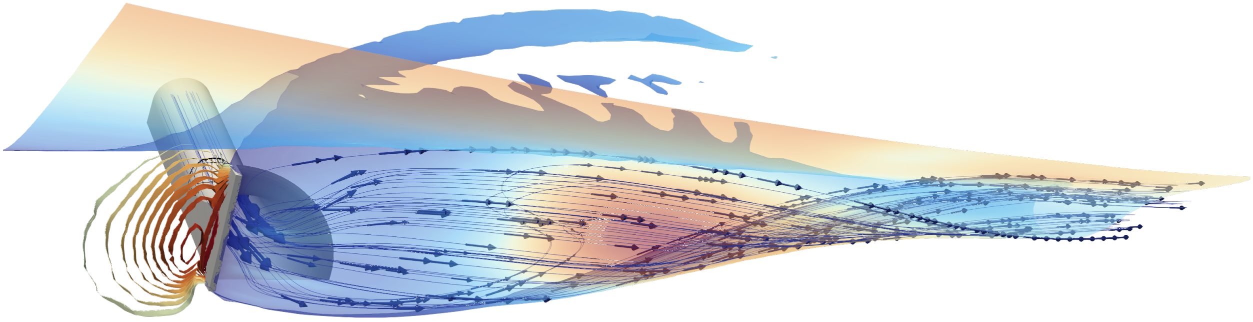

Development and Optimization of Underwater Exhaust Outlets for Sailing Yachts

A Product Development Approach Supported by CFD

Master's thesis in Product Development

HENRIK FRIDH & LUKAS HYLTÉN

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Master's thesis 2026

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Cover: Exhaust gas flow and pressure gradients from the Quarter Bell-Mouth concept's CFD simulation results.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2026

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Abstract

Although sailing yachts primarily rely on wind for propulsion, engines are used for propulsion in unfavorable sailing conditions and maneuvering in the marina. On sailing yachts, exhaust gases are typically expelled through outlets positioned above the waterline. This can contribute to noise, vibration, odor and increased piping requirements, which may negatively affect onboard comfort, weight and space utilization. One solution to reduce these issues is to relocate the exhaust outlet underwater and closer to the engine. While underwater exhaust outlets are commonly used on motor yachts, their application on sailing yachts remains largely unexplored.

This thesis investigates the development and optimization of an underwater exhaust outlet for sailing yachts using a structured product development approach supported by computational fluid dynamics. A representative 33 m sailing yacht hull was modeled and in total 30 exhaust outlet concepts were generated and evaluated with over 60 CFD simulations in OpenFOAM.

The final concept, called the Quarter Bell-Mouth, consists of a tapered underwater outlet combined with an interceptor positioned near the outlet. The interceptor creates a low-pressure region that helps reduce back pressure and promotes a steadier exhaust gas flow. Simulation results indicate that the concept can expel exhaust gases underwater without negatively affecting the propeller or rudders while maintaining acceptable back pressure between approximately 8 and 13 knots at heel angles of ±5°. However, oscillations at lower speeds indicate that a bypass exhaust is required below 8 knots.

The results of this thesis show that underwater exhaust outlets are a promising design alternative for sailing yachts, with potential benefits in comfort, weight and space utilization. Future work should include validation on additional hulls, material and manufacturing studies and sea trials with a physical prototype.

Keywords: Sailing yachts, underwater exhaust outlets, CFD, product development, back pressure

Acknowledgements

We would like to express our gratitude to Profjord for giving us the opportunity to carry out this thesis. A special thank you goes to Mr. Andreas Dahlgren for his continuous support, advice and patience throughout the work. His in-depth knowledge of CFD and naval architecture has been extremely valuable and he has been our go-to person whenever the simulations decided to cause trouble. We would also like to thank Mr. Anders Larsson at Profjord, as well as Mr. Henry Blount from the CAD department, for their support, input and help during the thesis.

We would also like to express our gratitude to the examiner and supervisor at Chalmers, Dr. Andreas Dagman, for his guidance, feedback and support throughout the thesis.

Furthermore, we would like to thank Mr. Philip Asplund and Mr. Tommy Johansson at Baltic Yachts, as well as Mr. Hakan Celik at Kraken Yachts, for taking the time to answer our questions and share their knowledge. We would also like to give a special thanks to Mr. Mikael Höglind and Mr. Peter Abrahamsson at Hallberg-Rassy for welcoming us to their shipyard, answering our questions and giving us the opportunity to learn more about their design process.

Finally, we would like to thank those close to us for their support and encouragement throughout the thesis.

Henrik Fridh & Lukas Hyltén, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ABS	American Bureau of Shipping
AI	Artificial Intelligence
BWL	Beam at Waterline
CFD	Computational Fluid Dynamics
CAD	Computer-Aided Design
DNV	Det Norske Veritas
DOF	Degrees of Freedom
GT	Gross Tonnage
HP	Horsepower
IMO	International Maritime Organization
LOA	Length Overall
LWL	Length at Waterline
LCA	Life Cycle Assessment
MVP	Minimum Viable Product
RANS	Reynolds-Averaged Navier-Stokes
RPM	Revolutions Per Minute
SBCE	Set-Based Concurrent Engineering
S/Y	Sailing Yacht
SCR	Selective Catalytic Reduction
VOF	Volume of Fluid

Nomenclature

Below is the nomenclature of symbols that have been used throughout this thesis.

R_e	Reynolds number
F_n	Froude number
g	Gravitational acceleration
L	Characteristic length; Submerged length of vessel
Ca	Cavitation number
Co	Courant number
Δx	Characteristic cell length in the flow direction
μ	Dynamic viscosity
v	Flow velocity
u	Vessel velocity
p_a	Ambient pressure
p_v	Vapor pressure
ρ	Fluid density
V	Characteristic flow velocity
U	Magnitude of the local fluid velocity
Δt	Time step
P_E	Effective power
R_T	Total hydrodynamic resistance acting on the vessel
P_D	Delivered power
η_D	Propulsive efficiency
C_p	Pressure coefficient
p	Pressure on the surface
p_∞	Pressure at infinity
$P_{E,\max}$	Maximum effective power
ν	Kinematic viscosity
T	Temperature

h	Submergence depth below the free surface
ϕ	Heel angle of the vessel
p_b	Exhaust back pressure
p_h	Hydrostatic pressure
p_{probe}	Pressure at the probe location inside the exhaust outlet
$\dot{V}_{\text{exh}}$	Volumetric exhaust gas flow rate
ρ_{w}	Water density
ρ_{a}	Air density; density of the modeled exhaust gas
k	Turbulent kinetic energy
ε	Turbulent dissipation rate
NO_{x}	Nitrogen oxides
N_2	Nitrogen
H_2O	Water

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1

Introduction

Sailing yachts are unique in their reliance on wind for propulsion, unlike motor yachts which rely solely on engines. As a result, every aspect of their design must work efficiently to minimize hydrodynamic losses, since even small inefficiencies can noticeably reduce speed or increase energy use. Modern larger sailing yachts, however, are rarely purely wind-driven. They almost always have engines and generators that provide auxiliary propulsion and electricity for onboard systems. These motors are not used continuously, instead they are mainly used when navigating in marinas or when there are unfavorable sailing conditions. However, using these engines presents issues regarding the exhaust gases. Traditional outlets above the waterline can produce unwanted noise, vibrations and odors which negatively affect the onboard experience for passengers and crew. They can also add extra weight through extended piping and take up valuable space within the vessel.

Underwater exhaust outlets offer a promising solution to reduce noise, vibration and odor while also potentially reducing weight and freeing up space. Yet their implementation on sailing yachts remains largely unexplored. This thesis investigates the development and optimization of underwater exhaust outlets for sailing yachts with an aim to improve the comfort while maintaining the hydrodynamic performance and overall efficiency. The thesis is approached from a product development perspective by using structured methods for concept generation, evaluation and iteration.

1.1 Background

All vessels that travel through water are highly dependent on their hydrodynamic properties, as these determine their overall performance. For sailing yachts, the need to minimize hydrodynamic losses is critical as their main method of propulsion relies on available wind energy which does not allow for wasting unnecessary energy. For sailing yachts equipped with an engine for propulsion and a generator to provide electricity for utilities, an exhaust can be implemented under the water surface. While underwater exhaust outlets are common on motor yachts, their implementation on sailing yachts remains both uncommon and unexplored. The objective of expelling the exhaust gases in the water is to lower the noise level on deck and to minimize the smell experienced by those on board while the vessel is traveling. The engine(s) for propulsion are not always in use when sailing, but instead used when navigating in marinas or when traveling when there is no wind.

For larger motor and sailing yachts, the engine room is often located in the stern or midship region, depending on the vessel type and layout. Placing the exhaust outlet close to the engine room can reduce piping length and thus weight. At the same time, the outlet should be positioned below the waterline to achieve the intended reduction in noise and exhaust smell. Consequently, the optimal location is typically a compromise: sufficiently close to the engine to limit piping requirements while positioned such that the discharged flow does not negatively affect hydrodynamic performance or interact with appendages such as propellers and rudders. In a suboptimal exhaust outlet design, the exhaust gases may be discharged as a pulsating flow, which can create unwanted consequences such as vibrations. In some cases, this flow may be directed towards the propellers and rudders of the vessel which can reduce hydrodynamic performance and cause damage to these components.

Profjord, a company in the marine industry, has developed a methodology for motor yachts to design and optimize exhaust outlets to achieve a constant and directed flow while maintaining acceptable back pressure [1]. Back pressure refers to the resistance experienced by the exhaust gases as they flow through the exhaust system, which must be controlled to ensure proper engine operation. The methodology also aims to minimize interference between the exhaust flow and the propellers and rudders. However, this approach has so far only been implemented on motor yachts. Therefore, the applicability of this concept to sailing yachts remains to be investigated.

Controlling back pressure is achieved by redesigning and optimizing the exhaust outlet and is verified by computational fluid dynamics (CFD) analysis. In order to reduce the back pressure and release a constant flow of gases, a small interceptor is placed in front of the exhaust outlet. This creates a high-pressure zone on one side of the interceptor and a low-pressure zone on the side closest to the outlet which reduces the back pressure in the exhaust outlet. This also reduces the pulsation of the gases which leads to less noise and vibrations.

Profjord specializes in hydrodynamics with their niche being high-speed and semi-planing vessels. Profjord works with developing optimal hull forms and appendages and predicting the overall performance of vessels. Their exhaust outlet design is optimized and customized for each vessel, engine and speed range. Implementing Profjord's exhaust outlet design methodology on sailing yachts presents new challenges as sailing yachts have different operating conditions, geometries and requirements. As a result, developing this methodology so that it is applicable to sailing yachts involves addressing complex and unique design constraints.

1.2 Purpose

The current configuration of exhaust systems on sailing yachts places the exhaust outlet above the waterline. This solution often requires additional piping, which increases both weight and space requirements onboard. In addition, it can contribute to higher levels of noise, odor and vibrations which negatively affect the comfort of the passengers onboard.

This thesis focuses on the development and optimization of an underwater exhaust outlet for sailing yachts. By relocating the exhaust outlet below the waterline, the exhaust gases can be expelled underwater leading to increased onboard comfort. In this new configuration, the exhaust outlet must be designed so that it avoids interference with the propeller and rudders so that the vessel's hydrodynamic performance is either maintained or improved.

1.3 Aim & Research Questions

The aim of this study is to iteratively design an exhaust outlet based on the technology Profjord has already developed that can be implemented in sailing yachts. To identify opportunities and challenges, a market analysis of high-performance sailing yachts will be carried out. The design will be evaluated with CFD using the software OpenFOAM in order to assess performance and measure the improvement.

The thesis aims to answer the following research questions:

- Q1: How can exhaust outlets for sailing yachts be redesigned so that the exhaust gases do not negatively affect the propulsion or rudders while also maintaining acceptable back pressure?

- Q2: How does the current technical and market landscape for sailing yacht exhaust outlets indicate the need for a redesigned solution?

- Q3: How does the redesigned exhaust outlet compare to the conventional design of the exhaust outlet for sailing yachts?

1.4 Delimitations

The main delimitation of the study is to investigate underwater exhaust outlet solutions for sailing yachts of sizes longer than 24 meters. The theory of fluid dynamics will not be treated in depth, as the methods Profjord has developed for CFD and hull design are based on established fluid dynamics theory and have been optimized for this specific use case. The thesis will not investigate the option to develop new or improve on the material selection of the hull or the exhaust. The materials that are currently being used and are available in sailing yacht manufacturing will instead be utilized in the study.

Furthermore, the thesis does not explore exhaust systems or outlets for the generators used on sailing yachts and will instead only investigate solutions for the main engine(s). The design and functionality of the bypass exhaust system are also outside the scope of the study and it will therefore be assumed that there is a functioning bypass.

Lastly, the study is limited to creating digital models of concepts and evaluating the design with CFD simulations. For this reason, no physical prototypes will be built, and no real-life testing will take place.

2

Theory

This chapter presents the theoretical foundation of the study and covers the fundamental principles of sailing yachts, fluid dynamics in naval architecture and marine exhaust systems. Section 2.1 presents the theoretical background of product development used in this thesis, Section 2.2 introduces the basics of sailing yachts, such as ship motions and hull design, which establishes the context for understanding how a vessel behaves. Section 2.3 delves into fluid dynamics and covers essential concepts and their relevance to yacht design and performance, such as the Froude number, cavitation, ventilation, oscillation and computational fluid dynamics. Finally, Section 2.4 presents the fundamentals of marine exhaust systems. Together, these sections provide the necessary background to understand the technical aspects of this project.

2.1 Product Development

Product development is the process of transforming ideas into new or improved products to meet customer needs and market demands. One important aspect of product development is that it can be approached in many different ways and more than one of those ways can be considered correct [2]. However, the generic product development process, as described by Ulrich and Eppinger [3], provides a widely recognized framework that guides product development. It consists of six phases: planning, concept development, system-level design, detail design, testing and refinement and production ramp-up. Within each of these phases, there are multiple activities and tasks that are typically carried out. However, the product development process may vary and be adapted depending on the specific product that is developed.

One adaptation of the product development process is Set-Based Concurrent Engineering (SBCE), which originates from practices developed within Toyota [4]. SBCE is an approach in which multiple design alternatives are explored in parallel, rather than selecting a single concept early in the process. As development progresses, less feasible alternatives are gradually eliminated based on constraints, testing and acquired knowledge. This allows the process to converge toward an optimal solution. SBCE reduces the risk of costly redesigns because problems are identified while several alternatives are still being considered [5]. It also leads to better informed decisions and reduced risk of failure, since choices are based on evidence gathered from comparing different design options.

Successful product development is difficult and comes with several challenges. The most obvious challenges are time and money, as product development is almost always a costly and time-consuming activity [3]. Beyond these practical constraints, dealing with uncertainty is a major challenge in product development [2]. Especially at the beginning of the process when the uncertainty is at its highest. This requires the designers to learn to work with the available information and make assumptions until new information is discovered. However, one of the most difficult challenges with product development is managing trade-offs [2, 3]. There are almost always competing objectives that the designer has to balance while keeping the customer and stakeholders in mind. For a successful product, the trade-offs need to be balanced well so that the success of the product is maximized.

2.1.1 Kano Model

The Kano model is a theory used in product development for analyzing and understanding customer satisfaction. The theory classifies product requirements into three types based on how they affect customer satisfaction: must-be requirements, one-dimensional requirements and attractive requirements. The must-be requirements are the basic features that customers expect from the product. If these requirements are not met, the customer will be dissatisfied, while fulfilling them will only lead to the customer being neutral or ”not dissatisfied”. One-dimensional requirements are features that directly affect customer satisfaction and the better they are fulfilled, the more satisfied the customer will be and vice versa. Usually, these requirements are demanded by the customer. Lastly, attractive requirements are features that the customers do not expect or request but are positively surprised by. If they are fulfilled, they will greatly increase customer satisfaction, however, if they are missing, they do not cause dissatisfaction [6, 7].

The model is useful for identifying and understanding product requirements which will enable more effective prioritization of product features. It is particularly valuable for product teams with limited time and resources, as it helps ensure the right balance of features is selected for development [7]. For example, when a must-be requirement is fulfilled, improving it further will add little value. Therefore, it is often better to invest in and prioritize the one-dimensional or the attractive requirements as they will have a greater influence on customer satisfaction [6]. Developing a product where only the must-be requirements are fulfilled is sometimes called a Minimum Viable Product (MVP), which is a product that includes only the most essential features needed to satisfy early users [8]. One of the main goals with an MVP is to get customer feedback as early as possible in the development process, which is used to guide the product’s future development.

2.2 Fundamentals of Sailing Yachts

A sailing yacht is a type of vessel primarily powered by wind and is designed for both recreational and competitive purposes. Understanding sailing yachts requires familiarity with their components and terminology, from ship motions and hull shapes to the forces acting on the vessel. This section introduces these foundational concepts and provides the necessary foundation for the topics covered in this and later chapters.

2.2.1 Ship Motions

A floating body such as a sailing yacht has six degrees of freedom (DOF) it can move in [9]. The translational movements along the x, y and z axes are referred to as surge, sway and heave, respectively. While roll, pitch and yaw are the rotational movements around the x, y and z axes, as illustrated in Figure 2.1. In sailing, ”roll” refers to the rotational motion of the vessel about its longitudinal axis, while ”heel” or ”heeling” describes the resulting angle of the vessel due to this motion. Heeling occurs as a result of the force of the wind on the sails and affects both the speed and handling of the vessel [10]. Different sailing yachts will operate within different heel angles depending on their design.

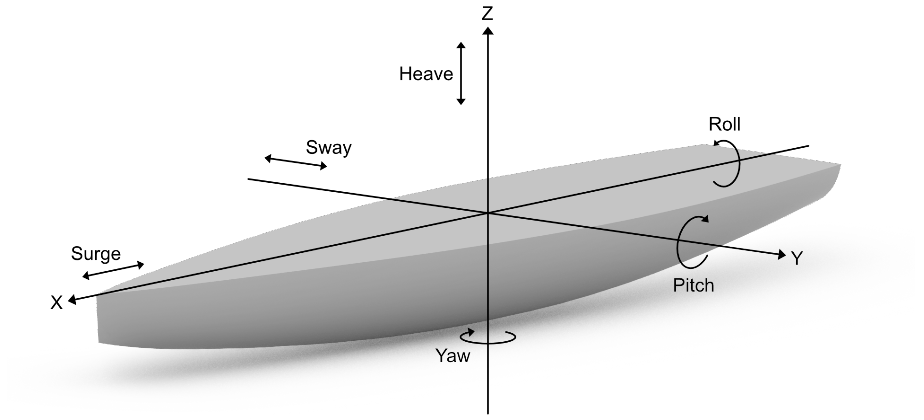


Figure 2.1: The six motions of a vessel: surge, heave, sway, roll, pitch and yaw.

2.2.2 Sailing Yacht Hull Design

The geometry of the hull of a yacht is a complex three-dimensional shape. Overall features of the hull can be described by dimensions such as length, depth and center of gravity, however there is no simple mathematical expression to define the complex geometry [11]. At a broad level, hulls can be categorized into monohull and multihull. A monohull is a vessel with only one hull, while a multihull can have two or more individual hulls that are then connected to each other. Catamarans and trimarans are common examples of multihull vessels [12]. Furthermore, vessels can also be categorized into three different types depending on their hull design and operating Froude number (F_n). These are called displacement, planing and semi-displacement vessels. For a detailed definition of the Froude number, see subsection 2.3.2. When F_n is below about 0.4, buoyancy will support most of the vessel’s weight, vessels with maximum operating speed within this range are called displacement vessels. A vessel is considered planing when F_n exceeds around 1.0 to 1.2, then the hydrodynamic force will carry most of the weight. Vessels operating at maximum speed in the range in-between ($0.4 - 0.5 < F_n < 1.0 - 1.2$) are called semi-displacement vessels [13].

For effective hull design, the forces acting on a sailing yacht must first be understood, Figure 2.2 shows these different forces. The most critical force relating to hull design is the resistance force, which develops as the hull is driven through water [11]. The resistance force has five major resistance components: viscous resistance, wave resistance, heel resistance, induced resistance and added resistance in waves. Proper hull design can minimize these resistance components and therefore improve the overall hydrodynamic performance. A yacht must therefore be designed for low resistance in varying sailing conditions, while also maintaining good balance and stability in these conditions. Although theoretical guidelines exist, yacht design remains an art based on practical experience [14].

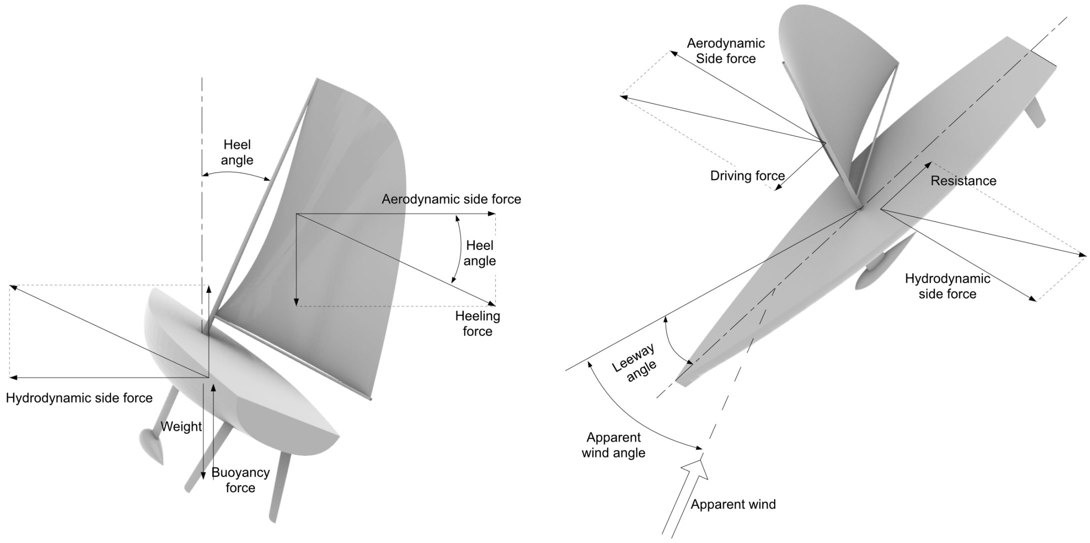


Figure 2.2: The different forces acting on a sailing yacht [11].

One method used to estimate the hydrodynamic resistance of displacement and semi-displacement vessels is the Holtrop-Mennen method [15]. The method is based on statistical regression of model test data from many vessels. The resistance is estimated using certain vessel characteristics such as hull length, beam, draft, displacement and wetted surface area, among other parameters.

2.3 Fluid Dynamics in Naval Architecture

Fluid dynamics is a subdiscipline of fluid mechanics that studies fluids in motion. Furthermore, hydrodynamics is a subdiscipline of fluid dynamics that studies the motion of water and other liquids. In these disciplines, both liquids and gases are considered fluids [16]. Fluid motion can be described by considering the behavior of small fluid parcels. As the size of a parcel becomes infinitesimally small, it can be treated as a point particle whose average velocity corresponds to the local fluid velocity. By studying the motion and deformation of these particles, the behavior of fluids in different situations can be understood [17].

An understanding of fluid dynamics is fundamental in naval architecture, as ship resistance and propulsion depend on the flow of water around the hull and propeller of the vessel. The characteristics of this flow determine the forces acting on the vessel and directly influence its speed, efficiency and power requirements [18]. This highlights the importance of fluid dynamics for predicting and improving ship performance. Therefore, this section aims to introduce the principal theoretical concepts of fluid dynamics needed to understand the methods and analyses discussed in later sections and chapters.

2.3.1 Laminar and Turbulent Flow

Fluid flow can generally be classified into two types: laminar and turbulent flow. Laminar flow can be characterized as smooth and orderly, with the fluid moving in layers with little mixing. In contrast, turbulent flow is irregular and chaotic motion with varying velocity and pressure [13]. The transition between these flow types is primarily determined by the Reynolds number, which is defined as:

$$R_e = \frac{\rho v L}{\mu} \tag{2.1}$$

where ρ is the density of the fluid in kg/m^3, v is the flow velocity in m/s, L is a characteristic length in m and μ is the dynamic viscosity of the fluid in Pa·s [16]. At low Reynolds numbers, the flow is laminar, however, as the Reynolds number increases beyond a critical value, the flow becomes turbulent [17]. On the hull of a sailing yacht, laminar flow results in lower viscous resistance because the water moves in smooth layers along the wetted hull surface [13]. This means that there will be reduced friction between the hull and the water. Turbulent flow near the hull will instead increase these frictional forces, leading to higher resistance and reduced performance.

2.3.2 Froude Number

The Froude number is a dimensionless number that can be defined as the ratio of the flow inertia to gravity. It is the dominant effect in free-surface flows (non-enclosed flows that can deform freely under gravity and pressure) such as ship resistance, surface waves and open channels [16]. The Froude number is expressed as:

$$F_n = \frac{u}{\sqrt{gL}} \tag{2.2}$$

where, in the case of naval architecture, u is the vessel speed in m/s, L is the submerged length of the vessel in m and g is the acceleration of gravity in m/s^2.

For vessels, this means that geometrically similar models moving at the same Froude number will generate similar wave patterns. Since smaller vessels have a shorter waterline length, they must move at a lower speed than larger vessels to achieve the same Froude number and thus the same wave pattern [19]. Essentially, the Froude number dictates how many waves will be along the hull of the vessel, which is of interest due to its effects on wave resistance and thus drag [11]. Figure 2.3 illustrates the waterline and wave pattern of a vessel traveling at 15 knots, which in the case of this hull corresponds to a Froude number of 0.44.

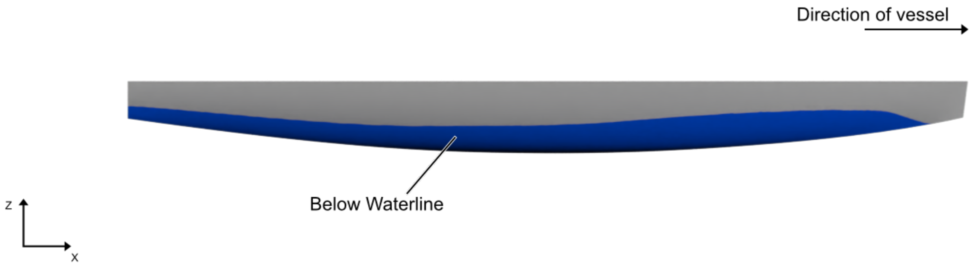


Figure 2.3: Waterline and wave pattern of a vessel traveling at 15 knots, illustrating a Froude number of 0.44

2.3.3 Cavitation

The pressure at which a liquid boils and is in equilibrium with its vapor is called vapor pressure. When the liquid pressure (the static pressure exerted by a liquid) drops below the vapor pressure, vapor bubbles begin to form in the liquid. This is similar to how water will boil at a lower temperature when taken to a higher altitude [16][19]. However, when the liquid pressure drops below the vapor pressure due to a flow phenomenon, it is called cavitation. Local high velocities in liquid flows will induce low pressures, which will cause voids to appear in the liquid [20]. For example, if water is accelerated from 0 m/s to 14.2 m/s, the pressure will drop by around 1 atm or 101 kPa, which could result in cavitation. The bubbles formed from cavitation implode when they move from a low-pressure region into a high-pressure region. If the cavitation collapse occurs close to metallic surfaces, it will cause damage and erosion to the surface [16][21]. The collapse also causes other consequences, such as the production of noise and vibrations [20]. Therefore, cavitation is generally an undesirable phenomenon in marine applications, as it can cause structural damage to vessels while also reducing comfort for passengers and crew due to the sound and vibrations.

The cavitation number is a dimensionless parameter that can be used to characterize cavitation within a system and is defined as:

$$Ca = \frac{p_a - p_v}{\frac{1}{2}\rho V^2} \tag{2.3}$$

where p_a is the ambient pressure in Pa, p_v the vapor pressure in Pa, V the characteristic flow velocity in m/s and ρ the density of the fluid in kg/m^3 [16]. Lower cavitation numbers correspond to a higher probability of cavitation, while higher cavitation numbers indicate a lower likelihood of cavitation [20].

2.3.4 Propeller Ventilation

Propeller ventilation occurs when either exhaust gases or air from the surface enters between and around the rotating propeller blades [22]. Essentially, it causes the propeller blades to lose their grip on the water due to the reduction of load. This leads to substantial losses in thrust, dynamic loads, noise and vibration, which in turn will contribute to increased wear of the propulsion system. Propeller ventilation may also arise as a consequence of cavitation [13]. Ventilation significantly affects propeller performance, in one case, a fully submerged propeller reached thrust losses of up to 40% and while partially submerged, the losses may increase to as much as 90% [19].

2.3.5 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is the study and application of numerical methods and data structures to solve problems involving fluid motion and the interaction of fluids with solid bodies [23][24]. It uses mathematical models, primarily the Navier-Stokes equations (partial differential equations that describe the motion of viscous fluids), to describe the behavior of fluids under different physical conditions. The equations are solved using computer simulations where the domain of the fluid is divided into small discrete elements or cells [25]. CFD allows for the prediction of variables such as velocity, pressure and temperature within a system. It is therefore widely used in industries such as marine, aerospace and automotive engineering. For example, in naval architecture, the use of CFD allows for insights into the flow dynamics before the hull of a vessel is constructed, which makes adjustments and corrections to the design possible before production [19].

Since the governing equations are discretized in both space and time, the choice of time step is crucial for maintaining numerical stability, accuracy and computational time in CFD simulations. The Courant number is a dimensionless number commonly used in transient simulations to control the time step [26]. It is defined as:

$$Co = \frac{U\Delta t}{\Delta x} \tag{2.4}$$

where U is the local fluid velocity in m/s, Δt is the time step in seconds and Δx is the characteristic cell length in the direction of the flow in meters. The Courant number represents the distance a fluid particle travels during a time step relative to the cell size [27]. High values of Co can lead to numerical instability, while too low values result in unnecessarily small time steps and increased computational cost. Therefore, an appropriate balance must be achieved by specifying a maximum value for the Courant number, so that the time step automatically adjusts to remain within the specified Courant number limit.

The interpretation of the results and predictions of CFD should be done carefully, as it is never exact [25]. There are several potential sources of error, the most common being: discretization error, input data error, initial and boundary condition error and modeling error. If the interpretation is done correctly and the errors are kept to a minimum, the accuracy of the CFD results is sufficient for many engineering applications [23].

2.3.5.1 Simulation Process

The CFD simulation process consists of five main stages, as shown in Figure 2.4: problem definition, creating the geometry, meshing, solving and post-processing [28]. It begins with identifying the problem, where the objective of the simulation is defined and relevant settings are applied. Next, the geometry, which represents the physical domain of the problem, is created using Computer-Aided Design (CAD) software. This geometry is then meshed, which means it is subdivided into small cells or elements over which the governing equations are solved.

The quality of the mesh plays a critical role in the accuracy and stability of the simulation. The quality depends largely on the size, shape, number and distribution of the cells. In the fourth stage, a solver, which is the numerical algorithm, iteratively computes the flow over the mesh until the simulation reaches the set end time. Finally, in the post-processing stage, the results are interpreted and visualized so that they can be analyzed and conclusions can be drawn. Generally, CFD simulation is an iterative process. Depending on the results of the simulation, the geometry might need to be updated and the simulation run again.

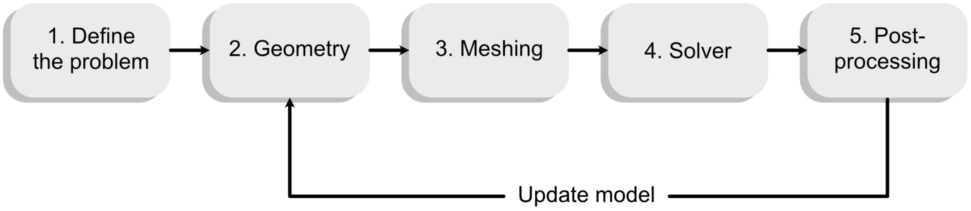


Figure 2.4: Overview of the CFD workflow.

2.4 Marine Exhaust System

A marine exhaust system is responsible for transporting the exhaust gases from the engine inside the vessel and then out to the surrounding environment. In marine applications, the design of the exhaust system is more complex than in land-based systems due to the interaction with water and the motions of the vessel. Some of the key design considerations include preventing water ingress into the engine, minimizing back pressure and reducing noise. Figure 2.5 shows a general overview of an exhaust system configuration that is commonly used in sailing yachts today [29, 30, 31, 32]. The following sections describe the main components and principles in marine exhaust systems for both motor and sailing yachts.

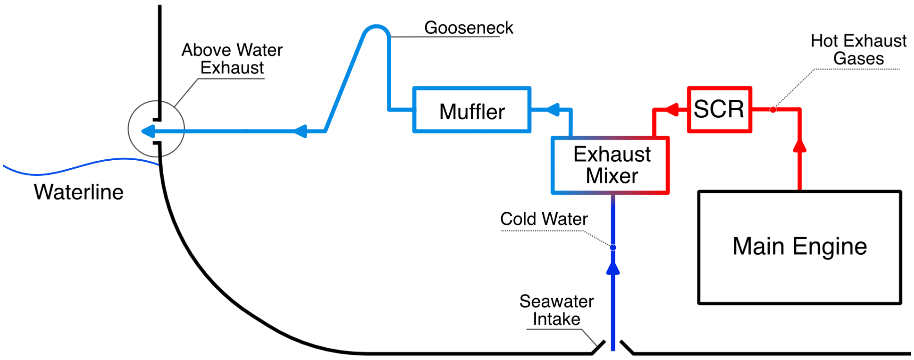


Figure 2.5: General overview of a sailing yacht exhaust system.

2.4.1 Dry and Wet Exhaust Systems

Since marine vessels operate in water, seawater can often be used in their engine cooling systems [33]. In many marine propulsion and generator installations, hot exhaust gases are cooled by introducing seawater into the exhaust stream, typically in an exhaust mixer. This arrangement is commonly referred to as a wet exhaust system. In contrast, a dry exhaust system is one in which no cooling water is introduced into the exhaust stream. Both wet and dry can be expelled above and under the waterline, even though the most common place to install the outlet is above the waterline.

2.4.2 Water Intake

The intake or inlet for seawater for cooling is generally located near the centerline of the vessel since it is required to always be submerged in water to not pull in air to the system. This placement is vital for the design of an exhaust system since the expelled gases can not interfere with the intake. A common solution is the use of a sea chest, which is a recess in the hull protected from debris by being covered by gratings [34]. The sea chest provides a reliable source of seawater to a vessel's systems, such as cooling water for the engine, ballast and firefighting systems.

2.4.3 Back Pressure

Back pressure is the resistance within the exhaust system that the engine must overcome to expel exhaust gases into the surroundings, such as the atmosphere or the sea [35]. It is essentially the resistance the engine must overcome to expel exhaust gases from high- to low-pressure regions. The back pressure is determined by factors such as pipe diameter and length, bends, mufflers, SCRs and other components, as well as the hydrostatic pressure. Too high back pressure can lead to reduced engine efficiency, increased fuel consumption, overheating and in worst case, engine shutdown or damage. For this reason, exhaust systems are typically designed with a target back pressure of around half the maximum allowed value [36]. For vessels with underwater exhaust outlets, back pressure is higher at slower speeds and underwater discharge may become ineffective or even cause backflow into the system [21, 33]. To prevent this, the exhaust is often diverted to an above-water outlet, which is commonly referred to as a bypass.

2.4.4 Selective Catalytic Reduction

Within the exhaust system, the requirement for reduction of pollution is required and is achieved by installing a selective catalytic reduction (SCR) system. This device utilizes a catalyst to convert the nitrogen oxides (NO_x) in the exhaust gases into nitrogen (N_2) and water (H_2O) using a catalyst that is sprayed into the gas [37]. These SCRs are common in yachts larger than 24 meters, both sailing and motor yachts that have a generator or engine with an output higher than 130 kW, according to regulatory standards [38]. It is positioned directly after the engine and controlled by a digital system that measures and controls the amount of catalyst that is used. The SCR adds back pressure to the system and thus affects the engine and the maximum pressure allowed at the exhaust outlet.

2.4.5 Muffler

As in many exhaust systems, there is a need to have a muffler to reduce the noise of the engine expelling the gases. In the case of the exhaust system for sailing yachts, the muffler is also used as a way to reduce the risk of water flowing back into the engine. This module adds back pressure to the exhaust system, and thus adds restriction and limitations to the exhaust design [36]. Although an underwater exhaust outlet is quieter than outlets above the waterline, there is still a need for a muffler [39]. There are specific mufflers for underwater exhaust systems that offer the best sound attenuation (around 25-30 dB), however, they must be installed above the waterline [40].

2.4.6 Bypass Exhaust

In motor yachts with underwater exhaust outlets, it is common to have a bypass exhaust, which is positioned over the waterline. At low speeds, low loads or during idling, exhaust gases are expelled through the bypass instead of underwater since the exhaust pressure is too low. This solution prevents excessive back pressure which could otherwise reduce engine efficiency. Then, when the engine operates at higher speeds or loads, the exhaust pressure increases and the exhaust gases can be expelled through the underwater outlet. The switching between the underwater exhaust outlet and the bypass exhaust is typically controlled by a valve system [39, 41, 42, 43].

2.4.7 Interceptor

On the underwater exhaust outlets on motor yachts, a small interceptor is often placed in front of the outlet, in the direction of travel [1]. This creates a pressure differential with a low-pressure area over the outlet and a high-pressure area on the other side of the interceptor, as can be seen in Figure 2.6. This low-pressure area helps to release the gases in a constant flow without pulsations, which reduces the noise and vibrations. The pressure also dictates the total resulting back pressure of the exhaust.

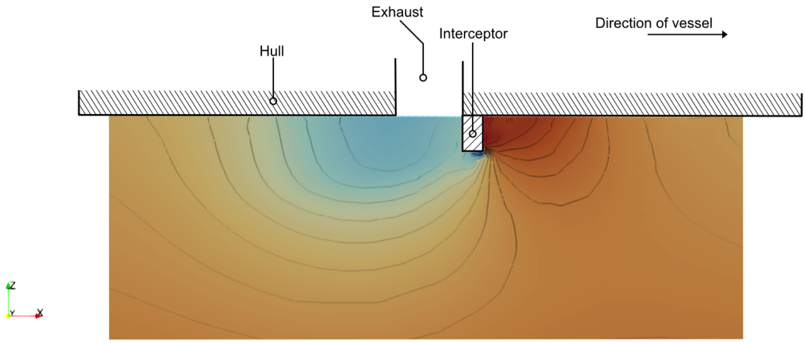


Figure 2.6: Function of an interceptor, creating a low-pressure zone at the exhaust. No exhaust flow is present in the figure.

3

Methodology

This chapter presents the methods and processes employed in the project. The product development methodology used in the thesis followed a structured and iterative approach, which was inspired by the framework outlined in *Product Design and Development* by Ulrich and Eppinger [3] as well as Set-Based Concurrent Engineering, as described in Section 2.1. Initial literature research was followed by a market analysis, which then led to the needs and requirements of the product. Subsequently, in an iterative process, concepts were generated, evaluated and then further developed and improved on. Lastly, the concept(s) were validated to ensure feasibility. Figure 3.1 presents an overview of the main product development activities in the project.

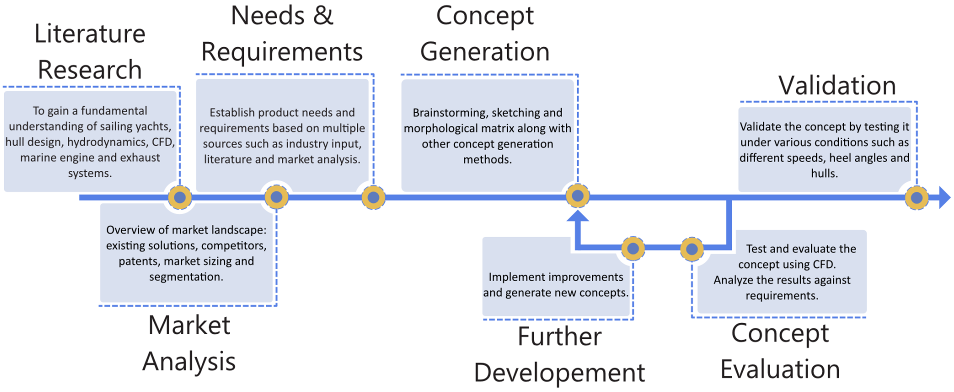


Figure 3.1: Primary product development activities in the project.

3.1 Initial Research and Modeling

The initial research of the project can be categorized as the first three stages illustrated in Figure 3.1: literature research, market analysis and needs & requirements. These three initial stages aimed to establish a theoretical and practical foundation for the subsequent stages. Before concept development could take place, a yacht hull was modeled to use as a reference geometry on which the developed concepts could be applied and evaluated through CFD simulations.

3.1.1 Literature Research

Before developing concepts, it was essential to gain a thorough understanding of the underlying theory and existing research needed to create the product. Available literature was therefore reviewed to explore relevant theories, methods and prior studies within the field. This provided a solid foundation of knowledge to support the subsequent stages in the methodology, such as concept generation and evaluation.

3.1.2 Market Analysis

A market analysis was conducted to help clarify the product's potential and to identify what is required to enter the market successfully. By reviewing literature and speaking with people within the industry, current and alternative solutions could be identified as well as the users, stakeholders and customers. In order to gain an understanding of the sailing yacht market, data was scraped from the database "The Superyacht Directory" [44], the largest database of sailing yachts. The acquired data was then compiled and structured for analysis, which provided information about the size of the market and segmentation. A competitor analysis was carried out to discover companies delivering similar and competing solutions as well as to identify if any of the alternative solutions could be threatening the proposed product. Furthermore, a benchmarking of a smaller selection of sailing yachts is made, mainly to motivate the parameters selected for the vessel used for the simulations. Lastly, a focused and narrow patent analysis is carried out to gain insights and inspiration for concepts. Overall, the findings of the market analysis are meant to guide the concept development.

3.1.3 Needs & Requirements

The needs and requirements of the product were formulated based on information from multiple sources. Discussions were held with shipyards and experts in the marine industry as well as insights provided by Profjord. Additionally, the findings from the literature research and market analysis contributed to identifying key criteria. Together, these sources made it possible to establish a structured list of needs and requirements to ensure that all relevant aspects of the product were considered throughout the development. The document was continuously updated as new insights and knowledge emerged during the development process.

3.1.4 Modeling of Hull

Since hull models of sailing yachts are generally not publicly available, a representative hull model was developed specifically for this study. The hull was modeled in computer-aided design (CAD) software Rhinoceros 3D 8 [45]. The geometry was created based on looking at different sailing yachts, general naval architecture principles and by using typical specifications for large sailing yachts. A hull length of 33 meters was selected which represents a relatively common size within the market segment of larger sailing yachts. This length was considered representative of a potential customer while also being suitable for CFD simulations. Based on the hull size and expected performance requirements, an appropriate engine was selected. The modeled yacht hull served as the baseline model onto which the generated concepts were applied. A visualization of the modeled hull is presented in Figure 3.2, while the dimensions and specifications of the hull and the engine selected are summarized in Table 3.1.

Figure 3.2: Model of hull with rudder, propeller and keel.

Table 3.1: Data and specifications of the sailing yacht model used in the CFD simulations. Engine data from Volvo Penta [46].

Sailing Yacht Specifications	
Engine	Volvo Penta D8 Marine Rating 2 Inboard 355 HP
Permitted exhaust back pressure	196 mbar
Displacement	103.5 t
LOA	33 m
LWL	32 m
Beam	6.9 m
BWL	6 m
Hull draft	1.3 m

3.2 Concept Generation

The first phase of the concept development was focused on generating concepts for the exhaust outlets. Initially brainstorming sessions were conducted and different ideas were explored, discussed and sketched out. A function tree was created to define and map out the different functions of the product.
The design space was mapped and divided up into different sub-functions, these were then put into a morphological matrix which is a product development tool used to synthesize concepts [47]. Solutions to the sub-functions were generated and then different combinations of the solutions to the sub-functions made up different concepts. The morphological matrix was mainly used for the generation of sub-solutions and as a structured library of design options. Inspiration was drawn from

various sources such as other marine vehicles but also airplanes, cars and other geometries relevant to the design of the underwater exhaust outlet. The concepts were then refined and modeled using Rhino 8 [45], which allowed for fine-tuning and a more accurate representation of each concept. This was done in an iterative process which enabled the creation of multiple concepts suitable for evaluation in the next stage.

3.3 Concept Evaluation

The purpose of the concept evaluation stage was to systematically narrow down the generated concepts based on their performance and how well they meet certain requirements. The concepts were primarily evaluated using CFD simulations in OpenFOAM 2.3.0 and OpenFOAM 8 [48, 49]. The simulations were performed on the yacht model with the different exhaust outlet concepts attached. The evaluation focused mainly on the resulting back pressure and the overall flow behavior of the exhaust gases. A more detailed description can be found in Section 3.3.2. In addition to the CFD analysis other criteria such as manufacturability, feasibility and aesthetics were also taken into account. A concept evaluation matrix was used to systematically document the generated concepts as well as their simulation results. Concepts were continuously added to the matrix throughout the evaluation process. This matrix served as a structured tool for comparing the concepts and identifying the most promising alternatives. The CFD simulations are described in greater detail in Section 3.3.1, which covers the procedure of the simulations including the general settings, creation of the mesh and the post-processing.

3.3.1 CFD Simulation Procedure

As part of the concept evaluation stage, CFD simulations were used to evaluate each concept. The simulations were carried out with the exhaust outlet concepts attached to the yacht model, where the flow of exhaust gases enters from the upstream section of the exhaust system and exits through the outlet. To allow for a consistent comparison between concepts, a probe point was placed inside the exhaust outlet, close to the exit. This probe was used to measure the pressure of this position, which served as a primary metric for evaluating performance directly correlated to the back pressure. Based on the measured pressure values, the concepts could be compared and ranked accordingly. The measured back pressure also served as a pass/fail criterion, concepts that resulted in excessively high back pressure could therefore be disregarded or modified at an early stage. In addition to this, qualitative assessment of the flow behavior was conducted through visualization of the flow of the exhaust gases. This made it possible to observe how the gases moved after exiting the outlet, ensuring that they avoided undesired regions, such as areas where interaction with the rudder or propeller could occur. It was also observed how effectively the gases moved towards the surface along the side of the yacht.

To generate the mesh and control volume, the meshing software snappyHexMesh was used [50]. An example of a generated mesh is shown in Figure 3.3. For the simulations, the interFoam solver was used which is a multi-phase RANS (Reynolds-Averaged Navier-Stokes) solver and a k-ε turbulence model. The properties of the fluids water and air used in the simulation can be seen in Table 3.2. The methods established at Profjord AB had been verified to be physically representative for this use case.

Table 3.2: Thermophysical properties of fluids used in the simulation.

Fluid 1: Water		
Temperature	15	°C
Density	1025	kg/m^3
Kinematic viscosity	10^{-6}	m^2/s

Fluid 2: Air		
Temperature	15	°C
Density	1.204	kg/m^3
Kinematic viscosity	$1.48 \cdot 10^{-5}$	m^2/s

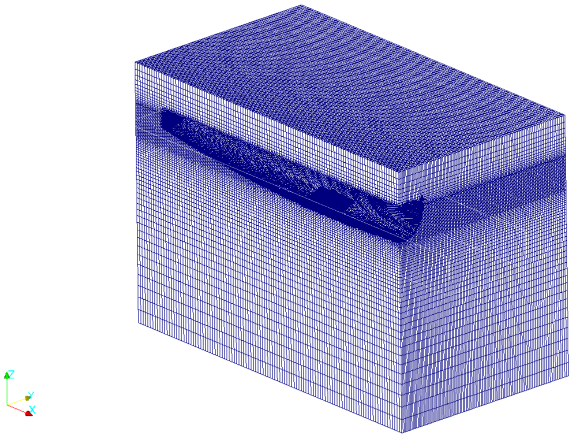


Figure 3.3: Isometric view of a control volume mesh.

3.3.2 Post-Processing

In order to be able to evaluate each concept, post-processing of the simulation results was carried out using ParaView [51]. Firstly, the pressure in the probe (the point placed inside the exhaust outlet) was analyzed to evaluate the value of the back pressure after convergence and to assess pressure fluctuations over time.

In ParaView, the flow of the exhaust gases is then visually inspected to verify that no exhaust gases enter the exhaust-free zone which is the region containing the appendages such as the propeller and rudders. Then the behavior of the flow of the exhaust gases is examined as well as the pressure. The desired result is a constant and smooth flow without pulsations or oscillations.

3.4 Further Development

After a concept had been evaluated using CFD, it was analyzed for potential improvements. Based primarily on the results from the CFD simulations, adaptations were made to increase the performance of the concept. These adaptations could be modifications of geometric features, positioning, features to direct the flow and other design parameters. Each concept that underwent evaluation represented a single iteration of the cycle: concept generation, evaluation and further development, as illustrated in Figure 3.1. Since insights and learnings were only available once the CFD simulation had been completed, most concepts were developed from earlier concepts. For this reason, each simulated concept corresponded to one full iteration of the cycle.

3.5 Validation

To validate a concept there are certain criteria that must be fulfilled. A concept needs to function without using bypass within a certain speed range, most importantly at and around cruising speed. At different speeds (or RPM) there will be differences in the exhaust gas flow which can be extracted from the datasheet of the engine. When the exhaust gas is cooled, the temperature decreases, which also reduces the flow. The new flow after the temperature drop is then calculated by multiplying the flow with the density ratio after the temperature change. In Table 3.3, the velocity and the corresponding exhaust gas flow in the ranges of 5 knots to 13 knots are presented. Furthermore, from the requirements specification presented in Section 4.2, a concept needs to function at heeling angles of ± 5°. Lastly, concepts should be validated with CFD on different hulls and with different engine data, which due to time limitations was not possible.

Table 3.3: Validation data for different velocities along with corresponding exhaust gas flow after temperature drop.

Vessel velocity [kn]	5	6	7	8	9	10	11	12	13
Vessel velocity [m/s]	2.57	3.09	3.60	4.12	4.63	5.14	5.66	6.17	6.69
Exhaust gas flow [m^3/s]	0.063	0.079	0.10	0.13	0.20	0.30	0.34	0.37	0.40

4

Results

This chapter presents the results obtained throughout the thesis, beginning with a market analysis to establish the context, identify stakeholders and assess the market. Based on these findings, along with the theory, the needs and requirements are defined, which form the foundation for the concept generation phase. The generated concepts are then evaluated based on certain criteria such as specific values for back pressure and the behavior of the exhaust gases. Finally, selected concepts are validated, which leads to the development and presentation of the final concept.

4.1 Market Analysis

Underwater exhaust outlets are commonly used on motor yachts, but their application on sailing yachts remains largely unexplored. To the authors' knowledge, there are no underwater exhaust outlets implemented on sailing yachts. This is largely due to the added complexity and problems associated with implementing the design into a sailing vessel. However, if a viable solution can be developed, there is potential to enter a new market. To evaluate the potential of an underwater exhaust outlet for sailing yachts, a market analysis was conducted. The findings of the analysis will be used to inform future product planning activities and thus serve as a foundation for a potential expansion into this new market.

4.1.1 Users, Stakeholders and Customers

The development of an underwater exhaust outlet for sailing yachts involves several users, stakeholders and customers, each interacting with or being affected by the product in different ways. These groups are identified in order to better understand the requirements and constraints set on the product design. Users are divided into primary, secondary and extreme users based on how they interact with the product. Primary users, such as the crew and passengers of the sailing yacht, are directly affected by factors such as noise, smell and vibration. Secondary users, such as shipyards and maintenance personnel, are involved in the installation, operation, and servicing of the system. Extreme users are users that may have higher demands on the product. Stakeholders are categorized as either primary or secondary depending on their level of involvement. Primary stakeholders are directly involved in the development and implementation of the underwater exhaust outlet, while secondary stakeholders are indirectly affected, for example, through environmental impact or exposure to noise and emissions. Lastly, regulatory and classification agencies such as the European Commission, Det Norske Veritas (DNV), Bureau Veritas, American Bureau of Shipping (ABS) and International Maritime Organization (IMO) can set requirements on the product through regulations and rules. A summary of the identified users, stakeholders and customers is presented in Table 4.1.

Table 4.1: Users, stakeholders and customers

Users & Stakeholders	**Actor**
Primary User	S/Y Crew S/Y Passengers
Secondary User	Shipyard Maintenance and service personnel Renting agencies
Extreme User	Extreme-weather sailors Competitive sailors
Primary Stakeholder	Profjord Shipyard
Secondary Stakeholder	Bystanders Nearby boat users Marina users Coastal residents Marine ecosystem
Customer	Shipyard S/Y owner
Regulatory Agencies	European Commission Det Norske Veritas (DNV) Bureau Veritas American Bureau of Shipping (ABS) International Maritime Organization (IMO)

4.1.2 Current Systems

To identify areas for improvement and establish a foundation for comparison, existing exhaust systems on sailing yachts are reviewed. These systems are generally categorized as either wet or dry exhaust systems, as described in Section 2.4.1. In wet exhaust systems, seawater is introduced into the exhaust stream to cool the exhaust gases, while dry exhaust systems operate without mixing cooling water with the exhaust gases.

On sailing yachts, the exhaust outlet is commonly positioned either at the transom, on the starboard side or on the port side. In these configurations the gases are expelled at or just above the waterline. Vessels with an exhaust outlet above the waterline avoid the issues with the gases affecting the rudders and propellers. However, it is not a complete solution, as smells, noise, vibration and soot deposits on the hull may still be an issue.

4.1.3 Alternative Solutions

To fully understand the offerings and solutions on the market, it is of importance to examine if there are entirely different ways to achieve the same result that the intended product will provide. Currently, two main alternative solutions have been identified, electric propulsion and vertical exhaust stack.

Electric Propulsion

Sailing vessels with electrically powered motors completely avoid the issues associated with the underwater exhaust outlets currently used. This means that there are no gases affecting the appendages of the vessel and reduced or no smell and noise. There may be concern that it could be a strong competing solution, as the electric boat and ship market has been steadily growing and is projected to continue expanding, at least in the near future [52][53]. However, electric propulsion comes with other issues and considerations, such as higher price and weight, limited range and the need for careful energy management, as the batteries will need to power not only the propulsion system but also all other electrical systems onboard [54]. Vessels utilizing electric propulsion are also subject to stricter design requirements regarding maneuverability and controllability, which are two parameters that directly impact operational safety [55].

Vertical Exhaust Stack

A vertical exhaust stack releases gases upward through an outlet positioned high above the deck [33, 56]. This type of exhaust is rarely seen on sailing yachts and instead is more common on cruise ships and larger motor vessels. A significant benefit with a vertical exhaust is that it avoids interference with propellers and rudders. It may also reduce noise, odor and vibrations on deck compared to outlets positioned on the hull above the waterline, although this depends on the specific vessel configuration. A vertical stack exhaust could also be heavy and add significant weight to the vessel. Additionally, it requires vertical space, which may make it difficult to implement in a sailing yacht as well as affect the aesthetics negatively.

4.1.4 Competitor Analysis

Competitor analysis involves identifying and evaluating competing products. This is done in order to understand the product's strengths and limitations to identify potential opportunities for improvement. Within the specific market segment of developing underwater exhaust outlets for sailing yachts, no direct competitors have been identified. While there may still exist competitors within this specific segment, there is limited available information, which makes this difficult to confirm. However, there are companies such as Mive Eco, MarQuip, and EcoExhaust that provide underwater exhaust solutions for motor yachts [41, 57, 58]. These companies may be considered potential competitors, however, no evidence has been found that indicates that these companies offer an underwater exhaust solution specifically for sailing yachts.

The solutions mentioned in Sections 4.1.2 and 4.1.3 are the current products that an underwater exhaust outlet would compete against. While these products have their benefits and drawbacks, an underwater exhaust outlet must provide clear improvements in certain areas, for example, sound, noise and vibration to be competitive. Electric propulsion, in particular, may be considered the most significant competitor, as exhaust emissions are eliminated entirely and thereby it addresses many of the same user needs as an underwater exhaust outlet. However, if the underwater exhaust outlet can offer improvements in terms of, for example, reduced weight or price, it may remain a competitive solution.

4.1.4.1 Benchmarking

Due to the absence of underwater exhaust outlets for sailing yachts on the market, benchmarking is instead conducted on a selection of existing sailing yachts that use conventional exhaust systems. The focus is on comparing different parameters and characteristics such as engine power, speed and hull dimensions. This is done in order to identify typical operating conditions and design constraints that are relevant for the exhaust system. In addition, the results also provide a general reference and method to validate the sailing yacht model developed for the simulations.

The benchmarking is illustrated in Figure 4.1–4.3, while the complete dataset with sources is provided in Appendix A.4. The benchmarking consists of nine different sailing yachts, all from different shipyards, produced between the years 2013 and 2026. Information regarding the price of the sailing yachts is limited and not consistently available and is therefore not included in the analysis, however, it would have been valuable to have it included for a more thorough comparison.

Figure 4.1 shows the relationship between engine power and gross tonnage (GT), which is a measure of a vessel's total internal volume. As expected, a general trend of increasing engine power with increasing GT can be observed. This is relevant for understanding how engine size varies with vessel size and thus defining the ranges that an underwater exhaust outlet solution should ideally be compatible with.

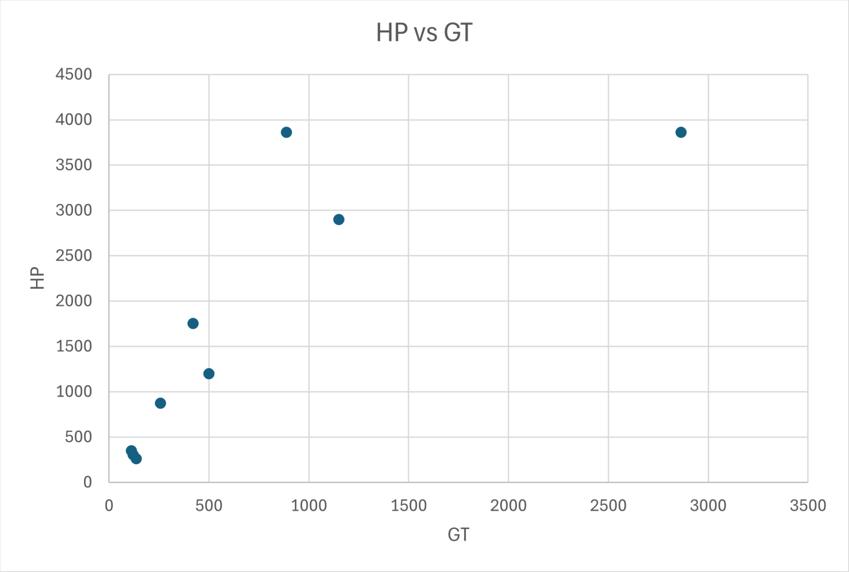


Figure 4.1: Relationship between HP and GT.

Figure 4.2 illustrates the relationship between the length and beam of the vessel. This relationship describes the general slenderness of the yachts and as can be seen in the figure the proportions are consistent across the selected yachts. This is useful for understanding geometric constraints for the design of yacht hulls. It also gives an indication of how much space can be expected for the exhaust outlet with increasing sizes of sailing yachts.

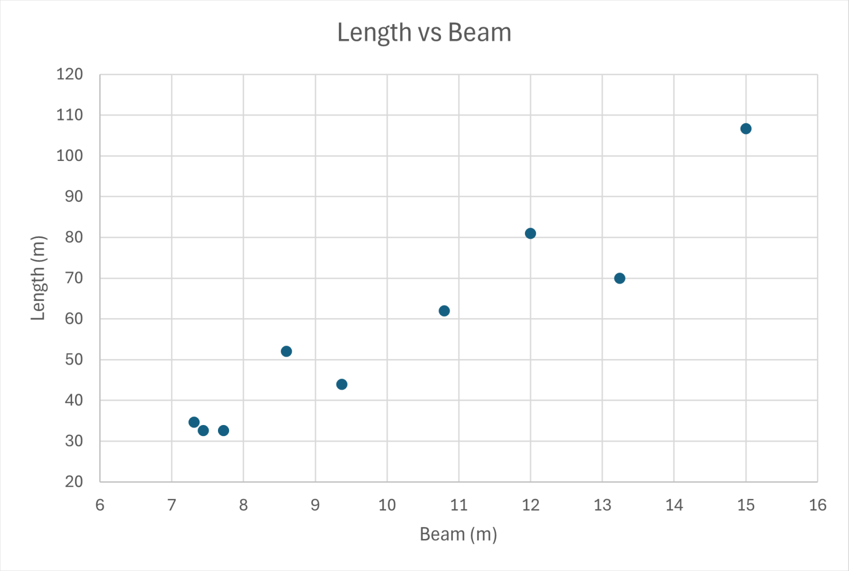


Figure 4.2: Relationship between length and beam.

Figure 4.3 presents the relationship between engine power and top speed. Higher engine power generally corresponds to higher speeds, although with some variation. This illustrates how top speed increases with engine power and provides an indication of the typical operating speed range of the selected vessels.

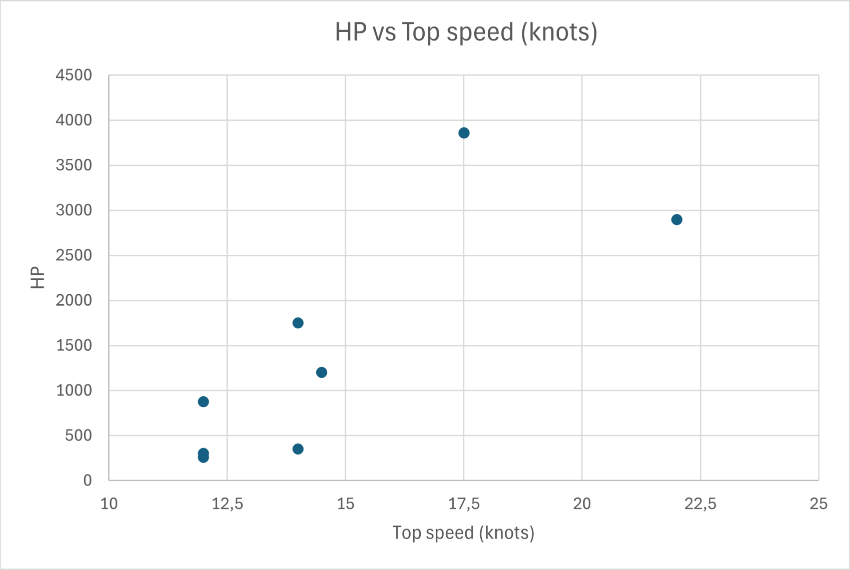


Figure 4.3: Relationship between HP and top speed.

Figure 4.4 shows the relationship between gross tonnage (GT) and top speed. GT is a measure of the vessel's internal volume. The results show a spread in top speed across the selected vessels, which indicates that vessels of different sizes operate within similar speed ranges.

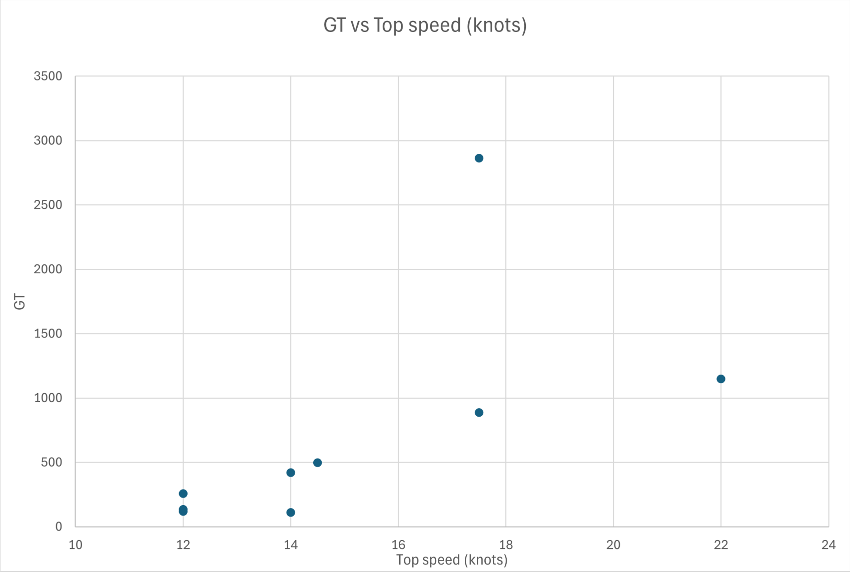


Figure 4.4: Relationship between GT and top speed.

4.1.5 Market Sizing

Understanding the size of the market is a crucial step in guiding strategic decisions [59]. By quantifying the market, insights about its scale and trends can be gained, which provides an idea of the market's potential. This can help to determine difficult choices such as when and how to enter a new market, where to allocate resources and identifying opportunities for growth.

In Figure 4.5, the distribution of different sailing yacht models per length span since the year 2000 can be observed. Note that this is not the amount or sum of sailing yachts since 2000, only the different unique models produced. More than one third of all these models are within the length span of 24-39 m. The length spans 80-99 m and 40-59 m are roughly even with 23.9% and 21.8% respectively and the span 60-79 m is slightly less common with 13%. Sailing yachts longer than 99 meters are rare, with only 40 different models since the year 2000, totaling to 3.4%. The division of length spans could skew the statistics, however, it gives a general idea of the lengths of the sailing yachts on the market. The data used has been scraped and compiled from the database "The Superyacht Directory" by the company BOAT International. It is the world's largest database of yachts with over 14,000 entries and roughly 2,000 of these are sailing yachts [44].

In Appendix A.1, a more detailed breakdown of the same data is provided. Here it can be observed that the number of different sailing yacht models across all length spans except for 99+ m has heavily decreased since the year 2000. One explanation for this declination is market consolidation, which has reduced the number of active shipyards and thus the number of distinct models on the market [60].

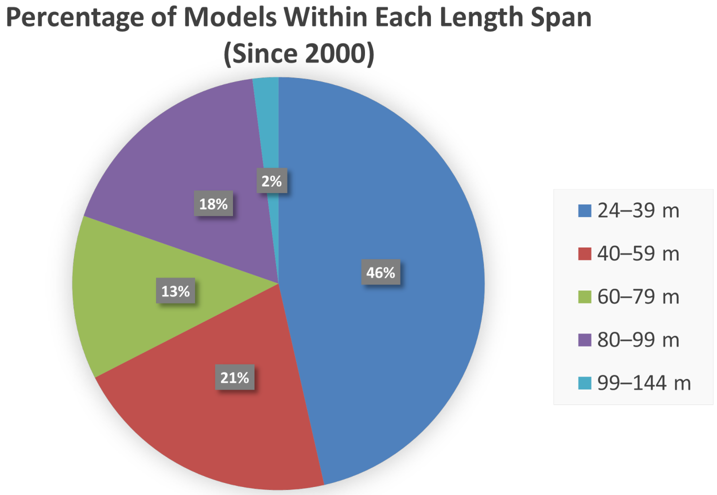


Figure 4.5: Number of sailing yacht models introduced since 2000, categorized by length span. Data from BOAT International [44].

While the number of different models provides an overview of the variety of models within each length span, the total number produced offers further insight into the actual volume produced since 2000. Figure 4.6 presents the total number of sailing yachts produced since the year 2000, scraped and compiled from ”The Superyacht Directory” [44]. The models listed with unknown or undisclosed production numbers have only been counted as one unit. In Appendix A.2, a similar chart is provided where these models are entirely excluded to highlight the difference caused by unknown production numbers. Since the year 2000, a total of 1,491 sailing yachts have been produced, with nearly half concentrated in the 24–39 m length span. It should be noted that this is an estimation based on available data and the actual number of yachts produced since 2000 may be higher.

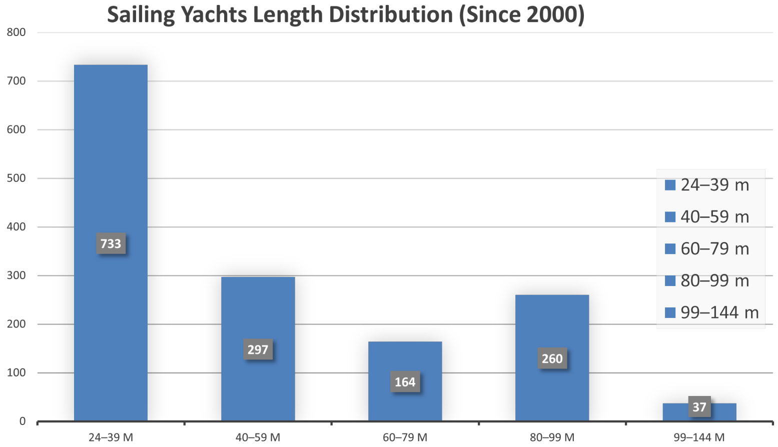


Figure 4.6: Total number of sailing yachts produced since 2000, categorized by length span (models with unknown production numbers counted as one unit). Data from BOAT International [44].

In Appendix A.3, the same data shown in Figure 4.6 are presented in more detail and instead showing the number of sailing yachts produced each year. The data show that the highest production levels occur between 2000 and 2009, with the exception of 2001. This is followed by a period of lower production from 2010 to 2017. From 2018 to 2025, production increases again to moderate levels, although noticeable dips occur in 2021 and 2025. As mentioned previously, the number of shipyards has decreased since the year 2000, partly as a result of market consolidation within the industry. While production levels have varied throughout since 2000, the data indicates that sailing yachts continue to be produced in relatively high numbers. As a result, the remaining shipyards may represent a larger share of the overall production. This highlights the importance of maintaining relationships with existing shipyards while also establishing new ones.

4.1.6 Segmentation

The main segment considered are sailing yachts equipped with an engine and with a length of 24 meters or longer. Yachts (motor or sailing) with a length of at least

24 meters are referred to as superyachts [61] and within the category of sailing superyachts, vessels in the 24-39 m range represent the most common segment. The 24-39 m span makes up for almost 50% of all sailing superyachts, as shown in Section 4.1.5. The segment of interest includes all sailing yachts within this size range that are equipped with engines, regardless of whether they are privately owned, part of charter fleets or used for racing. Although the solution could potentially be applied to smaller sailing yachts, there is likely a smaller benefit and thus a lower need.

4.1.7 Patent Landscaping

Researching patents can be a valuable approach to obtain insights into technological, business and scientific trends. By researching different types of patents concerning marine exhaust outlets, opportunities can be identified and new ideas can emerge. Patent landscapes can vary in scale and scope, from broader overviews to detailed reviews. In this analysis, a more focused and narrow approach is adopted to highlight certain patents of interest. Data for the selected patents were retrieved from the Espacenet database [62].

Patent 1: Underwater Exhaust Pipe
This patent describes an underwater exhaust pipe consisting of a main pipe body, a diffusion pipe with an increasing diameter and a perforated plate at the outlet [63]. This design prevents external water from flowing backwards while maintaining low exhaust back pressure thus improving safety and efficiency for marine vessels.

Patent 2: Improved Underwater Exhaust Device for Marine Engine
This patent shows an improved underwater exhaust device for a marine engine [64]. The engine's air outlet connects to an exhaust pipe via a hose, which leads to an exhaust box that is fixed on the hull. By using an underwater exhaust system and eliminating the muffler, space is saved in the engine room as well as material and labor costs. The exhaust gases are filtered underwater, which decreases noise. Additionally, by not having air discharge holes on the transom, the structural integrity is better preserved as well as the aesthetics.

Patent 3: Underwater Air-Exhausting Device for Yacht
This patent discloses an underwater air-exhausting device for a yacht, which consists of an inboard flow-guiding pipe, an installation plate and an underwater flow-guiding shell [65]. The inner walls of the pipe and the air outlet hole are coated with heat-resistant silicone paint, which protects the device against, for example, high temperatures and corrosion. The device can be implemented during the construction of the yacht without compromising the overall material quality.

Patent 4: Ship Exhaust Device
This patent showcases an invention of a marine exhaust system with a ventilation opening above the waterline and an exhaust outlet below it on the hull [66]. An exhaust pipe connects the two openings through a cooling mechanism that includes a ventilation pipe, a smaller air guide pipe with a baffle, an outer sleeve forming a

cooling water chamber and a sealing plate with spray holes. When sailing, the flow guide plate creates a low-pressure area that improves exhaust flow and reduces the noise. Cooling water sprays into the exhaust, which further lowers temperature and noise. A bypass exhaust outlet ensures the gases are emitted at low speeds while the baffle prevents backflow.

Patent 5: Under-water Exhaust
This patent is of an invention of an underwater exhaust system for boats that discharges engine gases below the waterline while reducing back pressure and noise [67]. It features a hull-mounted exhaust with side guards and an inclined deflector that directs exhaust and water flow. This creates a suction effect that helps expel gases more efficiently while also preventing debris from clogging the outlet. This is done by a small slit in the deflector, which allows a small stream of water to pass through, which clears any potential debris.

Patent 6: Underwater Exhaust Device for Glass Fiber
This patent describes an invention of an underwater exhaust system for fiberglass yachts [68]. It features an engine exhaust pipe, a mounting plate and a tapered underwater exhaust outlet. The outlet is a cone-shaped structure that is connected to the mounting plate and has an opening for discharging exhaust gases.

Overall, these patents demonstrate that underwater exhaust outlets can be designed in many different ways. Despite the difference in design, geometry and components, many of these patents focus on the same issues, such as improving exhaust flow, reducing noise and saving space in the engine room. Another insight is that several of the patents attempt to improve the performance through relatively simple modifications rather than entirely new system designs.

4.2 Requirements Specification

The final needs and requirements were compiled into a structured requirements specification, which is presented in Appendix A.5. The requirements specification was used as a basis for the development of the concepts and is intended to be used to guide subsequent development. In the requirements specification, each entry is classified as either a requirement (R) or a desire (D). This can be related to the Kano model described in Section 2.1.1, where a criterion classified as a requirement corresponds to a must-be requirement and a criterion classified as a desire corresponds to a one-dimensional requirement or an attractive requirement. The requirements specification was treated as a living document and was continuously updated and refined throughout the development as new insights were gained from stakeholders [29, 30, 31, 32, 69, 70, 71].

In Table 4.2, the most important requirements are listed along with their value, unit, verification method and by whom the requirement was requested. These requirements were identified as having the most impact on the final design in terms of functionality and have therefore been given the most focus. These selected requirements are also considered necessary to achieve a Minimum Viable Product (MVP), meaning it fulfills just enough features to satisfy early adopters. For this reason, some seemingly important criteria have been demoted to desires, such as the criteria that odor, noise, vibration and weight shall be minimized. The reasoning behind this is that all or most of these criteria will likely be fulfilled if the requirement to expel the gases underwater is possible. Therefore, having them as desires instead of requirements avoids unnecessarily constraining the design process and the development of an MVP.

The requirements specification contains relatively few numerical target values. This is because the product to be developed is intended to be parameterized in order to function on different sizes of sailing yachts and for different engines. For example, the maximum permitted back pressure of 98 mbar included in the requirements specification is specifically for the engine (Volvo Penta D8 Marine Rating 2 Inboard 355 HP) selected for the sailing yacht used in the simulation. The determination of this value is presented in Section 4.2.1.

Table 4.2: The most important product requirements.

Nr.	R. / D.	Criteria	Value	Unit	Verification method	Requested by
1	R	Exhaust gases shall be expelled underwater	pass/fail	-	CFD, sea trial	P. Stakeholder
2	R	Rudders function should be unaffected by exhaust gases	pass/fail	-	CFD	P. Stakeholder
3	R	Propeller(s) function should be unaffected by exhaust gases	pass/fail	-	CFD	P. Stakeholder
11	R	Back pressure shall be ≤ 50% of the permitted maximum	98	mbar	CFD, calculations	P. Stakeholder
13	R	Shall function at heeling angles up to ± 5°	pass/fail	°	CFD	P. Stakeholder, R. Agencies
16	R	Shall operate in non-bypass mode at cruising speed	pass/fail	-	CFD	P. Stakeholder
27	R	Exhaust outlet must fit between the structure of the hull	pass/fail	-	CAD	P. Stakeholder
32	R	Exhaust gases shall be expelled in a non-pulsating flow	pass/fail	-	CFD	P. Stakeholder

4.2.1 Maximum Permitted Back Pressure

From the specification of the selected motor chosen for the sailing yacht used in the simulation, the maximum permitted exhaust back pressure is 196 mbar. For the full specifications of the sailing yacht, see Table 3.1 in Section 3.1.4. As described in Section 2.4.3, exhaust systems are typically designed with a target back pressure of approximately half of the maximum allowed value. This is because components such as the SCR, muffler, the length of the pipe and 90-degree bends in the pipe each contribute additional back pressure to the exhaust system. This results in a target back pressure of a maximum of 98 mbar, which is calculated as half of the maximum permitted exhaust back pressure (196 mbar). This provides a safety margin that ensures the back pressure does not rise above the maximum permitted value.

4.3 Concept Generation

Largely due to the methodology being inspired by a set-based concurrent engineering (SBCE) approach as described in Section 2.1, many concepts have been generated. In total, the number of generated concepts is 30. Due to the iterative development process, the concepts have large variation between them, with some differing significantly and others being relatively similar. This is due to the modifications to the concepts were made either to explore entirely new designs or to improve on existing ones. Figure 4.11 presents renderings of a selection of the generated concepts. The figure illustrates some of the variation in geometry and design throughout the concept generation process.

Figure 4.7: Concept 16

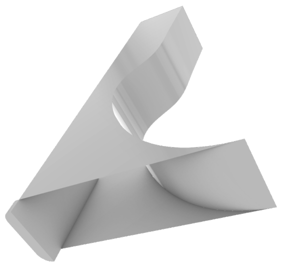


Figure 4.8: Concept 23

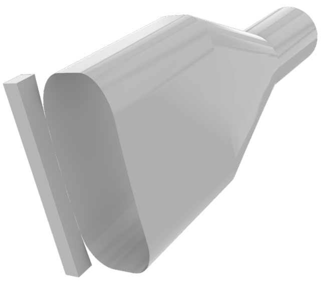


Figure 4.9: Concept 28

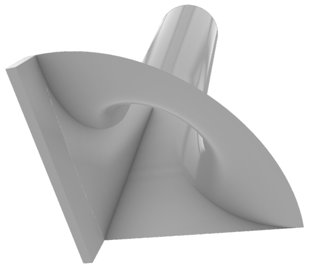


Figure 4.10: Concept 30

Figure 4.11: Rendered visualizations of concepts 16, 23, 28 and 30.

4.3.1 Concept Catalog

The concept catalog is presented in Appendix A.6. The catalog contains all the generated concepts developed during the concept generation phase. Each concept in the catalog represents a unique design, although several of the concepts in the catalog were later adjusted and modified slightly. Since the positioning of the exhaust outlet on the hull was an important design parameter, the catalog includes both visualizations of the concepts themselves together with their positioning on the hull.

Figure 4.12 presents an example from the concept catalog where the concept and its positioning can be observed.

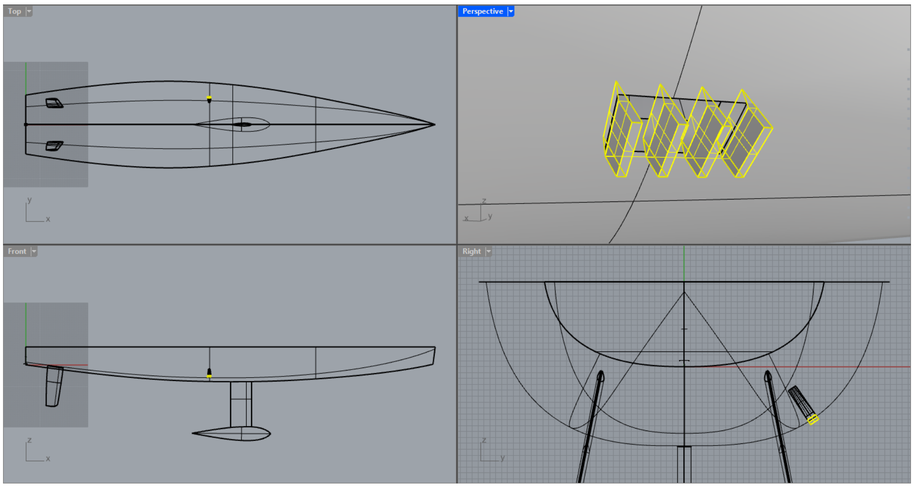


Figure 4.12: Example of a concept from the concept catalog showing the geometry of the concept together with its positioning on the hull.

4.3.2 Function Tree

Figure 4.13 shows the function tree, which was developed to define and understand the product's functions in order to support the concept generation phase. The function tree provides a structured breakdown of the product concept, where the top level represents the main function while lower levels are the subfunctions needed to accomplish the main function.

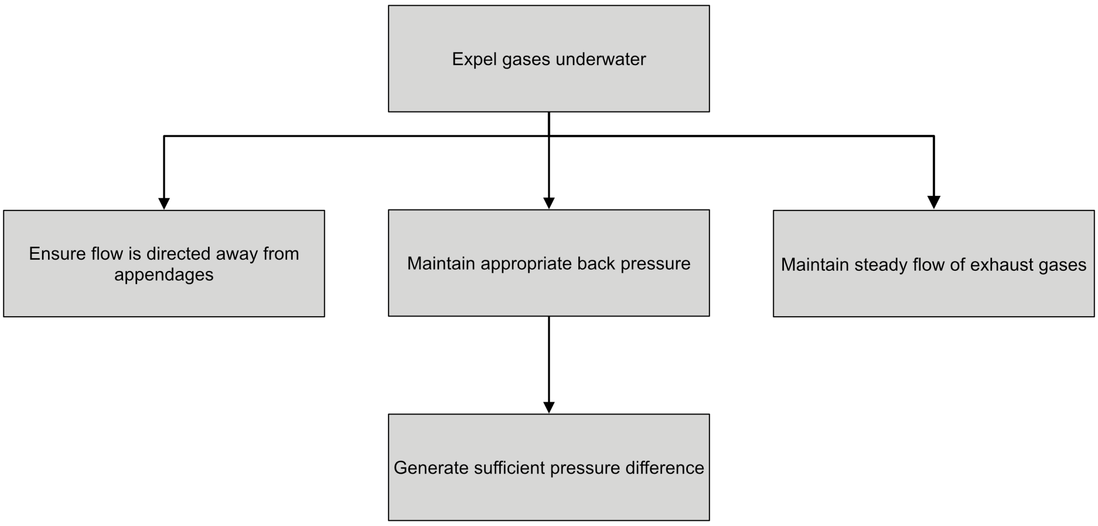


Figure 4.13: Function tree of the product concept.

4.3.3 Mapping the Design Space

In order to make the concept generation phase more structured and organized, the design space of the underwater exhaust outlet was mapped and divided up into five key design variables:

- Outlet position: the placement of the exhaust outlet on the hull.
- Outlet geometry: the shape and size of the outlet opening.
- Internal geometry: the shape, size and features added to the inside of the exhaust outlet.
- Outlet Feature: additional feature added to the outlet or the external hull surface.
- Number of outlets: the total number of exhaust outlets used.

Different variations and combinations of these five design variables make up all the generated concepts. In relation to the function tree from Section 4.3.2, the positioning of the outlet has a direct impact on the flow of the exhaust gases and back pressure. The outlet and internal geometry on all three of the mid-level functions in the function tree and the outlet feature have an impact on generating sufficient pressure difference as well as maintaining a steady flow of exhaust gases.

4.3.3.1 Interceptor Design

A large proportion of the generated concepts included an interceptor as an outlet feature. The outlet features that are defined as an interceptor are all the features that are protruding from the hull in front of the exhaust outlet in the direction of travel. For a more detailed description of its function, see Section 2.4.7. The design of the interceptor can be considered to have its own design space due to its number of geometric variables and its importance. Within the sub-design space for interceptors, several key design variables were identified:

- Geometry: the shape of the interceptor (e.g. rectangular, triangular or curved).
- Distance from the outlet
- Width
- Thickness
- Height

Together, these geometric variables define a secondary design space which exists within the broader underwater exhaust outlet design space. Thus, different combinations and variations of these variables will make up all the generated interceptor designs. In the function tree described in Section 4.3.2, the interceptor is meant to fulfill the function of generating a sufficient pressure difference which in turn partly fulfills the function to maintain appropriate back pressure.

4.3.3.2 Morphological Matrix

A morphological matrix was developed to explore solutions for the five design variables identified from mapping the design space. The morphological matrix is presented in Appendix A.7. The matrix was used to generate solutions for the subfunctions and also provided a structured overview of possible solution combinations. However, it was not used as the main tool for concept generation in the project. Instead, the morphological matrix was mainly used as a support tool to ensure that all important design aspects were considered and as a library for all sub-solutions generated. The concepts were instead mainly generated and developed iteratively due to this approach being more suitable as it allowed continuous refinement and modifications of concepts based on new insights.

4.3.4 Overview of Underwater Exhaust System

Figure 4.14 shows the general overview of how the underwater exhaust system developed in this thesis would be arranged in a sailing yacht. Compared to the configuration presented in Figure 2.5 in Section 2.4, the exhaust gases are expelled underwater when the vessel operates above a certain speed threshold. At lower vessel speeds, the exhaust gases are instead redirected through an bypass exhaust outlet positioned above water which is controlled by a valve.

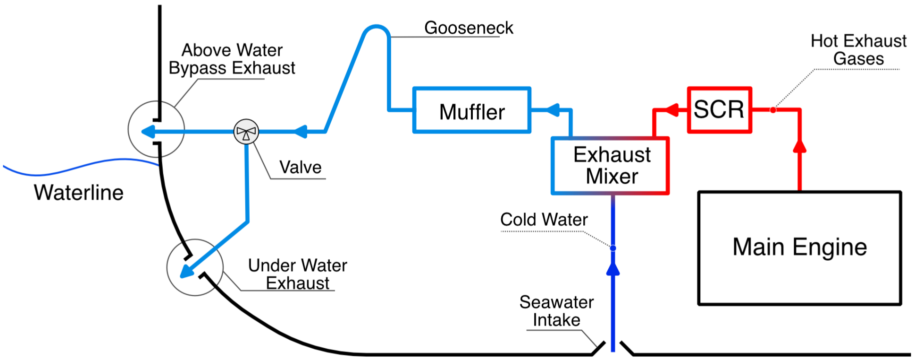


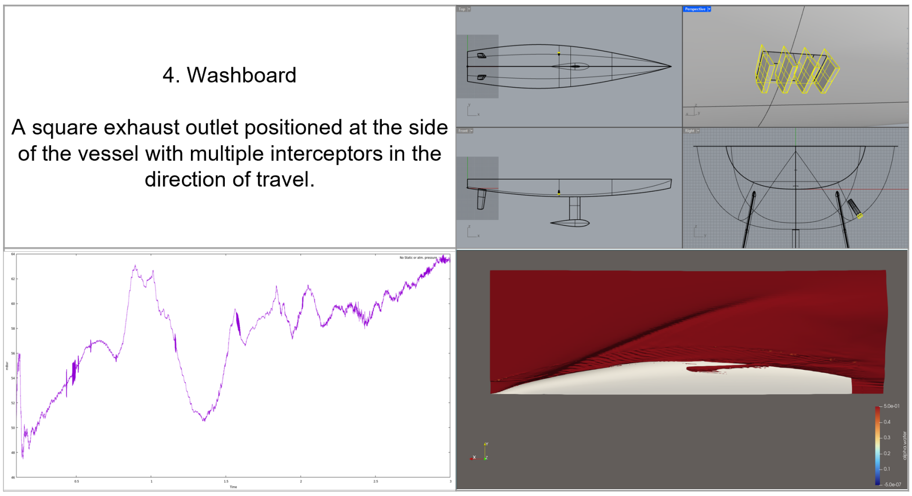
Figure 4.14: General overview of an underwater exhaust system on a sailing yacht.

4.4 Concept Evaluation

Almost all concepts that were generated were evaluated since it was difficult to reject a concept prior to simulation. This was mainly due to the limited amount of information that was available without simulating the concept. In order to determine the performance of a concept the back pressure and flow of exhaust gases needed to be known which is only possible by CFD simulation. However, concepts could theoretically be rejected based on aspects such as feasibility, manufacturability or other design constraints. The simulation of concepts was time-consuming but provided valuable insights into the strengths and weaknesses of the concepts. As hydrodynamics are chaotic and unpredictable, small differences in the design of concepts were shown to have a significant impact on, for example, the flow of the gases. For this reason, the choice of simulating each concept was thus deemed as the best course of action.

4.4.1 Evaluation Matrix

The evaluation matrix is presented in Appendix A.8 and Figure 4.15 presents an example of how an evaluated concept is documented in the matrix. The matrix contains all CFD simulations conducted throughout the project, including both concept evaluation and validation simulations. Each entry in the matrix includes the concept name, a brief description, a visualization of the concept and the positioning on the hull, pressure plots and flow visualizations from the simulations. The complete evaluation matrix also contained additional observations, comments and lessons learned throughout the development process. These were used internally during the iterative concept development and evaluation.



4. Washboard

A square exhaust outlet positioned at the side of the vessel with multiple interceptors in the direction of travel.

Figure 4.15: Example of an evaluated concept consisting of the concept number, name, description, image of the concept, and positioning on the hull together with the evaluation results in the form of a pressure plot and visualization of the exhaust gas flow.

4.4.2 Outlet Positioning

The positioning of the outlet on the hull plays a significant role in the performance of the concept. For example, an outlet position at the furthest point on the hull from the waterline will have the highest possible hydrostatic pressure such as position 1 in Figure 4.16. This means that in order for the concept to have an acceptable result in terms of back pressure, it has to reduce the back pressure more than an outlet positioned closer to the waterline would need to. Another drawback with a deep position is that the exhaust gases will take longer (both in terms of time and distance) to surface. This could increase the likelihood that the exhaust gases will interfere with the propellers and rudders. However, for saving space and weight due to minimum piping, a deep position can often be ideal. For example, if the engine is positioned midship, having the exhaust outlet directly below would be ideal in regard to the amount of piping. Another benefit with a deep position is that when the sailing boat is heeling, the back pressure will become lower with increasing heel angle and there will be less likelihood of the exhaust outlet not being submerged while heeling.

Positioning the outlet towards the stern aft of the propellers and rudders (or in between rudders) has other benefits and drawbacks (see position 2 in Figure 4.16). A stern positioning is relatively close to the waterline leading to low hydrostatic pressure and the exhaust gases surfacing quickly. A central position at the stern is also robust to heeling which means there will be little variation in back pressure and the outlet will stay submerged even for relatively high heel angles. However, the position is more sensitive to pitching as it might lead to the outlet emerging from the water. Depending on the position of the engine, an outlet at the stern could also require significant piping which would lead to increased weight and reduced available space.

A longitudinally central position at the starboard or port side (see position 3 in Figure 4.16), close to the waterline will have a low hydrostatic pressure as well as the exhaust gases surfacing quickly. The position requires relatively low piping as the gases only need to be routed from the engine and then laterally. Another benefit with this is that the amount of piping does not change significantly with engine position as it does in the case of an outlet with a stern positioning. However, the main drawback with this location of the outlet is that it is sensitive to heeling. Heeling to the leeward side will lead to the outlet reaching a deeper position and thus higher back pressure. Heeling to the windward side could potentially lead to the exhaust outlet emerging from the water which would result in a significant drop in back pressure.

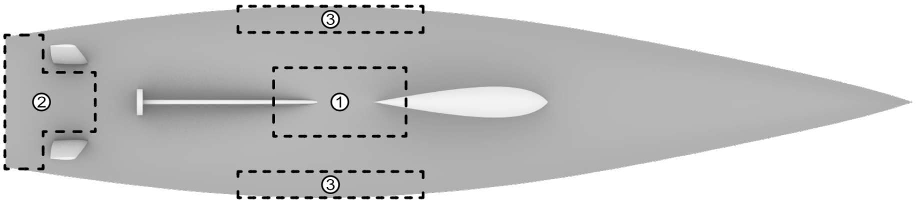


Figure 4.16: The different evaluated positions of the exhaust outlet, where the deep central position is labeled 1, the stern positioning is labeled 2 and the longitudinally central starboard/port side position is labeled 3.

4.4.3 Interceptor

The concept of an interceptor turned out to not be a definitive shape or structure, but rather a design tool that can be shaped in many different ways in order to induce the desired effect. As previously mentioned, the geometric parameters of the interceptor influence the induced low-pressure zone, with the interceptor height being the parameter with the greatest effect based on the different concepts and tests.

The development of an interceptor having a cutout was explored, but due to the increased turbulence it produced, the flow became unpredictable and induced oscillations and separated flow. This added to the conclusion that a good interceptor does not require shapes that are complex and generally difficult to manufacture, since it creates undesired effects over varying speeds, that are unpredictable. This behavior could be observed in many of the concept simulations.

To further understand the flow around a basic square interceptor and how the pressure zone developed with respect to the height of the interceptor, a test simulation was set up. This simulation had no exhaust outlet and thereby no gases expelled. The simulation showed that, depending on the interceptor height, there were two low-pressure zones that grew toward the edges of the interceptor which can be seen in figure 4.17, leaving the volume directly behind the center of the interceptor at a higher pressure than the regions next to it. This is presumably due to the three-dimensional flow swirls that occur at the corners of the interceptor. This shape, consisting of two spherical zones with the lowest pressure, was not visible on the smaller interceptors.

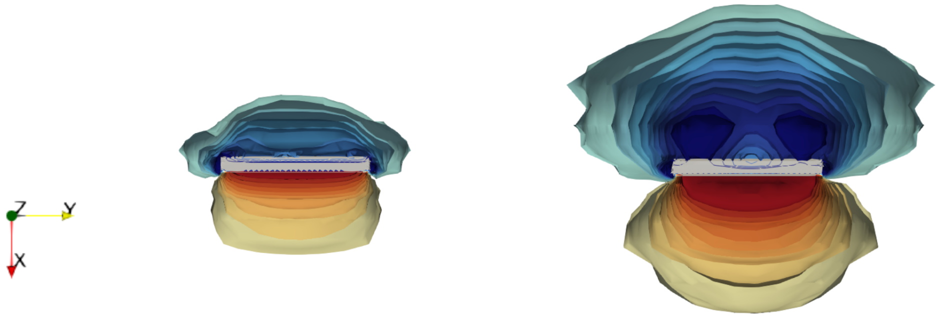


Figure 4.17: The induced pressure from testing the interceptor with two different heights.

The interceptor height test simulations were run at two different speeds in order to investigate how the flow over different interceptor heights varied with speed. The results are presented in Figure 4.18, where the pressure coefficient [72], calculated using the equation:

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V^2} \tag{4.1}$$

is plotted against the relative distance. These results are in line with the findings of Molini and Brizzolara [73], which supports both the method used and the reliability of the obtained results.

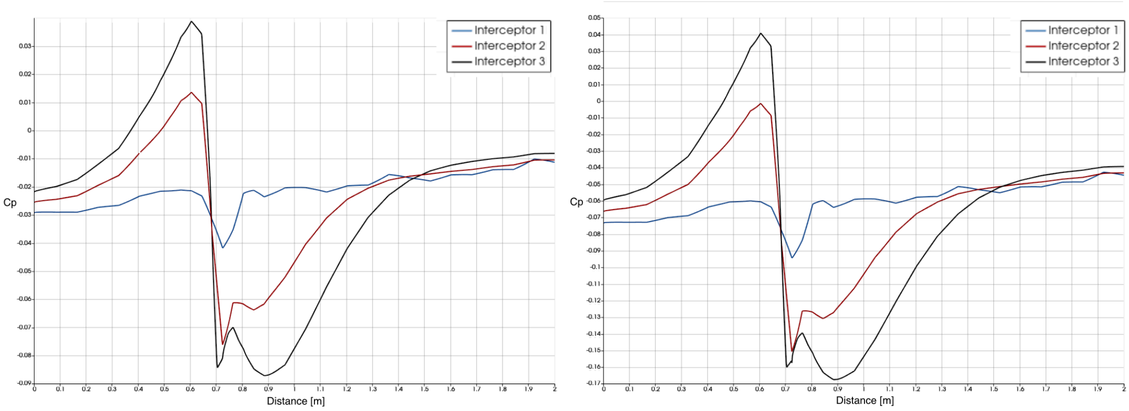


Figure 4.18: C_p for different interceptor heights. The lower speed is shown in the graph to the left, while the higher speed is shown to the right. Relative distance on the x-axis in meters.

The interceptor was initially not designed with sharp square edges, since such geometries are typically avoided in order to maintain a controlled and smooth water flow. However, from the concepts and simulations that were carried out, the flow behavior around the interceptor proved to be less intuitive than expected. Instead of minimizing abrupt flow changes, the most effective concepts utilized them to shape and control the water flow around the outlet. This means that the desired geometry forces the water to change direction rapidly, increasing the momentum of the flow. The accelerated flow then pushes the surrounding water away from the hull, thereby increasing the size of the low-pressure region behind the interceptor. The low-pressure zone begins at the leading edge of the interceptor. Therefore, to maximize the effect of the low-pressure region on the exhaust outlet, the leading edge should be positioned as close to the exhaust as possible. This can be achieved both by placing the interceptor closer to the exhaust outlet and by reducing the interceptor thickness. By rounding a corner, you can shape the size and form of the created low-pressure zone behind the interceptor. This can be utilized when trying to force the exhaust towards a desired position faster, by rounding the opposite side of the interceptor that is furthest from the desired position. This lets the water pass the interceptor without the abrupt change in direction and thereby reduces the low-pressure region created on that side.

4.4.4 Behavior of Exhaust Gases

Each concept was evaluated based on the flow behavior of the exhaust gases. For an acceptable result, the exhaust gases should be released in a smooth and constant flow without pulsation, while also remaining outside the exhaust-free zone defined in Figure 4.19. If the exhaust gases do not surface quickly enough, there is a risk that they enter this zone and interfere with the propeller and rudders.
Many of the concepts showed acceptable results regarding the flow behavior of the exhaust gases when simulated at a heeling angle of 0 degrees. However, increasing the heeling angle turned out to be problematic for some of these concepts. As discussed in Section 4.4.2, the position of the outlet on the hull plays a significant

role in whether the exhaust gases enter the exhaust-free zone or not. Other factors also affect the flow behavior, such as the outlet geometry, internal geometry, and the direction in which the outlet is oriented. It should also be noted that releasing exhaust gases at higher heeling angles may not be relevant in practice, as this is not a typical operating condition for the engine.

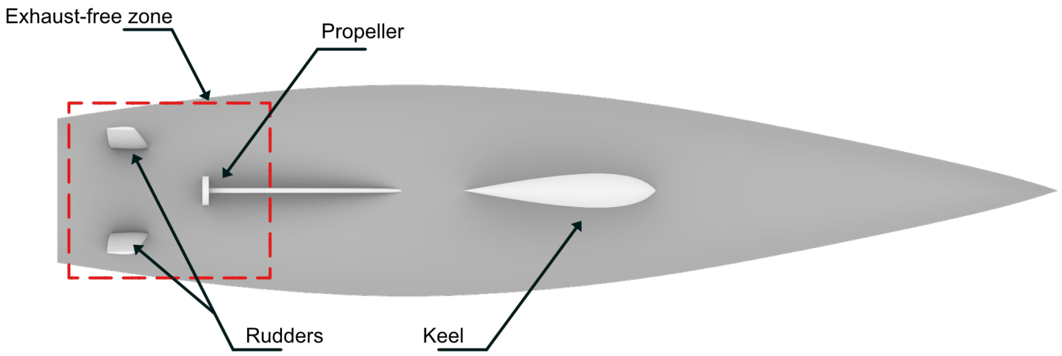


Figure 4.19: Illustration of a hull with appendages, showing the exhaust-free zone outlined in red.

If the solution requires the exhaust outlet to always remain submerged, the development process must account for the waterline at maximum heel. By simulating this maximum heeling condition in water, the results, as shown in Figure 4.20, clearly show the positions at which this criterion can be fulfilled. Since this represents an extreme condition for both the vessel and the exhaust system, it was used only as a design tool to map the requirements for such a concept.

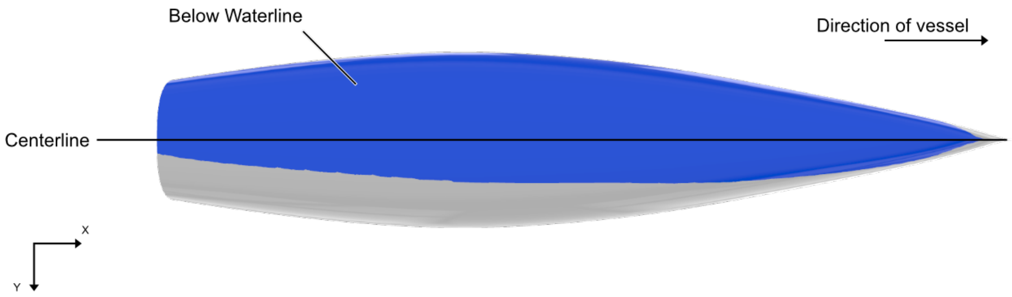
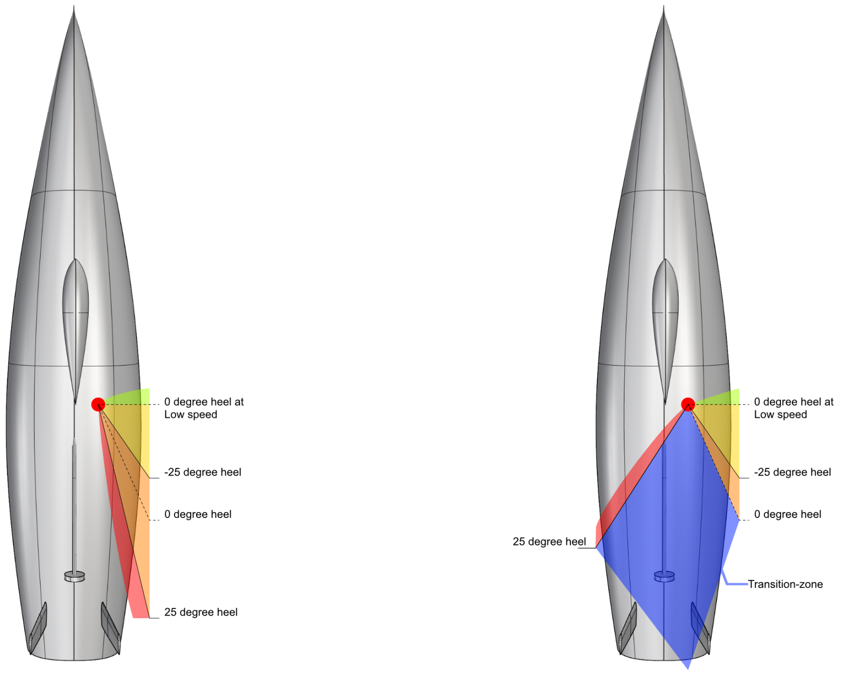


Figure 4.20: Waterline of the vessel at 15 knots and 25 degrees heel.

In the investigation of a concept where the exhaust gases cross the centerline of the boat in the water, the results showed that it would not be possible to fulfill the criterion of never entering the exhaust-free zone. For heeling angles between maximum heel, in this case 25 degrees, and no heel, the gas path would pass through a transition position. As a result, the gases would enter the propeller and rudder region. This is visualized in Figure 4.21.



(a) Gas paths at different heeling angles for a concept where the exhaust gases remain on the port side.

(b) Gas paths at different heeling angles for a concept where the exhaust gases travel along both port and starboard.

Figure 4.21: Visualization of gas paths for concepts with asymmetric gas behavior. For heeling cases, the vessel speed cannot be zero.

4.4.4.1 Guides

Although it was clear that the positioning of the outlet has a significant impact on the flow of the exhaust gases, it was experimented on whether the flow could somehow be controlled. This led to the design of the outlet feature ”guides”, which are rhombus-shaped features protruding from the hull. The idea is to create areas of pressure differentials along the hull which the exhaust gases will be pulled to and thus steered towards the desired direction. In Figure 4.22, a comparison with and without guides can be seen. The guides are the green features along the hull. The exhaust gases are shown in red for the simulation with the guides and in blue for the simulation without them. As can be observed in the figure, there is a difference in the path of the exhaust gases. In the simulation with the guides, the gases are pulled towards at least the first two guides and as a result, the gases surface earlier than in the simulation without the guides. As the guides are protruding features, they will negatively affect the hydrodynamic performance of the vessel and increase the drag. However, it indicates that the gases can be controlled to a certain extent but to what degree and at what cost is still unclear. Other geometries than rhombus-shaped features also remain to be explored. The incorporation of guides can also be further explored, especially the possibility to combine it with other protruding components already installed on the hull, for example anodes.

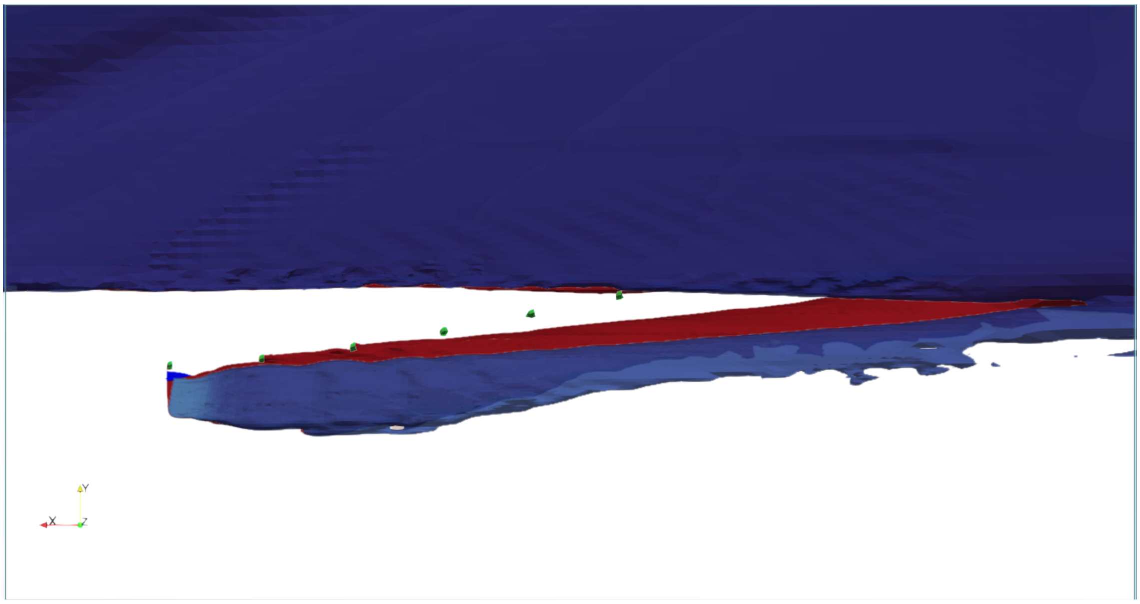


Figure 4.22: Comparison of exhaust flow with and without the guides. The guides are shown in green, red shows flow with guides and blue shows flow without guides.

4.4.5 Calculation of Maximum Speed

In order to determine the maximum and cruising speed of the vessel, the total hydrodynamic resistance R_T acting on the vessel was estimated using the Holtrop-Mennen method. This provided a resistance curve as a function of vessel speed and is presented in Figure 4.23. By using this curve, the required effective power at different vessel speeds could be determined and thus also the maximum speed of the vessel. The required effective power, P_E, was calculated as

$$P_E = R_T \cdot u \tag{4.2}$$

where P_E is the effective power in kW, R_T is the total resistance in kN and u is the vessel speed in m/s. The maximum delivered power, P_D, was obtained from the engine datasheet [46]:

$$P_D = 261 \text{ kW} \tag{4.3}$$

In order to calculate the maximum effective power, a propulsive efficiency, η_D, is estimated to

$$\eta_D = 0.55 \tag{4.4}$$

then, the maximum effective power was calculated as

$$P_{E,\max} = P_D \cdot \eta_D \tag{4.5}$$

which equals to about 143 kW. The maximum vessel speed was then estimated graphically by identifying the point at which the required effective power equaled the maximum effective power in the Holtrop-Mennen resistance curve. From this intersection, it was acquired that the maximum vessel speed is approximately 13 knots.

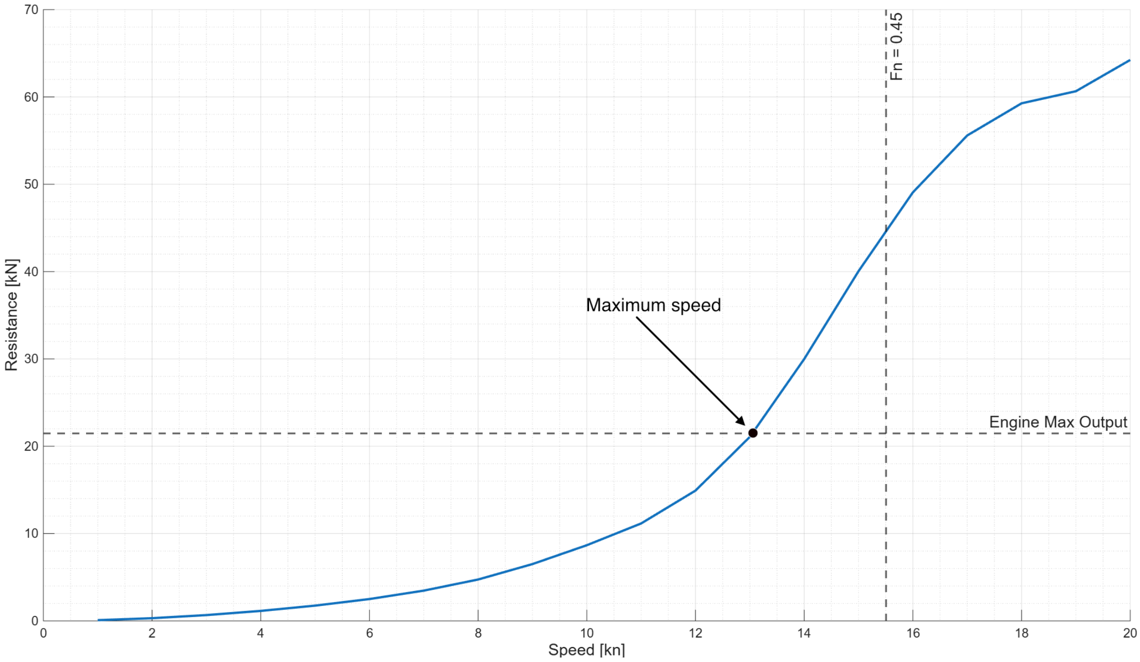


Figure 4.23: Holtrop-Mennen curve showcasing resistance as a function of vessel speed in knots. The horizontal dotted line shows the maximum effective power from the engine and the vertical line marks the upper limit of where the Holtrop-Mennen method loses accuracy at a Froude number of $F_n = 0.45$

4.4.6 Calculation of Cruising Speed

After determining the maximum speed of the vessel, the cruising speed of the vessel is estimated based on fuel efficiency. From the Holtrop-Mennen curve in Figure 4.23, the required power at different vessel speeds can be obtained. Then the corresponding engine operating points can be retrieved from the engine datasheet [46]. Since the engine datasheet only contains a certain number of points and does not correspond exactly to the resistance curve at the different speeds, linear interpolation was performed. This interpolation was used to estimate the corresponding RPM, fuel consumption and exhaust gas temperature for each vessel speed. The fuel consumption per nautical mile as a function of vessel speed in knots was then calculated. This was done by dividing the interpolated fuel consumption in liters per hour by the vessel speed in knots. This made it possible to compare the fuel efficiency at different speeds.

Figure 4.24 presents the fuel consumption per nautical mile as a function of vessel speed. From the figure, it is clear that fuel consumption increases significantly at higher vessel speeds. At 10 knots, the vessel has a lower fuel consumption per nautical mile than at 9 knots while it is also just before the drastic increase in fuel consumption at higher vessel speeds. This makes 10 knots a suitable cruising speed for the vessel from a fuel-efficiency perspective. It is therefore a requirement that the concepts function at a speed of at least 10 knots.

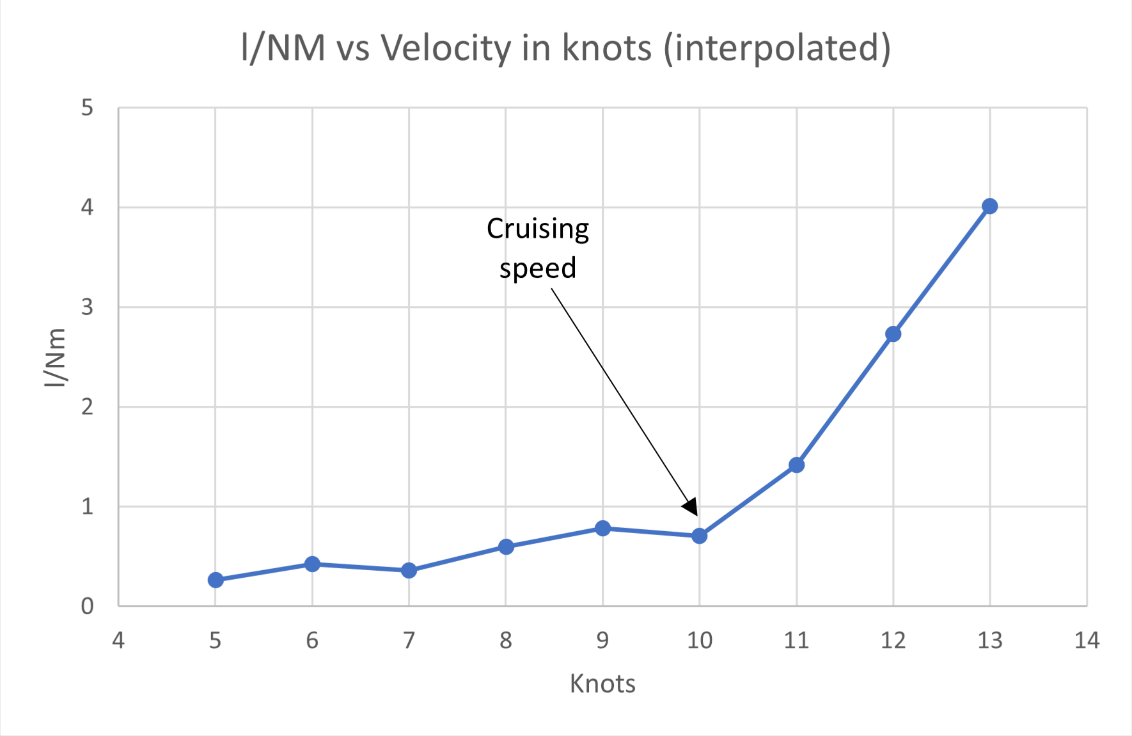


Figure 4.24: Fuel consumption per nautical mile as a function of vessel speed. The fuel consumption was calculated using interpolated data from the engine datasheet [46]. The cruising speed is indicated at 10 knots.

4.5 Final Concept: Quarter Bell-Mouth

After many iterations of concept generation, evaluation and further development, the concept called the ”Quarter Bell-mouth” was identified as the most promising alternative. The Quarter Bell-Mouth concept, shown in Figure 4.25, consists of an outlet geometry that resembles a bell-mouth with a tapered transition that is wide at the hull surface and then gradually tapers down into a cylinder. The Quarter Bell-Mouth has an interceptor as the outlet feature in order to maintain an acceptable back pressure and to reduce pulsations. The outlet is positioned longitudinally near the center of the vessel on the port/starboard side, corresponding to outlet position 3 shown in Figure 4.16 in Section 4.4.2. A detailed visualization of the positioning of the concept is shown in Figure 4.26, while Figure 4.27 demonstrates the concept during operation which shows the exhaust gases rising to the surface along the hull as well as the high-pressure region in front of the interceptor.

The Quarter Bell-Mouth concept was generated relatively early in the development process, however, the concept was abandoned to explore other design directions and because it was deemed to not meet the requirements. As the development progressed, two discoveries led to the revival of this concept. Firstly, the realization that the positioning of the first iterations of the bell-mouth is too deep which will add significant hydrostatic pressure that it needs to overcome in order to expel gases. Secondly, learning more about how interceptors work led to the realization that the interceptor design of the first iterations of the Quarter Bell-Mouth was inadequate.

From a manufacturing perspective, the Quarter Bell-Mouth geometry is well suited for materials commonly used in boat construction, such as composites and plastics. The curved surfaces can be produced more easily in these materials and integrated into the hull structure. In metal, the same geometry would be more difficult to manufacture since the geometry of the concept curves in more than one direction and would thus require more complex manufacturing methods.

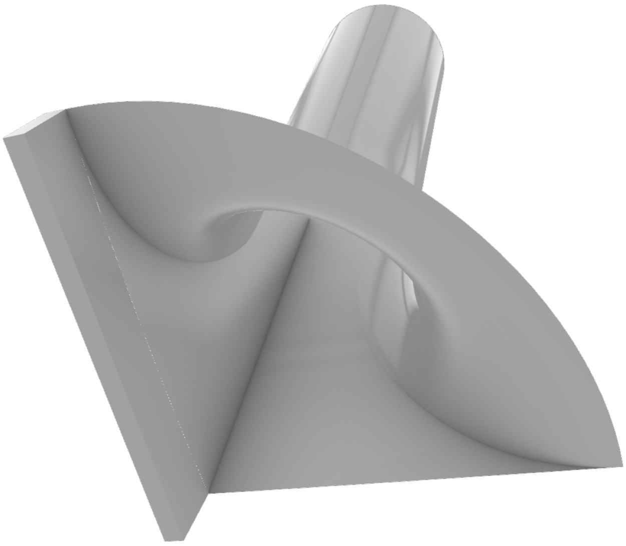
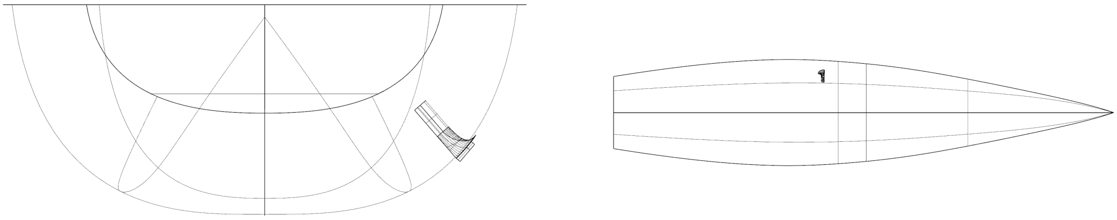


Figure 4.25: Rendering of the Quarter Bell-Mouth concept.



(a) Front view.

(b) Top view.

Figure 4.26: Positioning of the Quarter Bell-Mouth concept on the hull.

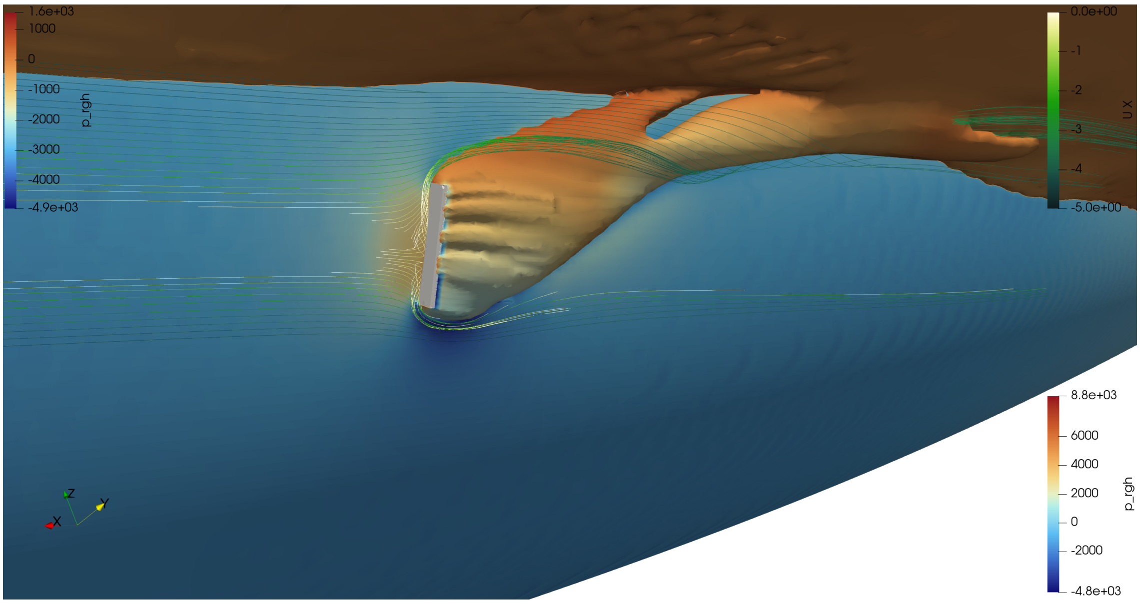


Figure 4.27: The flow of exhaust gas at 10 knots. The gas rises to the surface along the hull. The high-pressure zone in front of the interceptor as well as the path of the surrounding water can also be seen.

4.5.1 Validation of Concept

The Quarter Bell-Mouth concept was validated through simulations at different vessel speeds and heel angles. The purpose of the validation was to determine whether the concept could operate within the required speed range of cruising speed to maximum speed (10 knots to 13 knots). Table 4.3 presents the summarized results of these simulations, and Figure 4.28 presents the pressure plots from the simulation of different vessel speeds with zero heel angle. From this data, it can be observed that the Quarter Bell-Mouth concept functions acceptably within the speed range of approximately 8 knots up to the maximum vessel speed of 13 knots. At speeds below 8 knots, oscillations occur which indicates that the bypass exhaust is required at speeds below 8 knots.

Table 4.3: Summary of validation simulations for the Quarter Bell-Mouth concept with zero heel angle.

Speed [kn]	**Heel Angle**	**Result**
6	0°	Oscillations
7	0°	Oscillations
8	0°	Acceptable
10	0°	Acceptable
13	0°	Acceptable

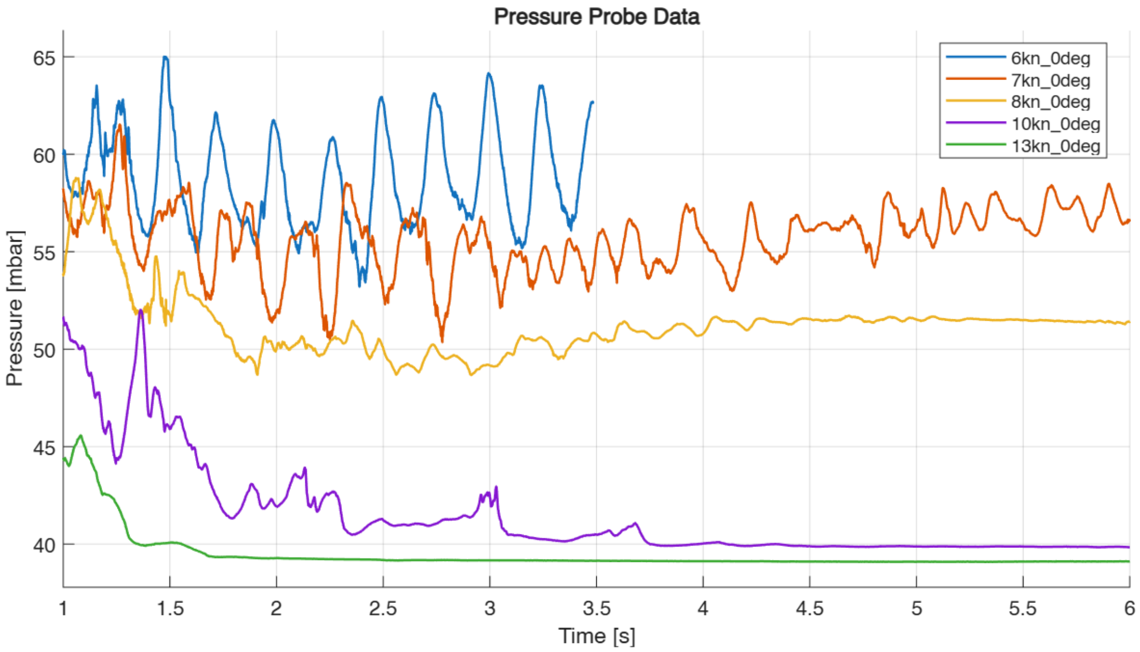


Figure 4.28: Pressure at the probe location inside the exhaust for the concept at different speeds. Variation in simulation time due to the difference in time is required to reach convergence.

A trend observed in the pressure plots is that the back pressure decreases as the vessel speed increases. This differs from what could generally be expected if the exhaust flow increases with engine load, as higher exhaust flow would normally increase the back pressure in the exhaust system. However, the simulations indicate that the pressure reduction created by the interceptor becomes more dominant as the vessel speed increases.

Table 4.4 presents the summarized results, and Figure 4.29 presents the pressure plots of different speeds when heeled ±5°. These simulations were done in order to assess whether the outlet maintains a stable pressure when the vessel is heeled since the heel angle can affect both the submergence of the outlet and the exhaust gas flow behavior. Therefore, these simulations are important and the concept is required to pass them according to the requirement specification.

Table 4.4: Summary of validation simulations for the Quarter Bell-Mouth concept with ±5° heel angle.

Speed [kn]	**Heel Angle**	**Result**
8	+5°	Acceptable
8	-5°	Acceptable
10	+5°	Acceptable
10	-5°	Acceptable
13	+5°	Acceptable
13	-5°	Acceptable

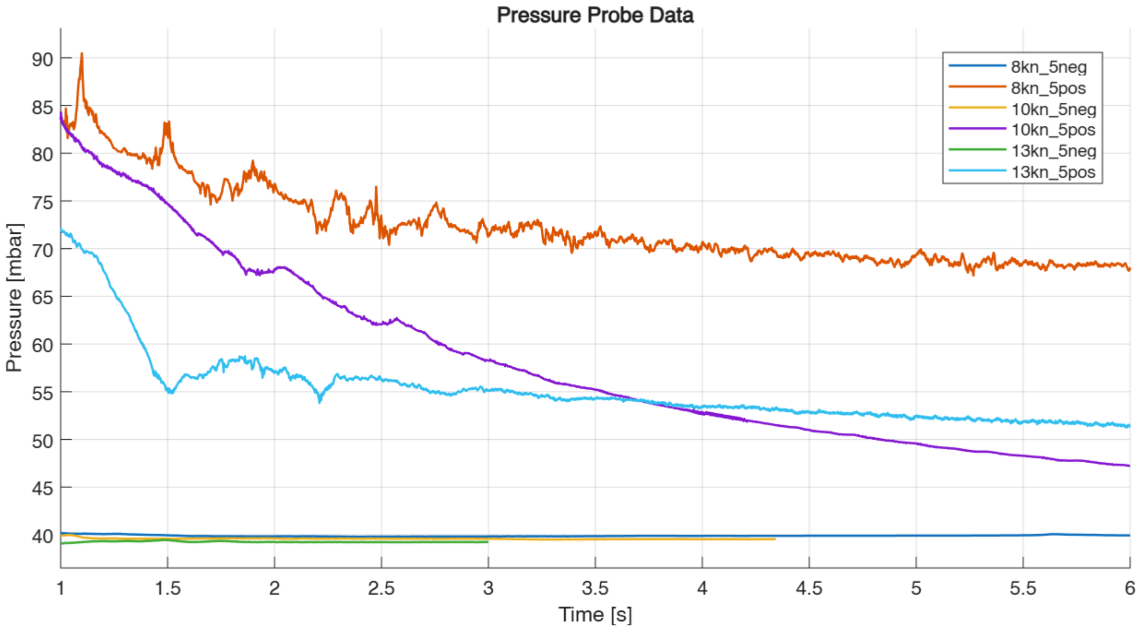
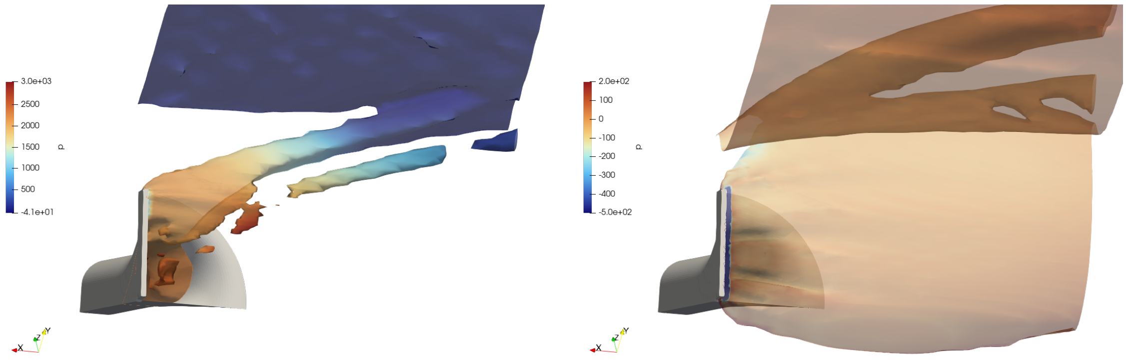


Figure 4.29: Pressure at the probe location inside the exhaust for the concept at different speeds and heeling for 5 degrees in both directions. Variation in simulation time is due to the difference in time required to reach convergence.

As seen in the plot in Figure 4.28, at lower speeds there is a pulsation and variation in pressure. This can also be seen in the flow of the exhaust gases in Figure 4.30, where the pressure variation over the flow for 6 knots is an indication of this pulsation. Such oscillations are undesirable, as the pulsating exhaust gas flow can contribute to increased noise and vibration levels experienced onboard. The flow results at 13 knots in the same figure are steadier with less pressure variation and pulsations.



(a) 6 kn **(b)** 13 kn

Figure 4.30: Comparing flow results for the final concept at 6 knots and 13 knots which shows the oscillation and variation in pressure.

4.5.2 Validation Against Requirements Specification

The final concept was validated against the requirement specification, as presented in Table 4.5. Each criterion was marked as either ”pass”, ”fail” or ”inconclusive” based on the available results. Pass means that the criterion was fulfilled, while fail means that the concept did not fulfill the criterion. Inconclusive means that there was not enough information to make a final assessment and that further analysis would be required.

Overall, the final concept passes the most important requirements. The criteria that failed are both classified as desires rather than strict requirements. Therefore, they do not make the concept unacceptable, but instead they indicate areas where the design could be improved in future development. The number of inconclusive criteria also shows that some aspects, such as installation, maintenance, drag, noise and vibration, require further investigation before the concept can be fully validated.

Table 4.5: Validation of the final concept against the requirement specification

Nr.	R. / D.	Criteria	Result
1	R	Exhaust gases shall be expelled underwater	Pass
2	R	Rudders function should be unaffected by exhaust gases	Pass
3	R	Propeller(s) function should be unaffected by exhaust gases	Pass
4	D	Exhaust gas odor should be minimized	Inconclusive
5	D	Noise should be minimized	Inconclusive
6	D	Vibration shall be minimized	Inconclusive
7	D	Weight shall be minimized	Inconclusive
8	R	Shall fit within available installation space	Inconclusive
9	D	Shall only add hydrodynamic drag within acceptable limits	Inconclusive
10	R	Shall operate without causing cavitation	Pass
11	R	Back pressure shall be $\leq$ 50% of the permitted maximum	Pass
12	R	Shall allow for installation that prevents water ingress into the engine	Pass
13	R	Shall function at heeling angles up to ± 5°	Pass
14	D	Should function at heeling angles up to ±30°	Inconclusive
15	D	Shall work when sailing yacht is reversing	Fail
16	R	Shall operate in non-bypass mode at cruising speed	Pass
17	D	Shall be located in non-visible areas of the hull	Pass
18	D	Shall be flush with the hull surface	Fail
19	D	Shall be visually pleasant	Inconclusive
20	R	Shall be applicable for sailing yachts larger than 24 m	Pass
21	R	Shall be applicable to different hull shapes and types	Inconclusive
22	D	Shall be applicable for different types of hull materials	Inconclusive
23	R	Should be possible to clean and maintain	Inconclusive
24	R	Exhaust outlet must fit between the structure of the hull	Inconclusive
25	R	Structure of the hull should be structurally uncompromised	Inconclusive
26	R	Should be made out of materials suitable for underwater use	Pass
27	R	Engine function should be unaffected	Pass
28	R	Exhaust gases shall be expelled in a non-pulsating flow	Pass
29	D	Shall allow installation to be certified	Inconclusive

5

Discussion

This chapter discusses the results and methodology of the thesis, together with the limitations and uncertainties. The chapter reflects on the product development process and how CFD influenced it, the concept evaluation and validation. The chapter also discusses the accuracy and reliability of the results and the reasoning behind the final concept. The research questions are then revisited based on the findings from the thesis. Finally, ethical considerations, the use of AI tools and recommendations for future work are presented.

5.1 Product Development Process

The product development process was strongly shaped by the use of CFD simulations as the primary method for evaluation. Since almost every generated concept was simulated, analyzed and then improved upon, the development process was highly iterative. For multiple reasons, this process was time-consuming. Firstly, OpenFOAM and the CFD procedure had a steep learning curve, which took an initial time investment. Secondly, the creation of CAD models for each concept and the setup of the simulation in OpenFOAM required a considerable amount of time. Lastly, the most time-consuming task was the simulation runs themselves, often requiring around one to five days to complete. Only when a simulation was completed could insights regarding that particular concept be obtained. As a result, it was difficult to rapidly generate and explore many concepts and evaluate them in parallel. Instead, the concepts are evaluated one at a time. However, once a handful of promising concepts had been generated and evaluated, it made the process faster, as small modifications and setup did not require as much time.

5.1.1 CFD Restrictions on Design

Due to time limitations with the CFD simulations, some of the concepts were simplified. For this reason, most of the concepts consisted of relatively simple geometries in order to keep the simulation time within reasonable ranges. However, in reality, more detailed and complex geometries could be possible, yet it is uncertain if it would be beneficial. The simplifications were made with an engineering approach and the purpose of the study was successfully met.

5.1.2 Dynamic Systems

Dynamic systems (e.g., electronically, mechanically or pneumatically controlled solutions) were initially considered. However, they were later excluded from the concept generation phase, as stakeholder needs and requirements underscored the importance of a simple and reliable solution that works no matter what. For example, a concept considered was a dual-exhaust configuration where one outlet closes during heeling. Another example was a dynamic interceptor, where the interceptor height or position could be adjusted depending on vessel speed, heel angle or pressure. However, these concepts were deemed to be less robust due to the increased complexity and reliance on active control mechanisms. This type of solution is also more difficult to evaluate using CFD, which is another reason for not being included.

5.2 Validation of Concepts

The validation of the concepts consisted of CFD simulations with different vessel speeds, exhaust flow and heel angles. However, the simulations were only performed on one single hull, which was custom-designed. It would have been beneficial for the accuracy and reliability of the results to simulate with multiple different hulls as well as with different engine specifications. It was initially considered to model more than one hull to validate with, however, it was later concluded that this would be too time-consuming within the time frame of the thesis. It would have been ideal to obtain hull models for simulations from shipyards or other sources, however, because of confidentiality and availability reasons, it was not possible.

The concepts were initially evaluated using the same vessel velocity. However, during the validation process, it became apparent that lower vessel speeds and exhaust flow introduced additional challenges. Beginning the validation stage earlier could have provided valuable and necessary insights earlier in the development process. This would have contributed to a more in-depth understanding of how the concepts need to be adapted and optimized to meet the constraints that arise with lower speeds and reduced exhaust flow.

5.3 Accuracy of Results

The accuracy of the results presented in this thesis is influenced by some assumptions and simplifications made throughout the process. Due to the concepts being evaluated using CFD simulations, the accuracy is affected by factors such as mesh quality and the simplification of geometries (as discussed in Section 5.1.1).
The calculations of vessel resistance, maximum speed and cruising speed are also subject to inaccuracies. The Holtrop-Mennen method used to calculate the hydrodynamic resistance is a method based on statistical regression and therefore only provides an approximation of the actual resistance. The method also depends on vessel specifications such as hull dimensions and displacement, which means that

uncertainties in these parameters may also affect the results of the method. Furthermore, assumptions such as the propulsive efficiency (η_D) and the interpolation of engine data are two other sources of uncertainty. Together, all these factors affect the calculations of maximum and cruising speed. However, these speeds and vessel specifications are still considered sufficiently accurate for evaluating and validating the concepts within a realistic operating range.

5.4 Final Concept

The final concept was selected because it was the most promising alternative within the scope of the thesis. The Quarter Bell-Mouth geometry showed more stable behaviour than the other concepts that were evaluated and was therefore chosen for further development. However, this does not mean that the Quarter Bell-Mouth is the only possible solution. Other concepts or variations could also prove to be suitable if they were developed and tested further. Due to the limited time available, the thesis focused on the concept that showed the clearest potential based on the results obtained.

The validation results showed that the concept functioned acceptably between approximately 8 and 13 knots. Since the required operating range was from cruising speed to maximum speed, this means that the concept fulfills this particular requirement. However, the oscillations observed below 8 knots show that the underwater outlet is not suitable at lower speeds. This confirms the need for a bypass exhaust when the vessel operates at speeds lower than 8 knots. Ideally, it is desired to be able to use the underwater exhaust at as low vessel speeds as possible in order to use the bypass as little as possible. In this case, the required cruising speed was 10 knots and the simulations showed acceptable results from approximately 8 knots. This is a positive result, as the underwater exhaust can thus be used two knots below the cruising speed.

The simulations that were done with ±5° heel angle showed that the concept was acceptable within this required heel range. Investigating heel angles is important for sailing yachts, since the back pressure, submergence level, and exhaust flow can change when the vessel is heeled. It would be valuable to run simulations for larger heel angles. However, it should be said that larger heel angles are usually expected when the yacht is sailing and in those conditions it may not be suggested to use the engine. Therefore, functionality at larger heel angles may be less important, however, it is still relevant to investigate in future work.

The concept would also need to be further developed in terms of material selection, manufacturing and installation. The material must be suitable for underwater use and resistant to corrosion, temperature variations and exhaust gases. Aesthetics are also relevant for sailing yachts, which is why the underwater exhaust outlet can be considered an improvement aesthetically. However, the outlet may still become visible when the yacht is heeled and the protruding interceptor may not be visually desirable.

Finally, the concept is not a fixed design but rather a design principle that can be adapted to different sailing yachts. The exhaust outlet design would need to be adjusted depending on factors such as the hull shape, vessel size and engine placement. Parameters such as outlet size, interceptor dimensions, bell-mouth radius, angle and positioning on the hull are all parameters that can be adjusted and tweaked. This means that parametrization of the concept is crucial for making the concept applicable to different types of sailing yachts.

5.5 Research questions

The research questions are revisited below to connect the results back to the original aim. Each question is discussed based on the main findings and learnings gained throughout the thesis through the theoretical background, market analysis, concept development, evaluation and validation.

Q1: How can exhaust outlets for sailing yachts be redesigned so that the exhaust gases do not negatively affect the propulsion or rudders while also maintaining acceptable back pressure?

The exhaust outlet can be redesigned by relocating it underwater while positioning it so that the exhaust gases are released away from the propeller and rudders. Since an underwater outlet expels the exhaust gases into the water, the placement of the exhaust outlet on the hull becomes important to avoid interaction with the vessel's appendages. The design and geometry of the exhaust outlet are also important for achieving acceptable back pressure and exhaust gas flow. This was done with the Quarter Bell-Mouth concept combined with an interceptor, where the interceptor contributed to maintaining acceptable back pressure. Therefore, the redesign shows that both the positioning and exhaust outlet design are important for making the concept function without negatively affecting propulsion, rudders or back pressure.

Q2: How does the current technical and market landscape for sailing yacht exhaust outlets indicate the need for a redesigned solution?

The technical and market landscape indicates that a redesigned exhaust outlet can create value for several stakeholders and that there is a need for it. The market analysis shows that many sailing yachts are in use and being built. As underwater exhaust outlets appear uncommon on sailing yachts, there is an opportunity to explore a solution that is not widely implemented in this market. The value an underwater exhaust outlet could provide for users is increased onboard comfort by reducing odor, noise, and vibration, as well as potential weight and space benefits. Together, the active market, limited use of underwater exhaust outlets on sailing yachts, and potential benefits support the need for a redesigned exhaust outlet solution.

Q3: How does the redesigned exhaust outlet compare to the conventional design of the exhaust outlet for sailing yachts?

In Table 5.1 a full comparison between the final concept and the existing above-water exhaust solution is provided.

Table 5.1: Comparison of the final concept and the existing above-water exhaust solution

Criteria	Final Concept	Above-Water Exhaust
Back Pressure	The backpressure remains acceptable within the required speed range. At higher speeds, the reduced backpressure may partly compensate for the increased exhaust flow from the engine.	It has the potential to be dimensioned for different exhaust flows by adjusting the outlet size. This could allow the required backpressure range to be achieved without the need for a low-speed bypass.
Aesthetics	As the concept is positioned close to the water surface, it may become exposed when the boat heels, which could be aesthetically undesirable. The smaller bypass exhaust will still be visible.	This solution is always visible, both when sailing and when docked. It also cannot be fully covered, as the gases need to be released into the open air or the discharged water must have a clear path to the sea.
Sound	Since this cannot be tested, only assumptions can be made. As the gases are released into the water, noise is reduced.	This solution is expected to produce higher perceived noise levels, since there is nothing blocking the sound between the exhaust outlet and the user.
Odor	The exhaust gases are more dispersed into the surrounding water, reducing the likelihood of them being perceived by the user.	Wind may cause exhaust gases to be blown into the cockpit and on deck under certain conditions.
Vibration	Within the operating speed range, no induced vibration is caused by the pulsating flow from the exhaust.	Does not increase the likelihood of additional vibration in the boat structure.
Space	Since the engine is preferably installed low and near midship, placing the outlet underwater reduces the required piping. A single outlet also further reduces the piping needed.	Since the outlet is located above the waterline and preferably in the stern, routing the piping to the stern requires more space.
Weight	Reduced piping means lower weight, especially important in the situation when the exhaust system is filled with water.	The additional piping may result in a higher overall system weight.
Drag	Although the final design introduces some additional drag, its overall effect is expected to be negligible.	Adds no additional drag.
Manufact-urability	With the two-way bending of the exhaust outlet surface, the limitation for material selection affects manufacturability.	No effect on the manufacturability.
Custom-ization	The final solution has many parameters that can be adjusted and optimized for back pressure, aesthetics and exhaust placement. This allows for a high degree of customization.	Few variables are available, which limits the possibility to adapt to a specific engine or vessel.

The final concept should be viewed as a design alternative rather than a direct replacement for all above-water exhaust systems. Its main strengths are related to reduced user exposure to exhaust gases, potential reductions in perceived noise and odor, shorter piping, and greater customization. At the same time, the concept introduces new limitations, particularly regarding manufacturability, design and hydrodynamic drag. This indicates that the suitability of the concept depends on the priorities of the specific vessel and installation.

5.6 Ethical Considerations

Ethical considerations were taken into account throughout the thesis, particularly regarding environmental impact, human exposure to exhaust gases, and the reliability of simulation results. One consideration of implementing underwater exhaust outlets for sailing yachts is the environmental trade-off between releasing the exhaust gases into the air versus the water. While expelling the gases underwater may reduce emissions locally, it may also negatively affect the marine ecosystem. On the other hand, if the underwater exhaust outlet saves weight compared to the current solution, it could potentially lead to less fuel consumption and thus less pollution. Another consideration is passenger exposure to exhaust gases. Releasing the exhaust gases underwater will drastically reduce direct exposure to exhaust gases for the passengers. From a health perspective, this may reduce the risk of inhaling potentially harmful emissions.

A full life cycle assessment (LCA) would be required to fully evaluate the overall environmental impact of the product concept. However, such an analysis was not feasible within the timeframe of this thesis. It can be argued that underwater exhaust outlets are already used in motor yachts, which would suggest that they would be accepted for sailing yachts as well. However, differences in design and use case mean that it may still need to be carefully considered and evaluated.

Furthermore, the CFD simulations rely on assumptions and simplifications of real-world conditions. This means that it is important to acknowledge the limitations of CFD and to interpret the results with caution. If possible, real-world testing needs to be done to validate the underwater exhaust outlets for sailing yachts.

5.7 Use of AI Tools

Artificial intelligence (AI) tools were used as a supportive aid in the thesis. It was mainly used for refining the language used in the thesis by grammar checking and improving the clarity and readability of the text. AI tools were also used to a certain extent for coding assistance and for learning about CFD, sailing yachts, and the marine industry as a whole.

All analyses, calculations, interpretations, simulations, engineering decisions, and conclusions presented in the thesis were done by the authors.

5.8 Recommendations and Future Work

Future work should include more extensive CFD validation using different sailing yacht hulls and engines. Instead of the custom-designed hull used in this thesis, it would be valuable to validate using an existing sailing yacht along with its engine specifications. The possibility of parameterizing the final concept should also be investigated, which would allow the geometry to be adapted for different hulls and engine configurations.

More thorough market research along with interviews with shipyards and other stakeholders could also help to establish a more detailed and complete requirement specification. It is also necessary for gaining a deeper understanding of the market and the demand for the product.

Lastly, a physical prototype needs to be built and installed on a sailing yacht. Real-life sea trials should then be conducted to validate the results of the CFD analysis.

6

Conclusion

The results of this thesis indicate that underwater exhaust outlets for sailing yachts are a promising design alternative. Through an iterative product development process inspired by SBCE and supported by CFD analysis, 30 concepts were generated and evaluated. The Quarter Bell-Mouth concept was identified as the most suitable solution, as it fulfilled the most important requirements. The concept successfully expelled the exhaust gases underwater while maintaining acceptable back pressure and avoiding interference with the propeller and rudders. The simulations showed acceptable performance between 8 and 13 knots, which includes the cruising speed of 10 knots, as well as at heel angles of ±5°. However, due to oscillations at lower speeds, a bypass exhaust is required below 8 knots.

The results showed that the interceptor was an important design feature for reducing back pressure and creating a steady exhaust flow. Its performance depends on its position, dimensions and relation to the outlet geometry which means that it needs to be adapted to each vessel. More complex interceptor geometries did not necessarily improve performance and could instead create undesired and unpredictable effects over varying speeds. Simple geometries are therefore preferred, since they are also easier to manufacture and install. Guides were also shown to influence the exhaust gas path and could be used as a tool to help the gases surface earlier, but at the cost of additional drag.

Compared to a conventional above-water exhaust system, the underwater solution has the potential to reduce odor, noise and vibrations, while also reducing piping length and thereby saving space and weight. This is especially relevant for larger sailing yachts, where comfort, space and weight are important design parameters. However, the concept also introduces challenges related to manufacturability, drag and heeling.

Overall, the thesis shows that implementing an underwater exhaust outlet on a sailing yacht is possible within the scope of this thesis. However, each yacht has a unique hull geometry, engine configuration, speed range and installation constraints which means that future solutions will require adaptations specific to each vessel. The Quarter Bell-Mouth concept should therefore be considered one promising example rather than the only possible solution. Future work should include simulations on additional hulls and engine configurations, parametrization of the geometry, material analysis and sea trials with a physical prototype.

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A

Appendix

A.1 Number of Sailing Yacht Models per Length Span Released Each Year

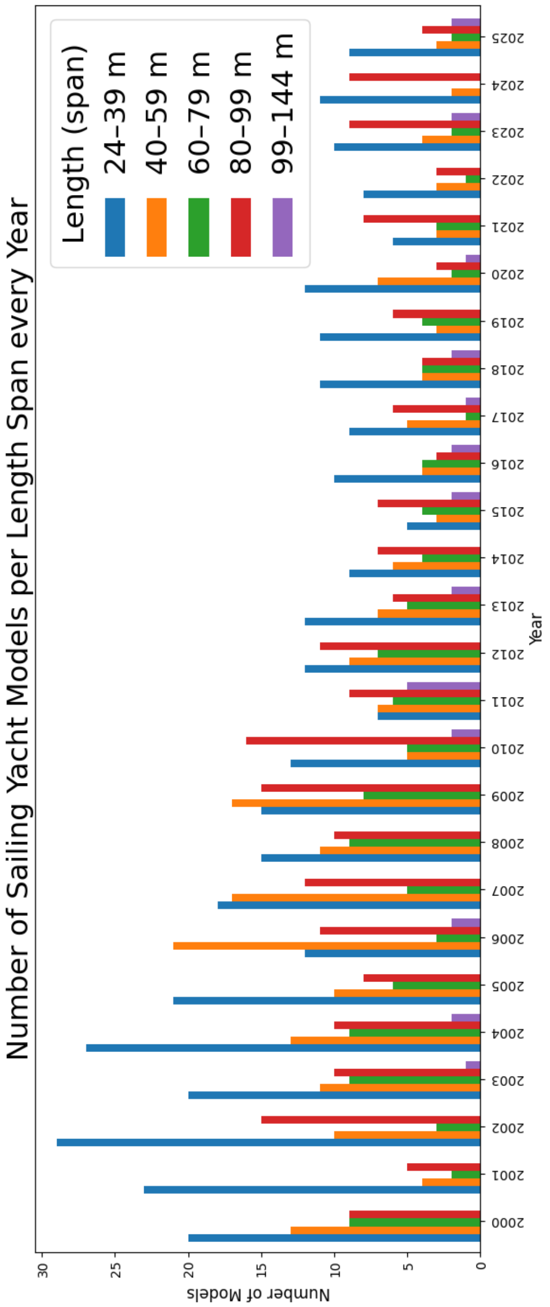


Figure A.1: Data from BOAT International Superyacht Directory[44].

A.2 Number of Sailing Yachts Produced per Length Span since 2000

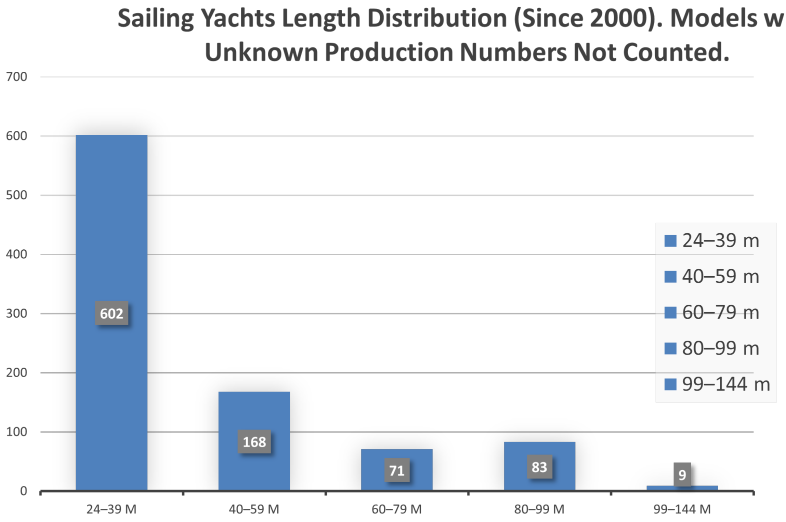


Figure A.2: Data from BOAT International Superyacht Directory [44].

A.3 Number of Sailing Yachts Produced Each Year

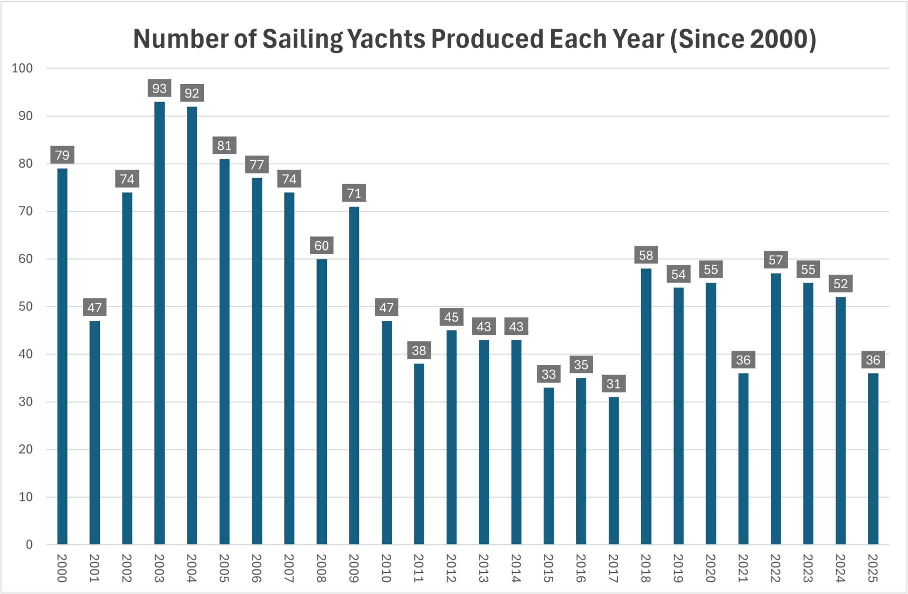


Figure A.3: Data from BOAT International Superyacht Directory[44].

A.4 Benchmarking of Selected Sailing Yachts

Shipyard	**Model**	**Year**	**Engine(s)**	**Engine model**	**HP (total)**	**Hull Material**	**Top speed (knots)**	**GT**	**Length (m)**	**Beam (m)**	**Draft (m)**	**Crew**	**Guests**
Baltic Yachts	Inukshuk [44][74]	2013	1	Cummins QSB5 9-355	350	Composite	14	111	32,61	7,44	4,9	5	8
Southern Winds	Sørvind [44][75]	2022	1	Cummins QSB 6.7MCD	305	Carbon Fibre	12	120	34,69	7,31	5,8	5	8
Vitters	Anomaly [44][76]	2017	1	Volvo Penta D7-CTA	261	Carbon Fibre	12	135	32,64	7,72	6,05	5	6
Alloy Yachts	Encore [44][77]	2013	1	CAT C18	876	Aluminium	12	258	43,9	9,37	4,3	6	10
Tramontana Yachts	Reposado [44][78]	2024	2	CAT C18	1752	Steel	14	420	51,99	8,6	3	10	12
Ares Yachts	Simena [44][79]	2026	1	MAN V8-1200	1200	Steel	14,5	499	62	10,8	4,5	9	12
Perini Navi	Badis 1 [44][80]	2016	2	MTU 16V 2000 M72	3860	Aluminium	17,5	887	70	13,24	11,74	11	12
Royal Huisman	Sea Eagle [44][81]	2020	2	CAT C32	2898	Aluminium	22	1150	81	12	6	14	12
Oceanco	Black Pearl [44][82]	2018	2	MTU 16V 2000 M72	3860	Steel	17,5	2864	106,7	15	6,8	27	12

A.5 Requirement Specification

Nr.	R. / D.	Criteria	Value	Unit	Verification method	Requested by
1	R	Exhaust gases shall be expelled underwater	pass/fail	-	CFD, sea trial	P. Stakeholder
2	R	Rudders function should be unaffected by exhaust gases	pass/fail	-	CFD	P. Stakeholder
3	R	Propeller(s) function should be unaffected by exhaust gases	pass/fail	-	CFD	P. Stakeholder
4	D	Exhaust gas odor should be minimized	-	-	Seatrial	P. User
5	D	Noise should be minmized	-	dB	Acoustic study	P. User
6	D	Vibration shall be minimized	-	-	CFD	P. Stakeholder, P. User
7	D	Weight shall be minimized	-	kg	CAD	P. Stakeholder
8	R	Shall fit within available installation space	-	m^3	CAD	P. Stakeholder, S. User
9	D	Shall only add hydrodynamic drag within acceptable limits	-	N	Calculations	P. Stakeholder
10	R	Shall operate without causing cavitation	pass/fail	-	CFD, sea trial	P. Stakeholder
11	R	Back pressure shall be $\leq$ 50% of the permitted maximum	98	mbar	CFD, calculations	P. Stakeholder
12	R	Shall allow for installation that prevents water ingress into the engine	pass/fail	Ca	CAD, system design	P. Stakeholder
13	R	Shall function at heeling angles up to ± 5°	pass/fail	°	CFD	P. Stakeholder, R. Agencies
14	D	Should function at heeling angles up to ± 30°	pass/fail	°	CFD	P. Stakeholder, P. User
15	D	Shall work when sailing yacht is reversing	pass/fail	-	CFD, sea trial	P. Stakeholder
16	R	Shall operate in non-bypass mode at cruising speed	pass/fail	-	CFD	P. Stakeholder
17	D	Shall be located in non-visible areas of the hull	pass/fail	-	CAD, system design	P. User, P. Stakeholder
18	D	Shall be flush with the hull surface	pass/fail	-	CAD, system design	P. User, P. Stakeholder
19	D	Shall be visually pleasant	pass/fail	-	User study	P. User, P. Stakeholder
20	R	Shall be applicable for sailing yachts larger than 24 m	24	m	CFD, sea trial	P. Stakeholder
21	R	Shall be applicable to different hull shapes and types	pass/fail	-	CAD, CFD	P. Stakeholder
22	D	Shall be applicable for different types of hull materials	pass/fail	-	Material analysis, DFM	P. Stakeholder
23	R	Should be possible to clean and maintain	pass/fail	-	User study	S. User
24	R	Exhaust outlet must fit between the structure of the hull	pass/fail	-	CAD	P. Stakeholder
25	R	Structure of the hull should be structurally uncompromised	pass/fail	-	CAD, structural analysis	P. Stakeholder
26	R	Should be made out of materials suitable for underwater use	pass/fail	-	Material analysis	P. Stakeholder
27	R	Engine function should be unaffected	pass/fail	-	CFD, sea trial	P. Stakeholder
28	R	Exhaust gases shall be expelled in a non-pulsating flow	pass/fail	-	CFD	P. Stakeholder
29	D	Shall allow installation to be certified	pass/fail	-	Certification requirements	P. Stakeholder, S. User, R. Agencies

A.6 Concept Catalog

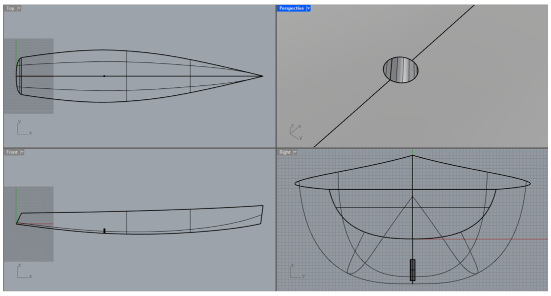


Figure A.4: Concept 1: Centerline Circular

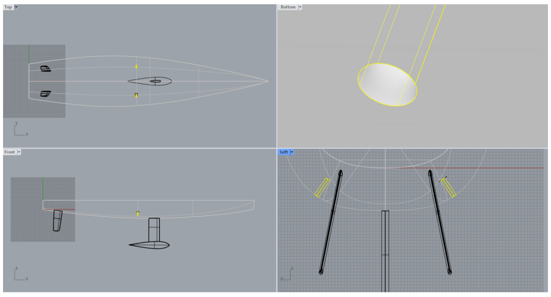


Figure A.5: Concept 2: Mid-ship Circular

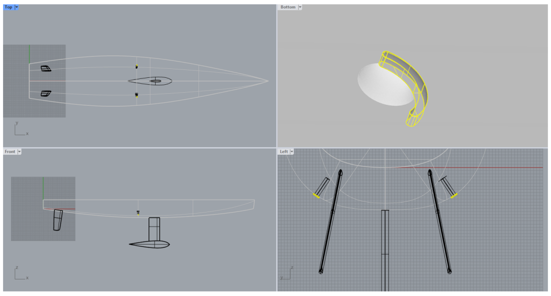


Figure A.6: Concept 3: Centerline curved with curved interceptor

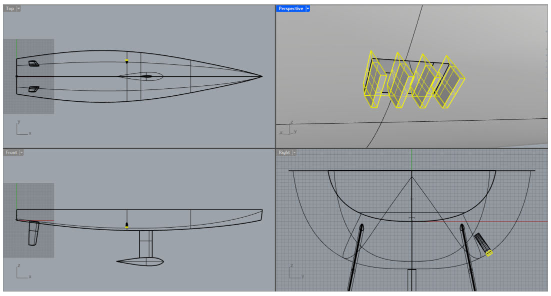


Figure A.7: Concept 4: Washboard

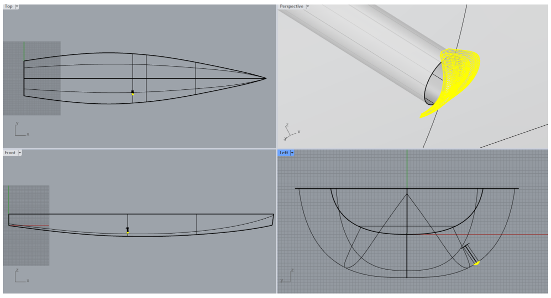


Figure A.8: Concept 5: V1 Scoop

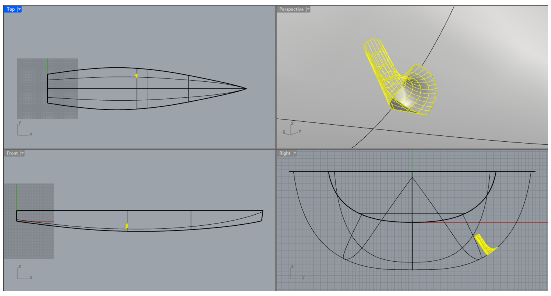


Figure A.9: Concept 6: V1 Quarter Bell-mouth

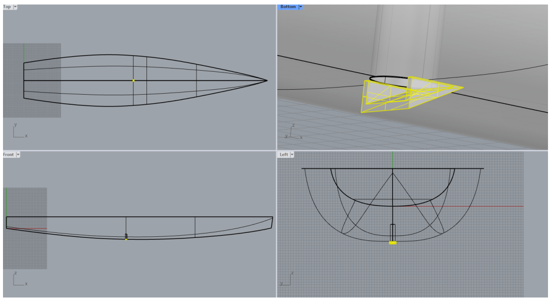


Figure A.10: Concept 7: V2 Scoop

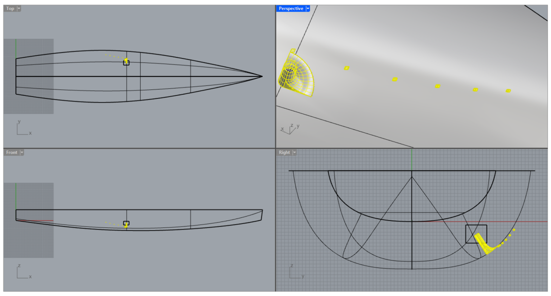


Figure A.11: Concept 8: V1 Quarter Bell-mouth with guides

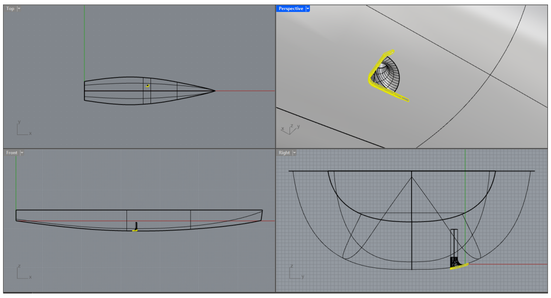


Figure A.12: Concept 9: V1 Quarter Bell-mouth with L interceptor

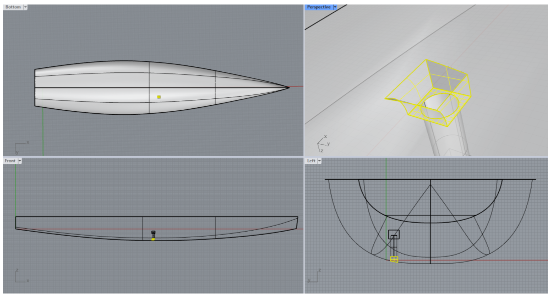


Figure A.13: Concept 10: V1 Boot

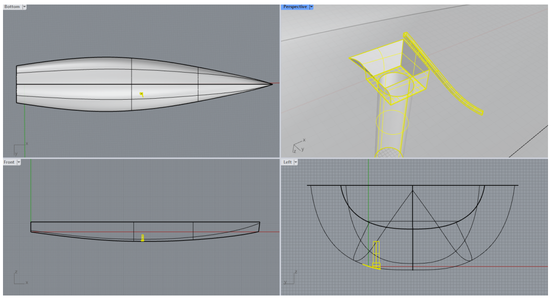


Figure A.14: Concept 11: V1 Boot with curved interceptor

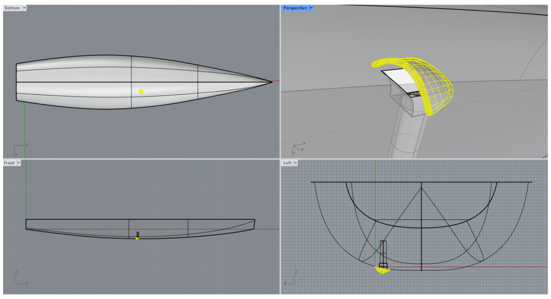


Figure A.15: Concept 12: V1 Boot with scoop

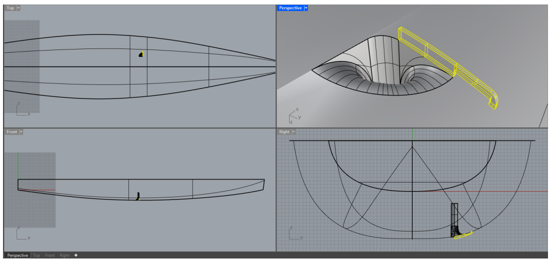


Figure A.16: Concept 13: V2 Quarter Bell-mouth with interceptor with hole

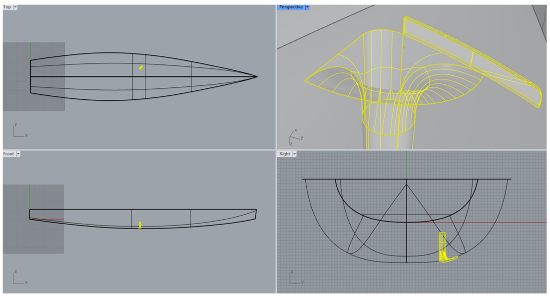


Figure A.17: Concept 14: V2 Quarter Bell-mouth with interceptor

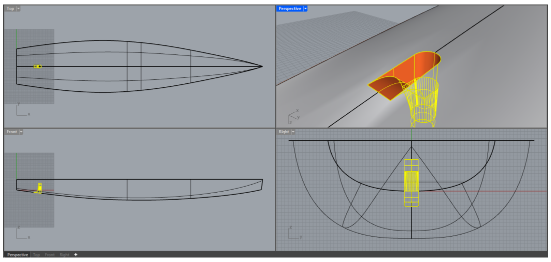


Figure A.18: Concept 15: V2 Boot

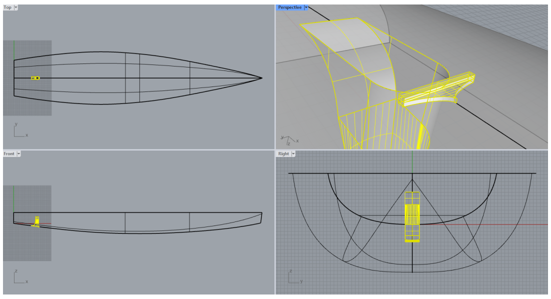


Figure A.19: Concept 16: V2 Boot with sharp interceptor

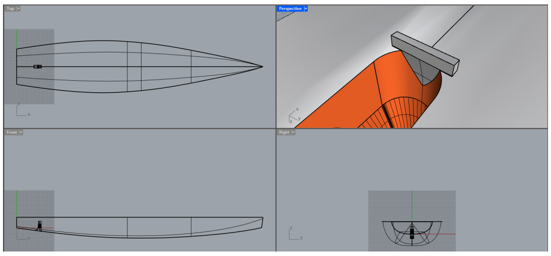


Figure A.20: Concept 17: V2 Boot with interceptor

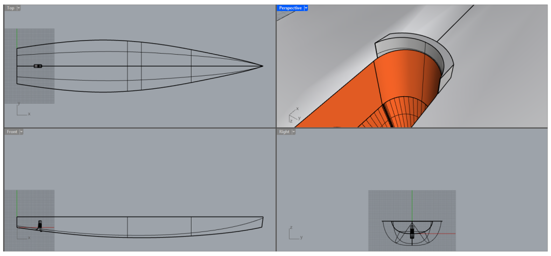


Figure A.21: Concept 18: V2 Boot with curved interceptor

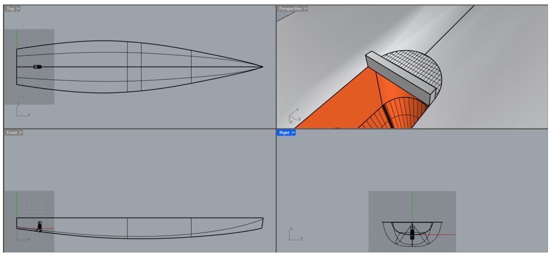


Figure A.22: Concept 19: V2 Boot with roofed interceptor

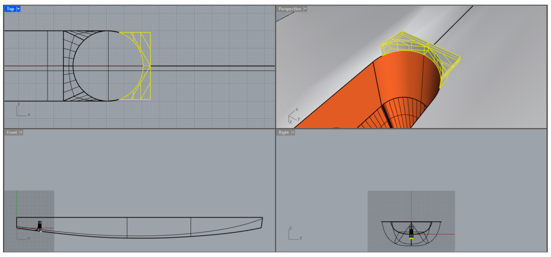


Figure A.23: Concept 20: V2 Boot sharp interceptor with roof

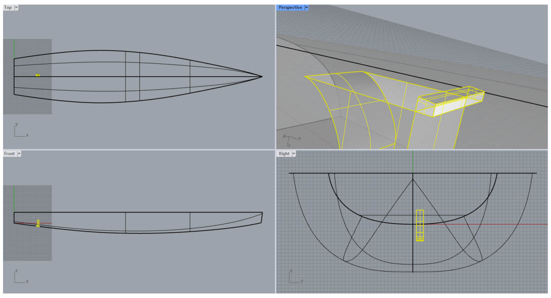


Figure A.24: Concept 21: V3 Boot with interceptor

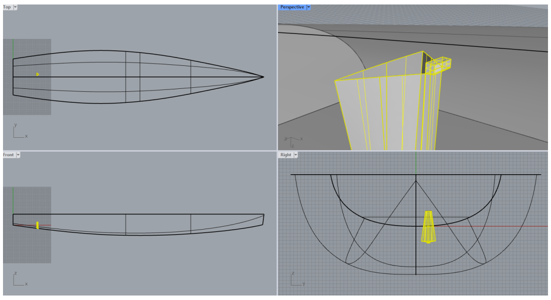


Figure A.25: Concept 22: Triangular boot with interceptor

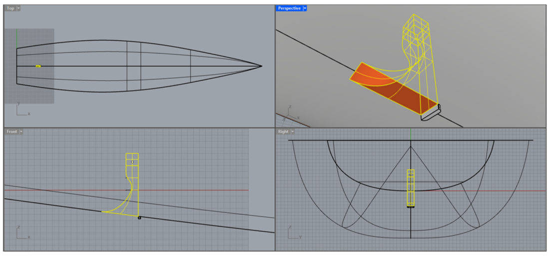


Figure A.26: Concept 23: Restrictor boot with interceptor

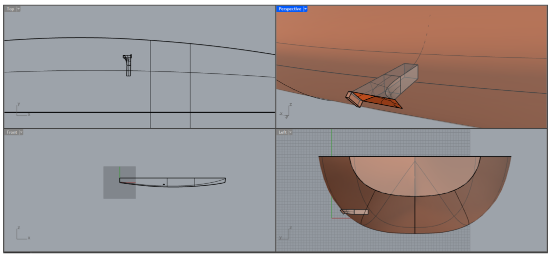


Figure A.27: Concept 24: V4 Boot horizontal

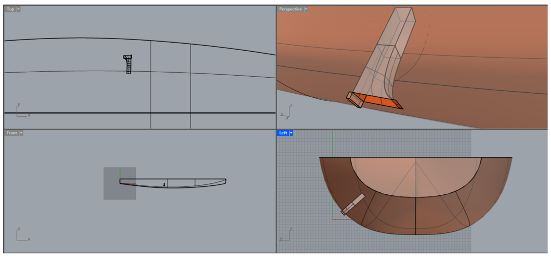


Figure A.28: Concept 25: V4 Boot normal

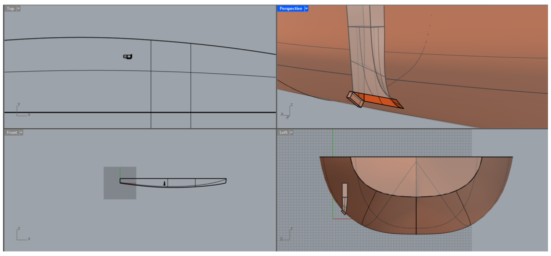


Figure A.29: Concept 26: V4 Boot vertical

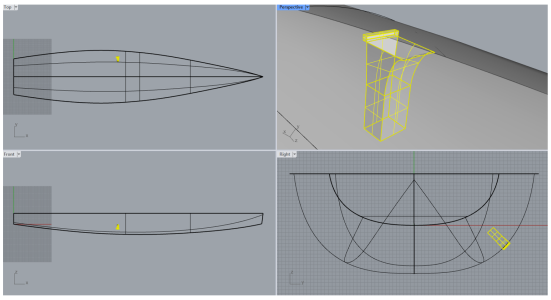


Figure A.30: Concept 27: V5 Boot

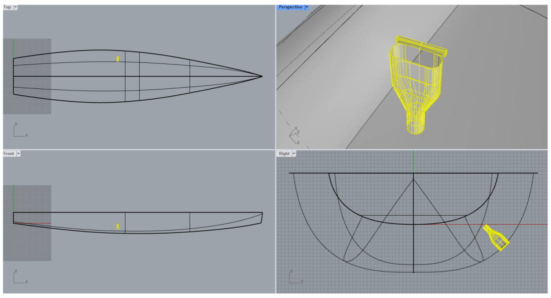


Figure A.31: Concept 28: Oblong

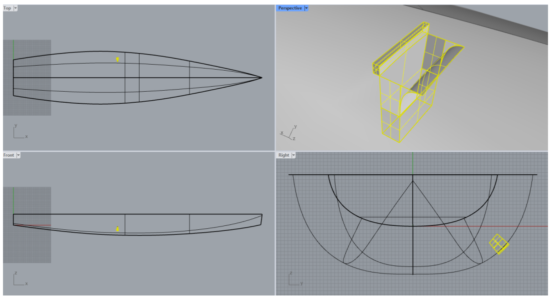


Figure A.32: Concept 29: Long boot

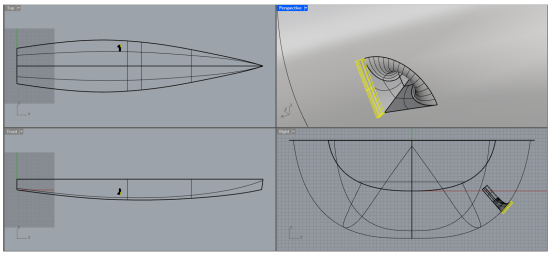
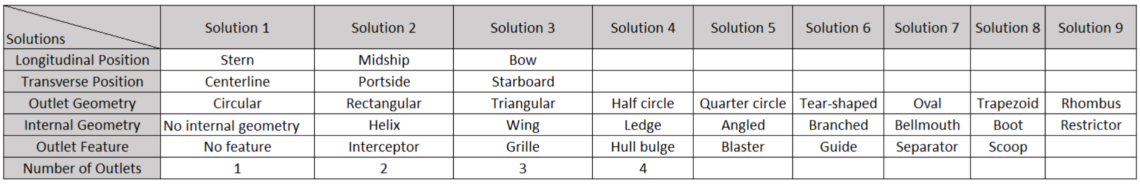


Figure A.33: Concept 30: V3 Quarter Bell-mouth

A.7 Morphological Matrix



Solutions	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8	Solution 9
Longitudinal Position	Stern	Midship	Bow						
Transverse Position	Centerline	Portside	Starboard						
Outlet Geometry	Circular	Rectangular	Triangular	Half circle	Quarter circle	Tear-shaped	Oval	Trapezoid	Rhombus
Internal Geometry	No internal geometry	Helix	Wing	Ledge	Angled	Branched	Bellmouth	Boot	Restrictor
Outlet Feature	No feature	Interceptor	Grille	Hull bulge	Blaster	Guide	Separator	Scoop	
Number of Outlets	1	2	3	4					

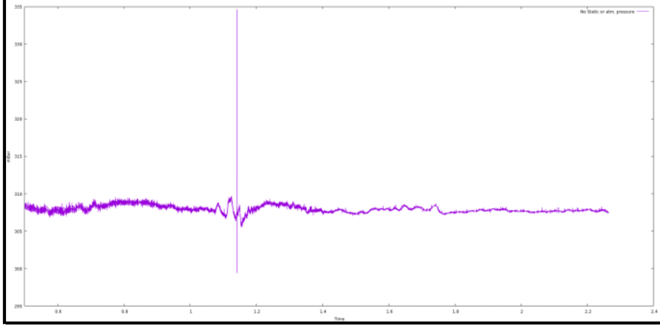
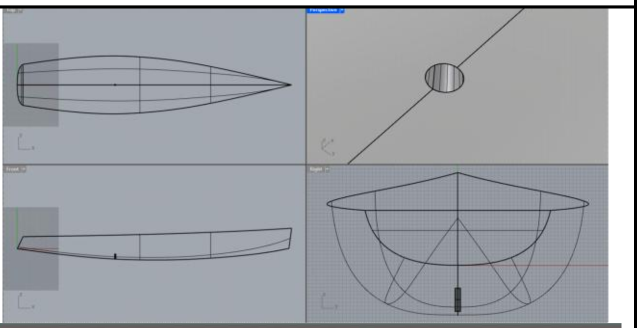
A.8 Evaluation Matrix

Evaluation Matrix

Project: Development and Optimization of Underwater Exhaust Outlets for Sailing Yachts

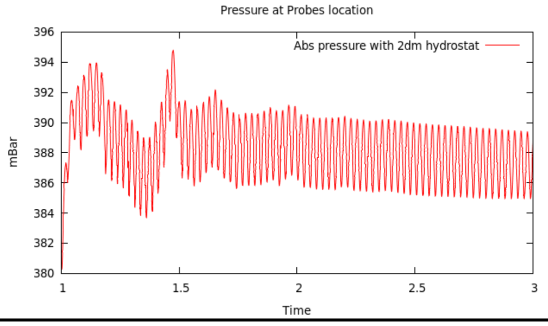
Created: 2026-02-26

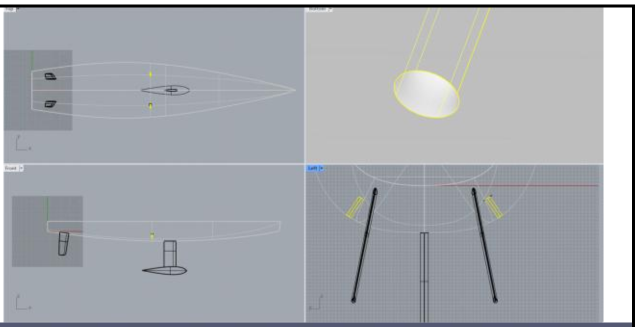
Modified: 2026-05-22

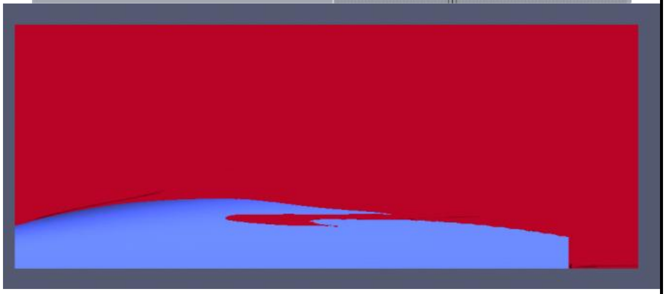
[Guide For Evaluation Matrix] This cell contains name and the corresponding number as well as a description of the concept.	[Guide For Evaluation Matrix] This cell contains CAD-drawings of the concept. Conveying the position it is placed relative to the hull and the outer parts of the exhaust.
[Guide For Evaluation Matrix] This cell contains the plotted pressure from the probe in regards to the simulated time. This value is without hydrostatic pressure.	[Guide For Evaluation Matrix] This cell contains the gases from the simulation with the color red. The image is taken from underneath the vessel towards the sky. The gases path can be seen as they are the only thing in front of the hull.
1. Centerline Circular A circular exhaust in the centerline of the vessel. Used for reference.  	 

2. Mid-ship circular

A circular exhaust outlet positioned on the side the vessel. Used for reference.

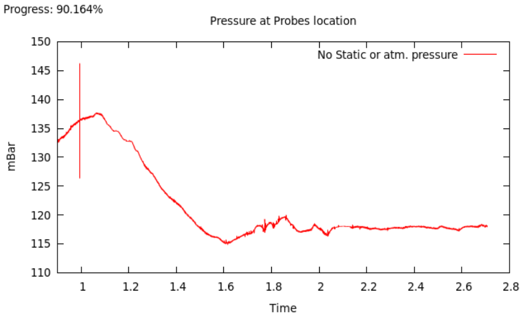


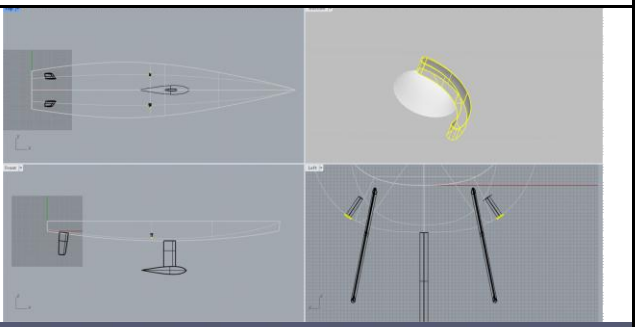


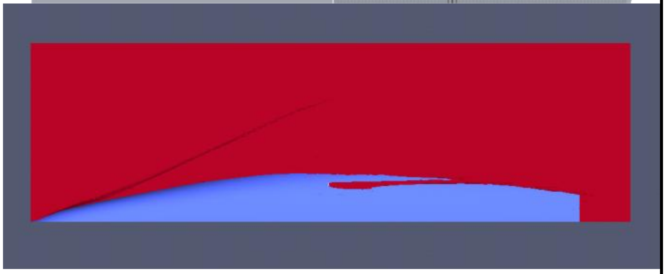


3. Centerline circular with curved interceptor

A circular exhaust outlet positioned on the side of the vessel with a interceptor to reduce the back pressure.

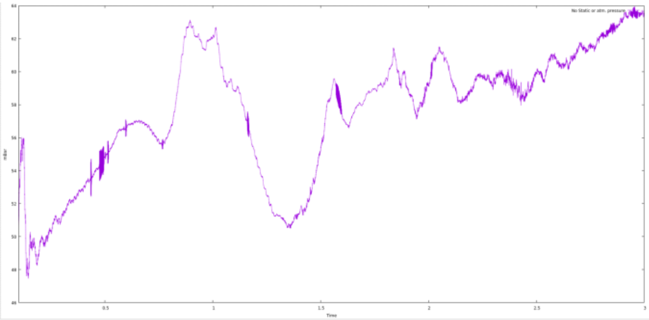


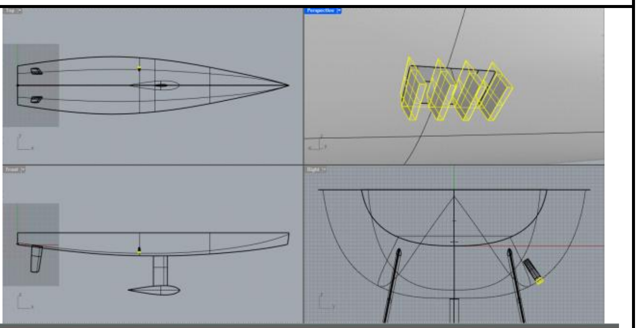


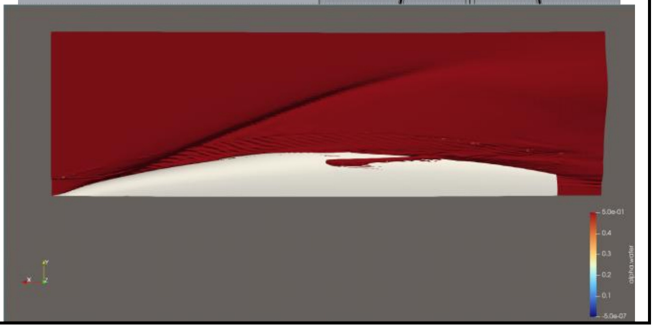


4. Washboard

A square exhaust outlet positioned at the side of the vessel with multiple interceptors in the direction of travel.

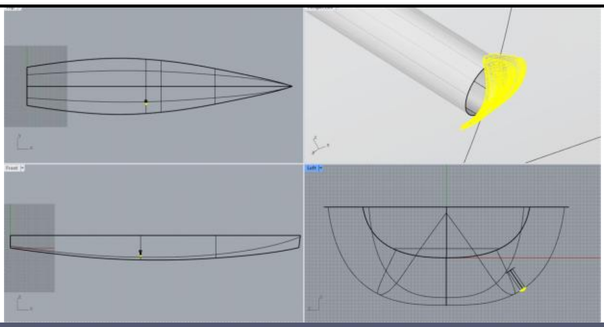


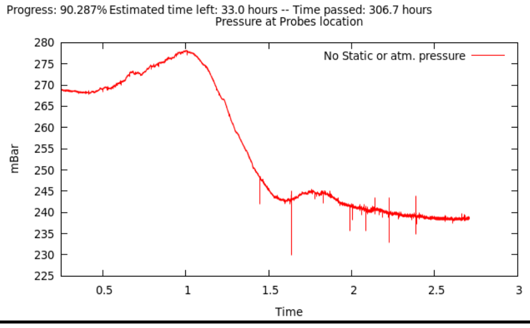


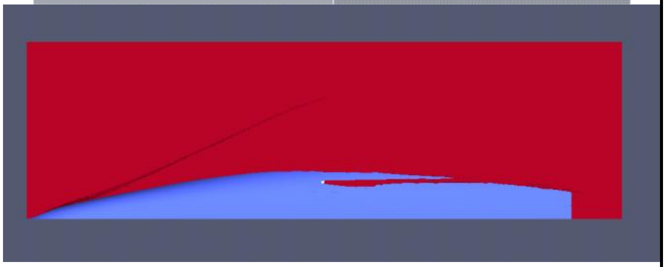


5. V1 Scoop

A "scoop" positioned over the exhaust outlet that is positioned on the side of the vessel. The scoop is meant to direct the flow and reduce pressure over the outlet.

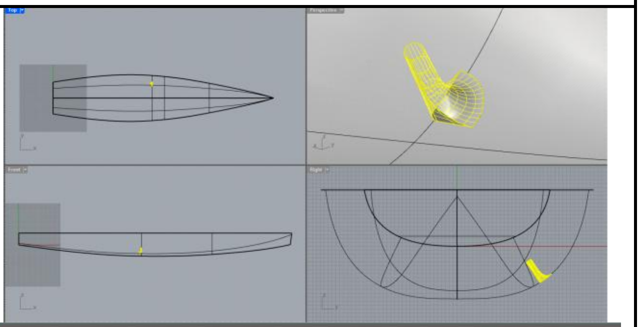


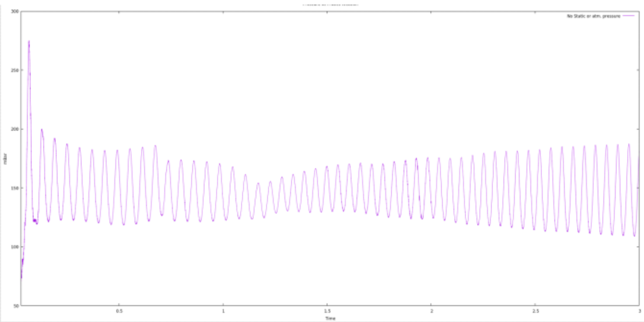




6. V1 Quarter Bell-mouth

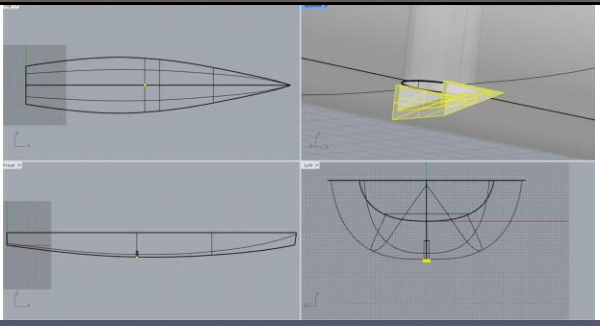
A quarter circulular outlet with fillet edge.

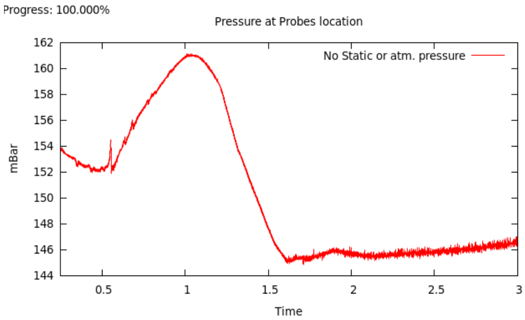


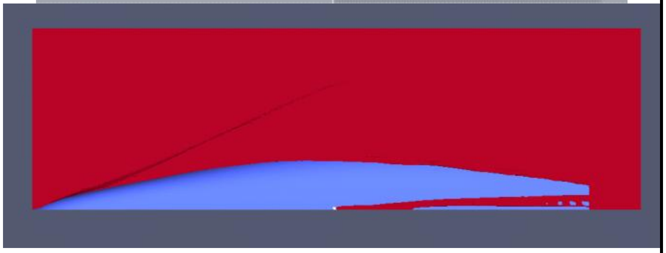


7. V2 Scoop

An improved scoop positioned along the centerline of the yacht. Area of outlet on the scoop is increased and the geometry is simplified for meshing purposes.

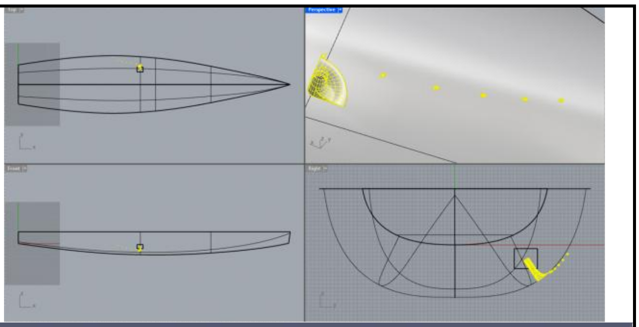


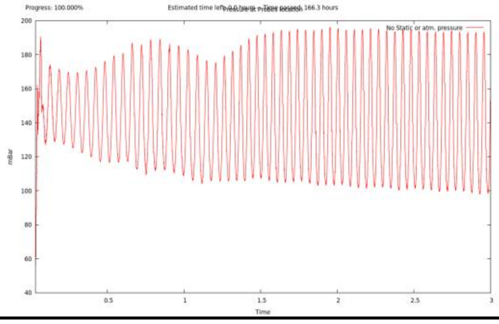


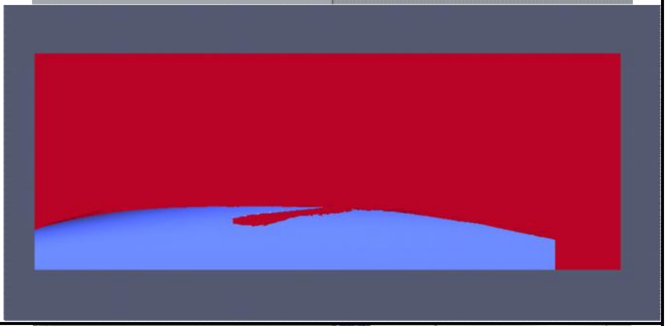


8. V1 Quarter Bell-mouth with guides

Small rhombi positioned in a desired flow path to induce a sharper bend for the gases, utilizing the bellmouth outlet.

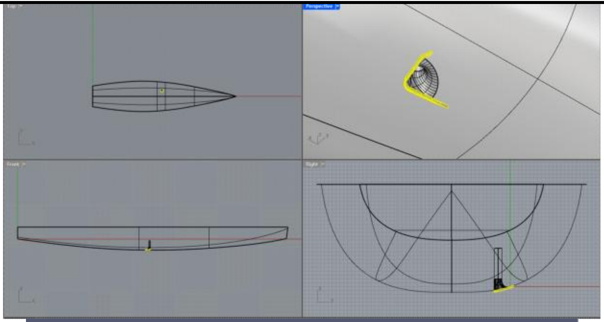


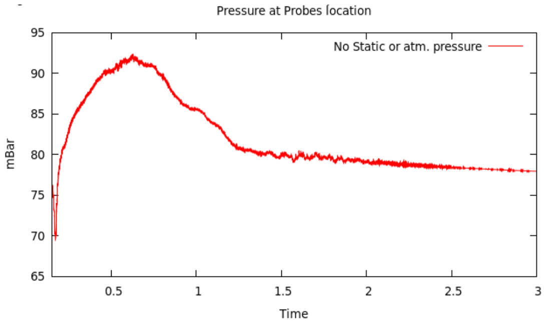


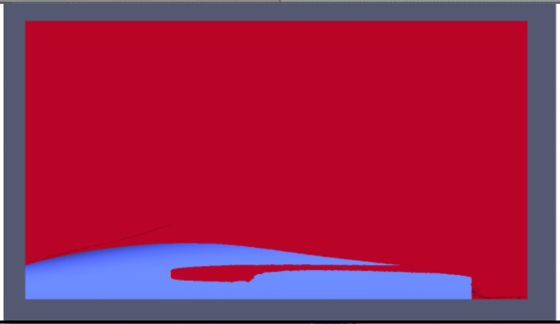


9. V1 Quarter Bell-mouth with L interceptor

A interceptor with a bend making part of it act as an extension of the internal exhaust wall. Positioned at the highest possible point where it is always in contact with water.

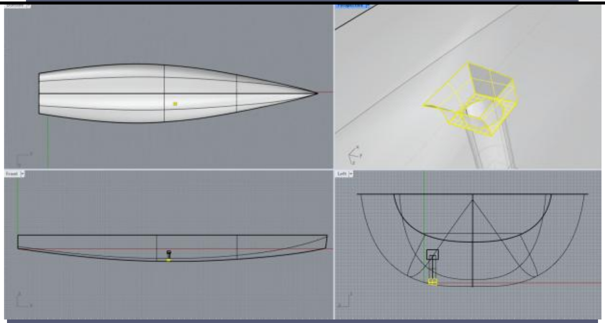


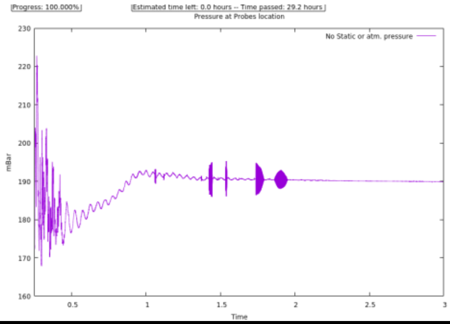


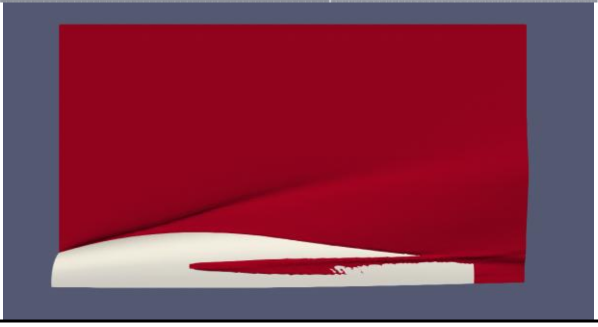


10. V1 Boot

The exhaust pipe opens into a boot-like geometry.

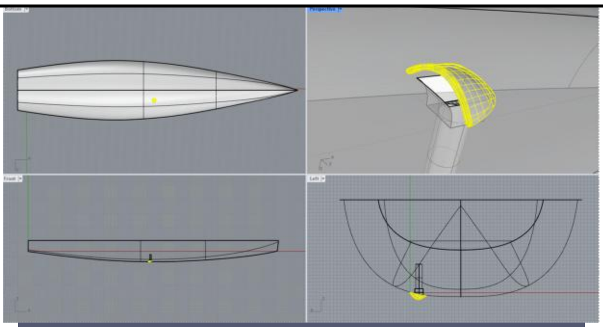


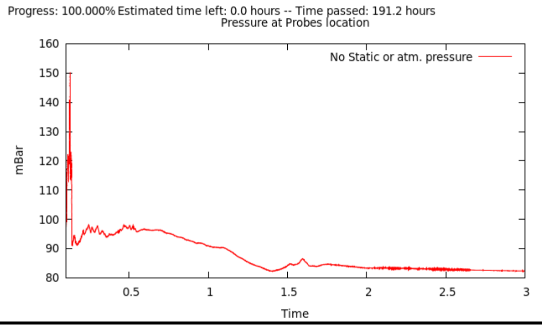


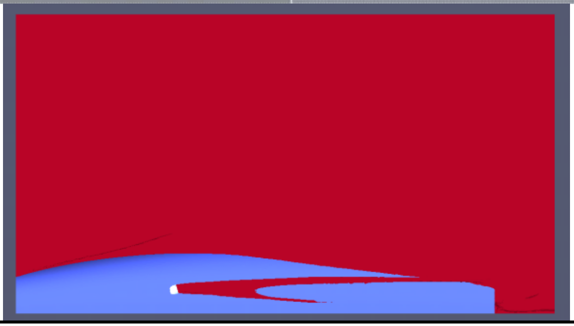


11. V1 Boot with Scoop

Same as V1 Boot but with a scoop to cover the outlet which acts is meant to reduce the back pressure and release the gas in a more controlled flow.

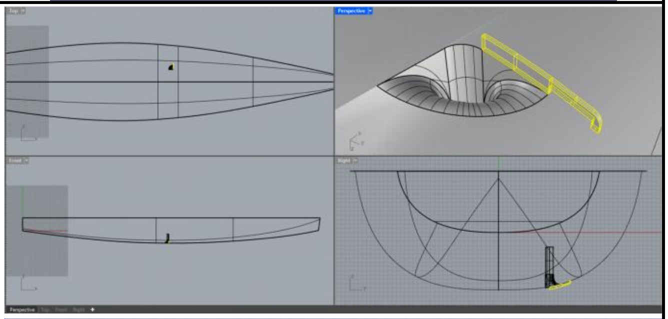


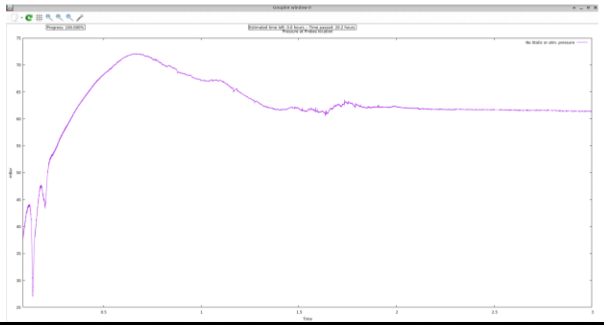

Progress: 100.000% Estimated time left: 0.0 hours -- Time passed: 191.2 hours
Pressure at Probes location

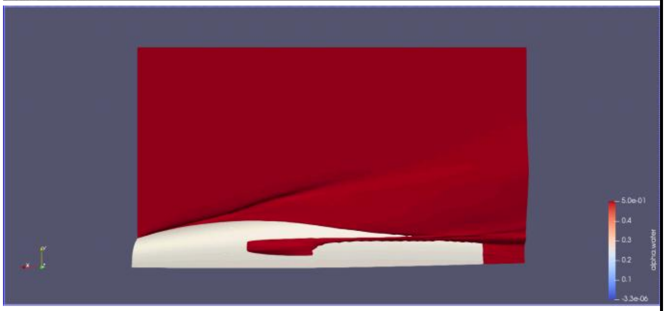


12. V2 Quarter Bell-mouth with interceptor with hole

An improved bellmouth with a interceptor with a hole towards the portside

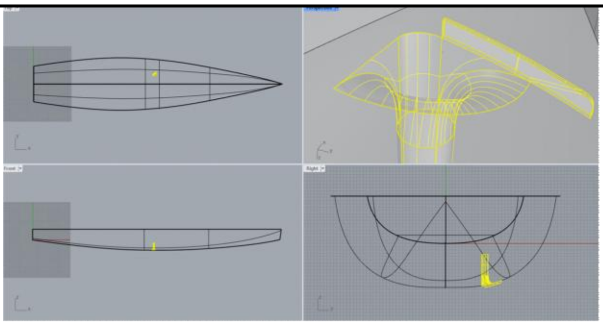


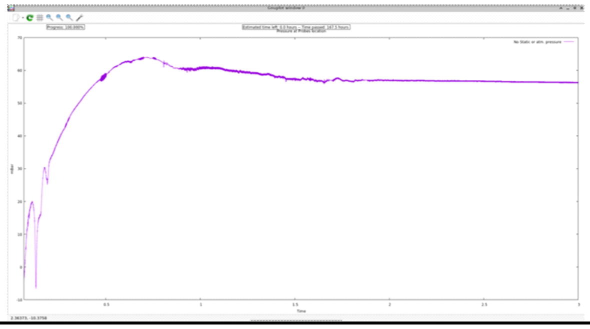


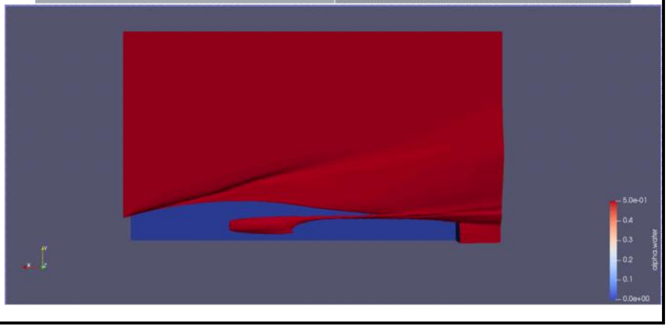


13. V2 Quarter Bell-mouth with interceptor

Same as number 12 but with an interceptor without the hole

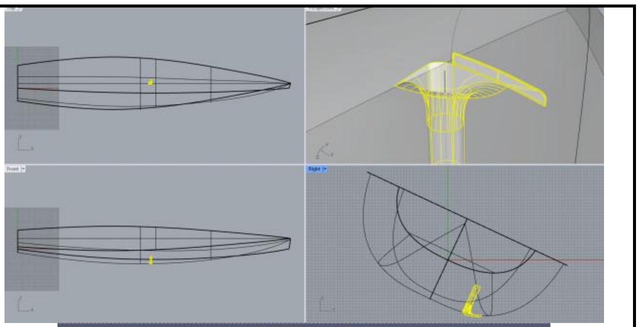


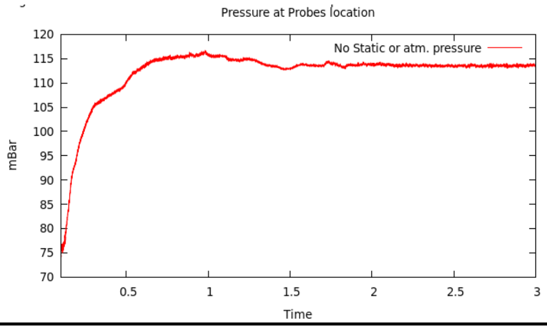


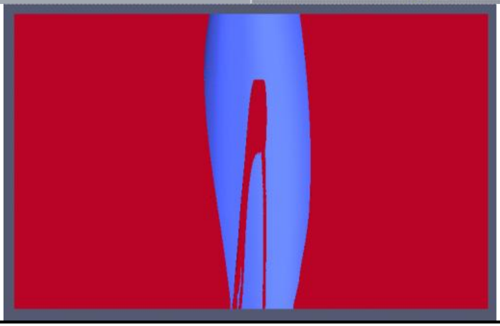


14. V2 Quarter Bell-mouth with interceptor

Same as number 13 "Bellmouth with interceptor with gap filled" but with the yacht heeling 25 degrees port side. This makes the position of the exhaust outlet deeper.

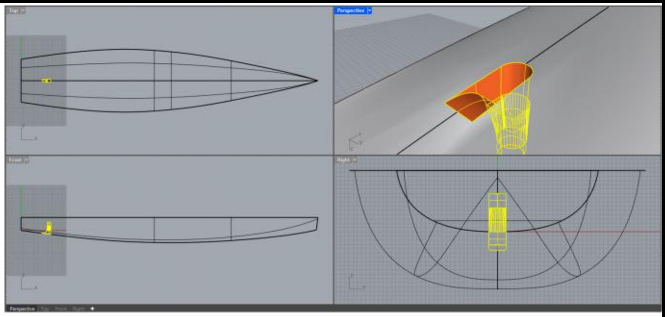


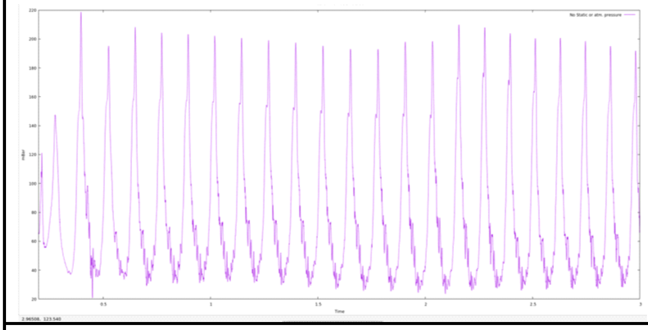




15. V2 Boot

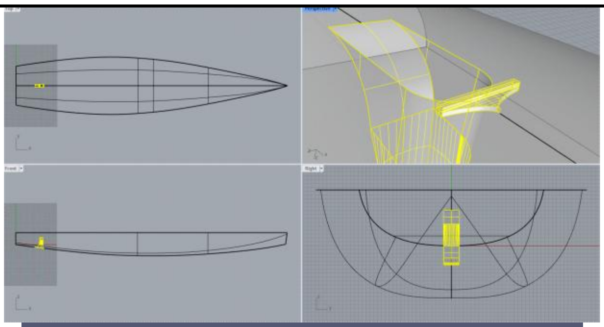
A boot exhaust outlet without a interceptor in the centerline of the vessel near the stern of the yacht

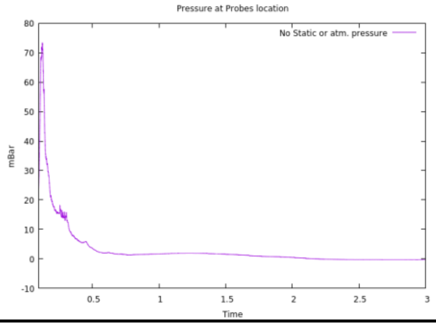




16. V2 Boot with sharp interceptor

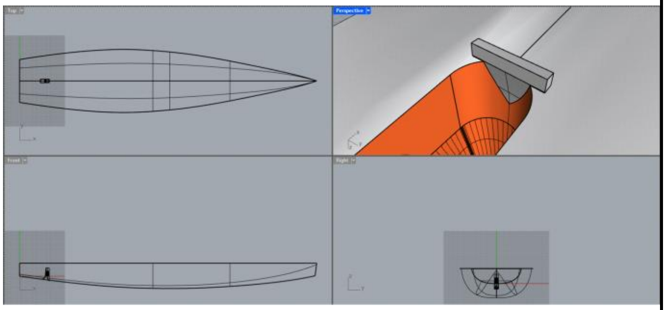
Similar to number 15 but with a interceptor with different geometry. The interceptor has a pointy edge along the hull and a raised lip. Interceptor height: 40.5 mm

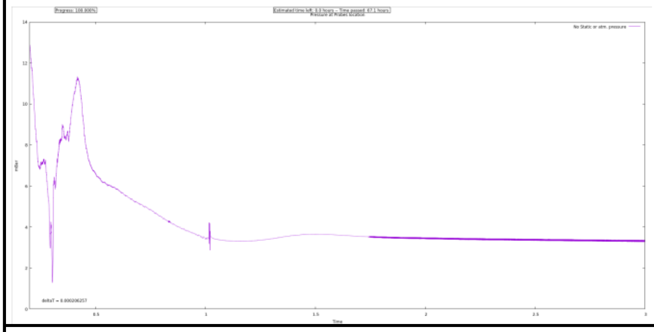




17. V2 Boot with interceptor

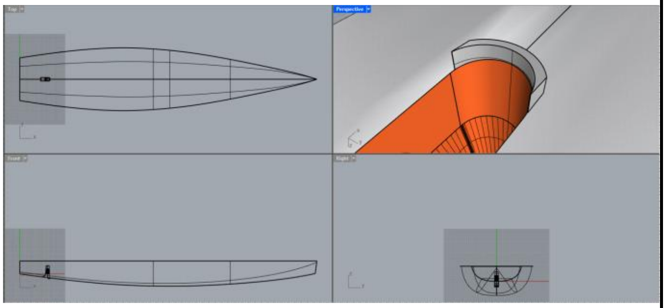
The same exhaust as 15, with a simple interceptor extending over the exhast. Interceptor height: 75 mm

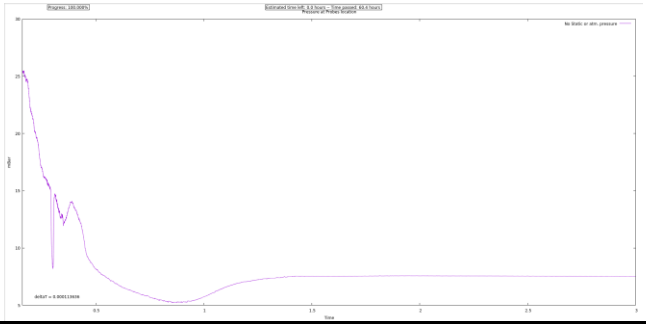


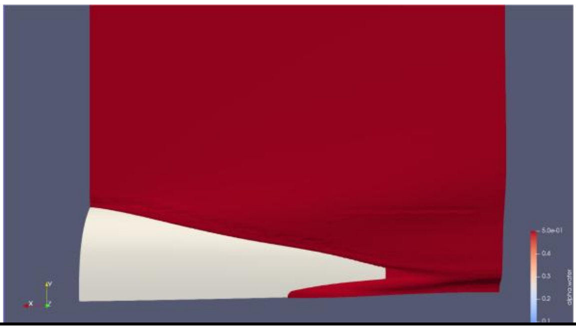


18. V2 Boot with curved interceptor

The same exhaust as 15, with a rounded interceptor. Interceptor height: 78 mm

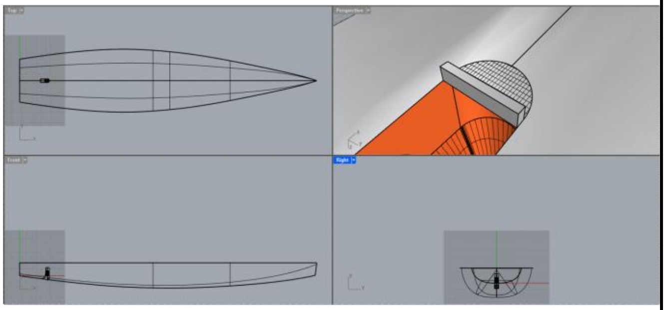


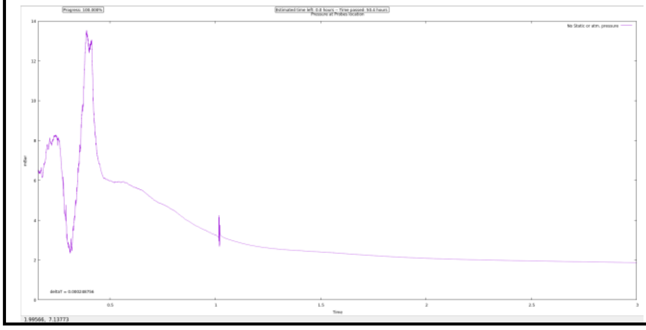


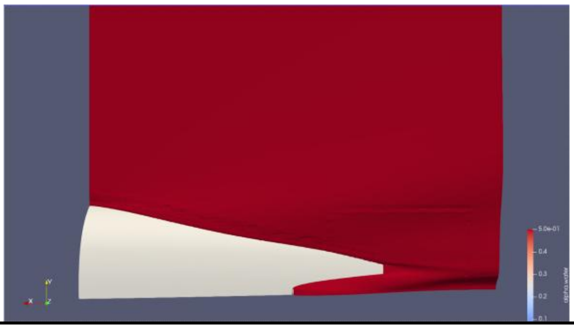


19. V2 Boot with roofed interceptor

The same exhaust as 15, interceptor having a rounded inside and thus places over the exaust. Interceptor height: 80 mm

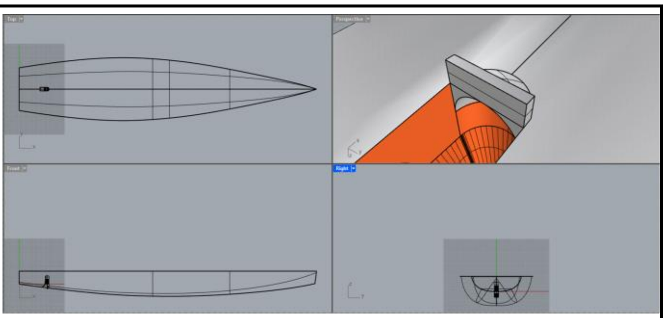


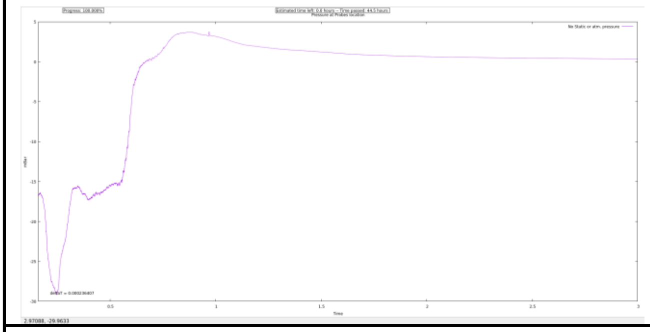




20. V2 Boot with roofed interceptor

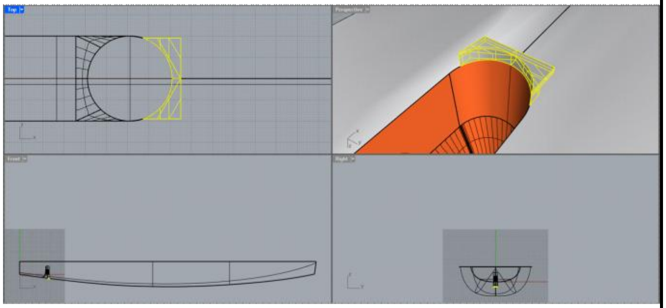
The same exhaust as 15, interceptor having a sphrical inside. Interceptor height: 128 mm

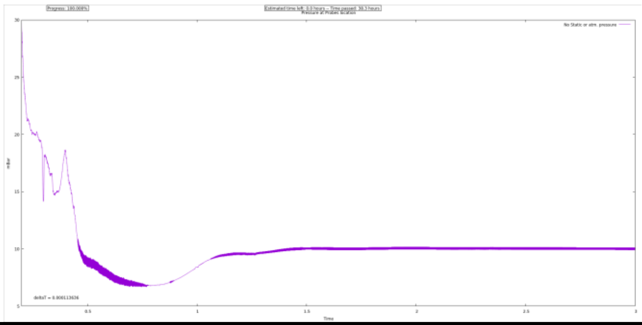




21. V2 Boot sharp interceptor with roof

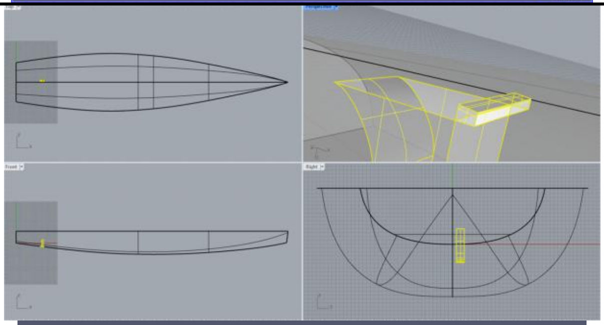
Similar to number 16, but the lip is extended past the sharp edge. Interceptor height: 76 mm

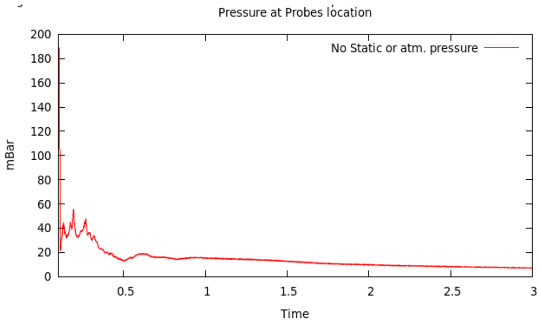


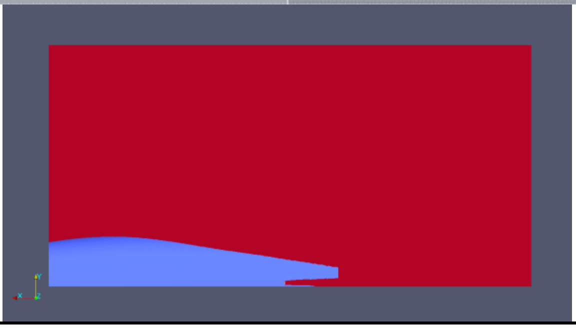


22. V3 Boot with interceptor

A redesigned boot exhaust with simpler geometry, positioned in the stern but slightly off center to allow for a dual exhaust configuration. Basic interceptor with height 30 mm.

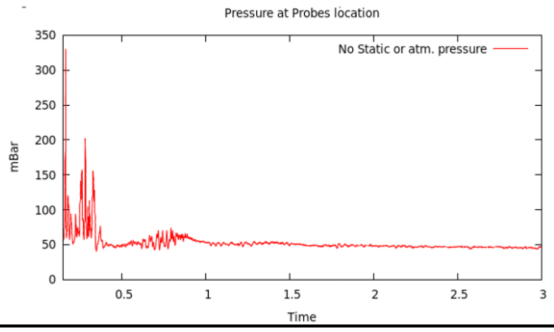


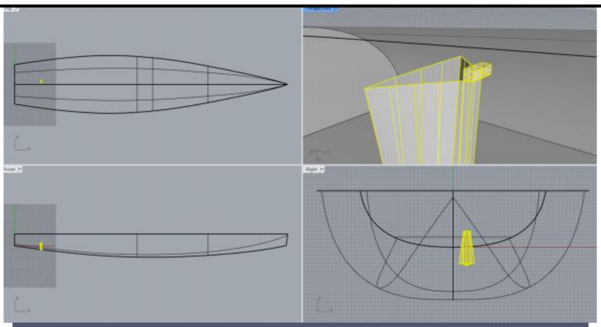


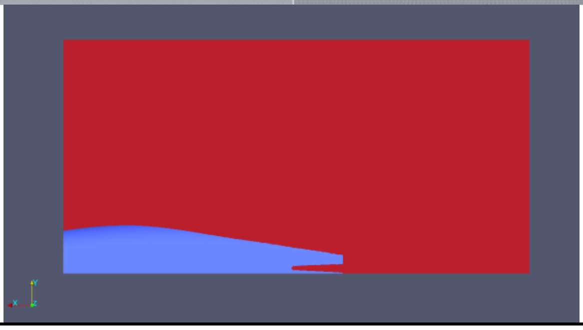


23. Triangular boot with interceptor

Similar positioning as number 22 but with a triangular outlet and small interceptor placed at the apex of the triangle. Interceptor height: 30 mm.

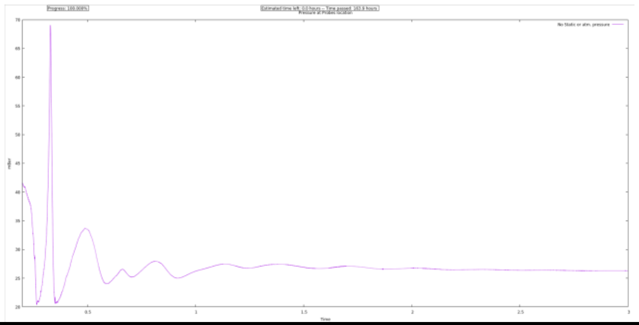


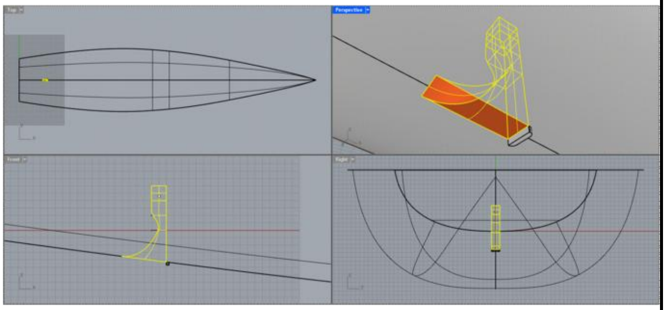




24. Restrictor boot with interceptor

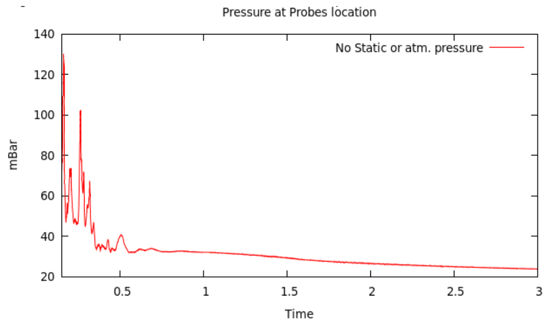
A near stern centered boot with a thinned part in the exhaust. The interceptor is a simple 42mm height with rounded edges.

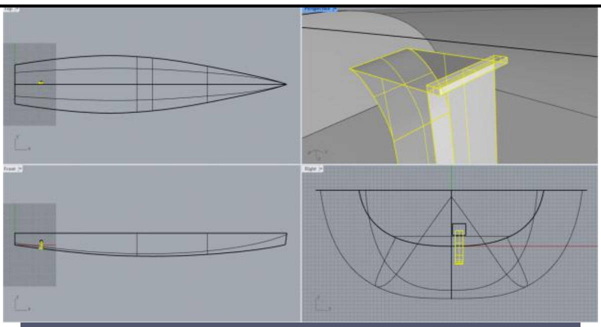


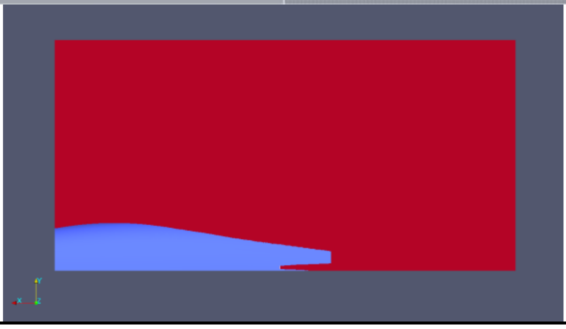


25. V3 boot with interceptor

Same as number 22 but with the interceptor height changed to 15 mm.

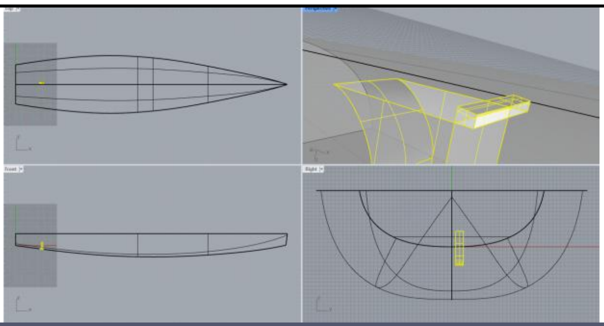


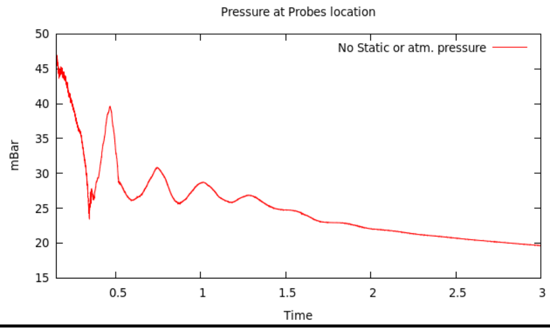


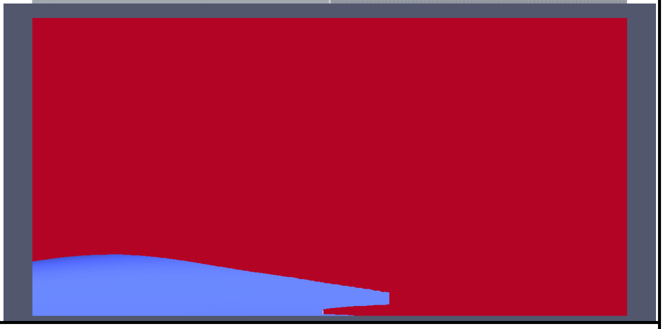


26. V3 boot with interceptor

Same as number 22 but it is a single, asymmetrical exhaust configuration instead of a dual exhaust. Inteceptor height of 30 mm.

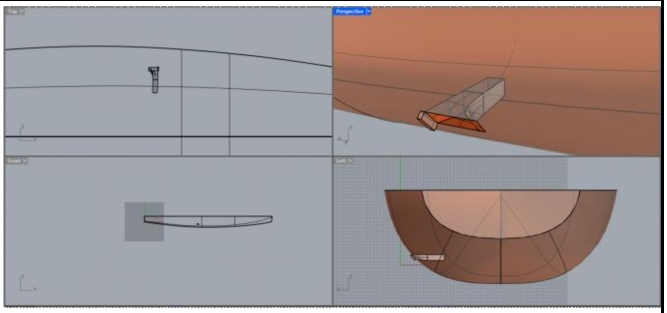


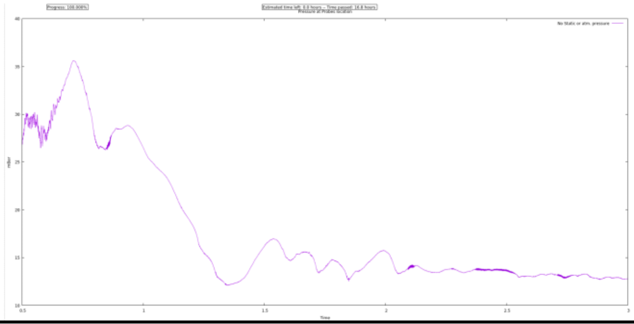




27. V4 Boot Horizontal

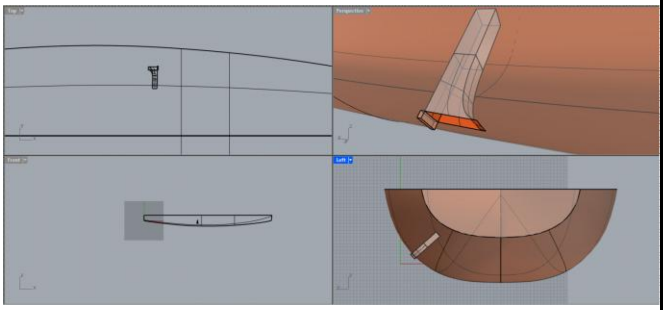
Another boot design but positioned midship at the side of the vessel. Direction of the exhaust is horizontal.

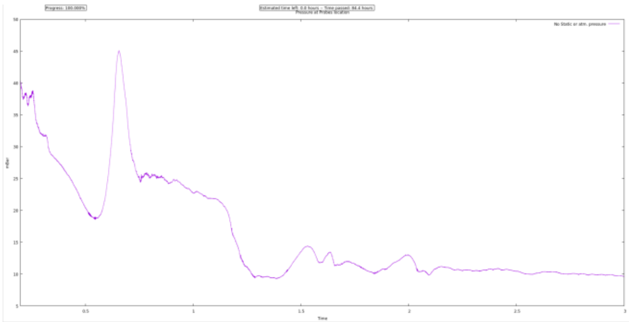


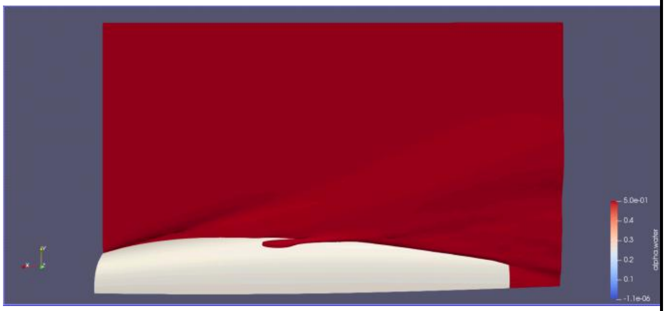


28. V4 Boot Normal

Same as number 27 but direction of the exhaust is normal to surface.

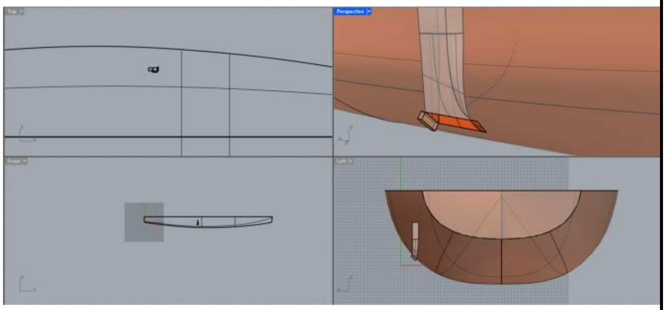


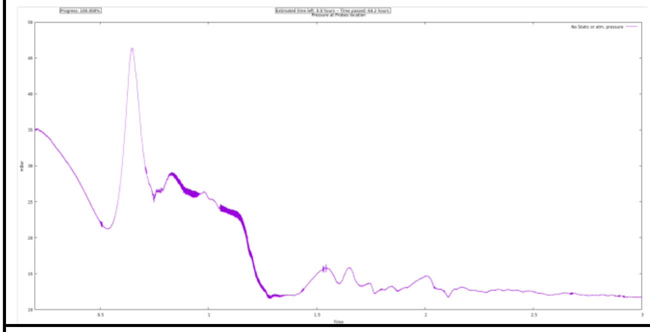




29. V4 Boot Vertical

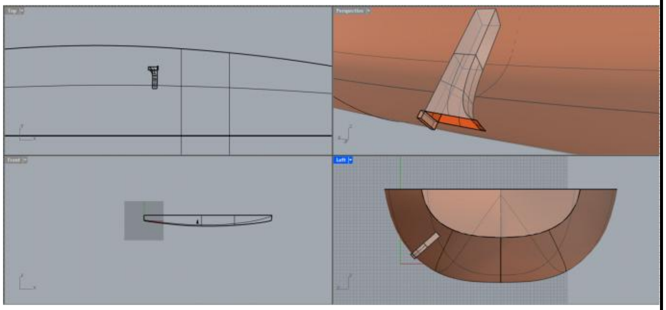
Same as number 27 and 28 but direction of the exhaust is vertical.

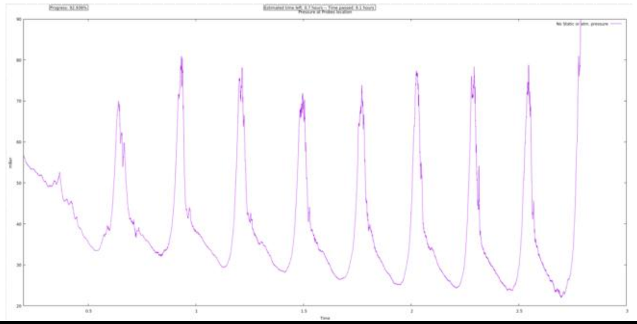




30. V4 Boot Normal

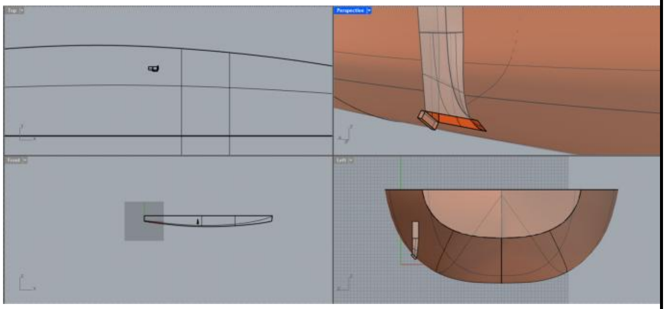
7.5 kn 30 mm thick int

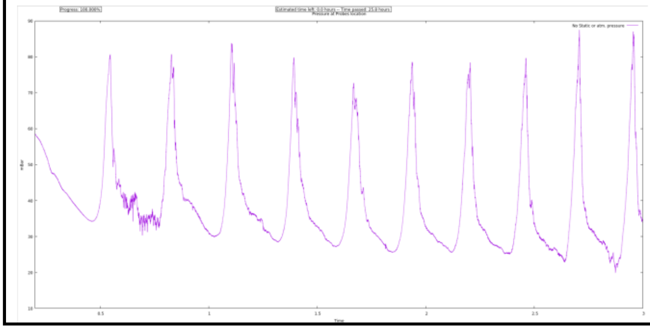




31. V4 Boot Vertical

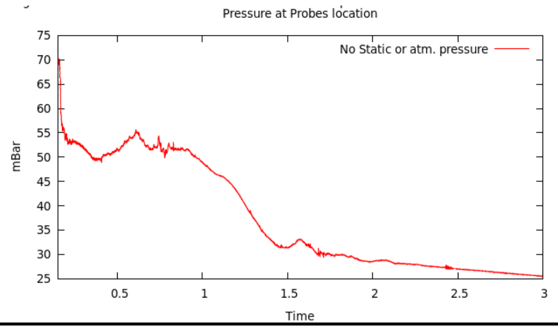
Same as 29 with 7.5 kn 30 mm thick int

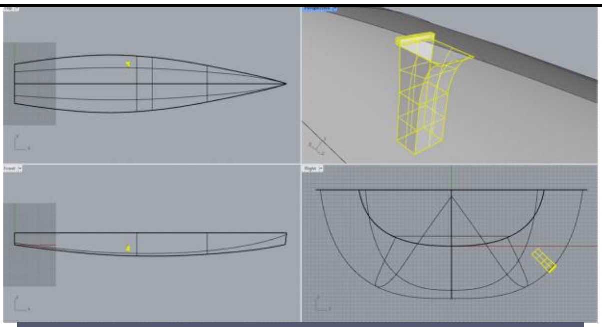


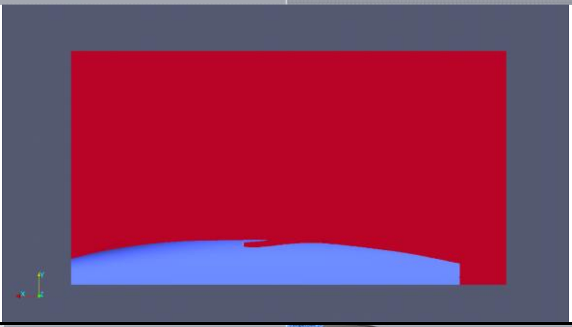


32. V5 Boot

Similar to concept number 28 but slightly different internal design. Speed 15 kn. Interceptor Height 35 mm.

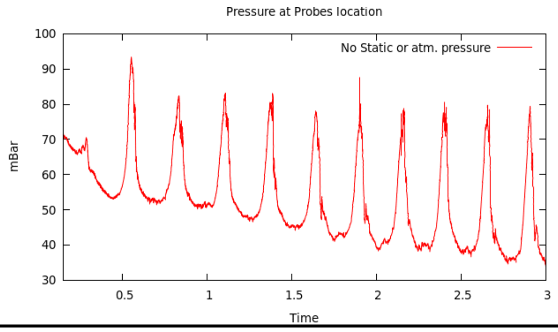


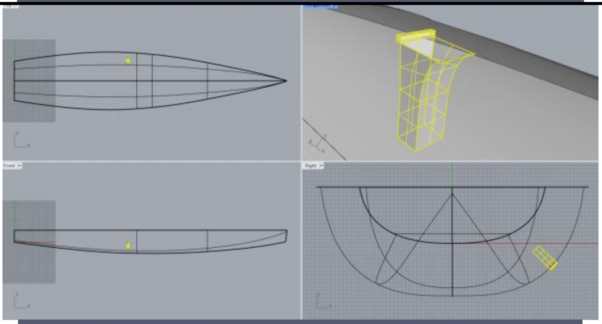


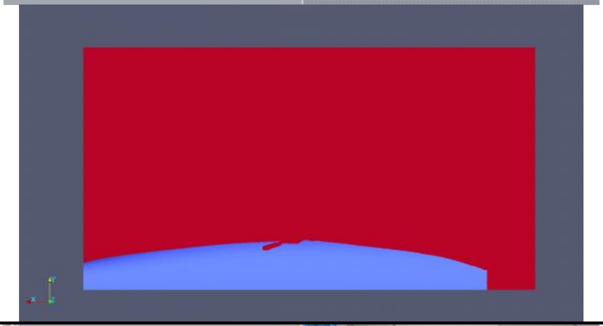


33. V5 Boot

Same as number 32 but with speed 7.5 kn.

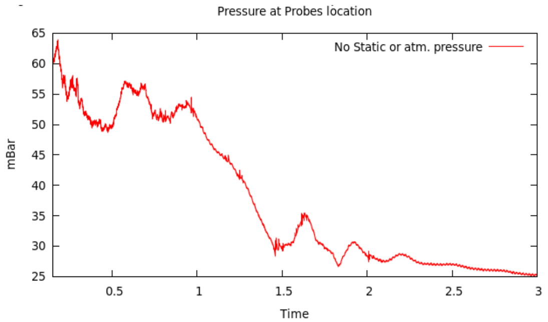


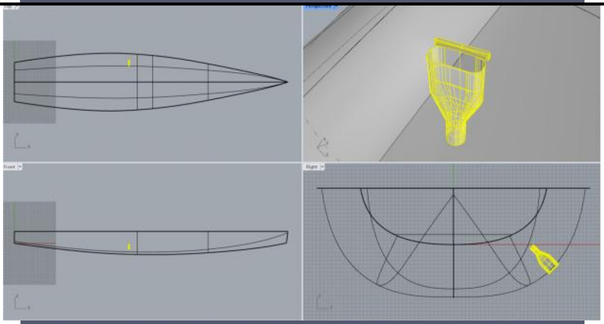


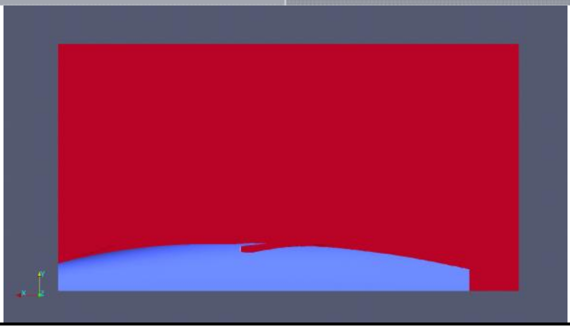


34. Oblong

An oblong design meant to make better use of the interceptor's low pressure zone.

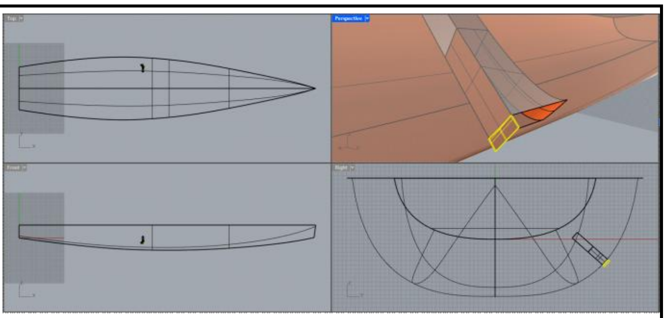


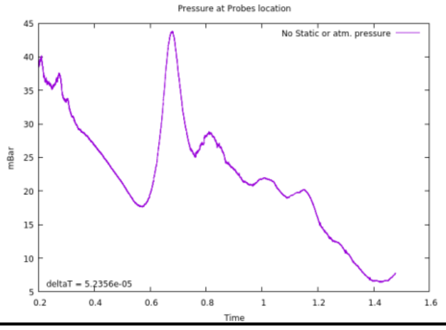




35. V4 Boot Normal

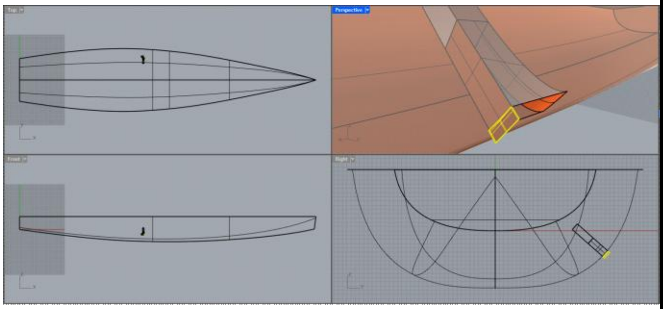
A thinner interceptor version of 26 but with 15 kn and a 5 mm thick interceptor

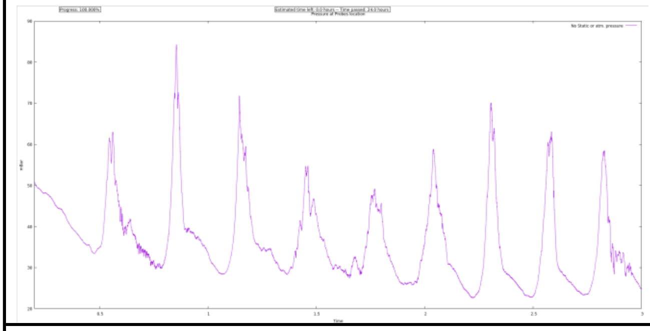




36. V4 Boot normal

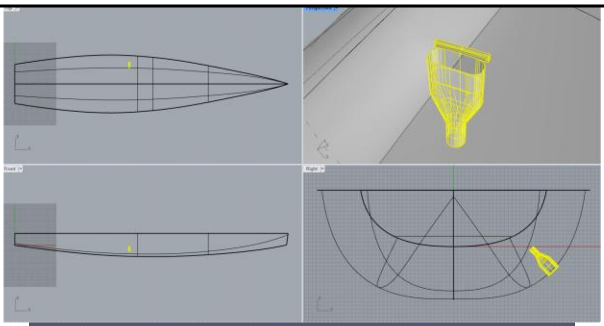
A thinner interceptor version of 26 but with 7.5 kn and a 5 mm thick interceptor

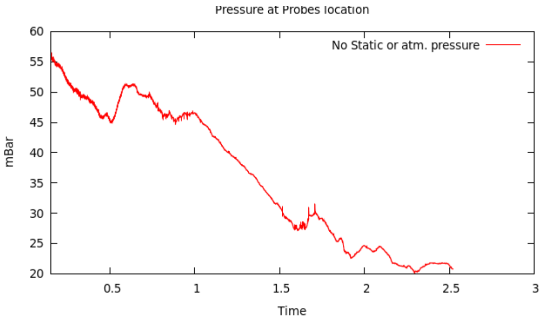


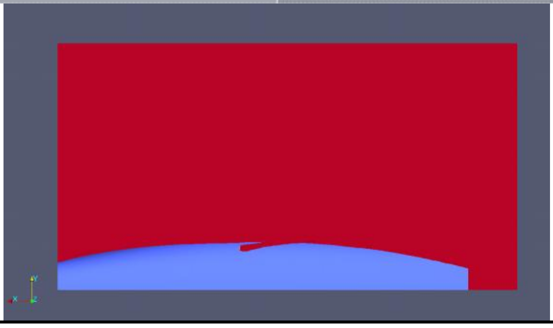


37. Oblong

13 kn

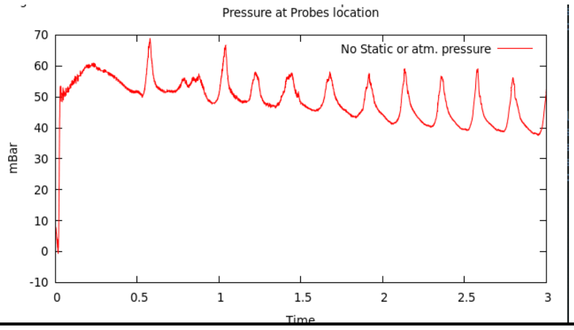


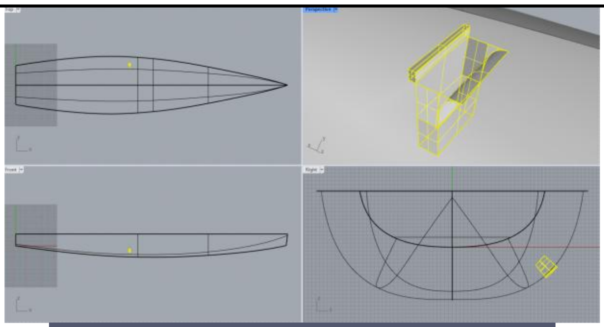


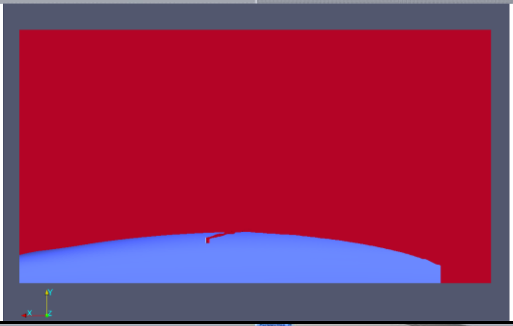


38. Long boot

A narrow boot exhaust with an 50 mm height interceptor. A combination of the boot and the oblong design. 5 kn.

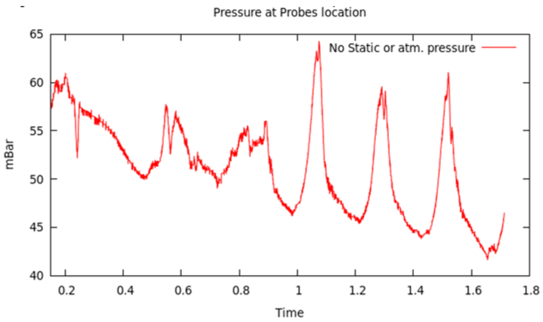


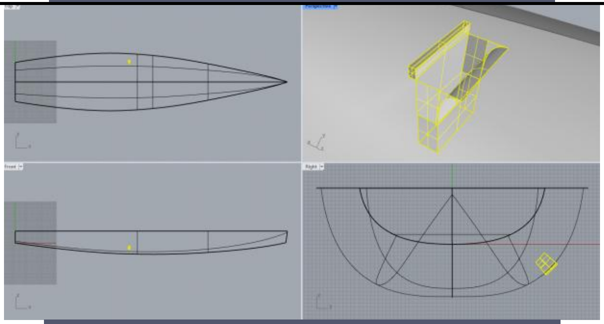


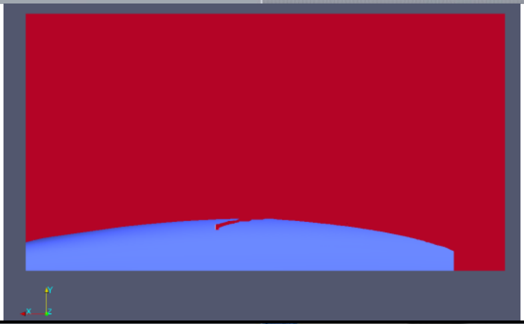


39. Long boot

6 kn

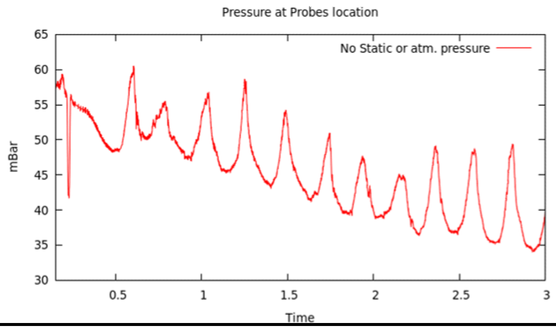


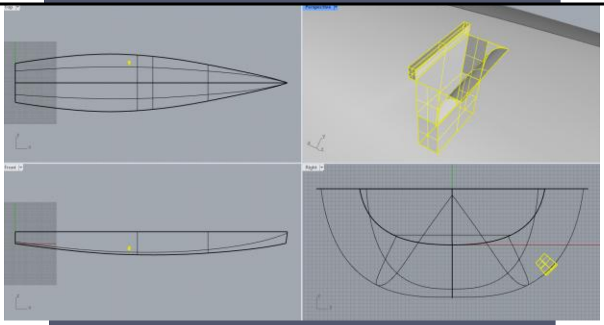


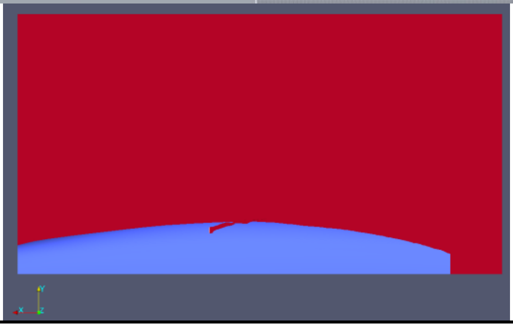


40. Long boot

7 kn

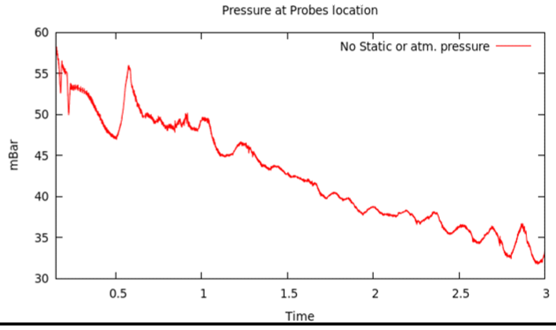


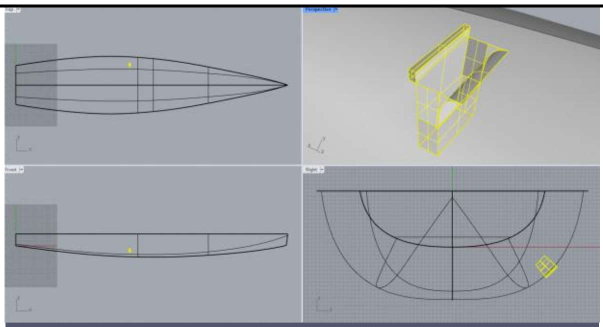


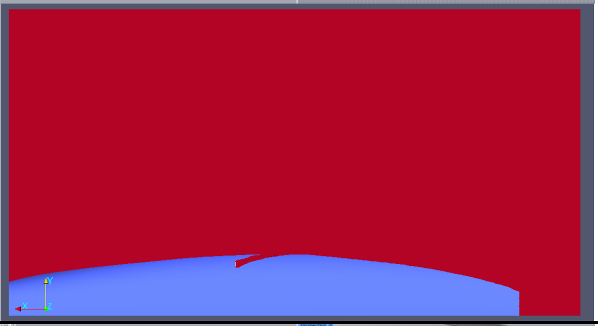


41. Long boot

8 kn

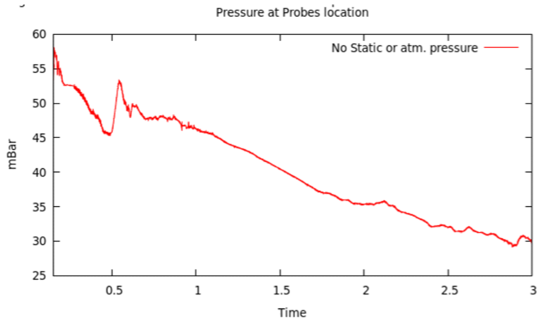


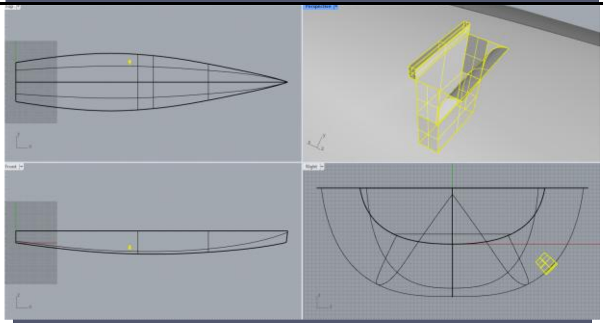


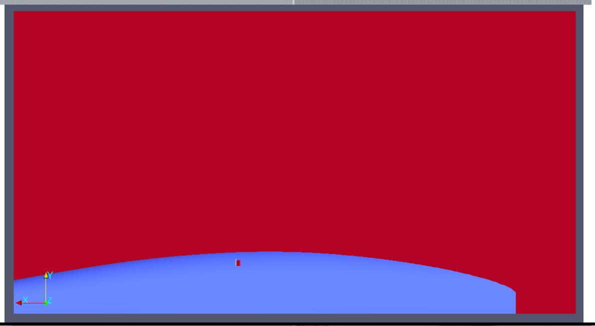


42. Long boot

9 kn

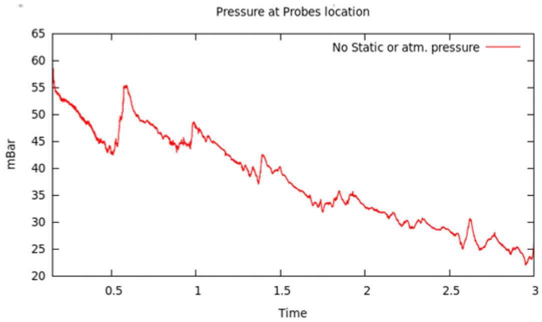


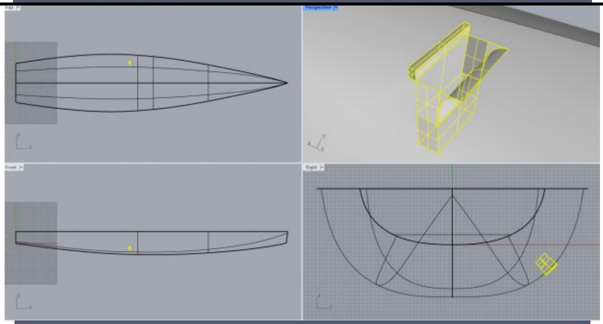


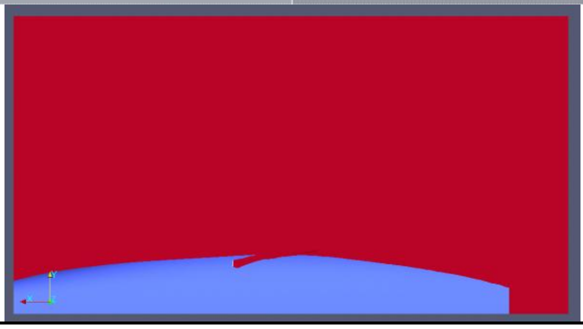


43. Long boot

10 kn

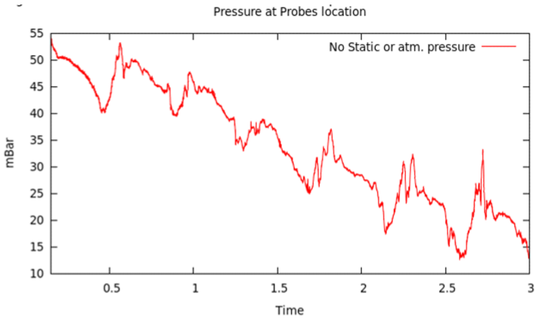


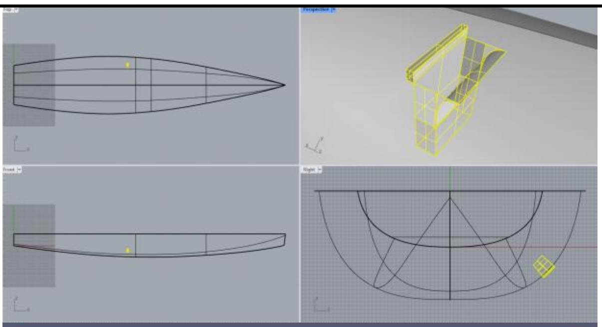


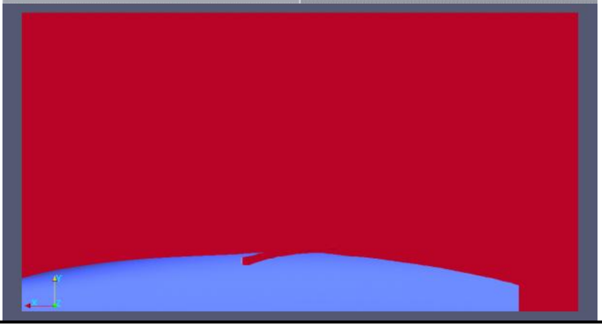


44. Long boot

11 kn

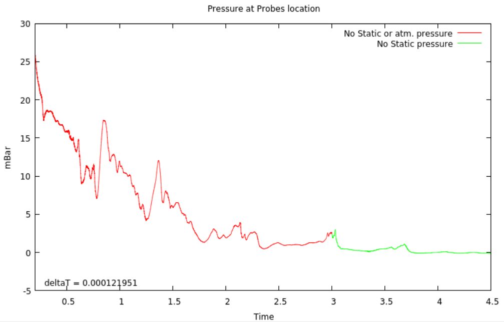


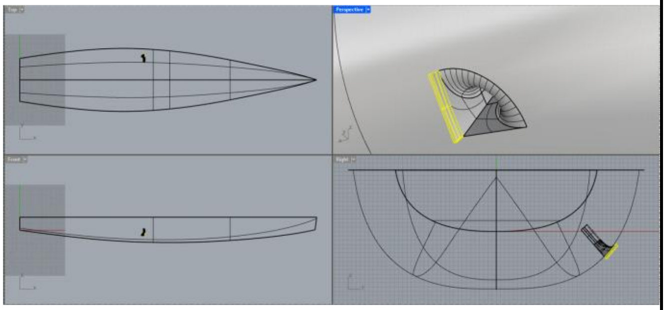




45. V3 Quarter Bell-mouth

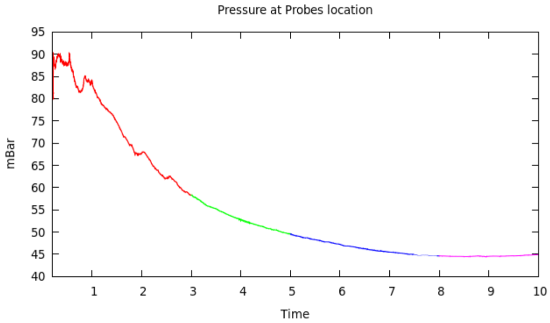
A improved quarter bell-mouth design but with better positioning and interceptor. 10 kn.

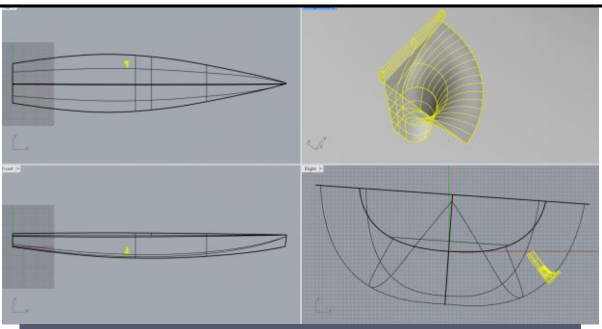


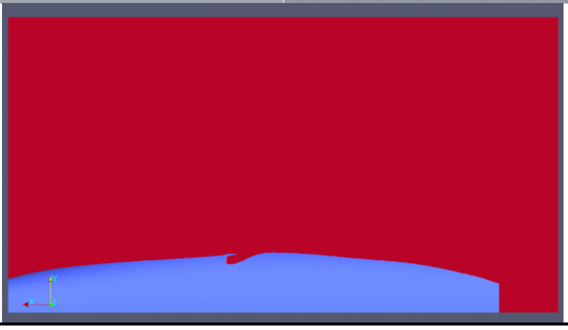


46. V3 Quarter Bell-mouth

+4 degree heel, 10 kn. 40 mbar hydrostatic pressure added to the plot.

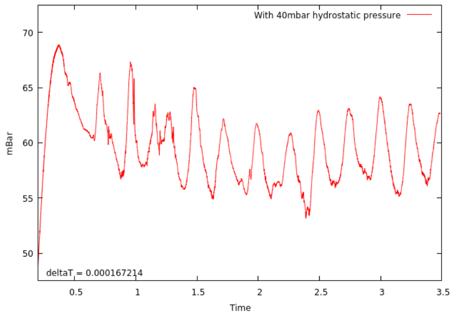


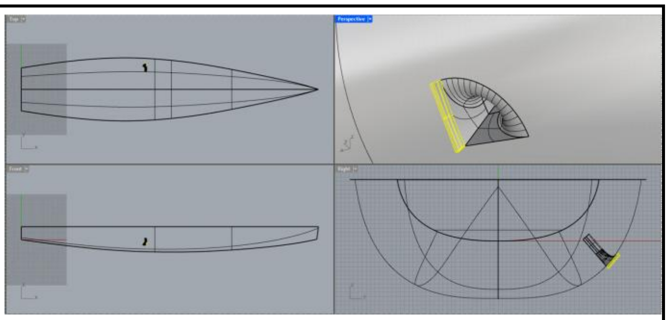


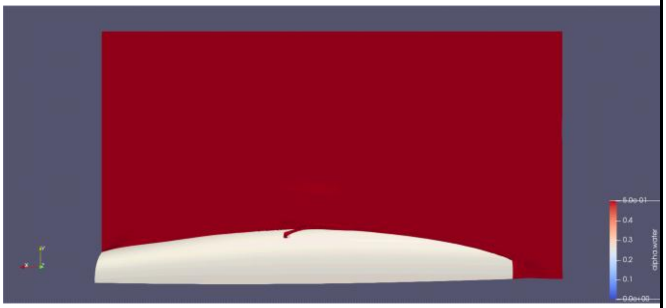


47. V3 Quarter Bell-mouth

Same concept as 45, 6 kn

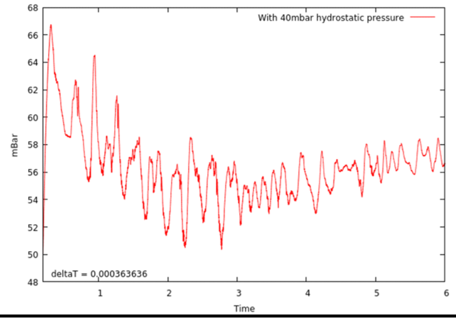


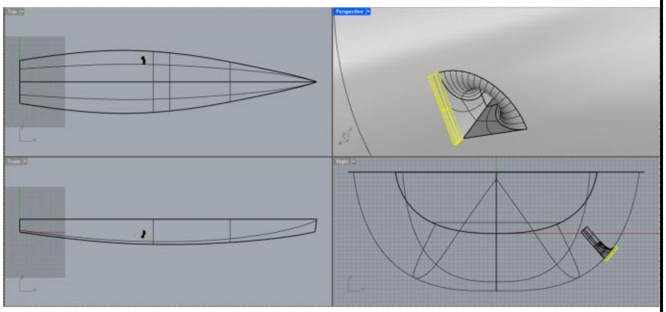


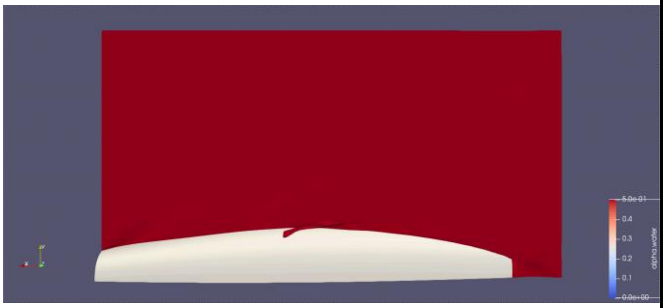


48. V3 Quarter Bell-mouth

Same concept as 45, 7 kn

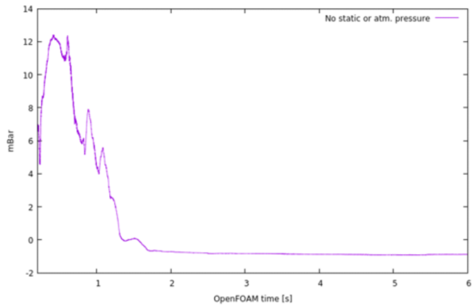


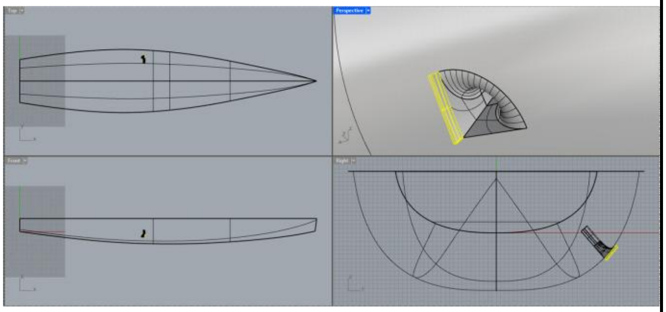


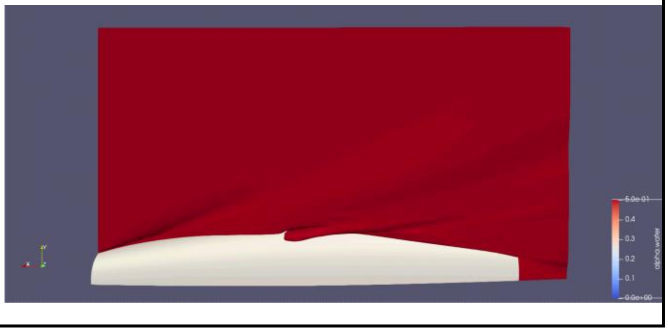


49. V3 Quarter Bell-mouth

Same concept as 45, 13 kn

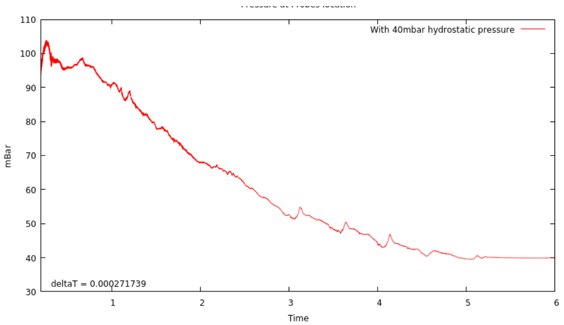


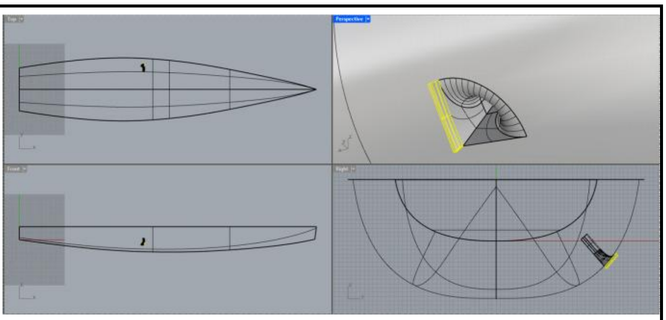


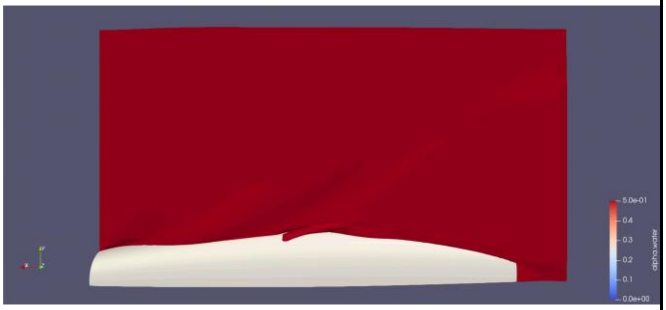


50. V3 Quarter Bell-mouth

Water surface moved up 3 dm, same interceptor and exhaust as 45, 8 kn.

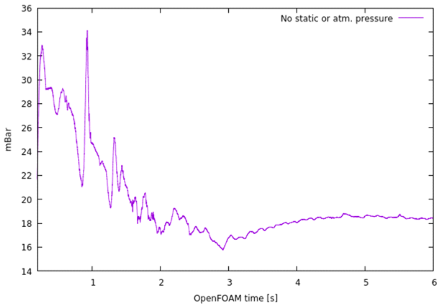


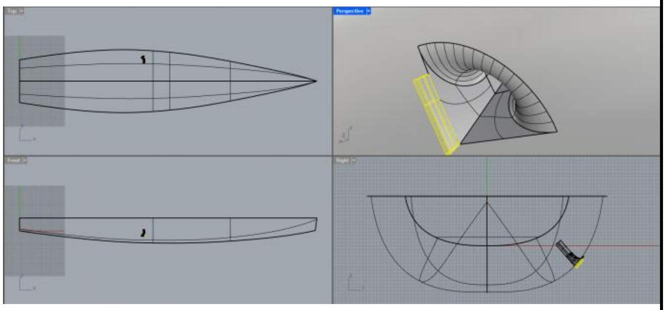


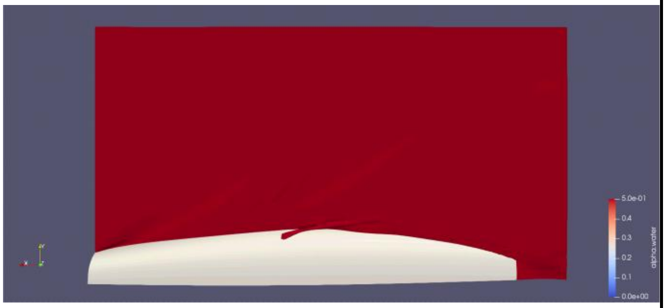


51. V3 Quarter Bell-mouth

Same as 45 but with a smaller interceptor of 300 mm. 8 kn.

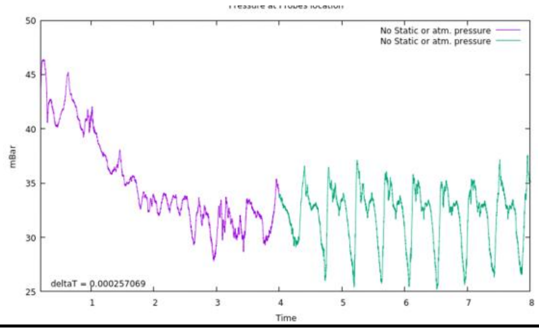


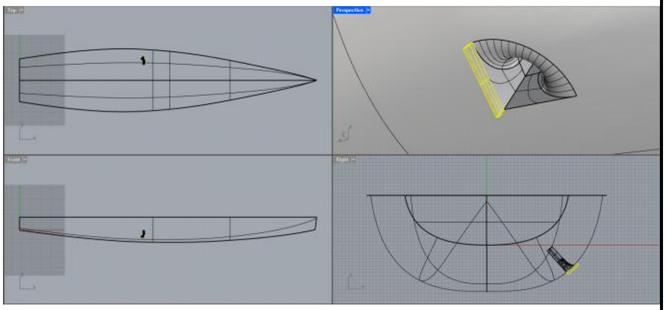




52. V3 Quarter Bell-mouth

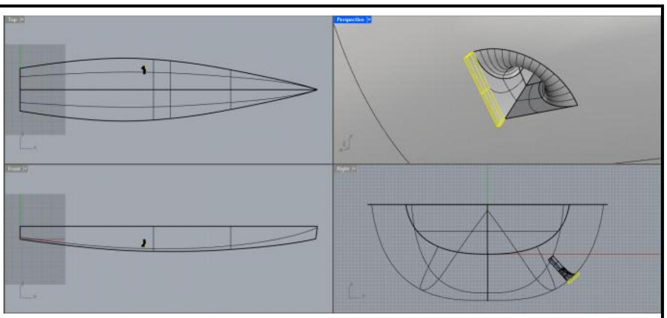
Similar to number 45 but with a lower position on the hull. 60 mm int height, 8 kn, no heel. Used to validate position.

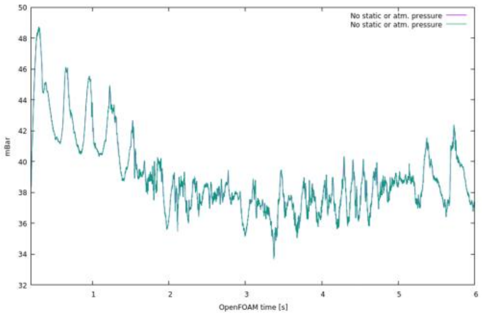




53. V3 Quarter Bell-mouth

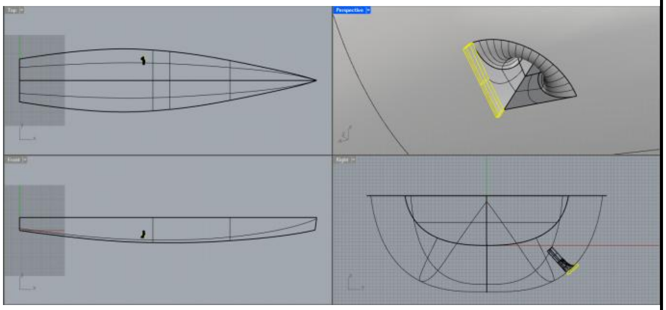
Same as 52 but 7 kn.

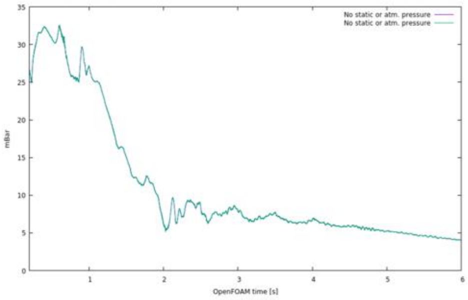




54. V3 Quarter Bell-mouth

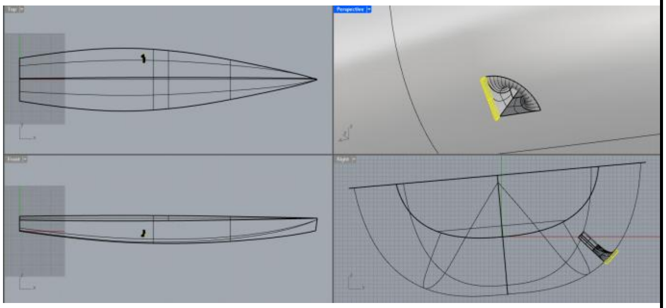
Same as 52 but 13 kn.

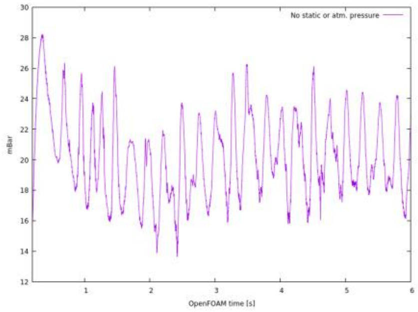




55. V3 Quarter Bell-mouth

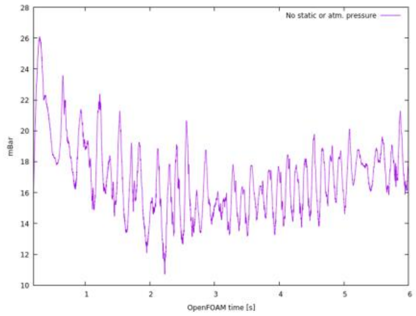
Same as 52 but 6 kn and negative 5 degree heel.

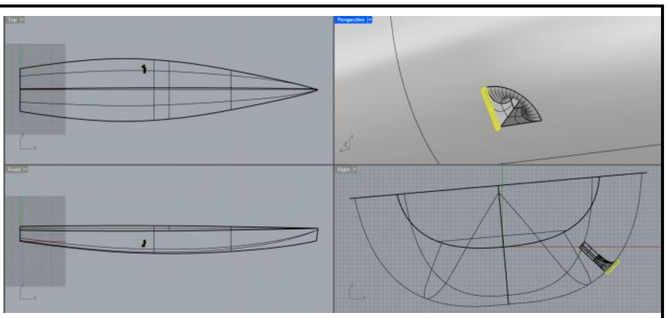




56. V3 Quarter Bell-mouth

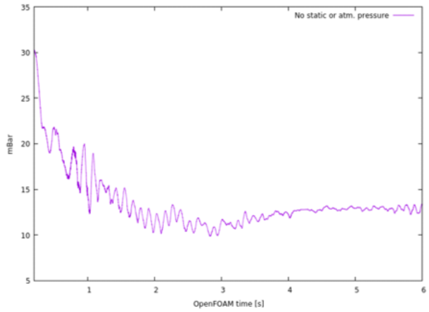
Same as 52 but 7 kn and negative 5 degree heel.

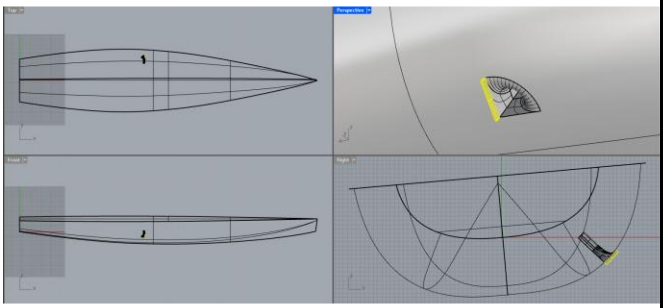




57. V3 Quarter Bell-mouth

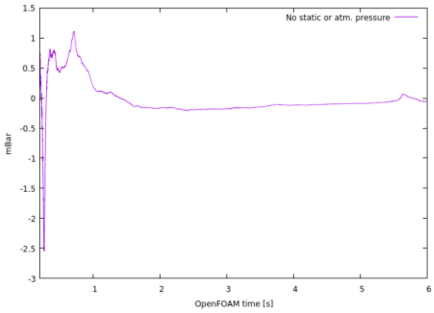
Same as 52 but 8 kn and negative 5 degree heel.

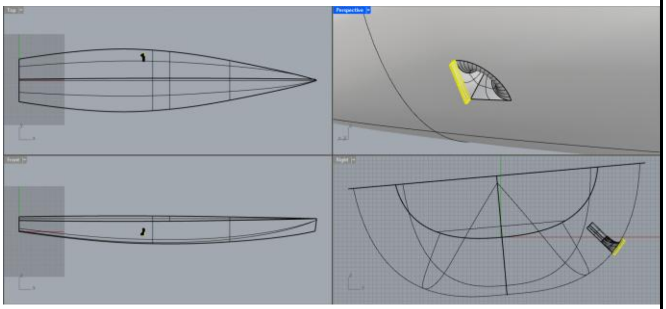




58. V3 Quarter Bell-mouth

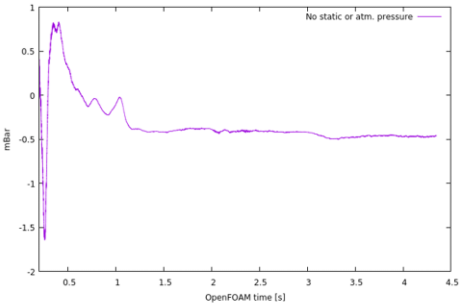
Same as 45 but 8 kn and negative 5 degree heel

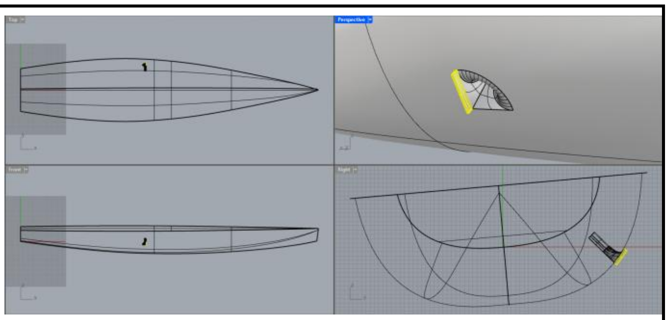


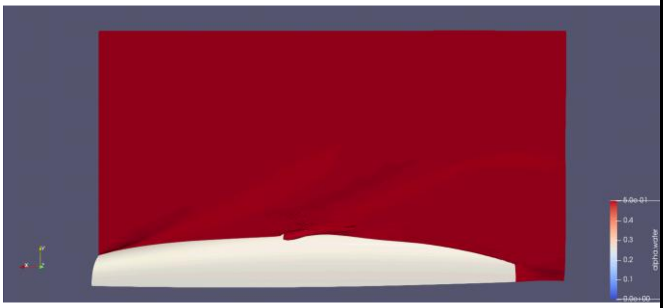


59. V3 Quarter Bell-mouth

Same as 45 but 10 kn and negative 5 degree heel

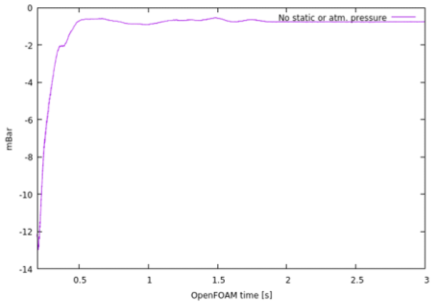


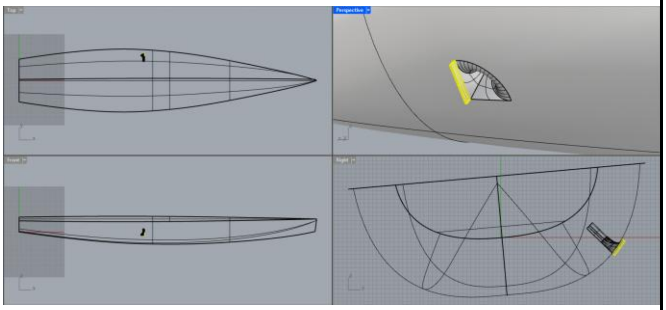




60. V3 Quarter Bell-mouth

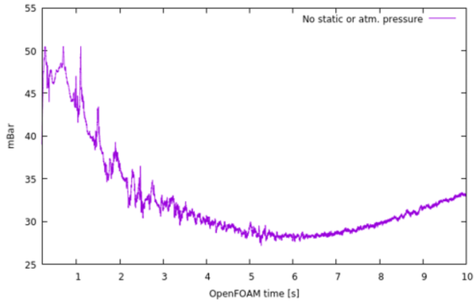
Same as 45 but 13 kn and negative 5 degree heel

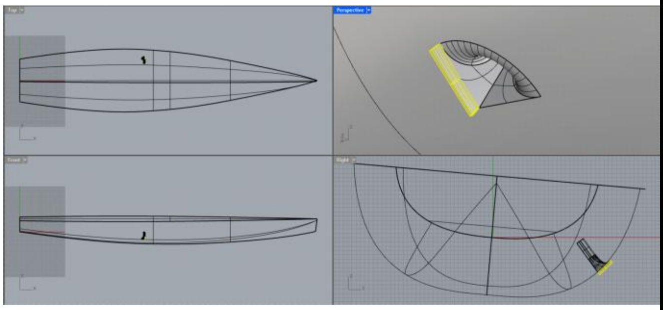




61. V3 Quarter Bell-mouth

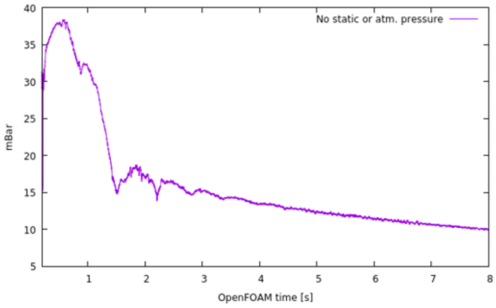
Same as 45 but 8 kn and positive 5 degree heel

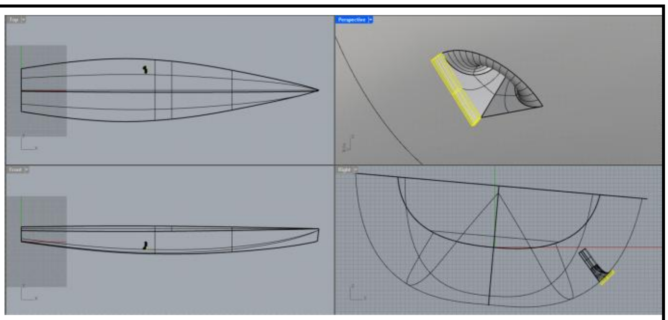




62. V3 Quarter Bell-mouth

Same as 45 but 13 kn and positive 5 degree heel





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