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Exploratory Study of Effects of Ejectors on Drag Reduction

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Ejectors have the prime function of thrust augmentation by mixing secondary flow with primary flow to impart greater momentum change. The original flow is referred to as the primary flow while the additional flow is referred to as the secondary flow. This paper explores usage of ejectors as drag reducing devices using numerical techniques by utilizing CFD FLUENT software. The reference geometry of a high speed drone is chosen and modelled for current study. 2D axisymmetric and 3D half body symmetric analysis have been carried out on different ejector configurations at two Mach Nos (0.4 & 0.6) along with the variation of angle of attack. The results have been compared with the original body consisting of blunt and streamlined rear exhaust. Results show significant drag reduction along with thrust augmentation, giving greater net propulsive force at both Mach number. Further experimental validation is recommended to validate the findings of this paper.

I. Nomenclature

2D	=	two dimensional
3D	=	three dimensional
C_D	=	drag coefficient
Sref	=	reference area
CFD	=	computational fluid dynamics

Introduction

For making aerospace vehicles more reliable and to optimize their performance different techniques are used. One of them is the use of different configurations of ejectors. Ejectors are majorly used for thrust augmentation and noise reduction of jet engine. Previously a solution was proposed by a research program in 1994, the proposed solution was introduction of mixer ejector diffuser system for thrust augmentation and noise reduction. Which used the concept of introduction of secondary air flow to augment the thrust by ejector. They made it more competitive by use of mixers

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which lead to forced mixing and diffusers to reduce the mixing losses [1]. The results shown the boost in thrust augmentation and reduction of noise.

Another research publication was presented by NASA in 2010, the major problem was noise of the jet engines. The researcher presented the solution via use of mixer ejector phenomenon. Which was dedicated to noise reduction and thrust augmentation. The results presented in the research were highly efficient for performance predictions and thrust augmentation potential of ejectors. The results clearly indicated significant reduction in noise and increase of thrust augmentation by use of properly designed configuration of ejector [2].

US Air Force Academy in 2010 published their research on ejector thrust augmentation. In that research they thoroughly elaborated the use of ejectors in steady and unsteady conditions with specific diffusers for thrust augmentation. Their results proved the desirable augmentation of thrust by means of diffusers with ejectors [3]. In 2014, University of Miami presented their experimental research regarding pressure drag reduction on bluff body by using passive jet boat tail flow control. In passive jet tail flow control a secondary flow was introduced to reduce the wake region which leaded to reduction in pressure drag. Their findings explained the successful reduction of wake length and width of aerodynamic body [4].

Another similar research and experimental study of drag reduction by passive flow control of jet boat tail was done by University of Miami in 2015. Their experimental study and numerical simulations concluded the significant reduction of drag on a bluff body by using jet boat tail passive flow control [5]. In 1988 experimental study was published by Western New England College regarding advantages of using different configurations of forced mixer lobes in ejector designs and its impact on overall efficiency of ejector. Their results were much encouraging as forced mixer lobes increased the pumping of ejector and reduced the friction losses which resulted in less overall losses [6]. In 2019, research published by Oregon State University mainly focused on CFD optimization of ejector flaps in a one-sided mixer ejector nozzle. The results were quite encouraging, with an explanation of the ejector gap height [7]. In 1973, research was published by Aerospace Research Laboratories, Ohio. It was focused on thrust augmentation, varying the different parameters of the ejector to increase the overall thrust of the aircraft performance [8].

A similar research was carried out in 2007 by QSS Group, Inc., Ohio. Their research was directed towards effect of varying parameter of ejectors i.e ejector radius on unsteady ejector performance. Their results showed thrust augmentation by varying pulse length and ejector diameter [9]. In 2005, research was published by The Pennsylvania State University on effect of operating frequency on PDE driven ejector thrust performance. They tested ejectors with varying lengths and two different inlet geometries. The results of thrust augmentation were concluded [10].

Previous researches were focused towards thrust augmentation and noise reduction by using ejectors. In our case, we are primarily focused on exploring the drag reduction effects of ejectors which has not been studies in depth yet. The need arose when we had a case in which we needed to install a centrifugal compressor small engine inside a drone. Due to the size and location of the installed engine as shown in Fig. 1, additional drag would hinder the aircraft performance. Hence idea was proposed of using ejectors as thrust reducing device which is being explored in this paper.

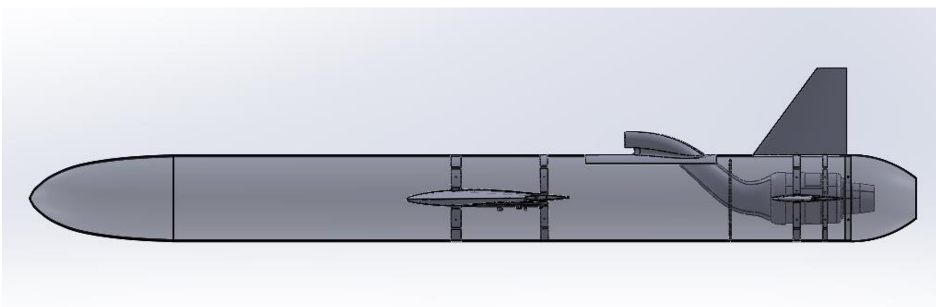


Fig. 1 Drone Geometry Showing Engine

II. Numerical method

A. Domain and Boundary Conditions

A cylindrical body representing the fuselage was taken of 3.1m length and 0.3m diameter. Pressure farfield is kept at 20m from the body and at 15m height. Nozzle is modelled with inlet radius as 0.051 and exit radius as 0.043 and is at choked conditioned for this analysis. Pressure inlet conditions are given on the inlet of nozzle. A fine unstructured mesh of 39k was prepared in GAMBIT for 2D axis symmetric calculations as shown in Fig. 3. To keep a Y+ value between 30 and 200, we have given an inflation layer with first layer thickness of 0.0005m as to remain in the log-law inner layer region. Study is being carried out at 0.4 Mach and 0.6 Mach number. Turbulence model of k-epsilon, k-omega and transition k-kl-omega were tested out and we found that transition k-kl-omega model showed good approximation with the physical phenomena of flow mixing associated with ejectors. To find net propulsive force on the body we have modeled surface of 1m radius surface 1m upstream from body and another 1m radius surface 1m downstream from body and found out the momentum flux across them as shown in Fig.2.

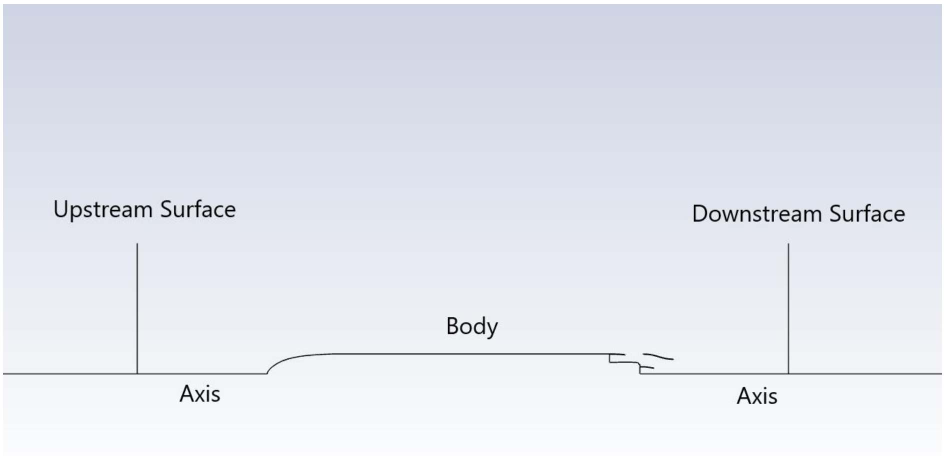


Fig. 2 Domain Parts

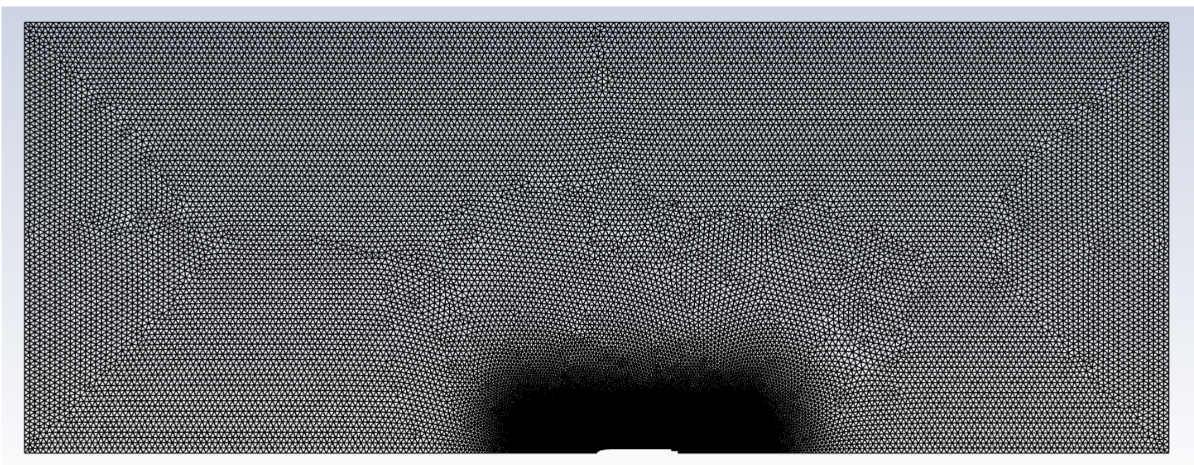


Fig. 3 Domain Mesh

B. Ejector Models

For the current study, seven different rear models have been designed and analyzed. The nomenclature of the ejector is shown in Fig. 4. Table 1 shows the parameters of the ejector models with respect to the fuselage diameter D. The ejector gap varies from 0.38D to 0.46D. Similarly, the distance from the rear, exhaust radius, and inflow angle are varied from 0.76D to 1.2D, 0.22D to 0.33D, and 2 degrees to 7 degrees.

Table. 1 Ejector Parameters

Model	Ejector Gap	Distance From Rear	Exhaust radius	Inflow Angle
Original	-	-	0.22D	-
Rear	-	-	0.22D	-
E1	0.456D	1.2D	0.33D	2 Degrees
E2	0.456D	1.2D	0.33D	7 Degrees
E3	0.46D	1.2D	0.226D	7 Degrees
E4	0.39D	0.76D	0.226D	2 Degrees
E5	0.386D	0.76D	0.226D	7 Degrees

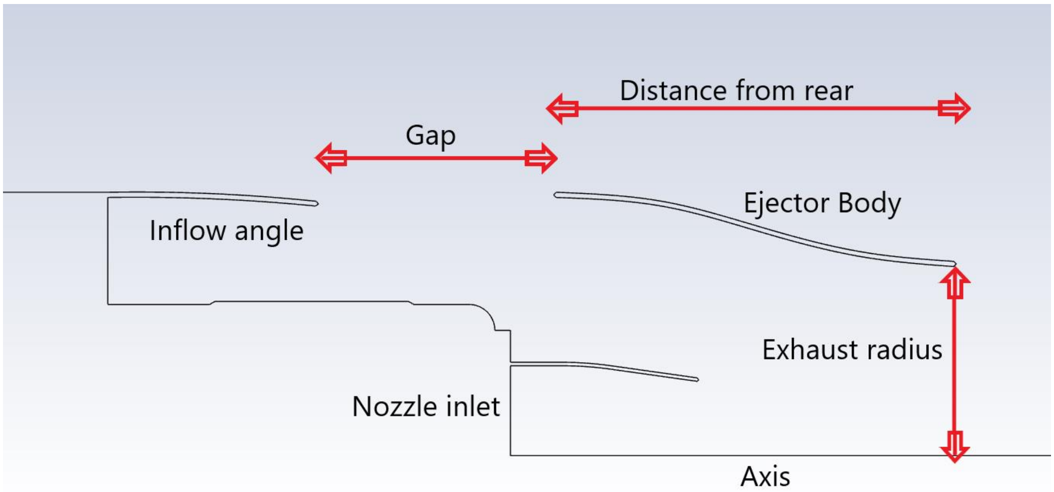


Fig. 4 Model Nomenclature

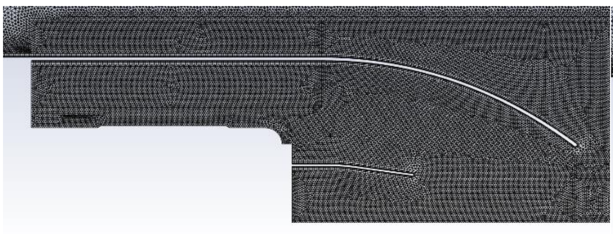


Fig. 5 Original Model

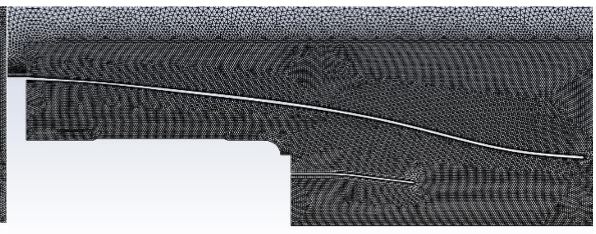


Fig. 6 Rear model

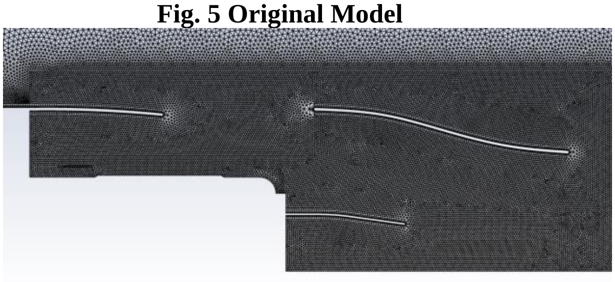


Fig. 7 E1 Model

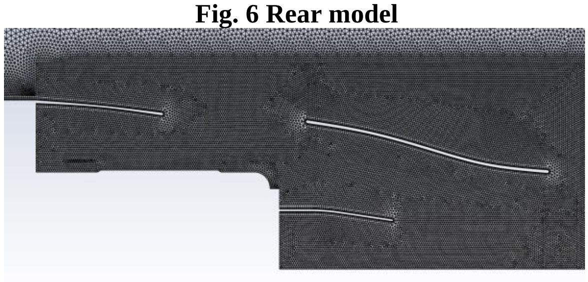


Fig. 8 E2 Model

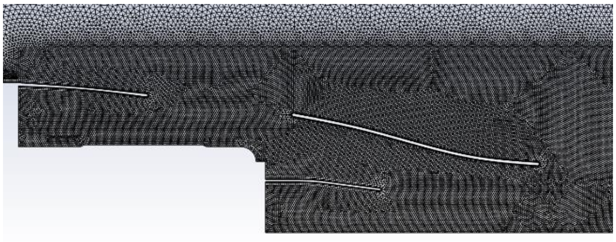


Fig. 9 E3 Model

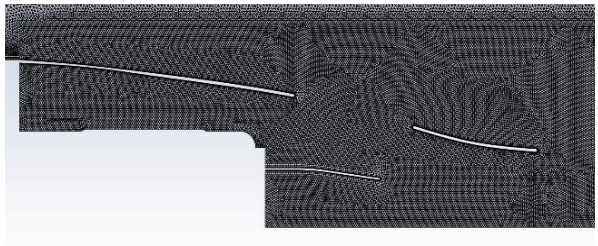


Fig. 10 E4 Mode

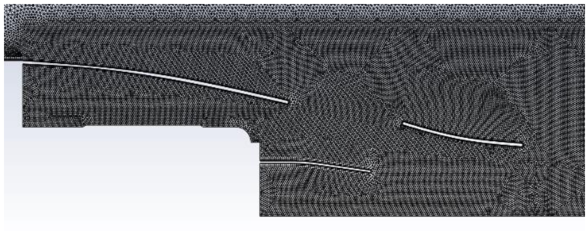


Fig. 11 E5 Model

III. Results

A. Pressure Contours

Now we will have a look at the pressure contours of E1, E5, original and rear model to get a better understanding of the phenomenon at play here.

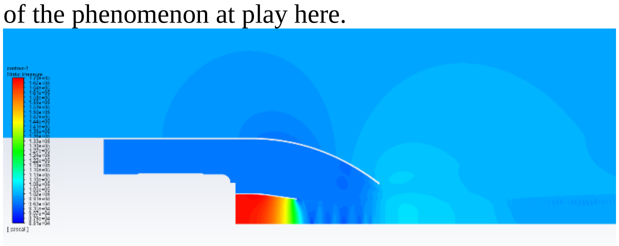


Fig. 12 Original Model 0.4M

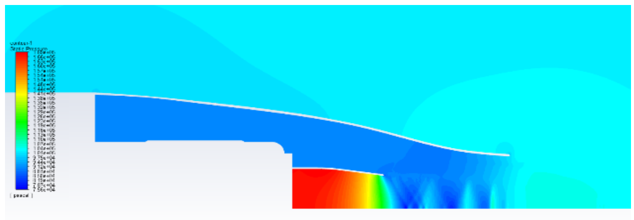


Fig. 13 Rear model 0.4M

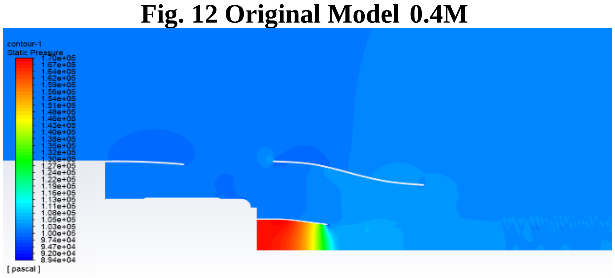


Fig. 14 E1 Model 0.4M

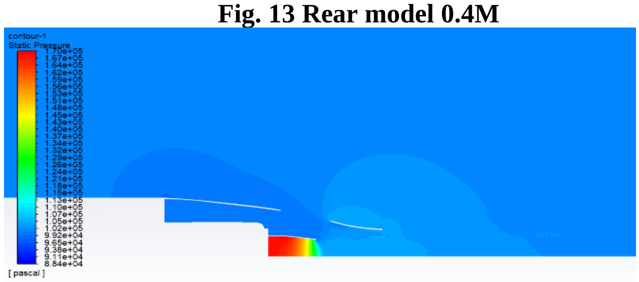


Fig. 15 E5 Model 0.4M

Comparing these pressure contours at 0.4 Mach, it can be seen that the main cause of pressure drag here is the pressure in the cavity region. This pressure will act on the inside wall of the fuselage of the drone. While a value of 98k Pa in the cavity region has been obtained in the original model, there is a lower pressure value in the same cavity region of the rear streamlined body at 90k Pa, which is contributing to the greater pressure drag for the rear streamline model. Taking a look at the ejector models, it can be seen that the inflow of secondary flow from the gap given helps to relieve pressure in the cavity by increasing it to 100k and causing the drag due to pressure difference to reduce.

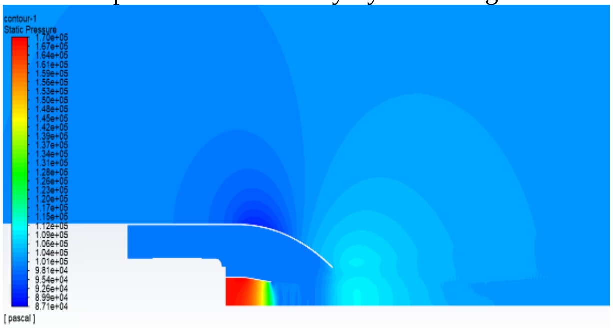


Fig. 16 Original Model 0.6M

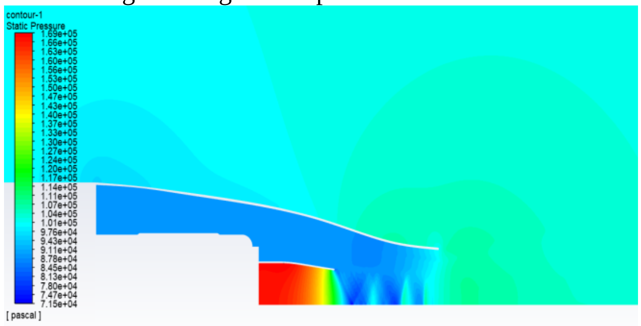


Fig. 17 Rear model 0.6M

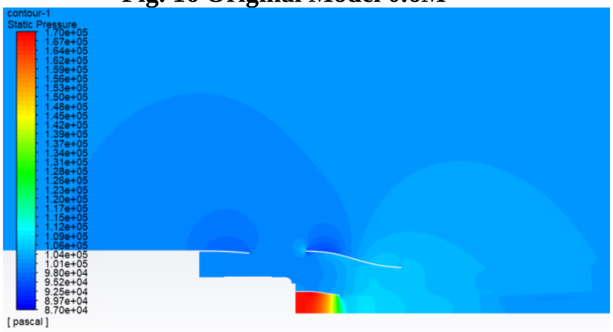


Fig. 18 E1 Model 0.6M

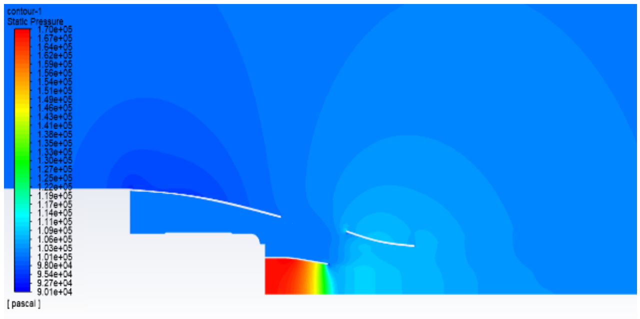


Fig. 19 E5 Model 0.6M

Compared to the pressure contours at 0.6 Mach, a similar trend can be seen as at 0.4 Mach but amplified. The pressure of 98k Pa in the cavity region of the original model, 88k Pa for the rear model, and 101k Pa for ejector models can be seen.

B. Velocity Contours

Now we shall look towards velocity contours of E1, E5, original and rear models.

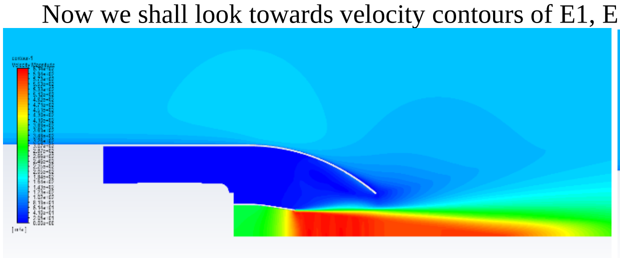


Fig. 20 Original Model 0.4M

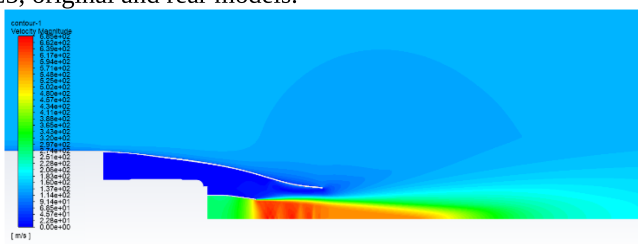


Fig. 21 Rear Model 0.4M

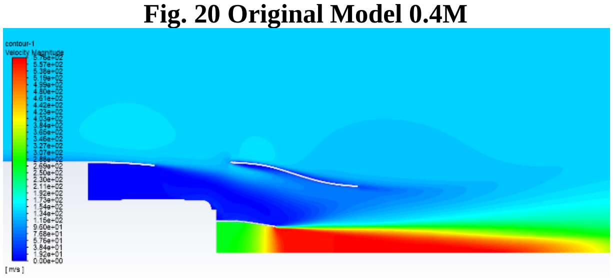


Fig. 22 E1 Model 0.4M

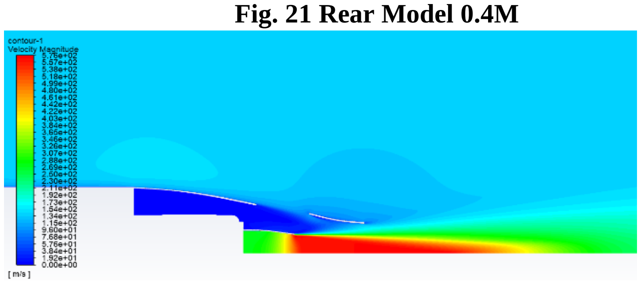


Fig. 23 E5 Model 0.4M

Here it is observed that the flow separation is not as profound as one might guess for the original blunt rear body when compared with the velocity contours of the rear streamlined body, hence indicating that an appreciable reduction in flow separation does not take place. Looking at the ejectors, it can be seen that the rear exhaust radius is a great factor in the working of ejectors, together with the gap length and the distance from the rear end. The E1 model doesn't show appreciable mixing of primary and secondary flow, which is the main reason behind thrust augmentation and, conversely creates a greater wake region than the original and rear models, this translates to an overall greater drag of the E1 model. As the exhaust end radius is reduced and the gap is moved closer to the rear end, mixing of flow starts to occur and a reduction in wake region is observed till the E5 fuselage model is reached where appreciable mixing of flow can be seen, thrust augmentation and greatest wake reduction translating into having the least drag.

Moreover, reducing the distance of the ejector gap from the rear causes the ejector body to become smaller. The ejector body at the rear is acting like a kind of airfoil, which is generating a lift that is contributing to the drag increase. Hence, reducing this surface causes less lift to be generated at the end, ultimately causing less drag.

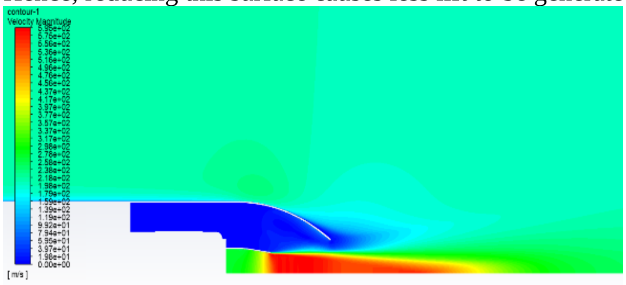


Fig. 24 Original Model 0.6M

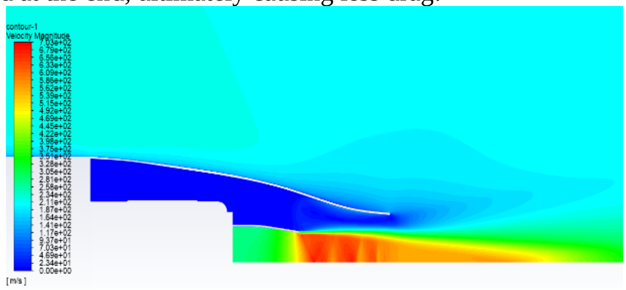


Fig. 25 RearModel 0.6M

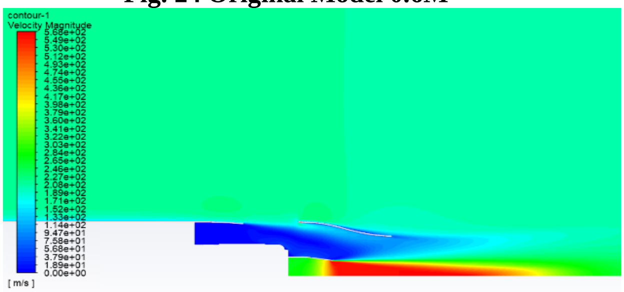


Fig. 26 E1 Model 0.6M

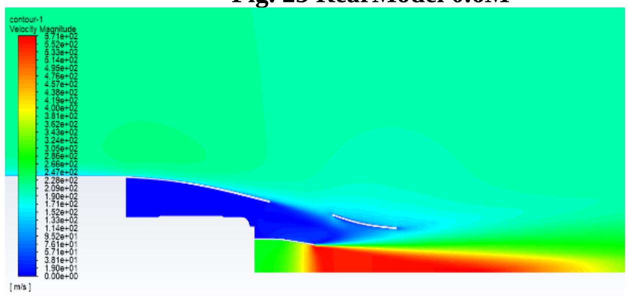


Fig. 27 E5 Model 0.6M

Changing the Mach number from 0.4 to 0.6, the same phenomenon can be seen taking place but magnified. It can be clearly seen that the wake region forming on the original model at 0.6 Mach is greater than at 0.4 Mach. In contrast, the rear model shows a significant reduction in wake. Looking at the ejector model, it is observed that the same trend holds true for 0.6 Mach as it did for 0.4 Mach, but due to the higher Mach number, it becomes more critical for the spacing to be given correctly.

C. Drag Comparison

0.4 Mach and 0.6 Mach conditions were given at 101325 Pa ambient pressure and 300K ambient temperature. The solver used is a density-based axisymmetric with flow aligned with the axis. The Sref used is 0.71m^2.

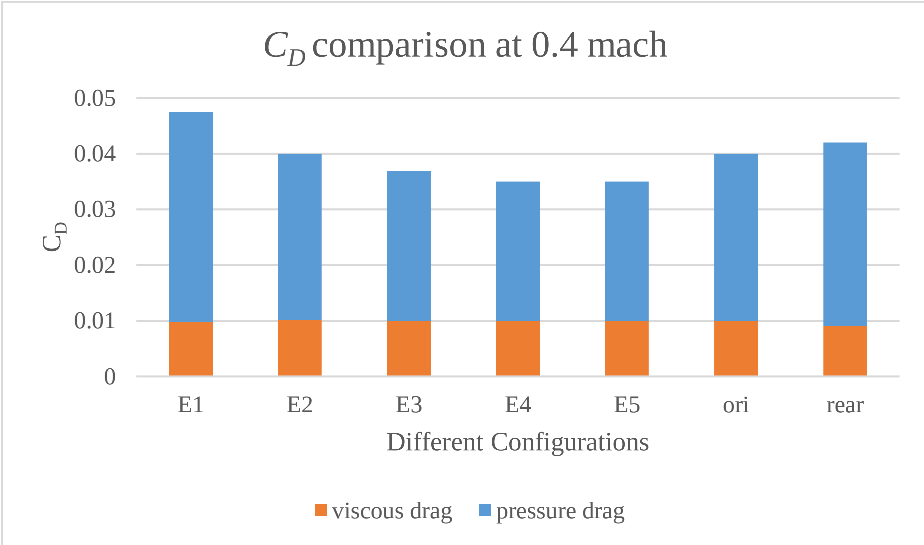


Fig. 28 C_D at 0.4M

At 0.4 Mach, almost the same CD for the original blunt body can be seen and the modified rear body models, hence noting that the change in the rear streamlined body did not have such an effect as one might expect. Interestingly, pressure drag is greater for the rear body, which can be accounted for by noting the lesser pressure in the cavity at the rear than in the original body. This additional drag overcomes the drag reduction due to wake reduction by streamlining the body. Then an interesting trend in the ejector models can be noticed, with E1 giving the most drag while E5 gives the least drag. When comparing E5 to the original model, it is observed that E5 offers lower drag than the original model.

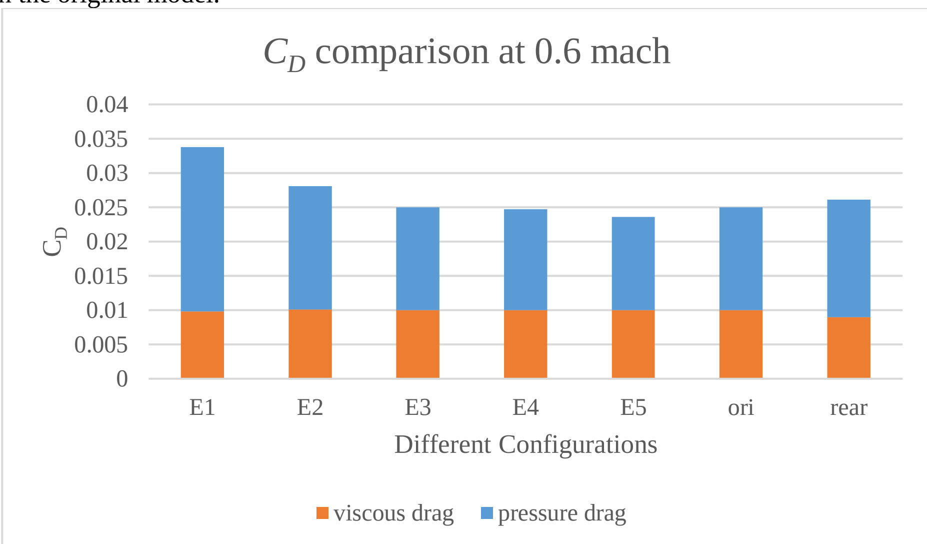
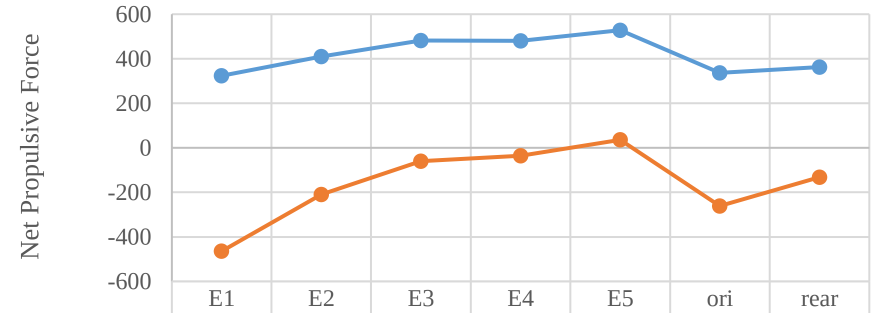


Fig. 29 C_D at 0.6M

At 0.6 Mach, a similar trend is seen as shown for 0.4 Mach. The original and rear models offer about the same drag, while the E1 model offers the greatest drag and the E5 model offers the least drag. In both cases of 0.4 Mach and 0.6 Mach, it can be seen that the viscous drag remains about the same while the pressure drag is changing. However, the pressure drag of the original blunt rear body and the streamlined rear body remains about the same, indicating that the decrease in drag in the E5 model is not due to a reduction in wake pressure drag but some other type of decrease in pressure drag.

D. Propulsive Force Comparison

Fig. 30 Net Propulsive Forces



	E1	E2	E3	E4	E5	ori	rear
net force 0.4 Mach	323.65	409.6	481.22	479.8	528.2	336.67	362.26
net force 0.6 Mach	-464.35	-208.83	-60.18	-35.8	35.7	-261.04	-132

Looking at Fig. 30, it can be seen that the original and rear models are quite close to each other, while the E1 model offers the least amount of force in terms of net propulsive force. Hence, it can be safely assumed that E1 is degrading the performance of the body while E5 is offering the greatest benefit across the board. It can be clearly seen that the benefit of thrust augmentation of the ejectors coupled with the drag reduction gives us a greater net propulsive force than what the original body was capable of.

E. 3D Ejector

To see the effects in 3D of the ejector on drag, the original and E5 models are modelled in 3D. The mesh was prepared in ICEM for half-body symmetric analysis. Mesh independence was carried out at 5 million, 7 million, and 14 million mesh size and 5 million mesh was selected for this study.

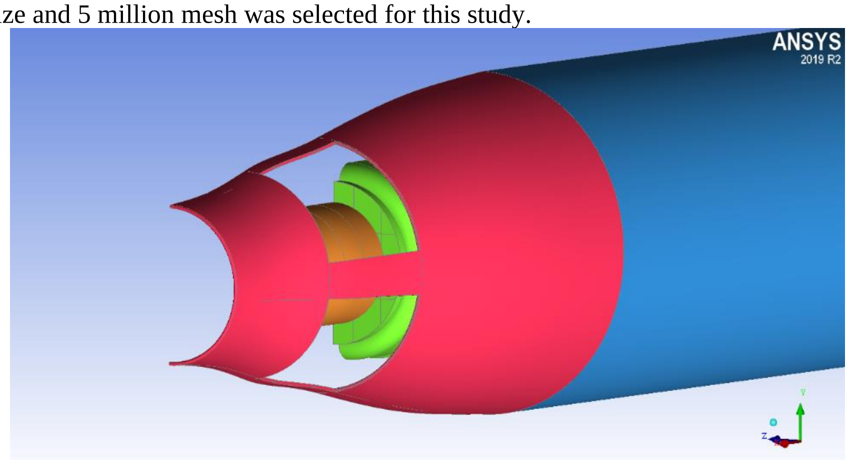


Fig. 31 CAD Model of E5 Model

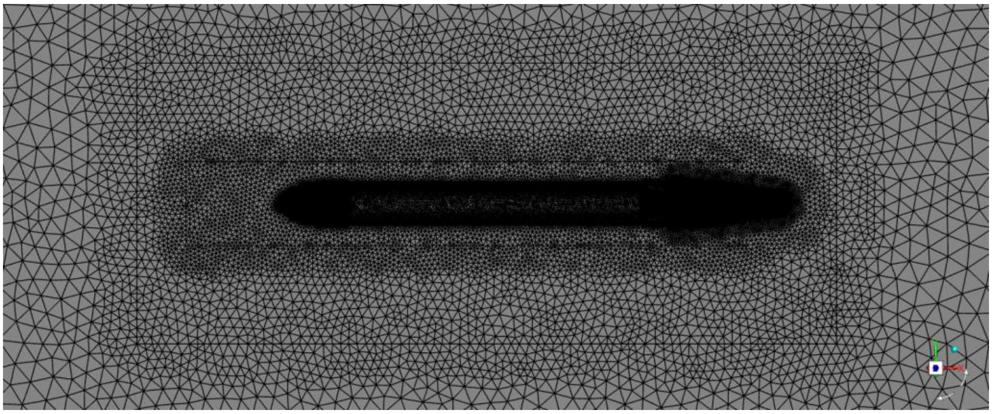


Fig. 32 E5 Half Body Symmetry Mesh.

F. Streamlines and Velocity Vectors

Observing streamlines on the rear of the ejector model is a clear indication of the occurrence of flow mixing with the secondary flow entering the gap created at the rear and mixing with the primary flow of the engine due to the suction being created by the primary flow. At 18 AOA, it is observed that flow is mixing with the added effect of secondary flow, which induces a swirl in the flow. Additionally, the support of the ejector gap also induces a vortex in the downstream direction.

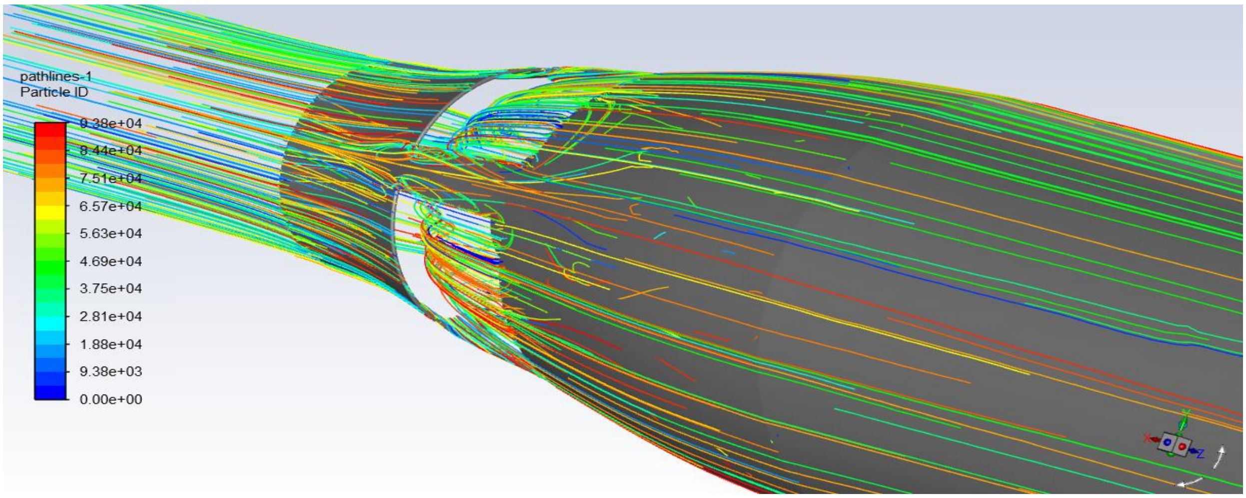


Fig. 33 At 0 AOA Streamlines Ejector Body

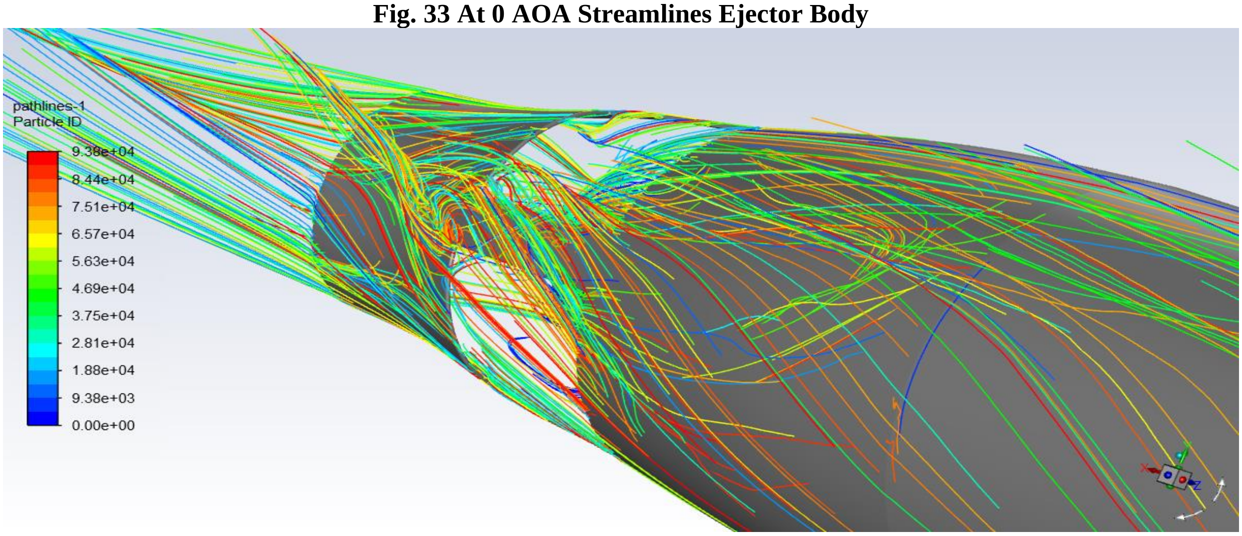


Fig. 34 18 AOA Streamlines Ejector Body

By comparing the velocity vectors, it is observed that the flow, in accordance with the velocity contours and streamlines, has a greater circulation of secondary flow above the ejector body as compared to the flow below the ejector body at 18 AOA, which is attributed to the angle of secondary flow with respect to primary flow. Due to the angle of the secondary flow, the flow above the ejector body has to turn a greater angle to meet with the primary flow than the flow below the ejector body, which causes greater circulation above the ejector body as compared to below.

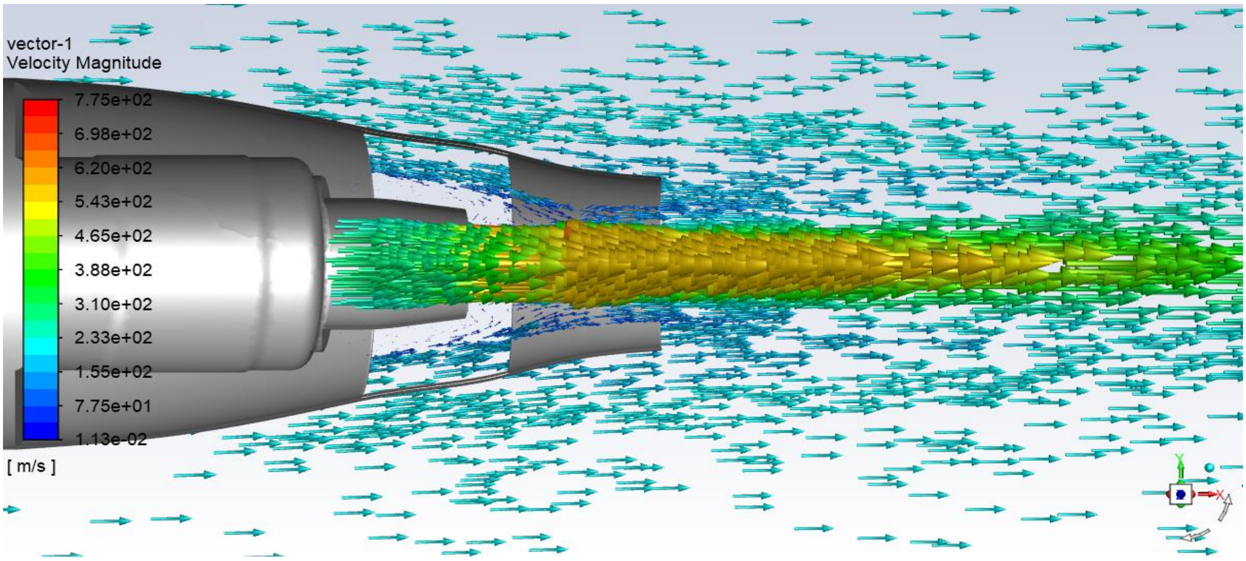


Fig. 35 At 0 AOA Velocity Vectors Ejector Body

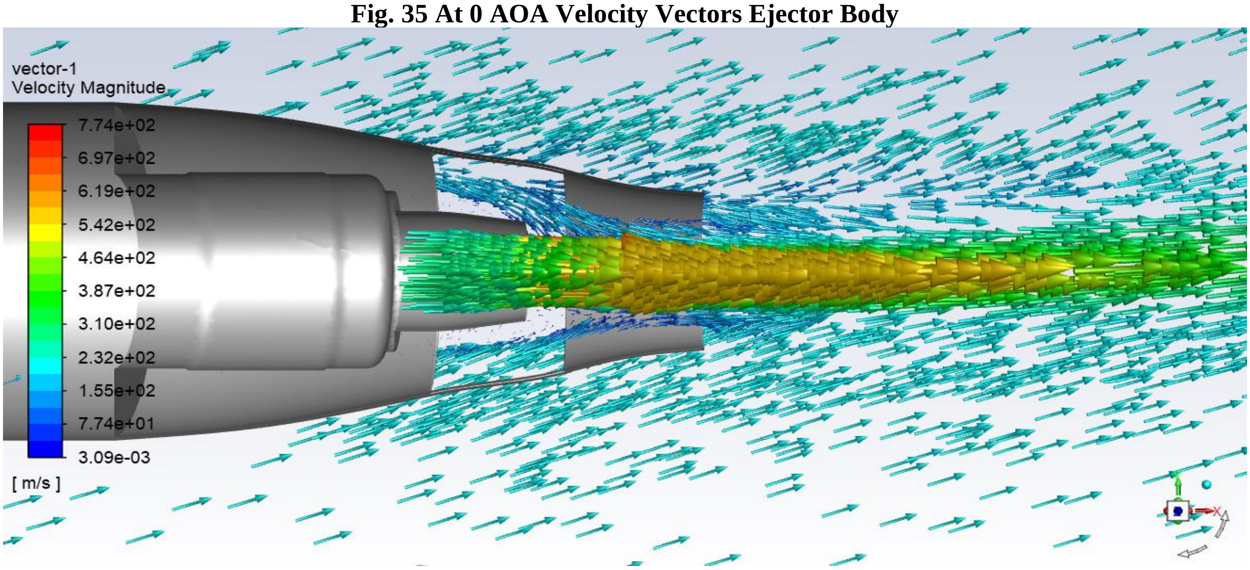


Fig. 36 At 18 AOA Velocity Vectors Ejector Body

G. Lift and Drag Comparison

True to its aim, the ejector gives a clear drag reduction advantage over the blunt rear body model. It can observed that there is a clear drag reduction at all AOA for the ejector model for both 0.4 Mach and 0.6 Mach, although we can observe that the difference in 0.4 Mach original vs Ejector model is far greater than 0.6 Mach (around 20-25% through 0 to 18 AOA).

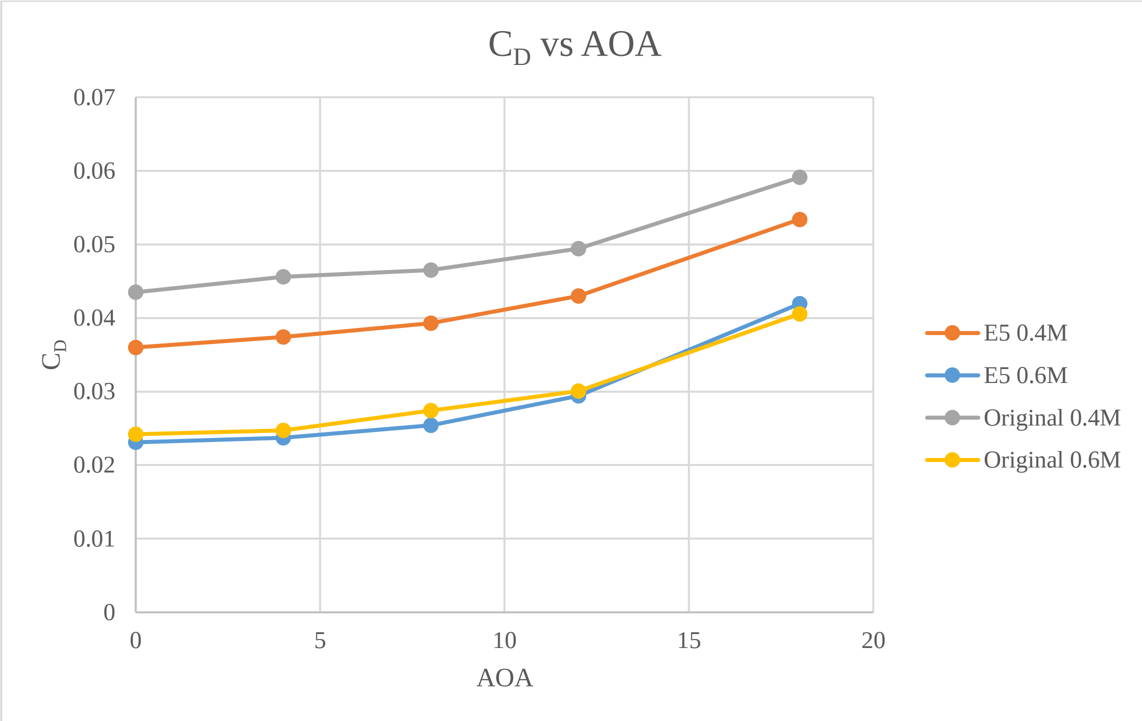


Fig. 37 Variation of CD with AOA for original and E5 model

When comparing the lift coefficient, an increase in lift compared to the original model can be seen. This is due to the component of thrust in the lift direction, which indicates an augmentation in thrust. However, this difference is not great and again the same pattern is observed as we saw in the drag comparison that at 0.4 Mach the difference is quite a bit more as compared to 0.6 Mach, indicating that thrust augmentation greatly depends on the Mach number.

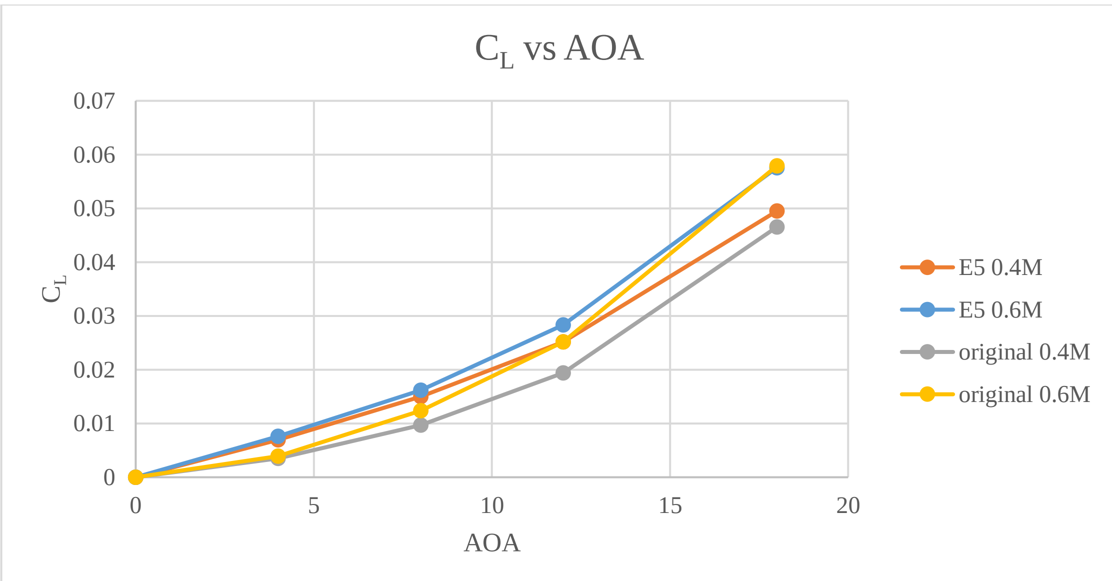


Fig. 38 Variation of CL with AOA for original and E5 model

H. Propulsive Force Comparison

As in the case of 2D axisymmetric cases, a virtual control volume was created and the net propulsive force was calculated from the net momentum flux across the control volume. The previous results translate into an overall greater net propulsive force as shown. There is a thrust increase at 0.4 Mach, but the results of 0.6 Mach are more interesting. Where previously our original model at 0.6 Mach produced a negative net propulsive force (meaning drag is greater than thrust), our modified model with ejector included has started giving positive net force. Meaning drag reduction coupled with thrust augmentation has enabled our body to give net positive thrust at 0.6 Mach. Net propulsive force is becoming smaller and smaller with AOA, which is to be expected, but the delta magnitude suggests that moderate AOA does not hinder the performance of ejectors as can be observed from Fig. 40. Comparing this data to the 2D axisymmetric model, a slight increase in viscous drag due to the introduction of ejector supports can be seen while the pressure drag remains almost the same. However, net propulsive forces for both 0.6M and 0.4M have been reduced due to the decrease in ejector gap area and the hindrance to the flow caused by the support.

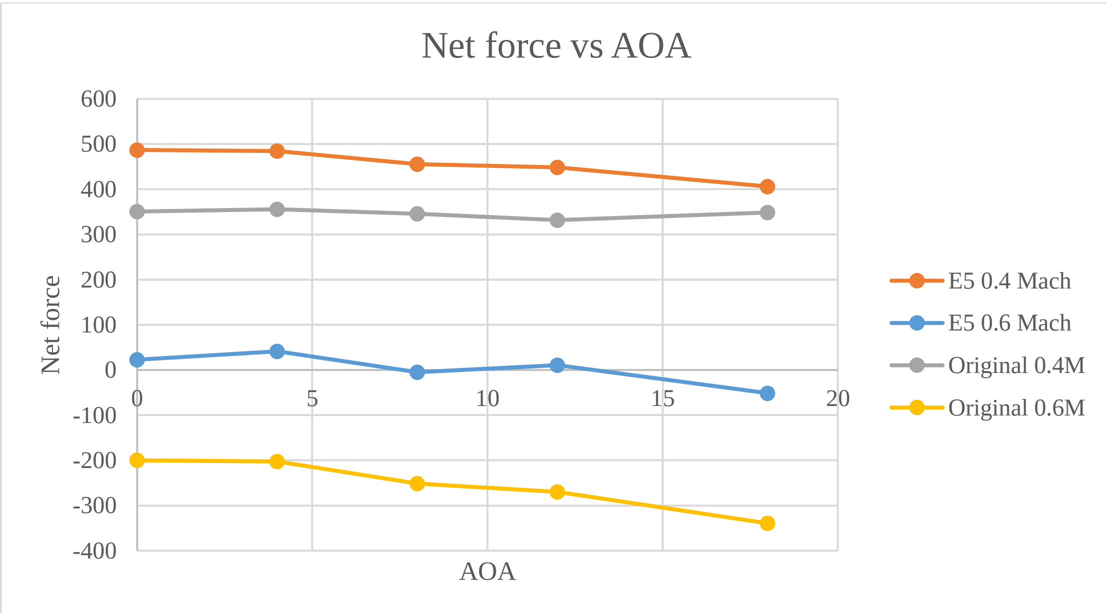


Fig. 39 Variation of Net Propulsive Force with AOA for original and E5 model

V. Conclusion

This study presents the drag reduction and thrust augmentation of a drone model at 0.4 and 0.6 Mach with the use of ejectors. It is clear from the results that use of ejectors helps in both thrust augmentation and drag reduction. Both axis-symmetric and 3D-symmetric analysis show that this difference in drag reduction is greater at 0.4 Mach than at 0.6 Mach. Moreover, the use of ejectors has enabled our model to give a positive net force at 0.6 Mach as compared to the negative net force given by the original model. Drag reduction may be attributed to the fact that the secondary flow helps to relieve the suction pressure inside the cavity, and the flow mixing at the rear helps to reduce the wake region. Changes in AOA have little effect on the thrust augmentation, and appreciable net thrust augmentation is seen at all AOA.

VI. Recommendations

Experimental validation should be carried out to validate the findings of this paper along with structural analysis to examine the structural loadings on the ejector supports.

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