the cone (engine nozzle interface) which is placed at the center of the duct inlet. Since the static pressure near the cone is low, the secondary air is sucked to the centre of the duct, thus enhances proper mixing of hot gas and secondary air. This reduced static pressure also tends to suck the burnt gases from the turbine, avoiding the accumulation of gases in the turbine. This will increase the turbine efficiency there by increasing the engine efficiency.

From the table it is known that, from the duct surface to the cone the reduction in static pressure is more and the average static pressure is less for the divergent duct when compared to cylindrical duct. From static pressure point of view, divergent duct is suitable for helicopter exhaust system.

Table 8. Comparison of hover and forward condition

FLOW PARAMETERS	HOVER				FORWARD FLIGHT (50 m/sec)			
	CFD		THEORETICAL		CFD		THEORETICAL	
	Cyl	Div	Cyl	Div	Cyl	Div	Cyl	Div
Inlet Static Pressure (N/m ²)	100773	100302	100828	100443	101203	100678	100945	100626
Outlet Velocity (m/s)	111	99	111	98	113	101	113	100
Exhaust Outlet Temperature (K)	859	838	860	842	833	810	836	816

The velocity of the gases reduces from the inlet to outlet. When the hot gas from the engine nozzle passes through the inlet of the exhaust duct, the velocity is decreased due to the increase in cross sectional area of the duct. The velocity will further decrease because of the increase in static pressure along the exhaust duct. When the flow velocity along the duct is low, mixing of gases will be proper. This is because when the gas moves with a low velocity, it will remain in the duct for a long time so that the duration of mixing is higher. Also if the velocity of gases leaving the exhaust duct is low, it will not affect the aerodynamics of the nearby components such as rotors.

The reduction in the temperature of the exhaust gases increases as the amount of secondary air entering the exhaust duct increases. The amount of secondary air entering the duct is inversely proportional to the inlet static pressure. Therefore, as the inlet static pressure decreases, temperature reduction will be more. Also the temperature reduction depends on proper mixing of hot gas with the ambient air. This mixing will be proper only when the gas mixture moves with a low velocity along the duct. Thus the temperature reduction depends on the inlet static pressure and the flow velocity along the duct.

From the above discussion and the values from the table, it is seen that the temperature reduction will be more in the divergent duct than the cylindrical duct because it has lower inlet static pressure and outlet velocity.

7. Conclusion

The theoretical and the computational study of cylindrical and divergent exhaust duct have been carried out. The effect of primary inlet area, secondary inlet area and the outlet area of the duct on the flow parameters such as primary inlet static pressure, outlet velocity and the outlet temperature was studied for both the cylindrical and the divergent duct for Hover and Forward flight condition.

From the result it is observed that the divergent exhaust duct is better than the cylindrical exhaust duct for helicopter applications due to the following reasons:

4.1 Reduced inlet static pressure for better engine efficiency.

4.2 Reduced velocity of the exhaust gases at the outlet so that it won't affect the aerodynamics of the helicopter.

4.3 Reduced temperature at the exhaust outlet and hence less structural damage and extended life of the surrounding components.

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