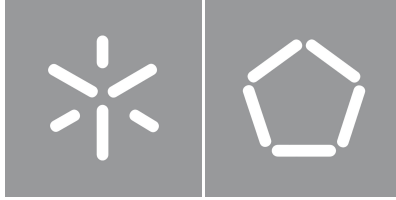


University of Minho
School of Engineering

Leonardo Beckhauser Mazzitelli

Small Aircraft Fuel System Model Analysis



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Leonardo Beckhauser Mazzitelli

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Master's Dissertation
Master's degree in Mechanical Engineering
Area of Specialization in Mechatronic Systems

Dissertation supervised by
Professor Doctor José Mendes Machado
Professor Doctor José Carlos Teixeira

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Statement of Integrity

I hereby declare having conducted this academic work with integrity.

I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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University of Minho, Braga, october 2023

Leonardo Beckhauser Mazzitelli

Abstract

An aircraft's fuel system can be understood as a set of components that act together to store, manage, and deliver fuel to the engines. In this context, the model of such a system tries to represent its behavior through mathematical equations that describe pumps, valves, and tanks and their dynamic interaction, thereby creating a means for performing comprehensive studies. With the model, systems engineers can evaluate the aircraft fuel system architecture and performance from conceptual to more detailed design phases. This master's thesis focuses on developing a generic twin-engine aircraft fuel system model using MATLAB/Simulink software, which later is used to perform simulations on the system's behavior under various scenarios and extract valuable insights about its fluid mechanical behavior.

Aircraft fuel system modeling requires knowledge about the system's characteristics, functions, and components. In this work, the system is treated as a fluid-mechanical circuit. Hence, the theoretical introduction presented here connects fundamental concepts of aircraft fuel systems with fluid-mechanical systems modeling, which were the two core areas of this thesis. In addition, brief considerations are given on CS-23, which is the set of regulations to which the aircraft category discussed here is subject.

Much of this work was dedicated to building, simulating the model, and choosing the most suitable software. Throughout the thesis, discussions about modeling include the development stages, modeling techniques, and the choice of MATLAB/Simulink over other tools. With the built model, various simulations were performed, demonstrating its capabilities and limitations and providing a reference for aircraft fuel system design. Some results verified the high influence of the nozzle area and pipe lengths on the scavenge jet pump's flow ratio and the dihedral angle's influence on minimizing unusable fuel quantities. In addition, studies were performed on the refueling case, where the pressure surge phenomenon and flow imbalance are analyzed, and finally, the crossfeed valve impact during an engine failure scenario is studied.

Keywords Aircraft fuel system, System modeling, MATLAB/Simulink

Resumo

Um sistema de combustível de uma aeronave pode ser entendido como um grupo de componentes que atuam em conjunto para armazenar, gerir e fornecer combustível aos motores. Nesse contexto, o modelo de tal sistema tenta representar seu comportamento por equações matemáticas que descrevem bombas, válvulas, tanques, e sua interação dinâmica, assim criando meios para realizar estudos abrangentes. Com o modelo, engenheiros de sistemas podem avaliar a arquitetura e desempenho do sistema desde fases conceptuais até as mais detalhadas de um projeto. Essa tese de mestrado foca no desenvolvimento de um modelo genérico de um sistema de combustível de uma aeronave bimotora utilizando o software MATLAB/Simulink, que mais tarde é usado para simular o sistema em diversos cenários e extrair noções valiosas sobre o seu comportamento fluido-mecânico.

A modelação de um sistema de combustível de uma aeronave requer o conhecimento de suas características, funções e componentes. Neste trabalho, o sistema é tratado como um circuito fluido-mecânico, pelo que a introdução teórica deste trabalho conecta conceitos fundamentais do sistema de combustível de aeronaves com a modelação de sistemas fluido-mecânicos, que foram as duas áreas centrais desta tese. Adicionalmente, são apresentadas breves considerações sobre a CS-23, que é o conjunto de regulações as quais a categoria de aeronave aqui discutida está sujeita.

Grande parte deste trabalho dedicou-se à construção, simulação do modelo e à escolha do software adequado. Ao longo da tese é discutido o desenvolvimento do modelo, técnicas de modelação e a escolha do MATLAB/Simulink em detrimento de outras ferramentas. Com o modelo, várias simulações foram feitas, demonstrando suas capacidades e limitações e fornecendo uma referência para projetos de sistema de combustível. Alguns resultados verificam a grande influência da área do bico e comprimento das tubagens no rácio de caudais produzido pela bomba injetora e o impacto significativo que o diedro positivo tem na diminuição do combustível inutilizável. Adicionalmente são feitos estudos sobre o reabastecimento, incluindo análises de picos de pressão, desequilíbrio de caudais e por final estuda-se o impacto da válvula de cruzamento num cenário de falha dum motor.

Palavras-chave Sistema de combustível de aeronave, Modelação de sistemas, MATLAB/Simulink

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List of Symbols

Greek Symbols

Symbol	Description	Unit
Γ	Wing dihedral angle	°
ΔP	Pressure differential	Pa
ΔP_L	Pressure loss due to friction	Pa
η	Efficiency	—
ρ	Fluid density	kg m^{-3}
ω	Shaft angular velocity	rad s^{-1}

Roman Symbols

Symbol	Description	Unit
A	Cross-sectional area	m^2
C	Hydraulic capacitance	$\text{m}^3 \text{Pa}^{-1}$
C_o	Orifice coefficient	-
C_D	Drag Coefficient	-
C_L	Lift Coefficient	-
C_{te}	Constant	-
D	Diameter	m

D	Drag force	N
H	Height, head or a vertical distance	m
I	Hydraulic Inertance	$\text{Pa s}^2 \text{m}^{-3}$
L	Level or length	m
L	Lift force	N
M	Flow ratio	-
N	Pressure ratio	-
P	Pressure	Pa
P_0	Atmospheric pressure	Pa
P_h	Hydrostatic pressure	Pa
Q	Volumetric flow rate	$\text{m}^3 \text{s}^{-1}$
R	Hydraulic resistance	Pa s m^{-3}
S	Surface Area	m^2
T	Thrust force	N
U	Fluid velocity	m s^{-1}
V	Volume	m^3
W	Weight	N
Z	Distance from a reference in the vertical axis	-
b	Height, head or a vertical distance	m
b	Wingspan	m
c	Chord Line length	m
e	Pipe elevation	m
g	Gravitational acceleration	m s^{-2}

m	Mass	kg
p	Pressure	Pa
r_1	Nozzle-to-throat ratio	-
r_2	Diffuser inlet-to-outlet ratio	-
t	Time	s
$\dot{m}$	Mass flow rate	kg s^{-1}
$\vec{x}$	Airplane longitudinal axis	-
$\vec{y}$	Airplane lateral axis	-
$\vec{z}$	Airplane vertical axis	-

Chapter 1

Introduction

Due to aircraft systems' increasing complexity and reliability, it has become almost mandatory for any project to have computational tools to test the systems in a low-cost setup and ensure financial success. In this context, computational tools are software capable of modeling and simulating 1, 2, or 3D models of engineering physical systems such as fluid, electrical, and hydraulic networks. The aircraft fuel system is much more complex and essential than the general public would at first realize, especially in the case of large transport twin-engine aircraft [1]. Even for smaller airplanes, modeling such a system can be precious since simulations provide a low-cost way of testing different configurations and scenarios. Some common problems that models and simulations highly support include system requirements validation, fluid network design, and analysis, including pump location optimization, verification of refuel times, and sizing of the worst-case vent system (in case of emergency descent).

1.1 Motivation

Aircraft fuel systems are a critical part of an aircraft since they are responsible for storing, managing, and providing the fuel flow at the correct rate and pressure to ensure proper engine operation. Besides its vital role, modern aircraft fuel systems may include advanced features for the system's thermal and health management, unusable fuel control, fuel gauging, and others. One big motivation for the modeling and analysis of such a system comes first from the complexity of the aircraft systems and the costs avoided by ensuring most of the errors are corrected in an early phase of the aircraft design. A significant motivation for developing a fuel system dynamic model is the ability to simulate test cases within minutes or seconds instead of making a real case test of an aircraft mission, which could take hours [2]. Additionally, the simulations are an easy way of testing different system configurations and scenarios. Various configurations can be achieved by varying the number and location of tanks and pumps, the wing dihedral angle, and the valve pressure drop coefficient. These variations in the system are not only studied to improve the perfor-

mance of the system itself but also to bring advantages in other areas, such as aircraft mass and balance, avionics, and structural strength. Some examples of simulation scenarios can be the ground refueling process, engine feed function, and the occurrence of an engine failure or valve malfunction. These scenarios can be switched in every simulation setup, and the necessary boundary conditions and parametrization are set automatically. Another reason for using models that can accurately represent a physical system is that the results extracted from the simulations can be used as support for design decision-making and certification processes. Moreover, the system model gives the user the ability to monitor the system's behavior in detail, having access to individual components if needed, which otherwise, in an actual physical inspection, would not be as straightforward.

1.2 Basic notes about airplanes

Since this work deals with airplane's specific terms and fundamental concepts, it is essential to introduce some basic concepts about airplanes, which later will help interpret the fuel system characteristics and functions. To begin, a reference frame must be specified, and this is the airplane's body axis system, which is a reference frame attached to the body of the airplane (Figure 1).

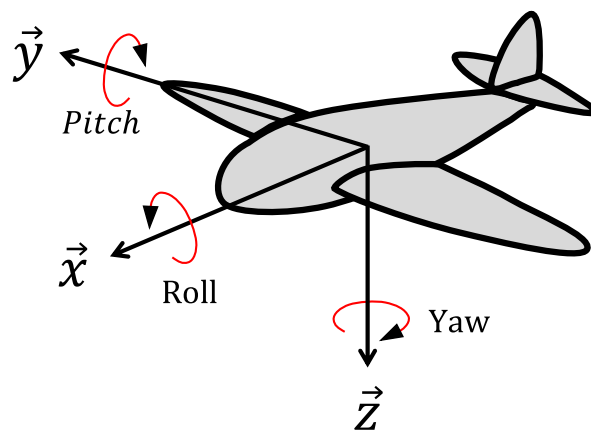


Figure 1: Airplane body axis system.

The airplane's principle relies on Newton's second law of motion: The engine accelerates the air backward, accelerating the airplane forward as a reaction called the thrust force. The acceleration gives the airplane the necessary speed to generate lift, which is the upward force that makes the airplane fly. The primary forces acting on the airplane's body can be shown in the schematic from figure 2.

The vectors L , W , T , and D are the lift, weight, thrust, and drag forces, respectively. The drag is the force caused by friction due to the air resistance to the airplane motion. The lift and drag forces can be calculated through equations 1 and 2:

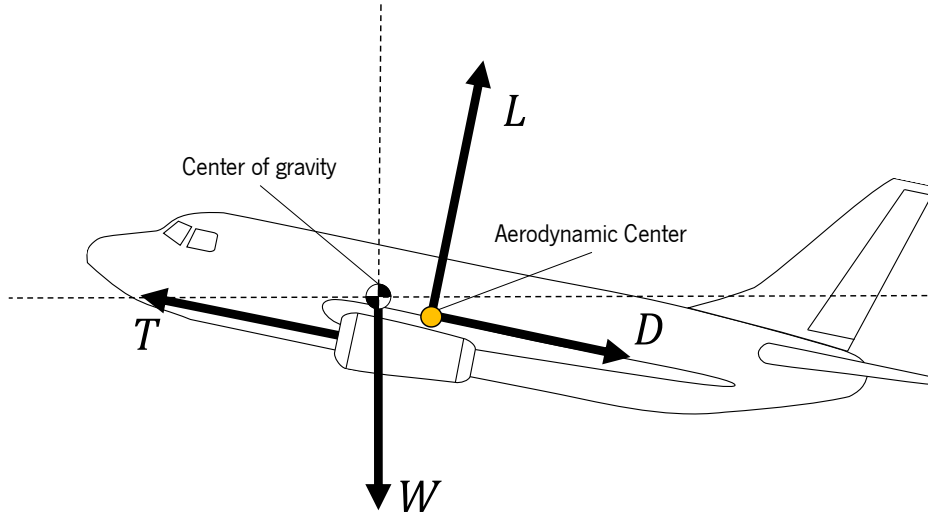


Figure 2: Main forces applied to the airplane body during flight.

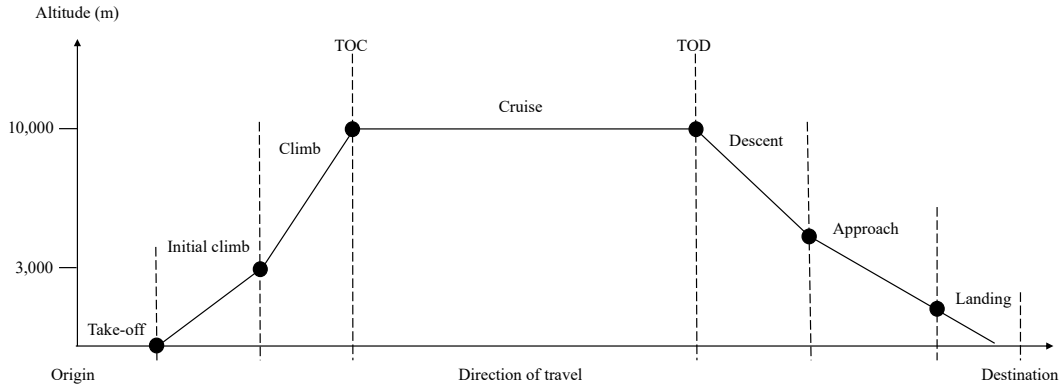


Figure 3: Flight Phases vs altitude graph.

$$L = \frac{1}{2} C_L \rho U^2 S \quad (1)$$

$$D = \frac{1}{2} C_D \rho U^2 S \quad (2)$$

Both lift and drag forces increase proportionally to the square of the airplane's velocity U^2 , so the price to pay for generating a lot of lift is to deal with the significant dissipating drag component. The most critical phase for the airplane's engines is the take-off, when the aircraft accelerates until it reaches the required speed for the lift force to overcome its weight. The typical flight phases are shown in Figure 3, which indicates that commercial airplanes reach altitudes up to 11,500 meters, where the outside pressure is about 0.2 atm [3]. This brings a lot of operational constraints, mainly because of fuel volatility, which is a critical fuel characteristic to be discussed in chapter two.

For the airplane to take off and climb, it needs a lot of acceleration, so these two phases of flight are the most fuel-demanding, while cruise, descent, approach, and landing consume less fuel. This will be important for modeling and simulating the fuel system behavior over time and defining the maximum flow rate output for pumps.

1.3 Historical background

The evolution of aircraft fuel systems has been a significant aspect of aviation history, spanning over a century from the Wright Flyer to modern aircraft. At the beginning of the 20th century, the first airplanes, like the Wright Flyer and 14-Bis, used a simple fuel system that relied on gravity to deliver fuel to the engine [4]. Over time, airplane engines became more advanced and reliable, and fuel systems evolved to keep up. During World War II, fuel systems became even more sophisticated, with features like multiple fuel and self-sealing tanks to keep planes safe from enemy fire. As jet engines were introduced in the 1950s, fuel systems became even more complex to accommodate their needs. Today, airplanes are continually evolving to become more fuel-efficient, with materials, aerodynamics, and engine technology advancements. In recent years, the aviation industry has been working on developing alternative fuels to reduce its carbon footprint and become more sustainable. Airplane engines can be powered by various energy sources, which include fossil fuels, electrical batteries, or hydrogen. Recently, the popularity of electrical batteries and hydrogen has dramatically increased since many aviation-related companies are prioritizing sustainability. However, despite the increasing popularity of electrical batteries, their implementation is hindered by their low specific energy. On the other hand, hydrogen has a very high specific energy, but its storage is limited as it needs to be stored at extremely high pressures. Fossil fuels are still favored as an energy source for thrust generation since they have advantages over the newest technologies, and therefore, aircraft fuel systems still have room for development. Although this thesis focuses on fuel, it is essential to stress that electrical batteries and hydrogen are promising alternatives to fossil fuels, and their exploration is necessary to accelerate sustainability achievements. Today's aircraft fuel systems include modern features such as automatic control of the center of gravity through fuel management, accurate fuel properties sensing, fuel leak detection and prevention, thermal management, fire suppression systems, and in-flight refueling (air refueling). The next generation of fuel system designs is expected to improve sustainability to some degree. Therefore, research on fuel system technologies must be encouraged to shorten the way to a greener world.

1.4 Thesis objectives

This master's thesis was developed alongside the Portuguese aerospace company CEiiA (Center of Engineering and Product Development), which established some goals for the conceptual phase of the aircraft design, one of them being the development of a fuel system model. The fuel system model aims to represent the behavior of a generic fuel system of a small aircraft under CS-23 regulations and simulate the system to analyze flow rate, pressure, and tank level variation under different conditions and flight scenarios. To reach this objective, intermediate goals were defined and accomplished, such as:

- Having a deep understanding of typical aircraft fuel system characteristics and main components;
- Understanding the physics behind the components and their interaction within the system;
- Conduct a literature review to find common system modeling practices and the best-suited computational tool;
- Studying physical system modeling, understanding software solver methods and capabilities;
- developing a flexible and adaptable fuel system model with system parametrization.

The end goal of this thesis was to perform simulations with the model created t the model's capabilities and provide relevant insights into fuel system modeling literature.

1.5 Reading Guide

The structure of this master's thesis is divided into six chapters, which are briefly explained here for organization purposes.

Chapter 1 introduces the airplane fuel system, highlights the reasons for aircraft fuel system modeling, and later introduces the reader to some important facts about airplanes. Chapter 2 covers the fundamental knowledge of aircraft fuel systems with a brief discussion about the aviation regulatory authorities and fuel properties. Chapter 3 is also part of the literature review, where concepts about dynamic system modeling are discussed and how this modeling theory can be applied in fluid-mechanical circuits, such as the fuel system, and at the end shows the mathematical modeling of some of the essential components of the fuel system. Chapter 4 starts with the software selection process and later the model development process, when the choices for the final model architecture are made. Chapter 5 presents case studies that reveal

the model's capabilities, simulation results and analysis, and also the model's limitations. Chapter 6 is the final chapter, where conclusions are presented and future work is discussed.

Chapter 2

Aircraft Fuel System Fundamentals

In the early days of aviation, the aircraft's fuel system was basically a fuel tank connected to an engine, which consumed this fuel to generate the necessary thrust for the aircraft to be pushed forward. By accelerating forward, the airplane gains speed, and at some point, the lift force generated from its wing will overcome its weight, thus lifting the aircraft. Over the years, with more passenger demand, engineers developed larger, safer aircraft requiring more reliable fuel storage systems and management. Today's generic aircraft fuel system comprises fuel tanks, valves, filters, pipes, pumps, and other accessories. These components are interconnected and distributed along the aircraft structure and provide the critical functions of a fuel system. Two main functions are fuel storage and engine feed (both already present in the Wright Flyer aircraft), while fuel transfer, jettison, measurement, and indication are other functions that developed later. The fuel tank is typically located within the wing, as shown in figure 4.

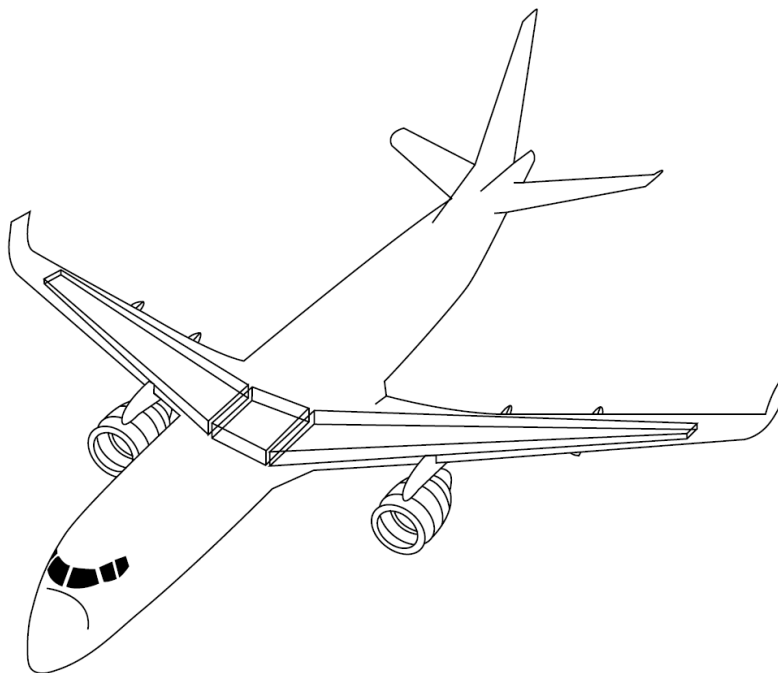


Figure 4: Typical fuel system arrangement [1].

It is important to emphasize the aircraft fuel system serves multiple functions, not for sophistication purposes, but to improve the aircraft's performance and safeguard the aircraft from potentially dangerous situations.

2.1 Fuel System Functions

The fuel system may comprise many functions, some of which are not always used, but when studying such a system, it is essential to know about them. In this section, the reader can expect to have an overview of typical aircraft fuel system functions, with a particular focus on the civil airplane category, hence emphasizing two key factors: safety and reliability.

2.1.1 Fuel Storage

Storing large quantities of fuel can be challenging, especially when weight and safety are design drivers. In aviation, the structures are usually made hollow to reduce weight as much as possible. The airplane's wings are hollow (Figure 5), and ribs, spars, and stringers structurally reinforce it [5]. The cavities inside the wing are an excellent spot for storing fuel since its weight counteracts the wing bending moment caused by the lift, and other systems would not be readily implemented in the wing structure due to geometry and difficult access. For smaller aircraft, fuel is stored in the wings only, while larger aircraft might take additional fuel within the fuselage and horizontal stabilizer. In the literature, the wing available volume for fuel tanks can be determined as a function of wing geometric parameters [6], which are mainly the chord and half of the wingspan, represented by c and $b/2$, respectively. Figure 6 shows a schematic of the available volume inside the wing.

After defining the available volume for fuel storage, the next step is to determine in which type of tank it will be stored. The most common fuel tank types are integral tanks and bladder tanks. Integral wing tanks are built within the airframe, so it is not removable, while bladder tanks are separate units attached to the wing's structure. Figure 7 shows an example of an integral wing tank, which encompasses several fluid-mechanical and avionic equipment subjected to certification to operate immersed in fuel.

The storage function encompasses a few operational issues that need to be addressed throughout the design, and some of them are studied using the fuel system model. Usually, airplanes can have a wing sweep, an angle measured between the lateral axis and the leading edge, as seen in figure 8. Consequently, while fuel is being burned, the center of gravity (CG) tends to move longitudinally, affecting the plane's static stability. This issue is usually addressed using the horizontal stabilizer trim or by transferring

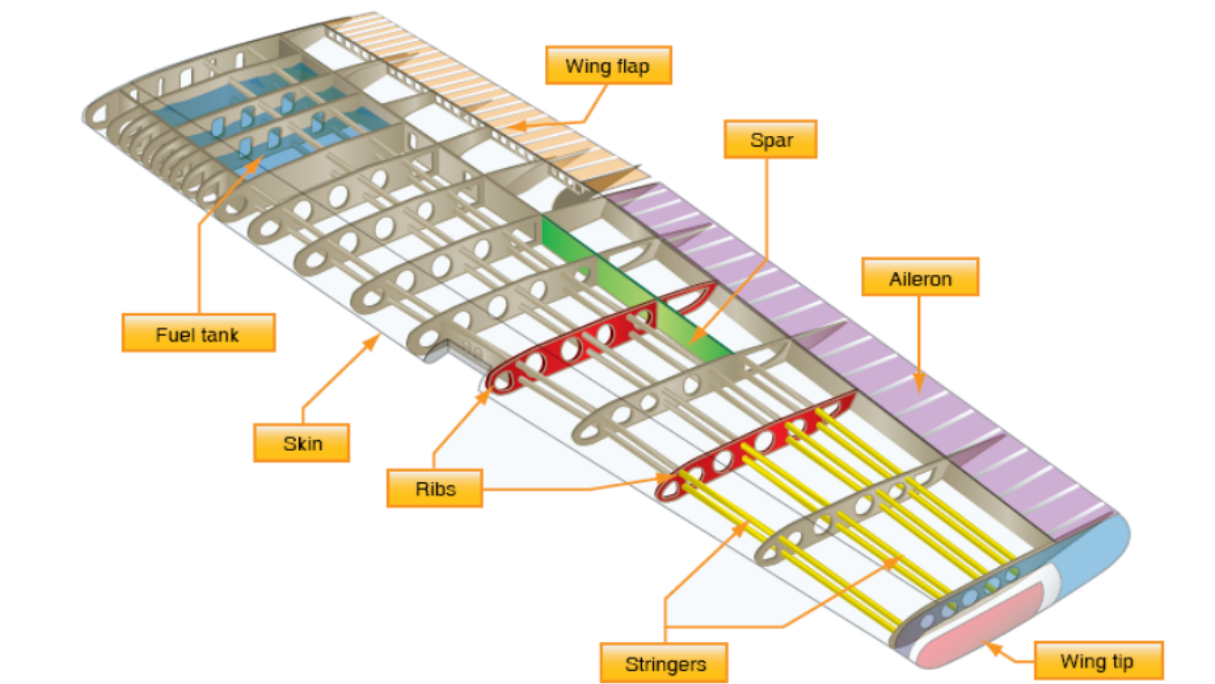


Figure 5: Wing structure.

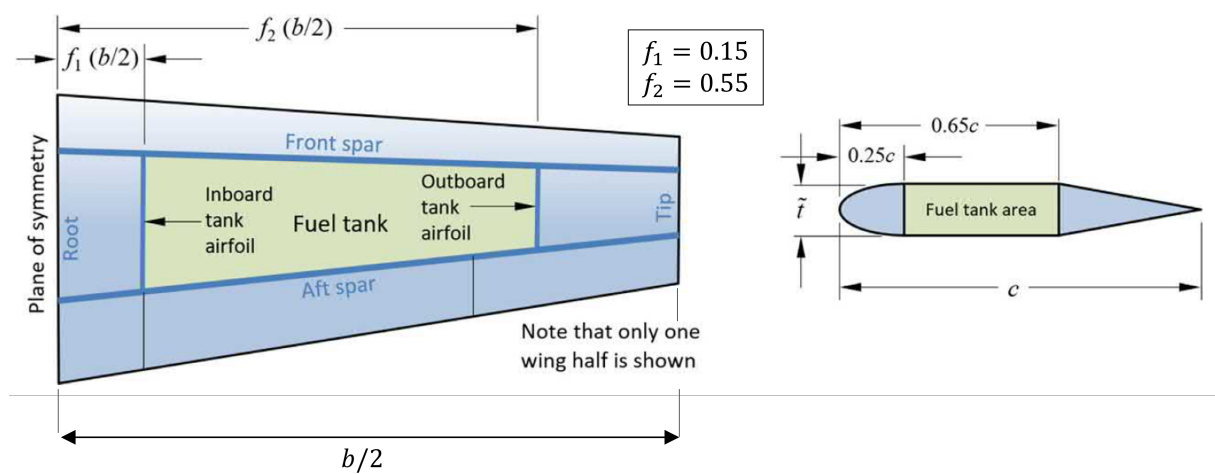


Figure 6: Wing tank sizing.



Figure 7: Interior of an integral wing fuel tank.

fuel from one tank to another using fuel management algorithms when available. Besides the CG variation, the unusable fuel quantity is also a major problem, so the location of pumps and transfer valves must be carefully assessed. A design approach for minimizing the unusable fuel quantity is using collector tanks or collector cells, which are small compartments that stay full of fuel during all the flight phases. From there, the fuel is drawn to feed the engines while the transfer pumps take fuel from auxiliary tanks and discharge it into the collector tank, thus keeping it topped up. This strategy also helps against boost feed pump starvation, which becomes more critical in negative g conditions (when the aircraft is accelerating downwards and fuel tends to go up). Another critical issue is the management of the tank ullage¹. The "empty" volume of the tanks tends to increase over time since the fuel pumps are sucking fuel from this compartment, creating a vacuum pressure that, in extreme cases, can cause severe damage to the wing tank structure. To deal with this, engineers implemented a tank venting system, which, in the case of commercial airplanes, is an open vent system because the tank ullage is directly connected to the external atmospheric pressure. Nevertheless, the vent lines must be designed so that when the airplane needs to execute an emergency descent (fast altitude/pressure variation), it can balance the pressure within the tanks with outside air pressure.

¹ The space above the fuel surface inside the fuel tank, which is filled by air.

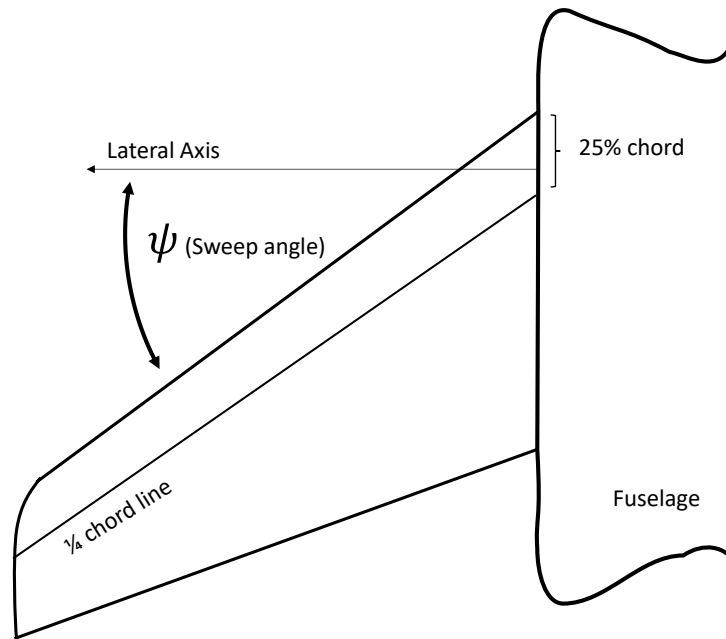


Figure 8: Wing sweep.

2.1.2 Refueling and Defueling

Refueling and defueling are also considered functions since the fuel system is designed with additional features to refuel the aircraft properly. The refueling process is performed with the aid of the airport ground refueling system. The fuel from the airport is most commonly provided at a high flow rate and pressure, ensuring that the airplane is refueled safely and quickly to meet the turnaround time², which is usually required by the airline. For this, the refueling and defueling lines, as well as refueling shutoff valves, must be designed to withstand this high pressure and flow rate. A common issue related to the refueling process is the pressure surge phenomenon, sometimes called the water hammer effect. This happens when the fuel quantity in the tanks reaches the required amount for the flight, and the refueling shutoff valve closes rapidly, causing a pressure wave to propagate along the piping system. This phenomenon is frequently studied in the literature using physical models, which can accurately capture the amplitude of the pressure peaks inside the pipe as a function of valve closure time.

Typically, the airplane's refueling is executed through a single side (usually the right wing), and from there, the fuel is distributed to the other tanks by a refueling gallery. In some cases, for larger airplanes, the turnaround time requirement cannot be met by refueling through a single side, then the refueling might be executed through 2 or multiple refueling ports. When wings have dihedral³, the fuel can flow first to

² Turnaround time is the time interval between the aircraft reaching the parking position and leaving the parking position. This includes unloading and reloading passengers, cargo, and fuel.

³ The wing has positive a dihedral when the wing tip is above the wing root.

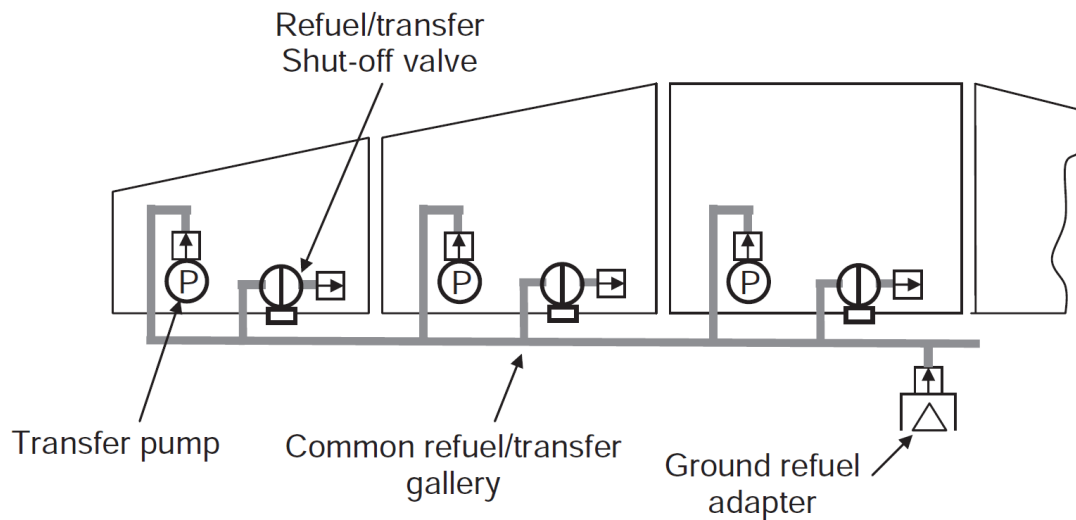


Figure 9: Combined refueling and transfer system schematic [1].

the outboard tanks, and the check valves will let the fuel flow towards the wing root by gravity, thus filling the remaining tanks. There are two types of refueling systems; the first type uses a dedicated refueling gallery to distribute fuel to the tanks, while the second type has the refueling gallery combined with the transfer system. An example of a combined refueling and transfer system appears in figure 9.

Regarding the defueling function, this is a requirement for maintenance purposes. For instance, a large aircraft can be accidentally over-fueled, and to meet the requirements for Maximum Take Off Weight (MTOW), the aircraft can be defueled. This process can be performed by suction, provided by the airport's ground refueling system, or the architecture might include a defueling valve, which connects the engine feed lines to the refueling gallery, thus enabling the feed pumps to pump fuel out of the aircraft, considering that all engines shutoff valves are closed.

2.1.3 Engine and APU feed

One crucial function of the aircraft fuel system is to provide uninterrupted fuel flow at the correct pressure and flow rate for proper engine and Auxiliary Power Unit (APU)⁴ operation. This is a general requirement for all fuel systems, also stated in the CS-23 document (set of standards imposed by the European aviation regulatory entity), which will be discussed later in this chapter. The pressure at which the fuel will be delivered to the engine is specified by the engine's manufacturer. This requirement ensures that the fuel pressure is maintained above the fuel vapor pressure. Another requirement for the fuel system is

⁴ APU is commonly found in large transport aircraft. It is a device used to power other systems in the aircraft by the electricity generated from fuel combustion. Although the APU releases exhaust gases, it does not contribute significantly to thrust generation.

to ensure that fuel contamination by water and air is kept below the safe limits imposed by the engine's manufacturer. The feed function will require specific fluid mechanical equipment, such as feed pumps. These pumps are either motor-driven or jet pumps (sometimes called jet or eductor pumps). The boost pumps must be designed to handle the most severe situation, commonly called "hot climb." This occurs when the fuel is hot and the plane is climbing, causing the pressure to decrease and approach the fuel's vapor pressure, which increases with fuel temperature. The centrifugal pump characteristic curve varies with altitude since the pump's inlet pressure is directly affected by the pressure at the current altitude, as depicted in figure 10. Besides high altitude, the pump must have enough power to overcome the pressure drop in the feed lines and keep the pressure above the fuel vapor pressure of the fuel used with a safety margin. The feed system can be written in a block diagram form, showing the relationship between the engine, feed lines, feed pumps, and atmospheric conditions (Figure 11).

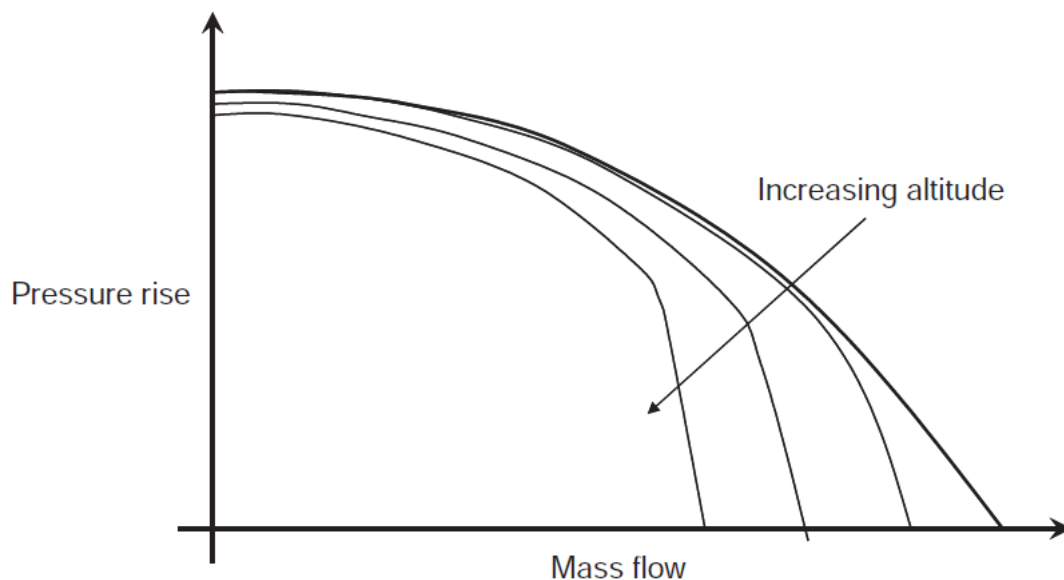


Figure 10: Generic centrifugal pump characteristic curve varying with aircraft's altitude [1].

The jet pump, on the other hand, is a pump with no moving parts based on the Venturi effect. For this pump to work, it needs a motive pressure source, which can come from a centrifugal pump, for example. This pump and its characteristics will be discussed in more detail in the next chapter. In smaller aircraft, this pump is often used as the primary feed pump, while the centrifugal pumps are used as a backup. The jet pumps can also be used for fuel transfer purposes. This strategy will be discussed in the following subsection. When talking about airplanes with two or more engines, the fuel system design will have two independent fuel systems in each wing, meaning that the failure of one component from the right wing will not affect the operation of the components located in the left wing and vice versa. In the case of an engine

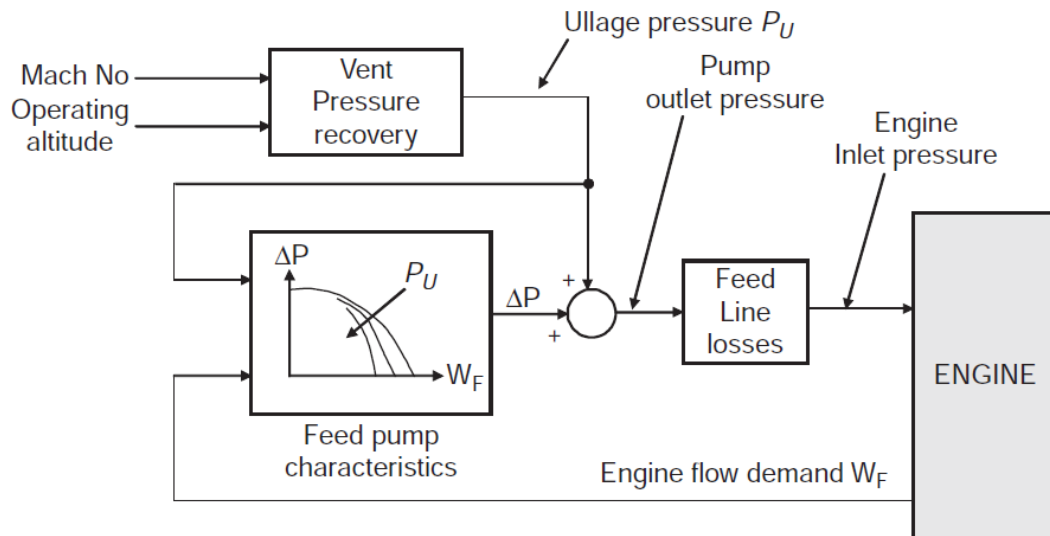


Figure 11: Feed system block diagram schematic, neglecting the fuel temperature effect on the pump's requirements [1].

failure, the feed tanks from this wing would be unused, creating a mass difference between the right and left wings, thus shifting the center of gravity laterally. For this purpose, the crossfeed valve is a crucial component included in most fuel system designs. This valve works as a shutoff valve that connects the feed lines from both sides of the airplane. When set to open, the crossfeed valve enables the feed tanks from both wings to feed a single engine, avoiding a lateral imbalance scenario.

2.1.4 Fuel Transfer

In applications where multiple tanks are needed, the fuel transfer system is required. The fuel transfer can happen by the aid of gravity or by transfer pumps. The first case, often called gravity transfer, occurs only in the direction of the wing root, with the aid of the flapper valves, which are uni-directional valves. Between each tank, there is a flapper valve, often called a baffle check valve, which is the device that enables the transfer of fuel inboards when the head difference between two tanks is greater than the cracking pressure of the valve. The other method uses transfer pumps, typically jet pumps, which will be covered later. The transfer function allows the airplane to address operational issues, such as:

- Airplane's center of gravity (CG) shift in-flight;
- Wing bending moment alleviation;
- Maximum and minimum tank fuel quantities.

The position of the center of gravity (CG) is a critical operational consideration for large aircraft due to the significant variation in its position between full and empty fuel tank conditions. The CG must stay within a given range, the so-called static margin, and the fuel transfer system can be helpful by transferring fuel from the outboard tanks to the inboard tanks. The transfer system also manages the wing load alleviation. The airplane's wing is subjected to a strong bending moment around the $\vec{x}$ axis caused by the lift force. To counteract this, the fuel can be kept in the outboard section of the wing for an extended period, thus reducing the bending moment and, hence, the magnitude of the structural stress cycles. The level of fuel can also be monitored and controlled by the fuel transfer system. This is useful, mainly because the pumps and valves are located at certain heights within the tank, and if the fuel level is too high, there could be a risk of fuel entering the vent lines, while if the fuel level is too low, the boost pumps can experience fuel starvation.

As mentioned before, the scavenge jet pump can be used for transfer purposes. One common application of jet pumps in the transfer system is auxiliary tank scavenging. The scavenge jet pump is responsible for extracting unusable quantities of fuel from the corners of the auxiliary tanks and discharging it into the feed tank or collector cell. The motive source for the scavenge pump can come from the engine fuel metering unit (which bypasses the excess fuel delivered to the engine), an engine-driven fuel pump, or even a centrifugal boost pump.

2.1.5 Fuel Jettison

The need for fuel jettison is explained by the difference between the Maximum Take Off Weight (MTOW) and Maximum Landing Weight (MLW) of an airplane. The larger the aircraft, the more significant the difference between MTOW and MLW, and the more critical the fuel jettison function becomes. Considering the case of an emergency a few minutes after take-off, the fuel consumed onboard so far is negligible, meaning that the aircraft's weight is much higher than what it is allowed for landing. To execute an emergency landing, part of the fuel onboard must be dumped, which is done by the fuel jettison system, illustrated by figure 12. The challenge associated with the fuel jettison is providing the pumps and lines with the necessary capacity to dump fuel as quickly as possible since the emergency landing procedure usually happens in a very short time interval.

The jettison system faces its worst-case scenario when larger airliners need to execute an emergency landing with almost full fuel tanks. The time it will take to dump all the necessary fuel can take from 30 to 45 minutes. This is, of course, a long time to wait in an emergency scenario, so in most cases, the captain might decide to land the aircraft even with the weight above the MLW, and the risk of landing gear

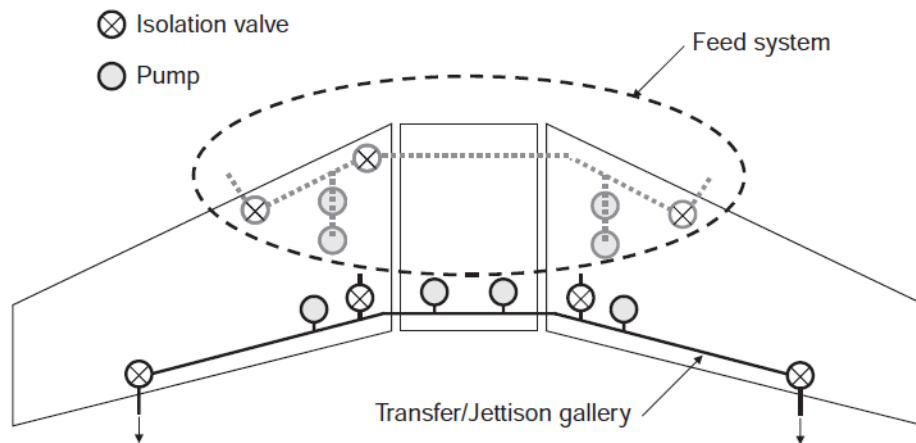


Figure 12: Fuel jettison schematic [1].

collapse or permanent structural deformation must be recognized, as well as potential sub-consequences.

2.1.6 Other Functions

As this work primarily concerns fluid mechanics, less attention will be given to the sensing and control aspects. Therefore, fuel quantity gauging, fuel management, and control are briefly discussed. Fuel quantity gauging involves measuring fuel content and delivering mass quantity data. It faces challenges like variable fuel properties, attitude shifts due to maneuvers, and tank structural distortions. This function provides continuous and precise fuel quantity information, essential for flight planning, safety, and maintaining proper weight and balance. It employs sensors and algorithms to adapt to changing conditions and communicates this information to both the flight deck and the refueling station. On the other hand, fuel management encompasses the coordination, control, and monitoring of all fuel system operations. Its complexity varies, from simple systems in small aircraft to intricate, automated setups in large, long-range transports. Fuel management handles tasks like automatic refueling, managing engine-out situations, and cross-feed operations. In larger aircraft, it automates fuel distribution to optimize balance and consumption. It interfaces with various aircraft systems, minimizing crew workload and enhancing operational safety and fuel efficiency across all aircraft types.

2.2 Fuel properties

When studying aircraft fuel systems, it is crucial to discuss the physical properties of fuels, as they play a pivotal role in understanding their behavior and safety considerations. Fuel specifications were first established in the 1940s to regulate properties such as composition, volatility, energy, stability, lubricity,

and corrosion. Its production comes from crude oil, and after the distillation process, various types of hydrocarbons can be extracted, including kerosene, which is from what most aviation fuel is derived. In this section, some fuel properties that are mentioned throughout the thesis are outlined, and they are fuel vapor pressure, flash point, fire point, and freeze point.

2.2.1 Vapor pressure

One major issue in aircraft fuel systems is managing fuel vapor pressure. This property is the pressure at which the fuel begins to vaporize at a given temperature. If the fuel vaporizes within the tank, it can lead to various hazardous situations, including the engine's inability to receive fuel, as the pumps cannot pump vaporized fuel. The main challenge associated with fuel vapor pressure is preventing the fuel from vaporization when the aircraft reaches high altitudes, where the air pressure is reduced. The temperature is also a critical factor for the fuel vapor pressure. As it increases, the vapor pressure tends to decrease, as shown in figure 13. The graph shows that the JP-4 type fuel is more volatile than the Jet-A type, meaning that for the same temperature, it will resist less vaporization, and this is another reason for implementing closed vent systems in military applications.

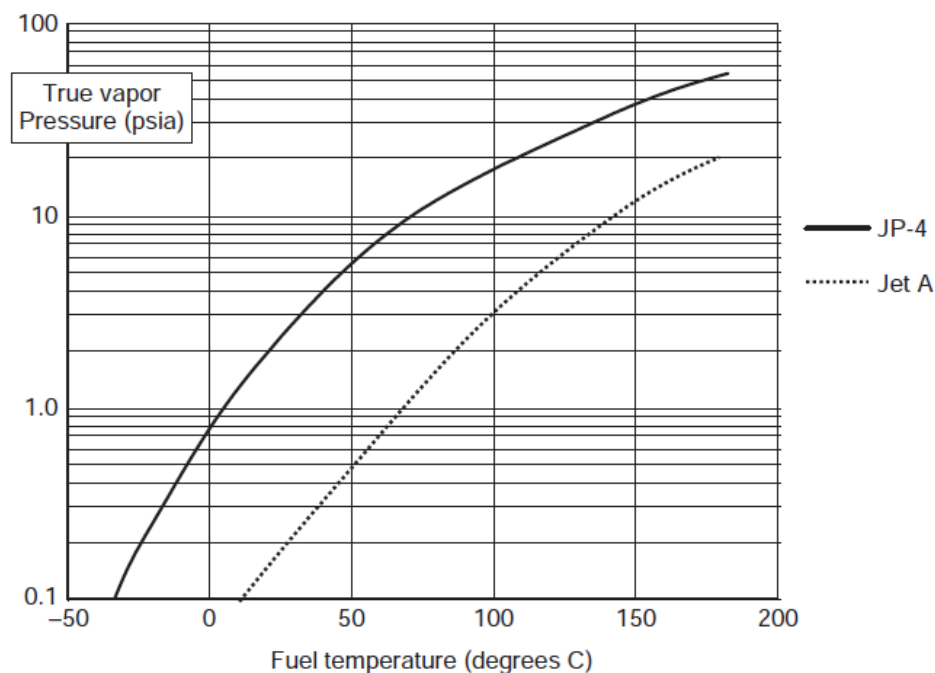


Figure 13: Vapor pressure versus Temperature [1].

2.2.2 Flash and Fire Point

The flash point is the lowest temperature at which the fuel will form sufficient vapor capable of igniting. The Fire point, on the other hand, is the lowest temperature at which the fuel vapors created can sustain a fire even without the ignition source. Within an aircraft fuel system, the temperature of the fuel should remain below these points, ensuring there will be no risk of fuel vapor ignition.

2.2.3 Freeze Point

When the airplanes reach high altitudes, the temperature can drop to about -50°C , and this can be below the freezing point of some of the hydrocarbons contained in the fuel, which is a mixture of them. Although the fuel might not be completely frozen, wax crystals are formed due to some hydrocarbon freezing, which may lead to pump inlet blockage. For this purpose, engine manufacturers may require a minimum inlet pressure for their pumps so these scenarios are avoided.

2.2.4 Density

The fuel density is the amount of mass contained in a given amount of volume. Typically, aviation fuel quantities are informed to the pilot in terms of mass because the mass is what is actually converted to energy, not the volume. The volume of the tanks is always the same, but the mass of fuel it can carry depends on the fuel density. One important factor about the density is it affects the pressure created by the fluid in terms of liquid height, referred to as the hydrostatic pressure, which will be discussed later.

2.2.5 Specific Energy

The specific energy is probably one of the most critical factors behind choosing fossil fuels over electrical batteries to power the aircraft's engines. The specific energy is the amount of energy contained in a given amount of mass. For the sake of comparison, aviation fuel (Jet A) has 43.2 [MJ/kg] of specific energy, while a modern electric battery may have around 1.62 [MJ/kg] , which is about 4% of the jet fuel's specific energy [7]. It is worth noting that gas turbine engines typically waste 2-3 thirds of fuel energy as heat, indicating that there is still room for improvement if it is to remain the primary energy source.

2.2.6 JET-A Fuel

Jet fuel, also known as aviation turbine fuel (ATF) or avtur, is specifically formulated for use in gas turbine engine-powered aircraft. It is colored transparent to light yellow. The most widely used types of jet fuel for commercial aviation are Jet A and Jet A-1, which are manufactured according to an internationally recognized standard. The model presented in this thesis has been simulated using the Jet-A fuel properties, which appear in the table 1 [8]:

Table 1: Jet-A and Jet-A1 properties.

	Jet A-1	Jet A
Flash point	38 °C	
Autoignition temperature	210 °C [9]	
Freezing point	-47 °C	-40 °C
Density at 15 °C	0.804 kg/L	0.820 kg/L
Specific energy	43.15 MJ/kg	43.02 MJ/kg

As seen, the most significant difference between Jet-A and Jet-A1 is in the freezing point, with the Jet-A1 being more suitable for long-haul international flights, especially when flying over polar regions.

2.3 CS-23

The CS-23 (Certification Specification 23) is a regulatory set of standards established by EASA for small civil aircraft with a maximum takeoff weight (MTOW) of 5,700 kg or less. To ensure the safety and reliability of aircraft fuel systems, compliance with CS-23 is crucial as it sets rigorous requirements and testing procedures to prevent fuel-related accidents, such as leaks, fires, or engine failures. These rules safeguard passengers, crew, and aircraft by guaranteeing the integrity of fuel systems, making it an essential aspect of aviation safety and certification [10].

One general requirement for the fuel systems under CS-23 regulations is that *"Each fuel system must be constructed and arranged to ensure fuel flow at a rate and pressure established for proper engine and auxiliary power unit functioning under each likely operating condition, including any maneuver for which certification is requested and during which the engine or auxiliary power unit is permitted to be in operation"*. The fuel flow is a consequence of the engine demand, which will be specified by the engine's manufacturer. The fuel flow pressure at the engine fuel system inlet must be at least 5 psi (34.5 kPa)

above the fuel vapor pressure to minimize fuel vaporization, even in high altitudes. Another relevant requirement states that *"Each fuel system for a twin-engine airplane must be arranged so that, in at least one system configuration, the failure of any one component will not result in the loss of power of more than one engine or require immediate action by the pilot to prevent the loss of power of more than one engine"*. This imposes that the left and right sides of the fuel system should operate independently. Regarding the fuel system components, one key requirement is that the fuel tank must have an expansion space of not less than 2% of its total capacity; this must be considered when setting boundary conditions in the model. Another important requirement when building a fuel system model is that there must be at least one pump for each turbine engine, plus an emergency pump in case of failure. The valves are also subjected to regulations, where one of them says that *"There must be a means to allow appropriate flight crew members to rapidly shut off, in flight, the fuel to each engine individually"*. This means the model should include controlled shutoff valve components for the engines.

2.4 Chapter summary

As seen in this chapter, the aircraft fuel system is critical for the aircraft's performance, being subject to strict regulations and rules, in this case, CS-23. The system can be broken into smaller parts or subsystems, each with specific functions, such as feeding the engines, transferring and managing fuel quantities, and refueling/defueling. A common architecture might include several tanks integrated into the wing structure, which are connected by flapper valves that allow fuel to be transferred by gravity. The fuel transfer can be aided by the scavenge jet pumps, which extract fuel from the auxiliary tanks and discharge it into the main feed tank or collector tank, keeping it always full of fuel. The high complexity of the global system creates the need for modeling and simulation, and the next section will introduce the reader to fundamental concepts related to system modeling, focusing on fluid systems.

Chapter 3

Aircraft Fuel System Modeling

In general, a system is a combination of components that work together to achieve a specific goal. The systems can be seen as isolated parts of the universe which are studied separately from its environment [11]. The system interacts with its environment like the aircraft fuel system interacts with the outside air pressure. In the literature, generally, there are two groups of system variables: the system inputs and outputs. The first group is not dependent on what happens within the system (the outside air temperature in the case of a fuel system), while the second group depends (e.g. outlet fluid pressure generated by a centrifugal boost pump). The system outputs are of primary interest to engineers. The system can be described by states or state variables. For instance, the fuel system can be partially described by one of its tanks' volume, which is a state variable. Systems can be discrete or dynamic; when state variables continuously change over time, the system is called dynamic. A schematic of a dynamic system with its input and outputs is represented in figure 14.

The big advantage of system modeling comes from the easy, time and cost-saving way of acquiring technical data from the system's behavior. The data obtained by tests made with physical prototypes are, of course, very valuable, but most of the time, it is too costly and time-consuming. Actually, neither the physical experiments nor the simulations are 100% accurate. The physical experiments rely on the sensor's and setup accuracy, while the computational model simulations rely on the accuracy of mathematical models and equation solvers. These never correspond to reality, but if the mathematical models are accurate enough, they can be very important in any engineering project.

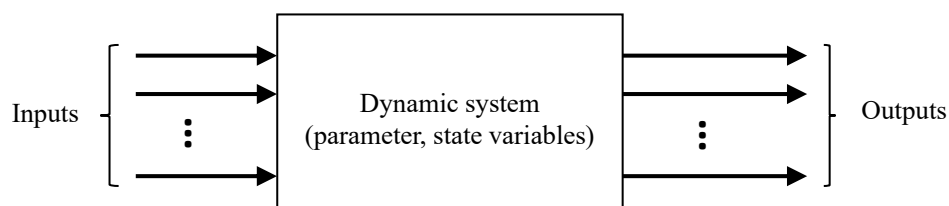


Figure 14: Dynamic system representation.

3.1 Fluid system modeling basics

The aircraft fuel system is a physical system that integrates fluid, mechanical, thermal, and electric systems. In this thesis, the focus is on the fluid mechanical part of the system. Hence, the model built only uses fluid system model building blocks. The fluid system is often compared to an electric circuit because the basic governing laws are the same. While electric circuits have electrical resistance, capacitance, and inductance, fluid systems have fluid resistance, capacitance, and inertance. Examples of fluid resistance include orifices, valves, nozzles, and pipe friction. The fluid resistor can be any element that dissipates fluid energy when it flows across it. This energy loss is translated into the pressure to drop. The elemental equation that expresses the amount of pressure drop ΔP required to force a unit of flow rate Q through the resistor is:

$$Q = \frac{1}{R} \Delta P \quad (3)$$

Where the resistor is characterized by its resistance factor R . The fluid capacitor can be considered an energy storage in the form of liquid with potential energy. The fluid capacitance C can be expressed by:

$$C = \frac{\Delta V}{\Delta P} \quad (4)$$

where $\frac{\Delta V}{\Delta P}$ is the volume variation per unit of pressure change, meaning that the more volume the system can store for the same amount of pressure difference, the more capacitance it has. The fluid inertance, on the other hand, is the ability to resist acceleration. Considering a very long pipe, the mass of liquid that is flowing through it has a lot of momentum, and therefore, to stop this flow from coming out of this pipe, a big deceleration is required because the long pipe element introduces high inertance to the system. The inertance I can be described by the following equation:

$$\Delta P = I \frac{dQ}{dt} \quad (5)$$

Where ΔP is the pressure drop required to stop the fluid flow with a flow rate of Q from moving through the inductor element. Additionally, fluid systems may also include fluid sources. The fluid source can be a pressure or a flow rate source, for example, and they are frequently used to set boundary conditions in fluid systems. For instance, an ideal flow rate source can generate a constant flow rate regardless of the pressure difference required. In summary, a fluid system can have several components, such as pumps, control valves, and tanks, and each of these components can be modeled as the building blocks presented so far. For complex fluid systems with complex components, the mathematical modeling will

look more complex as well. Most of the analyses of fluid systems rely on pressure and flow rate information. Therefore, it is important to understand how they relate to each other. One important equation is the one that defines the pressure of the fluid at a given point as a function of liquid height:

$$P_h = \rho gh \quad (6)$$

Where ρ is the fluid's density, g the gravitational acceleration, and h the liquid level. Another important fluid mechanics equation is Bernoulli's equation (7). This equation states that the total pressure energy contained in a fluid particle along a streamline is conserved if no additional work is applied to it.

$$P + \frac{\rho U^2}{2} + \rho gh = Cte \quad (7)$$

The first term in this equation is the fluid's static pressure, which is the pressure related to the forces acting on the fluid. The second term is the dynamic pressure, which is associated with the fluid's kinetic energy, and the third term is the hydrostatic pressure, which is related to the fluid's gravitational potential energy. To understand this principle, a fictitious scenario involving a fuel system can be analyzed (Figure 15). Considering that two fuel tanks are connected through a pipe, where there is a shutoff valve, initially closed. The tanks have different fuel levels (H_1 and H_2), and at some point, the shutoff valve is open. Considering that there is no pressure loss due to friction ($\Delta P_L = 0$), the Bernoulli's equation can be applied as follows:

$$P_1 + \frac{\rho U_1^2}{2} + \rho g H_1 = P_2 + \frac{\rho U_2^2}{2} + \rho g h_p + \Delta P_L \quad (8)$$

where P_1 is equal to the ambient pressure P_0 and P_2 is equal to the ambient pressure plus the pressure caused by the mass of liquid above point 2, which can be calculated using equation 6:

$$P_2 = P_0 + \rho g(H_2 - h_p) \quad (9)$$

By combining equation 9 with 8, a new expression can be written:

$$P_0 + \frac{\rho U_1^2}{2} + \rho g H_1 = P_0 + \rho g(H_2 - h_p) + \frac{\rho U_2^2}{2} + \rho g h_p + \Delta P_L \quad (10)$$

Considering the tank is very large, the fluid velocity at point 1 can be considered zero. Assuming there is no pressure drop due to friction, the ΔP_{loss} term can be considered zero. So, some terms canceled out:

$$\cancel{P_0} + \frac{\rho U_1^2}{2} + \rho g h_1 = \cancel{P_0} + \rho g(H_2 - h_p) + \frac{\rho U_2^2}{2} + \rho g h_p + \cancel{\Delta P_L} \quad (11)$$

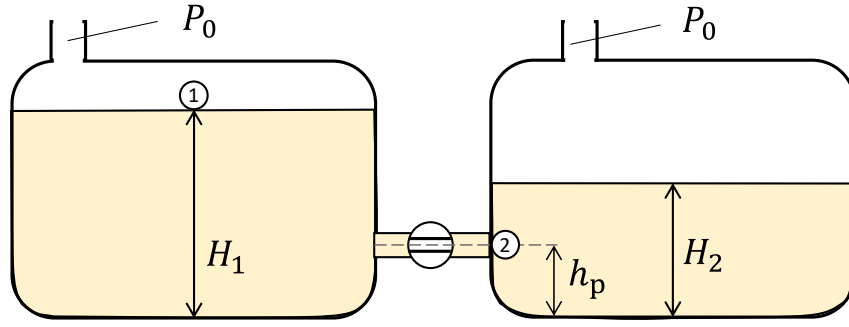


Figure 15: A fictitious scenario in which the Bernoulli's equation can be applied.

So the new equation becomes:

$$\rho g h_1 = \rho g (H_2 - h_p) + \frac{\rho U_2^2}{2} + \rho g h_p \quad (12)$$

By rearranging the terms and isolating the fluid velocity v , one can have:

$$U_2 = \sqrt{2g(H_1 - H_2)} \quad (13)$$

The volumetric flow rate Q through the transfer pipe at point two can be calculated by the formula:

$$Q = AU \quad (14)$$

where A is the cross-sectional area of the transfer pipe. Now, with the fluid velocity defined, the flow rate of the fuel transfer between the tanks can be calculated by combining equations 13 and 14. The flow rate is then defined as:

$$Q = A\sqrt{2g(H_1 - H_2)} \quad (15)$$

This equation shows that the fluid volumetric flow rate at point 2 when the shutoff valve opens depends mainly on the height difference between the liquid levels H_1 and H_2 . This simple problem is useful to understand how properties such as pressure and flow rate can be determined at different points in the system at a specific time by using fundamental laws of fluid mechanics.

3.2 Dynamic systems simulation

The previous section has shown how to determine some state variables at a specific time; however, dynamic system simulations are performed by determining how these state variables evolve over time [12].

As mentioned earlier, the flow rate, height of liquid, and pressure can be considered state variables because they, together, describe the system's current state. When simulating a dynamic system in software such as Simulink, the solver algorithm calculates the value of the state variables based on their previous value. By taking the same example of the last section in figure 15, the tanks' level is expected to change over time as fuel is transferred from one tank to the other. Considering that tank one has an initial volume of $V(t_0)$, and since it is transferring fuel to tank two, the volumetric flow rate at the boundary of tank 1 will be considered negative ($Q_{12}(t_0) < 0$). At time t_1 , tank 1 volume will be smaller than the previous value at t_0 and this, in turn, will result in a different flow rate $Q_{12}(t_1)$. To determine the volume of Tank 1 after a single time step ($\Delta t = t_1 - t_0$), the following equation is used:

$$V(t_1) = V(t_0) + Q_{12}\Delta t \quad (16)$$

When using computational tools, usually the time step value is very low ($dt \ll \Delta t$), meaning that the continuous dynamic systems can be approximated to differential equations:

$$V(k) = V(k-1) + \int_{k-1}^k \dot{V} dt \quad (17)$$

where k and $k-1$ represent the current and previous time step. With equation 17, the volume V at a given time step k can be determined by integrating its time derivative $\dot{V}$ and adding it to the previous value.

To solve the system's differential equations, the software uses numerical methods called solvers. The solvers can be of two types: fixed-step and variable-step solvers. The first group solves equations like 17 by numerical integration at every time step, keeping the time step at a fixed value. Figure 16 shows different types of solvers and time steps. The "Ode" term stands for Ordinary Differential Equation, and the following number represents the order of integration. T_s is the time step size of each simulation, and it can be verified that reducing the step size by two improves the simulation results. The higher order of integration also yields a better result, but as usual, the price to pay is an increased simulation time.

The accuracy of the simulation can be achieved by either reducing the step size of the solver or increasing the order of the numerical integration, which consequently will increase the simulation time. This is a classic trade-off addressed by numerical simulation specialists, who face the challenge of reducing the simulation time while keeping accurate results on a daily basis. However, most software allows the solver to vary the step size applied depending on the simulation error. For instance, one variable step solver might use both first and third-order numerical integration, and after measuring the error obtained between both, it compares to an error tolerance and, if less than the error, it can keep simulating with the

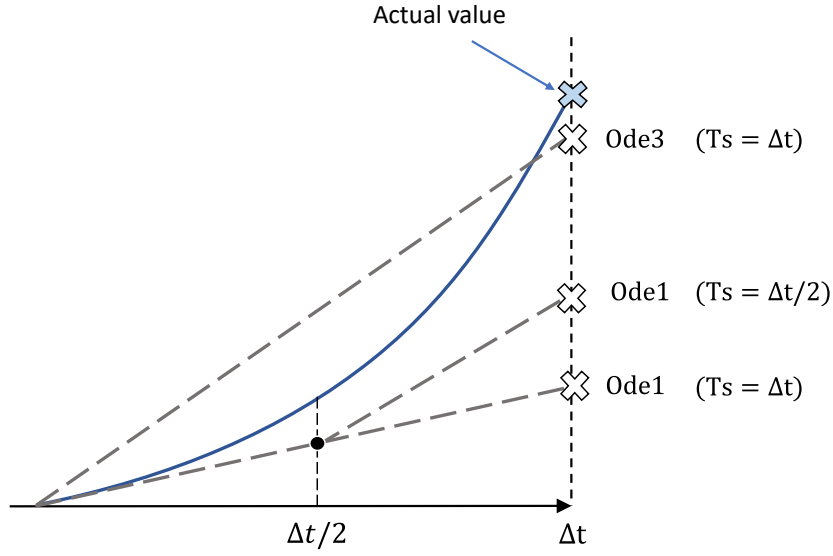


Figure 16: Fixed-step solver demonstration.

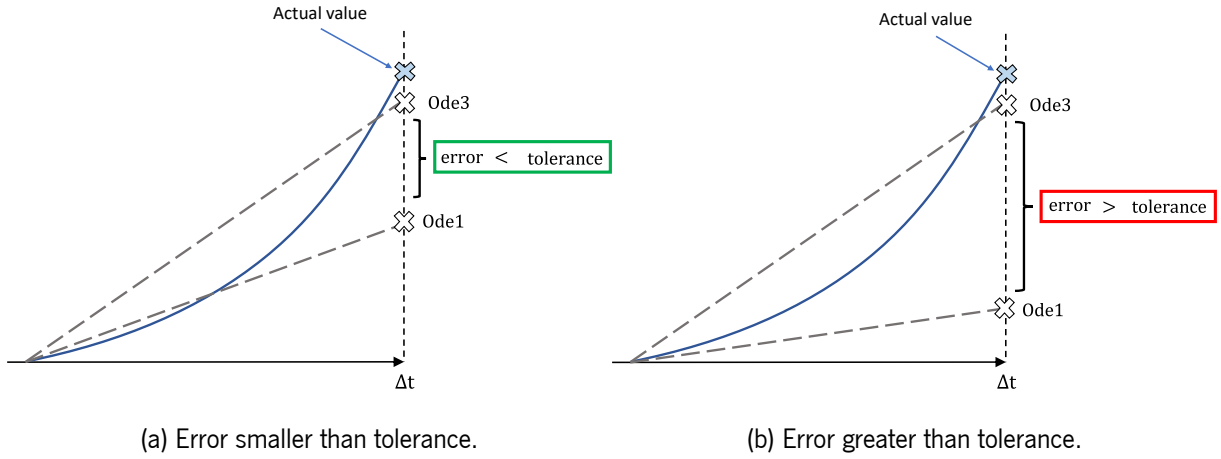


Figure 17: Strategy behind the variable step solver algorithm with two numerical integration orders.

same step size; otherwise it will adjust the step size until the error between ode1 and ode3 solvers are less than the imposed tolerance (Figure 17).

With a variable step solver, the simulations can take a use time step in each iteration when the error tolerance is not exceeded, therefore decreasing simulation time significantly and improving results according to the error tolerance.

3.3 Fuel system components modeling

Chapter 2 mentioned some of the most used fuel system fluid mechanical components, and in this section, they are explored in the mathematical modeling aspect. The tool used in this project for the fuel system

modeling was Simscape from MATLAB/Simulink, and the concept of Simscape is to provide the user with the ability to model the physical systems without writing all the differential equations that describe the component's physics. Instead, when inserting a Simscape component in the model, it already comes with its intrinsic mathematical equations.

3.4 Tanks

The tanks are one of the most important components in the fuel system model since it is from there that information about the fuel quantity, in terms of level, volume, or mass, can be taken. A schematic of a fuel tank is shown in figure 18.

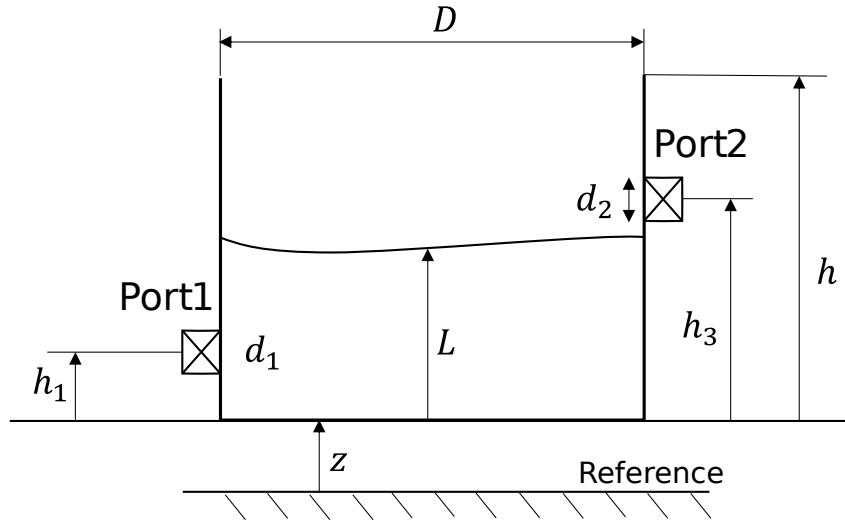


Figure 18: Tank model schematic.

The tank can have several inlet and outlet ports. Each port is connected to a pipe, and in the case of the collector tank, it will need at least 2 ports, one to feed the engine (outlet port) and the other to receive fuel from the inboard tank (inlet port). To make the model more accurate, it should include 4 ports, where the 2 additional ports are for the higher outlet to the inboard tank (in case of tank overfilling) and the inlet to receive fuel from the inboard tank through the flapper valve. If the tank is approximately cylindrical, its geometry can be defined as a function of D and h , which are tank diameter and height. Other parameters, like the height of the inlet/outlet and its cross-sectional area, can also be specified. The pressure at port 1, if $L > h_1$ can be calculated by:

$$P_1 = P_0 + \rho g(L + Z) - \Delta P_{port} \quad (18)$$

where the ΔP_{port} is a function of the port's flow resistance coefficient K_{port} , which can also be defined in the tank's component block. If $L < h_1$, the pressure at port 1 will be calculated differently:

$$P_1 = P_0 + \rho g(h_1 + Z) - \Delta P_{port} \quad (19)$$

To define the total flow rate entering/leaving the tank, the continuity equation can be used:

$$\dot{m}_1 + \dot{m}_2 = \frac{\rho dV}{dt} \quad (20)$$

Since this work was mostly dedicated to studying the isothermal model of the fuel system, the equations related to thermal energy will not be presented.

3.5 Pumps

Pumps are also crucial components in the fuel system and can be classified into two major categories: dynamic and displacement pumps [13]. The first group is more likely to be found in aircraft fuel systems. The dynamic pumps can be subdivided into more categories, but the most common type is the centrifugal pump. The displacement pumps are divided into reciprocating and rotary types and can further be subdivided into more specific categories. When buying a centrifugal or a positive displacement pump, for instance, it is important to interpret its characteristic curve, which is a graph that relates the pump's capacity (Volumetric flow rate) with the pressure added to the fluid (Head). Figure 19 show typical HQ curves for centrifugal and positive displacement pumps. As it can be seen, the positive displacement pump will have almost the same flow rate regardless of the pressure added to the fluid, meaning this could easily be modeled as a constant flow rate source, as presented previously in this chapter. The centrifugal pump, however, will behave differently, and using a flow rate source to model its behavior might be inappropriate. In the context of aircraft fuel systems, the most common pumps are centrifugal and jet pumps, and both fall into the dynamic pump category because they are based on the same principle of adding kinetic energy to the fluid, either by rotating the impellers or by using a high-velocity jet as motive flow.

3.5.1 Centrifugal Pumps

The centrifugal pumps are usually used for fuel feed and transfer purposes. Their modeling in Simscape is usually done by analytical parametrization or using tabulated data. The analytical parametrization takes inputs as the pump's nominal capacity Q_{nom} and head H_{nom} , maximum head at zero capacity H_{max} , and maximum capacity at zero head Q_{max} . With this information, it is possible to create a quadratic fit

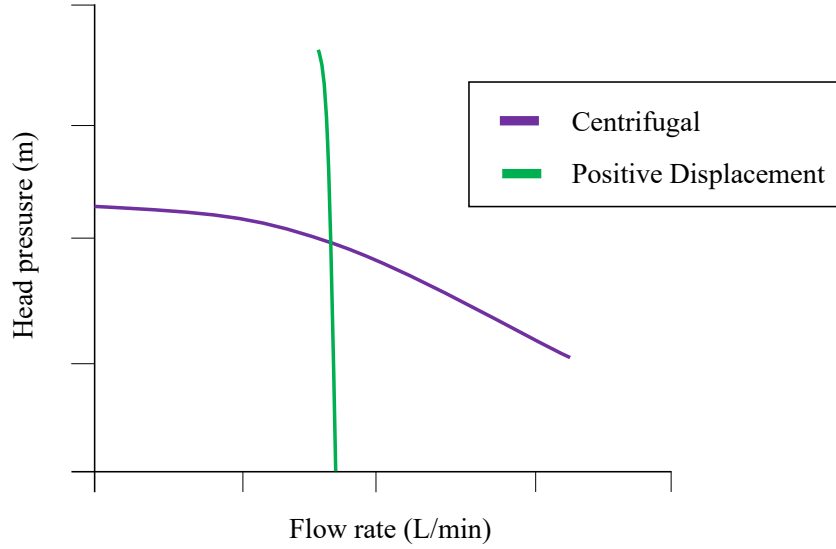


Figure 19: Typical HQ curves for Positive Displacement and Centrifugal Pump.

curve that approximates the pump's characteristic curve. The pressure gain over the pump inlet port (A) and outlet port (B) can be modeled as:

$$p_B - p_A = \Delta H_{ref} \rho g \left(\frac{\omega}{\omega_{ref}} \right)^2 \left(\frac{D}{D_{ref}} \right)^2 \quad (21)$$

where g is the gravitational acceleration, ΔH is the reference pump head, which the block derives from the approximate characteristic curve, ω is the shaft angular velocity, ω_{ref} is the value of the reference shaft speed parameter and $\frac{D}{D_{ref}}$ is the value of the Impeller diameter scale factor parameter, normally set to 1.

Another way to model the block is to specify vectors for reference capacity and head, reference brake power and reference shaft speed. These will define points where the pump behavior is defined, and the values in between will be derived through interpolation.

3.5.2 Jet Pump

The jet pump is frequently included in the fuel system design of smaller aircraft. This pump does not have moving parts, its energy source comes from a motive flow of fuel, which can be created by another pump. It's working principle is based on the Venturi effect, which happens when a fluid flows through a constricted section of a pipe, thus creating a low-pressure zone. Figure 20 shows that at the constricted zone (point 2) the pressure is reduced, since the column of liquid is lower. The reduction in pressure can be explained by Bernoulli's principle presented in equation 7. At section 2, since the cross-sectional area was reduced, the fluid velocity will increase, and to meet the Bernoulli's energy conservation rule,

the increase in kinetic energy will be compensated by a reduction in pressure (in this case the hydrostatic pressure).

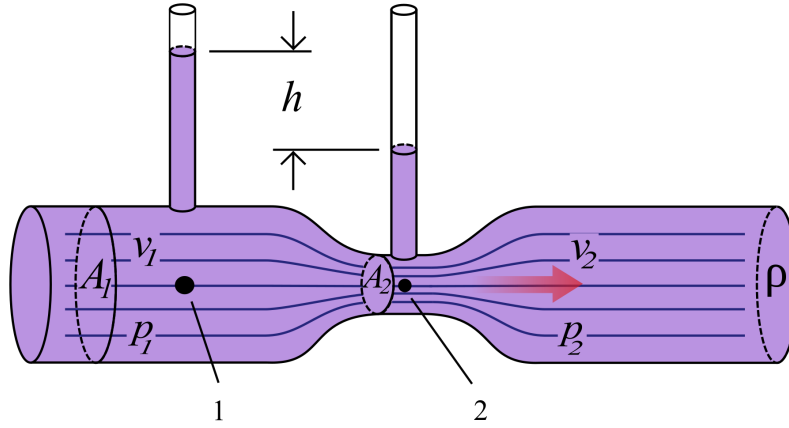


Figure 20: Venturi principle schematic.

A Jet pump is constructed in a way that there is a reduction in pressure at the suction port because of the reduction in the cross-sectional area. A schematic of a jet pump is shown in figure 21, where it can be seen that the cross-sectional area reduces close to the nozzle, and a suction effect will be created that will induce the fluid to flow inside the throat and exchange momentum with the motive fluid. The discharge flow is the sum of the motive and induced flow.

Regarding the geometric parameters of the pump, two important ratios are of great importance when modeling its behavior: the diffuser inlet-to-outlet ratio r_1 and the nozzle-to-throat ratio r_2 :

$$r_1 = \frac{A_{th}}{A_d} \quad (22)$$

$$r_2 = \frac{A_n}{A_{th}} \quad (23)$$

where A_{th} , A_d and A_n are the cross-sectional areas of the throat, diffuser outlet, and nozzle, respectively. One of the most important quantities to define is the induced flow, sometimes called secondary flow. This parameter can be modeled with the following equation:

$$q_2 = \frac{A_n c}{\sqrt{1 + K_{en}}} \sqrt{\frac{2}{\rho} (p_2 - p_0)} \quad (24)$$

where A_n is the nozzle area, K_{en} is the hydraulic loss coefficient at the throat entry, p_2 and p_0 are the pressures at the suction port and throat inlet, respectively. The factor c is a function of the throat and nozzle cross-sectional areas, expressed by:

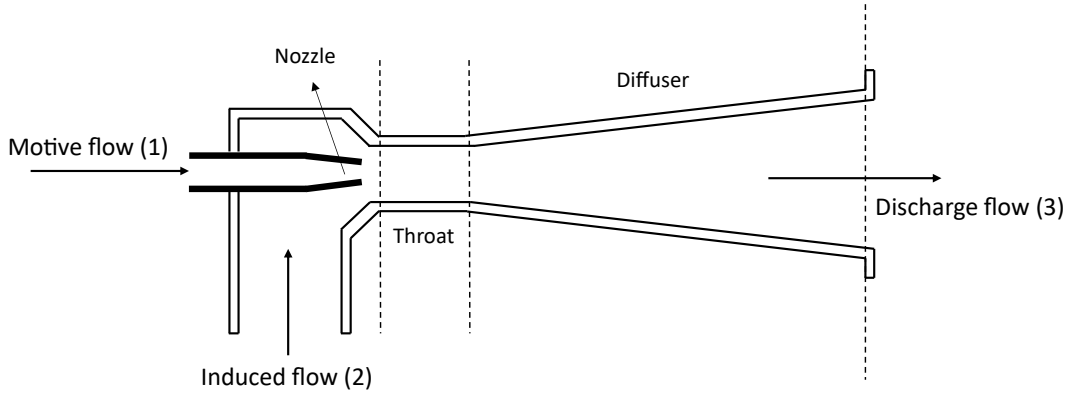


Figure 21: Jet pump schematic.

$$c = \frac{1 - r_2}{r_2} \quad (25)$$

As seen, the secondary flow rate depends a lot on the geometric parameters of the pump and motive flow rate. Typical values for jet pump efficiency range from 15 to 35% [13], and this efficiency can vary a lot depending on the pressure drop at the discharge port, as will be explained in the model analysis chapter. An important parameter to evaluate the jet pump's performance is the pressure ratio, described by:

$$N = \frac{P_d - P_i}{P_m - P_d} \quad (26)$$

where P_d , P_i , and P_m are the discharge, induced, and motive port pressures, respectively. Besides the pressure ratio, a very important parameter is the flow ratio, which can be calculated by:

$$M = \frac{Q_s}{Q_m} \quad (27)$$

where Q_s and Q_m are the suction and motive flow rates. The value of the flow ratio generally ranges from 0.5 to 2.5. For instance, a jet pump with a motive flow rate of 1 liter per minute can induce 2 liters per minute if it has a flow ratio of 2. The efficiency of the jet pump depends both on the flow ratio and the pressure ratio, so with N and M the pump's efficiency can be calculated:

$$\eta = NM \quad (28)$$

As will be shown in later sections, the jet pump is an extremely sensitive device in terms of flow and pressure variation of its neighborhood, so its operating range needs to be carefully studied so it can meet its output requirements.

3.6 Valves and orifices

Valves and orifices are also essential blocks when modeling fluid circuits. Their main function is to add pressure drop to the system, and this can be useful to control the amount of fuel that goes to the engine or interrupt refuel flow when the aircraft fuel tanks reach the desired level. The orifice equation states that the flow through a pipe is proportional to the square root of the pressure drop across the orifice [14].

$$Q = C_o A \sqrt{(2g\Delta P)/\rho} \quad (29)$$

where Q is the flow rate, C_o is the orifice coefficient, A is the orifice area, g is the gravitational acceleration, ΔP is the pressure drop across the orifice, and ρ is the fluid's density.

The valves are more complex components, which can be of various types, including shutoff valves, check valves, flow control valves, and crossfeed valves. The multi-way directional valves (3 or more ways) are not covered here since they were not used in the fuel system modeling. The shutoff and flow control valves are considered two-way directional valves because they enable the flow from port A to B and vice versa. These valves are modeled as a variable orifice, which can be controlled by a linear spool. The spool actively controls the orifice area, consequently controlling the pressure drop across it, so in the shutoff scenario, the spool position can go from totally open ($x = 5$ mm) to totally closed ($x = 0$ mm) for example, while in the flow control scenario, the spool position has to be adjusted to achieve the required flow rate. The check valves are slightly different, as they only enable the fluid to flow in one direction, so they are classified as one-directional valves. In the context of a fuel system, check valves can act as flapper valves, which let the fuel flow from one tank to another by gravity in the direction of the wing root only. Check valves can also be placed before the suction inlet of the jet pumps, preventing the fuel from flowing back to the auxiliary tank.

3.7 Chapter summary

This chapter introduced the reader to simple concepts about fluid circuits and fluid mechanics, where some equations were presented, such as Bernoulli's equation, which was further applied to a simple example of fuel transfer between tanks. Later in the chapter, the fundamentals of dynamic system modeling were presented, including common simulation solver types. Finally, the key components of the fuel system, such as tanks, pumps, and valves, were briefly discussed from a modeling perspective.

Chapter 4

Model Development

A significant part of this work was dedicated to developing the system model, which became a tool to perform simulations and understand the system from another perspective. This section is divided into three subsections: software selection, model objectives, and model building.

Usually, the works related to system modeling and simulation address the validation of the model [15, 16, 17, 18, 19], which supports the reliability and accuracy of the model by comparing the model results with real-world data, or even with theoretical predictions based on analytical equations. In the context of this master's thesis, the validation process was not strictly necessary. However, this opens space for future work, where the model results presented in Chapter 5 can be compared with the previous works used as reference for this project and add value to the current model.

4.1 Software Selection

Extensive research was conducted as part of this thesis to identify a software tool suitable for system modeling of Aircraft fuel systems. Several different tools are available for system modeling, such as OpenFOAM, OpenModelica, and MATLAB/Simulink. Each of these tools has its own unique features. For example, OpenFOAM requires 3D geometry input and uses 3D Computational Fluid Dynamics (CFD) solvers to calculate pressure, temperature, and flow rate, which demands high computational power. On the other hand, Flowmaster is a general-purpose 1D computational fluid dynamics (CFD) code that allows users to choose pre-modeled components and connect them as required without needing 3D geometry input. Conversely, MATLAB is a high-level programming language that usually comes with Simulink as an extension. With its add-on Simscape, users can model systems in a component-based modeling approach involving multiple physical domains and integration capabilities. With so many software tools available, it is easy to become overwhelmed. To begin, a list of potential candidates was created, which included:

- MATLAB/Simulink + Simscape;

- Simscenter Amesim;
- OpenFOAM;
- COMSOL Multiphysics;
- Easy5;
- Flowmaster;
- OpenModelica;
- Modelon Impact;
- AxStream;
- Altair Activate.

From the list above, only 4 programs were found in the literature, with Flowmaster leading the list with 6 papers mentioning its applicability to aircraft fuel system models [20, 21, 22, 15, 16, 23], followed by MATLAB/Simulink [24, 25, 17, 26, 27], and finally Simcenter Amesim [28, 18, 29] and Easy5 [30, 31, 32] appearing in the same number of published articles 2. The software from the list not mentioned in the literature could also be used as a tool for this project, but one key factor for the software selection for this thesis was the amount of previous work already published. Among the criteria for selecting software, cost, availability of online documentation, and versatility were also relevant. Flowmaster lacks capabilities in modeling other physical domains since it is focused on fluid mechanical circuits, which makes it a less versatile option. MATLAB/Simulink, on the other hand, is already a very well-known software applied in many engineering fields. MATLAB itself is just a programming language, but Simulink can be acquired as an integrated product that works simultaneously with MATLAB. Additionally, Simulink has an add-on called "Simscape" which brings the versatility of modeling systems in various physical domains, such as hydraulic, electrical, thermal, magnetic, and mechanical. From an industry perspective, although the model presented here explores only the fluid mechanical area, the final objective remains integrating this system with the electrical and mechanical systems linked to it, thus the need for a more versatile option. In this field, MATLAB proved to be an excellent option, being used in almost 30% of the published articles and having extensive online documentation and support available for its tools.

Table 2: Number of times the software was identified in the literature.

Software Count		%
MATLAB/Simulink	5	29%
Simscenter Amesim	3	18%
Flowmaster	6	35%
EASY 5	3	18%
TOTAL	17	100%

4.2 Model Objectives

Until now, the model objectives and requirements were mentioned superficially. In a more detailed way, the model should be built so that the user can quickly identify the fuel's physical properties, such as fluid flow rate and pressure in different system locations at different time instants. To define the model requirements, it is important to first state where it starts and ends, in other words, the system's boundaries. Here, the focus will be on the airframe part of the fuel system and not on the engine part, where the high-pressure boost pump is located [33]. So, the end of the fluid circuit will be at the border (Airframe-Engine), well represented by the dotted line in figure 22.

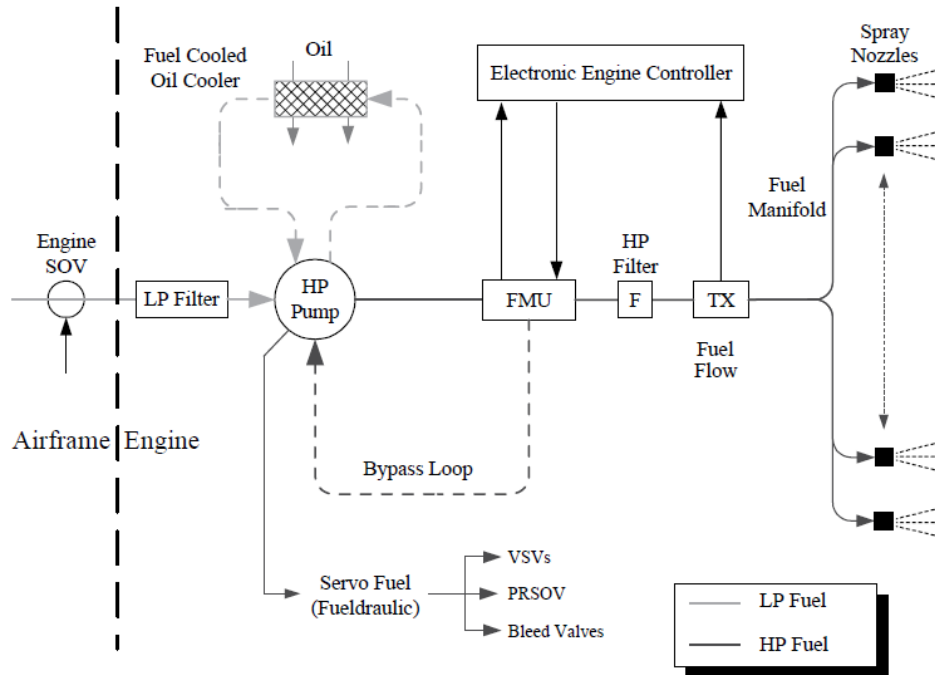


Figure 22: Fuel control system.

4.3 Building the model

To start building a model, it is important first to have a reference architecture, including the components needed and the connections between them. Based on the gathered knowledge about reference fuel systems from the same airplane category, some premises for the model were:

- Does not include center tank;
- Does not include Auxiliary Power Unit (APU);
- Includes 2 engines, one in each wing;
- Includes at least one centrifugal boost pump for each wing;
- Contains 3 tanks in each wing, including a collector cell;
- Has a single port for refueling/defueling;
- Includes a crossfeed valve;
- Uses at least one scavenge jet pump.

Besides the premises presented, for a complete representation of the system, it should be capable of simulating the critical functions of a fuel system, as presented in chapter two. These are fuel storage, engine feed, fuel transfer, refueling/defueling, and being able to crossfeed fuel from one wing to the other. The jettison function, although present in many systems, is not considered mandatory in this category of aircraft, so it was left aside. With these assumptions, a schematic of the reference fuel system system was built, serving as a guide for further model development, shown in the figure 23.

4.3.1 Feed System

The feed system model is the most basic model of a fuel system, including at least one tank, a booster pump, the feed line, and the engine fuel system inlet, which can be considered as a fluid reservoir. Figure 24 shows one example of the first models built to represent the feed system. The figure shows the tank connected to a centrifugal pump, acting as a booster pump, which will increase the pressure of the fluid to reach the engines. The check valve is included in the feed line to prevent fluid from flowing in the opposite direction. With this initial model, the user is already capable of simulating the feed function and observing the values of pressure and flow rates being delivered to the engine.

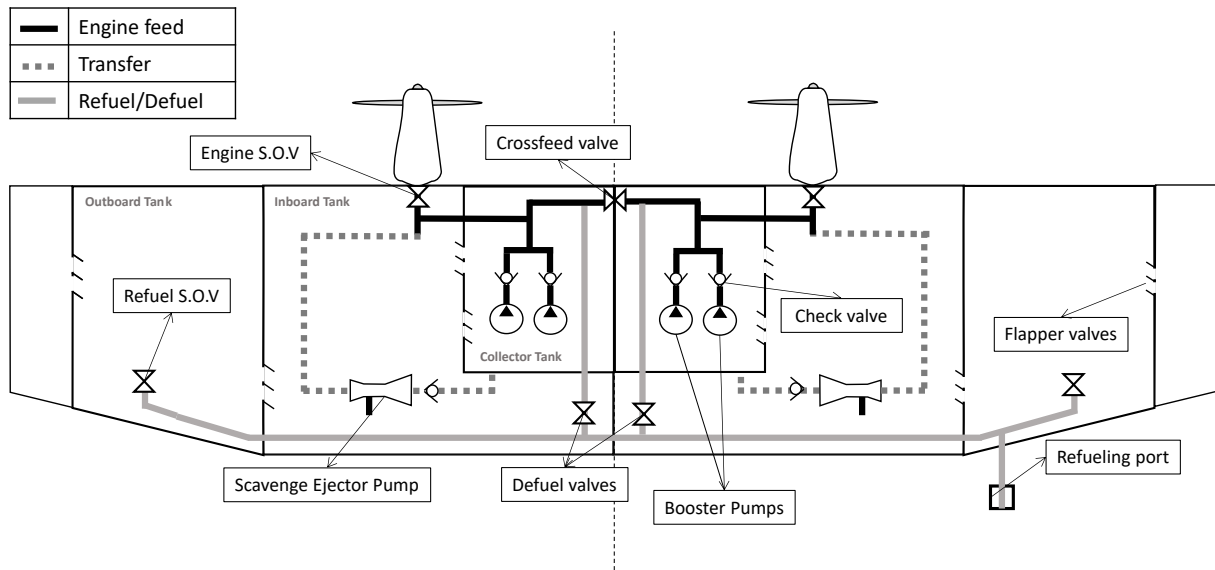


Figure 23: Reference fuel system schematic.

The centrifugal pumps must be capable of providing enough fuel to the engines in the most critical phase, which is the take-off phase. One way to calculate the required flow rate output is by

One constraint in this system is that the centrifugal pump's speed should not be controlled, meaning it operates with a constant shaft angular velocity during the simulation time. This brings the need to use a flow control valve so the fuel consumption by the engine can vary over time. In the model presented here, the flow can be controlled by a flow control valve or completely interrupted by a shutoff valve. The control over the valves is an input signal, which can be defined by the user as a 2-D array (time and data vectors), where the data represents the valve's spool position at a given time. This is important to simulate the engine demand, which will differ in each flight phase.

Creation of nodes

Simscape does not have, by default, a straightforward way to check how fluid properties vary in each location of the system. To overcome this, subsystems were created inside Simscape, which function as the system's nodes. A node represents the connection between two components, and inside the node, the user can check the properties such as mass/volumetric flow rate and pressure. These subsystems, called nodes, were built using flow rate and pressure sensor components from the Simscape Isothermal Liquid (IL) library (25), and their implementation enables the user to check the fluid properties in any location of the system.

The node has an input port A, where is the expected fluid "inlet," and a port B, the "outlet". If, for some reason, the value of the flow rate on this node is negative, the user can imply that the fluid is flowing

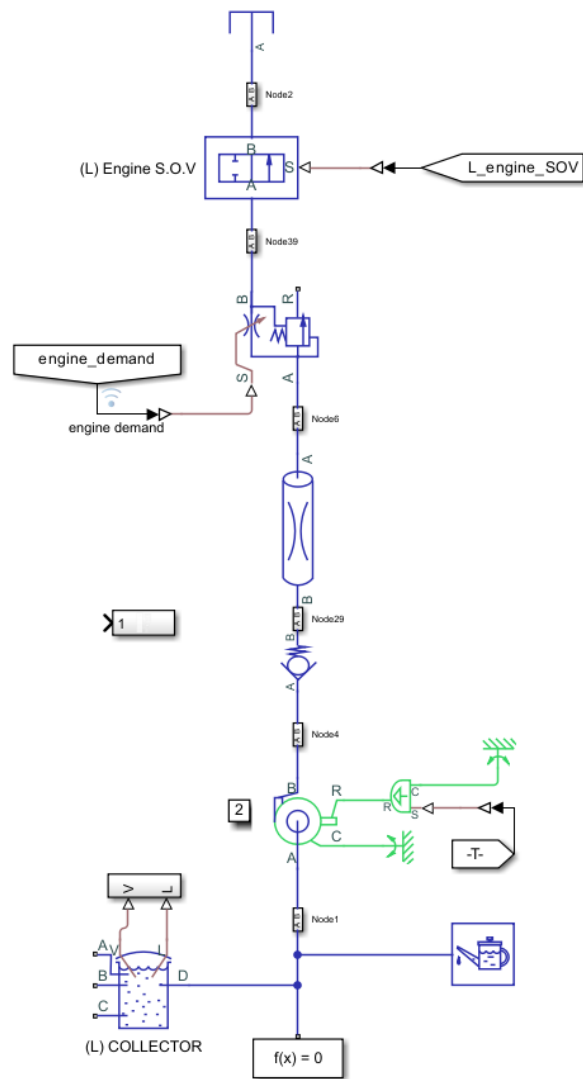


Figure 24: Basic feed system.

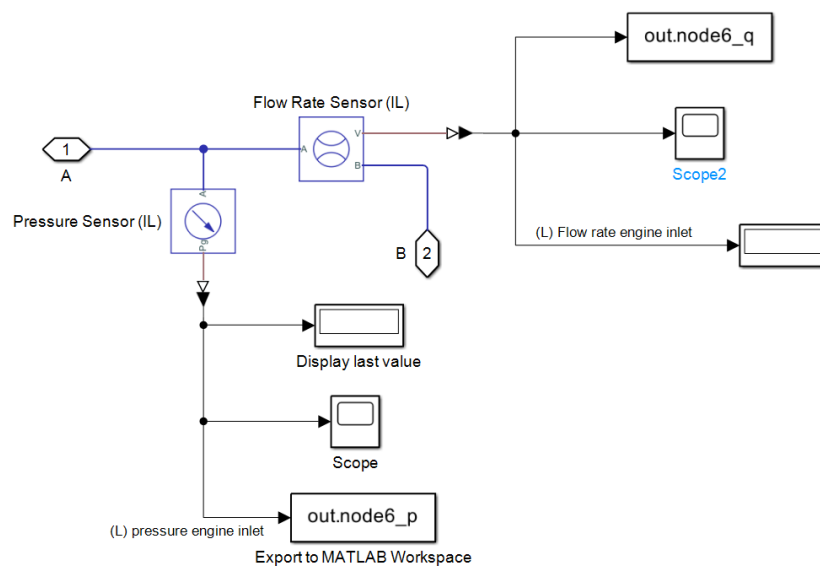


Figure 25: Node structure.

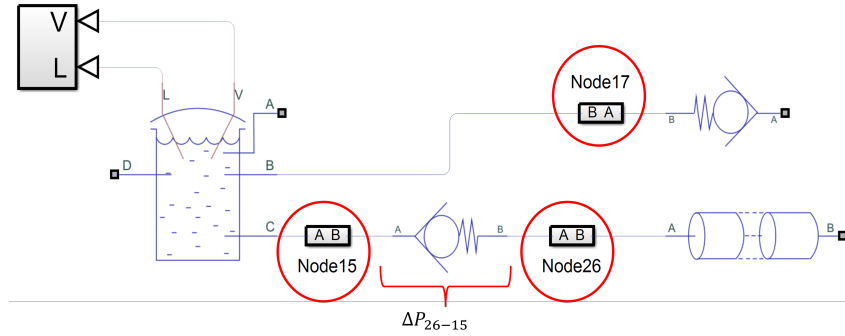


Figure 26: Example of how the nodes are used.

in the opposite direction. Each node also includes a display block for quick check, which is useful for stationary analysis, because it can hold the values of the parameters calculated in the last time step of the simulation. Additionally, a scope block is included to see the variation of the state variable over time, and finally, a "To Workspace" block, which sends the time and data vectors in 2-D array form to MATLAB workspace with the name of the node, so this data can be manipulated in a MATLAB script if needed. One example can be when the user wants to calculate the pressure drop value locally, for instance, across a check valve component 26. For this, the node's information is sent to the workspace, and considering the expected direction of the flow ($A \rightarrow B$), the pressure upstream is subtracted from the downstream pressure, thus resulting in the localized pressure drop.

4.3.2 Transfer System

With a single-wing feed system correctly built and performing as expected, the transfer system can be integrated into it by adding more tanks, valves, and a scavenge jet pump. The tanks added to this system represent the outboard, inboard, and collector tanks. The new configuration of the system appears in figure 27, where the feed system incorporated another centrifugal pump, which operates in parallel to the one in the previous model. This additional pump must work mainly as a backup pump, as required in most fuel systems. In extreme cases, when the fuel flow to the engine is higher than expected, both booster pumps might operate together. The new model also incorporates a jet pump, which has the function of transferring fuel from the inboard tank to the collector tank, thus keeping it always full as fuel is being consumed by the engine. The booster pumps usually supply more fuel flow rate than the engine requires, resulting in extra fuel. This excess energy can be bypassed at the engine interface and be re-directed to another part of the system and be used as the motive flow for the jet pump. The bypassed flow is directed to the motive port of the jet pump, resulting in a secondary flow coming out of the inboard tank.

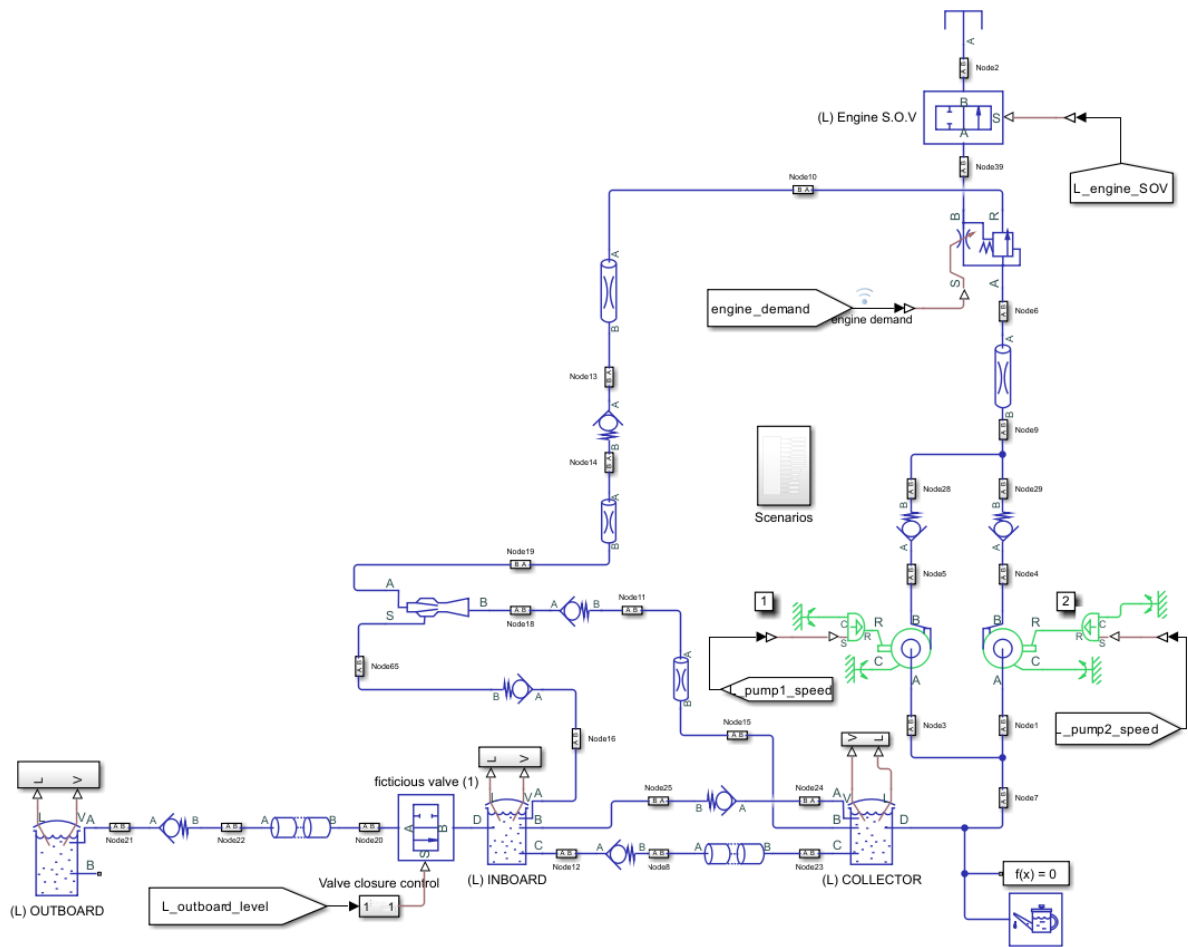


Figure 27: Feed and transfer system integrated.

Jet Pump Parametrization

Often, the default configuration of a jet pump component is not suitable for the specific requirements of the system it is being used in. For instance, the jet pump may produce a low flow ratio when the default geometric parameters are used, which can result in the collector tank fuel level decreasing over time. One way to estimate the jet pump geometric parameters to obtain a certain flow ratio is using the parameter estimator tool from Simulink.

The three basic geometric parameters that define the jet pump in Simscape are the nozzle area, the nozzle-to-throat area ratio (ratio 1), and the diffuser inlet-to-outlet area ratio (ratio 2). When testing the system with the default jet pump parametrization, the induced flow produced is almost zero because the pressure created at the throat region is not significantly low to suck fuel from the inboard tank, so the pump discharges only the motive flow it receives. This causes the flow ratio to be almost zero, which is undesirable.

Before estimating the parameters, the user can specify the range of values that each parameter can

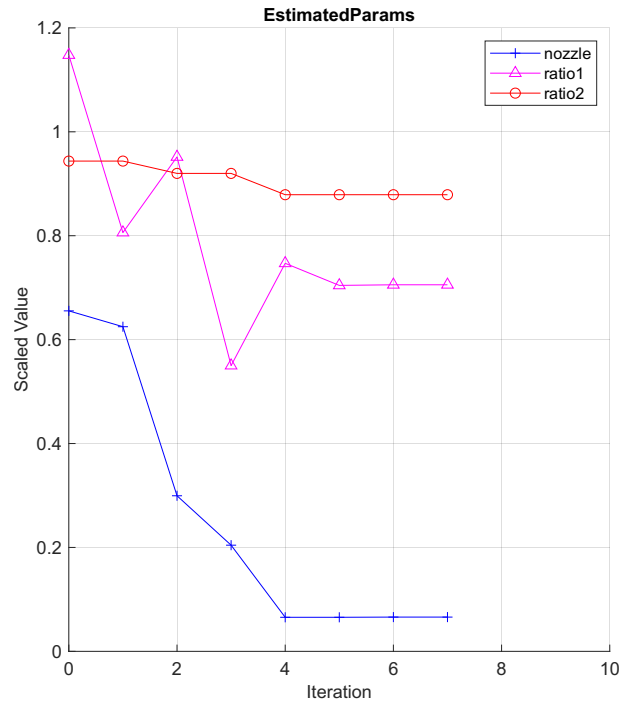


Figure 28: Example of the iterations taken to optimize jet pump parameters in the parameter estimator tool.

assume. This range of values will determine the scale factor of each parameter so the final results can be normalized. In the literature, a moderate value for a jet pump's flow ratio is around 2 [34]. By assuming a required flow ratio of 2, the estimated geometric parameters are calculated as shown in figure 28.

The vertical axis shows each parameter value normalized by the scaling factor previously mentioned. The horizontal axis shows the iteration number, where the higher the iteration number, the closer the flow ratio is to 2. It is possible to identify the convergence of the solution at the last three iterations, showing that the cost function was minimized and, therefore, the estimated parameter values for the jet pump will generate a flow ratio of approximately 2.

Although the flow ratio of 2 is high enough to make the collector tank always full, it does bring another issue, which is the over-pressurization of the collector tank because it discharges more fuel in the collector tank than what it actually needs. One way to make the collector tank level stable is to add a return line at the top of the collector tank so when fuel reaches a certain level,

The introduction of the dihedral angle

The dihedral angle is the upward angle of an airplane wing, measured from the horizontal axis. This is illustrated in figure 29. In simple terms, if an aircraft has a positive dihedral, its wing tip will be higher than its wing root. Conversely, a negative dihedral is also known as anhedral. The wing dihedral enhances

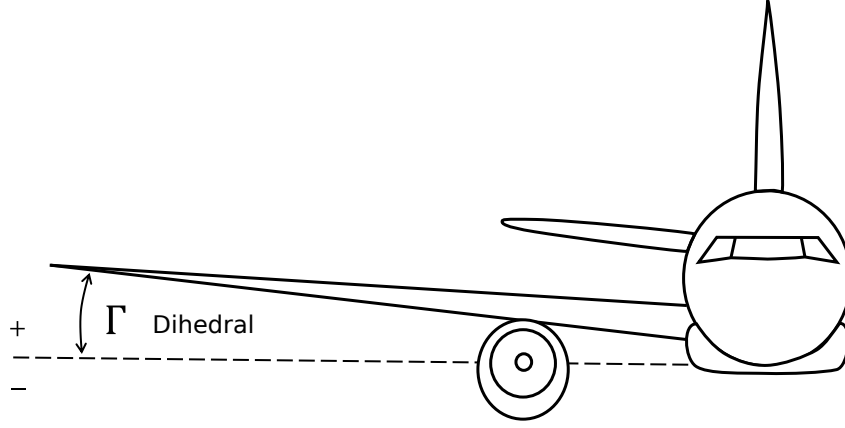


Figure 29: Dihedral angle measurement.

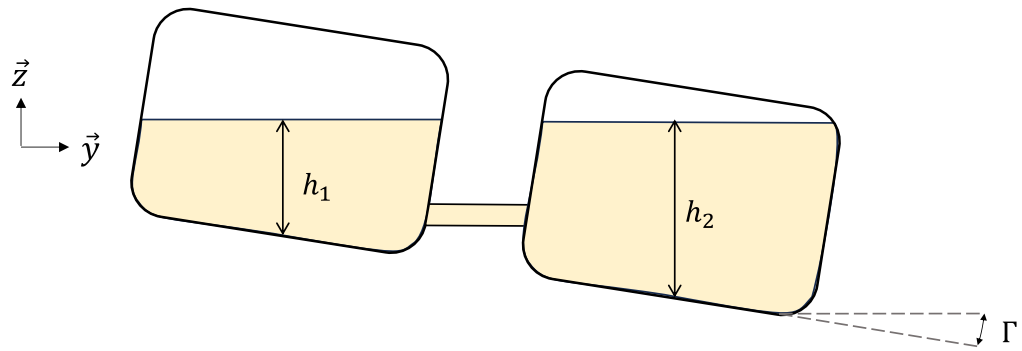
stability during rolling and improves ground clearance. In the context of a fuel system, although it might seem negligible, it does affect how fuel is transferred between the tanks. Naturally, when there is a difference in fuel level between two tanks, gravity will generate a flow from the upper to the lower tank. However, the addition of the dihedral angle will change the way in which the fuel is distributed along the tank's geometry.

The first approach to model this effect would be looking into Simscape fluids library and finding a tank component which 3D geometry could be specified with respect to the horizontal plane, but the current version of Simscape does not include this feature in the tank component. In Simscape, the tanks are always defined as an area contained in the horizontal plane extruded to the 3D space when multiplied by the tank's height. Since the height difference cannot be modeled within the tanks, another way to model the dihedral angle effect was using the pipe component, which can model the elevation between the tank ports. A comparison between the real case and the proposed model is shown in figure 30.

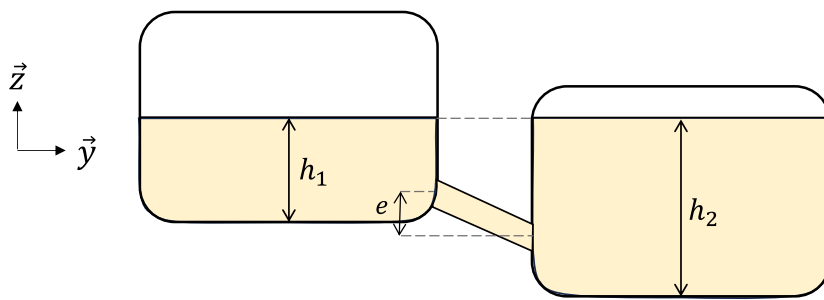
To make an approximate model, the dihedral angle (Γ) needs to be converted to a pipe elevation (e), as observed in Figure 30b. The elevation of the pipe is a consequence of tank geometry, which is derived from the wing geometry. For this model, each wing is assumed to have 3 tanks, and each tank centerline is spaced by L_{tank} , as shown in figure 31. Assuming that the length $b/4$, dedicated to wing tanks, is equally divided between three tanks, the value of L_{tank} can be derived as a function of the aircraft wingspan b :

$$L_{tank} = \frac{1}{12}b \quad (30)$$

Having the tank spacing defined, the next step is to define the pipe elevation as a function of the dihedral angle, and for this, the schematic presented in figure 32 was built. From the triangle formed by L_{tank} and e can be computed by the following equation:



(a) Tanks inclination due to the dihedral angle.



(b) Proposed model for the dihedral angle effect on the fuel system.

Figure 30: Comparison between the real case and the model proposal for the tanks and piping configuration

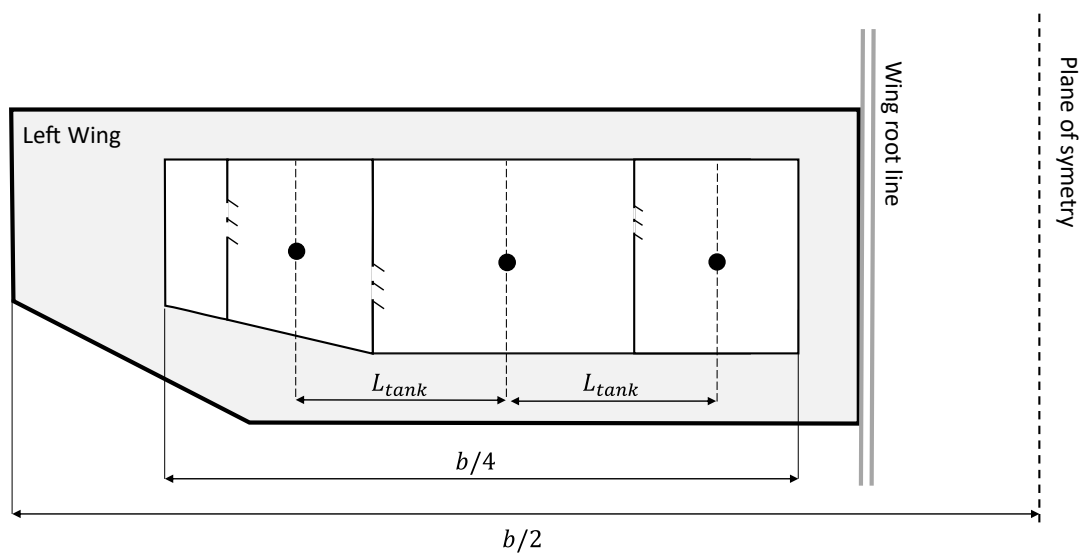


Figure 31: Wing and tank dimensions and spacing.

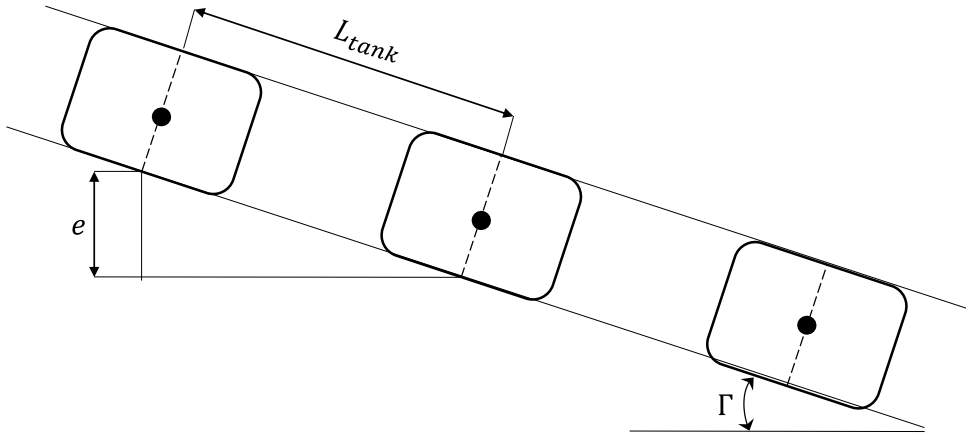


Figure 32: Pipe elevation model schematic.

$$e = -\sin(\Gamma) \times L_{tank} \quad (31)$$

Where the minus sign appears because the elevation is negative from port A to B, assumed to be the direction of the flow. Equation 31 was included in a MATLAB script used for the system's parametrization (Appendix A), so it automatically computes the piping and tank configuration according to the dihedral angle value entered at the beginning of every simulation. This is useful for performing studies with different dihedral angles or even simulating the rolling maneuver.

Flapper valves

As mentioned in chapter 2, the flapper valves are devices that let the fuel flow from external tanks to inboard tanks when there is a head difference greater than the valve's cracking pressure differential. In Simscape, these valves are modeled as simple check valves because they have the property of enabling the fuel flow only from port A to B, considered the normal direction of the flow. In the feed system, the outboard tank is connected to the inboard tank by a flapper valve, while the inboard tank is connected to the collector tank by the flapper valve and jet pump to ensure that the level of the collector always stays above the inboard tank's.

Considering the second model (Figure 27), another valve was added between the outboard and inboard tanks, with a shutoff function. This valve was added to the model with the only purpose of interrupting the fuel flow coming out of the outboard tank when it was almost empty because in Simscape, when the tank level is lower than the flapper valve's height, the simulation fails. In reality, this valve doesn't exist, but it helps avoid simulation errors in the model.

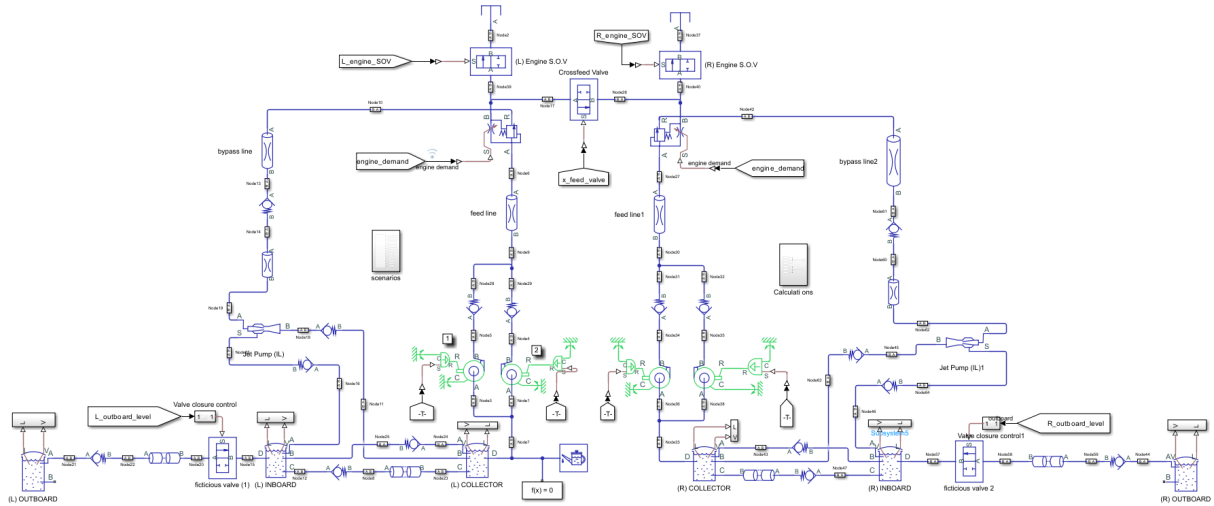


Figure 33: feed and transfer system with crossfeed function.

4.3.3 Crossfeed Function

After concluding the feed and transfer system integration, the two-wing fuel system model was built, duplicating the single-wing system and adding a crossfeed valve. The crossfeed valve is modeled as a shutoff valve that connects both left and right-wing feed lines, as shown in the previously presented schematic 23. The Simscape model with the crossfeed function appears in figure 33. The figure shows that the crossfeed valve is in the symmetry line of the model, and it is controlled by a signal X_feed_valve , which defines the position of the valve's spool over time.

4.3.4 Refueling/Defueling System

As a final step, the refueling and defueling functions were added to the system. In Chapter Two, the discussion highlighted two different types of refueling architectures: the combined transfer and refuel/defuel system, and the dedicated refueling gallery. The present model incorporates the dedicated refueling gallery, that dispenses fuel to the outboard tanks. The process of refueling is typically done through a single port located on the right wing. To accomplish this, an additional tank inlet was added to the right outboard tank. Attached to it, a branch was created that connects the right and left outboard tanks, effectively creating the refuel/defuel gallery with intermediate pipe components. Each outboard tank refuel inlet must have a shutoff valve so the refueling process can be interrupted when the tank levels reach the desired value.

The defueling is what enables the airplane to pump fuel out of the tanks, and this is done by the aid of the feed pumps. As seen in the model, the feed lines are connected to each other by the crossfeed valve,

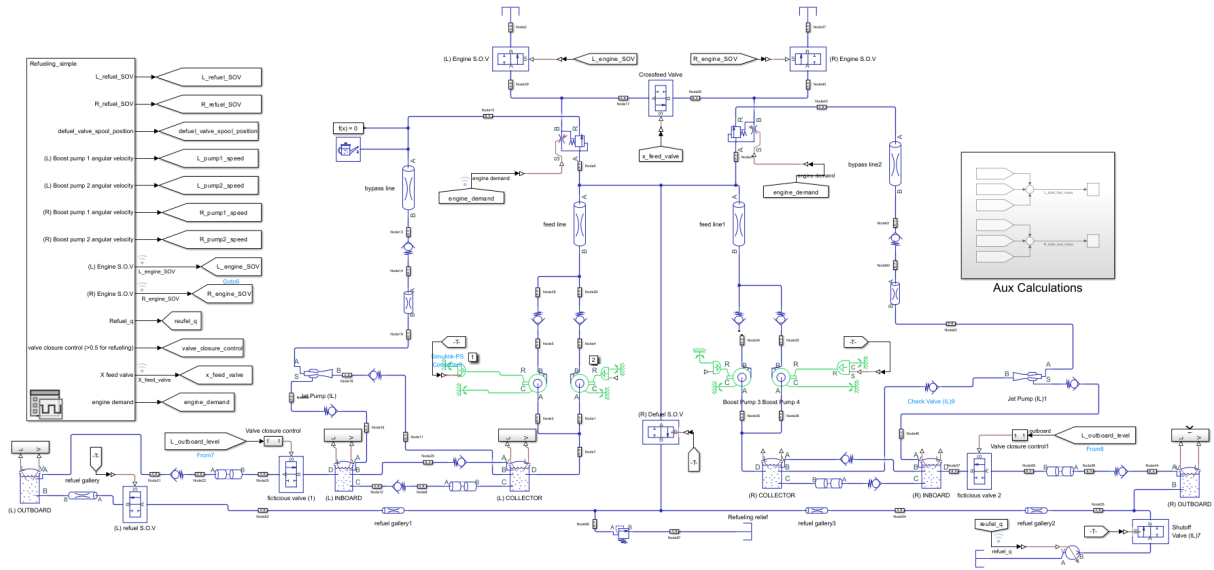


Figure 34: Complete system.

but in the last model, each feed line has a branch that connects it to the refuel gallery, enabling the feed pumps to pump fuel out of the tanks. For this case, the engine shutoff valves must be closed, and the defuel valves shutoff valves open so fuel is directed to the refuel/defuel gallery. The final model appears in figure 34, but in the appendix B, it is shown with higher resolution.

4.3.5 Model limitations

At the end of this chapter, it must be noted that the model has some limitations and might not apply to every study regarding the identification of physical properties inside the fuel system. The model encompasses several pre-modeled components, and they are integrated based on architectures observed in the referenced articles. The fuel system model considered the liquid phase, however, since the tanks are also filled with air, the gas phase must be included in the modeling for more accurate simulations, also because the air pressure in the tank ullage will determine how close the fuel is to evaporate. Additionally, the architecture proposed in this thesis uses a jet pump that takes fluid from the feed line as a motive source, and this might not apply to every architecture, causing the study of the jet pump sensitivity to be less relevant. It should be noted that the model's simulation results were not validated by comparing them to experimental data. As a result, the only measure that can be obtained is from the solver configuration used in Simulink, which was the ode15.

4.4 Chapter summary

This section covered the methodology of the thesis, from software selection to the final model architecture. MATLAB is a very popular software in various engineering applications, while Simulink is an additional product from Mathworks, which uses a block diagram approach for modeling systems. Inside Simulink, the Simscape add-on can be used to model fluid systems with its extensive library of physical components, making it a suitable option for the task. At the beginning of the model development, a reference architecture was presented, and the first step was to model the feed system; then, the transfer system was integrated, including more tanks, a scavenge jet pump and inclined pipe components to model the dihedral angle effect. Later, adding the crossfeed valve, modeled as a shutoff valve, enabled the connection of the right and left sides of the system. The refueling gallery was integrated into the system as the last modeling stage.

Chapter 5

Model Simulations and Analysis

The final part of this work was dedicated to using the model capabilities to study some issues that are present in the fuel system. Some of the simulations are presented to demonstrate the model's capabilities and flexibility, while other studies bring relevant insights for system engineers. In this section, some issues are studied, such as the sensitivity of the jet pump to its geometric parameters and position in the system, the influence of the dihedral angle on the fuel transfer, the imbalance caused by single-sided pressure refueling, the "water hammer" phenomenon during refueling and finally an engine failure scenario in which the crossfeed valve impact is analyzed.

5.1 Jet Pump Sensitivity Analysis

The scavenge jet pump brings a lot of advantages for being a low-cost device with no moving parts and, therefore, extremely reliable. One drawback is that this pump is very sensitive to some parameters, such as the motive flow rate, nozzle area, nozzle-to-throat ratio, throat-to-diffuser ratio, and outlet and inlet pressure. These parameters can significantly affect the efficiency and how much fuel is drawn from the inboard tank and discharged into the collector tank. This is important to verify since the collector tank must always be full. To keep the collector tank always full, the flow rate that goes out needs to be replenished by the inboard tank, and this is accomplished by the scavenge jet pump, as seen from the figure 35. The flow rate measured at the jet pump's discharge port should be at least equal to the flow rate drawn from the collector tank to feed the engine. If the discharge of the jet pump is greater than the flow going out of the collector tank, the additional fluid can return to the inboard tank through a return line.

Mathematically, this condition can be expressed as:

$$Q_{in} \geq Q_{out} \quad (32)$$

In which Q_{in} and Q_{out} are the flow rates in and out of the collector tank. Based on figure 35, the equation

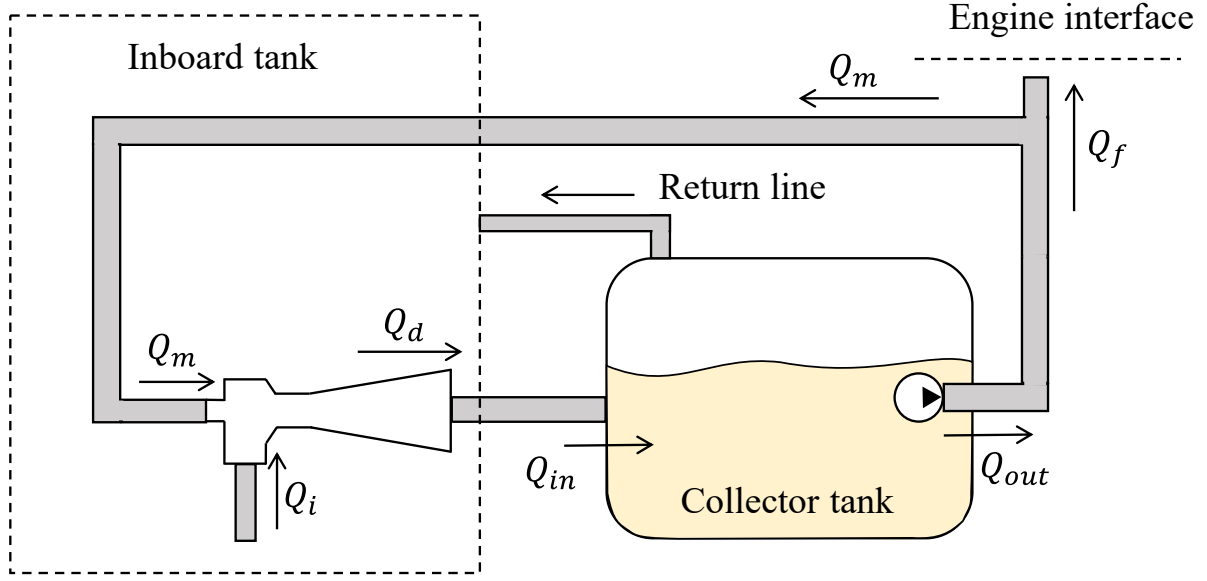


Figure 35: Scavenge jet pump and collector tank flow balance.

32 can be written as:

$$Q_d \geq Q_f + Q_m \quad (33)$$

Where Q_f is the engine feed flow rate, Q_d and Q_m are the discharge and motive flow rates of the jet pump, respectively. Considering that the discharge flow rate is the sum of the motive flow with the induced flow Q_i , the equation (33) becomes:

$$\cancel{Q_m} + Q_i \geq Q_f + \cancel{Q_m} \quad (34)$$

The motive flow is canceled out of the equation, and the requirement for the jet pump is written as a function of the induced flow:

$$Q_i \geq Q_f \quad (35)$$

To ensure that the induced flow is at least the same as the maximum engine feed flow rate, the jet pump performance needs to be studied.

The jet pump's efficiency is the product of the flow ratio by the pressure ratio, and in the case of the scavenge jet pump, the flow ratio is more important to meet the requirement imposed by equation 35. The flow ratio can be affected by several factors, and in this study, seven of them were analyzed. Some of the analyzed parameters were already presented in earlier chapters, namely the geometric parameters of the pump as nozzle area, nozzle-to-throat ratio, and diffuser inlet-to-outlet ratio. The other variables that

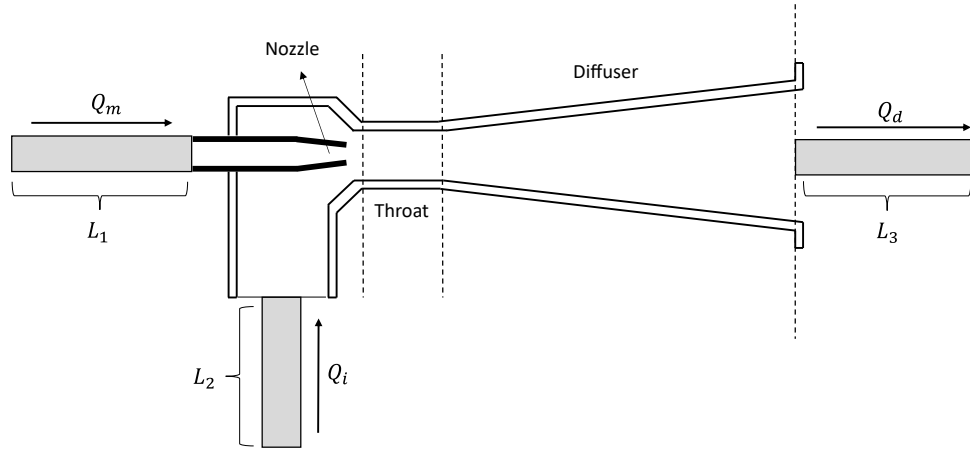


Figure 36: Jet Pump study variables.

might impact the flow ratio are the lengths of the pipes in each jet pump port, as identified by L_1 , L_2 , L_3 in figure 36. In the schematic, each port is connected to a pipe component, and each pipe might have a different length, depending on the position of the jet pump in the system. The different pipe lengths will lead to different pressure drops due to friction, affecting the flow ratio.

The last parameter to evaluate is the engine demand, which varies during flight. As discussed earlier, the motive flow is the bypassed portion of the flow that is pumped to the feed lines, and since the engine demand varies, the bypassed flow used to power the jet pump will change as well, which might impact its performance.

A sensitivity analysis was conducted to understand how each variable is correlated to the system output, namely, the flow ratio. The approach taken was to generate random values in a given range for each parameter, following a uniform distribution (Table 3).

Table 3: Parameter range specification for random values generation.

Parameter	Min	Max	Type of distribution
Nozzle area [m ²]	1.00E-05	1.00E-04	Uniform
Ratio1	0.1	0.4	
Ratio2	0.1	0.4	
L_1 [m]	0.01	2	
L_2 [m]			
L_3 [m]			
Engine Demand [L/min]	0.8	5.3	

The number of values generated for each parameter was set to 50, resulting in 50 different simulations,

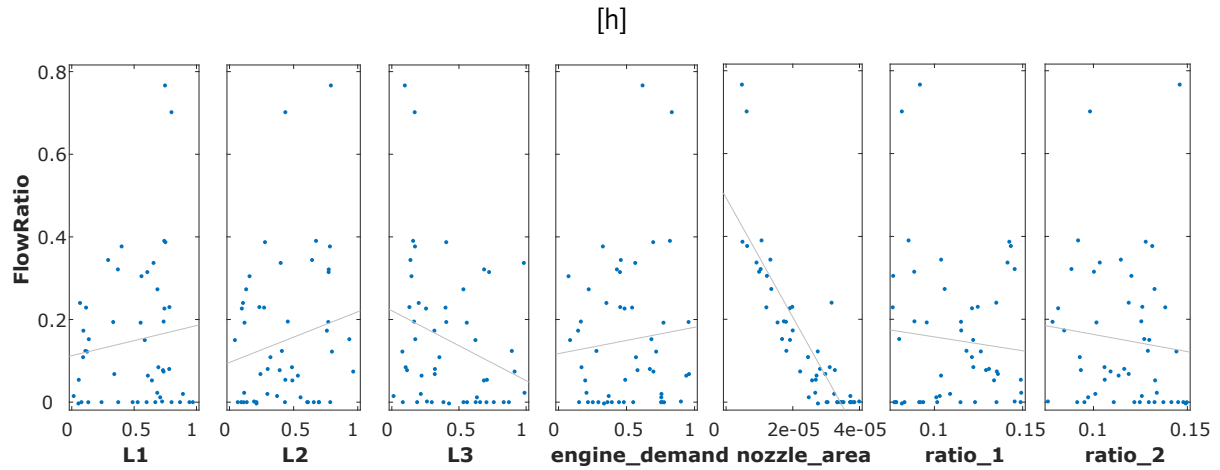


Figure 37: Sensitivity analysis for all 7 variables.

producing 50 different flow ratios. Each parameter range was defined based on common values found for smaller aircraft fuel system applications.

In the table, the variables *ratio_1* and *ratio_2* refer to the nozzle-to-throat ratio and diffuser inlet-to-outlet ratio, respectively. After simulating, the flow ratio is plotted against each variable, as shown in figure 37, where the first sensitivity analysis results are shown. The variables with higher correlation can be identified by looking at the line created by the linear regression from the plotted results. The first sensitivity analysis demonstrated that the flow ratio ranges between almost zero to about 2 within the results of the simulations performed, indicating an extremely high variability. From the variables plotted, the nozzle is the only one that presents an evident correlation to the output, while the others do not illustrate any specific bias. The correlation values are presented in the tornado plot from figure 38.

The tornado plot shows that the jet pump's nozzle area highly affects the flow ratio. The correlation between these two variables is negative, indicating that smaller nozzle areas must produce higher flow ratios. Considering the optimal value for the nozzle area being $1e-5 \text{ (m}^2\text{)}$, a further step was taken by analyzing the sensitivity of the flow ratio when the nozzle area was fixed.

A second sensitivity analysis was performed by removing the variation of the nozzle area and generating 50 more random values for the remaining parameters. The second sensitivity study is shown in figure 39. The figure indicates that when removing the nozzle area, the flow ratio values fluctuate between 0.9 and 2.4, which is still a significant variation. From the plots observed, the linear fit from most of the data does not show any trend, except for *ratio_1*, which illustrates a strong negative correlation.

By computing the statistics from these results, a second tornado plot was created, appearing in figure 40. After analyzing the tornado plot, it is clear that, up to this point, only the geometric parameters have been significant in maximizing the flow ratio. Nevertheless, the dominance of the *ratio_1* might have

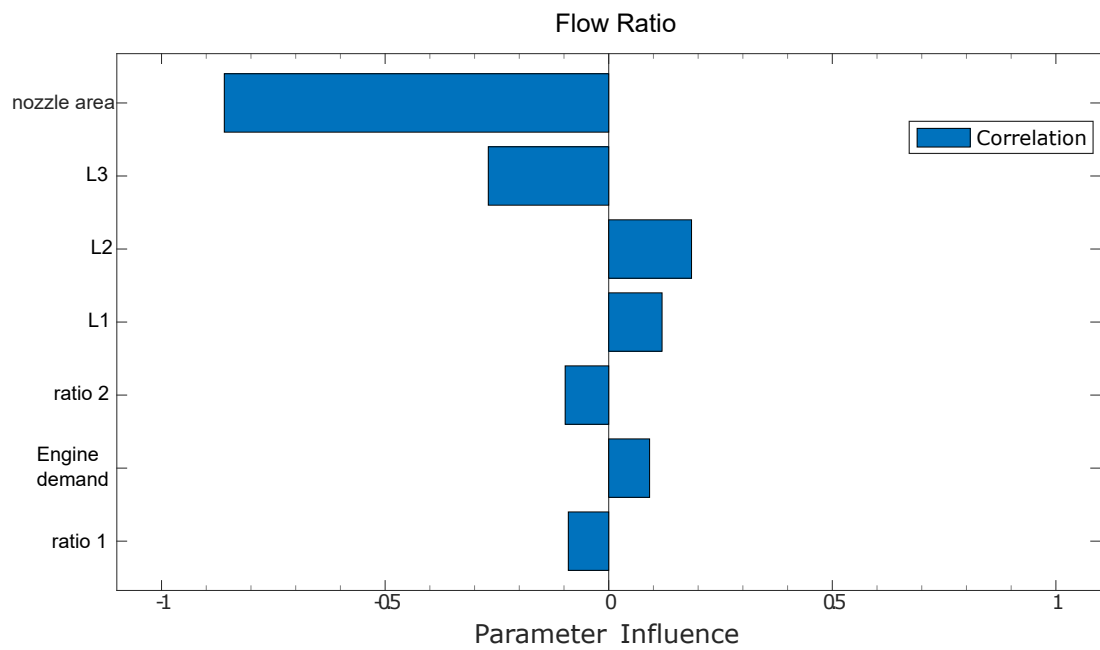


Figure 38: Tornado plot of the sensitivity analysis for all variables.

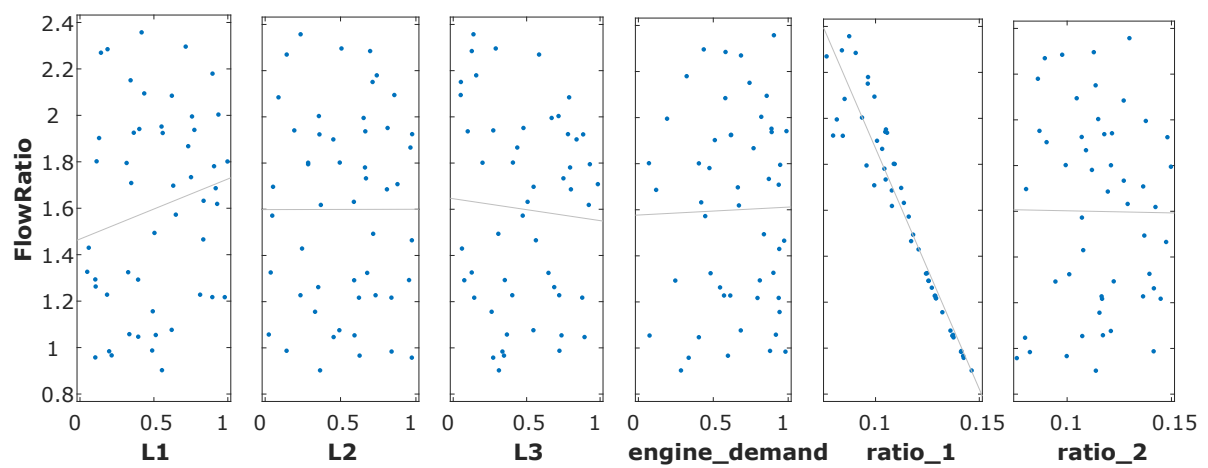


Figure 39: Sensitivity analysis excluding the nozzle area.

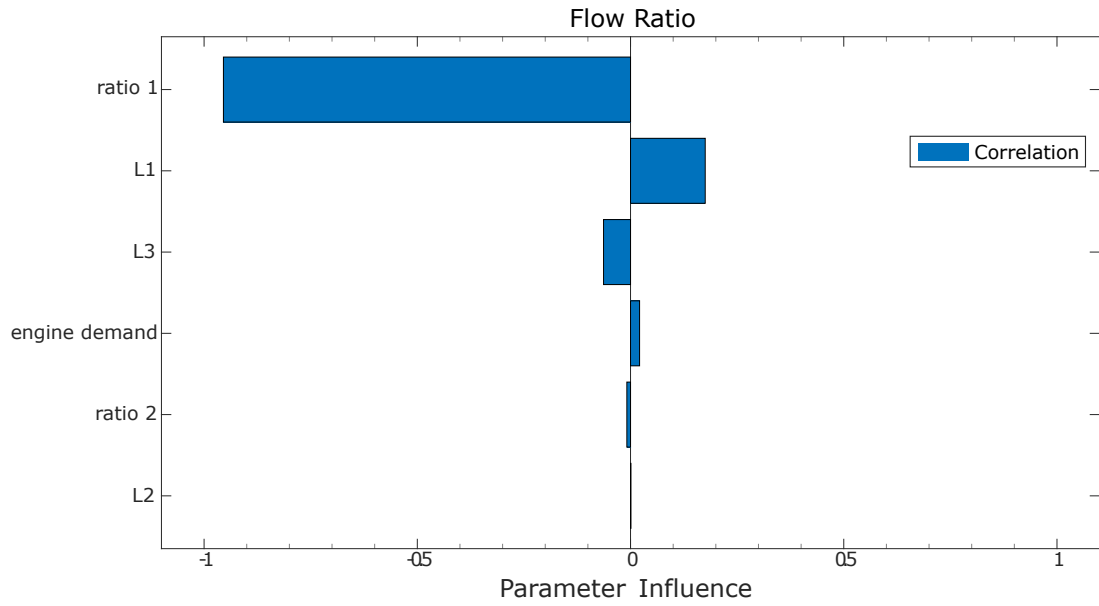


Figure 40: Tornado plot of the sensitivity analysis excluding the nozzle area.

hidden the influence of the other parameters, motivating another sensitivity analysis to be conducted while excluding the *ratio_1* variable from the analysis by setting it to constant.

The next study considered the nozzle area and the nozzle-to-throat ratio fixed at $1\text{e-}5 \text{ m}^2$ and 0.1, respectively. The remaining parameters used a new set of random values, generated again with the same specifications previously presented. The results are plotted in figure 41:

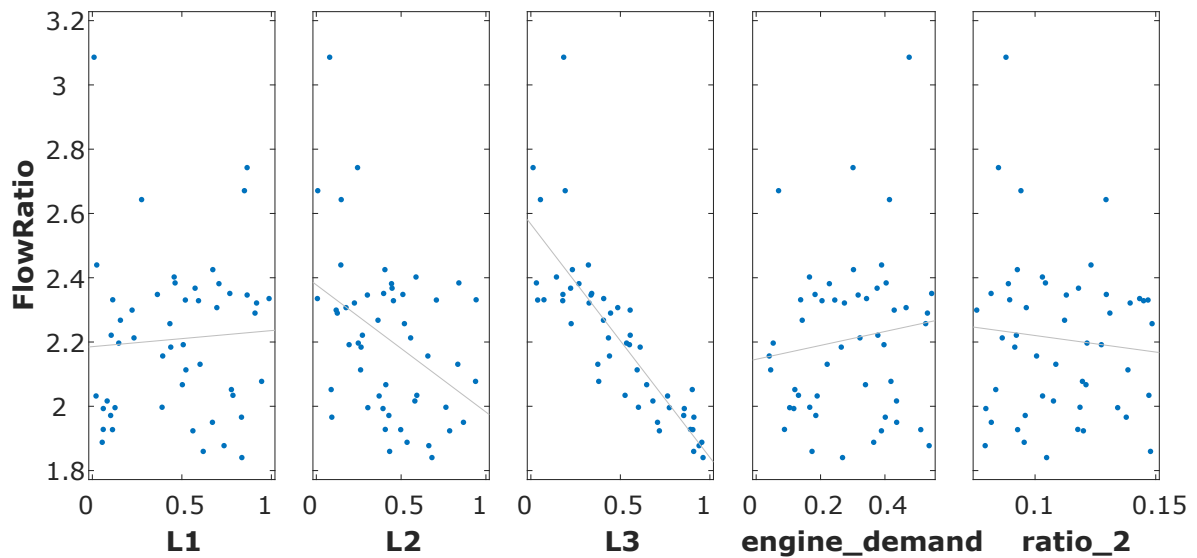


Figure 41: Sensitivity analysis excluding nozzle area and *ratio_1*.

The last sensitivity analysis shows that the flow ratio ranges approximately from 1.9 to 3.1, but most of the values appear between 1.9 and 2.5. The higher values of the flow ratio resulted from the lowest

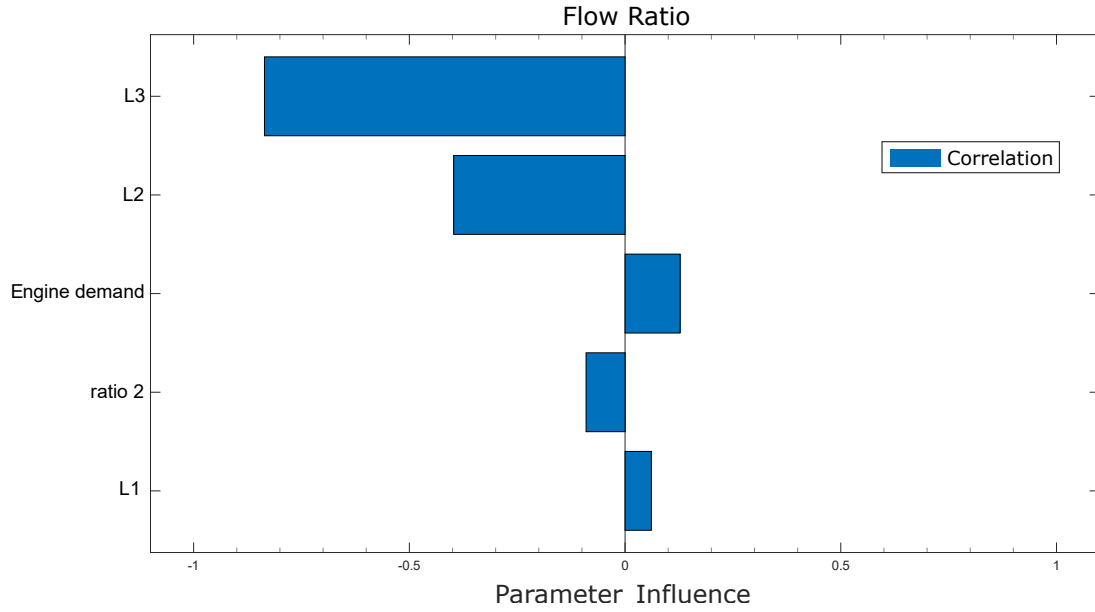


Figure 42: Tornado plot of the sensitivity analysis excluding nozzle area and *ratio_1*).

values of L_1 , L_2 , and L_3 , which agrees with the hypothesis that the pressure drop in the lines affects the amount of flow drawn from the inboard tank. Although this hypothesis may sound obvious, the lengths of the lines have different impacts on the system's output. The plots show that the length of the pipe at the discharge port L_3 has a significant negative correlation with the flow ratio, suggesting that when the pump is placed far from the collector tank inlet, it will affect the flow ratio produced. The tornado plot in figure 42 shows the parameter's influence, and unlike the previous graphs, here, 2 variables show a significant correlation, namely L_3 and L_2 .

As per the previous analyses, it is evident that a careful study of the placement of the jet pump can greatly benefit in achieving an optimized jet pump performance. In this scenario, where the flow ratio must be high enough to maintain the collector tank at its maximum capacity, the strategy for optimizing its performance should involve placing it as close as possible to the collector tank. The study also indicates that the engine demand does not significantly influence the flow ratio. Therefore, the flow ratio during flight is expected to remain constant regardless of the fuel consumption rate.

As a last step, a fourth sensitivity analysis was performed, excluding the higher correlation variable from the previous study, which was the length of the discharge pipe (L_3). From the remaining parameters, the parameter L_2 shows a higher correlation with the output, but since the range of values for the generated flow ratio was only about 0.25, this last analysis is not explored.

In summary, the sensitivity analyses conducted on the jet pump system have provided valuable insights into the key factors influencing the flow ratio. It became evident that the nozzle area is the most influential parameter, and the nozzle-to-throat ratio also plays a significant role when determining the flow ratio, both

with a negative correlation. Furthermore, the placement of the jet pump relative to the collector tank, specifically the lengths of the discharge and suction pipes (L_3 and L_2), also demonstrates a noteworthy influence on the flow ratio. The results suggest that optimizing jet pump performance involves carefully considering nozzle geometry and the spatial arrangement of the jet pump in relation to the collector tank. Importantly, these findings indicate that engine demand does not significantly impact the flow ratio, providing stability in fuel supply during flight. As the analysis evolves, a comprehensive understanding of these factors will guide the design and operation of jet pump systems for optimal performance and efficiency.

5.2 Dihedral angle effect on fuel transfer

Another interesting study can be done with the model, focusing on the transfer system, observing the tank levels and mass variation with the inclusion of a wing dihedral angle. The effect caused by the dihedral angle on the fuel transfer, although not obvious, plays an important role in the design of the fuel system, namely the amount of scavenge jet pumps used. By adding a dihedral angle on the wings, the fuel will transfer inboards faster, which, in turn, creates head differences, and these results are explored here by analyzing fuel tank level variation over the flight phases for different wing dihedral angles.

The first case considered that the airplane has no wing dihedral ($\Gamma = 0$), the engine demand is an input signal based on normalized data for a common flight mission profile, and the total simulation time is around 2.2 hours. Figure 43 shows the graph for the valve spool position of the flow control valve, placed before the engine fuel system inlet, to simulate the imposed engine throttle. The flight phases are represented by the fuel consumption variation over time, simplified by step functions, where the cruise is the predominant phase during the simulation. Initially, the tank levels are set to complete (98% of its maximum capacity).

As expected, the collector tank level (Figure 44) is maintained during the entire flight. This happens because the jet pump is always drawing fuel from the inboard tank and discharging it into the collector tank, thus decreasing the level of the inboard tank over time. As the inboard tank empties, the head difference between the inboard and outboard tank increases, which generates a fuel flow toward the root of the wing. However, a minimum head difference must first be created for the fuel to overcome the flapper valve cracking pressure and be transferred from the outboard to the inboard, which only happens about 0.25 hours.

The graph shows that the inboard tank will empty before the outboard tank, creating a significant

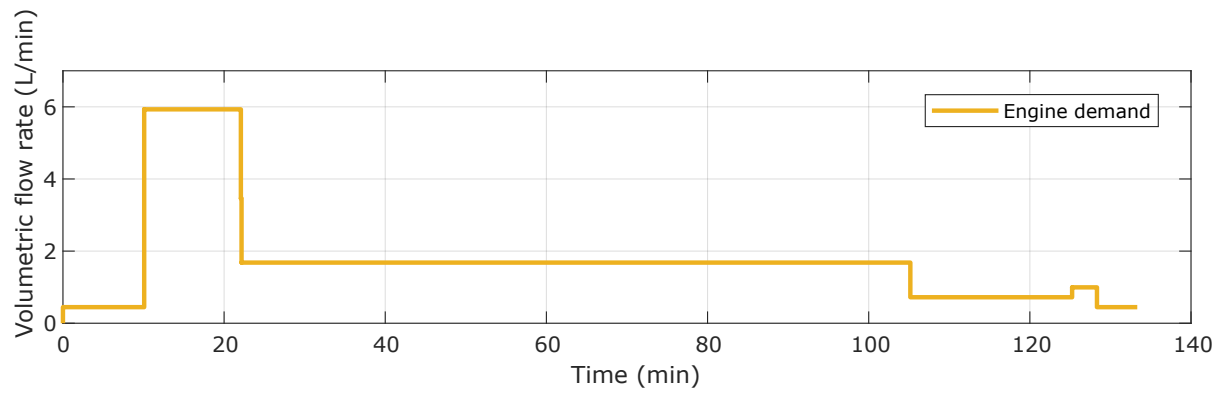


Figure 43: Engine consumption based on a typical mission profile.

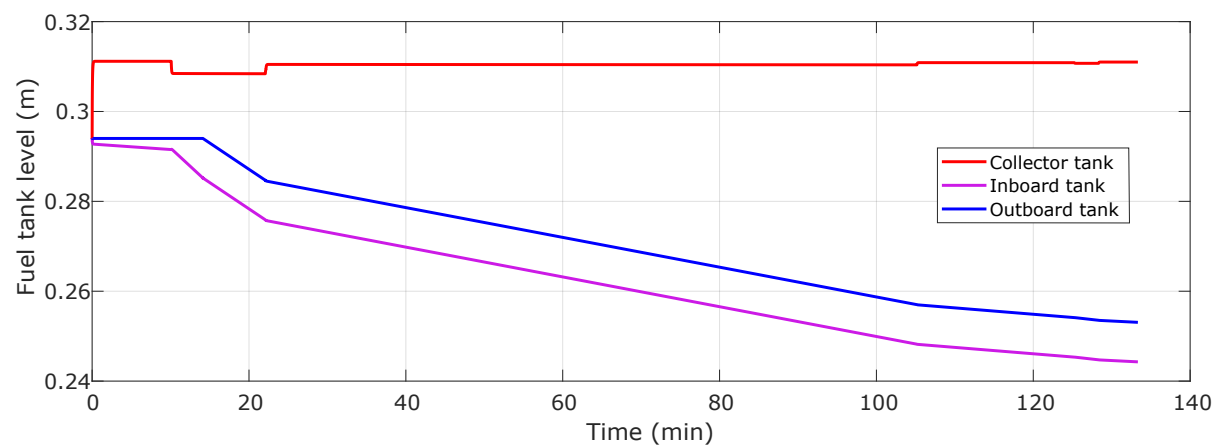


Figure 44: Tank levels for zero wing dihedral.

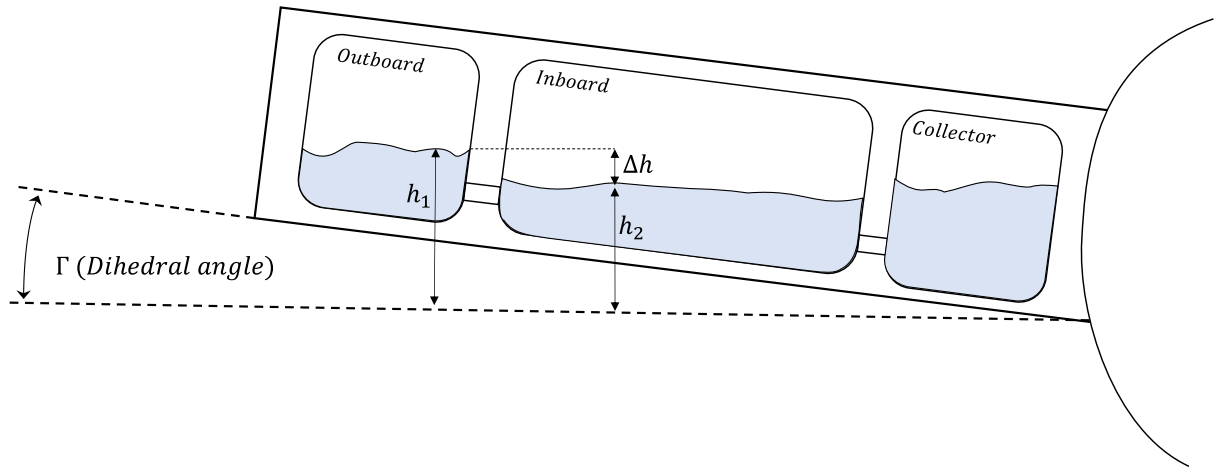


Figure 45: Schematic representation of the wing dihedral angle.

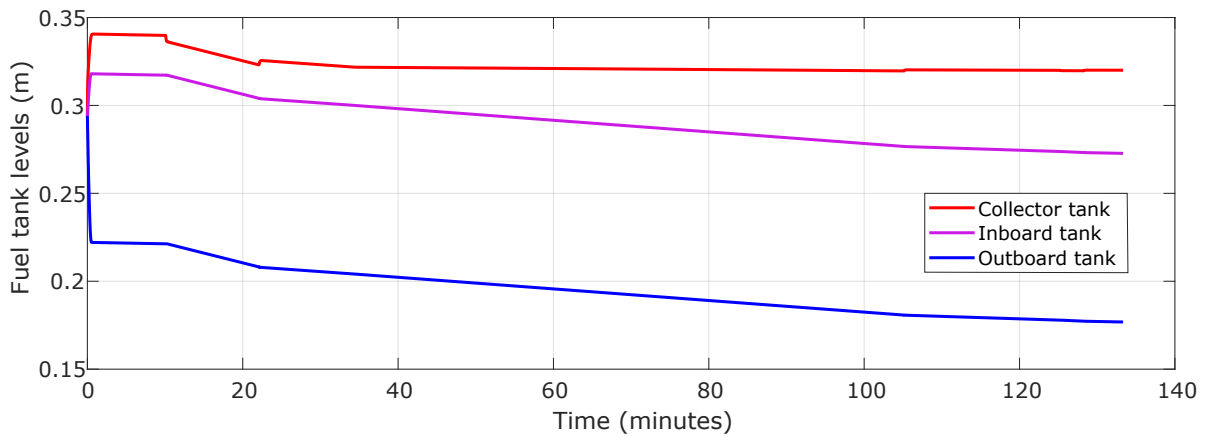


Figure 46: Tank levels for 2 degrees of dihedral.

amount of unusable fuel in the outboard tank. This situation should be avoided because the unusable fuel in the outboard tank will no longer be transferable to the collector cell, given the absence of a scavenge jet pump at the outboard tank, as proposed by the used fuel system architecture. One way to improve this fuel transfer comes from a positive wing dihedral angle, as shown in figure 45.

To understand this effect, another simulation was performed with the same settings but changing the dihedral angle of the wing from 0° to 2° . As depicted in figure 46, indicate that the dihedral angle produces a head difference of approximately 0.1 m between the outboard and inboard tanks. This is evident as their fuel levels initially match and then quickly alter due to the transfer caused by gravity. This behavior can be attributed to the fact that the dihedral was modeled considering pipe elevations, as explained in detail in Chapter 4. The revealing outcome is that, as opposed to the first case, the results show that the outboard tank will empty first, which is the desired behavior.

With this result, the absence of a scavenge pump in the outboard section of the wing can be justified.

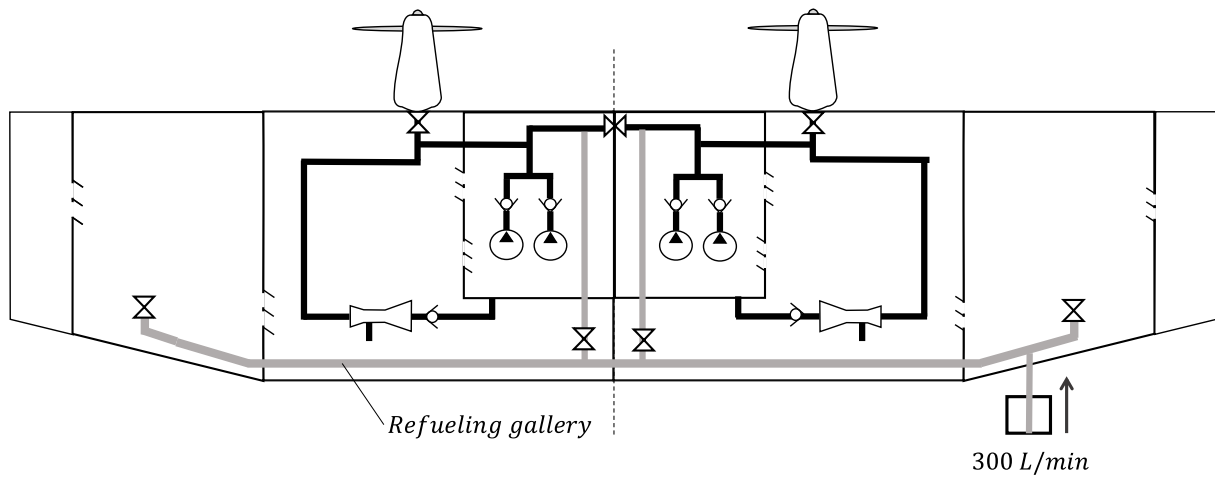


Figure 47: Refueling process schematic.

Nevertheless, although the simulation indicates that the outboard tank tends to empty before the inboard, it must be stressed that the levels presented in the graph are measurements from a single point at the center of the tank, which does not apply to all the point within the tank in a wing dihedral scenario.

5.3 Refueling imbalance

The single-sided pressure refueling often brings the need for careful pipe and valve sizing, and in this section, the refueling scenario is evaluated, attempting to assess the design considerations associated with the refueling process and also demonstrate another potential usage of the model developed.

To accomplish this, a scenario was created in the model, setting boundary conditions such as the refueling flow rate, the tanks' initial level, the spool position of the refueling and defueling shutoff valves, as well as the engine feed shutoff valves, which, in this case, always stay closed. The refueling port is located on the right side of the aircraft, and from there, the fuel is distributed to both left and right outboard tanks through the refueling gallery. Considering a requirement of 10 minutes for the refueling time and assuming the tanks will get completely filled, the necessary refuel flow rate is set at 300 L/min. This can be seen in the schematic from figure 47, where the white box outside of the wing represents the refueling source.

Some of the important parameters set for this simulation are presented in table 4:

After running the simulation, it was found that there is a significant difference in the amount of fuel being discharged into the left and right wing tanks (Figure 48). The right outboard tank, which is closer to the refueling port, receives fuel at a much faster rate than the left outboard tank. This difference in fuel flow rate is approximately 34 L/min, resulting in a mass difference of over 250 kg between the two wings

Table 4: Refueling pipe parameters.

	L (m)	A (m ²)
Refueling Pipe 1	5	0.00391
Refueling Pipe 2		
Refueling Pipe 3		
Refueling Pipe 4		

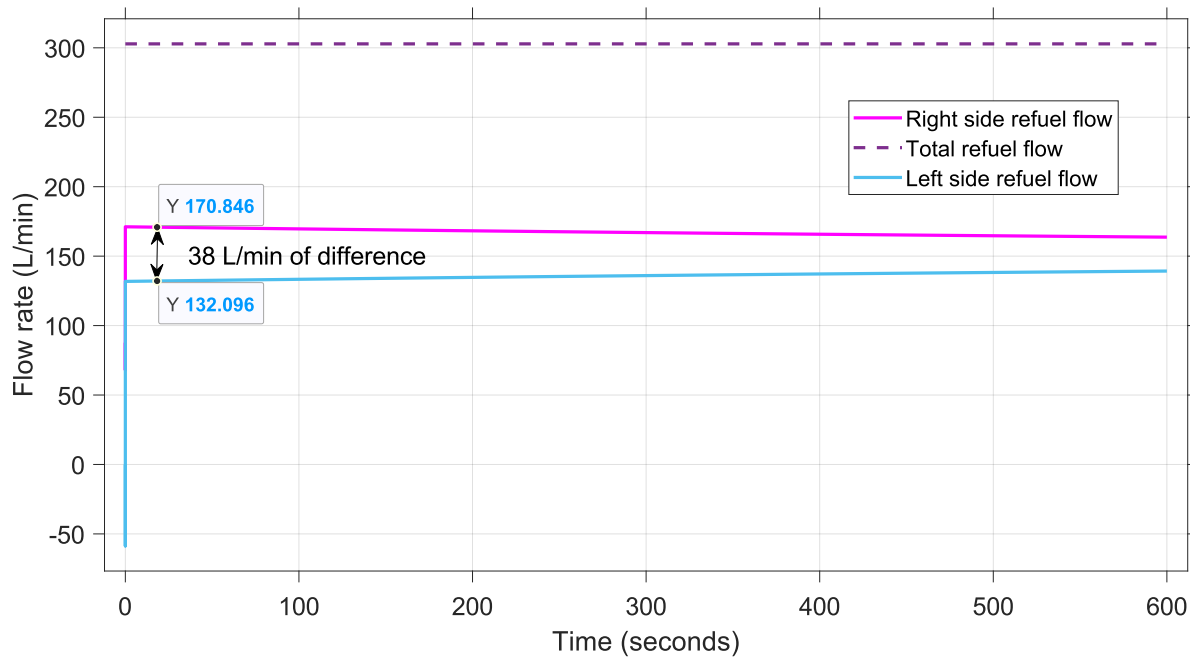


Figure 48: Refueling imbalance.

at the end of the simulation. The graph also shows that over time, this difference decreases, and this is because the tank that is being refilled faster will also increase the pressure at the tank inlet, due to the hydrostatic pressure of the fluid. This flow imbalance is due to the difference in flow resistances in each path. The right path is shorter, causing less pressure drop due to friction when compared to the left path. This is analogous to an electric circuit where the current splits according to the electrical resistances in each path.

Some possible solutions for this flow imbalance include reducing the area of the pipe in the right path, adding flow resistance to the shutoff valve, or adding a new component that acts as a fluid resistor. Since the model is suited for systems in early design phases, a simple flow restriction can be added, which later can be converted to a valve or a local restriction. In Simscape, the flow restriction is defined as a function of the nominal pressure drop and nominal mass flow rate that passes through it. For this example, the

Table 5: Flow imbalance varying with flow restriction nominal pressure drop.

ΔP (kPa)	Flow rate difference (L/min)
0.70	20.2
1.40	16.1
2.1	12.1
2.8	8.4
3.5	4.9
4.2	1.4
4.9	-1.9

nominal flow rate can be specified as 150 L/min (ideal flow rate for a balanced distribution). Regarding the nominal pressure drop of the flow restrictor, some simulations were performed to find the ideal pressure drop value to balance the flow. A nominal pressure drop of 0.7 kPa was initially set for the restrictor, and several simulations were conducted by gradually increasing the nominal pressure drop with 0.7 kPa increments in each simulation. For each simulation, the difference between the flow rates on the right and left sides was recorded, as presented in the table 5.

The results from the table show that the pressure drop of 4.2 kPa is the one that creates the most balanced refueling flow distribution, with a difference of just 1.4 liters per minute. The optimal value can be estimated with optimization algorithms inside the Simulink environment which will be somewhere between 4.2 and 4.9 kPa. Later in the design, this value can be used as a reference for whichever strategy will be chosen to make the flow split more equally. The model was finally simulated using a suitable parametrization of the flow restrictor component and the results are shown in figure 49.

5.4 Pressure surge analysis

The pressure surge is the pressure rise that occurs when a fluid in motion is suddenly stopped, either by a valve or a flow restriction in a piping system, generating a pressure wave that propagates within the fluid. This phenomenon is also known in the literature as the "water hammer" because the magnitude of the pressure waves can cause serious structural damage to the piping system as if it were hit by a real hammer. Besides the structural damage, other problems associated with this phenomenon are the significant amount of noise and vibration generated. In a fuel system, this phenomenon typically occurs during the pressure refueling process, when the fuel is transported in the refueling gallery with a lot of

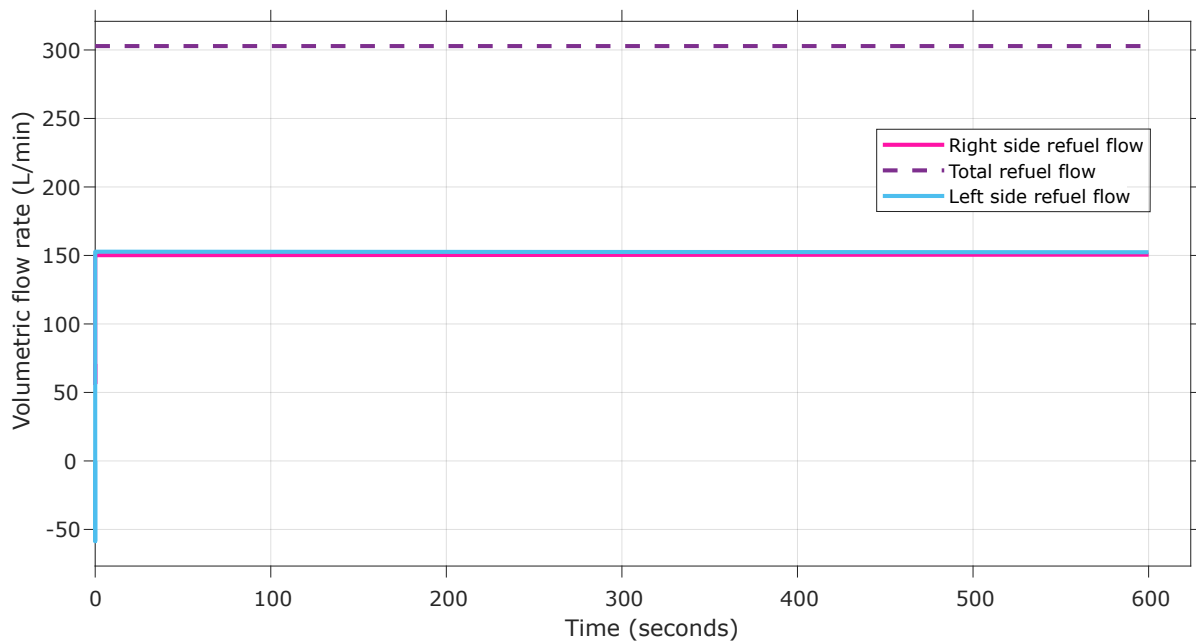


Figure 49: Balanced refueling flow simulation results.

momentum. When the desired tank fuel quantities are reached, the refuel shutoff valve closes rapidly, and this sudden change in momentum creates a shock wave due to the fuel inertia and incompressibility.

To understand the pressure surge case, a transient simulation was performed, activating the inertia and fluid dynamic compressibility mode of the pipe component in the Simscape. For the simulation, the valve spool position was controlled by a signal, thus controlling the valve orifice area. The orifice area varies linearly with the spool position, as shown in figure 50.

The signal that controls the valve was generated by combining a step, ramp, and saturation block from the Simulink library. The step block output passes by first-order filtering, where the filtering time constant simulates the valve closure time. Figure 51 shows the first simulation results, where the pressure at the refueling port is set to 2.8 bar and the tanks are open to atmospheric pressure, with the valve initially closed and slowly increasing the orifice area. At around 15 s, the flow in the pipe becomes steady, at a rate of approximately 150 L/min while the pressure stabilizes at around 1.8 bar. When the outboard tank has reached the desired value, at $t = 20$ s, the shutoff valve closes. In this first simulation, there is a notable decrease in pressure after valve closure, going below the atmospheric pressure and rapidly balancing with 1 bar. This behavior does not pose any danger to the system's structure; however, for quicker closure times, the pressure peaks might change significantly.

To visualize the valve closure time impact, additional simulations were conducted. Figure 52 shows the overlayed results from three simulations performed, using different valve closure times: 0.2, 0.25, and 0.5 s. The results for 0.5 s of closure time are shown in green, and the pressure after valve closure

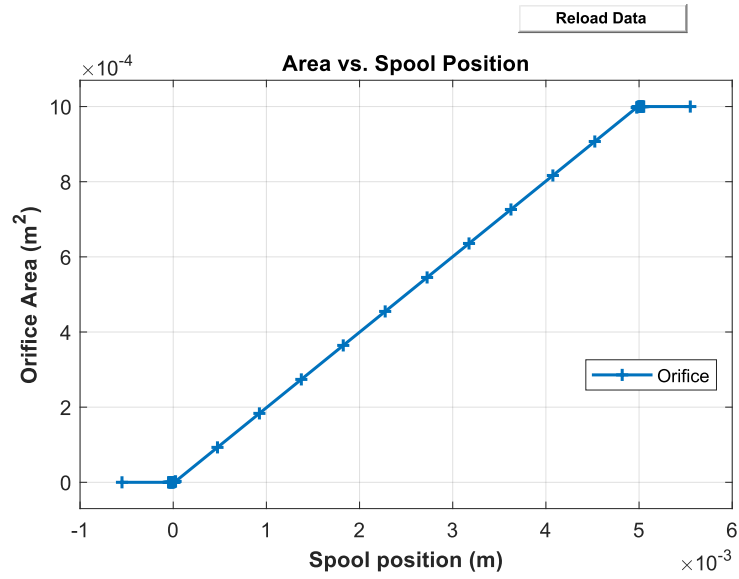


Figure 50: Valve characteristics.

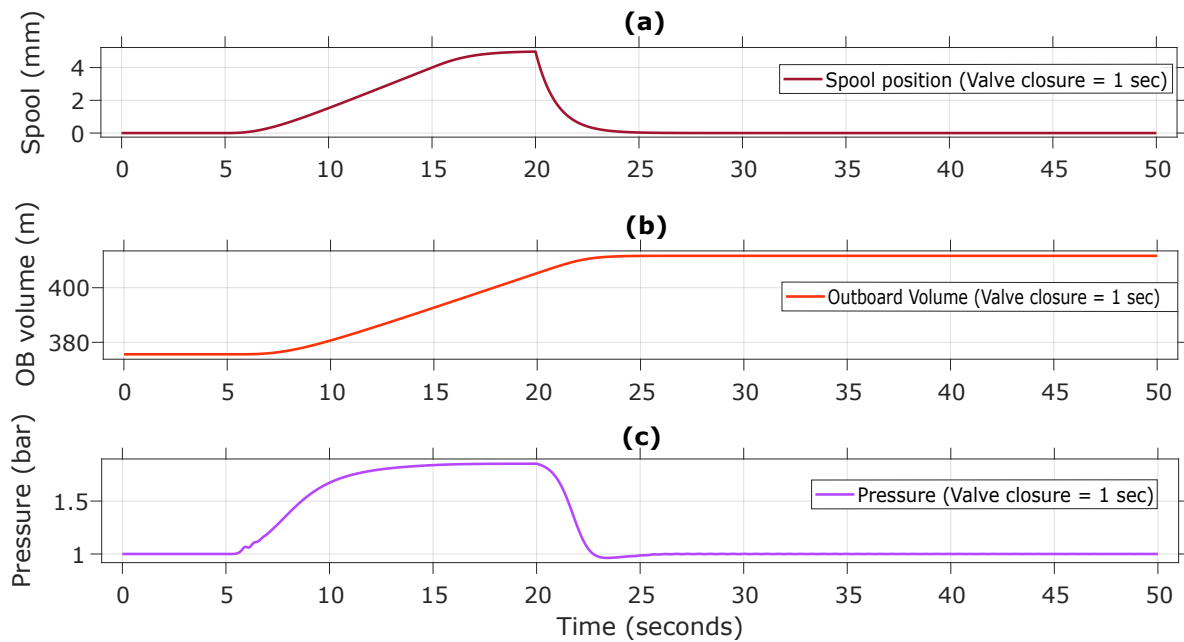


Figure 51: Simulation with valve closure time of 1 second. (a) Valve spool position, (b) Outboard tank volume, (c) Pressure in the middle of the refuel gallery.

has a similar behavior as in the previous simulation. For the simulation with a closure time of 0.25 s, the pressure already shows an oscillating profile, where the pressure signal takes much longer to stabilize at 1 bar. The absolute pressure has reached almost 4 bar, and the minimum value was about 0.5 bar. The results for 0.2 s of closure time show a dramatic increase in the pressure spikes, going up to 9 bar, creating a dangerous situation for the refueling system.

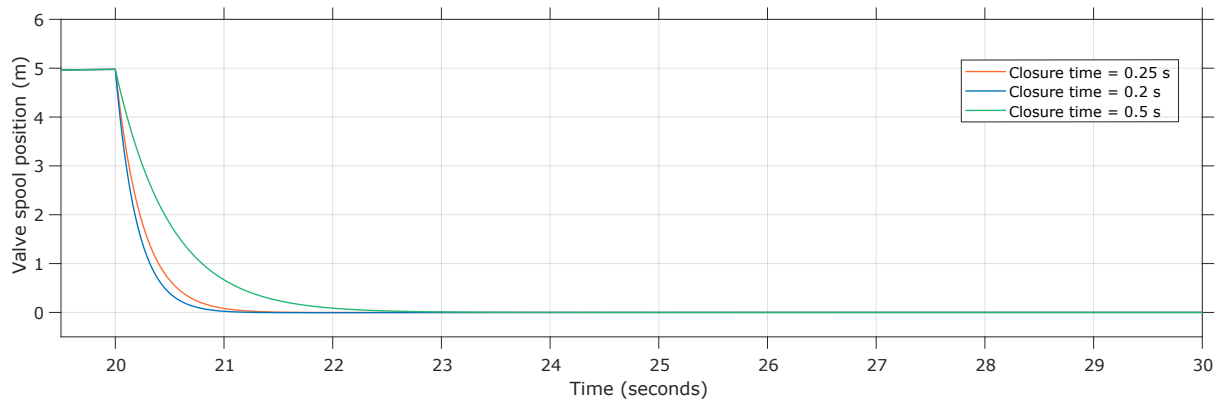
The simulations performed demonstrated that the quicker the valve closes, the stronger the shock waves produced, but other parameters, such as the refueling pressure, may also affect the pressure variation.

One last case was studied, considered to be the worst case scenario, where the refueling pressure was increased from 2.8 to 4 bar, and the simulation results show that the pressure peaks can reach 12 bars (Figure 53). Besides the high-pressure peaks, the oscillation reaches very low-pressure values, going below the Jet-A fuel vapor pressure, which is about 0.2 bar at 38 °C. This is significant especially right after the valve closure, where the pressure fell close to zero and this causes the fuel to cavitate. In the current simulation, the cavitation effects are not explored, since the chosen Simscape library only supports one-phase liquid simulations, ignoring the formation of fuel vapor and further mixing with the liquid fuel. If this effect was considered, the pressure profile would appear more irregular, due to the vapor bubbles collapsing due to the pressure oscillation, creating additional shock waves. However, this does not invalidate the pressure amplitude results obtained, whose accuracy depends mainly on pipe discretization and solver configurations.

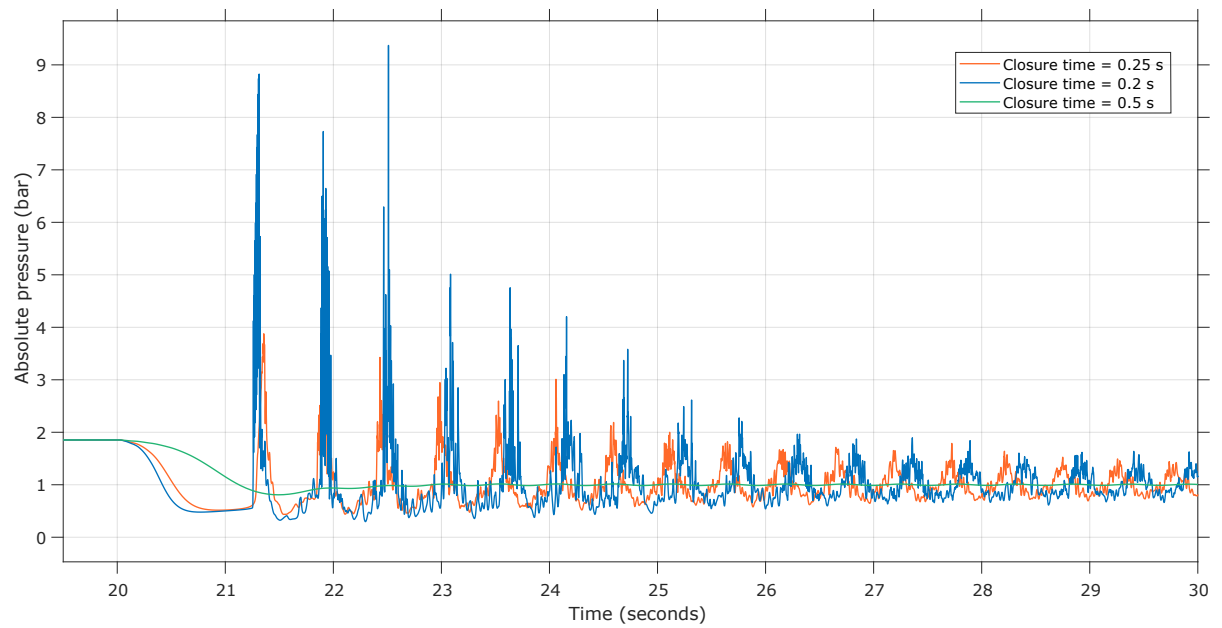
Nevertheless, it is important to note that cavitation is a major problem in many fluid systems, especially in an aircraft fuel system where not only the pipe and pumping equipment can be damaged due to cyclic vapor bubbles collapse, but also because the pumps should be able to provide an uninterrupted flow of fuel to the engines, which is not possible if vapor cavities are formed within the tank.

5.5 Crossfeed valve

When dealing with twin-engine aircraft, an engine crossfeed system is required so that fuel from the left wing collector tank can feed the right wing engine, and vice versa. This is particularly important during engine failure scenarios when one of the engines is shut down. In an engine failure scenario, fuel from only one engine is being consumed, and the crossfeed system enables the fuel from both right and left-wing tanks to feed one single engine. If this doesn't happen, the center of gravity of the plane will shift sideways as fuel is being consumed just by one side, creating an unwanted rolling moment.



(a) Refueling shutoff valve spool position over time.



(b) Absolute pressure inside the pipeline varying over time.

Figure 52: Comparison of the dynamic behavior of the fluid inside the pipeline for different valve closure times.

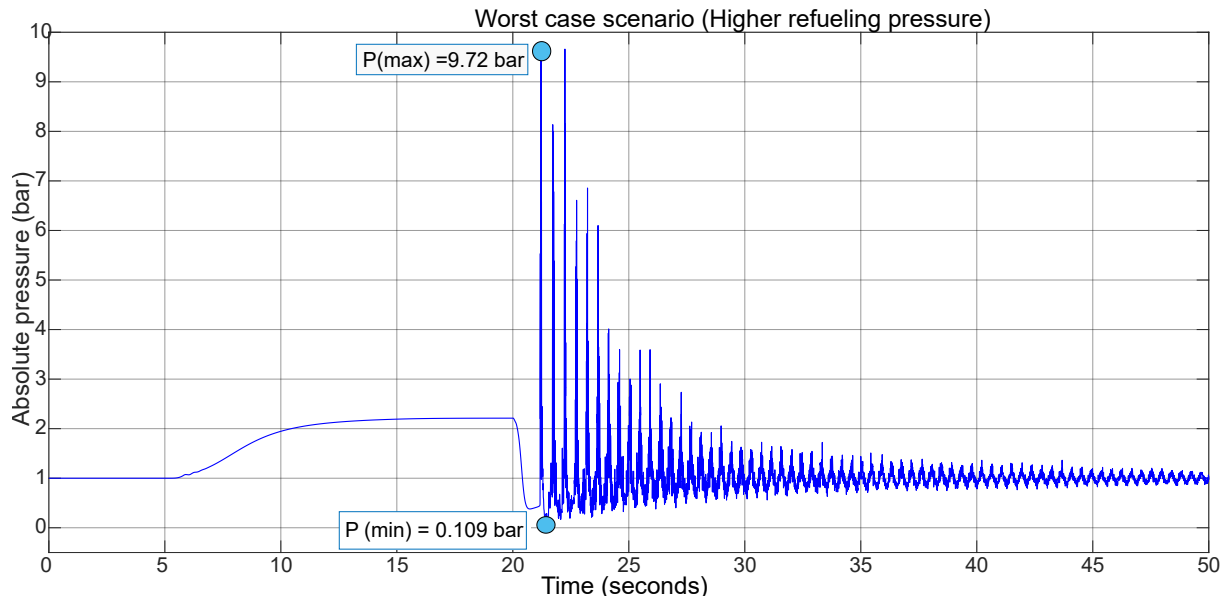


Figure 53: Worst case scenario.

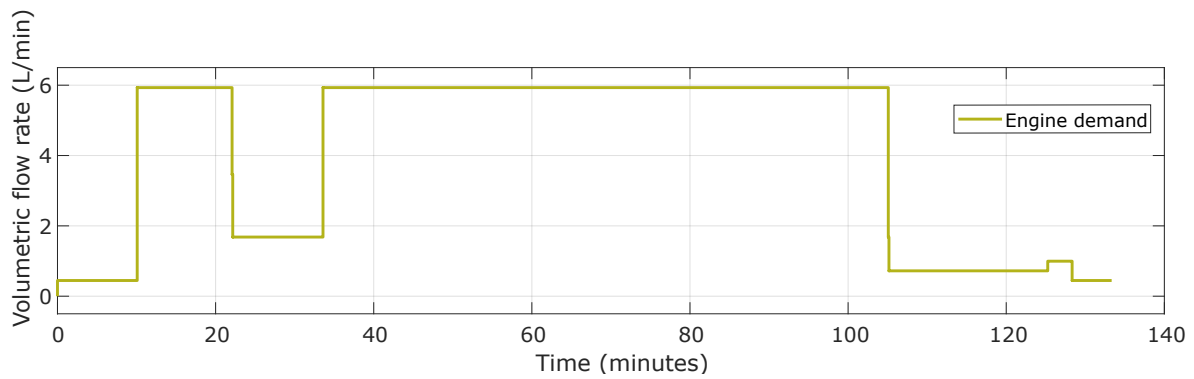


Figure 54: Right engine fuel consumption during flight.

The model developed for this thesis is also capable of simulating engine failure scenarios, as well as valve faults. The probability of having two failures like this simultaneously is very low, but for demonstration of the model capabilities, this is studied. The simulation considers an engine failure in the left wing at around 33 minutes. The fuel demand for both engines is an input signal that tries to represent the flight phases' usual fuel consumption. These phases can be identified from the graph in figure 54, where the take-off phase and initial climb happen around 10 and 20 minutes when the engine is configured for maximum power and from 20 minutes onwards, the plane would fly at cruise speed. At $t = 33$ minutes, the left engine fails, and since the airplane lost half of its thrust capacity, it is assumed that the remaining engine will be configured for maximum power again to keep flying at a constant altitude, so the fuel consumption rate returns to 6 L/min.

Regarding the tank levels, at the moment of failure, the left collector tank level decreases slightly,

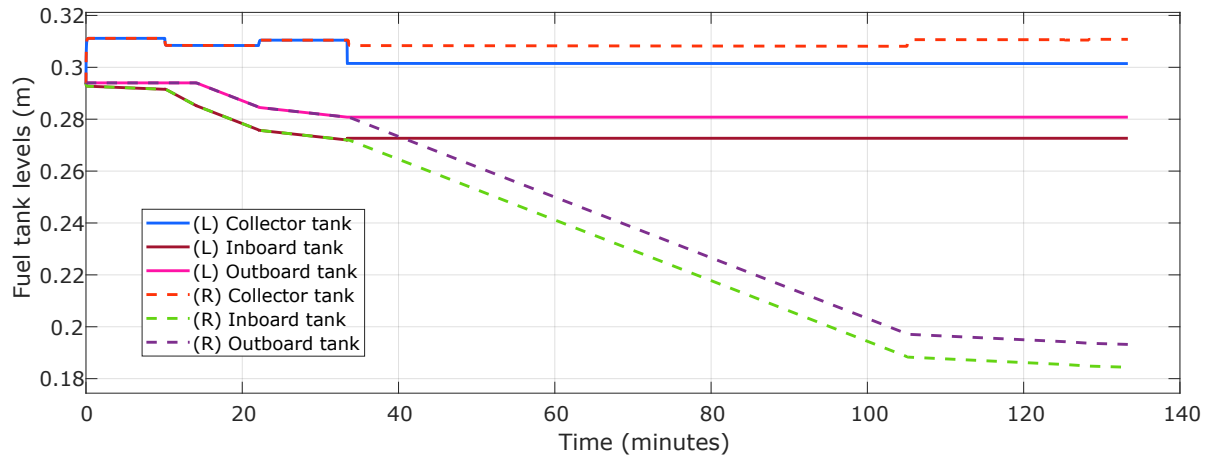


Figure 55: Tank levels variation. Continuous and dashed lines for left and right wing tanks, respectively.

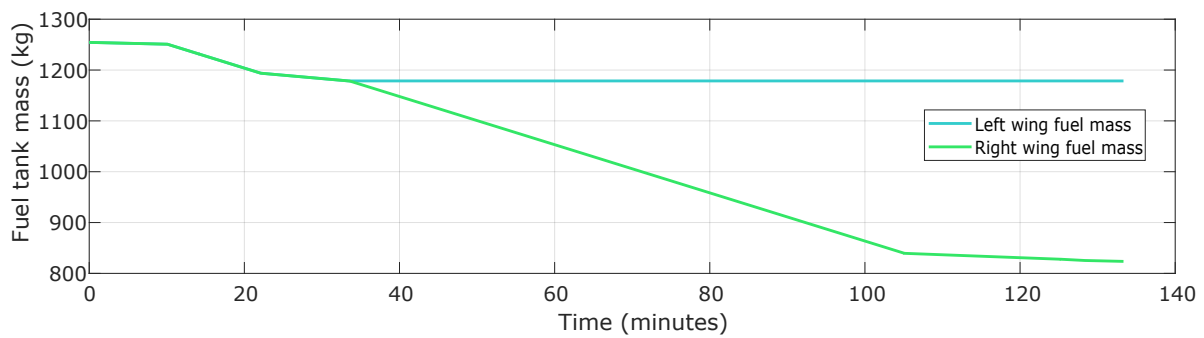


Figure 56: Total wing fuel mass variation.

while the other tanks stay at a constant level until the end of the simulation (Figure 55). This is related to the scavenge jet pump, which, after the failure, is no longer able to pump fuel to the collector tank, given that the motive flow has been interrupted. In normal conditions, the collector tank always receives more fuel than it needs, and the additional fuel returns to the inboard tank through a connection at the top of the collector tank. Now, without this additional fluid from the jet pump, the left collector tank level stays exactly at the height of the return line, which is about 0.3 m.

However, the right engine keeps consuming fuel from the right collector tank, then causing the fuel levels of the inboard and outboard tanks to drop. In this situation, the airplane's center of gravity will shift towards the left side since the wings' mass difference increases over time, as shown in figure 56.

The main purpose of this simulation is to demonstrate the model's flexibility in terms of simulation, despite the unlikely scenario of an engine and crossfeed valve failure. Nevertheless, larger commercial aircraft that need approval from the regulatory authority for ETOPS (Extended Twin OperationS) must include two redundant crossfeed valves in the system design, to minimize the probability of two combined failures, as this case illustrated.

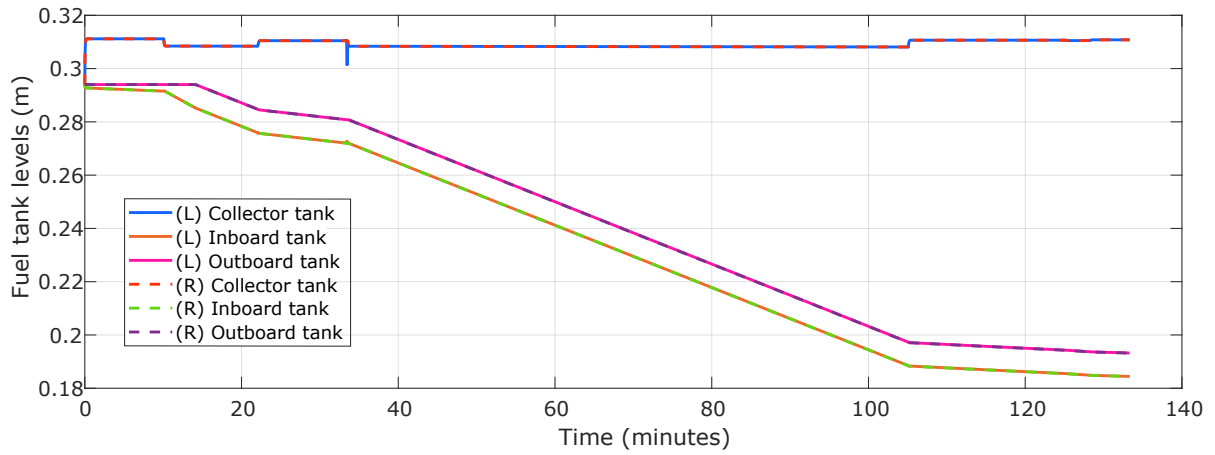


Figure 57: Tank levels variation. Continuous and dashed lines for left and right wing tanks, respectively.

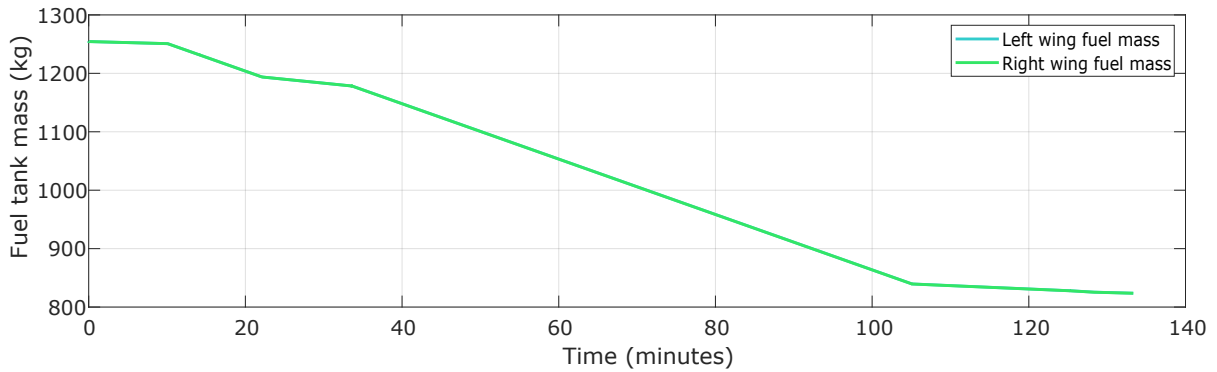


Figure 58: Total wing fuel mass variation.

A second case is studied with this model, considering a normal crossfeed valve operation in case of an engine failure. For this simulation, the boundary conditions and input signals are maintained from the previous study, except for the crossfeed valve control signal, which opens the valve seconds after the engine failure was detected. The time of failure was maintained at 33 min, and figure 57 shows the tank levels variation. The graph shows that at the time of failure, the left collector tank falls and rapidly recovers since the motive flow for the left jet pump was interrupted for some seconds.

By analyzing the mass variation over time, in figure 58, it can be seen that if the crossfeed opens seconds after the failure, the wing's mass from both sides will remain balanced.

Although the flow rates going out from both collector tanks are the same, this model can still be useful for designing the crossfeed valve and connections between feed lines since fuel flow is not always split equally, as demonstrated in the refueling imbalance case.

5.6 Chapter summary

A critical part of this thesis relies on the model analysis, where various features of the model are explored with simulations. This section presented some of the model capabilities, exploring the jet pump performance, dihedral angle effect on fuel transfer, refuel flow imbalance, water hammer phenomenon, and crossfeed valve impact on failure scenarios.

The scavenge jet pump has a highly non-linear behavior, varying significantly with its geometric parameters and the system's boundary conditions. The sensitivity analysis performed demonstrated that the nozzle area, length of the discharge pipe, and nozzle-to-throat area ratio are extremely influential for its performance in this type of application. Additionally, the dihedral angle of the wings creates an additional head to the outboard tanks which helps to transfer fuel inboards, eliminating the need for another scavenge jet pump at the outboard tanks. Moreover, the refueling process was simulated and a flow imbalance was identified due to pressure differences in the flow distribution. The transient behavior of the flow at the end of the refueling process was also studied, considering different valve closure times and identifying the best and worst-case scenarios. Lastly, the simulated engine failure highlights the importance of the crossfeed valve in the system's architecture, indicating the tank's level and mass variation over time post-failure.

The results presented are a way of showing the capabilities of the model built and bringing relevant insights on fuel system behavior in terms of fuel tank levels, mass, fuel flow rate, and pressure distribution along the system.

Chapter 6

Conclusions and Future Works

6.1 Conclusions

This work aimed to develop a small aircraft fuel system generic model, which later should serve as a tool to develop comprehensive studies on the fluid-mechanical behavior of the system by analyzing flow rate and pressure variations in different locations under various conditions. The fuel system is complex and essential, comprising several non-linear aspects, and the model of such a system has shown itself to be crucial for understanding the system's response to certain inputs and flight scenarios, as well as identifying potential problems with the used configuration or improvements to be made. There is an extensive market for computational tools capable of modeling and simulating aircraft fuel systems, so the research on software and previous works turned out to be critical for the quality of the model.

A general architecture for the fuel system was proposed, which aimed to include an additional degree of complexity compared to previous works in the field, so the wing dihedral and a scavenge jet pump were added to the model, creating more possibilities in terms of simulation. The simulations performed were related to the engine feed and refueling processes, which included components and overall system performance. One of the studies was related to the jet pump, which demonstrated that the induced flow rate created depends mostly on the pump's geometric parameters but is significantly affected by the discharge and suction line lengths, emphasizing the importance of optimizing the jet pump location in the system. The engine feed process was also studied in combination with the fuel storage and transfer functions, simulating the impact of the dihedral angle on fuel transfer, highlighting that an additional scavenge jet pump may not be needed for positive wing dihedral. Still related to the engine feed process, an engine failure was imposed on the system, and the crossfeed valve impact was observed, showing its critical role in the fuel system. Additionally, the refueling process was simulated, revealing important issues in the design, such as the flow imbalance caused by the different pressure drops along the different flow paths caused by the single-sided pressure refueling approach. The design solutions for this case were mentioned, and

the necessary pressure drop was calculated to balance the flow distribution within the refueling gallery. A last study regarding the refueling process was the pressure surge in the pipeline at the end of the refueling process, verifying pressure peaks of almost 10 bar for valve closure times of 0.1 seconds. The simulations performed have shown some of the model and software capabilities and limitations and how this can be explored for early aircraft fuel system design assessment. The studies performed with the model encouraged the development of a scientific article that was accepted for publication in the journal "*Technologia i Automatyizacja Montażu*". The article entitled "A Simulation Model for Small Aircraft Fuel System Model Analysis" includes a more focused analysis of two of the studies, namely the dihedral angle effect on fuel transfer and the jet pump sensitivity analysis [35].

Nonetheless, it is imperative to highlight some of the model limitations, such as the absence of the gas phase within the model, which in reality would correspond to the tank ullage and small quantities of fuel vapor, meaning that the fuel venting system and cavitation phenomenon cannot be simulated. Additionally, the model was built using the isothermal liquid library from Simscape, so the temperature variable is neglected in every simulation, making the model most suited for analyzing problems where only flow rate and pressure variations are significant. Additionally, the tanks are considered open to the atmosphere, indicating that the inner pressure will always equal 1 atm. This implies that the fuel volume can reach higher values than what is specified as its maximum capacity. Finally, it is important to state that the model was not validated carefully comparing it to experimental data, and its simulation results were only visually compared to those in the existing scientific publications.

Based on the lessons learned from this work, the main takeaways are that an aircraft's fuel system is highly complex and diverse, and its development and certification require proper modeling and simulation. The fuel system's functions are often critical, and it needs to be well integrated and designed to ensure the aircraft functions properly as a whole. The best approach to modeling a system is to keep it simple while generating results that are as close to reality as possible, requiring little computational power. Achieving this requires a thorough understanding of the system in question, its governing laws, and extensive knowledge of modeling techniques.

6.2 Future Works

Several promising avenues for future work can significantly enhance the modeling and simulation of aircraft fuel systems. In the current thesis, the modeling primarily focused on the simulation of liquid fuel, with the cavitation process omitted from the water hammer analysis. Future research could create a more

comprehensive model by incorporating both liquid and gas phases within the same system. This extension allows for a more accurate representation of water hammer effects. It also opens the door to modeling complex interactions, such as those in vent lines, where the behavior of fuel and air can be jointly simulated.

Moreover, the quest for accuracy can lead to a crucial phase of model validation using real-world data. Conducting experiments and gathering data from operational aircraft fuel systems will enable researchers to refine and validate the model, ensuring that it faithfully replicates the behavior of actual systems under varying conditions.

Furthermore, integrating the fuel system model with automation systems, controllers, and avionics systems represents a compelling area for future research. By merging the fuel system model with the broader aircraft control and monitoring infrastructure, it becomes possible to develop advanced control strategies, predictive maintenance algorithms, and safety protocols to enhance aircraft fuel systems' overall performance and reliability.

These future research endeavors offer opportunities to improve the precision and comprehensiveness of aircraft fuel system modeling and potentially advance the aviation industry's technology, safety, and environmental sustainability to new heights.

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Appendix A

MATLAB code

A.1 Initialization script

```
1
2 clc
3
4 %% INITIALIZE VARIABLES
5 %-----
6 %-----
7
8 %This script was built to improve the workflow while testing
   different values for different variables.
9 %
10 % The last update of this script is for: Fuel System Model V15.
11 % (25/10/2023)
12
13 %% SIMULATION SCENARIO
14
15 %1 = engine feed (1 pump) no failure
16 %2 = refueling
17 %3 = other cases
18
19
20 scenario=1;
21
22 %% Simulation parameters
23
24 %simulation time [s]
25 if scenario==1
26     Ts = 8000;
27 elseif scenario==2
28     Ts=600;
29 elseif scenario==3
30     Ts=16000;
31 else
32     fprintf('Case scenario not specified correctly. \n')
33 end
34
```

```

35 %-----conversions
36 m3s_to_gpm=15850.32;
37 psi_to_Pa = 6894.76;
38 Pa2psi = 0.000145038;
39
40 %% PIPES PARAMETERS
41
42 %feed line
43 feed_line_D=5/8; %[in]
44 feed_line_A=pi*feed_line_D^2/4; %[in^2]
45 feed_line_L=1; %[m]
46
47 %motive line
48 motive_line_D = 5/8; %[in]
49 motive_line_A = pi*motive_line_D^2/4; %[in^2]
50 motive_line_L = 1; %[m]
51
52 %Suction line
53 suction_line_D = 5/8; %[in]
54 suction_line_A = pi*suction_line_D^2/4; %[in^2]
55 suction_line_L = 0.5; %[m]
56
57 %Discharge line
58 discharge_line_D = 5/8; %[in]
59 discharge_line_A = pi*discharge_line_D^2/4; %[in^2]
60 discharge_line_L = 0.01; %[m]
61
62 %bypass line
63 bypass_line_D = 5/8; %[in]
64 bypass_line_A=pi*bypass_line_D^2/4; %[in^2]
65 bypass_line_L = 1; %[m]
66
67 %bypass to inboard line
68 inboard_bypass_line_D=5/8*10; %[in];
69 inboard_bypass_A=pi*inboard_bypass_line_D^2/4; %[in^2]
70 inboard_bypass_line_L = 1; %[m]
71
72 %Refueling lines
73
74 refueling_pipe_A=0.001; %[m^2]
75
76 %% PUMPS
77
78 %Centrifugal Pump (BOOSTER PUMP)
79 capacity_vec=[0 5 10 15 20 25]; %[gpm]
80 head_vec=[31.19 30.75 30.75 29.87 28.11 24.16]; %[m]
81 Reference_Power_vec=[0.42 0.48 0.53 0.59 0.63 0.64]; %[kW]
82

```

```

83 shaft_speed_1=0; %[rpm]
84 shaft_speed_2=0; %[rpm] --> (backup pump)
85
86
87 %Scavenge Ejector Pump
88 nozzle_area = 7e-5; %[m^2]
89 ratio1=0.25;
90 ratio2=0.25;
91
92
93 %% DIHEDRAL ANGLE
94
95 dihedral = 2; %[degree]
96 tank_L=3; %[m] --> considering the half wingspan divided into 3
    equal parts with same length
97 transfer_pipe_elevation = -tank_L*sin(deg2rad(dihedral)); %(
    minus) because the elevation from A to B is negative
98
99 if dihedral == 0
100     transfer_pipe_length=0.1047;
101 else
102 transfer_pipe_length=-transfer_pipe_elevation;
103 end
104
105 %the length of the pipe needs to be as short as possible to
    avoid fictitious high pressure drops
106
107 %% TANK PARAMETERS
108 %Tank volume coefficient (1 is full, 0 is empty)
109
110 if scenario==2 %refueling scenario
111     tank_k=0; % percentage of total capacity
112 else
113     tank_k=0.98;
114 end
115
116 %flapper valve height [m]
117
118 if scenario==1 %engine feed
119 fp_height = 0.01;
120 end
121
122 if scenario==2 %refueling
123     fp_height=0.01;
124 end
125
126 sec_flow_port_height = 0.01; %[m] -> port where the jet pump
    takes fluid from the inboard tank

```

```

127 |
128 | %tank height vectors
129 | outboard_heights = [fp_height, .1];
130 | inboard_heights = [sec_flow_port_height .3 fp_height fp_height
131 | ];
132 | collector_heights= [0.3 0.1 fp_height 0.01];
133 | %% VALVES/ORIFICES
134 |
135 | %PRESSURE COMPENSATED 3-WAY FLOW CONTROL VALVE (P_C_valve)
136 |
137 | pc_min_spool_position=0; %[mm]
138 | pc_spool_range=10; %[mm]
139 |
140 | pc_orifice_A=5e-5; %[m^2] (controls the flow to the engines)
141 | pc_orifice_pressure=26; %[psi]
142 | pc_regulation_range=2; %[psi]
143 | pc_valve_area=1e-3; %[m^2]
144 |
145 | %normal check valves
146 | cv_crack_p=1; %[psi]
147 | cv_max_pressure_diff=1.1*cv_crack_p; %[psi]
148 | cv_A= 1e-3; %[m^2]
149 |
150 | %flapper valve
151 | fp_crack_p=0.01; %[psi]
152 | fp_max_pressure_diff=1.1*fp_crack_p; %[psi]
153 | fp_valve_A=1e-2; %[m^2]
154 |
155 | %JET PUMP suction check valve (scv)
156 | scv_crack_pressure=800*9.81*0.3; %[Pa] --> full tank provides
157 |     the cracking pressure
158 | scv_max_pressure_diff=scv_crack_pressure+10; %[Pa]
159 | scv_A=1e-2; %[m^2]
160 |
161 | %JET PUMP discharge check valve (dcv)
162 | dcv_crack_pressure=1; %[psi]
163 | dcv_max_pressure_diff=dcv_crack_pressure*1.1; %[psi]
164 | dcv_A=1e-2; %[m^2]
165 |
166 | %collector return line Check valve (rcv)
167 | rcv_crack_p=800*9.8*0.0015; %[Pa]
168 | rcv_max_pressure_diff=800*9.8*0.0015+1; %[Pa]
169 | rcv_A=1e-2; %[m^2]
170 |
171 | %SHUTOFF VALVES general variable
172 | spool_position_range=5; %[mm]
173 | max_spool_position=5; %[mm]

```

```

173 SOV_orifice_A=1e-3; %[m^2]
174
175 %Refuel SOV
176 L_refuel_SOV_A = 1e-3; %[m^2] --> refuel SOV orifice area
177 R_refuel_SOV_A = 1e-3; %[m^2] --> refuel SOV orifice area
178
179 %Xfeed valve
180 xfeed_valve_A=1e-2; %[m^2] --> 1e-3 will cause flow imbalance (
    to be adjusted ...)
181
182 %refuel imbalance flow restriction optimization
183 delta_p = 0.7; %[psi]
184
185 %% fuel consumption varying over time [consumption x flight
    phase]
186
187 steady = 1; %(1 for steady fuel consumption, 0 to define a
    varying engine consumption)
188
189 if steady == 1
190     Engine_demand = timeseries(double(1*[1.3 1.3]')), [Ts*0 Ts
        *1]');
191 elseif steady==0
192     Engine_demand = timeseries(double(1*[0 0 1.3 1.3 0 0]')), [
        Ts*0 Ts*0.1 Ts*0.1+30 Ts*0.9 Ts*0.9+30 Ts*1]');
193 else
194     fprintf('Error defining timeseries object')
195 end
196
197 %refuel flow rate function (constant)
198 refuel_q = timetable(seconds([0 Ts]'), 1*[40 40]');
199
200
201 %% CORRECTION FUNCTIONS --> When dihedral angle != 0
202
203 %{
204 data = readcell('correction_functions.xlsx');
205
206 %--> this code calculates the error between expected value and
    the
207 simulated value for tank levels with non zero wing dihedral
208
209 %Extract the time vector (tout) and data vectors (g1, g2, g3)
    from the cell array
210
211 time = cell2mat(data(2:end, 1));
212 g1=cell2mat(data(2:end, 2));
213 g2=cell2mat(data(2:end, 3));

```

```

214 g3=cell2mat(data(2:end, 4));
215
216 g1=timeseries(g1, time); %collector
217 g2=timeseries(g2, time); %inboard
218 g3=timeseries(g3, time); %outboard
219 %}
220
221 %% END OF SCRIPT

```

A.2 Model output function

```

1      clc
2
3  %% OUTPUT VARIABLES
4  %-----
5  %----- This script was built improve the workflow, by
        calculating and printing the interest variables in the
        output window.
6
7
8  %% JET PUMPS MEASURED VARIABLES
9
10 %flow rates
11 jet_q_d=squeeze(out.node18_q);%jet discharge
12 jet_q_d=3.79*jet_q_d(end);
13 jet_q_i=squeeze(out.node16_q); %jet induced
14 jet_q_i=3.79*jet_q_i(end);
15 jet_q_m=squeeze(out.node19_q); %jet motive
16 jet_q_m=3.79*jet_q_m(end); %liters per minute
17 %pressures
18 jet_p_m=squeeze(out.node19_p);
19 jet_p_m=jet_p_m(end);
20 jet_p_i=squeeze(out.node16_p);
21 jet_p_i=jet_p_i(end);
22 jet_p_d=squeeze(out.node18_p);
23 jet_p_d=jet_p_d(end);
24
25 %TO ENGINE
26 delivered_q=out.node2_q(end); %engine feed flow rate
27 extra_q=out.node10_q(end); %extra feed line flow rate
28
29 %pressures
30 delivered_p=out.node6_p(end); %engine inlet pressure
31
32 %Gravity flows
33 inb2col_q=out.node23_q(end); %flow from inboard to collector
        though flapper valve

```

```

34 out2inb_q=out.node20_q(end); %flow from outboard to inboard
    though flapper valve
35
36 %% TANKS
37
38 %INBOARD TANK
39 back_to_inboard_q=out.node17_q(end); %remaining flow back to
    inboard tank
40
41 %COLLECTOR TANK
42 col_q_in = jet_q_d + inb2col_q; %flow in the collector tank
43 col_q_out=out.node7_q(end); %flow out of the collector tank
44
45 %pressures
46
47
48 %% PRESSURE DROPS (PUMPS, PIPES)
49
50 pumps pressure gain
51 boost_pump1_p_gain = out.node4_p(end)-out.node1_p(end);
52 boost_pump2_p_gain = out.node5_p(end)-out.node3_p(end);
53 jet_pump_p_gain_23 = out.node18_p(end)-out.node16_p(end);
54 jet_pump_p_gain_13 = out.node18_p(end)-out.node19_p(end);
55
56 pipes pressure drop
57 feed_line_delta_p = (out.node9_p(end)-out.node6_p(end));
58 bypass_line_delta_p = (out.node10_p(end)-out.node13_p(end));
59 bypass_inboard_line_delta_p=(out.node27_p(end)-out.node17_p(end
    ));
60 motive_line_delta_p=(out.node26_p(end)-out.node19_p(end));
61 scav_line_delta_p=out.node11_p(end)-out.node15_p(end);
62 total_pipes_delta_p=(feed_line_delta_p+bypass_line_delta_p+
    bypass_inboard_line_delta_p+motive_line_delta_p+
    scav_line_delta_p);
63
64 transfer pipes pressure drop
65 out_inb_pipe_delta_p = out.node22_p(end)-out.node20_p(end);
66 inb_col_pipe_delta_p = out.node8_p(end)-out.node23_p(end);
67
68 %% VALVES
69
70 check valves pressure drops
71 boost_pump1_CV_delta_p=out.node4_p(end)-out.node29_p(end);
72 boost_pump2_CV_delta_p=out.node5_p(end)-out.node28_p(end);
73 bypass_CV_delta_p=out.node13_p(end)-out.node14_p(end);
74 jet_pump_CV_delta_p=out.node18_p(end)-out.node11_p(end);
75
76 %% JET PUMP PARAMETERS

```

```

77
78 %JET PUMP CALCULATIONS
79 N=(jet_p_d-jet_p_i)./(jet_p_m-jet_p_d); %pressure ratio
80 eta=(jet_q_i./jet_q_m).*N; %jet pump efficiency
81
82
83 %% PRINT RESULTS
84 %-----
85
86
87 %Delivered flow rate and pressure
88 fprintf('\n-----STATIONARY ANALYSIS: Delivered flow rate [
    gpm] and pressure [psi]: \n\n')
89
90 if scenario==1
91 fprintf('\n Case number = %0.0f (ENGINE FEED)\n\n', scenario);
92 elseif scenario ==2
93     fprintf('\n Case number = %0.0f (REFUELING)\n\n', scenario)
94     ;
95 end
96
97 fprintf('Delivered flow rate: %0.2f\n', delivered_q);
98 fprintf('Delivered pressure: %0.2f\n', delivered_p);
99
100 %Tank flow rates (in and out)
101 fprintf('\n----- Tank flow rates (in and out) [gpm]: \n\n')
102     ;
103 fprintf('Flow out of the collector: %0.2f\n', col_q_out);
104
105 %Pressure gain or drop (Pumps)
106 fprintf('\n\n----- Pressure gain/drop (Pumps): [psi] \n\n')
107 fprintf('Boost pump 1 pressure gain: %0.2f \n',
    boost_pump1_p_gain);
108 fprintf('Boost pump 2 pressure gain: %0.2f \n',
    boost_pump2_p_gain);
109 fprintf('jet pump pressure gain (2-3): %0.2f\n',
    jet_pump_p_gain_23); %23 -> from induced port (2) to
    discharge (3) port
110
111 fprintf('\njet pump pressure drop (1-3) due to orifice: %0.2f\n
    ', -jet_pump_p_gain_13); %13 -> from motive port (1) to
    discharge (3) port
112
113 %Pressure drops (PIPES)
114 fprintf('\n\n----- Pressure drops (PIPES): [psi] \n\n')
115 fprintf('Pressure drop (feed line): %0.2f\n', feed_line_delta_p
    );

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115 fprintf('Pressure drop (bypass line): %0.2f\n',
    bypass_line_delta_p);
116 fprintf('Pressure drop (bypass line back to inboard): %0.2f\n',
    bypass_inboard_line_delta_p);
117 fprintf('Pressure drop (motive line): %0.2f\n',
    motive_line_delta_p);
118 fprintf('Pressure drop (scavenge transfer line): %0.2f\n',
    scav_line_delta_p);
119 fprintf('\nTotal pressure drop in the pipes: %0.2f\n',
    total_pipes_delta_p);
120
121 %pressure drop (TRANSFER LINES)
122 fprintf('\n\n----- Pressure drops (TRASNFER PIPES): [psi] \
    n\n')
123 fprintf('Pressure drop (Outboard to Inboard): %0.2f\n',
    out_inb_pipe_delta_p);
124 fprintf('Pressure drop (Inboard to Collector): %0.2f\n',
    inb_col_pipe_delta_p);
125 fprintf('\n These are pressure gains instead (elevation
    increases the pressure at the outlet.\n')
126
127 %Pressure drops (CHECK VALVES)
128 fprintf('\n\n----- Pressure drops (CHECK VALVES): [psi] \n\
    n')
129 fprintf('Pressure drop (boost pump 1 check valve): %0.2f\n',
    boost_pump1_CV_delta_p);
130 fprintf('Pressure drop (boost pump 2 check valve): %0.2f\n',
    boost_pump1_CV_delta_p);
131 fprintf('Pressure drop (bypass line check valve): %0.2f\n',
    bypass_CV_delta_p);
132 fprintf('Pressure drop (Jet pump outlet check valve): %0.2f\n',
    jet_pump_CV_delta_p);
133
134 %Jet Pump INFO
135 fprintf('\n\n----- Jet pump (RESULTS) ----- \n\n')
136
137 fprintf('Motive flow [lpm]: %0.2f \n', jet_q_m);
138 fprintf('Induced flow [lpm]: %0.2f \n', jet_q_i);
139 fprintf('Discharge flow [lpm]: %0.2f \n', jet_q_d);
140
141 fprintf('\nPressure ratio: %0.2f \n', N);
142 fprintf('Efficiency: %0.2f \n', eta);
143
144 %Collector tank info
145 fprintf('\n\n----- Collector tank info \n\n')
146
147
148 %Total pressure drops

```

```

149 fprintf('\n\n----- Total pressure drops [psi] \n\n')
150 fprintf('Pressure drop - extra flow until collector tank inlet:
      %0.2f \n', out.node10_p(end)-out.node15_p(end)+
      jet_pump_p_gain_13);
151
152
153 %% CORRECTION FUNCTION --> for dihedral angle != 0
154
155 %this block calculates the real tank levels based on the error
      calculated for non zero dihedral simulations.
156
157 %{
158 f1_t = squeeze(out.collector1_level); %collector tank 1
159 g1_t=0.3*tank_k-f1_t;
160 f2_t = squeeze(out.inboard1_level); %inboard tank 1
161 g2_t=0.3*tank_k-f2_t;
162 f3_t = squeeze(out.outboard1_level); %outboard tank 1
163 g3_t=0.3*tank_k-f3_t;
164
165 %Exporting Correction Functions to Excel --> g(t)
166
167 writecell(['Time', 'g1(t)', 'g2(t)', 'g3(t)']; num2cell([out.
      tout, g1_t, g2_t, g3_t])), 'correction_functions.xlsx');
168 %}

```

Appendix B

Fuel System Model information

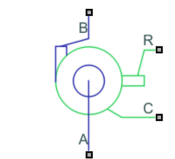
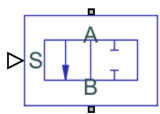
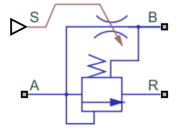
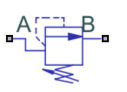
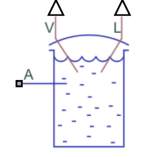
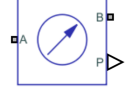
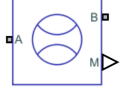
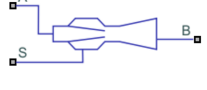
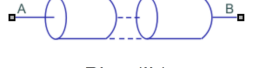
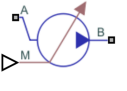
 Centrifugal Pump (IL)	 2-Way Directional Valve (IL)	 Pressure-Compensated 3-Way Flow Control Valve (IL)	 Pressure Relief Valve (IL)
 Tank (IL)	 Reservoir (IL)	 Pressure Sensor (IL)	 Flow Rate Sensor (IL)
 Jet Pump (IL)	 Check Valve (IL)	 Pipe (IL)	 Flow Rate Source (IL)

Figure 59: Fuel system model building blocks from Simscape Isothermal Liquid Library

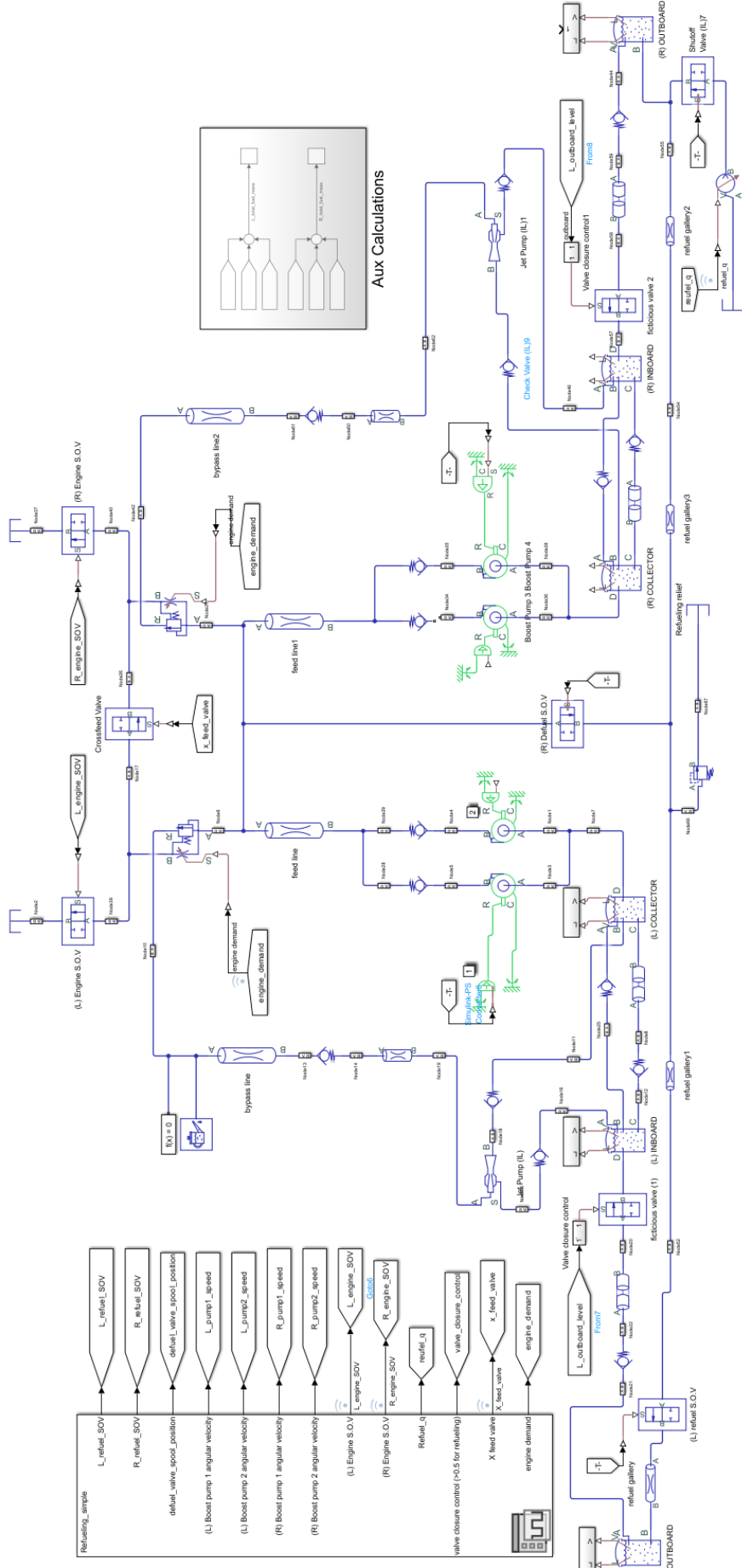


Figure 60: Fuel System Complete Model

Table 6: Unusable fuel quantities versus dihedral angle, for the proposed architecture.

Γ (°)	Outboard Tank			Inboard Tank			Collector Tank		
	$V(L)$	$\Delta V(L)$	Variation	$V(L)$	$\Delta V(L)$	Variation	$V(L)$	$\Delta V(L)$	Variation
0	14	0	0%	36.6	0	0%	2.67	0	0%
1	1.72	12.28	88%	1.72	34.88	95%	1.63	1.04	39%
2	0.86	13.14	94%	0.86	35.74	98%	0.86	1.81	68%
3	0.57	13.43	96%	0.57	36.03	98%	0.57	2.1	79%
4	0.43	13.57	97%	0.43	36.17	99%	0.43	2.24	84%
5	0.34	13.66	98%	0.34	36.26	99%	0.34	2.33	87%

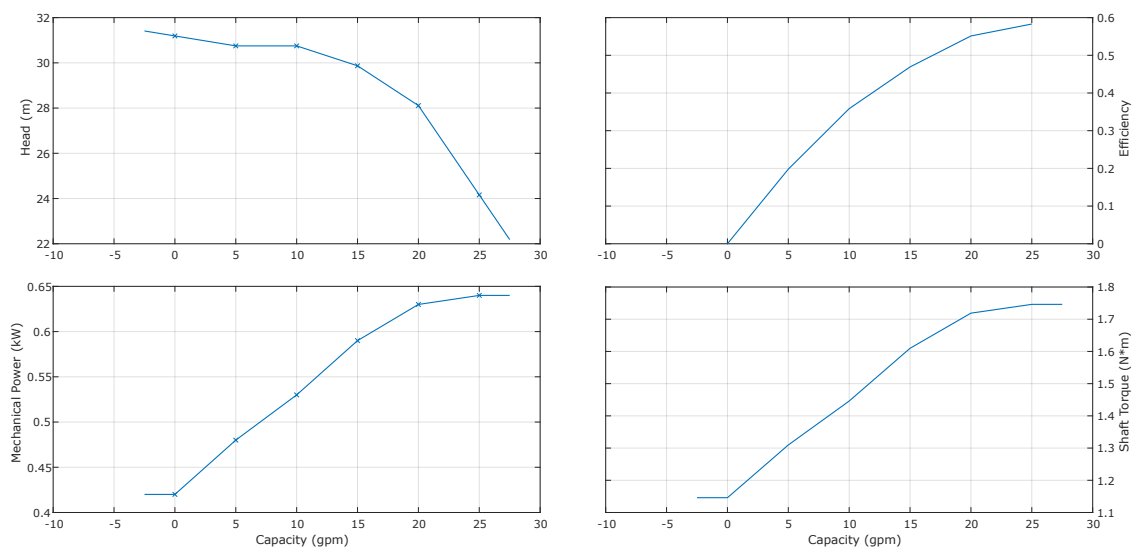


Figure 61: Booster pump characteristics.

