

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

THEORETICAL DATA DRIVEN VORTEX TUBE SEPARATOR
PERFORMANCE PREDICTOR MODEL



AYBERK KARACELIK

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN ENGINEERING IN
AEROSPACE TECHNOLOGIES PROGRAM

ADVISOR: ASSIST. PROF.DR. MAHMUT AKSIT

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*To my
Family and
.....*

ABSTRACT

This research introduces the development of a theoretical data-driven model to estimate pressure loss caused by vortex tube separators (VTS) in helicopter engine intake systems. These separators are critical components for foreign object damage prevention, particularly in challenging operational environments. By proposing a scalable, regression-based predictive model, the computational inefficiency of performing full-scale CFD simulations was addressed. High-fidelity CFD simulations were performed on small-scale vortex tube separator configurations (1x1, 3x3, 5x5) to extract key aerodynamic parameters for multiple freestream velocities and angles of attack. These outputs were analysed to construct a multivariable linear regression model, where variables are tube count, logarithmic Reynolds number, and dynamic pressure due to the orientation of the incoming flow. The model achieved an R^2 value of 0.9835. This value confirms that the model captured nonlinear trends obtained in simulation results. In comparison to theoretical pressure loss calculations, the model demonstrated physical consistency and acceptable predictive accuracy. Additionally, its simplicity allows for rapid evaluations of different design alternatives during the conceptual design phase. While the extrapolation capability of the model to bigger panels was constrained, it proved effective for interpolation within the trained domain. The modeling approach also enables sensitivity analysis to explore the influence of each input variable on pressure loss. Moreover, the generated dataset can be further used to train advanced machine learning models for future studies. Overall, the approach reduces reliance on resource-intensive simulations, enabling faster turnaround in engineering workflows. This study offers a quick, low-cost method for preliminary design and assessment of VTS panels, making it a useful tool for early-stage integration in rotorcraft engine air particle separation systems.

Keywords: Vortex Tube Separator, Pressure Loss, Regression Model, CFD, Rotorcraft Inlet, Theoretical Modeling

ÖZET

Bu çalışma, vorteks tüp ayırıcıların neden olduğu basınç kaybını tahmin etmek amacıyla teorik veri ile beslenmiş bir modelin geliştirilmesini tanıtmaktadır. Vorteks tüp ayırıcılar, helikopter motorlarının toz ve yabancı madde kaynaklı hasarlardan korunmasında önemli bir rol oynamaktadır. Bu sistemlerin etkin bir şekilde tasarlanabilmesi, aerodinamik performansın doğru şekilde öngörülebilmesini gerektirir. Tam ölçekli hesaplamalı akış dinamiği simülasyonlarının yüksek hesaplama maliyetine karşılık olarak ölçeklenebilir ve regresyona dayalı bir tahmin modeli önerilmiştir. Bu kapsamda farklı akış hızları ve hücum açıları altında belirli aerodinamik parametreleri elde etmek için küçük sayıda tüp içeren vorteks tüp ayırıcı panelleri üzerinde hesaplamalı akış dinamiği analizleri gerçekleştirilmiştir. Elde edilen veriler, yüzey basıncı, kütleli debi ve akış yönelimi gibi girdilerden oluşmaktadır. Tüp sayısı, logaritmik Reynolds sayısı ve açısal dinamik basınç gibi çıktılar analiz edilerek çok değişkenli bir doğrusal regresyon modeli oluşturulmuştur. Geliştirilen model $R^2=0.9835$ gibi yüksek bir determinasyon katsayısına ulaşarak simülasyon sonuçlarında gözlemlenen ve doğrusal olmayan eğilimleri başarılı bir şekilde yakalayabilmiştir. Bir sonraki adımda teorik basınç kaybı hesaplamalarının sonuçları ile karşılaştırıldığında da fiziksel anlamlılık açısından tutarlılık sergileyerek kabul edilebilir düzeyde bir tahmin doğruluğu sunmuştur. Model, aynı zamanda tasarım değişkenlerine karşı duyarlılık analizi yapılmasına da olanak tanımaktadır. Ayrıca, model çıktılarının mühendislik karar destek süreçlerinde kullanılabilirliği test edilmiştir. Eğitilmiş veri aralığı dışındaki büyük panellerin sonuçlarını tahmin etme yeteneği sınırlı olsa da eğitim aralığı içerisindeki ara noktaların tahminlerinde etkili bir performans göstermiştir. Sonuç olarak bu çalışma, vorteks tüp ayırıcı panellerinin ön tasarım aşamalarında kullanılabilecek hızlı ve düşük maliyetli bir performans değerlendirme aracı ortaya koymuştur. Ayrıca oluşturulan veri seti, gelecekteki çalışmalarda yapay zekâ tabanlı modellerin eğitilmesinde de kullanılabilir niteliktedir.

Anahtar Kelimeler: Vorteks Tüp Ayırıcı, Basınç Kaybı, Regresyon Modeli, Hesaplamalı Akışkan Dinamiği, Rotorcraft Girişi, Teorik Modelleme

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LIST OF SYMBOLS AND ABBREVIATIONS

ρ	: Air density [kg/m ³]
α	: Angle of attack [°]
g	: Body force per unit volume [N/m ³]
F	: Darcy-Weisbach Friction Factor
Y_k	: Dissipation of k due to turbulence [W/kg]
Y_w	: Dissipation w due to turbulence [W/kg]
μ	: Dynamic viscosity of air
Γ_k	: Effective diffusivity of k [m ² /s]
Γ_w	: Effective diffusivity of w [m ² /s]
G_k	: Generation of k due to velocity gradients [W/kg]
G_w	: Generation of w [1/s ²]
q	: Heat flux vector [W/m ²]
K	: Permability of the filter media
ΔP	: Pressure Loss
w	: Specific dissipation rate [1/s]
τ	: Stress tensor [Pa]
E	: Total energy per unit mass [J/kg]
D	: Tube diameter [m]
L	: Tube length [m]
k	: Turbulence kinetic energy [m ² /s ²]
V	: Velocity [kts]
AIP	: Aerodynamic Interface Plane
CFD	: Computational Fluid Dynamics
EAPS	: Engine Air Particle Separation
FOD	: Foreign Object Debris
GTU	: Gebze Technical University
IPS	: Inertial Particle Separation
IBF	: Inlet Barrier Filter
ISA	: International Standard Atmosphere
KIAS	: Knots Indicated Air Speed
OEI	: One Engine Inoperative
OSG	: Outer Scavenge Geometries
RANS	: Reynolds Averaged Navier Stokes
Re	: Reynolds Number
SST	: Shear Stress Transport
VTs	: Vortex Tube Separator

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1. INTRODUCTION

1.1. Background and Motivation

Modern aircraft propulsion systems which are used in helicopters and other rotary wing aircrafts utilize gas turbine engines. Gas turbine engines generate thrust or shaft power through the compression of air, combustion of air with fuel, and expansion of these mixed hot gases. In these engines, ambient air is drawn into the intake, compressed via axial or centrifugal compressor stages, mixes with fuel in the combustion chamber and expands through turbine stage to generate thrust or mechanical power for the rotor. A schematic diagram of these engines is given in **Figure 1.1**. Thus, it is safe to say that performance and reliability of these engines are critically dependent on the quality of incoming airflow since it is a part of the chained events to generate thrust or mechanical power. Any foreign objects to degrade the quality of the incoming air, such as dust, sand, salt or ice droplets can severely affect engine operation leading to compressor/turbine blade erosion or even combustor flameout under extreme conditions.

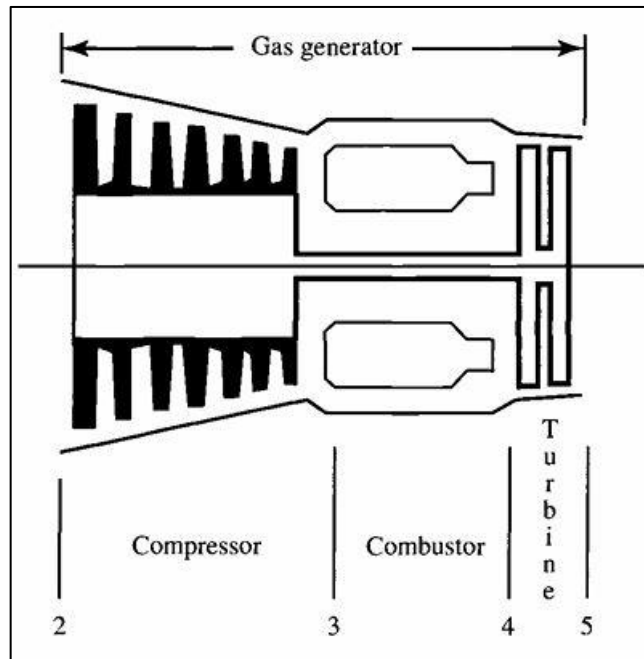


Figure 1.1: A schematic representation of gas generator [1]

Helicopters differentiate from fixed wing aircrafts in terms of runway areas. Fixed wing aircrafts typically operate from predefined runway areas where the strict foreign object debris control programs, regular runway inspections and sweeping operations take place. On the other hand, helicopters are not restricted to predefined runway areas. Since one of their key operational advantages is the ability to take off and land vertically, helicopters are suitable to operate in remote environments such as deserts, mountains, forest and offshore platforms. Thus, operations like search and rescue, offshore transport, urban mobility and aerial firefighting missions favors helicopters where air intake systems are exposed to foreign objects. As a result, unlike fixed wing aircrafts, helicopters need additional air inlet protection systems to provide reliable and safe operations during critical missions.

In the absence of these protection systems, foreign object damage can be observed on compressor blades and turbine vanes, but mainly on the first stage of compressor blades [2]. It can also cause clogging of cooling passages. All of these changes in the closed cycle of gas turbines could eventually alter the flow patterns within the engine core [3]. In extreme conditions, it can end up with the flameout and ignition instability in the combustion chamber. Accumulation of these degradation effects leads to reduced efficiency, increased specific fuel consumption and higher risk of engine failure. These scenarios not only reduce engine life and performance but also increase maintenance costs and cause serious safety concerns.



Figure 1.2: Damaged blade by small objects [5].

Helicopter engines are equipped with Engine Air Particle Separations (EAPS) systems to avoid those scenarios. The goal of these systems is to provide clean airflow to the

engine and provide reliable operation throughout operations under severe conditions. The most common EAPS technologies are:

- Inlet Barrier Filters (IBF)
- Vortex Tube Separators (VTS)
- Inertial Particle Separators (IPS)

Every solution has its unique benefits and drawbacks. Firstly, IBFs provide higher separation efficiency at the beginning of the operation. Due to the accumulation of particles over filters, separation efficiency starts to decrease throughout the operation time. This comes with the need of scheduled maintenance and replacements. They are still widely used in utility helicopters. Secondly, IPSs offer more compact solution since they are integrated into gas turbine engines. They utilize particle inertia to separate contaminants from the airflow, but their performance is limited to coarse particles and high speed flow regimes.

Because of its compact design, low maintenance requirements and passive functioning, VTS offers a good substitute among these technologies. In a typical VTS configuration, air enters through cylindrical tubes. As the airflow moves through each tube, a swirling motion generated by internal fans causes heavier particles to migrate toward the tube walls. These particles are subsequently diverted and discharged by the help of scavenge fan, allowing cleaner air to proceed toward the engine intake.

In contrast to its advantages, VTS poses several challenges when it comes to design and evaluation of the system. A full scale Computational Fluid Dynamics (CFD) simulation of a VTS is computationally expensive and time consuming. Since it consists of thousands of tubes which comes with complex internal flow dynamics, swirl formation, secondary flows and strong boundary layer interaction, simulation requires fine mesh resolution and high fidelity turbulence modeling. Furthermore, simulation includes multiphase flows due to particle separation. Combined with the non uniformity of the inflow particularly caused by curved inlet ducts, these factors significantly increase the complexity of CFD analysis.

As a result of these challenges, there is a growing demand for efficient, low cost models that can estimate pressure loss due to VTS panels without utilizing full scale CFD simulations. Its importance stands out especially in the preliminary design phase. Pressure loss is a critical parameter since it directly affects the total pressure available

at the engine intake. Total pressure at the intake affects total pressure at the compressor exit, then total pressure at the combustor exit which finally affects the extracted power from the air at the turbine stages. This cause loss of power, decrease in the fuel efficiency and engine stability.

This study addresses this challenge by developing a physics informed regression based predictive model to estimate the pressure loss induced by VTS panels. Instead of resolving every geometric detail, the approach adopts a modular and scalable methodology:

1. CFD simulations of small VTS panel configurations (1x1, 3x3, 5x5, 9x9) were conducted using STAR-CCM+ under realistic engine boundary conditions, including a representative cylindrical plenum.
2. For each scenario, critical variables such as total pressure at the ambient, tube inlet and tube exit, mass flow rate and velocity components at the tube inlet were gathered.
3. Data was reduced in MATLAB.
4. Theoretical calculations were performed to evaluate simulation results validity.
5. Lastly, a data driven model was developed in Python using multivariate linear regression with predictors such as tube count, logarithmic Reynolds number and dynamic pressure loss due to inflow angle.

Ultimately, the proposed methodology reduces reliance on expensive CFD simulations during the conceptual design phase of rotorcraft inlet systems. It provides engineers with a fast, flexible tool to estimate the pressure loss due to VTS integrations.

1.2. Problem Statement

Helicopters often operate in conditions where the cleanliness or quality of the incoming air cannot be assured. Sand, dust, salt spray, and several other debris can be ingested into the engine inlet and severely reduces engine performance and safety. These conditions are especially encountered in operations such as firefighting, military logistics, or desert surveillance, where it is highly possible to include foreign objects or particles in the incoming airflow.

Engine Air Particle Separation systems are utilized for these conditions. VTS stands out among these technologies thanks to its passive and self cleaning solution.

Additionally, compared to IBFs, VTS systems require less maintenance while offering higher separation efficiency than the IPS systems. Despite their advantages, VTS systems remain limited in terms of performance predictive approaches. The current literature cannot offer a applicable, generalized predictive model that connects geometric and flow variables to performance parameters such as pressure loss across a full scale of VTS system.

Since full scale helicopter application involves thousands of VTS tubes, solution demands high mesh resolutions, which in turn leads to high computational cost. This situation limits the design iterations. Engineers are forced to rely on empirical estimates or overly simplified models. It results with underestimating the risk or overdesign.

So, in order to predict VTS performance without requiring full scale CFD simulation each time a new configuration is presented, an analytical, low cost approach is required.

1.3. Aim and Scope of This Study

This study aims to develop a regression based, modular model for predicting the pressure loss across VTS panels. The proposed model is desired to be inserted between high fidelity CFD simulations and simplified theoretical calculations. The model is trained by the data of controlled simulations of small scale panel geometries under varying flow angles and velocities.

This study is limited to:

- Forward facing VTS panel geometries.
- Simulations performed under ISA sea level conditions.
- Freestream velocities and inflow angles covering typical rotorcraft flight envelopes.
- Pressure loss analysis without modeling actual particle separation or swirl vanes inside the tubes.

This study does not include:

- Internal vane swirl modeling withing each vortex tube.
- Real particle tracking or particle loading analysis.

- Mechanical design aspects.

By concentrating on this aspect, the research seeks to develop a predictive framework that can be generalized to larger panel or inter points, based solely on data obtained from smaller CFD simulations on specific conditions.

1.4. Methodology

The methodology consists of five main stages:

1. Geometric Design and CFD Simulation: VTS panels of 1x1, 3x3, 5x5, 9x9 tube configurations were designed using Siemens NX. Simulations were conducted in STAR CCM+ with proper inlet boundary conditions reflecting engine inlet pressure and freestream flow.
2. Data Gathering and Reduction: For each tube, total pressure at inlet and outlet, flow velocities at the inlet and mass flow rates were extracted. Simulations were repeated for 6 angle of attack and 6 freestream velocities, resulting in 36 cases per configuration.
3. Theoretical Calculations and Assumptions: Parameters such as Reynolds number ($\log Re$), dynamic pressure loss due to angle and ΔP values were computed from raw data.
4. Model Development: Using Python, regression model was trained on small panels data.
5. Model Extrapolation Capability: A 9x9 panel case results were used to test model's extrapolation performance.

This methodology ensures both physical consistency and computational efficiency, making it practical for integration into the preliminary stages of helicopter engine inlet design.

1.5. Structure of the Thesis

The remainder of this thesis is organized as follows:

1. Chapter 2 provides a detailed review of gas turbine air intake protection systems, with a focus on vortex separators and their aerodynamic impact.

2. Chapter 3 outlines the geometric design, simulation setup, data gathering and data reduction which are used to train regression model.
3. Chapter 4 presents the results of this study by comparing and explaining the critical points.
4. Chapter 5 concludes the thesis with key findings, limitations, and suggestions for future work.



2. LITERATURE REVIEW

To protect turboshaft engines and to provide safe and reliable operation, engine intakes must be protected from foreign object ingestion. Particles like sand, dust or salt can cause erosion, corrosion, fouling and blockage of important engine parts, specifically in the compressor, since they are located in the front of the gas generator. Ultimately, this leads to increased maintenance cost, decreased engine life and decreased performance. EAPS systems have been developed to reduce these concerns, however, each has unique filtering efficiencies, integration issues and operating principles. A thorough analysis of EAPS technologies, such as vortex tube separators (VTS), inertial particle separators (IPS), and inlet barrier filters (IBFs), is provided in this chapter. Every system is investigated in terms of its operational applications, modeling techniques, structural variations, and operating mechanisms.

2.1. Inlet Barrier Filter

Initial solutions focused on IPS but they were less effective for fine and sub micron particles. To address this shortfall, the concept of mechanical filtration at the engine inlet was introduced. Inlet Barrier Filters are widely adopted EAPS systems designed to protect gas turbine engines. They are the mostly used solution for both military and civilian helicopters thanks to its proven ability. By doing so, they help mitigate erosion, enhance engine reliability, and lengthen maintenance intervals, especially in challenging environments such as deserts, coastal areas, and volcanic regions. But, it should be noted that IBF comes with its own scheduled maintenance requirements [6].

In contrast to inertial based systems, which separate particles by exploiting momentum differences, IBFs utilize mechanical filtration through multi layered fibrous media. The filter matrix traps particles using a combination of physical mechanisms including inertial impaction, interception, Brownian diffusion, and in some advanced designs, electrostatic attraction [8]. This approach offers superior performance in retaining fine and sub micron particles, which typically hard to capture in vortex or inertial separation systems [6].

Filtration efficiency depends heavily on fiber diameter, packing density, filter thickness, and media properties. Dry media filters typically exceed 95% efficiency for particles larger than 10 μm , while coarse particulate ($>30 \mu\text{m}$) can surpass 99% [10]. The U.S. Army's Rotorcraft Engine Inlet Study demonstrated that IBFs contributed to significant reductions in engine compressor erosion, resulting in improved engine time on wing and fewer unscheduled maintenance events for platforms like the UH 60 Black Hawk and Eurocopter AS 350 [6].

IBFs are typically installed at the engine inlet plenum and come in various geometries such as flat panel, wrap around, or modular designs, depending on platform requirements. Many systems also incorporate automatic bypass doors that activate when pressure drop across the filter exceeds a predefined threshold, ensuring uninterrupted engine airflow in case of clogging, which is shown in **Figure 2.1**. Differential pressure sensors are often integrated to monitor filter loading in real time [6]. They are used mainly in notifying the pilot when the difference reaches an unacceptable level.



Figure 2.1: Filter integration for Bell 429 platform [10].

From a modeling perspective, IBFs introduce a measurable aerodynamic penalty, primarily in the form of total pressure loss (ΔP). This resistance arises due to the obstruction of flow through the porous media and is characterized by the modified Darcy–Forchheimer equation:

$$\Delta P = \frac{\mu}{K} \cdot L \cdot V + C_f \cdot \rho \cdot V^2 \quad (2.1)$$

Where:

- μ : dynamic viscosity of air
- K : permeability of the filter media
- L : filter thickness
- V : superficial velocity through the filter
- C_f : inertial resistance coefficient
- ρ : air density

These coefficients (K , C_f) are obtained from experimental data or manufacturer datasheets. They depend on filter material, fiber packing density, and particle loading. As dust accumulates, the effective permeability K , decreases, increasing the pressure loss nonlinearly over time [6].

Since modeling fiber structures explicitly in the computational environment offers several challenges, CFD simulations represent IBFs using porous media zones. By this method, momentum sink terms are introduced into the Navier–Stokes equations. It allows the accurate prediction of pressure losses and flow distortion with manageable computational resources. Studies [6] using ANSYS Fluent demonstrate that, when resistance parameters are appropriately defined, porous zone approximations yield reliable predictions.

While IBFs offer exceptional filtration capability, they also present several limitations:

- Dust accumulation increases pressure drop and can trigger bypass events, risking unfiltered air ingestion.
- Icing risk is prominent in humid, cold weather operations, requiring heating elements or hydrophobic media.
- Bypass door systems, if mechanically compromised, may lead to partial engine starvation or internal damage.

Despite these drawbacks, IBF's ability is proven by field and laboratory data. For example, Van Der Walt and Nurick [2] showed that compressor erosion decreased dramatically even under partial filtration conditions. IBF systems are also favorable due to their suitability for simulations when it's compared to VTS. It offers multiple advantages during design phases. It is further demonstrated that porous media CFD

models, calibrated against empirical test data, can accurately represent IBF performance in realistic geometries and flow regimes.

Daldal [4] performed a CFD study for IPS configurations under dusty airflow conditions. This study also mentioned that IBFs achieved better fine particle retention but at a higher aerodynamic cost. These findings supported the need of trade offs between filtration efficiency and inlet pressure recovery especially for power limited platforms.

In conclusion, IBFs have become a cornerstone of helicopter inlet protection strategies. Their modular integration, well understood performance characteristics, and high efficiency across a wide particle size range make them the reference standard against alternative systems like Vortex Tube Separators (VTS). However, the growing demand for low maintenance, low drag, and self cleaning solutions requires continued exploration of passive systems, which will be examined in the following sections.

2.2. Inertial Particle Separator

Inertial Particle Separators (IPS) are among the most mature and widely adopted air particle separation systems in rotorcraft propulsion. Particularly valued for their passive operation and low maintenance design. In contrast to VTS and IBF systems, IPS systems are integrated into the engine. This more compact design resulted with lower pressure loss and improved system level performance [12].

IPS relies on the inertia of particles relative to the flow to achieve separation without the need for porous media. As contaminated air enters a curved duct or vane system, heavier particles such as sand, dust, or water droplets are unable to follow the streamlines due to their momentum. Then, they are redirected into a scavenge path, while cleaner air proceeds into the engine core. Sample presentation scheme of IPS is given in **Figure 2.2**.

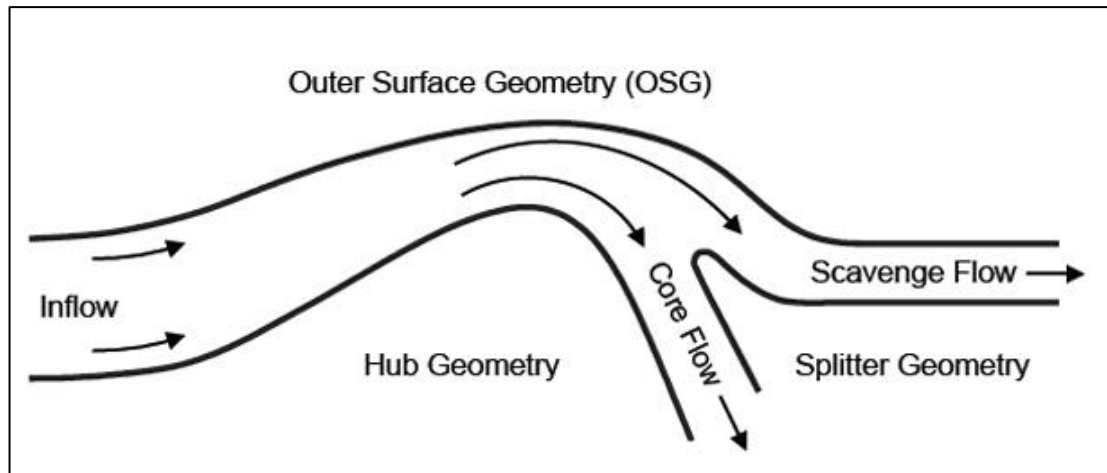


Figure 2.2: Inertial Particle Separator Cross-section [12].

This mechanism's efficiency depends on the particle's Stokes number since Stokes number is directly influenced by flow velocity, curvature, particle size and density. In terms of the separation performance, IPS systems show high separation ability for coarse particles while their performance significantly drops for finer particles which is an expected phenomenon. Thus, it is safe to say that IPS systems can offer limited capability in high dust or fine ash environments [4]. From geometrical standpoint, IPS systems vary across engines. The most common configurations include scroll ducts, swirl vanes and multi turn systems integrated at the inlet.

From a fluid dynamics standpoint, IPS systems introduce relatively low total pressure loss (typically 1500 –3000 Pa) compared to IBFs, making them more suitable for power limited operations. However, their internal flowfields are inherently complex. They are characterized by swirl, secondary flows, boundary layer detachment, and recirculation zones near the splitter and scavenge interfaces. Experimental investigations by Brian J. Connolly et al. [11] confirm the presence of asymmetric recirculation regions and particle bounce effects that significantly impact separation performance. The University of Virginia's 2D IPS research facility further revealed that geometry induced flow asymmetry, especially near the outer scavenge geometries (OSG) can degrade particle capture efficiency. Numerical simulations, typically conducted with RANS based CFD solvers (e.g., realizable $k-\epsilon$, SST $k-\omega$) combined with Lagrangian discrete phase modeling, are capable of resolving macroscopic trends. But, they struggle to accurately capture microscale phenomena like particle wall interactions and turbulent shedding. Daldal [4] also demonstrated that meshing fidelity

and inlet boundary conditions substantially affect simulation accuracy. Additionally, particle loading and scavenge to core flow ratio were found to influence the mass balance across the inlet, especially under varying engine throttle settings [11].

As in the IBF systems, IPS systems exhibit several limitations. Their inability to capture fine particles increases the risk of compressor damaging. Moreover, since they depend entirely on flow induced separation, their efficiency degrades sharply at low velocities. These challenges have led to growing interest in hybrid solutions or alternative systems. Thus IBFs and VTSs are introduced to the industry. These systems aim to combine the pressure performance of IPS with higher fine particle retention. In this context, while IPS remains a cornerstone of EAPS design due to its reliability and simplicity, its physical limitations necessitate further research into next generation systems like Vortex Tube Separators (VTS), which offer the potential for improved separation with minimal performance penalties.

2.3. Vortex Tube Separator

Vortex Tube Separators (VTS) are increasingly utilized in rotorcraft propulsion systems as an effective Engine Air Particle Separation (EAPS) technology, especially in mission profiles involving dusty, sandy, or salt laden environments.



Figure 2.3: S61 operates in dusty environment [17].

VTS units utilize internal swirling motion within cylindrical tubes to achieve separation [13]. As contaminated air enters the vortex tube, vortex generators induce rotational flow. Heavier particles unable to follow the curved path due to their inertia. They move radially outward and are purged through scavenge ports. At the same time, cleaner core flow proceeds toward the engine [14]. VTS unit's working principle is shown in **Figure 2.4**. Systems like the Centrisep is utilized on helicopters such as the AW-139, CH-47, and EC-130. By combining aerodynamic efficiency with robustness under severe operating conditions, they have become favorable choice for engine intakes. [6].

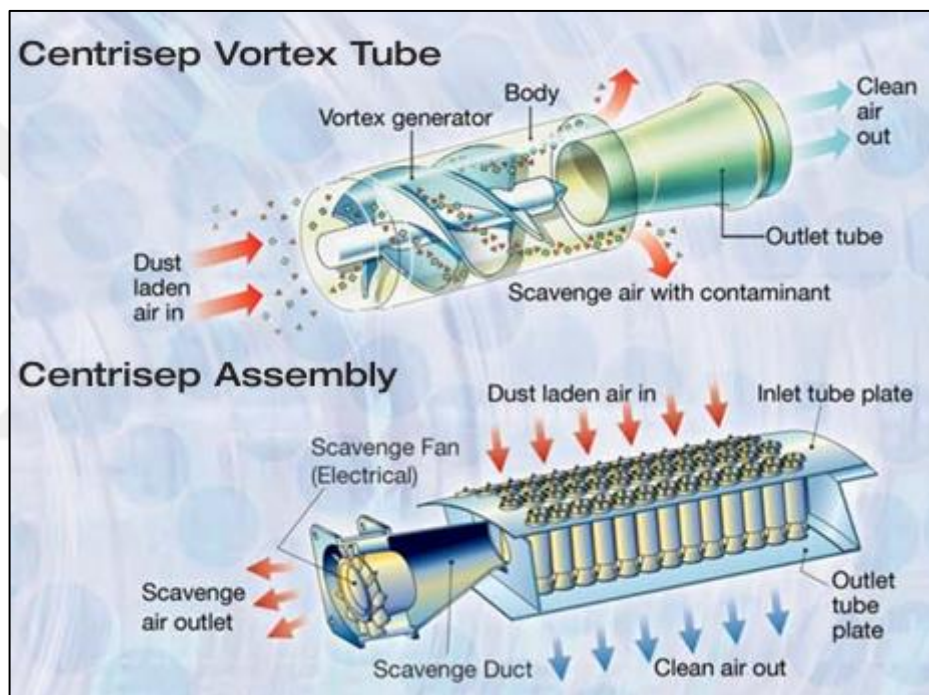


Figure 2.4: VTS tube working principle [7].

This passive separation mechanism offers distinct operational advantages. VTS units are compact and they require minimal maintenance. Additionally, they are less susceptible to clogging or icing under severe weather conditions. These features make them attractive for helicopters operating in desert or maritime zones, as emphasized in early EAPS deployment reviews. Pall PUREair System states excellent snow and icing protection without any significant power loss [17]. As shown in **Figure 2.5**, ice formation around the Vortex Tube Separator is visibly localized and does not obstruct the main airflow path through the tubes. This figure represents the hover case's results.

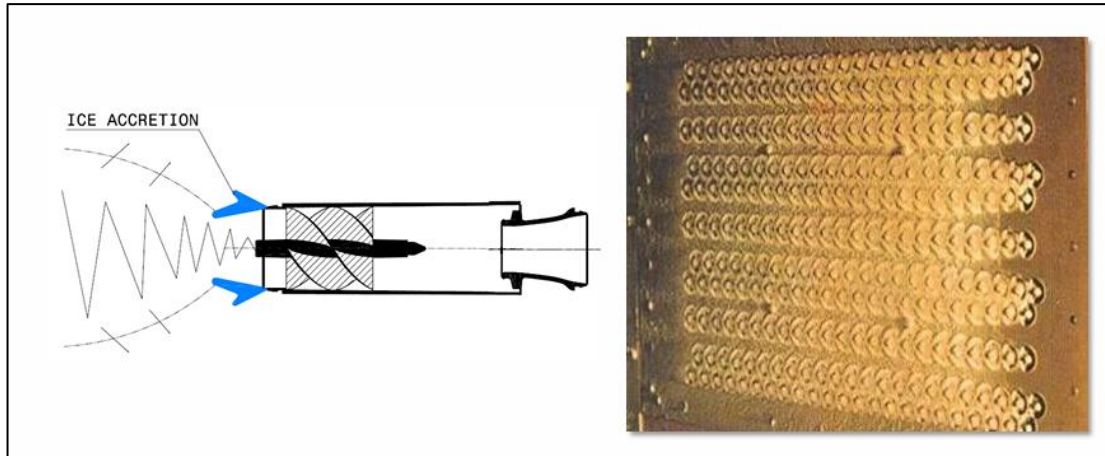


Figure 2.5: Ice accretion in hover [17].

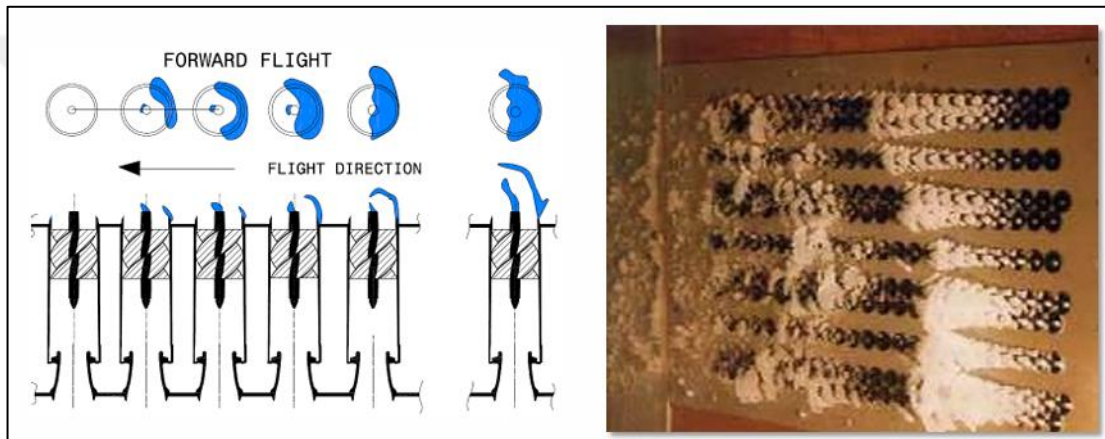


Figure 2.6: Ice accretion in forward flight conditions [17].

In forward flight conditions, illustrated in **Figure 2.6**, additional ice accumulation is observed along the leading edges of the system. However, the axial core of the tube remains largely open. Thus, it allows the sufficient airflow by preserving the separation mechanism induced by swirl.

From a structural standpoint, VTS panels are modular and can be configured in arrays. This panel configuration simply depends on engine requirements and platform's geometrical limitations. Advanced vortex tube designs have incorporated scavenge port placement and internal geometry optimization in order to improve vortex core stability and reduce pressure losses. Prinsloo and De Villiers contributed notable design enhancements through improved separation chamber geometry and axial flow uniformity management [15].

However, simulating VTS performance remains challenging due to the complex internal flow Dynamics [9]. CFD tools must resolve swirl, secondary flows, boundary layer separation, and high turbulence intensity regions. All of these requires fine mesh and advanced turbulence models which ended up with high computational cost.

A comparative study by Bojdo and Filippone evaluated the overall performance characteristics of various EAPS Technologies. It includes VTS systems, by considering separation efficiency, pressure drop, and operational trade offs. Their analysis showed that VTS systems offer lower maintenance and greater modularity. On the other hand, they cause higher pressure losses and provide moderate efficiency in fine particle separation [16]. Thus, VTS technology presents a compelling middle ground between the high efficiency but maintenance heavy IBFs and the low drag but particle limited IPS units. Industry is still learning about these systems thanks to ongoing computational and experimental studies. These studies strengthen their potential as a viable solution for next generation rotorcraft inlet protection.

3. METHODOLOGY AND DATA COLLECTION

A systematic methodology has been developed to estimate the pressure loss caused by VTS panels in helicopter engine air intake systems. Due to the high computational cost and complexity associated with modeling full scale VTS systems, which include typically thousands of vortex tubes, this study aims to build a scalable and data driven predictive model. Data is based on limited number of high fidelity CFD simulations. These simulations are performed on panels containing relatively small numbers of tubes. As a result, output of these simulations are used to train a regression model capable of interpolating inter points or extrapolating larger configurations.

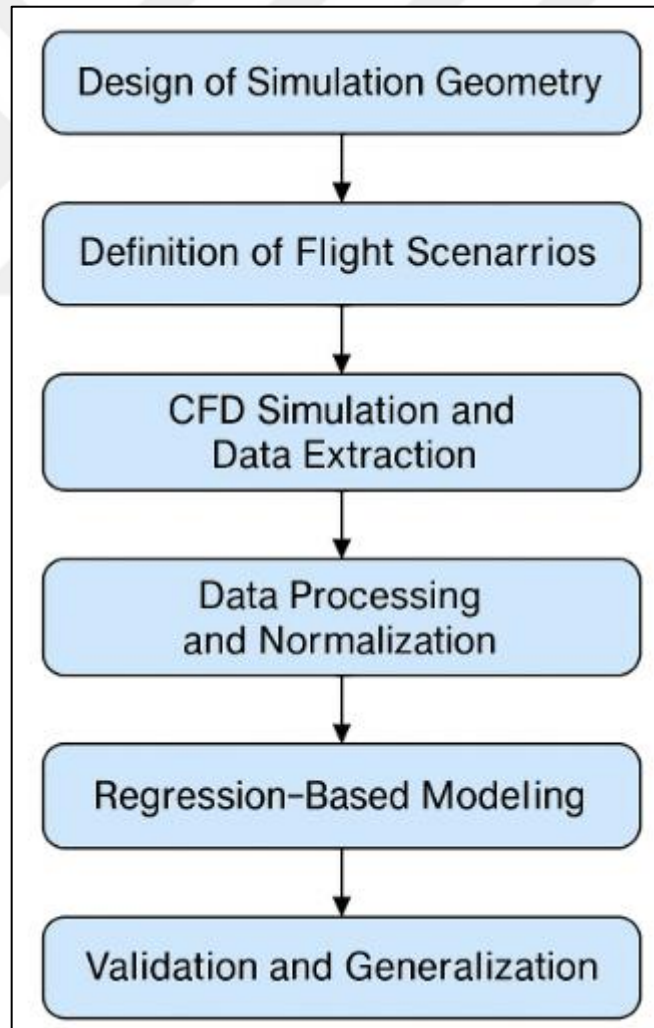


Figure 3.1: Methodological Flowchart of this thesis

3.1. Geometry

To simulate the inlet particle separation system's behavior under realistic conditions, a series of simplified yet physically representative computational geometries were created. These geometries were constructed to simulate forward facing VTS panel configurations. The primary and only objective was to analyze pressure loss behavior in varying panel sizes. Thus, findings could be used to estimate panel performance.

The panel geometries consisted of arrays of cylindrical tubes with internal diameters and lengths based on sample VTS dimension used in operational systems. Four distinct configurations were modeled:

- 1x1 panel,
- 3x3 panel,
- 5x5 panel,
- 9x9 panel.

Three configurations are given in **Figure 3.2**.

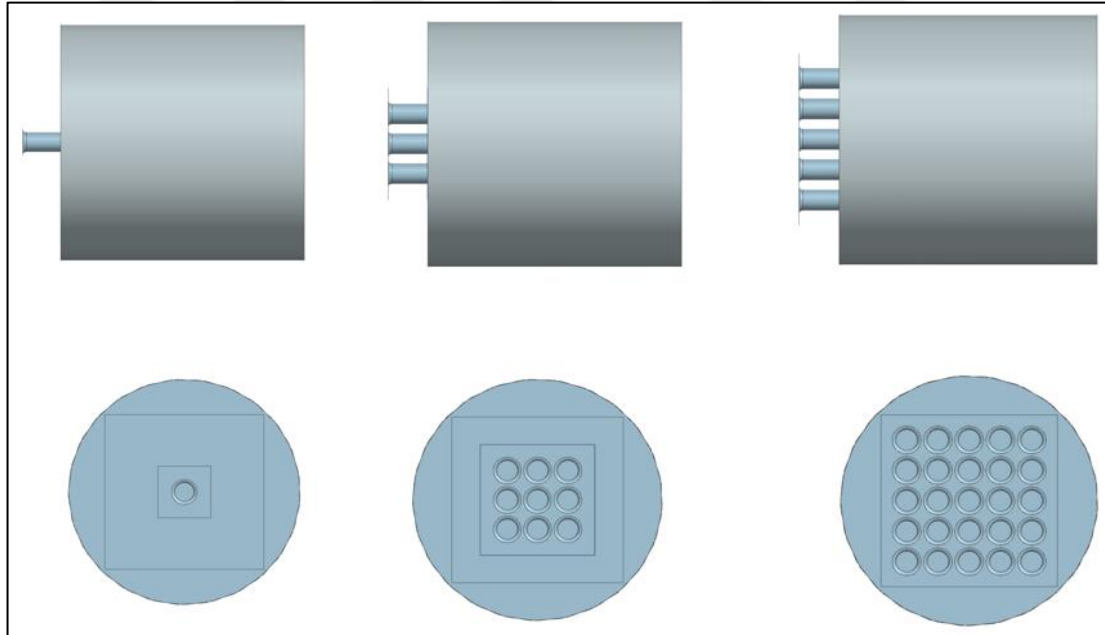


Figure 3.2: Panel configurations with 1, 9 and 25 tubes.

Each panel was positioned perpendicular to the freestream flow to simulate a forward facing intake design. The tubes were placed with a fixed center to center spacing equal to 1.5 times the tube diameter to maintain consistency across configurations.

To simulate downstream flow resistance and boundary condition to representative of actual engine suction, a cylindrical plenum was connected to the outlet of the tubes. This downstream section was critical in stabilizing backpressure and ensuring mass flow continuity. The domain was enclosed with a half spherical farfield region to define freestream boundaries. Farfield provide the development of uniform inlet conditions.

These geometries were created using Siemens NX and exported in parasolid format for meshing and CFD processing in STAR-CCM+.

3.2. Flight Scenarios/Analysis Conditions

To evaluate the performance of the VTS panel configurations under a range of realistic operating conditions, a comprehensive set of flight scenarios was defined. These scenarios were selected to reflect typical rotorcraft operational envelopes, particularly in low altitude and particle contaminated environments such as desert operations and firefighting missions.

The flight conditions were parameterized based on two key variables:

- Freestream velocity and
- Angle of attack.

A total of 36 unique operating points were constructed by combining six freestream velocity with six angle of attack values as given in **Table 3.1**.

Table 3.1: Flight Conditions

Cases	Altitude [ft]	OAT [°C]	KIAS [kts]	Alpha [°]
1	0	15	20	0
2	0	15	20	15
3	0	15	20	30
4	0	15	20	45
5	0	15	20	60
6	0	15	20	75
7	0	15	40	0
8	0	15	40	15
9	0	15	40	30
10	0	15	40	45
11	0	15	40	60
12	0	15	40	75
13	0	15	80	0
14	0	15	80	15
15	0	15	80	30
16	0	15	80	45
17	0	15	80	60
18	0	15	80	75
19	0	15	120	0
20	0	15	120	15
21	0	15	120	30
22	0	15	120	45
23	0	15	120	60
24	0	15	120	75
25	0	15	150	0
26	0	15	150	15
27	0	15	150	30
28	0	15	150	45
29	0	15	150	60
30	0	15	150	75
31	0	15	175	0
32	0	15	175	15
33	0	15	175	30
34	0	15	175	45
35	0	15	175	60
36	0	15	175	75

These combinations were applied to each of 1x1, 3x3, 5x5 and 9x9 VTS panel configurations, resulting in a total of 108 baseline simulations and 36 validation simulations. The full matrix of test conditions ensures that both hover and high speed

forward flight conditions are captured, as well as extreme angular inflow conditions representative of unsteady maneuvering or crosswind operations.

Although many of the defined flight conditions reflect operational profiles frequently encountered by rotorcraft platforms, extreme combinations such as very low forward velocity coupled with high angles of attack (e.g., 20 knots at 75°) do not represent typical flight conditions. However, these scenarios were deliberately retained in the analysis to broaden the diversity and density of the simulation dataset. The purpose of this inclusion is to support the development of a generalized regression based model. It provides the capability of interpolating and extrapolating across a wide flight envelope. Including both realistic and unrealistic scenarios allows the model to better capture nonlinear aerodynamic trends. It enables more robust performance predictions during early stage inlet protection system design and evaluation.

3.3. CFD Simulations

A series of Computational Fluid Dynamics simulations were conducted using Siemens Star-CCM+ software. This section outlines the simulation methodology, turbulence modeling approach, boundary condition definitions and the data collection process employed throughout the study. Before proceeding, assumptions made for CFD simulation and theoretical calculations are:

- Steady state flow field,
- Fully developed flow region,
- Incompressible fluid flow,
- Ideal gas and
- No heat generation.

3.3.1. Solver Settings and Turbulence Modeling

The simulations were performed under the assumption of steady state flow field. Convergence is achieved in 2250 iterations by monitoring pressure values at the domain and mass flow rate values at the tube inlet. A coupled implicit solver was used to ensure strong interaction between momentum and continuity equations since they

are solved simultaneously in this solver. Continuity, momentum and energy equations are shown in Equations 3.1-3.3.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (3.1)$$

$$\frac{\partial (\rho V)}{\partial t} + \nabla \cdot (\rho V x V) = \nabla \sigma + F_b \quad (3.2)$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E V) = F_b \cdot V + \nabla \cdot (V \cdot \sigma) - \nabla \cdot q \quad (3.3)$$

where, ρ is density, V is the velocity vector, σ is the stress tensor, F_b is the body force per unit volume, E is the total energy per unit mass and q is the heat flux vector [18].

For turbulence modeling, the k- ω Shear Stress Transport model was selected due to its robustness in predicting separation, recirculation and swirl dominated flows. Transport equations for k- ω turbulence model are given in Equations 3.4-3.5.

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho k u_i}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k + G_b \quad (3.4)$$

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial \rho \omega u_i}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega + G_{\omega b} \quad (3.5)$$

In these expressions, G_k represents the production of turbulent kinetic energy resulting from mean velocity gradients, while G_ω corresponds to the generation of ω . The terms Γ_k and Γ_ω refer to the effective diffusion coefficients for k and ω , respectively. Meanwhile, Y_k and Y_ω represent the energy losses of k and ω caused by turbulent dissipation [18].

3.3.2. Boundary Conditions and Domain Configuration

The simulation domain included a forward facing VTS panel, a short downstream cylindrical plenum and a circular outlet representing the engine aerodynamic interface plane. Depending on the configuration, the VTS panel consisted of 1x1, 3x3, 5x5 or 9x9 cylindrical tubes. The following boundary conditions were applied:

- **Farfield:** A freestream boundary condition is applied to define the incoming airflow. The direction of the velocity vector was varied to simulate the selected angles of attack ($\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$) with 6 discrete velocity magnitudes: 20, 40, 80, 120, 150, and 175 knots.
- **Outlet:** A mass flow inlet boundary condition is applied to the engine aerodynamic interface plane. The mass flow rate calculated based on the engine manufacturer's data at 0ft and 15°C.
- **Panel Walls and Tube Surfaces:** All solid surfaces except tubes were modeled as slip walls.

3.3.3. Mesh Dependency Study

To ensure the reliability and mesh-independence of the simulation results, a comprehensive mesh dependency study was conducted using the vortex tube model within a simplified inlet system. The geometry comprised three main domains: a cylindrical vortex tube, a larger cylindrical plenum simulating the air intake chamber, and a hemispherical farfield region representing the surrounding atmosphere. Initially, two different mesh types were tested—polyhedral and tetrahedral—while keeping the same surface mesh. Although the tetrahedral mesh yielded a higher cell count (approximately 1.6 million) compared to the polyhedral mesh (approximately 599,000), it resulted in significantly longer computation time (53 minutes 40 seconds vs. 29 minutes 36 seconds). However, the resulting flow characteristics and performance indicators showed negligible difference between the two mesh types, indicating that the increased computational cost of the tetrahedral mesh was not justified by a corresponding improvement in solution accuracy. Therefore, the polyhedral mesh was selected for further refinement.

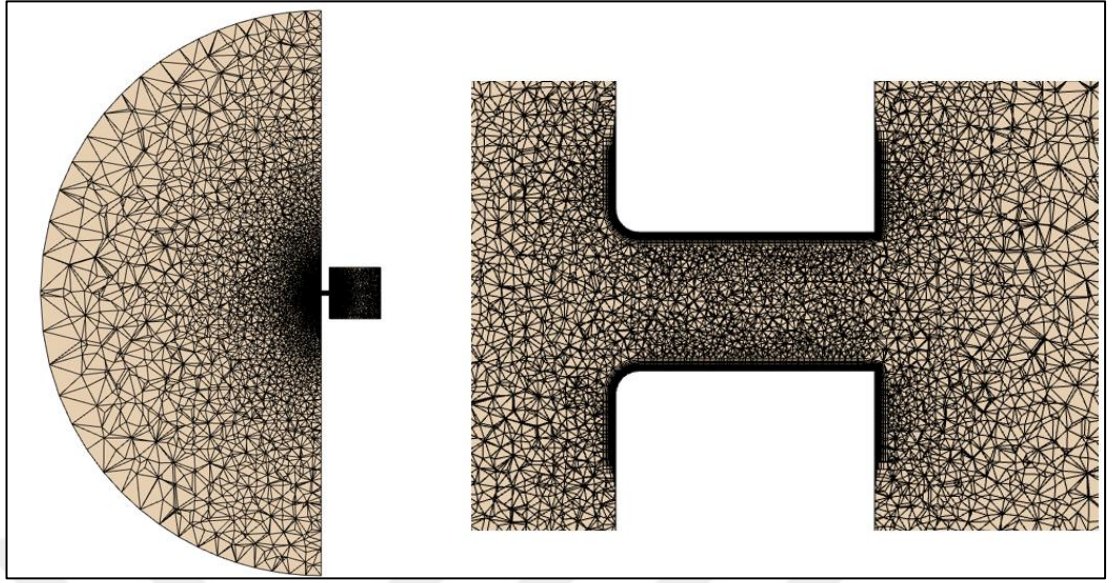


Figure 3.3: Domain with tetrahedral mesh

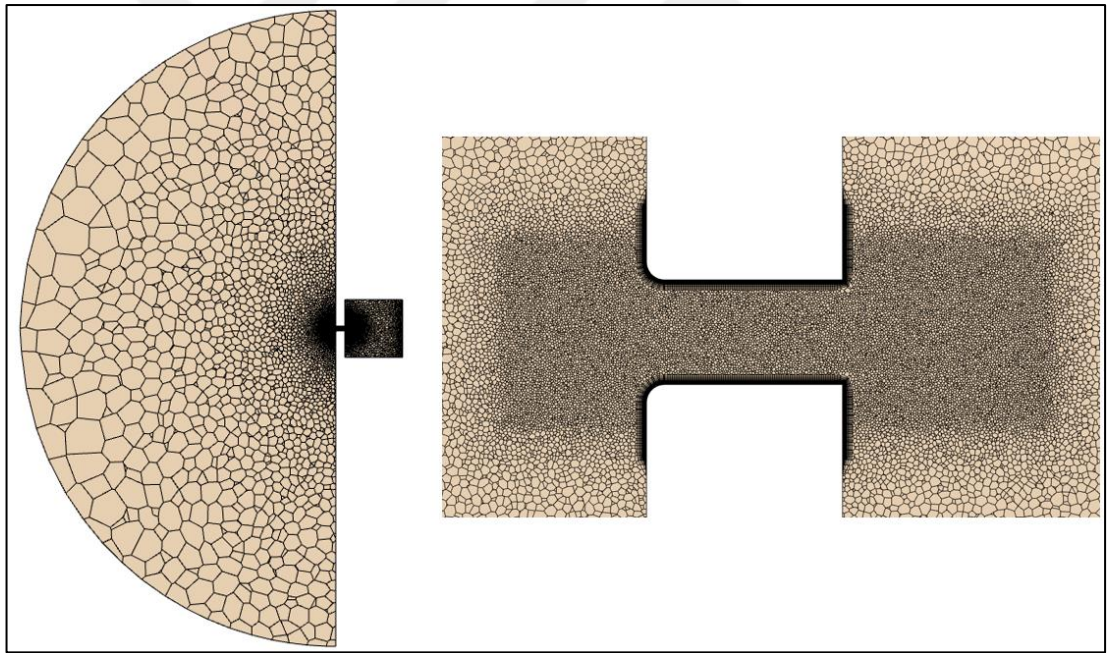


Figure 3.4: Domain with polyhedral mesh

The difference between the two mesh types can be visually observed in **Figure 3.3** and **Figure 3.4**, which shows the tetrahedral mesh (top) and polyhedral mesh (bottom) applied to the same geometry. The tetrahedral mesh exhibits a highly irregular and spiked element structure with more abrupt transitions between regions, while the polyhedral mesh demonstrates a more uniform and smoothly graded distribution.

Despite the denser tetrahedral mesh, the additional resolution did not lead to significant differences in flow field prediction, reinforcing the decision to proceed with the polyhedral mesh for its computational efficiency and smoother element transitions.

Subsequently, a series of polyhedral meshes were generated with varying base sizes to identify the point beyond which mesh refinement had negligible impact on solution accuracy. Four different mesh densities were tested, ranging from approximately 195,000 to over 2.1 million cells. A Body of Influence (BoI) was implemented around the vortex tube region to locally refine the mesh and better capture critical flow features such as separation and recirculation zones. This targeted refinement was particularly important due to the high gradients expected in the vicinity of the vortex-generating geometry.

Table 3.2: Mesh Dependency Test Matrix

Mesh Type	Total Cell Count	Mesh Size Description	Refinement Region
Tetrahedral	1624863	Fine	Uniform
Polyhedral	599455	Medium	Uniform
Polyhedral	194814	Coarse	BoI around vortex tube
Polyhedral	395682	Medium	BoI around vortex tube
Polyhedral	973169	Fine	BoI around vortex tube
Polyhedral	2168525	Very Fine	BoI around vortex tube

To evaluate mesh sensitivity, two key parameters were monitored across varying mesh densities: the total pressure at the tube exit and the tube mass flow rate. As shown in **Figure 3.5**, the total pressure rapidly stabilizes after the initial iterations and converges to nearly identical values for all mesh levels except the coarse case, which exhibits a slightly lower final value. Similarly, **Figure 3.6** presents the evolution of tube mass flow rate, where all meshes except the coarse case converge to nearly the same steady-state value. The coarse mesh notably overpredicts the mass flow rate due to insufficient resolution near critical flow regions. On the other hand, the fine and very fine meshes yield results that are only marginally different from the medium mesh, despite having significantly higher computational costs.

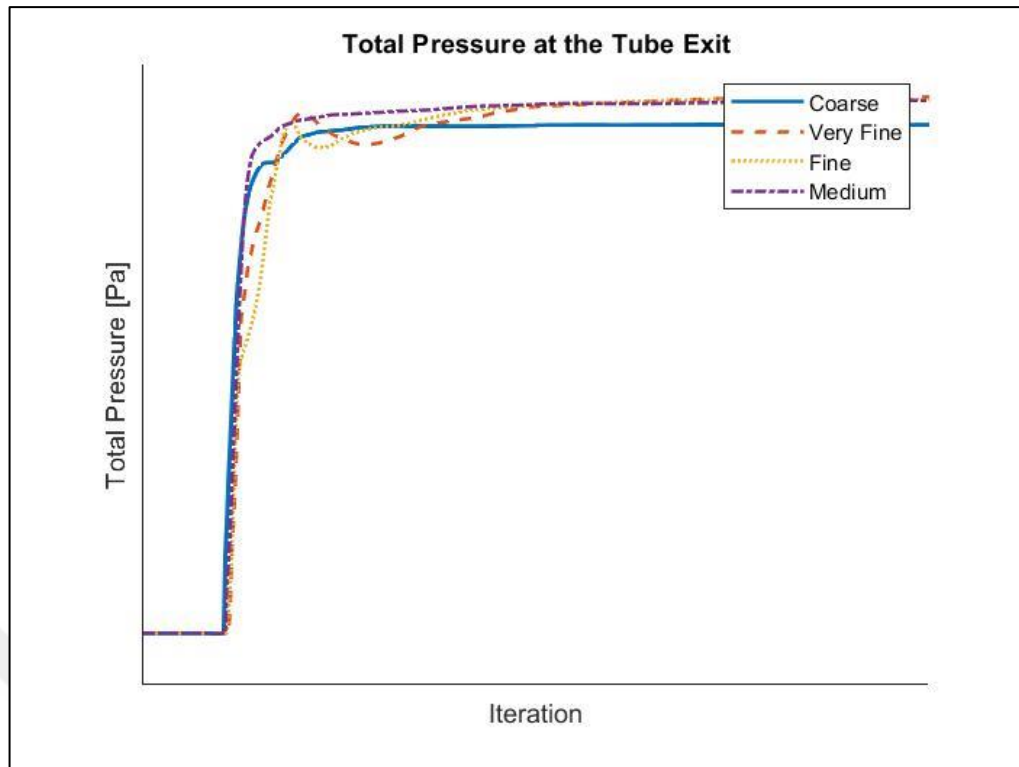


Figure 3.5: Iterative convergence of total pressure at the tube exit for different mesh densities.

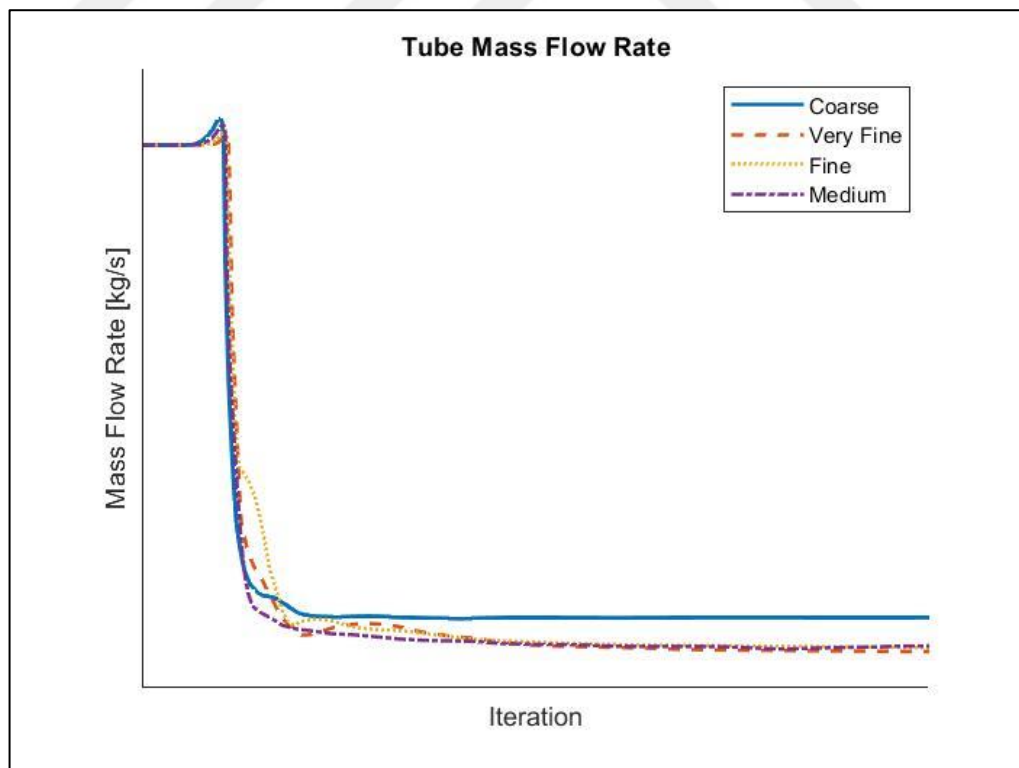


Figure 3.6: Iterative convergence of tube mass flow rate for different mesh densities.

Given the minimal variation in key flow parameters between the medium, fine, and very fine meshes, and considering the balance between accuracy and computational efficiency, the medium mesh configuration with 395682 cells was selected for all subsequent simulations. It provided sufficient resolution to capture the relevant flow features while maintaining a reasonable solution time. Mesh configuration with medium density is given in **Figure 3.7**.

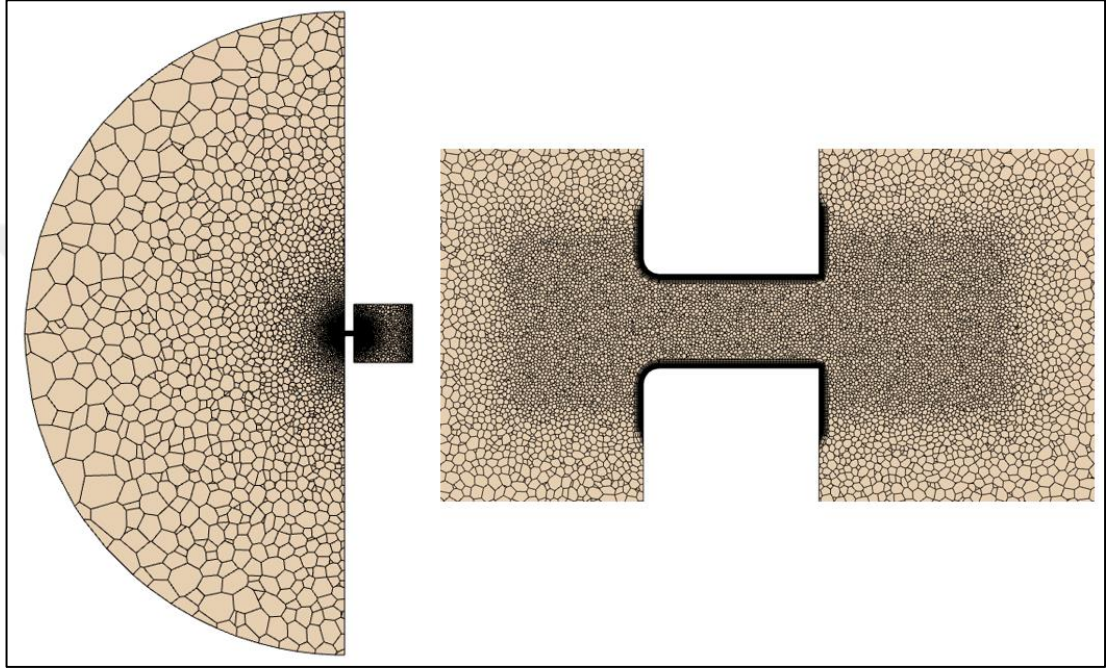


Figure 3.7: Medium density mesh configuration with body of influence

3.3.4. Data Collection Points and Quantities

To extract meaningful performance indicators from the simulations, data was collected at four strategically defined locations:

- Farfield:
 - Total Pressure: Serves as the reference pressure condition for calculating pressure losses.
- Tube Inlet:
 - Total Pressure, Mass Flow Rate and Velocity Components: Provides detailed information about flow orientation and magnitude entering the tube.

- Tube Exit:
 - Total Pressure: Allows estimation of pressure loss through the tube.
- AIP:
 - Mass Flow Rate: Used for ensuring boundary condition consistency and validating suction performance.

The center tube in each panel configuration was selected for data extraction to understand aerodynamic interactions with neighbour tube.

These extracted parameters formed the primary database. It is used for the data reduction and regression analysis stages of the thesis, enabling correlation between freestream conditions, geometry parameters, and resulting pressure loss across the VTS panels.

3.4. Data Processing and Theoretical Calculations

After the completion of CFD simulations, the raw data extracted from the data collection points which are mentioned in Chapter 3.3.3. The raw data were subjected to structured data processing and normalization workflow. This provided consistent performance indicators derived from simulations across different panel configurations and flow conditions. Normalization process ensured the generalization of regression model which is capable of making accurate predictions beyond the simulated scenarios.

Data processing and normalization operations were performed using MATLAB. It allowed efficient handling of multidimensional datasets obtained from CFD simulations. The pressure losses at each configurations were mathematically evaluated using built in functions and customized scripts. Frictional pressure loss and angular pressure loss were also calculated through same process. The use of MATLAB ensured consistency, repetability and traceability in the data reduction process. Finally, processed data is feeded into the regression model.

3.4.1. Calculation of Pressure Loss from Simulation Data

The primary quantity of interest in this study was the pressure loss (ΔP) across the Vortex Tube Separator. For each case, ΔP was calculated as the difference between the farfield total pressure and outlet total pressure of the center tube.

$$\Delta P = P_{t_{\infty}} - P_{t_{exit}} \quad (3.6)$$

To express the result in a non dimensional form and account for variation in freestream conditions, the pressure was also normalized by the farfield total pressure:

$$\Delta P_{\%} = \frac{P_{t_{\infty}} - P_{t_{exit}}}{P_{t_{\infty}}} \quad (3.7)$$

This ratio facilitated a consistent comparison of pressure loss performance across the full range of configurations.

3.4.2. Theoretical Calculation of Pressure Loss

To validate simulation results, pressure loss through a duct is calculated with theoretical formulations. The pressure loss induced by a VTS can be split into two categories: friction losses and dynamic pressure losses. Darcy-Weisbach relationship is utilized for friction loss through a duct [19]:

$$\Delta P_f = f \cdot \frac{\rho L V^2}{2 D_h} \quad (3.8)$$

where f is the friction factor, L is the length of tube and D is the diameter of the tube. The f can be computed in variety of ways but The Blasius and MacAdams Correlations are used to determine the Darcy Weisbach friction factor for turbulent flow in smooth pipes [20]. Both are simple and widely used formula which correlates f to Re .

$$f = 0.3164 \cdot Re^{-0.25}, Re < 30000 \quad (3.9)$$

$$f = 0.184.Re^{-0.2}, Re > 30000 \quad (3.10)$$

On the other hand, dynamic pressure loss due to orientation of the flow was incorporated using the z-component of the velocity. The angle induced loss parameter was derived as:

$$\Delta P_{angle} = 0.5\rho V_z^2 \quad (3.11)$$

Thus, the total pressure loss through a VTS will be the sum of the above 2 components:

$$\Delta P_{total} = \Delta P_{angle} + \Delta P_f \quad (3.12)$$

Pressure loss calculated with theoretical formulas were discussed in Results section.

3.4.3. Dataset Construction

For each simulation scenario, the following key variables were extracted and compiled into a structured dataset:

- Number of tubes in the panel: represents VTS panel configurations.
- Natural logarithm of Reynolds number: represents outside air conditions such as altitude, air temperature and flight velocity.
- Pressure loss due to orientation: represents the flow orientation.
- Pressure loss of simulations.

3.5. Regression-Based Modeling

In order to predict the pressure loss behavior of Vortex Tube Separator (VTS) panels without the need for costly and time consuming CFD simulations for every new configuration, a regression based modeling approach was implemented using Python and the Scikit learn library. The primary aim of this model was to generalize the relationship between pressure loss and key flow parameters such as Reynolds number, inflow angle, and panel configuration. This way enables the accurate estimation across a broad range of operating conditions and panel geometries.

The dataset used to train the regression model was built from CFD simulations of VTS panels with different sizes (1×1, 3×3, 5×5) under 36 flight scenarios each. The key input variables were selected as: the number of rows of vortex tubes in the panel (x_1), the logarithmic Reynolds number (x_2), and a velocity based term representing dynamic pressure loss due to inflow angle (x_3). The target variable was the normalized pressure loss extracted from CFD results.

The model is expressed as a non linear regression formulation consisting of all polynomial combinations and interactions terms among the input variables. In general, the model solves the given Equation 3.13:

$$\Delta P_{total} = \sum_1^n a_S \cdot \prod_{i \in S} x_i \quad (3.13)$$

Here S denotes the all subsets of the input feature indices and each a_S is a regression coefficient that is determined through the training process. These coefficients represent the contribution of each individual variable and their contributions to the predicted pressure loss. In essence, the learning algorithm adjusts the a_S values to minimize the difference between the predicted and actual pressure loss values in the training data. For example, if $n=3$, the expanded version of the Equation 3.13 becomes:

$$\begin{aligned} \Delta P = & a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + a_{12} \cdot x_1 \cdot x_2 + a_{13} \cdot x_1 \cdot x_3 + \\ & a_{23} \cdot x_2 \cdot x_3 + a_{123} \cdot x_1 \cdot x_2 \cdot x_3 \end{aligned} \quad (3.14)$$

This formulation enables to model to capture non linear dependencies and higher order interactions among the variables. The coefficients $a_0, a_1, a_2, \dots, a_{123}$ are automatically calculated by regression algorithm based on the training dataset.

The model was implemented in Python using the Linear Regression function from the Scikit learn library. Despite its name, Linear Regression is capable of solving non linear problems where the input features are expanded to include polynomial terms as in Equation 15. This function with CFD data allowed the training of regression model that reliably estimates the pressure loss across various VTS configurations and flight scenarios.

To evaluate the model's accuracy, the coefficient of determination (R^2) was used. This parameter indicates the proportion of the variance in the dependent variable. R^2 close to 1 implies a strong fit between the predicted and actual pressure loss values, which are simulation values in this study.

3.6. Extrapolation Capability

Developed regression model is tested outside of its training dataset to evaluate the extrapolation capability. This test was conducted using CFD simulation results from 9x9 VTS panel configuration. Since it consists of 81 tubes, it represents more realistic inlet protection system scale used in rotorcraft applications, relatively.

In each case, the pressure loss prediction from the regression model was compared with the actual CFD computed pressure loss for the center tube of the 9x9 configuration.

This study showed the extrapolation ability of regression model which is trained only on center tube data from smaller panels.

4. RESULTS AND DISCUSSION

This chapter shows the results of CFD simulations, theoretical calculations and regression based modelling explained in the previous sections. A step by step approach was used. Firstly, simulation results are checked if they are physically consistent. Then, data driven model is checked to see how well it can predict the pressure losses. The chapter starts with CFD results for panel configurations. It shows how pressure loss changes under different flight conditions. Next, the theoretical results are compared with CFD data. This helps to confirm that the model gives reasonable and accurate predictions. Lastly, the regression model is tested. The model's accuracy and how well it fits the data are checked. Extrapolation and generalization tests are conducted to assess how well the model performs under configurations and flow conditions that are not seen during training. Each section includes quantitative figures to interpreting the results and trends.

4.1. Baseline CFD Results and Pressure Loss Trends

The baseline CFD simulations were performed for three different VTS panel configurations consisting of 1, 9, and 25 vortex tubes. Each configuration was evaluated under a range of operating conditions by varying the freestream velocity (V_∞) from 20 to 175 knots and the angle of attack (α) from 0° to 75° . The resulting pressure loss values (ΔP) as a percentage of upstream total pressure, are plotted in **Figure 4.1** to **4.3**.

As illustrated in **Figure 4.1**, the 1×1 VTS configuration exhibits a clear nonlinear increase in pressure loss with increasing velocity. The effect of the angle of attack becomes more pronounced as α increases beyond 30° , especially at higher velocities. For example, at 175 knots and $\alpha = 75^\circ$, the pressure loss reaches approximately 2.2%, while it remains below 0.2% at $\alpha = 0^\circ$. This behavior is encountered, because, at higher angles, the air hits the tube more directly. As a result, the dynamic pressure increases in the direction of the tube's surface. This leads to more pressure loss due to the tube blocking the airflow.

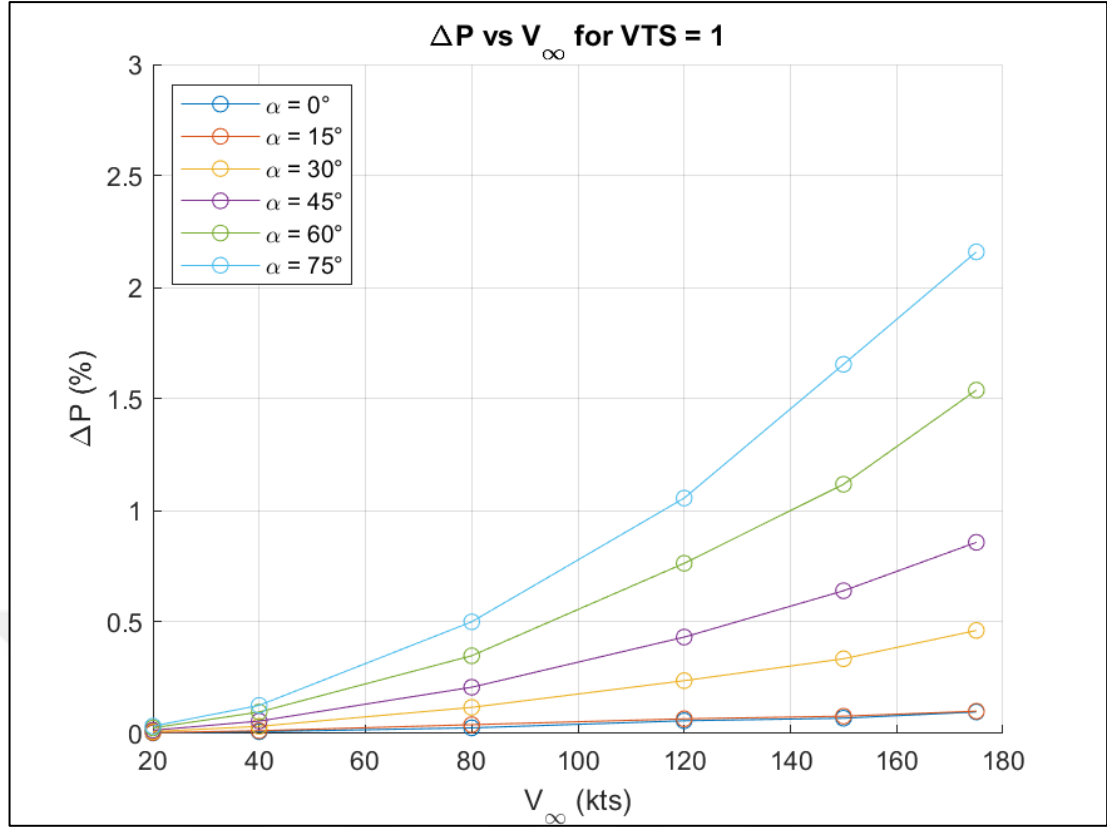


Figure 4.1: Variation of ΔP with V_∞ for different angles of attack, $VTS = 1$.

The 3×3 VTS panel configuration, shown in **Figure 4.2**, demonstrates a similar trend but with moderately higher ΔP values across all angles and velocities. The increase in pressure loss as the number of VTS tubes increases is caused by aerodynamic interference between the tubes and narrower flow paths. This creates stronger recirculation and stagnation zones inside the panel, especially at higher angles of attack.

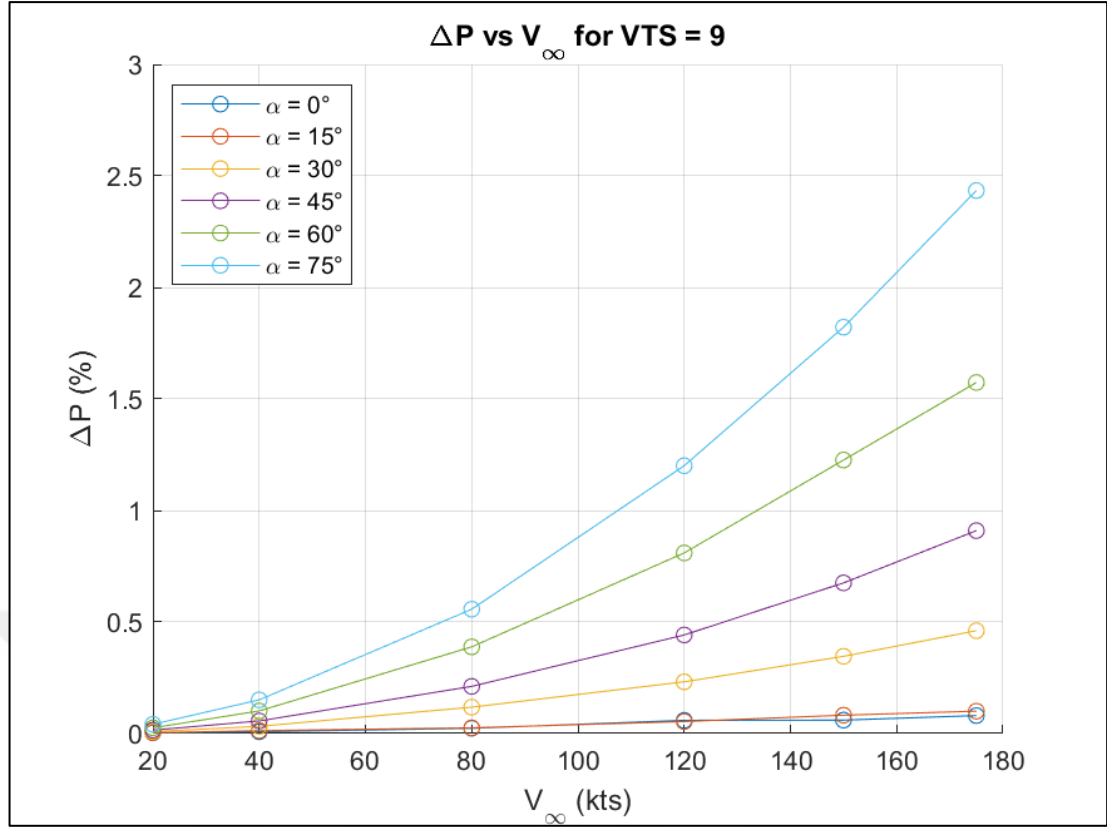


Figure 4.2: Variation of ΔP with V_{∞} for different angles of attack, $VTS = 9$.

In the case of the 5×5 panel (**Figure 4.3**), the ΔP values further escalate, with pressure loss exceeding 2.6% at $\alpha = 75^\circ$ and $V_{\infty} = 175$ knots. The pressure loss profile becomes steeper as the vortex tube density increase, supporting the hypothesis that pressure loss is strongly dependent on VTS array size in addition to flight conditions. The magnitude and growth rate of ΔP with α and V_{∞} indicate that the momentum loss and inlet flow distortion become more severe in larger panels.

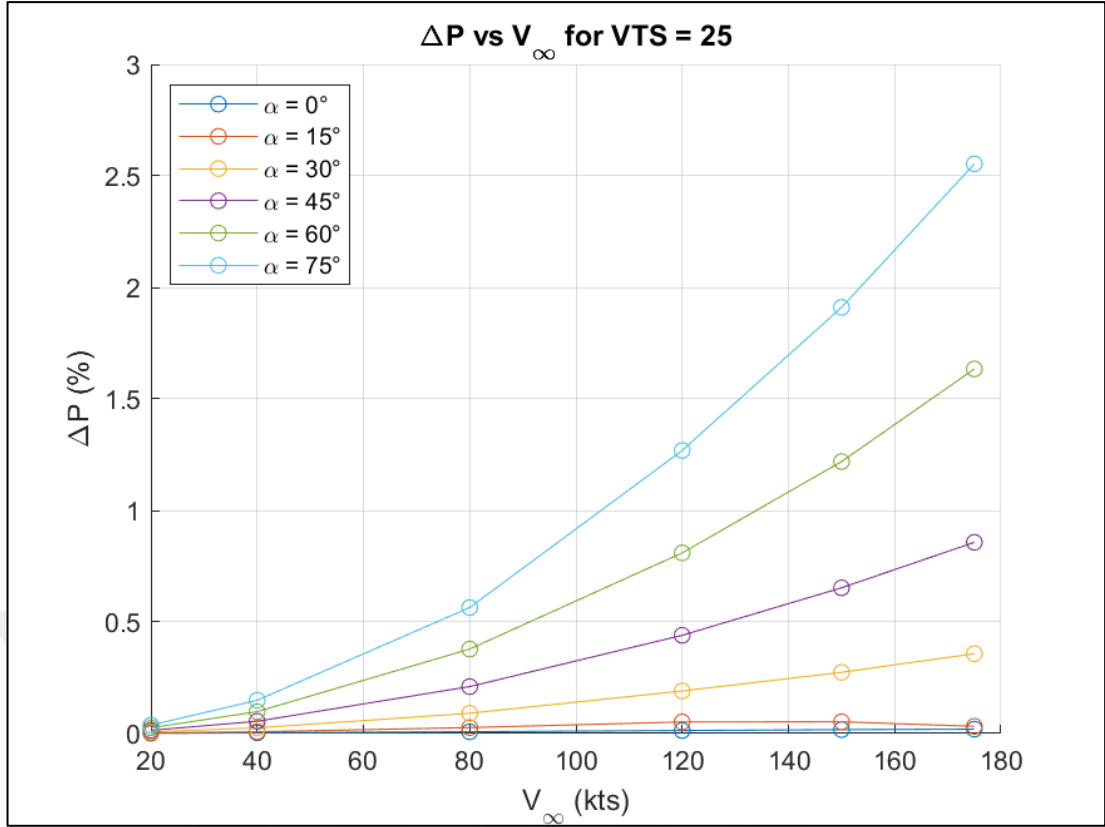


Figure 4.3: Variation of ΔP with V_∞ for different angles of attack, $VTS = 25$.

By keeping the vertical axis range constant across all three figures (0 to 3%), visual comparison becomes more meaningful and reveals a systematic increase in pressure penalty with increased number of tubes in the panel. These observations highlight the importance of capturing nonlinear effects arising from flow incidence and panel geometry. They form the basis for the development of the regression based pressure loss model discussed in the next sections.

4.2. Comparison with Theoretical Pressure Loss Estimation

In this section, the results of the analytical model developed based on idealized pressure loss mechanisms are compared with those obtained with CFD simulations. The aim is to assess the capability of the proposed model to replicate the physical behavior of pressure drop across VTS configurations under varying flight conditions. The analysis considers both the relative pressure loss ratios as well as the absolute contributions of friction and inflow angle.

The theoretical model's components, wall shear related loss and dynamic pressure losses due to the orientation of the flow is analyzed to understand their contributions. These contributions are visualized separately in **Figure 4.4** to **Figure 4.6**.

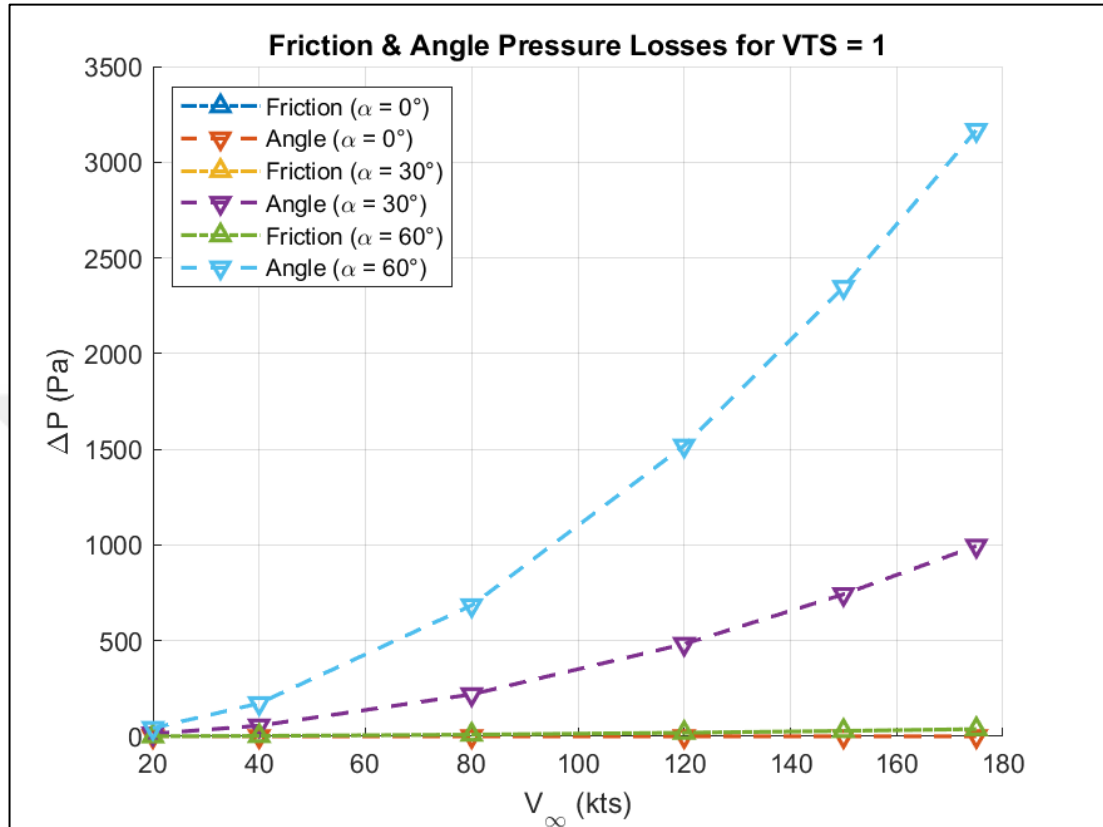


Figure 4.4: Friction and angle-based pressure losses for VTS=1.

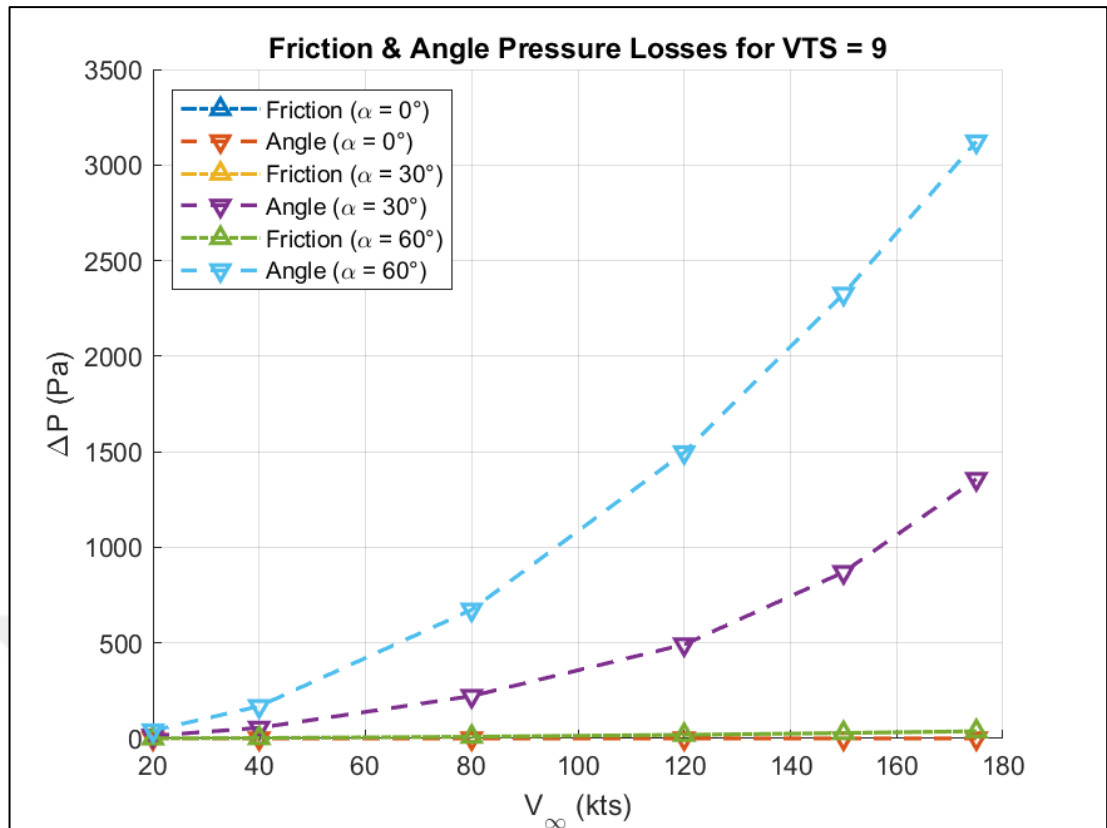


Figure 4.5: Friction and angle-based pressure losses for VTS=9.

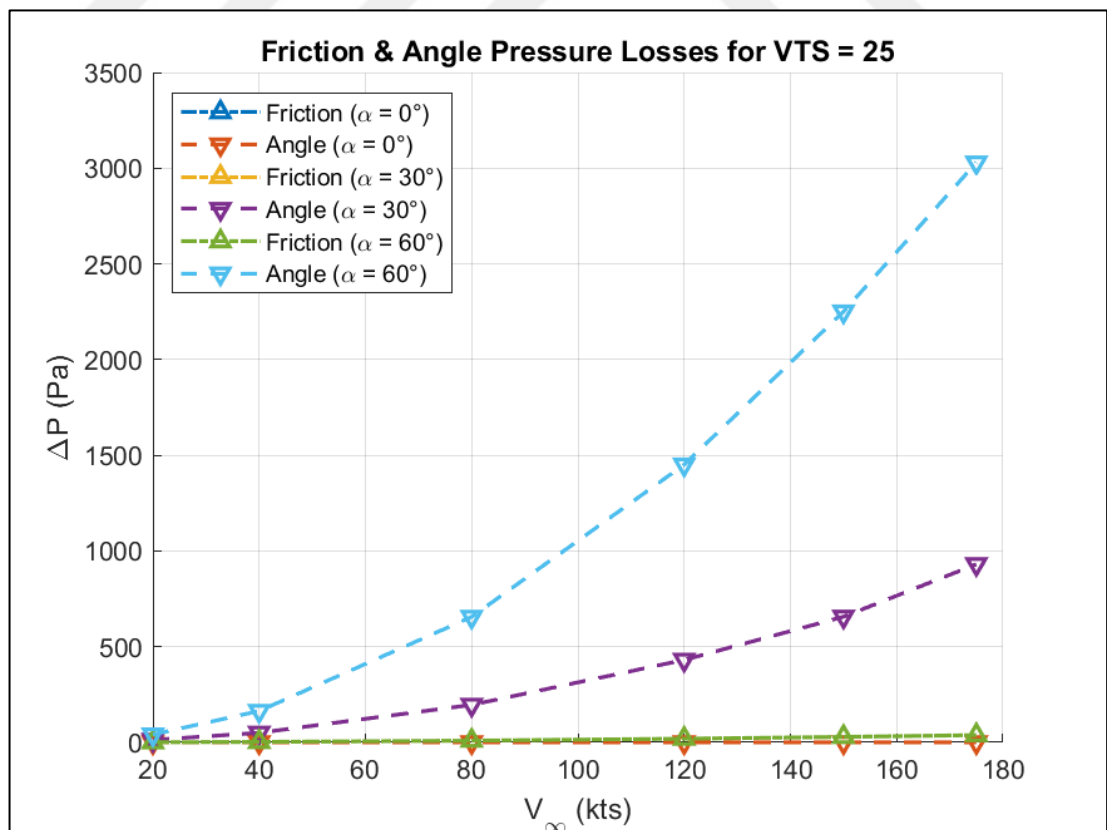


Figure 4.6: Friction and angle-based pressure losses for VTS=25.

- Across all VTS configurations, it is evident that losses due to orientation of the flow dominates the total pressure loss, especially at higher velocities and inflow angles. At $\alpha = 60^\circ$ and $V_\infty = 175$ kts, the angular contribution exceeds 3000 Pa in all three cases.
- On the other hand, friction losses remains relatively constant across different velocities and angles, indicating that wall friction plays a minor role in the overall pressure loss. This aligns with expectations for high Reynolds number internal flows where pressure drop is more sensitive to flow deflection than to viscous effects.
- As shown in **Figure 4.4** (VTS=1), **Figure 4.5** (VTS=9), and **Figure 4.6** (VTS=25), the angular pressure loss contribution increases sharply with both velocity and angle, reaffirming that flow misalignment is the primary driver of performance loss in VTS systems.

The decomposition of the total loss into frictional and angular components not only validates the physics based assumptions in the theoretical model but also offers a clear interpretation of how inlet conditions affect performance.

To validate simulation results with theoretical calculation results, **Figure 4.7** to **Figure 4.9** are shown. Several flight condition's results are selected to prevent image confusion.

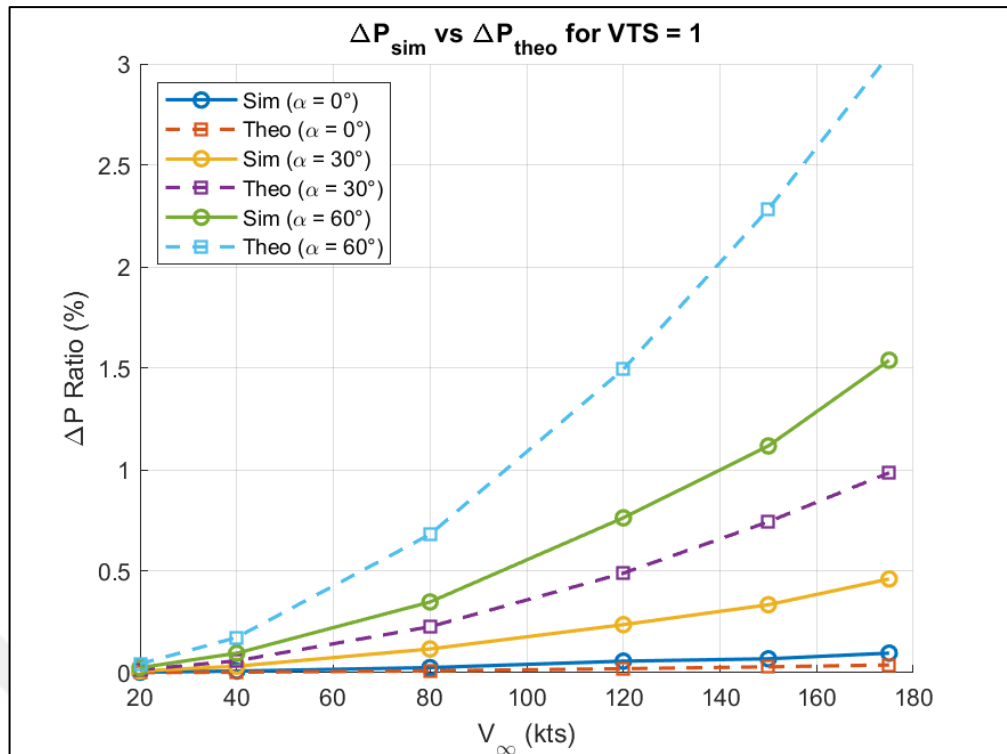


Figure 4.7: Comparison of simulation pressure loss and theoretical pressure loss for VTS=1.

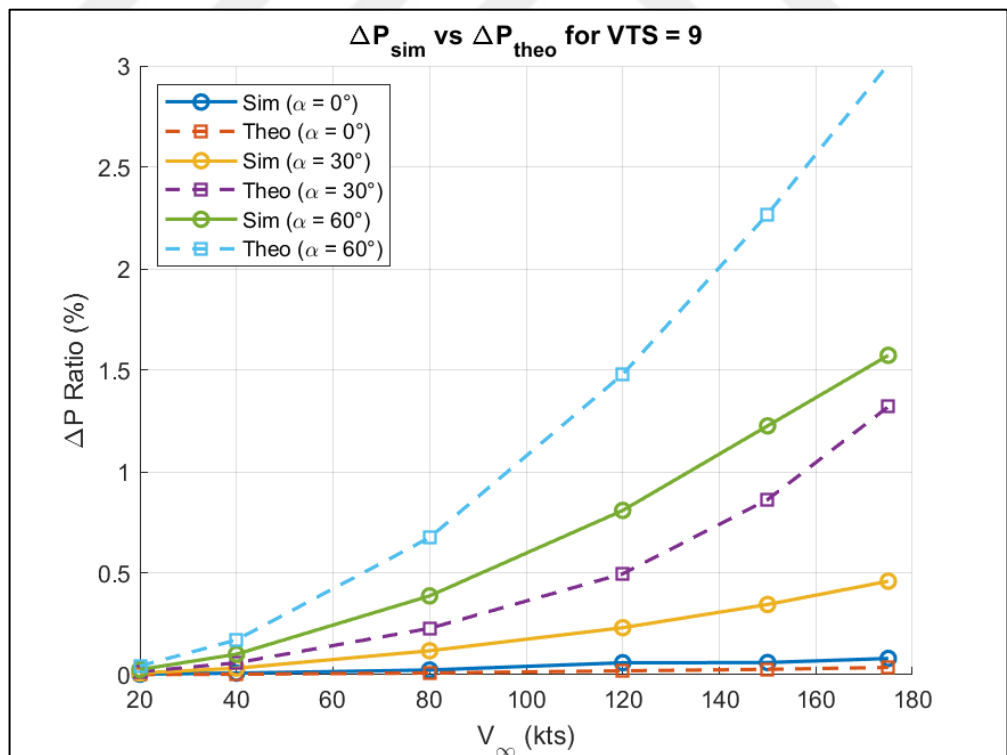


Figure 4.8: Comparison of simulation pressure loss and theoretical pressure loss for VTS=9.

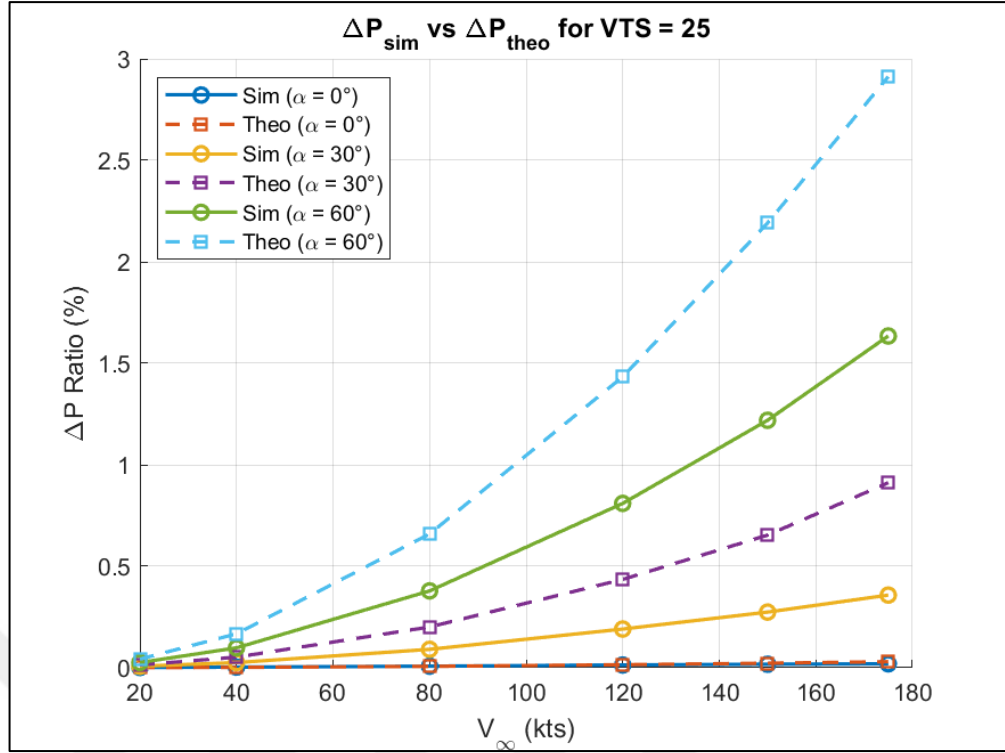


Figure 4.9: Comparison of simulation pressure loss and theoretical pressure loss for VTS=25.

- In all three cases, both simulated and theoretical pressure losses increase monotonically with velocity, as expected due to the increased dynamic pressure.
- The theoretical model estimates consistently overpredict the pressure losses compared to simulation results. This discrepancy becomes more pronounced at higher angles of attack (especially $\alpha = 60^\circ$), as seen in **Figure 4.7** (VTS=1), **Figure 4.8** (VTS=9), and **Figure 4.9** (VTS=25).
- The agreement between simulation and theoretical estimates is reasonably good for $\alpha = 0^\circ$, indicating that the model captures axial flow behavior well. However, at skewed angles, simplifications in the theoretical formulation lead to higher deviations, potentially due to complex secondary flows or interaction effects not captured analytically.

Although there are clear differences between the theoretical and simulated pressure loss, the largest error in the relative pressure loss is around 1.5%. This level of error is acceptable for engineering applications, especially considering the complex internal turbulence and non uniform inlet conditions. The regression based model still captures the overall trend correctly. It adjust well with increasing velocity and VTS count and

gives numerically close results. This shows that the model performs reliably across the range of tested flight conditions.

Furthermore, the decomposition of the pressure loss into frictional and angular components confirms the physical assumptions behind the model formulation.

Overall, these results confirm that the proposed regression model is a useful and efficient alternative to full scale CFD simulations. It offers a good balance between accuracy and low computational cost, making it suitable for preliminary design evaluations and system level performance analysis.

4.3. Regression Model

In this section, a regression based pressure loss prediction model for VTS configurations is developed and evaluated. The aim is to predict the pressure drop caused by different numbers of tubes under varying freestream velocities and angles of attack without relying on computationally expensive CFD simulations.

The model is based on multiple linear regression with polynomial interaction terms. The input dataset contains:

- x_1 : Number of rows of vortex tubes (VTS),
- x_2 : logarithm of the Reynolds number,
- x_3 : Dynamic pressure component due to inflow angle.

To improve model flexibility, all first order, second order, and third order interactions were included but after checking coefficients, extremely small coefficients were erased from the equation. The fitted model takes the following form:

$$\Delta P_{total} = -0.0184 + 0.1 \times x_1 + 0.0201 \times x_2 + 0.001 \times x_3 - 0.0098 \times x_1 x_2 + 0.0002 \times x_1 x_3 \quad (4.1)$$

The model performance is shown in **Figure 4.10**, which plots predicted pressure loss values against the corresponding simulation derived pressure loss values. The coefficient of determination $R^2=0.9835$ confirms a high degree of correlation, meaning that the model explains over 98% of the variance in the dataset.

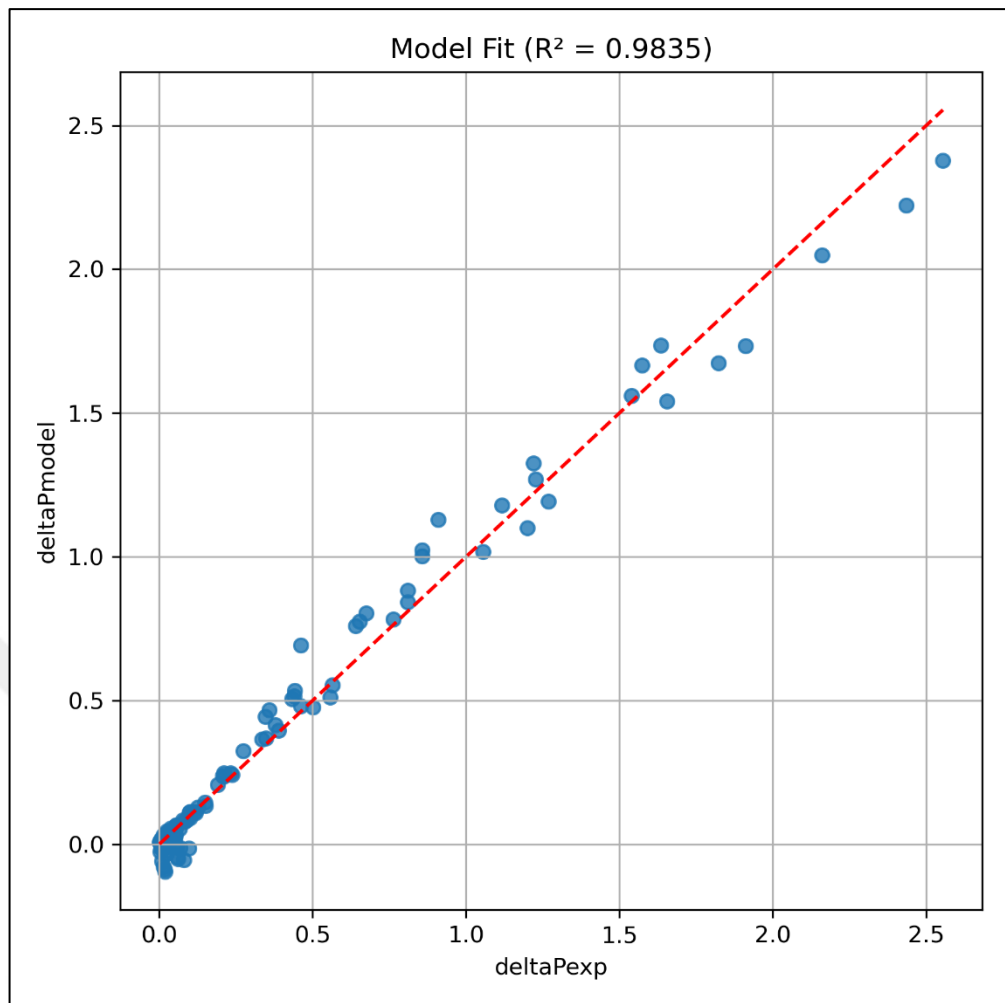


Figure 4.10: Model prediction vs simulation results.

5. CONCLUSION

This study has focused on developing a regression based model to predict pressure loss in VTS systems used in helicopter engine inlets. Because full scale CFD simulations of VTS arrays are highly complex and computationally expensive. CFD simulations were performed on smaller panels (1x1, 3x3, and 5x5 tube arrays). The resulting data were used to build a data driven regression model which is capable of estimating the pressure drop due to VTS implementation across various freestream velocities and flow angles.

The proposed regression model demonstrated excellent performance within the training range. As discussed in Chapter 4.3, the coefficient of determination (R^2) was found to be 0.9835, indicating that the model could explain over 98% of the variance in the pressure loss across the baseline configurations. The model's ability to interpolate was further validated in Chapter 4.2, where predicted trends for pressure loss closely matched those derived from theoretical estimations of friction and angle induced losses. This strong agreement reinforced the credibility of the regression formulation and its physical consistency.

However, the model's ability to extrapolate, particularly for larger tube arrays like the 9x9 VTS panel was found to be limited. As shown in **Appendix A**, the predicted pressure losses significantly underestimated the actual simulation values for the 9x9 case. The model exhibited saturation behavior, meaning it could not capture non linear effects like flow interactions and increased pressure resistance in densely packed arrays. This outcome emphasizes the need for caution when using linear models outside their training range.

Nevertheless, the regression model proves to be fast and reliable tool for early stage VTS performance estimation within the tested range of configurations and flow conditions. It provides a practical alternative to full CFD analysis when time or computational resources are limited.

Several potential directions for future research are recommended:

1. Non linear and hybrid modeling: Incorporating non linear regression techniques or machine learning methods [20] (e.g., support vector regression, neural networks) to better capture the complex interactions in large VTS arrays.
2. Incorporating spatial non uniformity: Developing a correction framework that accounts for non uniform inlet flow distributions, particularly for curved surfaces or off axis mounting.
3. Experimental validation: Conducting wind tunnel experiments or field tests to validate the model under real operating conditions.
4. Full scale VTS model: Conducting simulations with full configurations of VTS system.

By following these directions, future research can improve the reliability and practical use of VTS modeling methods. This will help achieve more accurate and efficient integration of VTS systems into helicopter engine inlets.

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BIOGRAPHY

Ayberk KARACELİK is a 3 year experienced Aerospace Engineer. He received his B.Sc. degree in Aerospace Engineering from Middle East Technical University in 2022. In the same year, he was admitted to the specialized Industrial Partnership M.Sc.program at Gebze Technical University.

His academic interests include computational fluid dynamics (CFD), helicopter engine inlet protection systems, and gas turbine performance modeling. During his graduate studies, he focused on developing predictive models for vortex tube separators (VTS) using simulation data and machine learning techniques.



PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Karaçelik A., Akşit M., (2025), “Theoretical Data Driven Vortex Tube Separator Performance Predictor Model”, Proceedings of the 11th International Azerbaijan Congress on Life, Engineering, Mathematical, and Applied Sciences, Baku, Azerbaijan, pp.41.



APPENDICES

APPENDIX -A: MODEL PREDICTION OUTSIDE OF TRAINING DATABASE

