# Design Optimization of a Boundary Layer Ingestion Propulsion System for a Long-Range, High-Altitude UAV

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**Recent studies have proposed using Boundary Layer Ingestion propulsion systems utilizing turboelectric generators to increase fuel efficiency in the next generation of airliners. Another aircraft platform where fuel savings would be highly valuable would be long-range UAVs. Therefore, a design optimization study was conducted on a BLI propulsor for an adaptation of a RQ-4 Global Hawk airframe, which is an airframe that is already proven to be ideal for long range missions. The study was performed on STAR CCM+ CFD software, using the Design Manager feature within the program. The interest was in optimizing the propulsor for cruise conditions, when the fuel savings will be most valuable in achieving a longer range. An initial simulation was performed, to act as the reference simulation for the Design Manager study. After initial values were obtained, the Design Manager study was conducted in two different iterations, searching for the ideal design. A variety of geometric variables were input into the Design Manager, such as inlet and outlet cross-sectional area, and the shape of the inner engine. Upon completion of the study, an ideal design of a BLI propulsor was found. The total power necessary to achieve static equilibrium flight was reduced from 222 MW to 193.2 MW, a savings of 12.87%. Such power savings are significant considering that a BLI propulsor already achieves fuel savings compared with a traditional propulsor that ingests air traveling at the free stream velocity. This study acts as a rationale for the further development of a physical scale model to validate such results, and the possibility of commercial development if satisfactory results are obtained**

## I. Nomenclature

BLI = Boundary Layer Ingestion
$\dot{m}$ = Mass Flow Rate
$\dot{m}_e$ = Exit Mass Flow Rate
$\dot{m}_i$ = Inlet Mass Flow Rate
MW = Megawatt
Rpm = Revolutions per Minute
$\rho$ = Density
PSC = Power Savings Coefficient
$V_e$ = Exit Velocity
$V_i$ = Inlet Velocity
W = Watt

## II. Introduction

Boundary Layer Ingestion propulsion systems provide an opportunity to decrease fuel consumption on a variety of aircraft platforms. Currently, the aerospace industry is experimenting with several different platform concepts, such as the NASA STARC-ABL, Empirical Systems Aerospace ECO–150R, and the NASA N3–X flying wing. [1] The

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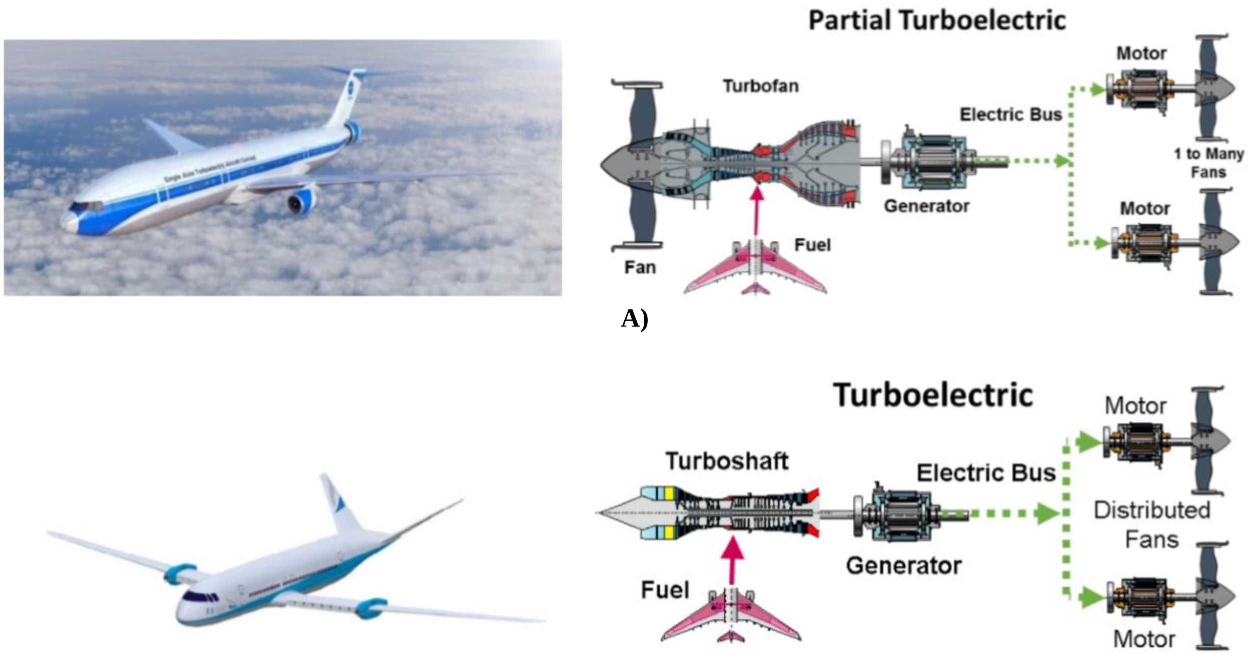
NASA STARC-ABL and the NASA N3-X flying wing concepts both utilize boundary layer ingestion turboelectric fans as a means of fuel savings. The NASA STARC-ABL concept is of particular interest due to the 7-12% fuel savings, and the relatively limited R&D which would be required to deploy a serviceable commercial concept. [1]

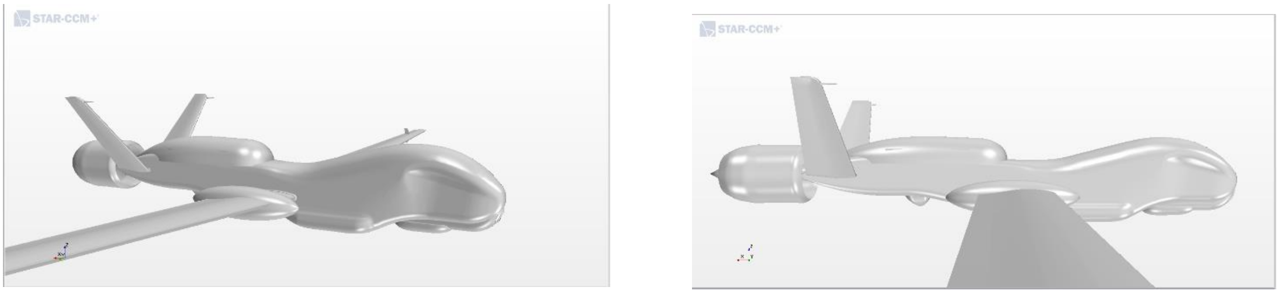


**A)**

**B)**

**Figure 1. Examples of BLI Turboelectric Propulsion Design Concepts (Figure from Reference [1])**

This project wished to perform a design optimization study on a conceptual long-range, high-altitude UAV utilizing this same technology, with the hope of increasing the operational range utilizing a boundary layer ingestion turboelectric propulsion system. Similar studies have been conducted on UAV's for a variety of applications, however, none observed the possibility of integrating a BLI propulsion system on a high-altitude, long-range UAV. [2] The conceptual design proposed uses the airframe of a RQ-4 Global Hawk, an already proven long-range, high-altitude UAV platform, and integrates a boundary layer ingestion propulsion system. The goal is to use the Design Manager feature of the STAR CCM+ to optimize the propulsor to achieve the maximally optimized design for such a propulsor in order to demonstrate feasible fuel savings for such a conceptual design. A BLI propulsor design that follows the NASA-STARC ABL airliner concept is chosen because of the limited technological innovation that would be necessary for such an aircraft to go into service, thus making the UAV concept presented here technologically feasible in the short-term.



**A)** **B)**

**Figure 2. Conceptual UAV Platform with BLI Propulsion system**

The fuel savings for a BLI propulsor come from the ingestion of air on the boundary layer of the aircraft that is slower than the free stream velocity. Because the thrust produced by a propulsor is proportional to the relative velocities of the inlet and outlet of an engine, and the velocity of air in the boundary layer around an aircraft is less than the free stream velocity, a BLI propulsor can produce the same amount thrust for less power input than a conventional propulsion system. This principle is shown in equation 1, which is the standard equation for the thrust of a propulsor.

$$F = \dot{m}_e V_e - \dot{m}_i V_i + (p_e - p_i) Area \tag{1}$$

This creates fuel savings which can ultimately increase the range of an aircraft. The RQ-4 Global Hawk currently utilizes an Allison AE-3007H turbofan engine and has a range of 11,000 nautical miles. In theory, this platform, utilizing an aft ABL propulsion system, could achieve fuel savings similar to the fuel savings that the NASA STARC-ABL platform achieved over a traditional airliner. This means that the Global Hawk airframe, when paired with a BLI propulsor in place of a traditional propulsor, has the potential of attaining over 1,000 miles in additional range.

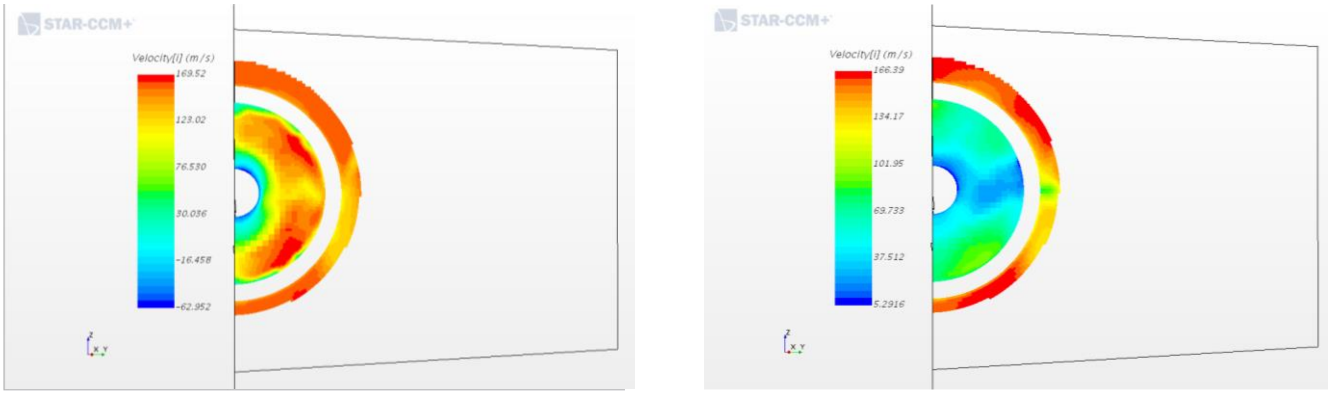
The goal of this design optimization was to decrease the net power necessary to drive the virtual disk propulsor in the CFD simulation while maintaining static equilibrium flight, where the thrust force was equivalent to the drag force. This was done by changing the rpm of the propulsor while executing several different geometric designs for the propulsor. Consistent with other optimization studies performed with single-aisle BLI Propulsion systems, the power savings coefficient, PSC, is defined by the following equation [3]:

$$PSC = \frac{Pwr'_{Shaft} - Pwr_{Shaft}}{Pwr'_{Shaft}} \tag{2}$$

By demonstrating the potential for fuel savings using a coupled CFD simulation, the rationale can be established for a physical prototype to be produced. Due to the high degree of situational utility that fuel savings would be for a reconnaissance UAV, it is believed that a demonstration of the possibility of fuel savings using a CFD optimization is a worthwhile exploration.

## III. Methods

### A. Justification for Coupled CFD Analysis



A) B)

**Figure 3. A) Engine Inlet Velocity Profile with Virtual Disk. B) Engine Inlet Profile without Virtual Disk.**

As it can be seen in Figure 3A and Figure 3B, the velocity profile at the engine inlet greatly differs when a virtual disk, which is intended to simulate the turboelectric BLI propulsor, is introduced in the engine inlet. The effectiveness of the geometry of the UAV in reducing inlet velocity can be observed as well in Figure 3B. The inlet velocity for the engine is greatly reduced from the free stream velocity of 160 m/s used in this simulation. This justifies using a coupled CFD simulation to ensure accurate results. In addition, this initial comparison also shows the initial effectiveness of the UAV airframe and propulsor geometry in ensuring that the inlet velocity is greatly reduced from the free stream velocity, thus proving the effectiveness of the design, and inviting a further design study for optimization.

### B. Reference Simulation

The design optimization study was conducted using Star CCM+ commercial CFD software and the Design Manager feature within the program. The initial CAD used in this study is a modification of a RQ-4 Global Hawk, with the engine removed and a BLI propulsor placed in the rear, consistent with the design of the NASA STARC-ABL aircraft. For the mesh, the Surface Wrapper, Surface Remesher, and Trimmer were used, with a Prism Layer around the aircraft. The Prism Layer is used to accurately capture the boundary layer flow around the airframe, which is of particular interest for this study. A volume of refinement around the propulsor was used to accurately capture the virtual disk interactions with the airflow. The mesh used for the reference simulation is shown below in Figure 4. This mesh was ideal because it accurately captured the boundary layer flow while focusing the computational power on ensuring an accurate simulation around the virtual disk and propulsor, giving accurate thrust and power values, which were of utmost importance for the validity of this study.

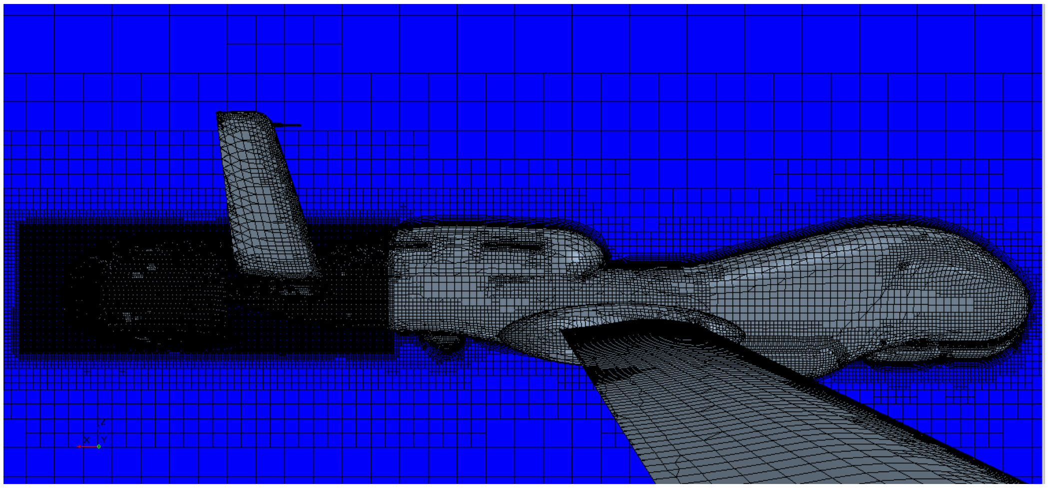


**Figure 4. Mesh illustrating Prism Layer and volume of refinement around propulsor**

A Blade Element Method virtual disk is used within the propulsor in the CFD simulation to represent the BLI propulsor. This method for simulating a BLI propulsor fan has been used in previous CFD studies exploring BLI propulsion design optimization studies. [3] The total torque on the shaft is calculated through the CFD simulation and is based upon the force that the virtual disk exerts on the incoming fluid in the propulsor From the torque value, the total power supplied to the propulsor can be calculated and can thus be used as the primary parameter to be minimized through the design study to achieve the optimal and most efficient design. The power supplied to the shaft is governed by the following equation:

$$P = Torque \times \omega \tag{3}$$

The design study will include various geometric variables, with the goal of reducing the power to the propulsor shaft required to maintain static equilibrium flight at simulated cruise conditions. The cruise condition selected for this study will be consistent with the RQ-4 Global Hawk with a speed of 160 m/s and air density at 65,000 ft since design optimization for these conditions would be most impactful for increasing total range of such an aircraft. Several geometric variables for the propulsor, including the diameter of the inlet and outlet of the propulsor, are input into the design study.

### C. Design Optimization Study

The design optimization study seeks to reduce the power required for the aircraft to be maintained in static equilibrium flight. This will be obtained by varying several geometric values as compared with the reference simulation, along with the rpm of the virtual disk. To limit the number of designs, the design study was conducted in several iterations, with a limited number of geometric variables being selected and run with several different rpm values. The design study was conducted in two iterations, with the best case being selected from the broader, first iteration of the study that included 405 different designs, and a second, smaller iteration of 30 designs. After running the Design Manager study, the best design was selected, and the relative specifications were compared with the original design.

## IV. Discussion of Results

Based upon the conditions discussed previously, a reference simulation was produced for the Design Manager Program within Star CCM+. The results for static equilibrium flight are given in Table 1.

| Initial Results | |
|---|---|
| Power | 222 MW |
| Drag & Thrust | 29072 N |

**Table 1: Reference Simulation Values**

These values served as a baseline by which the success of the Design Manager study was measured. The convergence of the power, drag, and thrust value is shown below in Figure 5 and Figure 6.

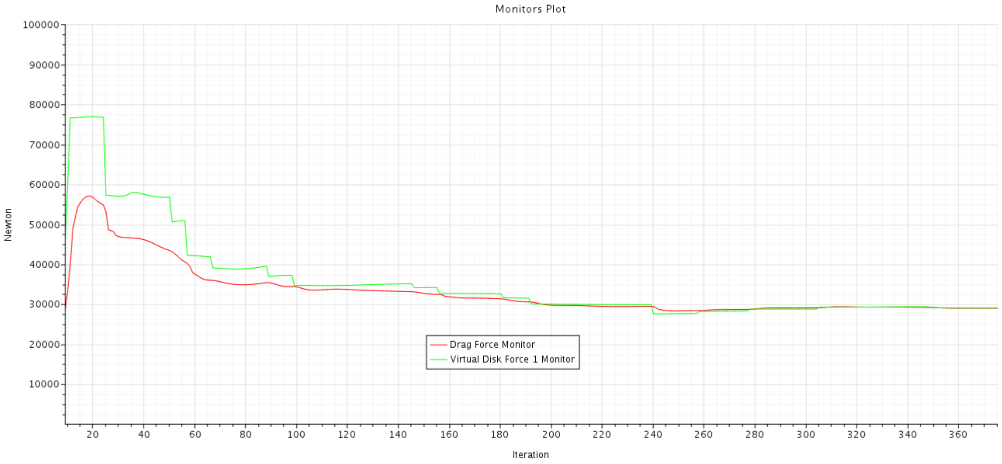


**Figure 5. Monitors plot demonstrating convergence of Drag Force and Virtual Disk Force.**

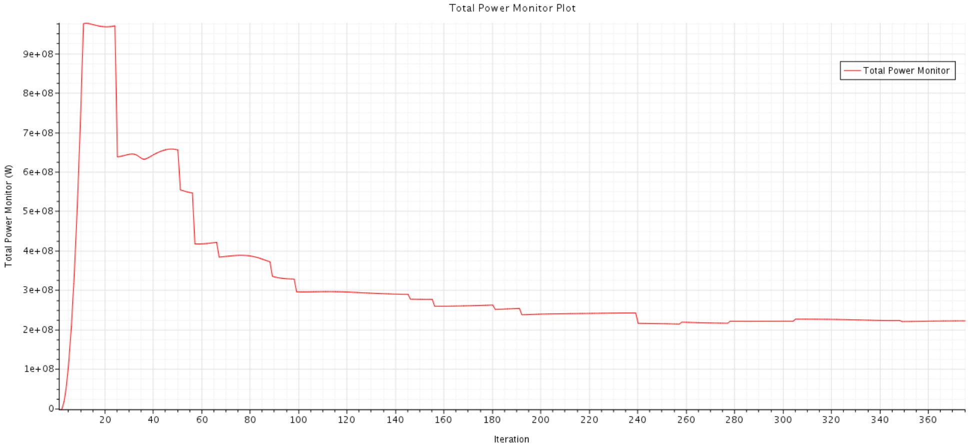


**Figure 6. Total Power Monitor plot demonstrating convergence.**

The design study was completed with three geometric parameters as shown in Figure 7, and the rpm was modulated to find the case where the flight was maintained in relatively static equilibrium. The first iteration included 405 design iterations total, with one inlet parameter and one outlet parameter while the rpm was decreased to find the greatest power savings. The CAD sketch of the three geometric parameters that were varied throughout the simulations is shown in Figure 7.

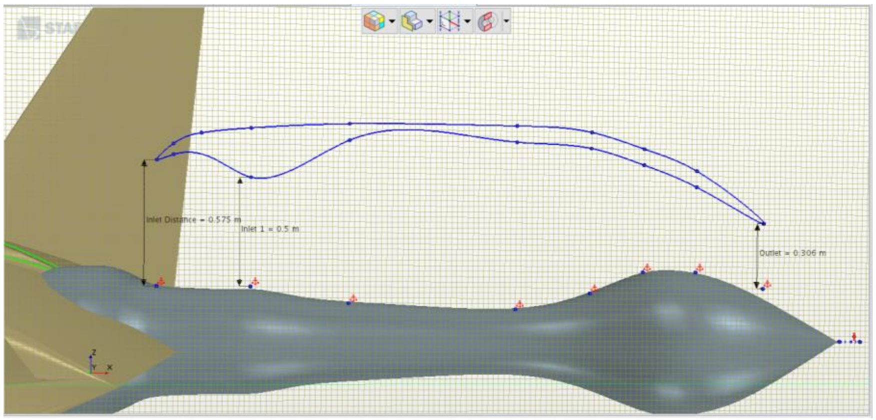


**Figure 7. Geometric parameters showing sketch before and after design study**

The first iteration of the Design Manager study is shown in Figure 8. The pattern shown in Figure 8 is due to the fluctuation of rpm for different geometric designs. The best design was chosen which both reduced power consumption and maintained static equilibrium flight. As can be seen in Figure 8, the selected design had the second-lowest power consumption amongst the first grouping of designs, while also maintaining static equilibrium flight, suggesting a proper result was reached. Amongst the second grouping of designs, shown from design number 135 onward, no design had both lower consumption than the selected design while also maintaining static equilibrium flight, thus showing that an optimized result has been reached and it is unlikely to be improved upon given the parameters selected. The best design was run through a further refinement iteration of 30 different designs. Each design failed to produce a better result than the first iteration, suggesting that the result obtained in the first Design Manager study was the optimal result given the parameters selected.

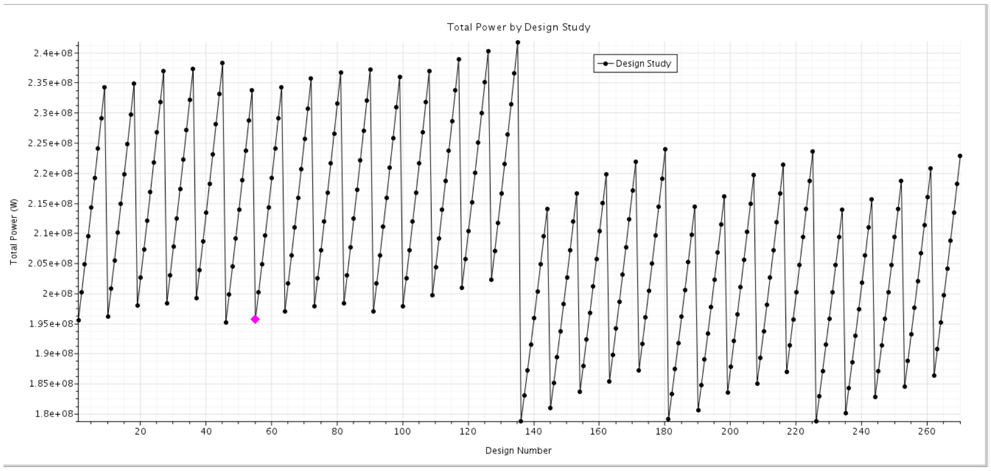


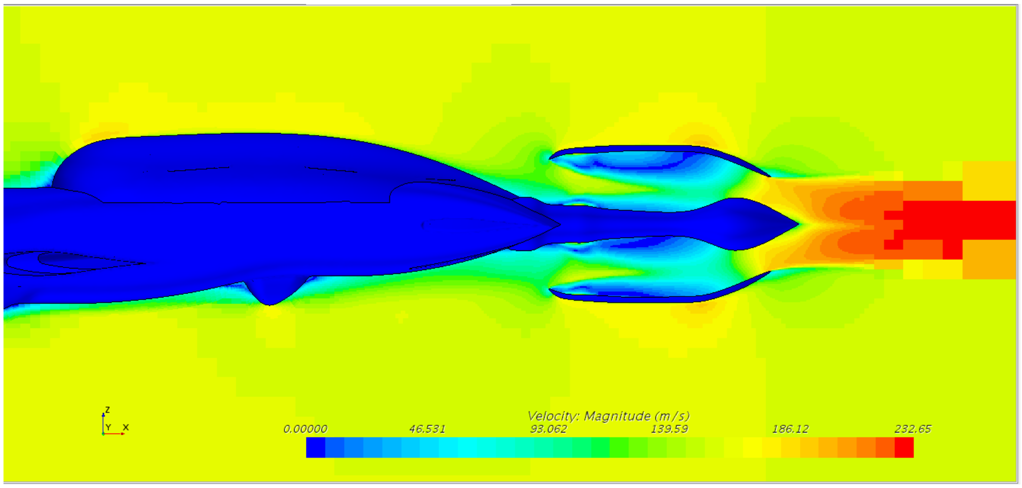
**Figure 8. First Design Study with selected design designated.**

Once the optimized design was found, the original design was able to be directly compared with the optimized design. The power savings coefficient, found according to Equation 2, was .129, which is significant considering the possible fuel savings already given by a BLI propulsor over a traditional propulsion system. The optimized design results are shown in Table 2.

| Optimized Results | |
|---|---|
| Power | 193.2 MW |
| Drag & Thrust | 23080 N |
| PSC | .129 |

**Table 2. Optimized Design Values with PSC.**

A side by side comparison of the velocity and pressure profiles of each simulation is shown in Figure 9. A high contrast scale is given for the pressure profile to show the specific differences between the designs, while a traditional scale is shown for the velocity profile.



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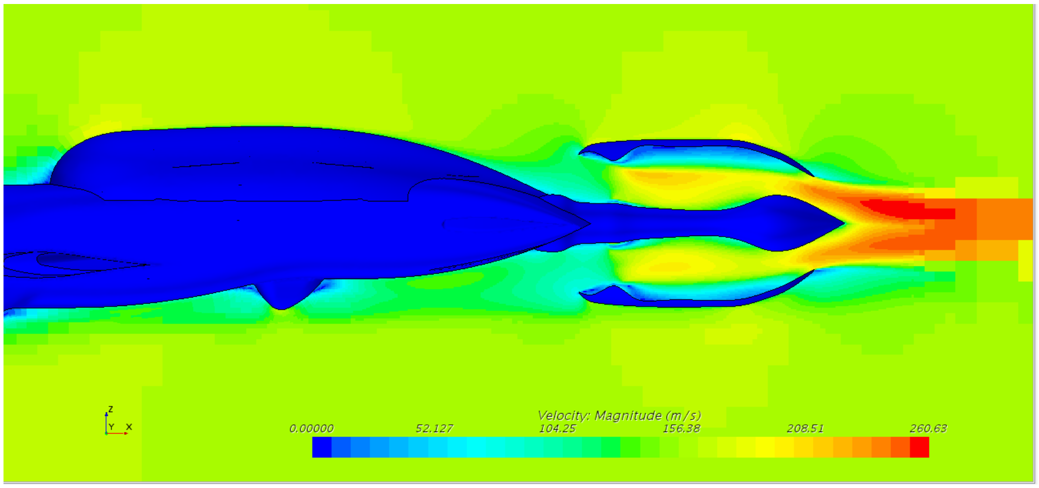

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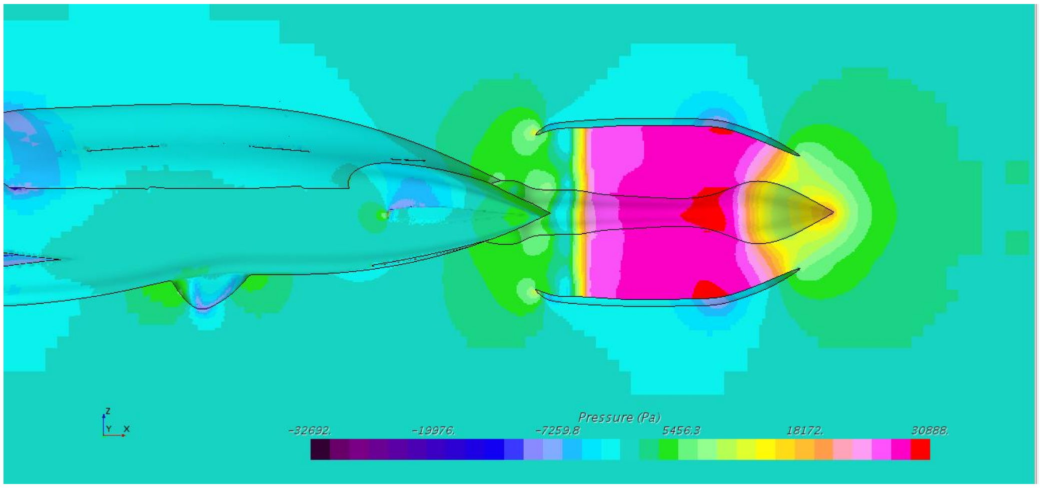

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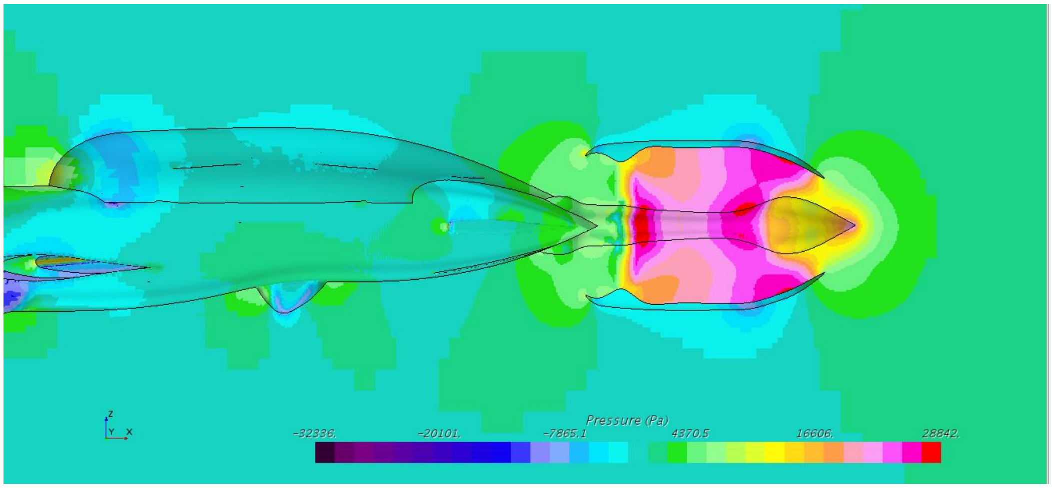

**D)**

**Figure 9. A) Velocity profile of airflow through original BLI Propulsor. B) Velocity profile of airflow through optimized BLI Propulsor. C) Pressure Profile through original BLI propulsor. D) Pressure Profile through optimized BLI propulsor.**

As shown in Figure 9A and 9B, there are dramatic differences in the velocity profile through each propulsor. In the original propulsor, it can be seen that large turbulent wakes form on both the upper and lower regions of the interior propulsor. In the optimized propulsor, this turbulent flow is minimized compared with the unoptimized design. In addition, the velocity profile through the interior of the optimized propulsor is much higher than the unoptimized propulsor, suggesting that the optimized propulsor accelerates the air behind the propulsor at a much higher velocity, creating more thrust. Also, the inlet airstream of the optimized BLI propulsor has a lower velocity profile than that of the unoptimized BLI propulsor, suggesting that the optimized design is enhancing the power saving effect of the BLI propulsor, by ingesting air at an even lower velocity than the free stream velocity.

The pressure profiles are shown in Figure 9C and 9D also shows differences that contribute to the power savings of the optimized BLI propulsor. The optimized BLI propulsor inlet shows a high-pressure region as compared with the unoptimized BLI propulsor. This is consistent with the velocity profile, showing that air is decelerating upon entry to the propulsor, which produces further power savings for the BLI propulsor.

## V. Conclusion

The Design Manager study was able to use the Design Manager feature of Star CCM+ to produce a significant amount of power savings while maintaining static equilibrium flight at cruise conditions for a conceptual RQ-4 Global Hawk powered with a BLI propulsor. Based upon the findings presented in this study, it can be concluded that further study into the possible fuel savings that a BLI propulsor is a worthwhile pursuit due to the possibility of significantly extending the range of a long-range, high-altitude UAV. With more computational power, a larger number of geometric parameters could be input into a design study, encompassing the whole of the fuselage along with the BLI propulsor. This could lead to the development of a physical scale model to validate such results and subsequently lead to commercial development if satisfactory results are obtained. Boundary Layer Ingestion propulsors are already in development for multiple conceptual airliners, and it would be a natural extension of such projects to utilize this propulsion system for common UAV platforms as well.

Another avenue of study could be to observe if the unique inlet shape found through this paper is applicable to other BLI propulsors. The inlet shape found through this design study is unique compared with other BLI propulsor inlets found on other CFD studies [4,5]. A 2D application of the inlet shape on other BLI propulsor platforms compared with the conventional BLI inlet shape could show if the power savings are specific to this study, or are applicable across all other BLI propulsor platforms, which would open up the possibility of experimenting with the air inlet found in the study with other common BLI conceptual designs.

## References

[1] Jansen, R., Bowman, C., Jankovsky, A., Dyson, R., and Felder, J., "Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports," *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Jul. 2017

[2] B. J. Brelje and J. R. R. A. Martins. Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches, Progress in Aerospace Sciences, 104:1– 19, January 2019

[3] Gray, J. S., Kenway, G. K., Mader, C. A., and Martins, J., "Aero-propulsive Design Optimization of a Turboelectric Boundary Layer Ingestion Propulsion System," *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[4] Rodriguez, D., "A Multidisciplinary Optimization Method for Designing Boundary Layer Ingesting Inlets," *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Apr. 2002.

[5] Blumenthal, B., Elmiligui, A. A., Geiselhart, K., Campbell, R. L., Maughmer, M. D., and Schmitz, S., "Computational Investigation of a Boundary Layer Ingestion Propulsion System for the Common Research Model," *46th AIAA Fluid Dynamics Conference*, Oct. 2016.