ANALYSIS OF AIR EJECTOR FLOW IN CONVERGENT AND CONVERGENT DIVERGENT NOZZLE OF AIRCRAFT

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Abstract: Ejectors are devices often used in aircraft systems. They typically have a main tube that ends in a nozzle, which is usually either converging or converging-diverging in shape. In this study, we focus on improving how well these ejectors work. The main goal is to see if changing the nozzle from a simple converging shape to a converging-diverging shape can make the ejector more efficient and easier to control.

To find out, we used Ansys Fluent software to analyze the airflow through the ejector. We looked at how pressure, temperature, and speed change inside it. The results showed that using a converging-diverging nozzle increases the mass flow ratio, which means better performance, compared to the regular converging nozzle, all based on the same size and shape.

Keywords: Nozzle, Ejector, Primary Flow, Secondary Flow, Mass Augmentation Ratio.

I. INTRODUCTION

A. Ejectors

In aircraft and aerospace systems, ejectors are widely used when there's a need to move a certain amount of fluid from one place to another. An ejector works by using the energy of a fast-moving fluid to pull in and move another fluid. It has a special duct where a high-speed jet of fluid is released. This jet creates a low-pressure area that draws in the second fluid. Both fluids then mix inside the duct and are pushed out together to a higher-pressure area.

Ejectors, also known as jet pumps, are often used in places where regular pumps like rotary or piston types aren't the best fit. They're popular because they're simple, have no moving parts, and can handle tough conditions. This makes them great for moving moderate amounts of fluid over short distances, especially in harsh environments. Ejectors are also used to increase the flow of air, acting as air mass boosters.

Ejectors are often used in wind tunnels and other large ground-based testing setups. When they're used as jet pumps, the main goal is to raise the pressure of the fluid, even if the amount of flow is small. But when the aim is to boost or increase the flow, the pressure (or head) produced is usually low.

B. Ejector Construction

An ejector primarily consists of three fundamental components: a diffuser, a mixing chamber, and a nozzle. In a standard ejector, the motive fluid (Ma) enters at point 1 and expands through a converging-diverging nozzle up to point 2. The suction fluid (Mb) is drawn in at point 3 and enters the mixing chamber, where it interacts and mixes with the high-velocity motive fluid at point 4. As shown in Figure 1, the two fluids (Ma and Mb) are recompressed together in the diffuser and exit at point 5. The nozzle of a steam-jet ejector is typically made of stainless steel, while the ejector body is generally constructed from cast iron or steel. Due to the wide range of applications for steam jet vacuum systems, special materials such as carbon steel, stainless steel, Monel, Ni-Resist, Teflon, titanium, and ceramics are frequently used in their construction. These designs are common in situations where keeping the initial cost low is more important than long-term efficiency, or when the system is used occasionally or in places where water isn't available.

Ejectors can be classified in many ways. One way of classified in ways, one classifying is based on the total mass of the fluid delivered by the ejector which comes from augmenters. This can be further classified into air or steam to air based on the fluid chosen for the primary and secondary flows respectively. In this, it can be further subdivided into subsonic or supersonic ejectors based on whether the Mach number of the induced flow is subsonic or supersonic. Ejectors can also be classified based on the thrust produced by the ejector system and this comes under thrust augmenters. As in the case of mass augmenters, thrust augmenters are also classified as subsonic air-to-air or supersonic air-to-air ejectors. Ejectors can be classified based on the type of mix between the primary and secondary streams. The mixing between the primary and secondary streams can take place either at the constant cross-sectional area or at constant pressure and are respectively called constant area mixing and constant pressure mixing. The pre-cooler installed in the series production LCA implements the constant area type mixing duct.

Ejectors are essentially emphasized to be of constant area type. An ejector of this type can pump secondary fluid into an exhaust space at a pressure higher than the pressure in the secondary chamber. If mixing occurs at constant pressure instead of at a constant area, the pressure at the exit of the mixing tube cannot exceed the pressure in the secondary supply chamber. This means that in the absence of a diffuser, a constant pressure type of ejector can serve only as a blower and not as a pump. Even when the ejector is serving as a blower i.e. delivering air at the pressure of the secondary supply chamber, constant area mixing gives higher secondary flows for a given exit area than constant pressure mixing.

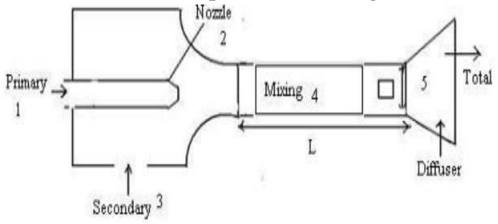

Figure 1: Components and Design of Ejector

C. Nozzle

A nozzle is a tool used to control how a fluid moves mainly to increase its speed at the entry or exit point. It's usually a pipe or tube with a changing diameter, designed to guide or adjust the flow. Nozzles help manage the flow rate, speed, direction, pressure, and even the shape of the fluid stream.

In rocket engines, the nozzle is a key part that influences overall performance. Its design creates a smooth, efficient flow path. In some rocket nozzles, combustion happens around the edges of a central spike, and the surrounding air pressure helps control the hot exhaust flow, which creates thrust and shapes the stream for maximum effect.

Liquid nozzles, like the ones used in fire hoses, are known as converging nozzles because their shape gets narrower along the length, which helps increase the speed of the liquid. These nozzles typically have a simple cone-like appearance and are made with the intake and outlet sizes in a particular ratio. On the other hand, gas nozzles operate differently. Since gases are compressible, their density can vary significantly due to the pressure difference between the nozzle’s inlet and outlet. At very high gas velocities, this effect becomes so pronounced that the nozzle must adopt a converging-diverging shape. The diverging section is essential to accommodate the gas's expansion as it accelerates toward a lower pressure.

A nozzle has three primary functions: regulating fluid flow, assisting fluid in traveling a specific distance, and mold A nozzle has three primary functions: regulating fluid flow, assisting fluid in traveling a specific distance, and molding the fluid's output.

D. Convergent-Divergent Nozzle

The purpose of these nozzles is to accelerate gas flow to supersonic levels. Their form narrows and then widens. The neck is the narrowest area. The gas accelerates as it moves toward the narrowing (converged) region. The gas achieves speed of sound, or sonic speed, as it enters the throat. After that, as it moves into the widening (diverging) section, the gas speeds up even more and reaches supersonic velocity.

E. Primary And Secondary Flow

Jet pumps increase the flow as well as pressure of a lower-pressure fluid by using the applied pressure of a high-pressure fluid. They are capable of working with both compressible and incompressible fluids as the primary or secondary flow. Figure 1 depicts a simple ejector diagram, with labels designating the primary flow as spot 1 and the secondary flow as spot 3. After passing through a nozzle, the primary fluid's pressure is converted to kinetic energy, or speed. The secondary fluid is then drawn in, or entrainment, by this rapid jet.

The two fluid streams come together and mix inside the mixing tube, which helps in recovering some of the lost pressure. After that, more pressure is regained in a gently widening section called a diffuser, placed just after the mixing tube. The primary fluid can be either a liquid or a gas, while the secondary fluid can be a liquid, a gas, or even a mix of both (called multiphase flow).

Augmentation: is a method used to enhance performance. It can be of two types: passive, which works without needing any extra power, and active, which needs some external power to function.

II. METHODOLOGY

Convergent ejector nozzles are typically utilized in the present one pre-cooler configuration. A convergent-divergent (C-D) nozzle was used in a simulation to examine how the flow behaves with a varied design. Since the inlet conditions of the ejector were already known, the next step was to figure out the right dimensions for the C-D nozzle. The nozzle's throat and exit diameter were the components that required computation. The exit pressure has been assumed to be 1 bar, which is the ambient pressure. Additionally, the calculations take into account choked circumstances at the nozzle throat, where the flow rates reaches their maximum and the flow velocity exceeds sonic state.

To carry out the analysis, the models were first created using Pro-E 4.0 software. Three separate models were designed: one for the convergent nozzle, one for the convergent-divergent nozzle, and another for the ramjet. The dimensions used for these models are listed in Table 1 below.

Table 1: Geometrical Data for Model Creation

Type	Convergent	Convergent-Divergent	Ram Jet
Inlet Diameter	17.6 mm	17.6 mm	2.5 mm
Exit Diameter	11 mm	19.98 mm	2.5 mm
Throat	-	11 mm	-
Length	26 mm	30 mm	13 mm (Height)

The dimensions were calculated using mathematical formulas based on the known inlet conditions: pressure of 7.7 bar (absolute), temperature of 843 K, and a mass flow rate of 12 kg/min. With these inputs, equations for critical flow conditions were applied. As a result, the critical pressure was found to be 406,791 Pa, the critical temperature was 710.54 K, and the critical velocity came out to be 534 m/s.

Next, the throat area was calculated to be 1.8760×10^{-4} m². For this analysis, the exit pressure was assumed to be at ambient conditions 1 bar and the process was considered adiabatic (meaning no heat is added or lost). Using the continuity equation, the results showed an exit temperature of 476.05 K, an exit velocity of 870 m/s, and the corresponding exit area was also calculated.

So, the calculated radii for the C-D nozzle section were: 8.8 mm at the inlet, 7.72 mm at the throat, and 9.98 mm at the outlet.

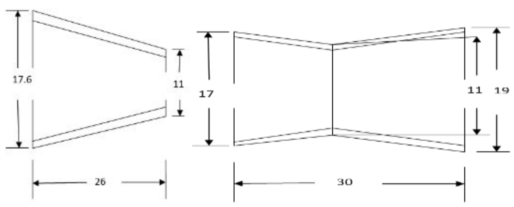

Figure.2: convergent nozzle and Convergent and Divergent Nozzle used for simulation

A. Modelling

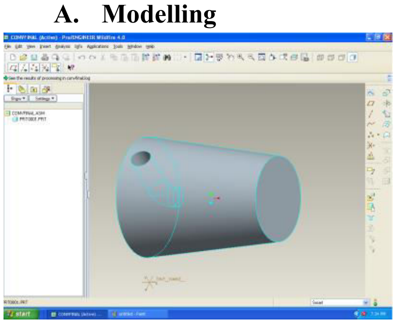

Figure.3: Modelling of convergent Nozzle

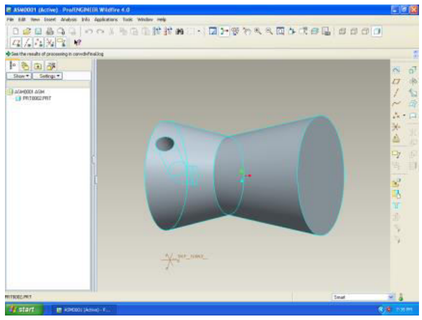

Fig.4: Modelling of convergent -Divergent Nozzle

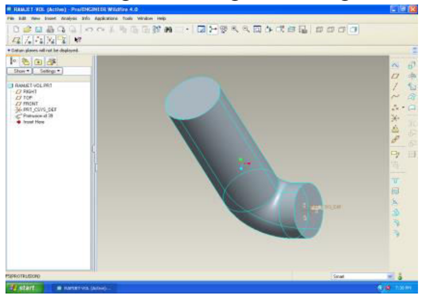

Figure.5: Modelling of Ramjet

B. Analysis

A. Velocity contour

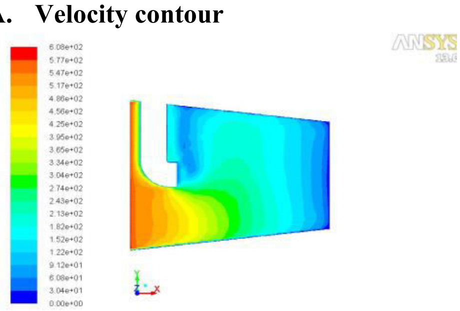

Figure 6. Convergent nozzle velocity contour

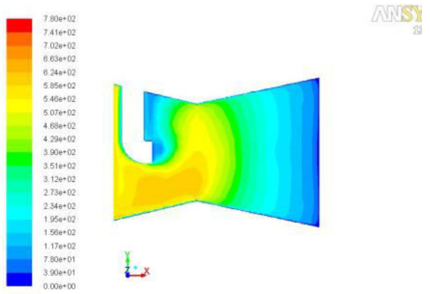

Figure 7. Convergent and divergent nozzle velocity contours

B. Pressure contour

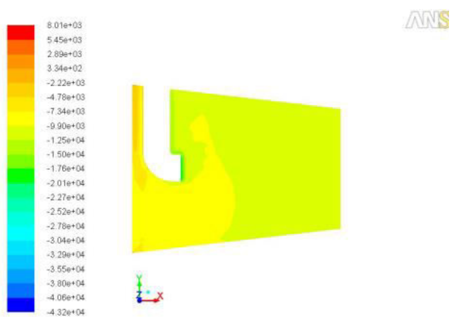

Figure 8. Convergent nozzle pressure contour

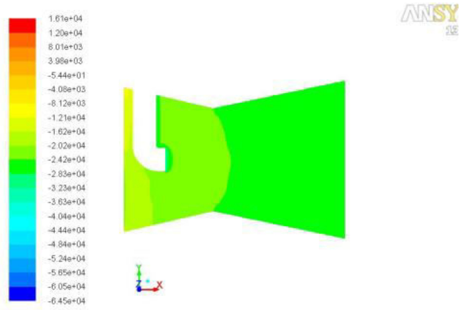

Figure 9. Convergent and divergent nozzle pressure contours

C. Temperature contour

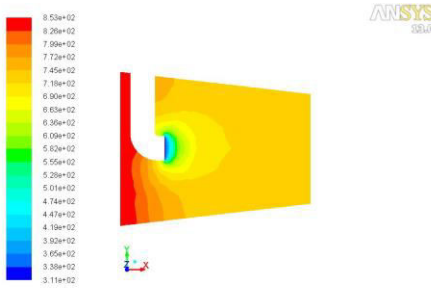

Figure 10. Convergent nozzle temperature contour

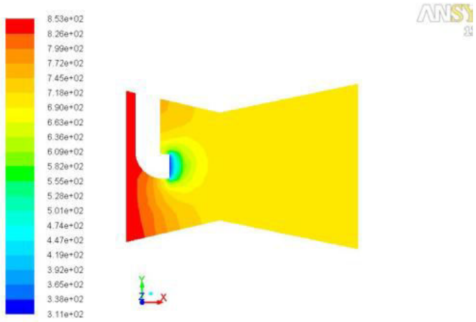

Figure 11. Convergent and divergent nozzle temperature contours

III. RESULTS

A. Velocity

Figure 6 illustrates this configuration. The initial velocity is 585.43 m/s, and the final velocity decreases by approximately 30.7% to 405 m/s. However, the final speed is still higher than the standard reference value. Similarly, in Figure 7, the initial velocity is again 585.43 m/s, but the exit velocity falls further to 260 m/s, which is a 55.5% drop. Even then, the output speed remains above the standard value.

B. Pressure

In a convergent nozzle, the pressure is very high at the inlet. As the flow moves through the nozzle, the velocity increases, but by the time it reaches the end, the velocity drops and there's a sudden drop in pressure. On the other hand, in a convergent-divergent nozzle, the pressure is also very high at the start. As the fluid flows through the converging section, its velocity rises. At the throat, there's a small drop in pressure as the speed peaks. Then, in the diverging section, the pressure drops sharply again while the velocity increases significantly — this is clearly shown in Figures 8 and 9.

C. Temperature

Figure 10 shows that in the convergent nozzle, the temperature starts at 853 K and drops to 745 K at the exit. The abrupt rise in velocity close to the nozzle's end causes this decrease. Figure 11 illustrates the convergent-divergent nozzle, the inlet temperature is also 853 K, but the exit temperature falls further to 672 K. The temperature gradually decreases at the throat but drops sharply at the end of the divergent section — as clearly seen in the temperature contour.

IV.CONCLUSIONS

According to the simulation results, using a convergent-divergent nozzle instead of a convergent nozzle resulted in a higher mass augmentation ratio. Whereas the latter yielded a value of 1.07, the former yielded 1.49. This demonstrates that the C-D nozzle produces greater amounts of air over the conversion model for a given amount of primary mass flow. The convergent and convergent-divergent nozzles have primary flow rates of 0.118 and 0.192 kg/s, respectively. The convergent and convergent-divergent nozzles have secondary flow rates of 0.126 and 0.285 kg/s, respectively.

The key result is the mass augmentation ratio, which is 1.07 for the convergent nozzle and 1.49 for the convergent-divergent nozzle. This demonstrates how the pre-cooler heat exchanger's efficiency can be increased by switching from the existing convergent nozzle to a convergent-divergent nozzle.

With more ram air flow, the heat exchanger becomes more efficient, helping to cool the bleed air to safe temperatures within the design limits. As a result, the pre-coolers would perform better not only during ground operations but also in hot weather conditions.

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