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PASSIVE FLOW CONTROL IN BOUNDARY LAYER INGESTING SEMI-SUBMERGED ENGINE INLETS AT TRANSONIC FLOW

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ABSTRACT

Submerged engine inlets are often used in multi-purpose multiple launch configuration cruise missiles. These configurations show low total pressure recovery characteristics. New UAV designs, on the other hand, incorporate flush inlets for low radar visibility and higher total pressure recovery. These inlet designs suffer from boundary layer ingesting flow, which results in loss of total pressure and high distortion coefficient at compressor pals. Current study introduces semi-submerged engine inlets that may be utilized at cruise missiles with size constraints and tight thrust requirements. Inlet flow control is applied with a series of vortex generators.

INTRODUCTION

Jet engine inlet duct design is one of the important design aspects in aircraft design. Inlet and duct design is affected with the flow regime, type of aircraft, type of engine and geometric constraints of the aircraft. Most of the cruise missiles fly at low transonic Mach region (0.75-0.95 Mach). Most of these missiles have single turbojet or turbofan engine at the aft section of the fuselage, while engine inlets are located at the aft section, since most of the forward and mid fuselage sections are packed with indispensable payload such as warhead, seeker, electronics, etc. There exists a thick boundary layer developed at the aft section of the fuselage; therefore inlet duct designs often incorporate a diverter structure high enough to feed the engine with clean air from outside of the boundary layer region, as can be seen in Figure 1(a).

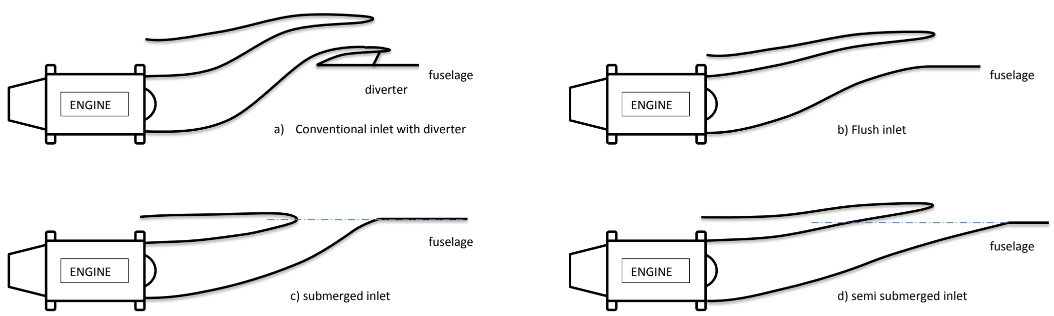

Figure 1: *Jet Engine Inlet Types by installation method used in Cruise Missiles*

However, some engine designs do not allow an inlet with diverter. The most common example for this situation is the missiles fired from a closed launcher. For those configurations, there is simply no space for a separate inlet structure, since all the missiles should fit into a closed launcher. In this case a structure called ‘submerged inlet’ is incorporated as can be seen in Figure 1 (b). The main drawback

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of the submerged inlets is the low pressure recovery ratio at the compressor entrance. This results in a decrease in engine thrust, and an increase in engine requirements.

Flush inlets are often incorporated in modern UAV designs, with low radar cross section and high range requirements. High pressure ratio requirements do not allow submerged inlets and low radar visibility requirements limit the usage of a diverter. A flush inlet, where the inlet entrance starts at the same baseline with the fuselage is utilized as it is seen in Figure 1 (c). Flush inlets are boundary layer ingesting inlets; therefore, often flow separation occurs near high curvature regions of the geometry due to high pressure gradient. This results in a high distortion number at the compressor entrance, which should be limited for maintaining engine health and to prevent flameouts. This brings the need for flow control inside the engine. Flow control to prevent vortex formation is a widely studied subject. An extensive review of the passive flow control methods can be found in [Lin 2002]. Most common types of the flow control techniques are the active and passive flow control methods. Passive flow control systems incorporate small structural parts to agitate flow mixing called Vortex generators (VGs), whereas active flow control systems add an external device to accelerate flow mixing, such as flow injection or suction, vibrating surfaces, etc [Wendt 1996].

In this study, a new inlet geometry, which is a combination of submerged and flush inlets- where flow control is maintained by vortex generators, is presented. This inlet type is named as semi-submerged inlet and shown in Figure 1 (d). Vortex generator base passive flow control and applications of different submerged flow techniques are also investigated.

METHOD

Thrust produced by a turbojet engine is a function of the pressure recovery at the upstream of the compressor stage, which is defined as the ratio of the total pressure at the engine face with respect to free stream total pressure. High pressure recovery means low energy loss for the fluid entering the engine, therefore it is highly desirable for an effective engine installation.

For the best pressure recovery, engines, or at least engine inlet entrances are located at a distance from the fuselage to eliminate total pressure loss due to the friction between the fluid and the fuselage or wings. The structure that separates the fuselage and the engine inlet is called a diverter. Inlet diverters provide high pressure ratio inlet flow, but produces extra drag for the aircraft, especially in cruise missile and fighter aircraft configurations. Pressure recovery is defined as:

$$P_R = \frac{P_{T\ AVE}}{P_{T\ \infty}}$$

where, $P_{T\infty}$ is the freestream total pressure and $P_{T\ AVE}$ stands for the average total pressure at engine face.

Distortion number is a measure of how an engine compressor breathes uniform flow. Distortion number is measured as the difference of minimum and mean total pressure. An engine with a high distortion is often susceptible to engine flameouts at maneuvers, high vibration at compressor stage, uneven combustion, etc. Therefore an ideal engine inlet should be designed for minimum distortion number.

Definition of the distortion number is selected using 60 degree circumferential pressure variation ratio which is defined as:

$$DC_{60} = \left(\frac{P_{T\ AVE} - P_{T\ MIN}}{Q_{AVE}}\right)$$

In this equation, DC_{60} is defined as the 60degree circumferential pressure variation where minimum pressure is measured at 60 degree circumferential slices over the end of the duct. There are other options for selecting the circumferential slices [Anderson 1992] to calculate other distortion metrics. DC_{60} is selected for compatibility with the existing engine performance tool.

Diverterless or submerged engine inlets are required in many applications. It is obvious that the pressure recovery of such engine inlets is lower than the diverter installed counterparts due to boundary layer ingestion. Another problem for the diverterless inlets is the high distortion due to the possible flow separation at the boundary layer side, caused by the difference of kinetic energies between the flow close to the boundary layer developed from the fuselage and the flow connected to the free stream. Typical total pressure profile is shown in figure 2.

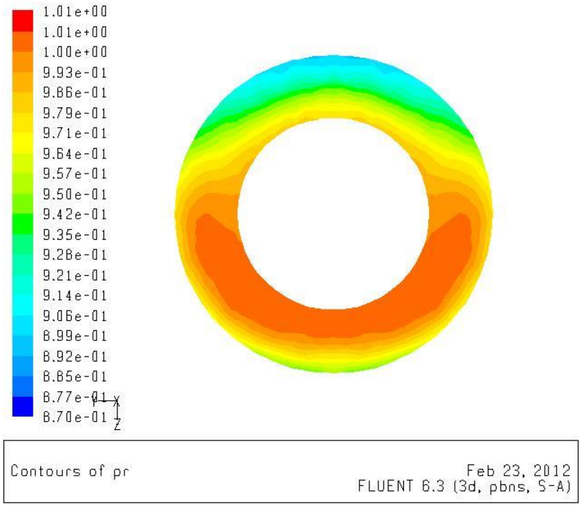


Figure 2: *Typical total pressure distribution for diverterless inlets with no flow control.*

It is obvious that such a pressure distribution results in high distortion ratio and thus should be eliminated for a better operation of the engine. There are a couple of methods to eliminate this kind of a total pressure distribution. Most common methods are active and passive flow control techniques.

This study focuses on the semi-submerged engine inlets. Such inlets can be considered as superior to fully submerged inlets in terms of pressure recovery, but they are still susceptible to the boundary layer ingestion and high distortion. In this study, the effect of vortex generators (VGs), which is a passive flow control technique, on engine performance is studied. For this purpose, a low radar visibility semi-submerged inlet is created over a concept missile geometry. Rectangular type VG's are selected for simplicity. A typical installation of the VG's is provided in figure 3

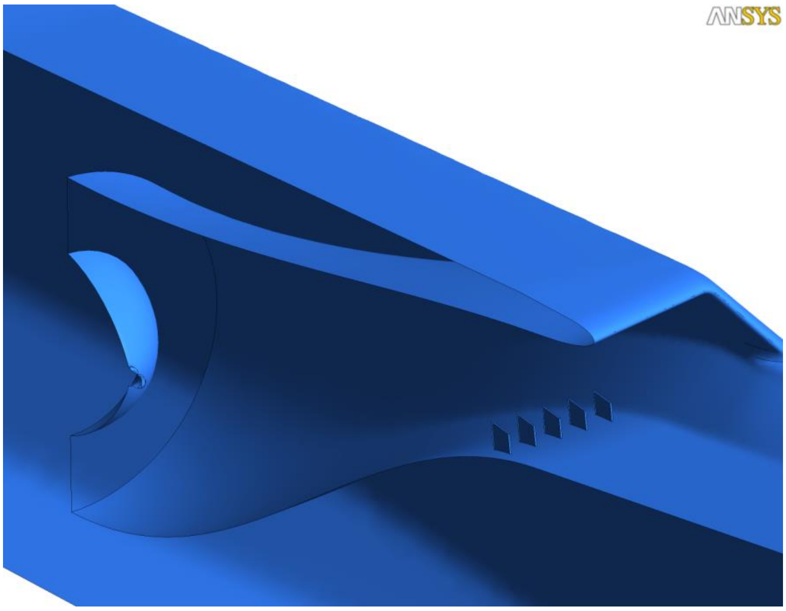


Figure 3: *Vortex generator application.*

As it can be seen from Figure 4, vortex generators are located at the side where pressure losses are excessive. The reason for installing the VG is to mix the flow at the opposite side of the separated flow, and to stop separation due to pressure loss. VG's should be located at a certain distance before the separation point.

In this figure, the top section shows the flow inside a semi-submerged inlet at the symmetry plane. It is clearly seen that separation occurs at the high curvature section of the inlet. In the picture at the bottom, flow at the same plane, after the application of the vortex generators, is visualized. It is clear that, vortex generators prevented the flow separation at the inlet.

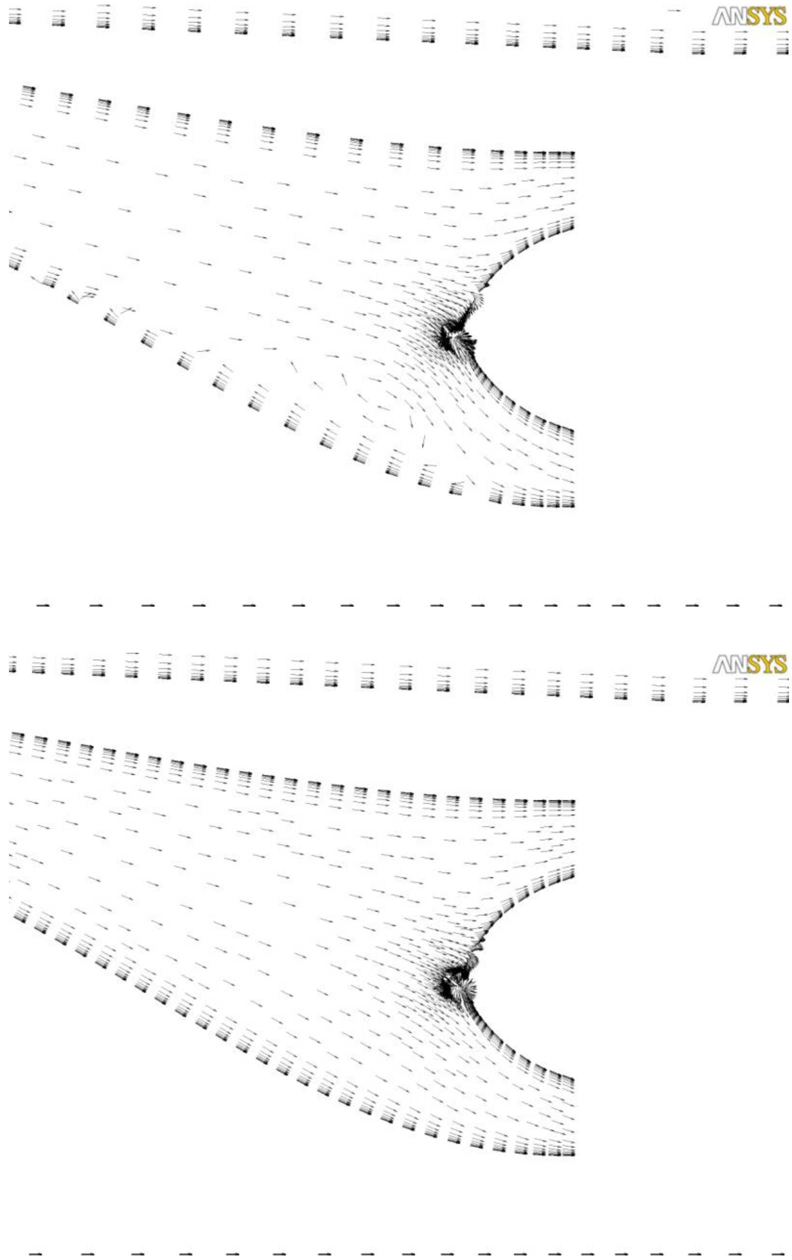


Figure 4: *Velocity vectors at engine duct symmetry plane. Top: no vortex generators, bottom: after application of vortex generators.*

A similar observation can be made by comparing streamlines for the same cases as it is seen in Figure 5: Streamlines show a very slow velocity zone close to the pals at the high curvature area, as it is seen in the first image, where there is no VG installation. This zone is shrunk in the second image that displays the streamlines for the configuration where vortex generators are applied. However, one should make another conclusion from the second figure. Vortices still exist in the VG installed case, however the direction of the vortices are different. This shows that, vortex generators do not prevent large vortices. They are used to initiate flow mixing between high energy and low energy flows. In other words, instead of a circulation zone that creates a trapped zone where no actual mass flow occurs, a new circulation zone which functions to mix the low and high energy zones is created. The rotation axis and kinetic energy of both vortices are totally different.

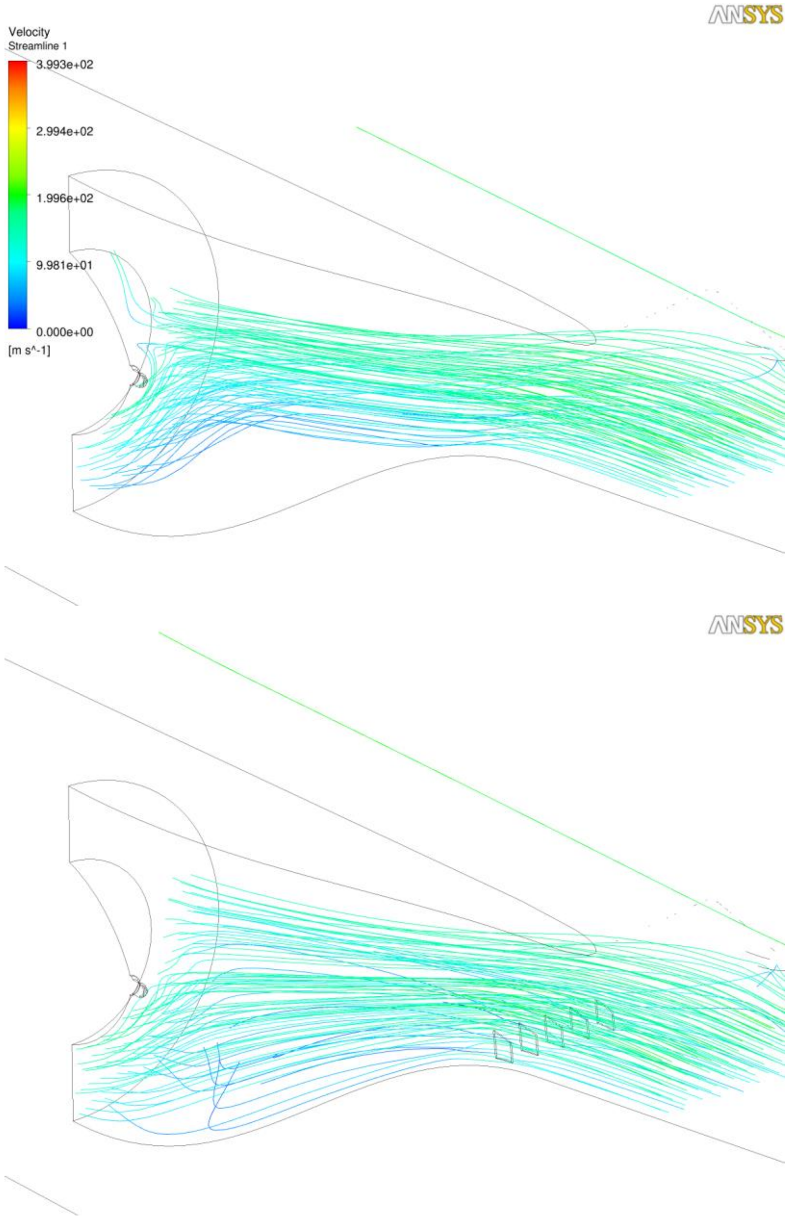
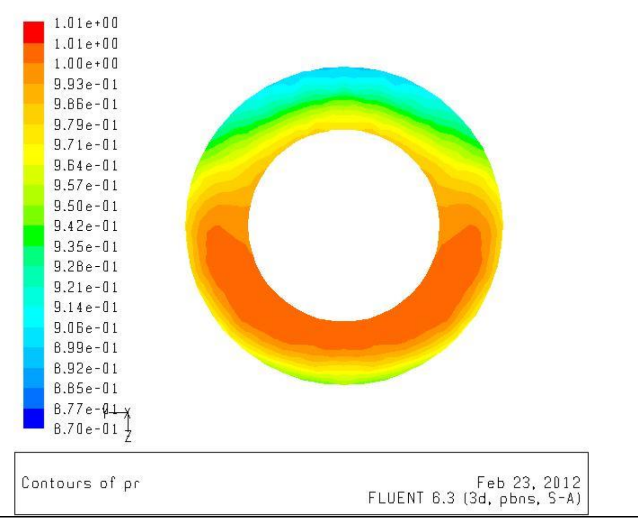
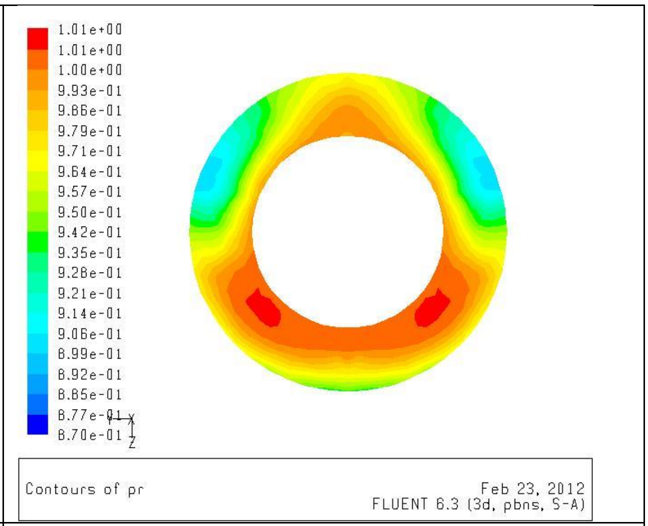


Figure 5: *Streamlines at engine duct. Top no vortex generators, bottom after application of vortex generators.*

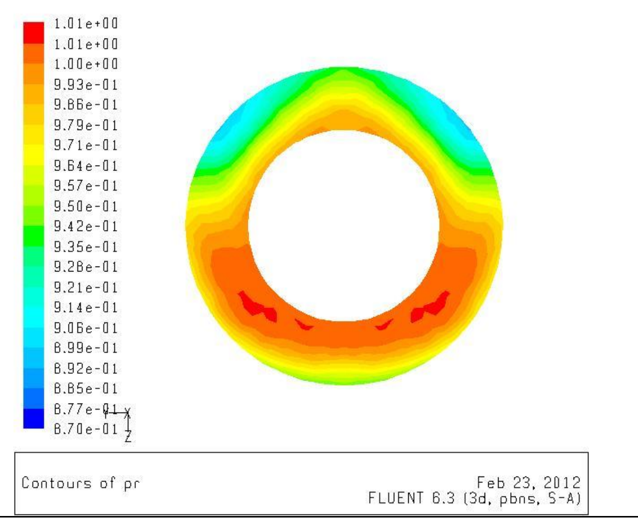
For the flow control of the engine inlet flow, different vortex generator configurations are applied for the baseline geometry. The number and height of the VG are chosen as the design parameters. The resulting total pressure distribution over the compressor inlet plane for different VG applications is given in Figure 6.



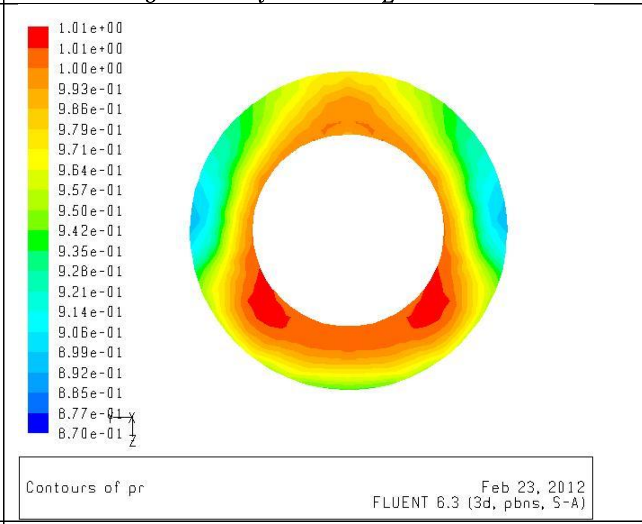
Baseline



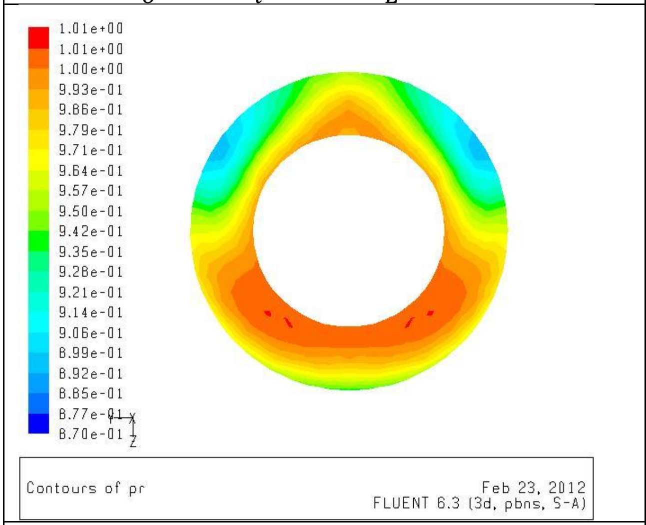
$\frac{h}{\delta} = 0.25, \frac{h}{l} = 1.0 \ \ at \frac{l}{L} = -20\%$



$\frac{h}{\delta} = 0.25, \frac{h}{l} = 1.0 \ \ at \ \frac{l}{L} = -10\%$



$\frac{h}{\delta} = 0.5, \frac{h}{l} = 1.0 \ \ at \ \frac{l}{L} = -10\%$



$\frac{h}{\delta} = 0.25, \frac{h}{l} = 1.0 \ \ at \ \frac{l}{L} = 20\%$

Figure 6: *Total pressure distribution at engine inlet*

RESULTS

The first parameter investigated in this study is the location of the Vortex Generators in longitudinal direction. It is reported that VGs can be located successfully between 6h to over 50h upstream of the separation [Lin 2002]. This range covers whole inlet and ramp part of the selected semi-submerged inlet. Therefore, vortex generator placement can be applied at both the upstream and the downstream of the inlet throat (i.e. the location where the ramp ends and the closed section of the duct starts). For this purpose, 20 percent upstream and 20 and 10 percent downstream of the throat with respect to inlet total length is selected. Low profile VGs with $h/\delta = 0.25$ and $l/h = 1.0$ are used for this case. CFD solutions on baseline geometry with no VG application results in 94 percent pressure recovery and a DC_{60} value of 0.57. Figure 7 and 8 shows the mass flow rate decrease and DC_{60} improvement in described cases,.where positive l/L denotes upstream location of the VG installations. In these figures it can be observed that, if vortex generators are located close to the inlet throat, DC_{60} improvement becomes insignificant and mass flow rate reduces dramatically. If the VG location is far enough from the throat, upstream or downstream location of the VG does not change the improvement if the DC_{60} value, however downstream placement shows slightly better mass flow rate (hence better pressure recovery) behavior

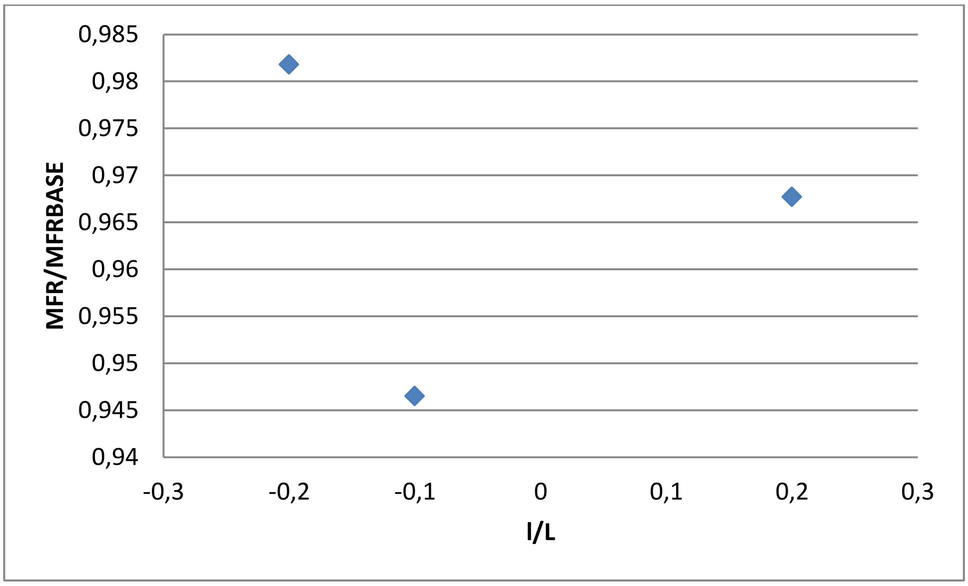


Figure 7: *Mass Flow Rate vs. VG Location*

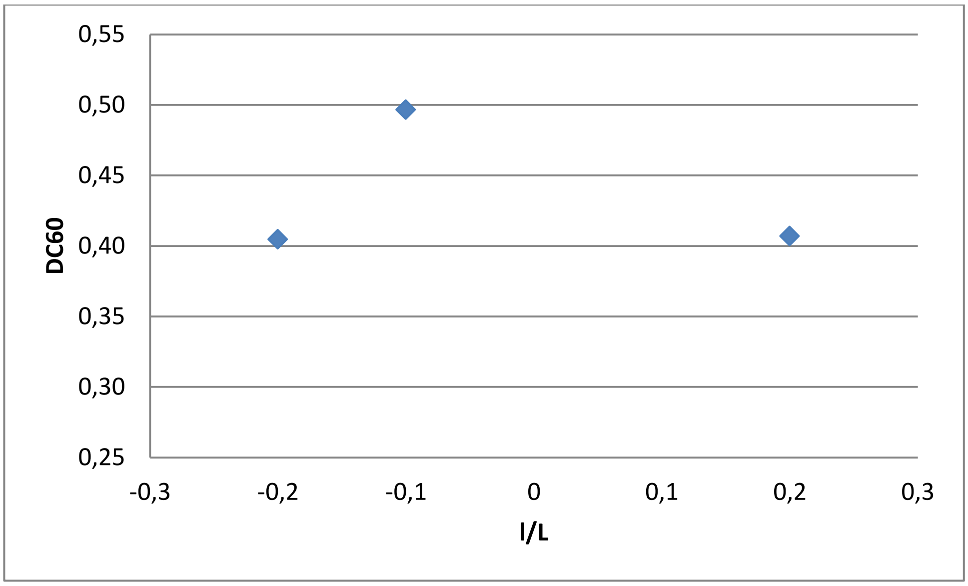


Figure 8: *DC60 vs. VG Location*

Other Design parameters under the investigation are the VG height and length and VG angle. For this purpose, new geometries where VGs are located at l/L = -10% are created. It should be noted that VG location is selected from the worst case to observe the improvements obtained from parameter selection clearly. The results are presented in the table below. In this table, baseline is the no VG configuration and Case 1 is the starting configuration, which is already discussed in previous section.

CASE	P_R	DC_{60}	$\frac{MFR}{MFR_{BASE}}$	h/δ	angle(deg)	l/h
Baseline	94.05	0.571	100,0			
1	92.99	0.496	94.,6	0.25	15	1
2	93.57	0.454	97.2	0.50	15	1
3	93.43	0.400	96.7	0.50	20	1
4	93.43	0.405	96.0	0.50	10	1
5	93.56	0.396	97.7	0.50	10	0.5

When the results are scrutinized, following observations are made:

- Low profile vortex generators are limited to $h/\delta = 0.2$ which correspond to the upper limit of transition zone of the boundary layer. From first two cases it is seen that, $h/\delta = 0.5$ give better results in terms of both mass flow rate (and hence pressure recovery) and engine face distortion. Therefore it is advised to implement vortex generators around this height, considering that the aircraft will fly at different flow conditions implying different boundary layer heights.
- Cases 2, 3 and 4 show the effect of the Vortex Generator placement angle. It is seen that between 10 and 20 degrees, vortex generators show similar behavior on distortion and slightly better mass flow rate.
- Cases 4 and 5 show the effect of Vortex generator length on engine parameters. It is seen that the shorter VG generates a slightly better distortion and better mass flow rate at the engine face. Better mass flow rate is expected, since the blockage created by smaller vortex generators is smaller. Improvement in distortion coefficient is however, marginal. Mass flow rate improvement obtained by shorter vortex generators can be achieved by simply increasing the throat area.

Applying the findings above, the distortion coefficient is reduced to 0.24 and pressure recovery to 93.8 percent, while keeping the mass flow rate over 97 percent of the baseline. These improvements are achieved by vortex generators located at 20 percent downstream of the throat and using $h/\delta = 0.5$ and 5 percent larger throat area. This is a remarkable improvement considering 0.571 distortion originally found at inlet face. Therefore, it is shown that semi-submerged inlets can be applied with passive flow control techniques.

During this study, it is also observed that parameters other than the vortex generator shape and location are also very important in semi-submerged inlet design. Most important parameters that affect the inlet performance are the ramp angle and shape, throat initial angles and inlet area distribution. Inlet base shape optimization and application of active control methods remain as the subjects of future studies.

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