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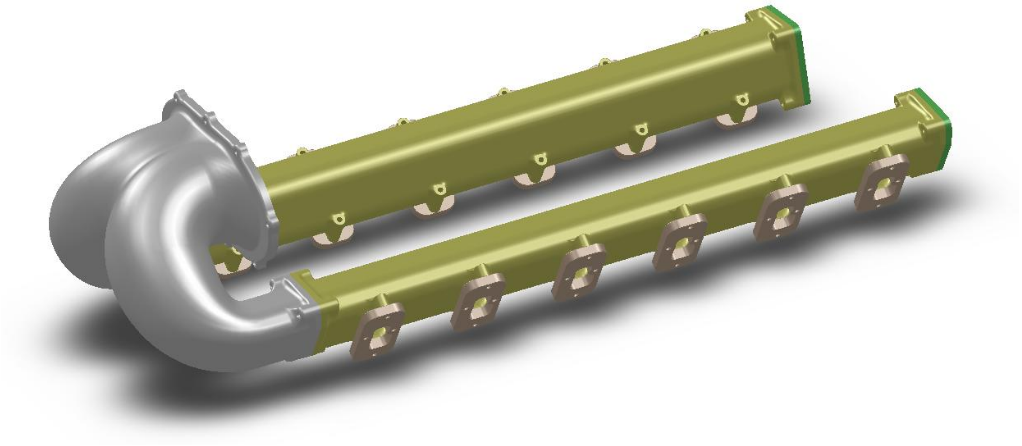

# Manifold design for a marine diesel air intake system

Master's thesis in the Master's program Product Development

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Master thesis 2011:44

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Cover:
The two intake manifold concepts designed in the Master thesis project are represented on the cover page of this report.

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# Abstract

The performance of the air intake system in a diesel engine could limit the overall engine performance. The intake manifold is an important part of the air intake system where enough air should be guided to the cylinder. Compactness is a conflicting feature to performance as engine rooms in general, and thereby engines, should use little space. Thus, the development of an air intake manifold requires knowledge about function and placement of most other parts in the engine so that a compatible and compact air intake manifold can be created.

MarineDiesel AB is a Swedish company from Ängelholm developing and manufacturing marine diesel engines. The Master thesis project work has been performed in a real project where an engine, previously used in a train, is converted into a marine engine with twice the power. The engine must be designed to fit with the new requirements of the customer. These requirements directly affect the air intake system which must, as all other engine system, match the desired performance.

A well-defined development process with theoretical and practical research together with company guidelines and engineering assessments has generated the concepts in this product development master thesis project.

Two different intake manifold concepts have been created. The concepts are different in aspect to both manifold design and air intake system configuration. The air intake system and the manifold are dependent and therefore a feasible system concept has also been developed to each of the concepts. The performance of the concepts has been verified through flow simulation and the development process has secured their feasibility.  The focus has been set on creating flexible feasible concepts that are possible to manufacture when adapted to future requirements. This creates the best possible prerequisites of implementation later in the project. In other words, the design limitations should be low in this stage of the project and thus the two final concepts are only conceptual and not ready for production. Worth mentioning is that the OEM manifold capabilities are deemed to be sufficient for implementation with both system concepts, replacing the manifold concept.

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# Preface

In this master thesis study an OEM air intake system used in a diesel engine has been evaluated through testing and simulation. In addition to this, a development process has been performed that resulted in two new intake manifold concepts. The new concepts have been evaluated in a similar way as the OEM intake system. The work has been performed at MarineDiesel AB located in Ängelholm, Sweden, where the master thesis study has been a part of a diesel engine marinization project. The project was performed for an external actor/customer and it should be noted that the project start unfortunately was delayed to such an extent that the study of the air intake system has been performed without direct input from other sub system studies that was supposed to be executed at the same time as the air intake system study.

The evaluation of the OEM intake system has been done with help of testing in a flow bench and simulation using SolidWorks flow simulation. The new concepts have been evaluated through simulations and with the help of rapid prototyping models.

This master thesis study has been performed with the guidance of project examiner, Associate Professor Sven Andersson at Chalmers department of Applied Mechanics, combustion division. Research and Development manager Christer Flodman at MarineDiesel AB has been supervising the project and has been contributing with expertise at all times. Their help have been highly valued throughout the project and our deepest appreciation goes to them. We would also like to thank the staff at MarineDiesel that has been highly knowledgeable and helpful during our time on site.

Göteborg, August 2011

Per Ahlm and Erik Froode

# 1 Introduction

This chapter will shortly summarize the project. The background and goals will be described as well as a quick summary of the final concepts designed. The introduction aims to give an overview and explain what the project results in, as well as why the project has been performed as a master thesis.

## 1.1 Project Background

MarineDiesel AB (further referred to as MarineDiesel) is a Swedish company located in Ängelholm that develops diesel engines for marine use. MarineDiesel has a product portfolio with a number of engines which they produce in Ängelholm and sells both in Sweden and on the Global market. The productions department works together with the engineering department and the total amount of employees are around 20. The engineering department, where this master thesis has been carried out, works with development of their own engines as well as development of engines for other companies to produce. The customers are usually boat manufacturers that need a customized engine for a certain boat.

An external actor has employed MarineDiesel to convert a diesel engine previously used in trains. The project involves extensive changes to the now 900 hp engine which should deliver 1800 hp after the project has been carried out at MarineDiesel. All engine systems and components must be tested and verified to meet the new requirements. If the OEM components fail to do so, new must be developed at the engineering department. The project aims to increase the performance, as well as adapting the engine to the marine conditions. The project involves the testing and development of a complete engine. This master thesis is limited to cover the air intake manifold which is part of a system, the air intake system, which is considered to be somewhat independent from the others.

## 1.2 Project problem and aim

The purpose of the master thesis project is both to evaluate the OEM intake manifold and to develop feasible intake manifold concepts that have good prerequisites to be implemented in the final engine design. Many uncertainties are involved in the project and the designs should thereby take these uncertainties into account and allow MarineDiesel to make changes to the chosen concepts easily. The design choices should be well explained, giving the concept credibility, and also guidelines for future development of intake manifolds. Broken down, the main objectives are:

- Describe the function of the air intake system in the engine and calculate required air flow.
- Evaluate and test the OEM intake system and thereby verify its capabilities.
- Develop new intake manifold concepts with increased performance.
- Test and evaluate the new concepts.
- Give recommendations regarding future air intake system configuration.

The purpose of the master thesis report is to describe the evaluation and development of intake manifolds for a turbocharged diesel engine.

## 1.3 Limitations

The project is limited to cover the development of intake manifold concepts to fit with an air intake system. No designs are final as decisions could not be final this early in the project. The concept will meet the overall requirements if produced, but details from customer, suppliers and from development of other systems are missing. Thus, to make one design that is ready for production would be waste according to MarineDiesel.

The project is of course limited by time. Two persons working 20 weeks, spent mostly at the MarineDiesel site in Ängelholm, hence approximately 1600 working hours in total.

Unfortunately the project start has been delayed and the master thesis project and the development of the air intake system have been performed in advance of the rest of the engine development project. The master thesis project has of this reason been limited and would have been more extensive and results more final if development and testing of other systems was running in parallel. For example no physical testing of OEM manifold or prototype concept was made, no laser scanning of vital parts did take place, and the uncertainties was big regarding size requirements and requirements from other engine systems.

## 1.4 Stakeholders

The master thesis project supervisor; R&D/engineering manager Christer Flodman at MarineDiesel, has been supervising the project to satisfying results. MarineDiesel has to respond to the customer in this engine development project, which could be seen as an indirect stakeholder. The project description has been approved by the Product Development division at Chalmers University of Technology. The master project and report has to be approved by the examiner; Associate Professor Sven Andersson.

## 1.5 Final concept summary

To conclude this introduction chapter the two final manifold concepts will be described shortly. Both concepts, with the working names Budget Viper and Rocket Sled, are visualized in Figure 1-1 and Figure 1-2. The two manifold concepts have similar performance, which is sufficient for the new requirements, but one big difference is that they are designed to fit different air intake system configurations. Worth mentioning is that the OEM manifold could be used to both air intake system concept as its performance is deemed to be sufficient.

Both concepts include twelve adapters that should be connected straight onto the cylinder heads. The adapters will make a change in the assembly hole pattern possible so that the design will be more flexible regarding location of fasteners. The manifold will then be assembled to the 12 adapters which imply that a manifold design could be finalized before the cylinder head port profile is set. The adapters have a simple design and could easily be re-designed. Both intake manifold concepts are symmetrical; hence the same manifold is used for the right and the left side of the v-engine.

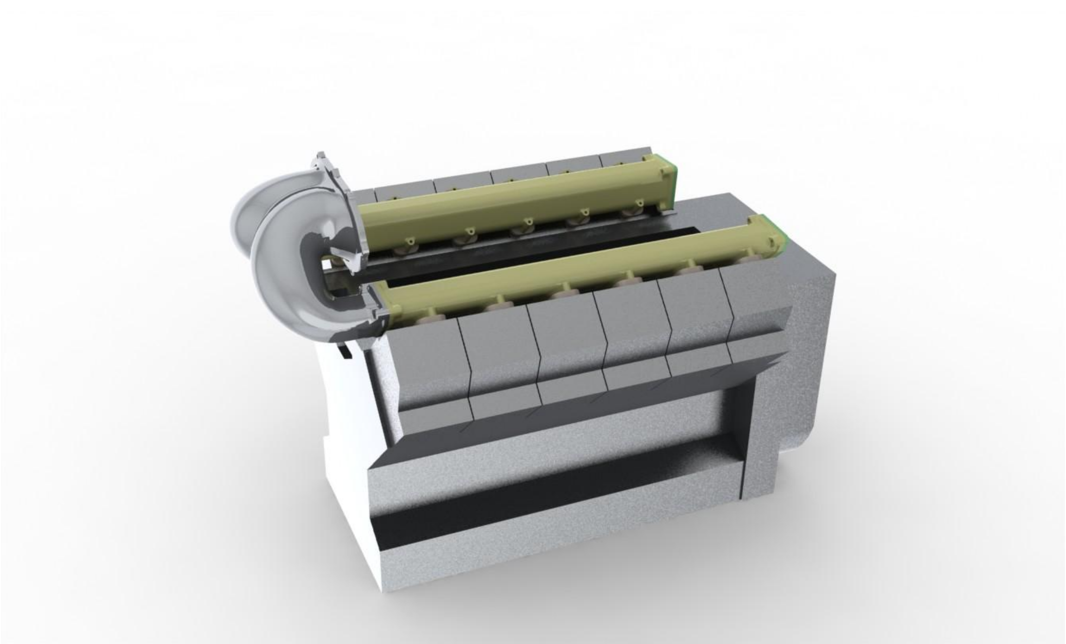


Figure 1-1 - Rocket Sled intake manifold concept

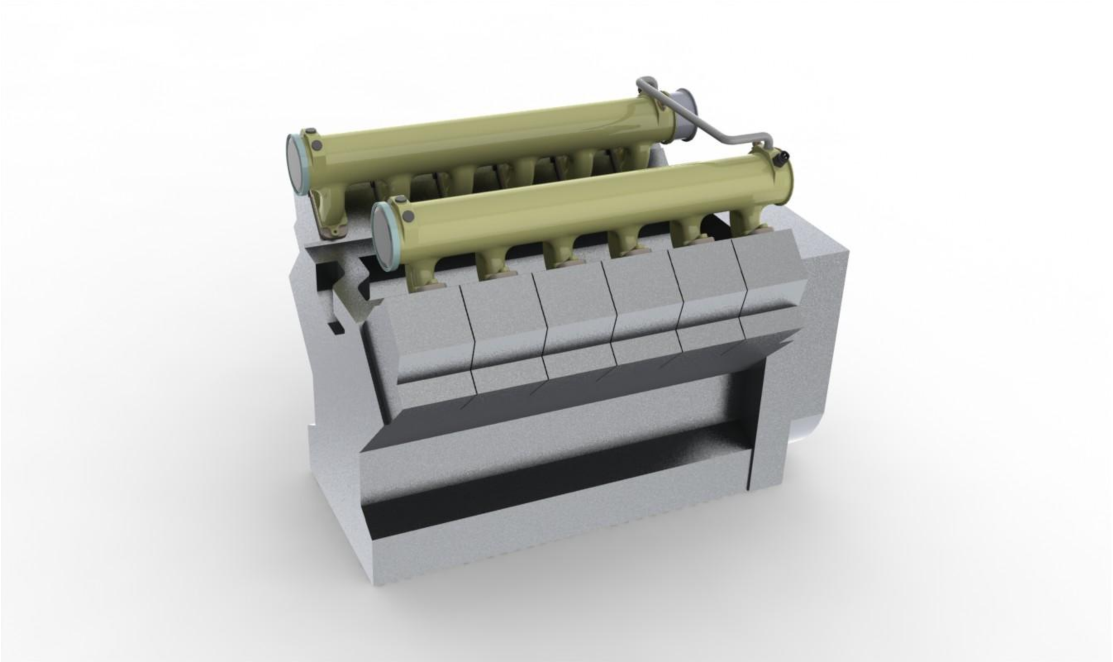


Figure 1-2 - Budget Viper intake manifold concept

The Budget Viper concept, see Figure 1-2, is built to include two separate intercoolers which could be placed with great flexibility to fit with future needs. The Rocket Sled concept, see Figure 1-1, has a connector that divides the intercooler outlet flow to the two compact manifolds, and is thereby dedicated for usage together with one intercooler on top. The two concepts are different so that MarineDiesel has more than one option to consider when a final concept should be implemented later in the project. In the pictures, both concepts are assembled to a rough packaging model of the engine. The concepts and their design are more thoroughly described in Chapter 9, Detailed Design of Chosen Concepts.

# 2 Theory

This chapter is the theoretical introduction to this master thesis. The theory mentioned is related to the project and its implementation. The information in this chapter is however basic and general since the master thesis outcome is not only based on available theory, but a combination of theory, engineering assessments and other company related factors. The theory have however guided decisions made in the project and will help the readers of this thesis to better understand the design choices made and to put the project into context.

## 2.1 The Diesel Engine

The diesel engine is also called compression ignition engine since the fuel auto-ignites when compressed in the combustion chamber (Ferguson & Kirkpatrick, 2001). In all internal combustion engines, the mechanical work performed by the engine comes from the release of chemically bound energy inside the engine, which in a diesel engine is a combustion process in the cylinder. The combustion particularities depend on the engine configuration, and the engine configuration is dependent on which application the engine is intended to be part of. Finally, all systems in the engine contribute to the overall engine performance.

### 2.1.1 Combustion processes and the engine cycle

The goal of the combustion process is to transform the chemical energy bound in the fuel into useful mechanical power. The chemical energy is firstly transformed into thermal energy as the fuel ignites. (Bergström, 1987). The combustions gases drive the piston down and the gases are removed as the expansion ends. The gases contains a lot of heat, hence a lot of the energy bound in the fuel leaves as heat in the exhaust gases instead of useful boundary work transformed into kinetic energy. The useful energy drives the engine and the supporting systems, but a lot of energy produced are lost as waste in friction and heat losses. There is thereby a big difference between the theoretical work and the useful work developed in the cylinder.

There are two major engine cycles; Otto and Diesel cycle with either two strokes (one revolution) or four strokes (two revolutions) per cycle. The engine involved in this project is a four-stroke diesel engine. In the four stroke diesel cycle the engine fills up with air during the inlet stroke (1), compresses the air to above auto-ignition temperature for diesel during the compression stroke (2), the fuel injected during the latter compression stroke and initial ignition stroke (3), ignites and combustion follows, and finally the exhaust stroke (4) pushes the burned gases out from the cylinder. The camshaft controls the opening and closing of the valves. It rotates with half the speed of the crankshaft in a four stroke engine as both the intake and exhaust valves should open and close once every second revolution. No spark plug is needed since the diesel engine fuel, as mentioned, auto-ignites (Ferguson & Kirkpatrick, 2001).

### 2.1.2 The Engine Configuration and performance

The piston-cylinder geometry (V, W, In Line, radial etc.), the fuel delivery system, the valve geometry, the usage of super or turbocharger and the type of cooling system are all part of the engine configuration and determines its performance. The requirements for the engines future application could thereby create different engine configurations.

The engines brake power is the rate at which work is done. The engine brake power is given by multiplying the engine torque, which is the work done per unit rotation, with the engine speed. The same brake power thereby is achieved with different combinations of torque and speed.  For example, giving the same brake power, a diesel engine has a lower engine speed and higher torque than a gasoline engine. The explanation to this is that diesel engines operate at a higher cylinder pressure due to the need of compressing the air to above auto ignition temperature. The stroke must thereby be longer (assuming the same bore area) which implies a larger diameter crankshaft. A larger diameter crankshaft has a longer lever arm and higher torque is achieved. More cylinder pressure generates more torque (Fleming, 2000).

The diesel cycle engine is required to operate at a higher compression ratio (maximum cylinder volume divided by the minimum cylinder volume) than the Otto cycle engine; hence a heavier construction of the engine block is needed. The displacement volume for the cylinder is the difference between the maximum and minimum volume of one cylinder, in other words the stroke length multiplied with the bore area. The engine displacement volume is the displacement volume of one cylinder multiplied with the number of cylinders.

The power delivered by the engine is controlled by the amount of fuel injected into the combustion chamber. In the Otto cycle engine, or the spark injection engine, a throttle is used so that the right air/fuel mixture is injected, hence controlling the power. In a diesel engine no throttle is needed, only fuel control. One factor to improve performance is to improve the mix of the fuel and air in the combustions chamber, in other words influencing the injection of both air and fuel so that ultimately a uniform mix is obtained.  The combustion chamber should be designed to improve the fluid motion in the cylinder to achieve more uniform mix of air and fuel.

In order to create prerequisites for complete combustion of the diesel fuel more air than the theoretical stoichiometric amount is needed. A sensor can measure the exhaust gas oxygen concentration, which in general is used to control the air-fuel ratio. For diesel engines this value could be high, as for Otto engines the value must be around 1% of the stoichiometric (Ferguson & Kirkpatrick, 2001). As mentioned, Otto engines require a throttle to regulate the flow of inlet air.

The volumetric efficiency rates the effectiveness of the air induction process from the manifold to the cylinder and is another performance parameter. A well designed manifold and valve raises the volumetric efficiency, which implies that more air could reach the cylinder during the inlet stroke (or the turbo charge pressure could be lowered still giving sufficient air flow). The periodic valve motions create pressure waves that propagate through the air flow. A manifold could be sized or “tuned” to optimize the volumetric efficiency at a chosen engine speed so that the pressure waves give extra charge during the intake stroke.

## 2.2 Flow theory

Fluid mechanics is the study of fluids and how forces are affecting their state and motion. A fluid is a substance that is continually deformed when put under shear stress. Liquids, gases and plasmas are such substances. Compressible flow theory concerns fluid that experiences a change in density as pressure is changed, e.g. air. The static pressure multiplied with the section area equals the force working on the fluid (The Venturi effect is well known in fluid mechanics and shows that there is a reduction in fluid pressure and an increase in fluid velocity, as the fluid passes through a tapered geometry).The fluid flows toward a lower pressure, thus a lower working force. The Law of mass conservation states that the mass flow that enters a system must be equal to the mass flow that leaves the system.

A compressible flow of air can get choked, which means that there is a mass flow limit when a decrease in downstream pressure does not implicate an increase in mass flow. This occurs when the flow velocity is sonic at the end of a pipe. In compressible flow, as pressure is varied, the density of the gas varies and the mass flow thereby increases. The speed of sound does not change with pressure, but increases with increased temperature. If assuming adiabatic flow conditions for compressible flow occurs without heat transfer, thus the total energy in the system remains constant throughout the system (pressure losses are converted into internal energy) (Miller, 1990).

### 2.2.1 Engine air flow

The most significant airflow restriction in an internal combustion engine is the flow through the intake and exhaust valves (Ferguson & Kirkpatrick, 2001). The air intake system should provide good prerequisites for the engine air intake sequence, hence cater for flow restrictions and losses. If learning about flow, flow restrictions and losses early, the design of the air intake system could be done better from the start. All components and features in the engine air system must hence be able to cope with the amount of air that is needed in the combustion process.

The engine involved in this project is a turbocharged Diesel engine. Few losses in the air intake system implicates that the charge provided by the turbo is closer to the one delivered to the intake manifold. The cylinders require a certain mass flow during the intake sequence, hence a certain air pressure to push at least the needed amount through the valves to the cylinders. If there are few losses, the turbo does not need to be oversized to provide the right charge pressure. The total pressure loss (between two points related to a common datum) should thereby be as low as possible.

The pressure pattern during the external gas exchange in a combustion engine consists of steady flow caused by normal pressure drop, and unsteady flow from pressure waves. Pressure waves are initiated when a valve opens and is affected by the pressure difference and frequency, thus engine speed and load. Waves reflect when there is a change in geometry and temperature. The pressure waves could in fact be an advantage as they can boost the air flow through promoting mass transfer through the engine. One should design inlet pipes and plenum so that the gas exchange process benefits at high speeds (Zander, 2007). This extra pressure could however be provided by an air compression device, like a turbo or a screw compressor. The plenum volume should be a function of engine displacement, in general 50-70% (Bell, 1997).

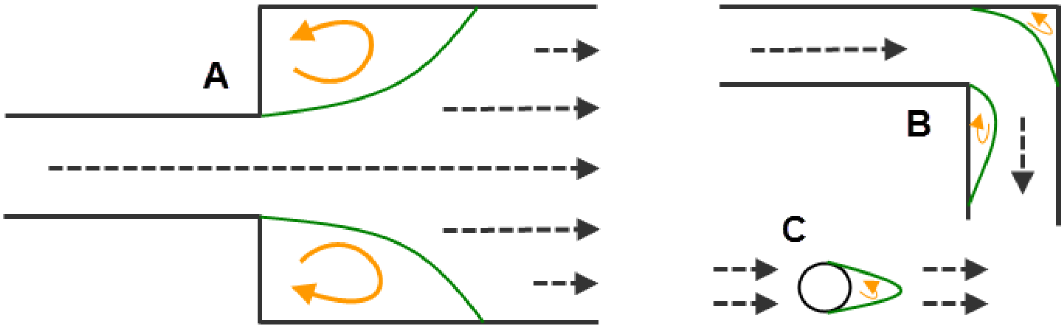


Figure 2-1 - Examples of flow separation (Miller. 1990)

### 2.2.2 Internal flow systems

Internal flow is concerned with fluids flowing in pipes, passages, ducts, conduits, culverts, tunnels and components such as bends, diffusers and heat exchangers (Miller, 1990). The overall pressure loss is the sum of all independent pressure losses from different components. Wall friction also contributes to the total loss through turbulent dissipation of energy. The dissipation is high when the turbulence is great, e.g. in regions close to boundaries and along the edges of discontinuities in velocity associated with wakes and flow separation. Intense turbulence arises in regions where velocity pressure is converted into static pressure. Pressure losses with turbulent flows are approximately proportional to velocity squared. The effect of turbulence is to even out the energy distribution and to induce flow re-attachment (Miller, 1990).

Low loss components involve no, or small, areas of separation (Miller, 1990). Separation occurs when the flow experiences a change in flow geometry and the low energy near-wall part of the flow is brought to rest (having only static pressure), and the flow is said to have separated. This could be avoided through long bend radii instead of sharp corners for converging, diverging, turning, as well as for divided and combined flow. Vanes could be added to the flow stream to guide the flow and improve the outlet flow profile from a component (Miller, 1990). Some examples of geometries that create separation could be seen in Figure 2-1.

The pressure and speed distribution of the flow is continually changed as the flow passes different components and features. Pressure is lost when the flow needs to be re-distributed and turbulence arises when the flow passes orifices, steps and cavities. In the intake manifold, the plenum to runner intersection must be carefully made so that the flow loss for the runner is small. One way to achieve this is to have a long bend radius towards the incoming flow. This provides more a more uniform pressure distribution over the manifold (Miller, 1990).

Turbo engines usually benefit from having long runners which provide long flat torque curves at low speeds, while the turbo keeps the top end strong. Symmetry of design is a desirable characteristic as it facilitates equal distribution of air flow to each cylinder, such as symmetry in runner lengths and uniform port shapes (Bell, 1997). In a manifold, the cross-sectional shape is usually not an important parameter, as regards pressure losses, more important are the junction edge geometry where chamfers and radiuses significantly lower losses (Miller, 1990).

The internal geometry wall exerts a frictional force on the flow which magnitude depends on the Reynolds number, the relative wall roughness and the cross-sectional shape (Reynolds number depends on the mean flow velocity, the hydraulic diameter of the pipe and the kinematic viscosity of the fluid). The turbulent (low energy fluid) boundary layer by the wall spreads over the cross-section as the fluid flows downstream (Miller, 1990). From a design perspective the air intake system should have low relative wall roughness and be compact, and the flow velocity should be low, to make the friction loss low.

Drag is the force which resists the motion of an object through a fluid. In the contrary; the flow of a fluid is restricted by objects that interfere with the flow. The objects/features put in a flow should therefore have geometry for minimal drag (e.g. Airfoil) to minimize drag and turbulence. There are turbulent flow losses in bends and friction in straight pipe sections, and there are laminar flow losses in heat exchangers and charge coolers (Zander, 2007).

## 2.3 How to get more engine power

There is mainly one way to drastically increase the power of an engine without altering cylinder volume or stroke length and that is simply to push more fuel in to the cylinders. When pushing more fuel into the cylinder the combustion process will however also requires more air. To be able to do this the air, as well as the fuel, needs to be highly pressurized when entering the cylinders and hence the need of turbochargers and advanced fuel pumps. This basically means that a lot more air and fuel is jammed in to the cylinders which bring more power out of each stroke. When this is done one must also make sure that the other engine systems are up for the new requirements. As an example the different cooling systems of the engine usually needs to be tuned up or replaced by more powerful coolers to be able to handle the extra heat created when bringing more power out of the engine.

There are also other ways to increase the engine power. One way is to increases engine speed (Bell, 1997). Tuning in different kinds of ways and making sub systems more effective is also ways of gaining engine power. It should also be mentioned that when drastically increasing the power of an engine it will also experience a drastic increase in stresses and hence brake down a lot more easily if not properly dimensioned. A lot of work if therefore done to make sure that the engine can withstand the new engine requirements, and if not how to alter the engine to make sure it does.

Considering the air intake system, when increasing engine power the main focus is to make sure that the intake system can deliver sufficient amount of air at a high pressure. The increase in air flow and pressure is usually quite high and to build an efficient engine one should make sure that a bottle neck does not occur in the air intake system.

## 2.4 Marine engine particularities

Marine diesel engines are often truck diesel engines converted to marine use. When converting the engine a few things are changed to better fit the new conditions.

The access to an endless supply of cooling water makes seawater cooled intercoolers very effective (MacInnes, 1984). Other heat exchangers such as oil coolers are also easily cooled with sea water. Marine diesel engines also tend to be a lot more powerful than truck engines about the same size. The extra output of power shortens the life of the engine, something that however is not deemed a problem due to that marine engines runs fewer hours than truck engines do.

Another particularity concerning marine engines is that the engine could be accelerated to near maximum speed long before the boat reaches maximum speed (MacInnes, 1984). In other words, the hull could be relatively still even though the engine is running in full speed during the initial part of acceleration. This fact could for example be used to optimize the turbocharger to the hull requirements.

Concerning the air intake system no particular changes due the marine conversion are directly needed. The extra output of power does however mean that the engine will require a lot more air than earlier. This means that the OEM air intake system must be evaluated and perhaps altered to meet the new requirements.

# 3 Functional Description of the Air Intake System

This chapter aims to theoretical describe the air intake system. To really understand the function and particularities of the intake manifold, knowledge about the air intake system is needed. As mentioned in Chapter 2.1 the combustion process needs oxygen. The air intake system should be designed so that an excessive amount of clean and cool air reaches the combustion space. This chapter describes theoretically how this could be achieved. The flowchart below, Figure 3-1, visualizes the functional description of the engine air system.

## 3.1 Air filter

The air filter should prevent unwanted objects to get in to the engine and cause various problems. Due to the flow restrictions in the air filter it increases the pressure ratio over the turbo which gives the same boost but to the cost of a higher working temperature. A low restriction intake system will be rewarded with more power and less heat (Bell, 1997). An engine consumes large amounts of air; therefore the choice of air filter must be based on both the engines air consumption as well as the pressure drop over the filter. An air filter can be seen in Figure 3-2.

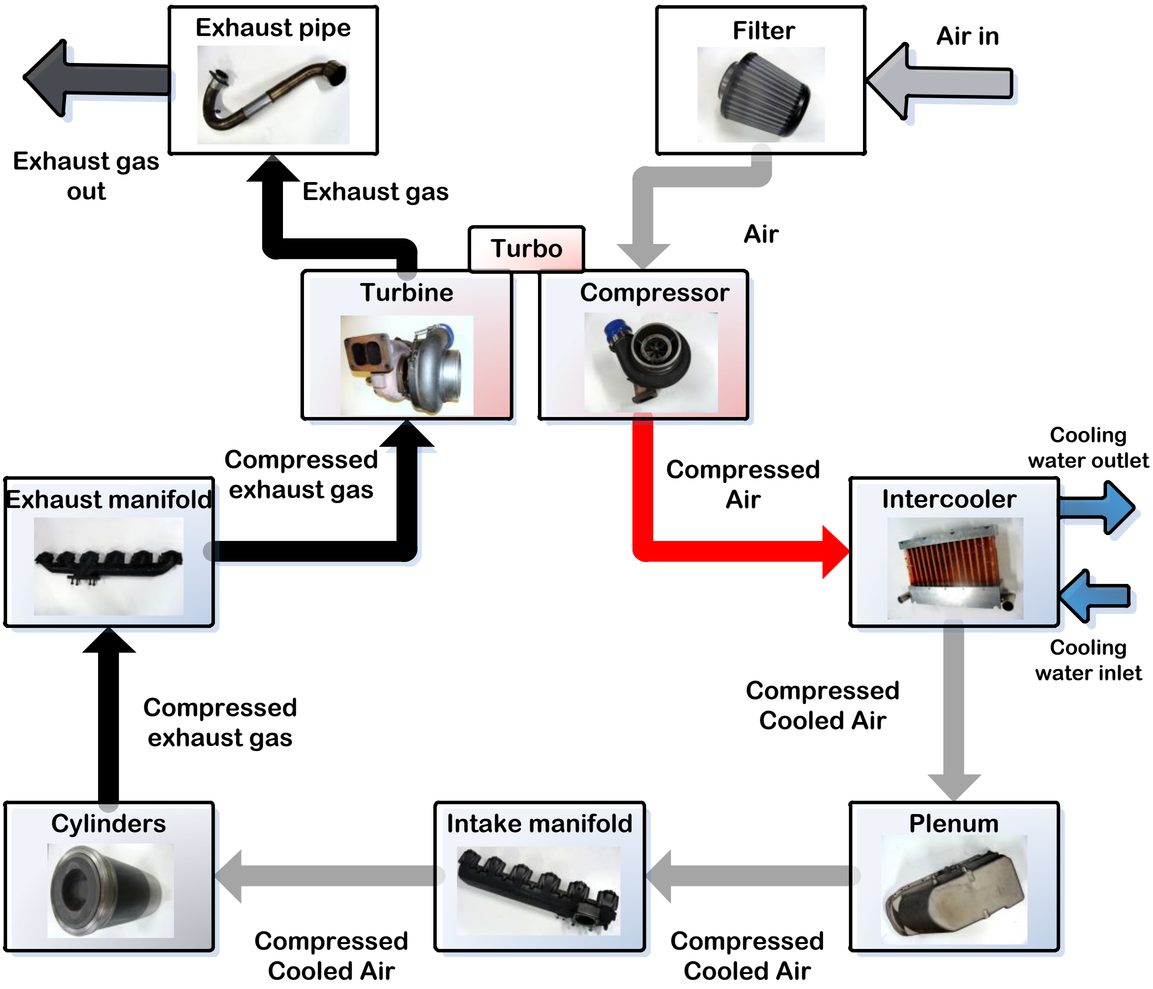


Figure 3-1 – Schematic flow chart of the intake system

Figure 3-2 - Air filter

## 3.2 Turbo

The exhaust gases carry approximately one third of the energy released in the combustion process (Bell, 1997). This energy could be used to power a compressor situated in the air intake system to push more oxygen into the engine. The turbocharger consists of a turbine that is driven by the exhaust gases from the engine, a compressor driven by the turbine, and a plain bearing for the connecting shaft.

The type of application determines what turbo to use and this is mostly dependent on the sizes of the compressor and turbine. The main objective when choosing compressor size is where on the revolution range one should place maximum efficiency. Several factors are to consider when doing this; pressure ratio (how much percentage air pressure the turbo can provide), density ratio (density of the air charge), airflow rate (volume over time) as well as compressor efficiency (depends on the increase in air temperature due to compression). The A/R-ratio is important when choosing turbine size and is a constant factor that describes the relationship between the cross sectional area and the radius of the turbine inlet. This ratio controls the air flow on the turbine hence the rotational speed of the turbine blades and the magnitude of the back pressure.

Two factors influencing the driveability when designing/choosing turbo charger are boost threshold and lag. Boost threshold is the lowest engine speed where the turbo will produce boost. The engine torque curve takes an upward swing at the boost threshold when having full throttle. The lag is the delay between throttling and receiving boost pressure due to rotational inertia in the turbine. The lag decreases as the engine speed increases. Once again, the vehicle application is important in turbochargers selection. Increasing the speed of the turbocharger increases the pressure ratio, not the flow (MacInnes, 1984).

Back pressure occurring from restricted flow of the exhaust gases through the turbine, creates small power losses. The back pressure brakes the engine and raises temperature in the exhaust manifold and turbo. The back pressure could be reduced through the use of a waste-gate or/and the use of a bigger turbo. The waste-gate wastes or by-passes a portion of the exhaust energy, hence controlling the turbine speed and thereby the boost. The variable area turbine nozzle turbocharger (VATN) can change the area of the turbine inlet over time hence control turbine speed and boost through varying the A/R-ratio. The VATN controller is the secret to the extreme benefit of the VATN concept (Bell, 1997).

Figure 3-3 - Turbocharger

Sometimes a twin turbo is suitable for the chosen application and the configuration could either be sequential or double. In the sequential turbo configuration the bigger turbo charges the smaller as the bigger turbo has lower back pressure and could provide enough charge for the smaller. An intermediate intercooler could also be installed if needed. The double turbo setup is more common in v-engines where the symmetrical layout could support one turbo on each side. The heat from the exhaust gases is also divided between the two and sometimes two smaller turbo is easier to fit than one big (MacInnes, 1984).Two turbo implies more power, but many factors are in fact involved to make the twin turbo configuration more powerful than one (Bell, 1997).

Several more design issues are important to consider when choosing/designing a turbo than those that effects placement of the maximum efficiency on the revolution range. For example choice of material, if the bearing should be water cooled (to extend turbo life), and the connections to the turbo need to cater for vast temperature fluctuations. A turbo (compressor side) can be seen in Figure 3-3.

## 3.3 Plenum

A plenum chamber is simply a pressurized housing that acts as a reservoir of air for the engine. The plenum chamber typically offers two quite clear benefits to the intake system. Firstly it makes the system more resistant towards pressure drops, i.e. the distribution of air over time is evened out. Secondly it makes the system less dependent of the path that the air flows, i.e. it evens out the distribution of air over space and hence evens out the distribution of air to the cylinders.

The plenum chamber is usually integrated in the intake manifold or placed in direct connection to the intake manifold but can also be integrated in intercooler. When dimensioning the plenum one should consider the air volume needed by the engine (Bell, 1997), the required pressure as well as the flow of air to the intake manifold. In turbo charged engines the plenum have less importance when considering the air distribution over time but more importance when considering the distribution of air over space.

## 3.4 Intercooler

When the turbocharger increases the pressure of the air in the intake the air will not only get more compressed but also hotter because of thermodynamic reasons. The more you increase the pressure the higher the temperature gets.

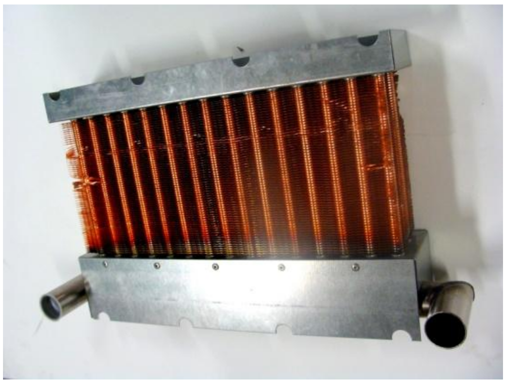


Figure 3-4 – Intercooler core

The intercooler is located after the turbocharger and has as sole purpose, to cool the air from the turbocharger before it reaches the cylinders. This is done because of three main reasons. Firstly and most importantly because cool air is denser then hot and hence carries more oxygen. More oxygen in the cylinders means that you can use more fuel which subsequently means increased power from the engine (Bell, 1997). Secondly a lower and more controlled temperature in the combustion process gives a steadier and more easily controllable combustions process. Third and last, the cooler the air is when entering the cylinder the cooler it will also be when leaving it as exhaust gases. The turbo turbine will then receive cooler exhaust gases and thereby the turbo will have a lower working temperature. There are also regulations regarding engine surface temperatures which will be easier to keep at a low level with an intercooler.

There are a number of factors that should be considered when choosing an intercooler. The main criterion is simply that it has to be able to cool the air the engine needs sufficiently. The single most important design feature of the intercooler is that it has to be able to do this without causing too much pressure loss (Bell, 1997). These two objectives, heat transfer and pressure loss, are somewhat contradictory since the more time it takes for the air to travel through the intercooler the more heat it will give up. The overall efficiency of the engine is however deemed to be much better with an intercooler since the increased performance due to the cooled air highly exceeds the loss due obstructed flows.

As mentioned in Chapter 2.4, Marine engine particularities, there is a great advantage using intercoolers in marine engines. This is due to the fact that you have unlimited access to cooling water. The intercooler can therefore be both compact and efficient in marine engines. An intercooler core can be seen in Figure 3-4.

## 3.5 Intake manifold

The intake manifold guides the air to the cylinder head. The general construction is that a plenum is followed by intake runners (pipes) which go to the valves. The manifold could look very different in different engines but the common function is that it should evenly distribute the intake air to the cylinders (Bell, 1997).

The construction must pay attention to some basics in fluid mechanics so that the manifold restricts the flow as little as possible. For example does smooth and uniform shapes benefit to the flow. The plenum, intercooler and manifold together should be designed to maintain the charge given by the turbo, in other words be designed for as little pressure drop as possible from the compressor to the cylinder so that air pressure is preserved.

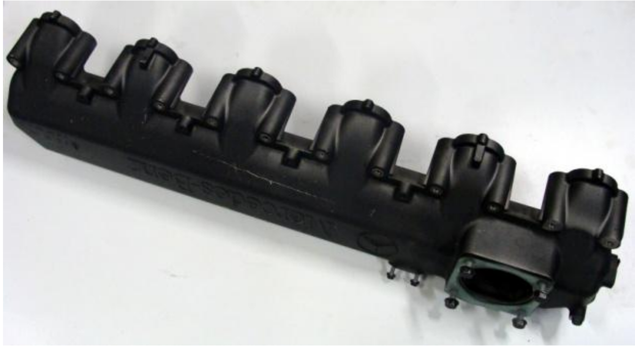


Figure 3-5 - Intake manifold

Furthermore does symmetry benefit to the need for equivalent flow. Runner length should also be considered in construction as long runners lower the volumetric efficiency. As the intake air should remain cool after the intercooler, the manifold should also take heat insulation into account. Figure 3-5 shows an intake manifold.

## 3.6 Valve to cylinder

The valves are situated at the cylinder head and have two main purposes; to control the air intake from the manifold to the cylinder and pass out exhaust gases from the cylinder to the exhaust manifold. It is common to have two valves at the intake side and two valves at the exhaust side, i.e. four valves per cylinder. It does however vary depending on the needed airflow. It is more likely to have a bigger airflow if you have more valves. It is beneficial if the air enters the combustions space with high speed as the following chamber filling and turbulence yields better combustion (Bell, 1997).

When choosing valves one should consider the thermal and mechanical stresses that affect the valves when they are in closed position. The valves must be able to withstand this stress, which can be quite extreme, without deformation or wear. It's also important to consider the speed at which the valves need to open, the lift of the valve as well as at what speed the valve can shut without springing back or being damaged (Bergström, 1987). A part of the valve can be seen in Figure 3-6.

## 3.7 Sensors

Sensors are needed both to evaluate the system during construction and when running the engine/intake system in the actual application. Following sensors are needed to test the system (Bell, 1997):

- A mass flow meter between the air filter and turbo to test the air flow in.
- A pressure gauge after the air filter should be used to investigate the pressure drop over the air filter.
- The compressor inlet temperature and the temperature raise over the turbo are important numbers to produce; hence one temperature sensor is needed on each side of the compressor. The compressor inlet temperature is not the same as the
- Ambient temperature (the temperature and pressure is ambient before the air filter).
- To find the true pressure boost given by the turbo a pressure gauge should be installed at the turbo outlet.
- Temperature and pressure is essential to know after the intercooler as these are the conditions the engine has to work with. Calculations can be made for pressure drop over the intercooler as well as its efficiency.

Figure 3-6 - Valve

When running the system in the application, information regarding the specific components is available and taken into account during construction. Information is needed to monitor and control the operations. The engine control needs the inlet pressure and temperature as two of the inputs to control the fuel injection. These sensors are often situated near the intake manifold inlet. In Table 3.1 the complete list of sensors in the air intake system can be found.

Table 3.1 - Sensors in the air intake system

| Sensor type | Placement | Measures |
|---|---|---|
| **Mass flow meter** | Between air filter and turbo | Mass flow in |
| **Pressure gauge** | Between air filter and turbo | Pressure drop over air filter |
| **Temperature sensor** | Between air filter and turbo | Air inlet temperature |
| | | |
| **Pressure gauge** | Between turbo and intercooler | True pressure boost |
| **Temperature sensor** | Between turbo and intercooler | Turbo temperature increase |
| | | |
| **Pressure gauge** | Between intercooler and manifold | Pressure drop over intercooler, engine working conditions |
| **Temperature sensor** | Between intercooler and manifold | Intercooler efficiency, engine working conditions |

# 4 Method

Using literature concerning product development processes (Ulrich & Eppinger, 2008) as well as the development process used at MarineDiesel, a specific method for this project was created early in the project. This chapter aims at describing this method and motivate why it is used. A flow chart describing the process can be seen in Figure 4-1. The main phases are posted within the arrows and the activities are placed next to the corresponding phase. The Manufacture Prototype phase was never executed because it was deemed to be too early in the project.

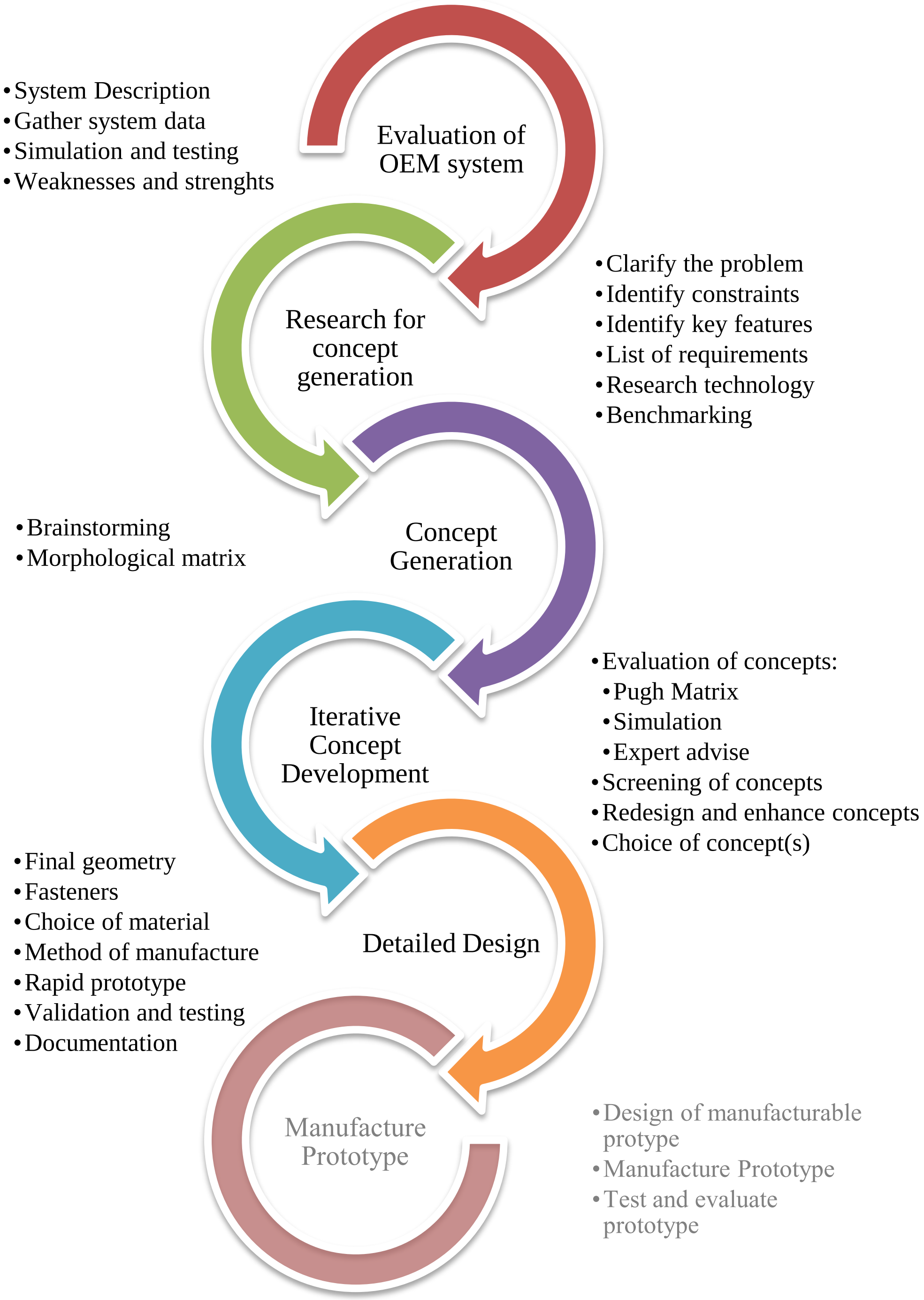


**Figure 4-1 - Flow chart of the development method**

## 4.1 Evaluation of OEM intake manifold

This part of the method describes the process of how the OEM intake manifold has been evaluated through simulations and testing. The OEM engine is developed and manufactured by MAN.

### 4.1.1 System data and calculations

In order to perform the simulations on the OEM manifold as well as the new concepts a lot of engine data had to be found and calculated. This was mainly done through research and using standard diesel engine calculations to obtain the data needed. The data sought was the needed mass flow of air to use for evaluation through simulation. More about this can be found in Chapter 5, Calculations of Required Flow.

### 4.1.2 Flow simulation

The simulations were absolutely essential in the evaluation of the OEM intake manifold as well as of the concepts. The main goal of the simulations was to investigate if the intake would be able to perform sufficiently in the new engine conditions.

In order to simulate the flow in the OEM intake manifold a reference CAD model was created. CAD models were also used for evaluation of the new concepts. Three different simulations were then performed in order to verify the performance of the OEM intake manifold as well as the new concepts. The results were then compared and each concept evaluated individually.

In addition to the numeric results from the simulations geometric evaluation was also possible to do using flow trajectories which were calculated by the flow simulation tool in SolidWorks. These also played an essential part when evaluating the OEM intake manifold as well as the concepts.

#### *4.1.2.1 Standard flow simulation*

This simulation is done using SolidWorks Flow Simulation. To be able compare and verify the results standard conditions has to be used. The specific conditions are listed below:

- 25 inch water pressure difference between intake and outlet (atmospheric pressure ≈ 407 inch Water ≈ 1,013 bar)
- Air at 20 degrees Celsius (indoor)
- 100 micrometer wall roughness
- Adiabatic manifold walls

Using a 25 inch water pressure difference at 20 degrees Celsius is standard in this case, which also allows comparison of results to other similar MarineDiesel projects. The simulation is setup so that the pressure is static in both ends of the intake manifold as can be seen in Figure 4-2. The volume flow rate is then measured for each port individually.

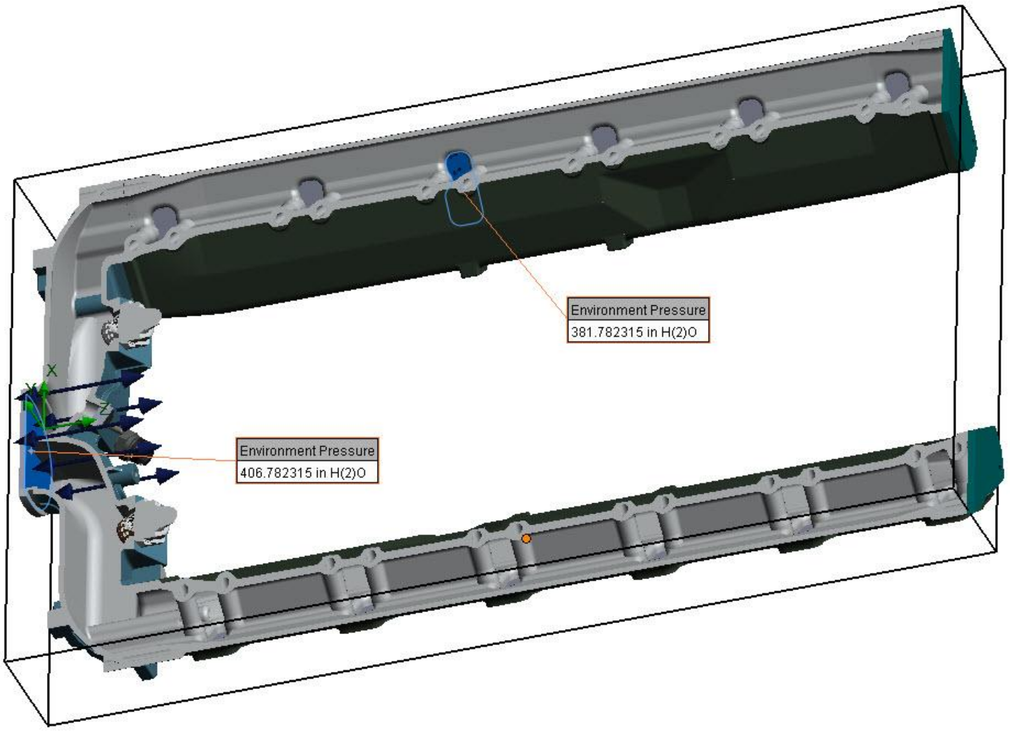


Figure 4-2 - Standard flow simulation setup for port 3

### 4.1.2.2 Deliverability of average mass flow during one intake sequence

One of many sequences suitable for simulation is the one involving port 1, 5, 8 and 12 (two on each side, according to an existing intake sequence). Twelve different sets of intake sequences could be found, however three were considered to be sufficient. The boundary conditions are set so that a relative charge pressure of 3,815 bar acts between the intake connector inlet and the ports respectively. This should act as if a 4,815 bar absolute charge pressure is working against 1 bar absolute back pressure. According to research and calculations, Chapter 5.1.3, there is at any instant of time air intake corresponding to an average mass flow of air through 4 ports, two on each side. The average mass flow rate was simulated for all four ports at the same time and then measured for each port individually.

Two other sets of ports were also simulated in the same way. Both according to the intake sequence (Chapter 5.1.3). These two were 3, 6, 7 and 10 respectively 2, 4, 9 and 11. The results are then compared to the calculated need of air in the engine and can hence indicate if the engine will get enough air or not.

### 4.1.2.3 Volume flow reaction to charge pressure variation

To evaluate what happens in the intake manifold when the pressure increases a simulation with varying charge pressure were performed. The volume flow was then measured when the turbo pressure was increased incrementally. The simulations were performed with flow on all ports at the same time. This is not the conditions the air will experience in the real engine since the ports will be open at different times. This simulation does however give a hint of how the ports may affect each other.

The simulation was setup as follows in the list below:

- A static pressure that was incrementally increased in the intake manifold inlet
- A low static pressure at the intake port
- Volume flow was measured for each different charge pressure and plotted in a diagram
- Adiabatic walls with 100 micrometer roughness and 20 degrees Celsius air temperature

### 4.1.3 Testing

Physical flow tests are performed to receive reference values for the OEM intake manifold. Flow test results were later compared to the reference CAD model simulation results and used to verify the accuracy of the CAD model. Since this is a standardized way of testing flow the results can also be used to compare the actual intake manifold to others, tested in earlier projects.

The physical flow tests are performed on a Super Flow SF-1020. The Bench is set to have a 25 inch water negative pressure (corresponds to 0,062 bar) and measures the volume flow rate of air (in CFM) through the OEM intake manifold. The flow bench display is shown in Figure 4-3, where the pressure condition (TP) and the flow result can be seen.

To be able to assemble the intake manifold to the flow bench a fixture plate had to been designed. The fixture plate is simply a thick metal sheet where a port identical to the intake manifold port is made together with suitable screw holes to be able to fixture it in the intake manifold as well as in the bench. The fixture plate can be seen in Figure 4-4 and a picture of the intake manifold assembled on the flow bench can be seen in Figure 4-5. The Ports not tested are carefully covered with tape.

Figure 4-3 – The flow bench display

**Figure 4-4 – Fixture plate between intake manifold and flow bench. The black tape on around the port hole is used as a seal to prevent leakage.**

**Figure 4-5 – Flow test of cylinder port number 9 in the flow bench. The bench ia set to have 25 inch water below ambient pressure and is hence sucking in air through the big inlet hole.**

## 4.2 Research for concept generation

Research was made before the initiation of the concept generation phase. The purpose of the research phase was to:

- Clarify the problem
- Benchmark
- Understand the basics of a diesel engine air intake system and different air intake system solutions
- Understanding flow mechanics for the intended use

The general knowledge increased and the tangible result of the research was a list of requirements (see Appendix B) and something that is called creative papers. The creative papers were something that was created in order to get extra input and creativity to the concept generation. The Creative paper is a simple tool, an A4 paper with pictures of subsystem solutions and lists of important sub solution features. An example of a creative paper can be seen in appendix C.

## 4.3 Concept generation

With knowledge from the research as well as knowledge learned from evaluating the OEM intake manifold a number of new concepts were created using brainstorming sessions and, so called, morphological matrices. Some concepts were also ideas created from scratch using no particular method. The brainstorming sessions was performed both individually and together. Overall this phase was kept quite fuzzy in order to not quench creativity. The concepts generated in this phase were very rough, thus had a very low level of detail. The level of detail was later enhanced as the concepts went through the iterative concept development.

A morphological matrix is a matrix consisting of a number of sub solutions together creating a full system solution. When creating concepts with a morphological matrix one chooses sub solutions with a goal, for example best individual sub solution or compactness. An example of a morphological matrix could be found in Appendix A.

To help to distinguish the concepts from each other, every concept created in this phase was given an individual working name that in one or two words described the concept. As the concepts evolved, so did the names, and new names were created when concepts evolved to such an extent that it could be thought of as a new concept.

## 4.4 Iterative concept development

An iterative concept development is a continuous evaluation, reduction and generation of concepts. The goal is to reach a certain number of feasible concepts which will be analyzed more thoroughly.

In this phase the number of concepts were brought down from 16 to two and the level of detail was increased to be able to investigate the feasibility of the concepts. Instead of a rough sketch on a paper, as the concepts were illustrated by at first, some CAD models were created in order to evaluate the conceptual design. The concept screening was done in a number of steps and between each step the remaining concepts were further developed or changed, hence the iteration in the concept development. In each step a number of concepts fell away because they were not deemed feasible or had obvious disadvantages compared to the others. Some concepts were also considered to be very similar and therefore merged into one.

The steps used in this phase were Pugh matrixes, a packaging model analysis, project group meeting and expert consulting. Extensive research was also performed during this phase to fill any gaps of knowledge that was found during the development of the concepts. As an example, an opportunity was given to look at similar marine diesel engines in crafts used by the Swedish Marine. This gave import insight about how the engine is installed in an actual engine room and more examples of how the air intake system could be configured which is hard to imagine in the workshop or when sitting in an office.

### 4.4.1 Pugh matrixes

A Pugh matrix is a method used to compare different concepts. In a Pugh matrix one sets up requirements that are deemed important. Each concept is then compared to a datum concept in each of these requirements. These requirements can also be weighted to get a more accurate result. The result from the Pugh matrix should however not be seen as exact truth but rather function as guidance for further screening. The most important thing about the Pugh matrix is however that it forces the development team to really think through each concept in all aspects that are considered to be important. This gives valuable insight into the problem and how to solve it.

Both weighted and non-weighted Pugh matrixes were used in this project and the result, together with the knowledge gained in the process, functioned as guidance in the screening process.

### 4.4.2 Packaging model

A rough packaging model using the real engine block and cardboard boxes for different engine components were made to get insight into how a functional system solution could be achieved. This was done together with the project group and gave very good insight in how much room the intake system could occupy without interfering with other engine systems. The knowledge gained from the packaging model further guided the screening of the concepts and some were deemed impossible to create due to lack of space.

### 4.4.3 Group meeting

After some screening the remaining concepts were presented to the project group. The project group was then given the opportunity to give their opinions regarding the concepts and to come with suggestions. This gave a lot of important insights to the project, especially considering other subsystems of the engine and how they would affect the intake system. The group meeting also provided the project group with info on where the intake system development was heading and how a possible solution eventually would look.

### 4.4.4 Consulting with expert

To further evaluate the remaining concepts they were also presented to a senior engineer with extensive knowledge within the subject. After the presentation a discussion was held about different aspects of the concepts and the input was used to further reduce the number of concepts as well as enhance and improve the ones that remained after the screening.

### 4.4.5 Final choice of concepts

After continuous screening, improving and enhancing the concepts, the number was still too high. All concepts remaining at this stage were all promising and to choose the two most promising ones required a lot of knowledge gained so far in the project. The final evaluation was simply done by summarizing any particularities; positive and negative about each concept. This collected information, together with some engineering assessments, was the basis for the choice of final concepts. In the end, two concepts were chosen to be passed on to the detailed design phase.

## 4.5 Detailed design

When the detailed design phase started the number of concepts were down to two, and the level of detail had already been raised quite a bit during the iterative concept development phase. The focus was however now switched to further develop only two chosen concepts instead of keeping a broad focus with many possible concepts. For example proper CAD-models were created to be able to perform simulations. During this phase the concepts went from a clear idea to a finished concept and went through quite a lot of alterations as the results from simulations and other evaluations brought up flaws and difficulties. In this phase, consideration to manufacturing as well as fastening and connections was also taken in a more profound way.

# 5 Calculations of Required Flow

## 5.1 Flow Calculations

This chapter will show how to calculate the required air flow needed for an 1800 hp engine and also investigate the intake sequences in this specific engine as well as the average mass flow needed during an intake sequence.

### 5.1.1 Calculations of required flow

The stoichiometric air-fuel ratio (a/f)  for diesel is 14.30 and defines how much air is needed to burn the fuel completely with only rest products carbon dioxide and water (Ferguson & Kirkpatrick, 2001). But diesel engines could have an excessive amount of air in the cylinder during combustion to cool the exhaust gases and create good conditions for the combustion process. The air/fuel ratio (a/f) 22 is a number validated by MarineDiesel from testing using a lambda sensor. In this case lambda is 1.54, which implies that 54% more oxygen is needed than the theoretical amount. This is according to MarineDiesel a number used by several engine developers so that conditions are advantageous.

The break specific fuel consumption (bsfc) has to be estimated as the true bsfc won’t be known until late in the project. The number below is the bsfc for an engine based on a similar engine as the DMD1800, however the maximum power is 1500 hp. The Equations, 1-3, calculates the average mass flow of air needed by the engine as well as for the other components in the intake system. Table 5.1 shows the parameters used for calculations of mass flow of air as well as the result. $W_{brake}$ represents the effect expressed in hp.

$$bsfc = \frac{\dot{m_{fuel}}}{W_{brake}} \qquad (1)$$

$$\dot{m_{fuel}} = \frac{\dot{m_{air}}}{a/f} \qquad (2)$$

$$\dot{m_{air}} \left[\frac{lb}{min}\right] = \frac{a}{f} * W_{brake}\,[hp] * bsfc \left[\frac{lb}{hp*h}\right] * \frac{1}{60} \left[\frac{h}{min}\right] \qquad (3)$$

### 5.1.2 Intake manifold pressure

In order to calculate the intake manifold pressure one can calculate the needed turbo boost pressure to create a manifold pressure which is sufficient to push the needed mass flow of air into the cylinder. The following chapter describes the derivation of the manifold pressure equation, as well as the assumptions made and the results.

**Table 5.1 - Parameters for calculation of required mass flow of air**

| Parameter | Value | |
|---|---|---|
| **a/f** | 22 | [ratio - no unit] |
| **bsfc** | 0,39 | [lb/(hp*h)] |
| **$W_{brake}$** | 1800 | [hp] |
| **$\dot{m}_{air}$** | 257,4 | [lb/min] |

#### 5.1.2.1 Ideal gas law

Many conditions could be described by using the ideal gas law, equation 4, as the state of a gas could be described with the pressure, volume and temperature. The manifold pressure is sought but the volume is unknown and thereby must the dependence of the volume be removed.

$$pV = nRT \qquad (4)$$

With the chemical relationships of molar mass:

$$m = nM \qquad (5)$$

And the definition of density:

$$\rho = \frac{m}{V} \qquad (6)$$

The Ideal gas law transforms into:

$$pM = \rho RT \qquad (7)$$

Solving for $\rho$ gives the equation:

$$\rho_{air}\left[\frac{kg}{m^3}\right] = \frac{p_{manifold}[bar]\ M_{air}\left[\frac{g}{mol}\right]}{R\left[\frac{m^3\ bar}{mol\ K}\right] T_{manifold}[K]} \qquad (8)$$

Where p is the intake manifold pressure, M is the molar mass for air, $\rho$ is the density of the manifold air, R is the molar intensive universal gas constant and T is the temperature of the air in the manifold.

#### 5.1.2.2 Volumetric efficiency

The volumetric efficiency, shortly mentioned in Chapter 2.1.2, is a performance parameter that defines the ratio between the mass of air inducted into the cylinder and the volume the same mass of air would displace in the intake manifold. In other words, the volumetric efficiency rates the effectiveness of the induction process hence it is desirable to maximize the outcome (Ferguson & Kirkpatrick, 2001). The volumetric efficiency is influenced by the manifold design as well as the valve size, lift and timing.

When the intake manifold is under development, a value of the volumetric efficiency ($e_v$) must be assumed. A number used by MarineDiesel for similar design projects is $e_v = 0{,}85$.

$$e_v = \frac{\dot{m_{air}}\left[\frac{kg}{min}\right]}{\rho_{air}\left[\frac{kg}{m^3}\right] V_d\ [m^3]\ \frac{N\left[\frac{revolutions}{min}\right]}{2}} \qquad (9)$$

Equation 9 shows the definition of volumetric efficiency where $\dot{m_{air}}$ is the mass flow of air, $\rho_{air}$ is the air density, $V_d$is the engines total displacement volume and N is the engine speed.

#### 5.1.2.3 Intake manifold pressure

Combining formula (8) and (9) through elimination of $\rho_{air}$ while solving for $p_{manifold}$ gives the equation:

$$p_{manifold}[bar] = \frac{\dot{m_{air}}\left[\frac{g}{min}\right] \; R\left[\frac{m^3\,bar}{mol\,K}\right] \; T_{manifold}[K]}{V_d[m^3] \; \frac{N\left[\frac{revolutions}{min}\right]}{2} \; M\left[\frac{g}{mol}\right] \; e_v} \quad (10)$$

#### 5.1.2.4 Parameters

The parameters in equation 10 are defined here in chapter 5.1.2.4. Calculations are made and the least needed manifold pressure can be found in Table 5.2 together with the parameters. The manifold temperature have been estimated to 50 degrees Celsius by MarineDiesel.

Conversion of the mass flow units from preceding section:

$$\dot{m_{air}} = \dot{m_{air}}\left[\frac{lb}{min}\right] \frac{1000}{2{,}2046}\left[\frac{g}{lb}\right]^{\cdot} = 116756\left[\frac{g}{min}\right] \quad (11)$$

Gas constant:

$$R = 8{,}314 * 10^{-5}\left[\frac{m^3\,bar}{mol\,K}\right] \quad (12)$$

Manifold temperature:

$$50℃ = 273{,}15 + 50 = 323{,}15\,K \quad (13)$$

Engine displacement volume:

$$V_d = 22l = 22[dm^3] = 0{,}022[m^3] \quad (14)$$

Engine speed:

$$N = 2400\left[\frac{revolutions}{min}\right] \quad (15)$$

The molar mass of air is calculated as follows:

$$M_{air} = M_{oxugen} * 0{,}21 + M_{nitrogen} * 0{,}78 + M_{argon} * 0{,}01 \quad (16)$$

$$M_{air} = 32 * 0{,}21 + 28 * 0{,}78 + 39{,}95 * 0{,}01 = 28{,}9595 \approx 29\left[\frac{g}{mol}\right] \quad (17)$$

Table 5.2 - Parameters for calculation of least needed manifold pressure

| Parameter | Value | |
|---|---|---|
| **$\dot{m}_{air}$** | 116800 | [g/min] |
| **R** | 0,00008314 | [$m^3$*bar/(mol*K)] |
| **T** | 323,15 | [K] |
| **$V_d$** | 0,022 | [$m^3$] |
| **N** | 2400 | [revolutions/min] |
| **M** | 29 | [g/mol] |
| **$e_v$** | 0,85 | [1/revolutions] |
| **$P_{manifold}$** | **4,815** | **[bar]** |

#### 5.1.2.5 Results

The needed boost pressure in the intake manifold needs to be at least 4,815 bar absolute, the turbo boost must be slightly higher to compensate for the losses since pressure drops when flow is restricted.

$$p_{manifold} = 4{,}815\ bar\ \ (= 69{,}83\ psia) \qquad (18)$$

Worth mentioning is that the temperature, the volumetric efficiency and the engine speed could be varied for changed conditions and requirements, hence the result is a good estimation.

### 5.1.3 The average mass flow of air

The piston cylinder geometry of this engine is of V-type with 12 cylinders. These cylinders ignite at different times to assure even power distribution, hence smoother run of the engine. As the cylinders ignite at different times, the air intake sequence is distributed accordingly. In a four stroke engine the cam shaft rotates with half the speed of the crank shaft, and it takes two revolutions for the crank shaft for the engine to complete a full cycle. In Figure 5-1 below the cylinder numbers and the ignition sequence is added to a rendered CAD model of the OEM intake manifold.

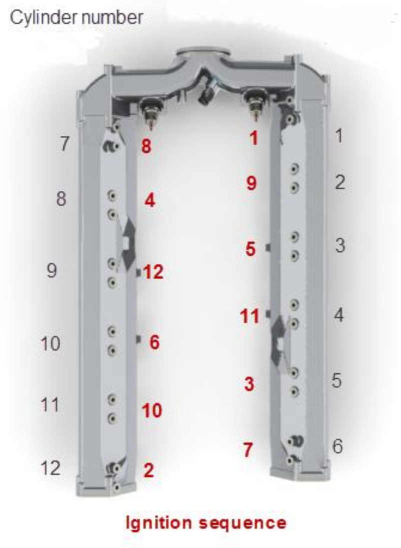


Figure 5-1 - Cylinder numbers and ignition sequence

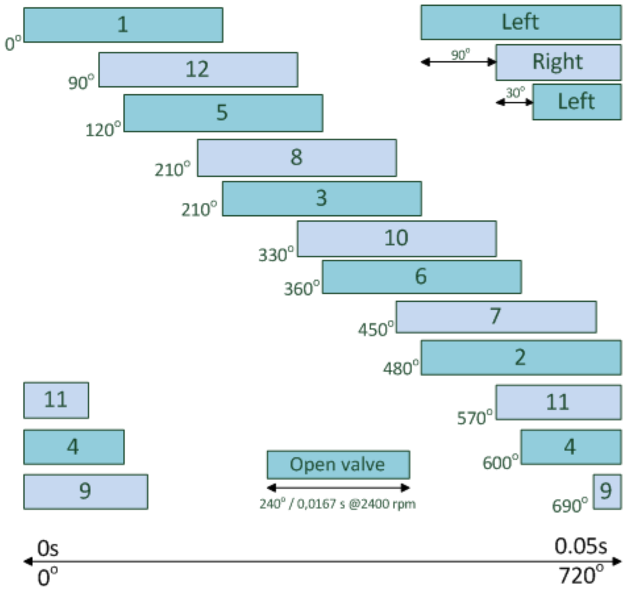


Figure 5-2 - Explanation of the air intake sequence in a V12 odd firing engine at 2400 rpm

A camshaft profile analysis reveals that this specific engine is a 90-30 odd firing V12, not the expected 60-60 even firing V12. The right engine side is delayed 90° even though there are two ignitions every 120 °, and hence the sequence is not evenly distributed as the ignition takes place with 90° and 30° separation instead of 60 °. Figure 5-2 visualizes and explains the air intake sequence, thus the ignition takes places in the end of each block.

As you can see above, if you measure the picture closely, is that two intake valves are continuously opened at the same time on each side. Which two valves changes rapidly. Every 240° on the crankshaft (120 ° on the camshaft) another valve starts to open on each side. At 2400 rpm, the expected maximum engine speed, each valve sequence takes place during 240 ° revolution of the crank shaft which corresponds to approximately 0.0167 s (see Equation 19).

$$t_{intake\ sequence} = \frac{60\left[\frac{s}{min}\right] * \frac{240}{720}\left[\frac{intake\ cycle}{engine\ cycle}\right]}{2400\ \left[\frac{revolutions}{min}\right] * 0.5\left[\frac{intake\ cycle}{revolution}\right]} \approx 0{,}0167\left[\frac{s}{intake\ cycle}\right] \qquad (19)$$

Based on that two intake valves are opened at the same time, each side of the manifold is required to deliver air flow to two cylinders during the time of an intake sequence. The calculations below results in the average air mass flow, $\overline{\dot{m}}_{air}$, for each cylinder intake sequence during full speed:

The total mass flow of air calculated in the previous section in this chapter:

$$\dot{m}_{air,\ engine} = 116755{,}875\left[\frac{\mathrm{g}}{\mathrm{min}}\right] \approx 116{,}8\left[\frac{\mathrm{kg}}{\mathrm{min}}\right] \qquad (20)$$

The number of intakes every minute:

$$n_{intake} = 2400\left[\frac{revolutions}{min}\right] * 0{,}5\left[\frac{intake\ cycle}{revolution * cylinder}\right] * 12[cylinders] = 14400\left[\frac{intake\ cycles}{min}\right] (21)$$

The required mass of air per intake cycle:

$$m_{\ intake\ cycle} = \frac{\dot{m}_{\ air}\left[\frac{\mathrm{kg}}{\mathrm{min}}\right]}{n_{intake}\left[\frac{intake\ cycles}{min}\right]} = 0{,}008108\left[\frac{kg}{intake\ cycle}\right] \quad (22)$$

The average mass flow:

$$\bar{\dot{m}}_{\ air,\ \ valve} = \frac{m_{\ intake\ cycle}\left[\frac{kg}{intake\ cycle}\right]}{t_{intake\ sequence}\left[\frac{s}{intake\ cycle}\right]} = 0{,}4865\left[\frac{kg}{s}\right] \quad (23)$$

$$\bar{\dot{m}}_{\ air,\ \ manifold\ side} = 0{,}4865\left[\frac{kg}{s}\right] * 2\left[\frac{intakes}{manifold\ side}\right] = 0{,}973\left[\frac{kg}{s}\right] \quad (24)$$

At maximum speed, when the engine requires most mass flow of air, 0,973 kg air per second is needed for each side of the V to supply the combustion process over time. This number will act as a reference number to compare to the results from the flow simulations. Figure 5-3 shows an estimation of the intake flow profile and the average flow. The flow profile has been estimated by the project team and is theoretically based on how pressure varies in the cylinder during the intake sequence. The flow profile estimation should only act as a rough description of the flow to help understand the characteristics of the flow.

The average mass flow of air is a simplification as the time dependence is removed from the calculations. The calculations have in other words been performed regardless of the intake flow profile. The result shows hence the least mass flow of air the intake manifold should provide over time. If the manifold air flow capabilities are close to this value, a more careful examination of the valve profile should be performed to ensure that the needed mass could be delivered.

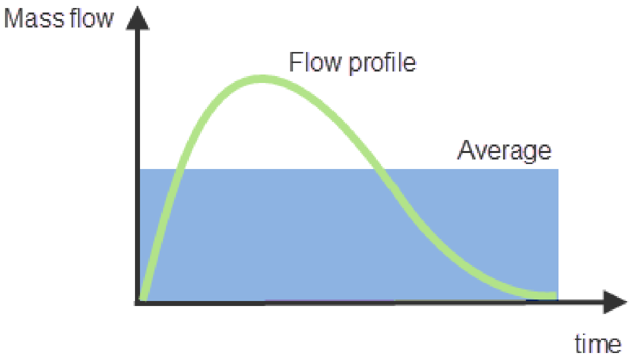


**Figure 5-3 - Comparison between an estimation of the actual mass flow  and the average mass flow**

# 6 OEM Intake Manifold

The existing manifold, produced by MAN, should be analyzed in order to both find requirements for the new manifold design, and provide knowledge about the present solution and if it could live up to the new requirements. Learning about the strengths, weaknesses and constraints of the OEM manifold will thereby guide the further design work.

## 6.1 Flow simulation and Testing

The main goal when evaluating the OEM manifold is to investigate the flow capabilities, i.e. find out whether or not the OEM manifold can deliver sufficient flow. The manifold flow capabilities cannot in this stage of the process be tested in a fully operational engine with the exact new conditions; hence tests and simulations are needed to verify the capability of the manifold.

### 6.1.1 Reference CAD model

The reference CAD model of the OEM manifold should be created for computer flow simulations. The software used is Solid Works 2010. Two important parameters of the CAD model are the interfaces and the flow path. These two parameters are essential for the future use of the CAD models as they must be similar to the ones tested in the flow bench. Other features as for example material and color requirements are not catered for in this model.

The lack of valid drawings is an issue as the method of measuring (using ruler, slide caliper and protractor) and estimating dimensions for complicated geometries is not exact. The same method has although been used before at MarineDiesel with satisfying results, thus supplies the initial method validation needed. 3D scanning could also be used to simplify the creation of the testable CAD model as well as making the outer surfaces more consistent with the OEM manifold. Continuous measurements are a part of the CAD work and the final measurement method was to print 1:1 drawings of the interfaces from the CAD model. These drawings were thereafter used to compare the drawing to the physical profile and verify the design.

The total mass flow of air is in the current application divided into two channels in the “intake connector”. The intake connector must therefore be created digitally, including geometries and features that could influence the flow, to deliver the simulated air flow to both sides of the engine. In Figure 6-1 are both the CAD model and a photo of the OEM connector shown.

The intake manifold provides air supply to the 6 cylinders on each side. Due to the non-symmetry in a v-engine (the cylinders are somewhat displaced) this particular connector is not symmetrical to make symmetrical manifolds possible. The final manifold CAD model and the OEM manifold can be seen in Figure 6-2.

Figure 6-1 - CAD connector & OEM connector

Figure 6-2 - CAD manifold & OEM manifold

The connector and the two manifolds should digitally be assembled as this constellation is the one used in the engine today, and hence the one for use in the flow simulations, as well as the flow bench tests. The intake connector and the two manifolds in one assembly can be seen in Figure 6-3.

### 6.1.2 Standard flow simulation

Using the reference CAD model it is possible to perform standard flow simulations. The results of the simulations can then be compared to physical flow tests with the OEM manifold in order to validate the CAD model.

The results of the flow simulation can be seen in Figure 6-4. Deviating results, such as port number six, was tested twice to verify that no mistake had been made the first time. No corrections were however needed. Flow is kept in CFM (cubic feet per minute) as the standard flow simulations mostly are made for comparison.

After simulating the flow it is possible to create flow trajectories that give a hint of how the air flows through the intake manifold. An example of this can be seen in Figure 6-5 where port 3 is the only port open.

Figure 6-3 - OEM Manifold assembly

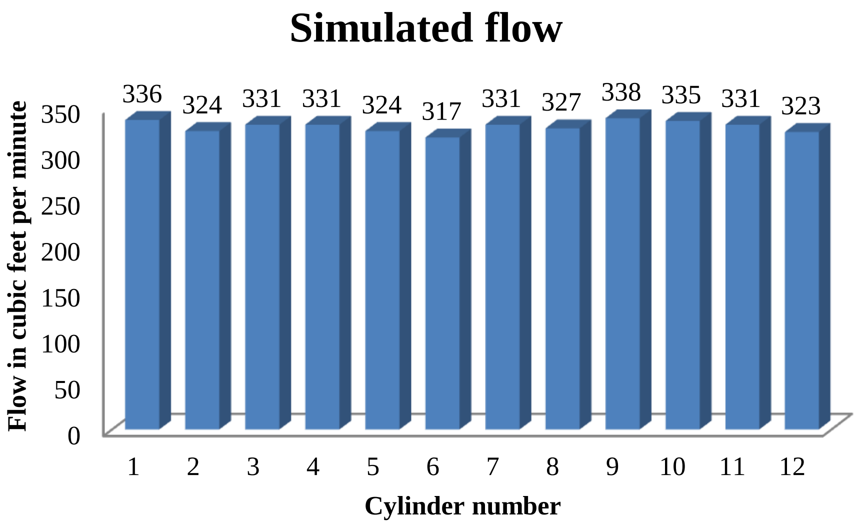


Figure 6-4 - Standard flow simulation results for the OEM intake Manifold

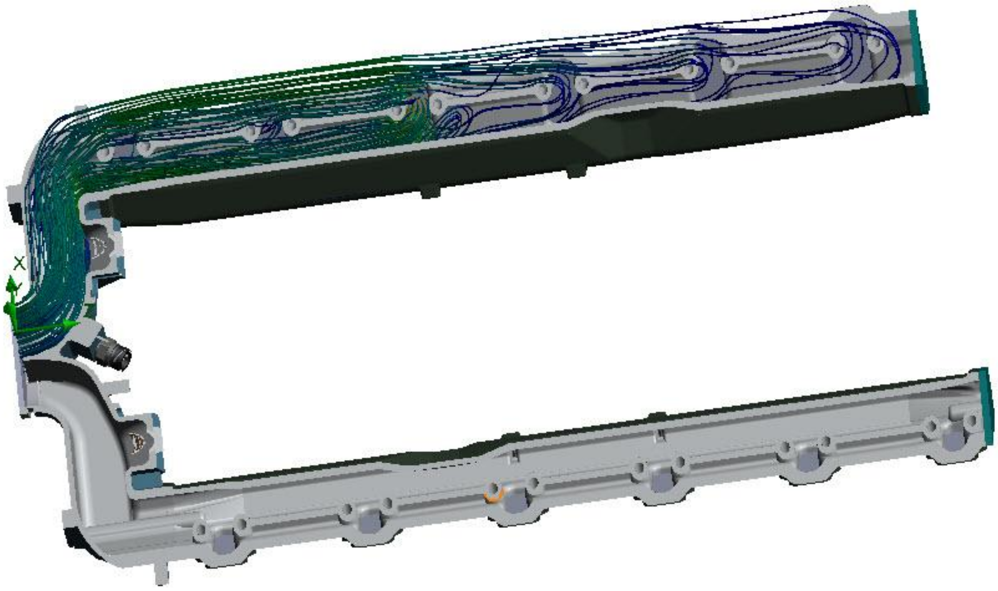


Figure 6-5 – Flow trajectories when flowing air to cylinder port number 3 solely.

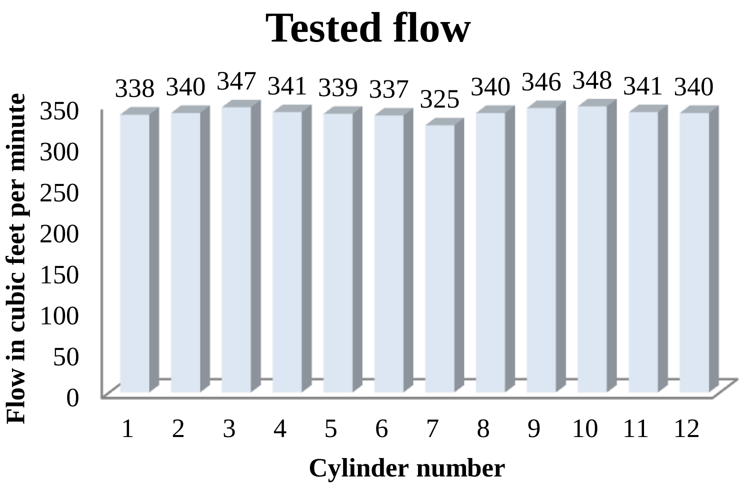


Figure 6-6 – Flow bench test results for the OEM intake Manifold

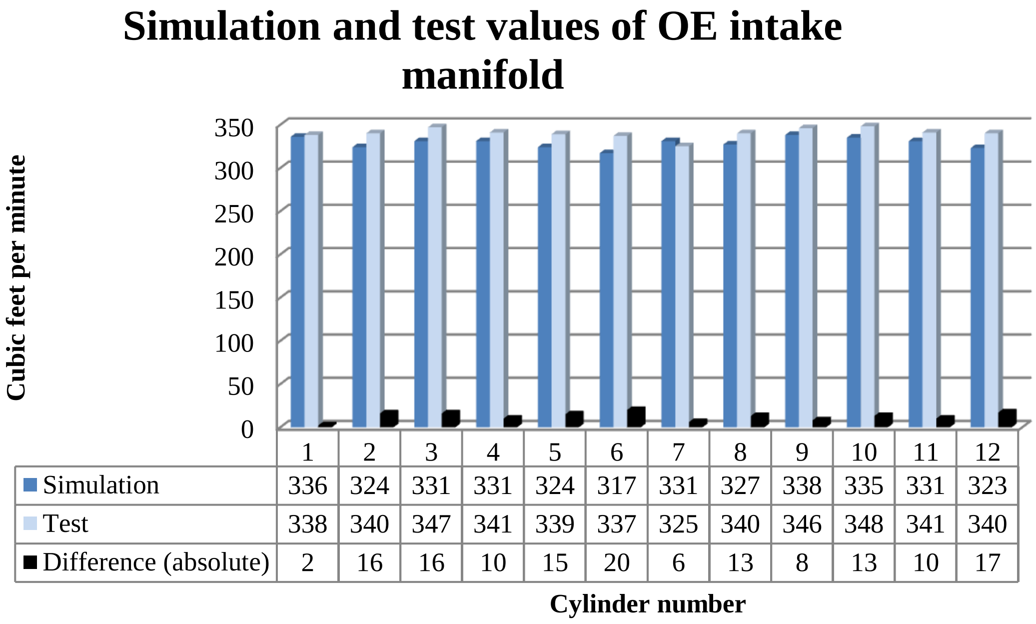
### 6.1.3 Standard physical flow test

The flow is tested in the flow bench according to Chapter 4.1.3 for each port individually. The results can be seen in Figure 6-6.

The flow is overall quite homogenous except for port seven which is somewhat lower than the rest. Port number seven was therefore tested two times in the flow bench to verify the result.

### 6.1.4 Validation of CAD model and simulated results

In order to use the simulated results and the reference CAD model as a base for further evaluation the simulation must first be validated. This is done by comparing the simulated results with test results from the flow bench.



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 Simulation | 336 | 324 | 331 | 331 | 324 | 317 | 331 | 327 | 338 | 335 | 331 | 323 |
| ⬜ Test | 338 | 340 | 347 | 341 | 339 | 337 | 325 | 340 | 346 | 348 | 341 | 340 |
| ■ Difference (absolute) | 2 | 16 | 16 | 10 | 15 | 20 | 6 | 13 | 8 | 13 | 10 | 17 |

Figure 6-7 - Test and simulation values for the OEM intake manifold

As shown in Figure 6-7; the difference between the simulations and tests are small and the tests generally show a little bit better result in flow than the simulation. This is good since the simulated results then likely will be on the safe side and not show too positive outcomes. It is therefore concluded that the simulated results can be used as a good base for further analysis of the OEM intake manifold. Looking closely at Figure 6-7 one can see that the result is different for port 1 and 7 which most likely is due to differences in the connector bend, which mainly influences the two closest ports. The general differences in the results between the simulation and test are probably due to the geometrical differences between the CAD model and physical intake manifold, but also the limitations of the simulation software when recreating reality in the computer. Differences can however also be due to for example the fixture plate design, leakage of air when testing, measurement errors when testing and so on.

## 6.2 Evaluation of OEM intake manifold

This chapter should guide decision making whether the OEM intake manifold could be used in the MarineDiesel engine or not and also provide valuable information for the new intake manifold designs.

### 6.2.1 Deliverability of average mass flow during one intake sequence

This test will reveal whether the manifold could deliver the average mass flow to two ports at the same time on each side, thus 4 in total. The theoretical background and figures used in these tests are explained in Chapter 5.1.3, The average mass flow of air. The average mass flow during an intake sequence needs to be higher than 0.49 kg/s for each port. However as the average value does not cater for the higher flows present in the real intake flow profile, a safety factor of 2 will give a reasonable safety margin. In other words the flow limit for each port becomes 0,98 kg/s.

One of many sequences suitable for simulation is the one involving port 1, 5, 8 and 12 (two on each side, according to intake sequence, Figure 5-2). The boundary conditions are set so that a relative charge pressure of 3,815 acts between the intake connector inlet and the ports respectively. This should act as if a 4,815 absolute charge pressure (See Chapter 5.1.2) is working against 1 bar absolute back pressure. The mass flow rate was simulated for all ports at the same time and then measured for each port individually. This is according to the method Chapter 4.1.2.2 and the result can be found in Table 6.1.

Table 6.1 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 8** | **1,86 kg/s** | **Port 1** | **1,81 kg/s** |
| **Port 12** | 1,68 kg/s | **Port 5** | 1,60 kg/s |

The next set of ports in the intake sequence to be tested is; 3, 6, 7 and 10. The results are shown in Table 6.2. The flow trajectories for this simulation are shown in Figure 6-8.

Table 6.2- Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 7** | **1,59 kg/s** | **Port 3** | **1,61 kg/s** |
| **Port 10** | 1,89 kg/s | **Port 6** | 1,69 kg/s |

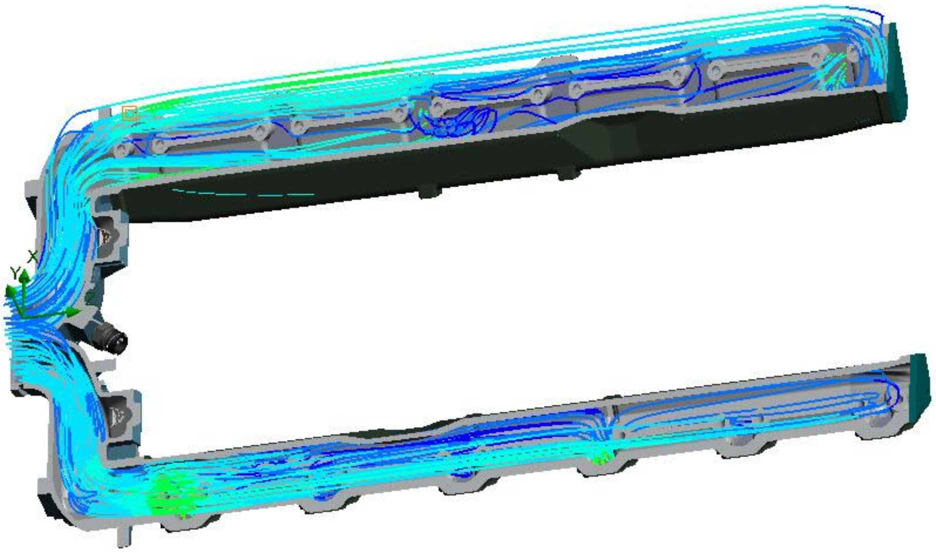


Figure 6-8- Flow trajectories from flow simulation of port 3, 6, 7 and 10

Table 6.3 - Mass flow simulation results

| **Port 9** | **1,85 kg/s** | **Port 2** | **1,53 kg/s** |
|---|---|---|---|
| **Port 11** | 1,82 kg/s | **Port 4** | 1,82 kg/s |

The third set to be tested involves ports 2, 11, 4, and 9. Worth mentioning is that all possible sets could be tested for a more exact result. However, tendencies for not achieving the average flow of air are expected to be distinguished from these three simulations. The results can be found in Table 6.3.

The final results of these simulations show that for a relative pressure difference of 3,815 bars between intake connector inlet and ports, all ports receive at least 50% more air than required using the flow limit with safety margin. More than three times the average mass flow needed could be delivered to every port.

### 6.2.2 Volume flow reaction to charge pressure variation

The simulations below have been made while giving flow to all ports at the same time, thus following the method 4.1.2.3. As can be seen in Figure 6-9, the flow increases with quite a high rate at low pressures and then levels out to gain a smaller amount of volume flow rate at higher pressures. Flow cannot travel faster than speed of sound. When flow of air reaches speed of sound in a larger and larger part of the port, the mass flow only increases with the small increase in density the increased pressure contributes with. According to theory, it is often by the valve the flow firstly gets limited, so there should not be a bottleneck in the manifold. The flow still increases between 4 and 5 bar which imply that there does not seem to be any choked flow at the engines future calculated working pressure.

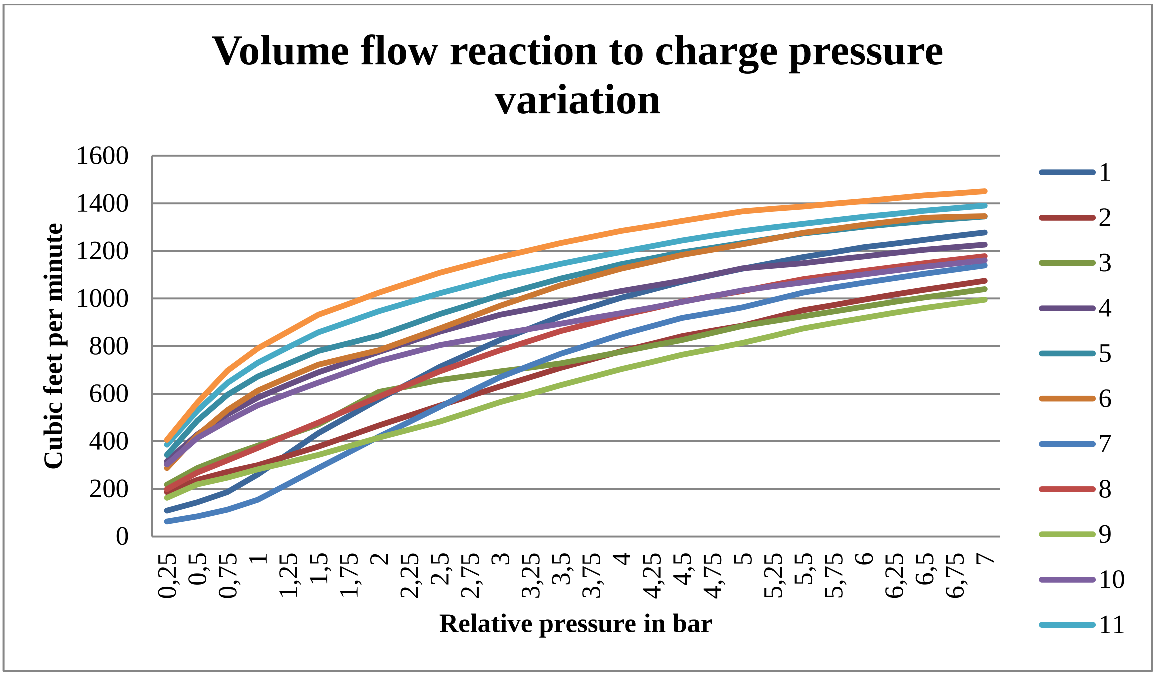


Figure 6-9 – Volume flow results for each port with increasing turbo pressure (flow on all ports simultaneously).

An interesting phenomenon in this simulation is that the flow is quite uneven between the ports. This is in contrast with the result from the simulation of each port individually where the flow was quite homogenous. However, these conditions are not the real ones, but apparently the ports are affecting each other quite randomly.

### 6.2.3 Geometry analysis based on flow trajectories

This analysis has been continuously running through this simulation process and aims to find particularities in the flow, positive or negative, that could have an influence on the flow behavior. The first issue is easy to detect due to the lower flow rate for port 1 and 7. The radii in the intake connector bends are too short which makes the flow separate from the inner wall and create some turbulence. Most of the air travels thereby the long way in the connector bend and leaves most air supply to the side of the manifold wall that has the smaller port inlet. This can be seen in Figure 6-10.

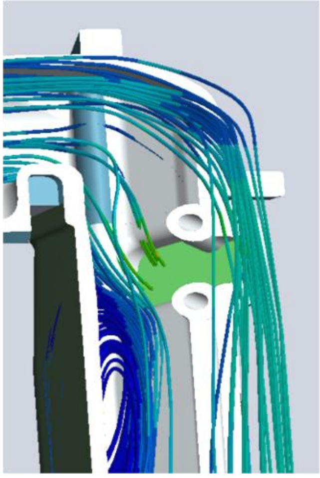


Figure 6-10 - Flow trajectories showing the flow to port 1, closest to the intake connector

After the first port the flow stabilizes and flows along the outer manifold wall. Much of the flow, flows past the open port and goes down to the rear wall, where it turns around, slows down and then flows back to the port. Most flow passes thereby on the side where the port opening is smaller. For every port, the incoming flow trajectories look different. This is because of the indirect flow entering the ports. The direct flow comes from the intake connector to the port without either flowing down to the rear wall and turns, or spins around one of the manifold walls. In the lower left image in Figure 6-11, the leftmost port receives a lot of indirect flow.

It is hard to determine the effect of the manifold wall. The wall guides the flow on both sides which could be a way to ensure laminar flow over the ports. The manifold wall does however restrict the flow of going directly towards the lower pressure in the open port. As the fasteners to the engine are going though the manifold, material for the bolts to run through is inevitable. The manifold walls are most likely designed to guide the flow between two bolts instead of having 12 round shaped obstacles creating turbulence and wakes, see the upper left image in Figure 6-11. The inner geometries have obvious influence on the flow which could be seen in the two right images in Figure 6-11. These Figures also show examples of indirect flow.

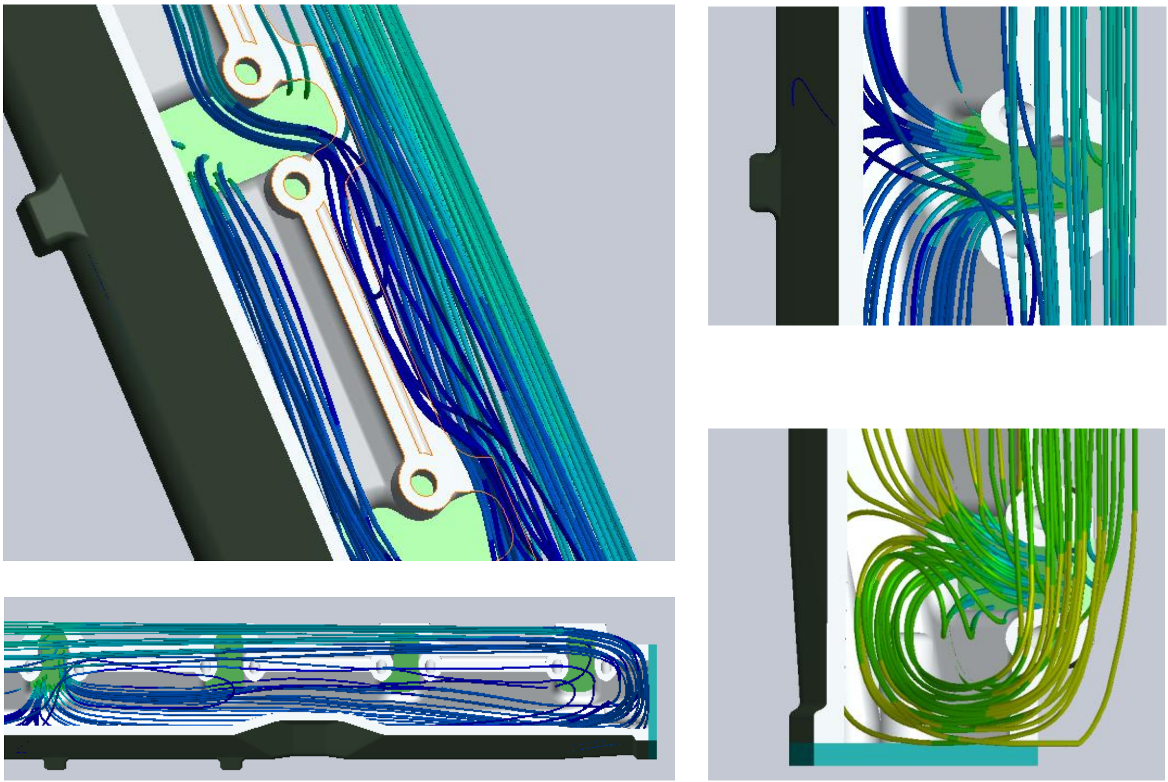


Figure 6-11 - Flow trajectories from OEM manifold flow simulation

## 6.3 Conclusions

This section concludes the evaluation of the OEM intake manifold. Worth noting is that there are a few uncertainties involved in the performed simulations; the back pressure when supplying air flow through the port to the cylinder is unknown as well as the influence on flow of continuous intake sequences. The CAD model is not an exact model of the existing manifold but deviation between simulation and testing is however lower than 6 %. Simulations have been made and targets have been set so that these uncertainties have been taken into account. Due to the similar results from flow bench testing and CAD simulation with the OEM manifold, the CAD model is considered to be adequate.

The simulations are, as earlier mentioned, not exact but as the real conditions will not be known until late in the project, the simulations gives insight and preparation for future testing and design work. The results combined with engineering assessments will guide whether a design is feasible or not.

### 6.3.1 Flow conclusions

Enough flow is delivered to all the ports according to the deliverability of average mass flow simulations. There is though up to 15% difference in average mass flow which could imply that problems can arise due to uneven flow. The flow is however even when simulations are made for each port individually. The flow capability of the OEM intake manifold seems to be sufficient for the new demands for an increase in air supply. The mass flow capabilities of the manifold exceed the average needs in full speed with at least a factor three. The flow trajectories look very different for different ports. A design factor to pay attention to would be to create prerequisites for a more uniform and predictable flow.

Simulations were also made for all ports at the same time during the volume flow reaction to variation of charge pressure. The flow rate differs much between the ports, and at 4.8 bar the difference between port 9 and 12 is almost 40% (Figure 6-9). These conditions, when all ports are open at the same time, are not the real conditions, but the big differences between ports imply that the manifold is not designed to deliver even flow. Furthermore there does not seem to be any complications regarding flow when charging the intake manifold with higher turbo pressure (up to 6.75 bars relative over pressure).

### 6.3.2 Geometry conclusions

The main functionality of the intake manifold is to flow air. When considering the flow in the OEM intake manifold, it is not optimal due to three main reasons:

- To short bend radius in the intake connector to maintain even flow.
- The attachment of the manifold requires inner geometries.
- Indirect flow to the ports is not preferable as redistribution of flow reduce pressure

When making the reference CAD model the manifold construction was considered to be complicated. A more simple design could reduce material and cost, and enhance flow. The need for a connector and inner geometries should be investigated. There are obvious drawbacks that could be eliminated through designing differently. The manifold port geometry is slightly complicated. The geometry will although be hard to change as the profile is the same in the cylinder head. Worth mentioning is that the intake valve capabilities of delivering the right amount of air to the cylinder under the short period of time is critical. The manifold design should give the valve the best possible prerequisites for deliverability. If the cylinder heads need to be replaced an optimal port shape must be chosen together with a suitable bolt pattern for attachment. A less complex and more efficient manifold could then be designed.

# 7 Pre concept Generation Research

This chapter will firstly clarify the design problem through a system boundary analysis. Important to notice is that the system boundaries is not connected functionally to other engine system than the air intake system (possibly the cooling system with water connections to the intercooler), but other system may physically interfere with the overall design through their placement, hence affecting the disposable volume of the intake manifold, which will be analyzed through packaging exercises. Guidelines regarding internal flow design and casting are also described below. The final outcomes of this chapter are conclusions for the design work and a list of requirements based on flow calculations, the OEM manifold evaluation results, the pre concept generation research, as well as general guidelines from MarineDiesel.

## 7.1 Clarify and define problem

One way to define the problem is to analyze the system boundaries of the problem. The purpose of the manifold is to guide sufficient air flow with the smallest possible effort. The air should be guided from an upstream connection to the plenum, through the runners to the ports with as little flow loss as possible. The intercooler could be integrated. The plenum design will then cater for the various intercooler designs with geometrical requirements as well as water connections. The upstream connection will still be considered to be in the plenum. Figure 7-1 visualizes the system boundaries.

## 7.2 Physical packaging model of complete engine

The MarineDiesel engine project is in the very first phase and no other subsystems are close to be completed. One of the outcomes of this is that there are very few restrictions, thus the intake could have a design that does not regard any other systems at all. The placement and design opportunities are thereby many. However many engine systems are in fact connected to the placement of the intake. There must be a possibility for other systems to claim sufficient space.

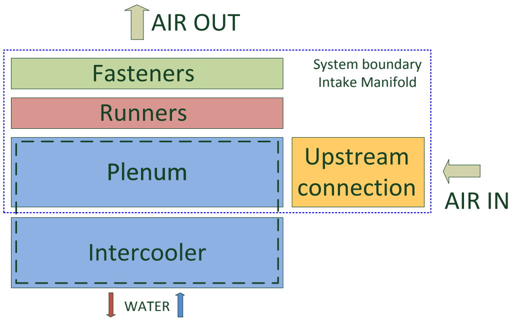


Figure 7-1 Intake manifold system boundary

Figure 7-2 - Physical packaging model

In order to analyze what systems that could interfere with the intake system, as well as receiving information how placement of the parts in the intake system are connected to the intake manifold, a physical packaging was made. The physical packaging was made for the whole engine where all major parts were represented by cartons which were attached to the engine with tape.

Many parts had natural positions due to engine requirements (exhaust manifold, water pumps, oil cooler, fuel pump) whereas others had to be placed and repositioned to create different system architectures (turbo, oil filters with bracket, expansion tank, heat exchanger, intercooler, intake manifold). Many components were of course left out due to their smallness and placement

flexibility.As could be seen in Figure 7-2, the low level of detail does not provide more than schematic guidelines for placement. Inlets, outlets and pipes are for example not represented. The conclusions below were made from the continuous analysis during rearranging and discussions. Worth mentioning is that the rest of the project group was involved since that the design choices made now will influence later stages in the project.

## 7.3 CAD packaging

Through measuring on the engine and using the CAD model of the OEM manifold a rough CAD packaging model could be created. As the engine is a 90 degrees v-engine the port surfaces are angled 45 degrees to the vertical plane. When assembling manifold concepts to the engine model their placement and occupied volume can be analyzed. New possibilities and restrictions could occur, mostly regarding complexity, size, flow and manufacturability. Every CAD-made concept should be assembled in the packaging model and its feasibility should be reviewed. Other components in the

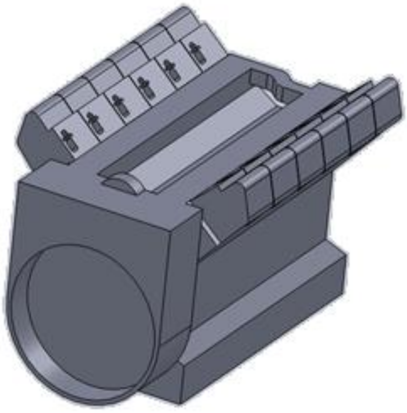


Figure 7-3 - CAD packaging model

air intake system (e.g. turbo and intercooler) will be added later as the system concept gets more detailed. Rough designs of other engine systems could also be assembled (e.g. fuel pump) when a component collision is likely to occur. The rough CAD packaging model of the engine can be found in Figure 7-3.

## 7.4 Internal Flow Design Guidelines

As a part of the research, the flow theory (chapter 2.2) has been applied to this project. The relevant information has been transformed into design guidelines rather than general theory. The theoretical flow research is a way to work proactively with design to avoid flow losses.

No calculations of flow losses will be made in this project as the design guidelines and flow simulations are considered to be sufficient for verifying the flow for this particular application (The complexity of the manifold would also demand many simplifications in the calculations). Future physical testing will show if there is a need to investigate the flow losses more thoroughly.

In theory, every component has a loss coefficient which contributes to the total flow loss. Reducing the number of components will reduce the total loss. Furthermore, keeping the flow path short reduces frictional flow losses, thus a compact air intake system is advantageous. Frictional flow losses could also be lowered through lowering the flow velocity (turbulent flow losses also increase with speed) and the wall roughness. To maintain a high flow rate the air temperature should be low. Thus the manifold should not raise temperature more than necessary.

One very simple and general design guidelines is to streamline the geometries. Smooth section changes are very important to avoid turbulence and flow re-distribution. The plenum to runner intersection must especially be carefully made. Inner geometries restrict flow through drag and separation. If inner geometries are necessary they should be designed to have as little drag as possible. Examples of inner geometries are vanes that could be added to guide flow.

Symmetry of design is a desirable characteristic as it facilitates equal distribution of air flow to each cylinder. Cylinder pressure is connected to the flow rate which should not differ much between the cylinders. Symmetry in flow paths, plenum shape, runner lengths and uniform port shapes are ways to provide good prerequisites for equal distribution.

## 7.5 Casting guidelines

Casting is quite a complex subject and the aspect of casting design is most commonly taken care of by the foundry man at the end of a project when a finished prototype is up for production. This can however lead to unexpected changes in the product due to casting difficulties. Therefore a short research on casting was done and some general guidelines were identified to aid the design work and reduce unexpected changes late in the project.

In general, casting is quite dependent on what kind of material and method you use. The casting characteristics can vary a great deal from material to material and hence makes it difficult to have specific rules that apply to all casting. There is however possible to draw up some general guidelines to help the engineer to improve the ability to cast a product.

General casting guidelines:

- Consider where the risers should be placed when designing the casted part, i.e. where the material should be poured in to the casting mold.
- Avoid isolated thick sections that only connect to the rest of the part by thin sections and aren't connected to risers.
- Maintain an even thickness in the part.
- Limit the use of big horizontal flat, surfaces.
- Design to avoid inner cores.

## 7.6 Research conclusions - what is affecting manifold design

Conclusions can be drawn from reviewing the research made so far in the project. These conclusions are used to lower the design options through learning about this particular engine project and thereafter apply this knowledge in the design work, thus put some feasibility into the concepts that will be generated. The conclusions are divided into three parts; the air intake system, engine dimensions and components. The internal flow design guidelines and casting guidelines are more general and are left out of this conclusion.

### 7.6.1 Air intake system design guidelines

There could be either one or two intercoolers, integrated in the manifold or not. The intercooler(s) should preferably be placed on top or in the rear part. The intercoolers will be heavy and its structural elements must be strong. If placed on top the design will at least be restricted by fuel pump, fuel lines, expansion tank and height limitations. If placed in the back the design will at least be restricted by the driveline and length limitations.

The exhaust manifolds (one for each side) will be jacketed and water cooled, and will be compactly designed and placed by the exhaust gates. The exhaust manifolds will have its outlets facing backwards somewhere over the manifold length. The outlets will be connected to the turbo turbine inlet with MarineDiesel designed pipes which could be designed in many ways as long as the backpressure resulting from restricted air flow is kept low, this implicates a low level of restriction for turbo placement.

The twin parallel turbo will be placed on the rear part of the engine.  The air filter does not restrict placement of the twin turbo as the placement is flexible as long as the turbo compressor inlet could be connected to the air filter. The compressor outlets could either be connected or separate when entering the intercooler. The compressor outlet pipes are to be designed later on and are also flexible in their design as long as flow is considered.

The degrees of freedom are still high but at least lower than before the physical packaging assignment. This will help to focus the design with considerations to the intake system and other systems. The focus should still lie on the manifold design, but the design of the manifold requires system thinking. Two types of concepts could in this case be distinguished; system design concepts, which have a predefined intercooler placement, and system independent concepts which are flexible when managing intercooler placement.

### 7.6.2 Engine dimension guidelines

The customer in the project has not yet decided a specific engine room and application(s) for the engine and hence there are no expressed space limitations. The future application(s) will most likely be a twin installation using water jet or surface drives which demands high end torque. Geometric competition analysis could be made in order to find engine dimensions where the engine could find a not satisfied market segment with this certain engine power (e.g. a straight 6 engine is longer but thinner than a V8 giving the same power). However, MarineDiesel is developing this engine for a customer which should list such requirements to be able to create competitive advantage for themselves.

A MarineDiesel common view of the engine dimensions is that it is preferable to build on top rather on the sides. In small engine rooms, this is the dimension that seems to be more critical than the others. The engine length is hard to change in the front due to the restrictions from the pulleys. If components can be placed in the back with enough stability and without interfering with driveline, this is also an option. These are some general guideline when the engine dimensions are not set. MAN, the original producer of the engine, is having at least three different engine configurations with the same engine block. Taking the smallest dimensions from each engine gives a very optimistic target dimension: L=1491 mm, W=1150 mm, H=1270 mm. A transparent box was created in Solid Works to fit the engine inside to compare the size with the target dimensions.

### 7.6.3 Component guidelines

The components should be designed for assembly/disassembly which is a way to ensure simpler repair work. A big casted component could be hard to handle and manufacture, especially for a v-engine where angled interfaces need to be perfectly fitted (smaller casted parts are easier to machine and better with tolerances). Components covering other components could also be a problem during repair work, and furthermore, if the engine is wide parts in the middle could be hard to reach. The goal is to have a compact engine which is still easy to repair. A system solution with integrated intercooler could be compact but could also cause difficult assembly and repair work.

If two manifolds are used, symmetry is good from an economic and manufacturing point of view as it only requires one cast form (the same manifold is used for left and right side). This is also a very useful design guideline for other parts. The manufacturing and assembly are simpler and less costly if less different parts are used. The manifold should preferably be small and regard other engine parts.

An intercooler used by MarineDiesel for a 900 hp engine has the approximate dimensions of 150 X 330 X 61 [mm] which corresponds to a volume of 0.0302 cubic meters or 30.2 liters. A twice the size intercooler should give approximately the double cooling effect. This volume, 60,4 Liters, will be used as a reference volume with some extra margin for the tank, couplings and other features. One liquid to air Intercooler found at Bell intercoolers website has the dimensions 229 x 523 x 508 [mm] which gives a volume of approximately 60.8 liters, thus just more than the double. The intercooler will be chosen later on and the dimension used in the CAD packaging models should be feasible intercooler sizes but not final. The dimensions can be modified to arising dimension requirements as many different sizes can be found at this particular manufacturer website.  At Bell intercoolers, the price seem to be proportional to the size, hence a twice the size intercooler is twice as expensive.

### 7.6.4 List of requirements

The list of requirements has been a living document during the development process of the intake system. The requirements is based on flow calculations, the OEM manifold evaluation results, the pre concept generation research, as well as general guidelines from MarineDiesel.  It should be noted that the customer requirements in this state of the project still were not fully defined and hence the development process of the air intake system lacked requirements other than that it should be able to deliver air enough to support 1800 bhp. This gave the development team a lot of freedom concerning design choices and hence the list of requirements where kept very short at this state of the project.

The list of requirements has been used when screening and evaluating the concepts during the iterative concept development phase. When performing the evaluation of the final concepts the list of requirements has also been used to make sure the quality of the concepts. The list of requirements can be found in Appendix B.

# 8 Concept Generation and Iterative Concept Development

This chapter will briefly summarize the concept generation and the iterative concept development. Methods used are more extensively described in the method chapter, Chapter 4. The text below will explain some results from the concept generation and act as bridge between the research part and the following chapter where the design of the two final concepts are described more thoroughly.

## 8.1 Concept generation

A well conducted concept generation phase is very important to cover as many feasible design options possible. To break down the problem into pieces and investigate them separately, as well as investigation of the whole problem is a good way to find many solutions that solves the same problem. A screening and evaluation of concepts must thereafter be carried out in order to find unfeasible, unwanted and similar concepts. But also to find strengths and weaknesses for the various concepts so that redesign or possibly creation of totally new concept with desirable features can be made. At the end of this chapter two intake manifold concepts have been chosen for detailed design; one with prerequisites for intercooler integration and one focusing on system flexibility.

The four boxes within the system boundary (Figure 7-1) are four issues that must be addressed in order to solve the main problem. Different solutions for all of these can be found not only on existing intake manifolds but for other applications as well. Research was made for these four subsystems independently; plenum, runner, fasteners and upstream connection.

Creative papers were created in order to visualize the solutions and issues found regarding each sub-problem. The creative papers can be found in Appendix C. These helped to distinguish design features which needed to be addressed. The various designs of manifolds and the four subsystems made it possible to break down the solutions further into design features. Different solutions found for these design features were placed in a morphological matrix so that systems concepts could be developed and described by choosing from the solutions posted. In total there have been 22 concepts and most of them are represented by a “concept description paper” where the morphological matrix, a characteristically name and rough handmade sketch visualizes and explains the concept. In Appendix A, a scanned example of a concept description paper can be found where the specific design features for this concept is marked.

## 8.2 Iterative concept development

The iterative concept development reduced the amount of concepts from the initial 16 down to 2. There has been, as mentioned above, 22 concepts in total which implies that concepts have been created while other has been eliminated. During this process two categories of concept could be distinguished dependent on their connection to the air intake system; concepts having integrated intercooler or concepts being independent of intercooler placement. As the manifold design affects the air intake system configuration a system view is needed to work proactively with system feasibility.

Further in the development process it is more difficult to eliminate concepts as their level of detail and feasibility increases. One criterion to take into account is the concept flexibility. If the manifold design is flexible, thus cater for various air intake system solutions and could easily be adapted to arising requirements, the possibilities are greater that a future implementation will become reality. The concept flexibility, size and expected performance were the properties that had most impact on the final decision which brought the number of concepts down to the final 2.

## 8.3 Conclusions

Through certain events has concepts been created, evaluated, redesigned and removed. The level of detail has increased as concept has been moved further in the development process. The following main concept development exercises have been performed after the initial concept generation:

- Pugh matrix to remove unfeasible and similar concepts
- Weighted Pugh matrix to evaluate the improved concepts
- Visual control and physical packaging of engine to imagine the future design and adaptability to other systems
- Expert opinions gives new input and new focus
- Rough CAD design and packaging reveals manufacturing and assembling difficulties

One outcome from the research and concept generation chapter is that a feasible system solution is needed for every intake manifold concept. A manifold design this early in the MarineDiesel project must therefore be flexible and easy to adjust to later design requirements. The design will most likely experience this change and the concepts will therefore be guidelines rather than final solutions. The design justifications must be transparent in the report so that MarineDiesel have guidelines to follow if changes are necessary. The chosen system concepts and their design are described in the next chapter, Chapter 9, Detailed Design of Chosen Concepts. Two system concepts have been developed instead of one. If requirements change, MarineDiesel will have two options instead of one which is valuable if one is considered to be unfeasible.

# 9 Detailed Design of Chosen Concepts

It is of great importance to motivate the design choices made. In some cases the explanation can be simple whereas in others the explanation is a combination of facts and engineering assessments. In this chapter the two chosen concepts will be explained and the details will be clarified. In the next chapter, Final Concepts, will the system concept be visualized and the design will be evaluated and justified more thoroughly as a whole.

As the concepts have developed, their names have been developed accordingly. A characteristically name makes it is easier to distinguish the different concepts from each other. Concept one, Rocket sled, has with some imagination similarities with a sled and concept two, Budget Viper, sprang up as an idea after looking at a performance intake manifold in a Dodge Viper engine. Worth mentioning is that these names are temporary working names.

## 9.1 System concept one – Rocket sled - One intercooler on top

The Rocket Sled idea is an idea for a system concept solution rather than simply an intake manifold solution. The first thought regarding the Rocket Sled system solution design was to place the intercooler on top of the engine and by that save space in the width and length dimensions of the engine. The main problem hence became to create a smooth transition from the intercooler to the manifolds while still keeping the system compact and flow efficient. The manifolds of the Rocket sled are also designed to be as compact as possible and still have good flow capabilities. The name Rocket Sled comes from the similarity to a sled which was noted by the design team.

### 9.1.1 General design

The Rocket Sled is a compact system solution dedicated for a top-mounted intercooler and with two parallel turbo chargers placed behind the intercooler. The manifolds themselves can however be used in other system solutions as well. It is also worth mentioning that the manifolds are identical and hence only one cast mold is needed when manufacturing the manifolds. The manifolds are also designed without complicated inner geometries which also enables easier manufacturing.

The two main goals when designing the connector between the intercooler and manifold were compactness and flow. However, it became evident quite early in the process that a tradeoff between compactness and flow was needed. The bigger radius in the connector bend, the better the flow, but also the bigger the connector became. The final solution is not the most compact but the advantage in flow performance is however deemed more important than the small increase in acquired space.

The manifolds were designed with the same main goals as the connector; compactness and flow. In this case, it became apparent that the cylinder head was a problem since the attachment of the manifold required inner geometries that obstructed the flow. A solution to this problem was the introduction of specially designed adapters on each port to enable attachment through geometries outside the plenum. The Rocket sled concept can be seen in Figure 9-1.

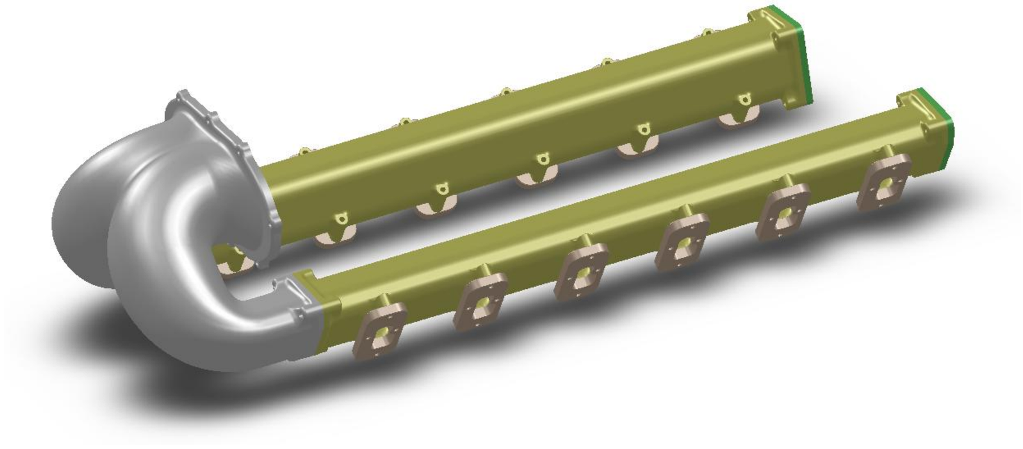


Figure 9-1 - Rocket sled concept

### 9.1.2 Plenum

The plenum cross section was designed to make the intake manifolds as low as possible and at the same time maintain a large cross section area and not claim too much space in the middle, between the manifolds. The volume of the plenum was also an important factor when designing the plenum. The chosen cross section gave the plenum a volume equal to about 50 % of the engine volume, which is just within the set requirements.

With the help of adapters it was possible to design a plenum without inner geometries that obstructs the flow. The solution is thanks to that very compact but has still a bigger plenum cross section than the OEM intake manifold.

The upper and inner surface of the plenum is horizontal respectively vertical to enable a close fit to intercooler and other engine components in the area.

The cross section of the plenum could possibly be made bigger if even better flow capabilities are required. This will however also affect the compactness of the design, and thereby the engine, since the intercooler possibly will have to be placed higher due to the increase height of the intake manifolds.

### 9.1.3 Runners

The Rocket Sled does not really have runners in the correct meaning of the word. It is rather just a smooth transition between the plenum and port. The radius of this transition has been kept as high as possible to enable good flow.

### 9.1.4 Upstream connection

The upstream connection of the Rocket Sled is oriented horizontally and aimed backwards because of the placement of the intercooler on the top of the engine. The shape of this connection was designed to keep a smooth transition from the two manifolds to the big square intercooler cross section. Many different cross sections were tested before settling for the ones chosen. It is however important to note that no real analysis have been made on the intercooler interface on this connector which should be further investigated when designing intercooler housing.

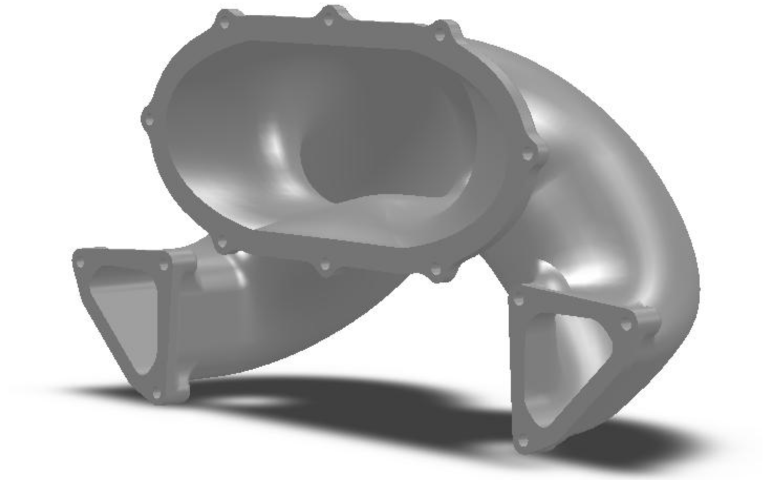


Figure 9-2 - Rocket sled connector

The connection to the intercooler cone are made with a screw joint and it is also worth mentioning that a proper intercooler cone has not yet been designed due to the fact that intercooler type have not been settled. A rendered picture of the connector that directs the air from the intercooler to the manifolds can be seen in Figure 9-2.

### 9.1.5 Fasteners and assembly

As mentioned earlier, the attachment to the cylinder head is made through adapters. One of these 12 adapters can be seen in Figure 9-3. The adapters are fastened to the cylinder head with M8 hex headed bolts and the intake manifold is fastened to the adapter through M8 bolts. Another very promising feature with the adapters is that they are very easy to adapt to other cylinder heads and port profiles. Even though some redesign will be required the main design of the intake manifold may be kept quite intact.

The manifold and connector are fastened to each other with M8 bolts as well. The bolt is meant to go in from the manifold side to avoid inner geometries in the connector. Other solutions for fastening of the connector was earlier tried but found unsatisfactory due to the problems they created by the need for inner geometries.

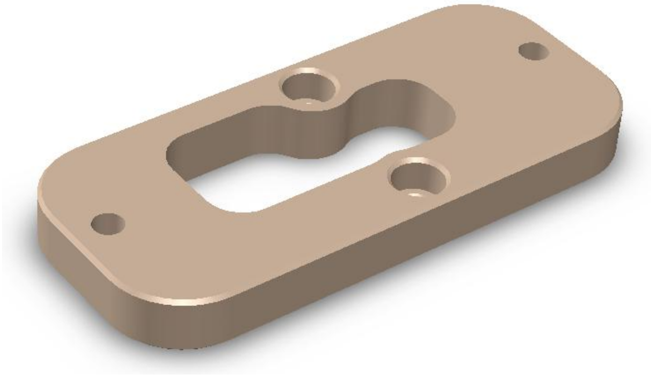


Figure 9-3 - Adapter

## 9.2 System concept two – Budget Viper - two flexible intercoolers

The Budget Viper is designed to be flexible concerning the air intake system. Thus the other components could be placed according to later requirements. There could be either one or two intercoolers which could be placed where suitable. The Viper concept, one of the first concepts generated, was found in a real Dodge Viper. A manifold having long runners and a round plenum is considered to be a performance intake manifold. Many of the MarineDiesel employees grew fond of the Viper concept of that reason. The present concept is less complex in its design and the runners are shorter, and hence the working name Budget Viper.

### 9.2.1 General design

The Budget Viper has one important similarity with the OEM manifold which is symmetry in design. The intake manifold is designed so that the same part could be used for both right and left side of the engine. Only one design and one big cast form has to be made which gives both economic and time advantages. However, some features must be added to the one manifold to make the symmetry work; a lid to close one side as well as features for attachment of the sensors. The manifold will be casted after which it will be processed to have the surfaces, holes, flanges and other features represented in the Figure 9-4.

The engine is a $90^0$ odd firing V12, thus the cylinders are angled $45^0$ from the vertical plane. The same applies to the cylinder heads and hence the ports are also angled $45^0$. The distance between the furthermost port edge and the end of the plenum is the same for both sides; hence the distance from the end of the manifold to the first port, independent of inlet side, is the same. This distance is easy to change which could be required if, for example, the plenum length, must be adjusted to fit fasteners.

The budget Viper concept consists of two independent intake manifolds. These two manifolds will be connected to either one or two intercoolers. If one intercooler is used, a connector between the two manifolds would have to be made. Two intercoolers can be placed with great flexibility later in the project. As long as connections can be accomplished between the components in the air intake system this intake manifold concept solution will be feasible.

Figure 9-4 - Budget Viper concept

### 9.2.2 Plenum

Given that runners should be used, the plenum geometry could be designed to have many different cross sections. Even though the Viper concept initially had a round plenum, polygon and square cross sections were also designed in order to consider the many possible design options. The polygon options however became very similar to the Rocket sled concept (with runners) and the Budget Viper would lose some of its uniqueness. The round profile has theoretically better flow capabilities and has an advantageous upstream connection profile.

The plenum diameter has been varied many times to find the best tradeoff between size and performance. The outer diameter is now 120 mm, the length is around 900 mm and the wall thickness is 8 mm. Calculations gives that the cross sectional area is approximately 8500 $mm^2$ (OEM manifold area ≈ 4750 $mm^2$) and the plenum volume is approximately 7.6 Liters per side (≈ 70% of engine displacement volume per side). The plenum diameter has also been increased to better fit with the intercoolers. A larger diameter reduces the length for the intercooler cone and the flow will not be re-distributed as much as with a sharper geometry transition.

The plenum can be made smaller. If the plenum diameter is decreased, the radius in the plenum to runner transition will have to be decreased. According to theory, this transition is very important and should be streamlined. There is a of course a lower limit of the plenum diameter. There must be room for a plenum to runner transition within the inner diameter of the plenum. The port length is 73 mm and the wall thickness is 8 mm. Thus, if the plenum outer diameter is 99 mm the runner and the plenum will be tangential. A smaller diameter than that would not give any advantages concerning flow or size. The plenum size should be a tradeoff between compactness and performance.

### 9.2.3 Runners

The runners are now bended $45^0$ so that the plenum to runner transition is designed to be in the horizontal plane. A straighter runner would result in a more uniform flow profile in the runner as all the flow travels approximately the same distance. Increasing the runner bend radius (going towards straight runners) does not however change the flow velocity profile much. The compactness of the system is more important in this case. This present concept is designed so that less space is claimed in the middle. The manifold gets also more separated so that intercoolers could fit side by side in the rear upper part of the engine. If altering the runner bend radius and the plenum diameter there must be enough room for fasteners and tools. There is now room for a 40mm M8 bolt which is the attachment needed to the present adaptor.

A concept with runner makes it possible to design fuel lines and wiring to run between the runners. There is an inner geometry transition between the port and the plenum. The runners start with the port profile and transforms into an oval profile at the runner to plenum intersection. This is mainly to create smooth transitions as well as facilitate equal flow as the flow is coming from different sides in the two intake manifolds, see Figure 9-5.

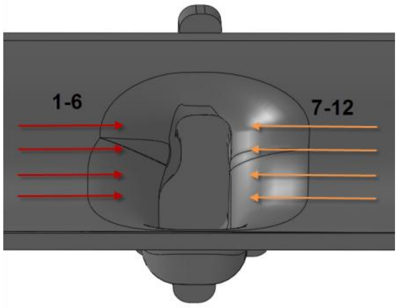


Figure 9-5 - Flow direction in the Budget Viper concept manifold

### 9.2.4 Upstream connection

The upstream connection is affecting the geometry of the pipe/connector going to the intercooler. For example, if a polygon cross section is implemented, there must most likely be a transition to different cross-section geometry between the manifold and intercooler. One reason for the round plenum is that standard pipes, cones and bends of different materials could be used in the connection of the manifold to the intercooler.

The connection from the Intercooler to the manifold must have the same interface, thus round. In this case the intercooler cone ends with a round profile with a flange for a v-clamp. A v-band clamp is not a good solution for bending forces, but is a good for leaks when adding an o-ring. An o-ring has a good leak preventing effect with little clamping force. Other options for attachments are adding flanges or bosses for bolts and nuts. Flow is now coming from the back of the engine according to the research conclusions. However, if new requirements arise, the lid in the front could be moved to rear part and the inlet will be facing forward. In Figure 9-6 the attachment of the lid with a v-band clamp could be seen as a cross-section. Features as a flange for alignment and a small cavity for the o-ring are added.

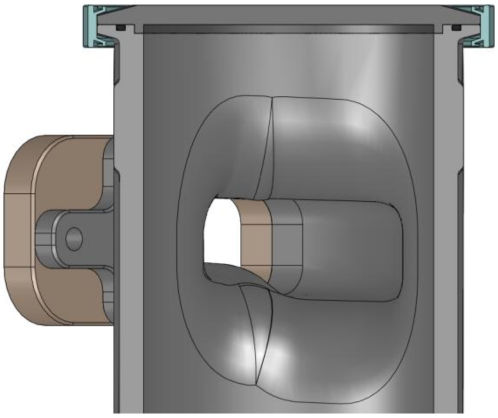


Figure 9-6 - Cross section of the end of the Budget Viper plenum

### 9.2.5 Fasteners and assembly

As for the Rocket Sled concept, adapters (Figure 9-3) are used to allow a greater wall thickness with a maintained port profile through the runner. The adapters are fastened with two insex bolts to the actual cylinder head that are lowered into the goods so that the intake manifold could be attached to the adapter that is having a different hole pattern. Preferably can same bolts be used to all attachments points.

## 9.3 Wall thickness

The wall thickness in the concepts has been chosen with respect to durability and casting. In earlier projects at Marine Diesel a wall thickness of at least 8 mm has been preferable by the foundry. It is also considered to be thick enough to withstand a high inner pressure as long as there are no big flat surfaces. The wall thickness is therefore at least at 8 mm in both of the new concepts.

# 10 Final Concepts

The two concepts are different from each other, thus none of the two can be considered to be better than the other as their advantages and disadvantages depend on requirements that do not exist. The advantages and disadvantages will in this chapter be concluded so that one concept can more easily be chosen to fit future requirements. Both system concepts will also be visualized and the design will be evaluated through flow simulation, prototype build and packaging. The design choices made are more thoroughly described in the previous chapter whereas this chapter verifies the concept designs and gives recommendations to further work so that guidelines for redesign and hopefully implementation are clearly described.

## 10.1 Concept description – Rocket Sled

In Figure 10-1 the suggested system solution to the Rocket sled concept is shown. The suggested system solution also includes a rough model of an intercooler and one of two turbochargers assembled to the intercooler in the rear part of the engine.

The system consists of four different parts. Firstly the two intake manifolds that are identical. Secondly the 12 adapters that are placed between the cylinder head and the intake manifold. Thirdly the connector that connects the two manifolds to the intercooler. Fourth and last there is an endplate that is placed on the opposite side of the connector on each manifold. The intercooler cone, housing and the turbo is only assembled for packaging reasons.

### 10.1.1 System design features

The Rocket Sled concept is a very compact and yet powerful solution. The concept is optimized for flow through the connector, from the intercooler to the manifolds. The flow through the manifolds has also been improved by getting rid of inner geometries and the use of a big radius in the transition from the plenum to the ports.

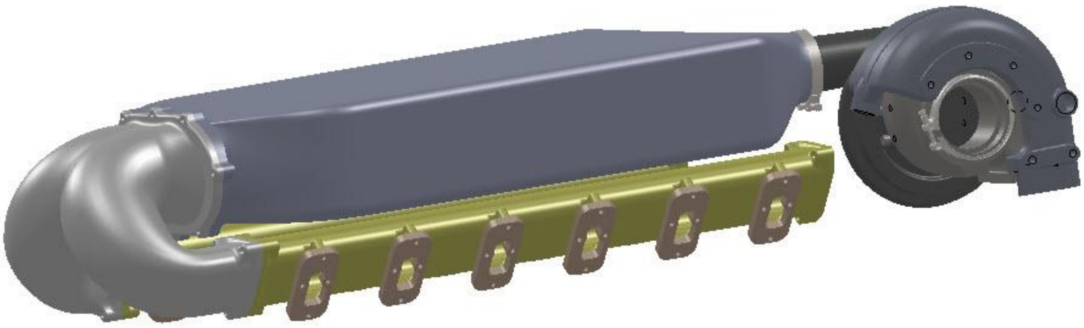


Figure 10-1 - System concept with Rocket Sled

The design also focuses on keeping it easy to assemble and disassemble. Even though the implementation of adapters requires a few extra bolts they however make it easy to access all bolts, and provides much space for tools to fasten them. The Rocket sled system solution saves a lot of space in the width dimension of the engine since the intercoolers and turbochargers are placed above the engine, not on the sides.

### 10.1.2 Concept evaluation

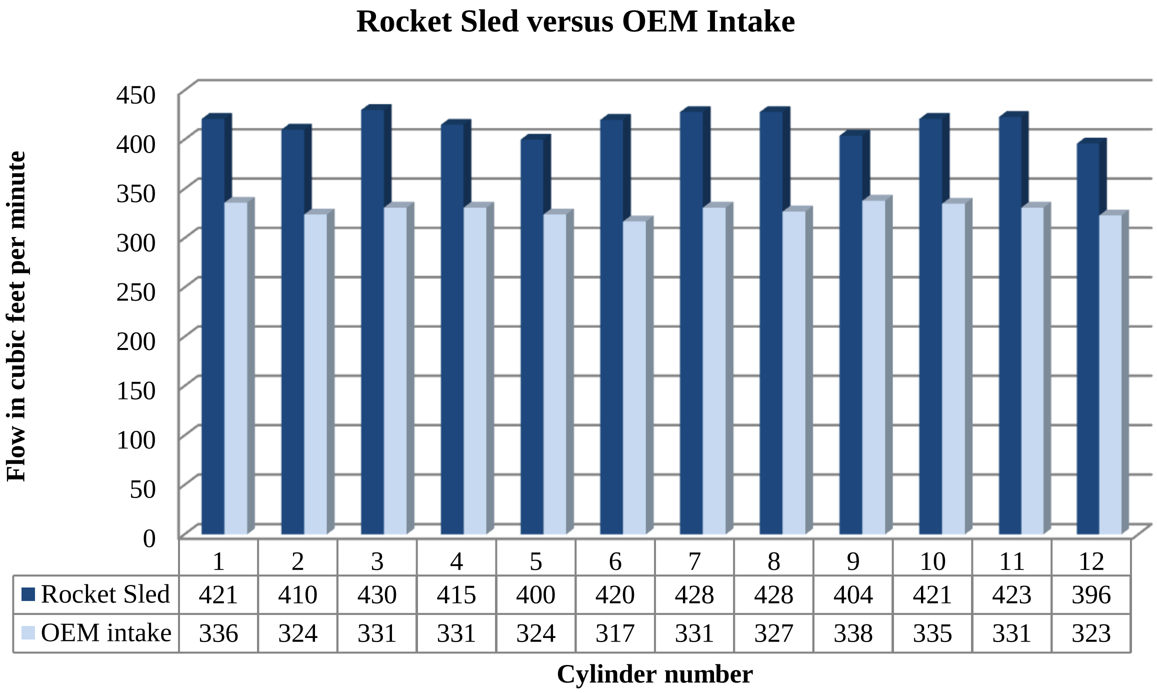
The simulations of the Rocket Sled concept have been performed with the two manifolds, the adapters and the connector. This system concept is quite similar to the OEM intake system (two symmetrical manifolds and a connector) and hence adequate comparisons to the OEM simulation could be made.

#### *10.1.2.1 Standard flow simulation*

The standard flow simulation of the Rocket Sled was on average more than 20 % better compared to the OEM intake as can be seen in Figure 10-2. The flow is however slightly more unequal between the ports. The difference between the ports does however not exceed 5 % deviation from the average.

#### *10.1.2.2 Deliverability of average mass flow during one intake sequence*

The results from this simulation, which can be seen in Table 10.1, Table 10.2, and Table 10.3, were quite extraordinary. Compared to the OEM intake the Rocket Sled has a 40 % higher mass flow during one intake sequence. The deviations of the flow between the ports are also lower, 9% compared to 19%, which is good.



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ Rocket Sled | 421 | 410 | 430 | 415 | 400 | 420 | 428 | 428 | 404 | 421 | 423 | 396 |
| ■ OEM intake | 336 | 324 | 331 | 331 | 324 | 317 | 331 | 327 | 338 | 335 | 331 | 323 |

Figure 10-2 - Standard flow simulation results for OEM and Rocket sled

Table 10.1 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 8** | **2.56 kg/s** | **Port 1** | **2.59 kg/s** |
| **Port 12** | **2.60 kg/s** | **Port 5** | **2.58 kg/s** |

Table 10.2 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 7** | **2.56 kg/s** | **Port 3** | **2.61 kg/s** |
| **Port 10** | **2.40 kg/s** | **Port 6** | **2.63 kg/s** |

Table 10.3 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 9** | **2.55 kg/s** | **Port 2** | **2.48 kg/s** |
| **Port 11** | **2.60 kg/s** | **Port 4** | **2.47 kg/s** |

### 10.1.2.3 Geometry analysis based on flow trajectories

As can be seen in Figure 10-3 the flow trajectories run smoothly through the connector and manifold. The flow has a generally low flow velocity throughout the entire flow path and only accelerates very close to the ports. This implies that it is the ports that limit the flow instead of the intake manifold and hence the intake manifold and connector will not be a bottleneck in the system. Analysis of the trajectories also confirms the research that implied that smooth transitions and bends with big radii is very good for the flow characteristics.

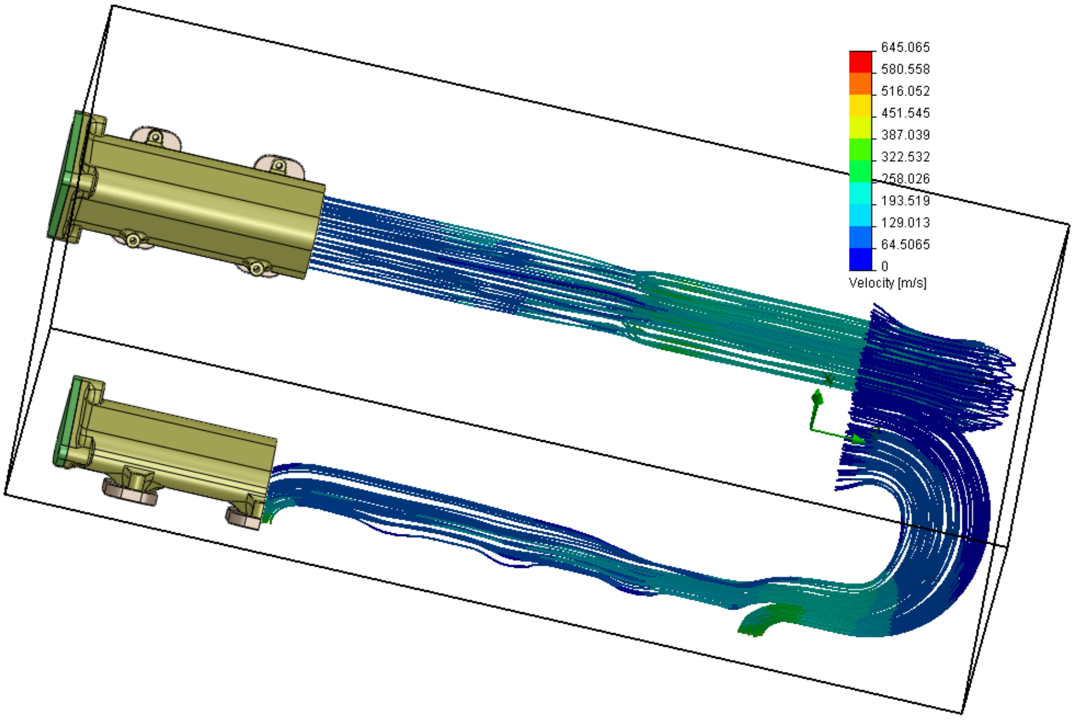


Figure 10-3 - Flow trajectories for mass flow simulations

### 10.1.3 Rough dimension Drawings

In Figure 10-4 the wanted dimensions of the engine is compared to the Rocket Sled concept with the rough intercooler model and one of two turbochargers assembled at the back. As can be seen the engine is slightly longer with this concept but also extremely compact in width and height. It is however worth noting that quite a lot of parts still lack from the engine and the final engine will be much bigger. This intake system solution however leaves a lot of room for other systems which will make the development of the other systems easier. In Figure 10-5 and Figure 10-6 rough dimension of the Rocket Sled concept can be seen. These dimensions are not exact and are only meant to give the reader an understanding for how big this part will become.

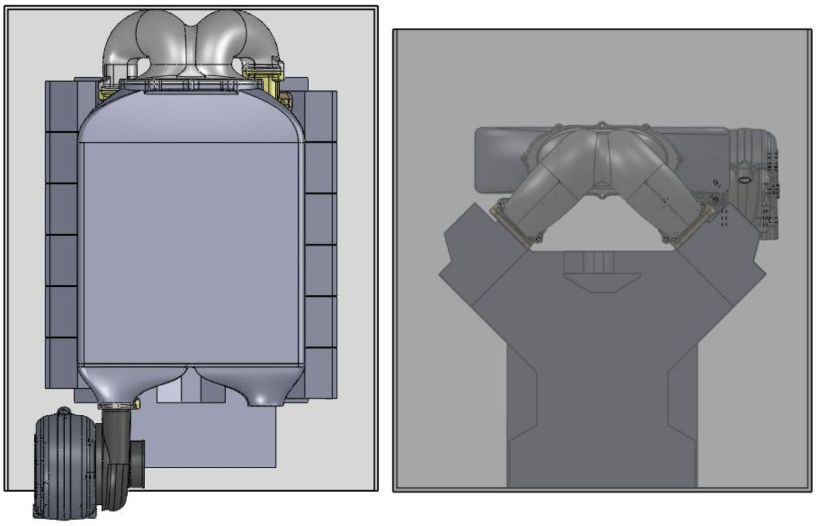


Figure 10-4 - Rocket sled concept compared to wanted dimensions

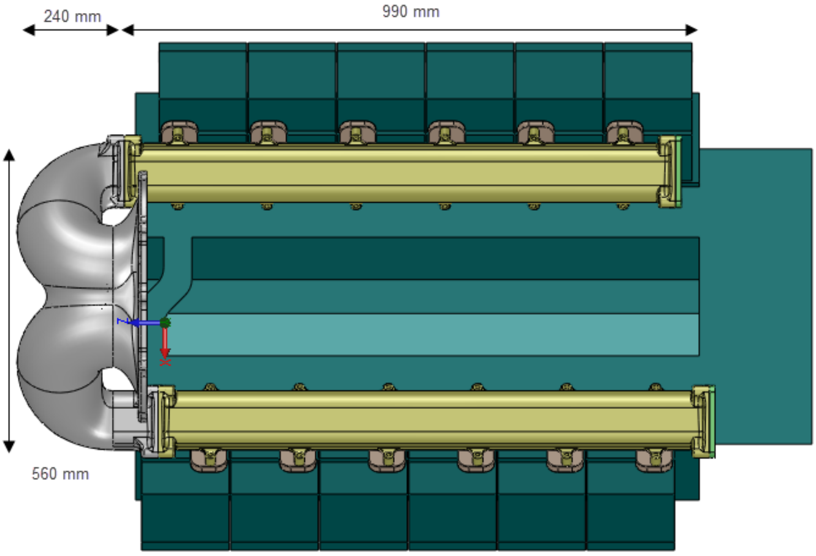


Figure 10-5 - Rough dimension drawing for Rocket sled concept, top view

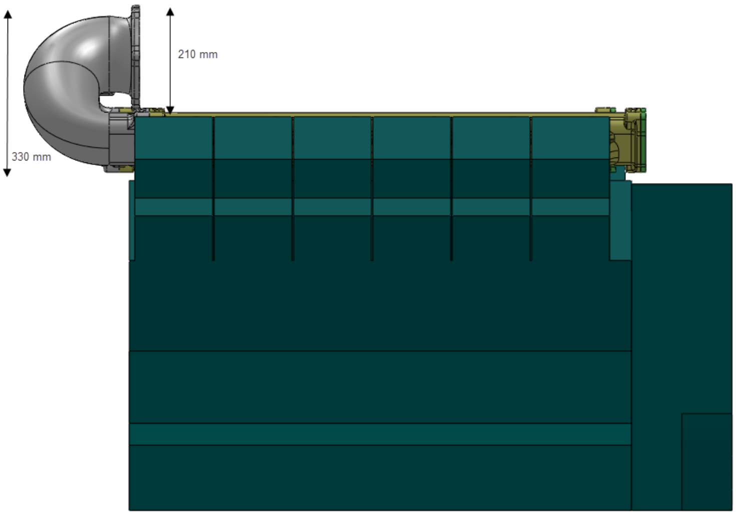


Figure 10-6 - Rough dimension drawing for Rocket sled concept, side view

### 10.1.4 Conclusions

The simulations performed on the Rocket Sled concept shows that it will perform well above the stated requirements for the new engine. The simulation results also show that the performance of the Rocket Sled greatly exceeds the performance of the OEM intake system.

The Rocket Sled solution is limited to have an intercooler on top of the engine. This solutions is considered to be compact and yet efficient. The manifolds could however be used in other system solutions. The Rocket Sled solution is deemed to be easy both to manufacture and assemble due to the use of adapters.

The printing of the rapid prototypes and the following assembly indicated that the CAD model of the Rocket Sled needs to be adjusted to better fit the port and attachments to the cylinder head. A laser scan of the engine parts should solve this issue.

## 10.2 Concept description – Budget Viper

Figure 10-7 shows an example of a system solution using the Budget Viper intake manifold concept. Note that this is one of many air intake systems possible using two separate manifolds and that the intake manifold concept is not looked to any certain system solution. This particular system is designed to be compact and to have good flow capabilities.

### 10.2.1 System design features

The pipe that is connecting the two manifolds is necessary due to pressure distribution causes. There could be unwanted torsion in the engine block if the two sides are totally separated in the air intake system and thereby delivers different moment to the crank shaft. This particular pipe design is just one of many that could be implemented and adjusted to different air intake system configurations.

The sensors measuring temperature and pressure must be located between intercooler and manifold according to Chapter 3, Functional Description of the Air Intake System. In this case where no connecting pipe or connector between the manifolds exists, the sensors are placed before the first port in the plenum. The sensor placements could be removed from the plenum if the systems solution changes. This also implies a slightly more simple manifold design.

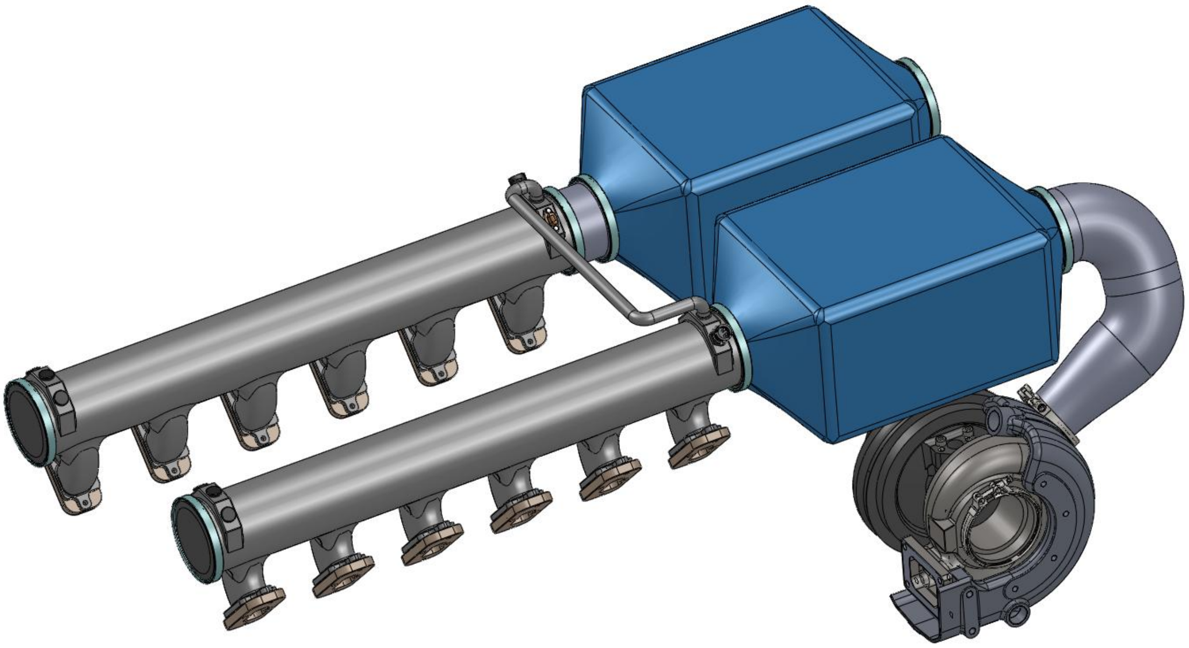


Figure 10-7 - System concept with Budget Viper

The diameter of the plenum is also, in this system, connected to the intercooler. In order to decrease the cross sectional area in the intercooler down to the plenum diameter, tapered geometry should be used. In a flow perspective the cone should in this case be long to preserve good flow. If the plenum diameter is bigger the re-distribution of flow from the intercooler to the intake manifold will be less extensive. The designer of the intercooler will be responsible for the transitional geometry between intercooler and manifold.

The same diameter and the same v-band clamps have been used for the flow path to demonstrate the benefits of having few different fasteners. The intercooler cone could preferable look the same for both sides on both intercoolers. Furthermore, a short extension pipe has been designed, placing the two intercoolers side by side, which is good for the engine symmetry and centre of gravity.

### 10.2.2 Concept evaluation

The flow simulations have been made with the manifold only. The other parts in the system are very conceptual and the main reason for the simulations is to verify the flow capabilities of the manifold separately. This manifold does not have a dedicated connector as the system solution is very flexible. It would thereby be wrong to add a connector to the flow path.

#### *10.2.2.1 Standard flow simulation*

Firstly it is interesting to compare the standard tests made with the OEM manifold (Figure 6-4) with the Budget Viper when flowing one port at the time. The initial tests with the first Budget Viper concept showed around 20% increase in performance. Both samples are compared in Figure 10-8. When comparing the results one can easily see that the flow is more equal and the volume flow is approximately 30% higher under these conditions. The flow rate is gradually lowered (very little) as simulations are made further away from the manifold inlet (inlets by ports 6 and 12), which is according to theory. The simulations have been made exactly the same way for both samples and hence a valid comparison can be made.

### *10.2.2.2 Deliverability of average mass flow under one intake sequence*

The same evaluation has been made once again for the Budget Viper as for the OEM manifold. The same three intake sequences (out of twelve possible) are re-used and the results are show in Table 10.4, Table 10.5 and Table 10.6. The differences are once again concerning equal flow and an increase in performance. All ports are within a deviation of 0.03 kg/s (≈1%) from each other and more than 4 times the average mass flow (Chapter 5.1.3) is delivered. Comparing this to the results obtained from the simulations with the OEM manifold where the deviation was up to 16% and the lowest mass flow (OEM port 2) is 30 % lower than the same port in the Budget Viper concept.

Worth noting is that when performing flow tests on more than one port simultaneously, the flow profile is very similar, hence predictable, both in the manifold and in the runners. This is a preferable quality according to theory.

Table 10.4 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 8** | **2.18 kg/s** | **Port 1** | **2.19 kg/s** |
| **Port 12** | **2.19 kg/s** | **Port 5** | **2.18 kg/s** |

Table 10.5 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 7** | **2.18 kg/s** | **Port 3** | **2.20 kg/s** |
| **Port 10** | **2.17 kg/s** | **Port 6** | **2.18 kg/s** |

Table 10.6 - Mass flow simulation results

| | | | |
|---|---|---|---|
| **Port 9** | **2.21 kg/s** | **Port 2** | **2.18 kg/s** |
| **Port 11** | **2.18 kg/s** | **Port 4** | **2.18 kg/s** |

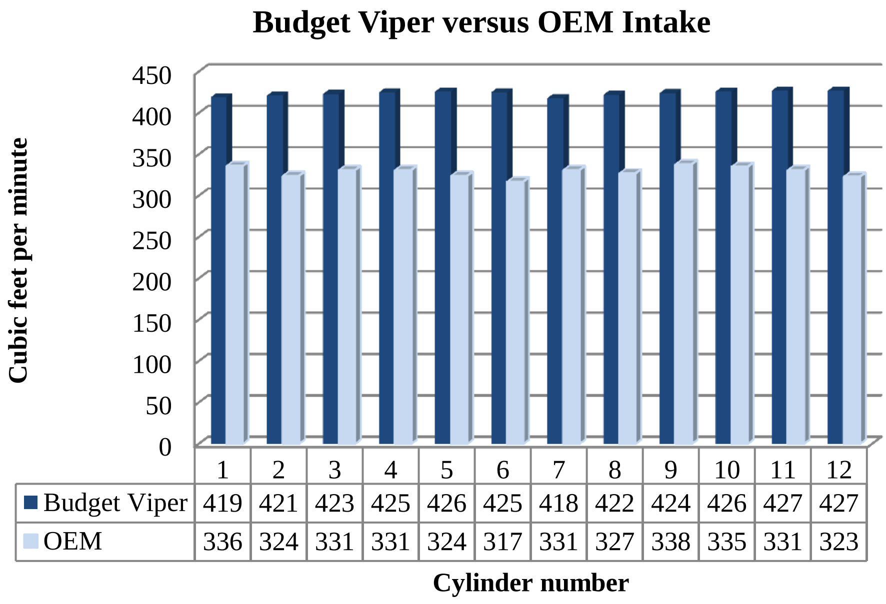


Figure 10-8 - Standard flow simulation results for OEM and Budget Viper

### 10.2.2.3 Geometry analysis based on flow trajectories

There is a big difference between the trajectories from the simulations with the OEM manifold. The flow profile in the plenum is very good. There seem to be laminar flow over the runner cross section and no potential disturbance could be seen except for the runner bend. The velocity/pressure distribution in the runner is dependent on the bend radius. A straight runner will deliver a uniform flow distribution. According to these simulations the flow is accelerated more close to the inner curve, which is due to the port geometry. The port geometry is smaller in the upper end of the port but the plenum to runner transition is oval, thus just as big over the whole port, and there is a velocity increase due to that. If MarineDiesel experiences velocity problems in the runners, one way to counteract this is to have the port profile in the plenum to runner transition so that less flow is going through where the port is smaller. In Figure 10-9 the flow trajectories for the mass flow is shown.

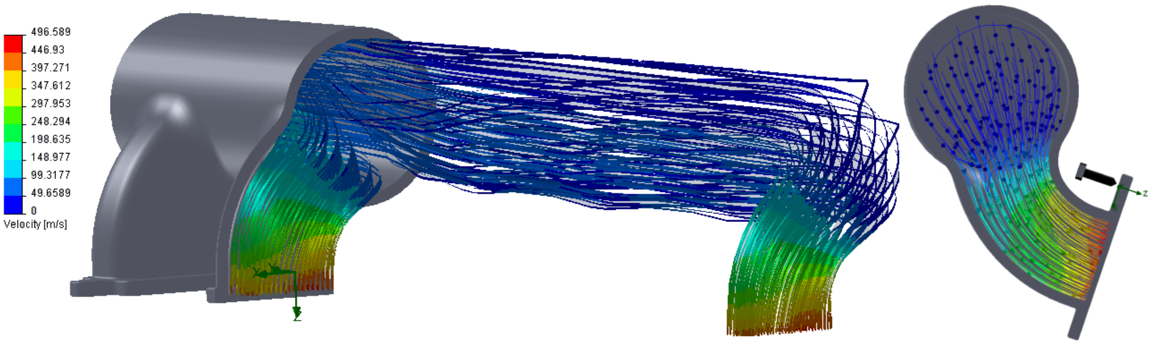


Figure 10-9 - Flow trajectories for mass flow simulations

Flow tests with the present intercooler box are unnecessary since the probability that the air intake system will have another configuration is quite big. These flow tests are based on that air is flowing straight towards the plenum which may be different from reality. As intercooler placement and its connection to the plenum are not known in this system concept, the recommendation is to perform these tests again when more details are known.

### 10.2.3 Rough dimension Drawings

As mentioned in the research chapter (Chapter 7) the wanted dimensions are based on the least dimensions from three other MAN engines using the same engine block. In Figure 10-10 it is visible that the height and the width are within the limits. Using 200 mm for other components in the front, the system builds approximately 450 mm in the back. The turbo will most likely fit over the transmission box in the back, but if shortness is factor of importance the components should be placed differently (Intercooler(s) on top or on the sides).

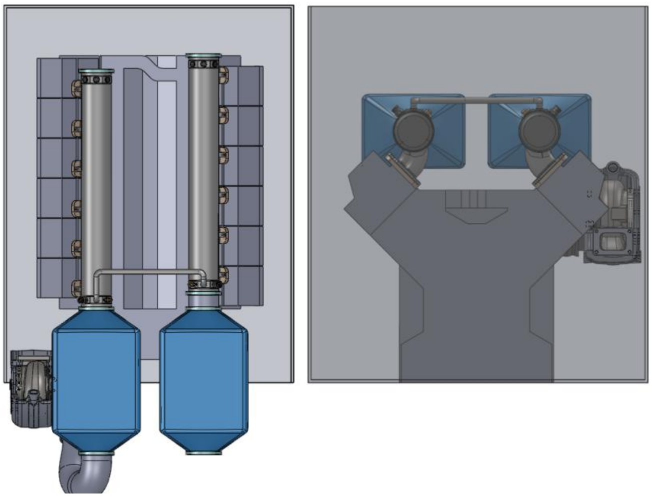


Figure 10-10 - Rocket sled concept compared to wanted dimensions

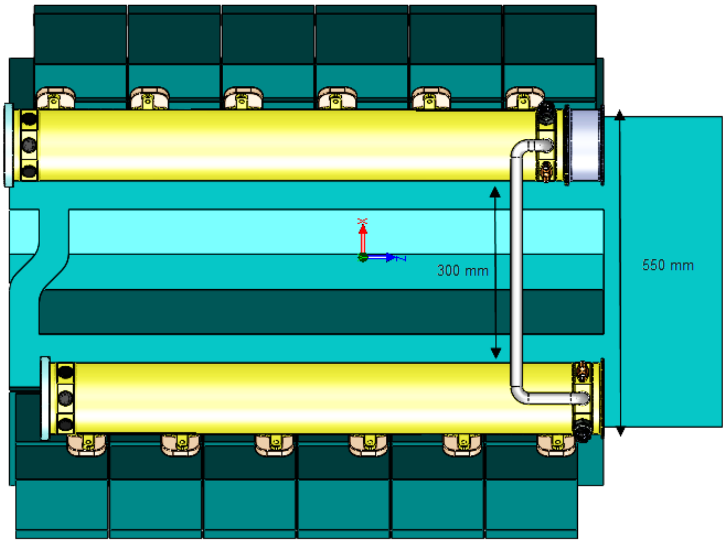


Figure 10-11 - Rough dimension drawing for Budget Viper concept, top view

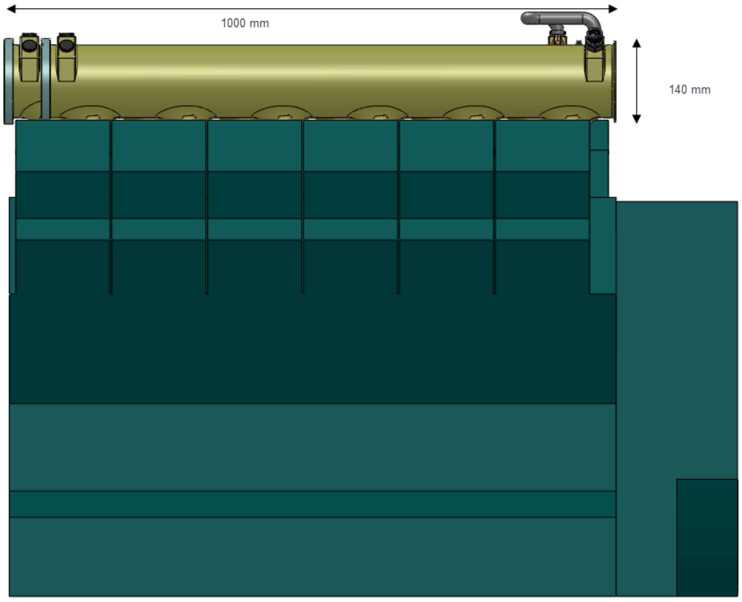


Figure 10-12 - Rough dimension drawing for Budget Viper concept, side view

Figure 10-11 and Figure 10-12 shows more clearly the size of the Budget viper intake manifold. Rough dimensions are also added to the Figures.

### 10.2.4 Conclusion

The Budget Viper air intake system concept is a flexible option. Two intercoolers that could have different dimensions and locations can be placed later in the project when more details and requirements are known. This could be the case if MarineDiesel are obligated to fix the designs of other systems and components before the air intake system, which could limit the design possibilities.

Altogether the Budget Viper manifold could be made smaller with sufficient performance. Once again, there is a tradeoff between size and plenum diameter, plenum to runner transition radius, runner length, runner bend radius and upstream connection interface. However, small decreases in these dimensions are not giving very much new free space. Worth noting is that a reduction in size can be made (down to 99 mm outer diameter) and the flow capabilities are still sufficient.

The Budget Viper concept in its present form builds in the length dimension but is actually within the wanted height and width dimensions (Figure 10-10). The system solution shown in this chapter is a compact solution. The feasibility must however be reviewed mostly concerning the potential clash with gearbox and water pump which are placed in the rear part of the engine.

## 10.3 Rapid prototype assembly

The plastic prototypes created in the rapid prototype printer cannot be flow tested but is still a very cheap, fast and effective way to evaluate concepts at an early stage. Two prototypes were created in this project, one for each concept. The concepts were not printed in full scale, instead cross sections of the intake manifolds, about one fourth of the full length, was created. The rapid prototype length allowed the prototypes to be mounted on the engine for evaluation considering size, geometrical restrictions, interfaces, possible clashes with other engine systems and also the overall feeling. The rapid prototypes are also valuable as a visual tool to present the concepts to other staff at the company and allow them to give feedback. The mounted prototypes can be seen in Figure 10-13 and Figure 10-14.

### 10.3.1 Observations

There is a good general impression of the prototypes. They are deemed to be well designed by staff as well as project team. The two concepts differ a lot in size, which is illustrated in Figure 10-15 where you can see the two prototypes mounted side by side.

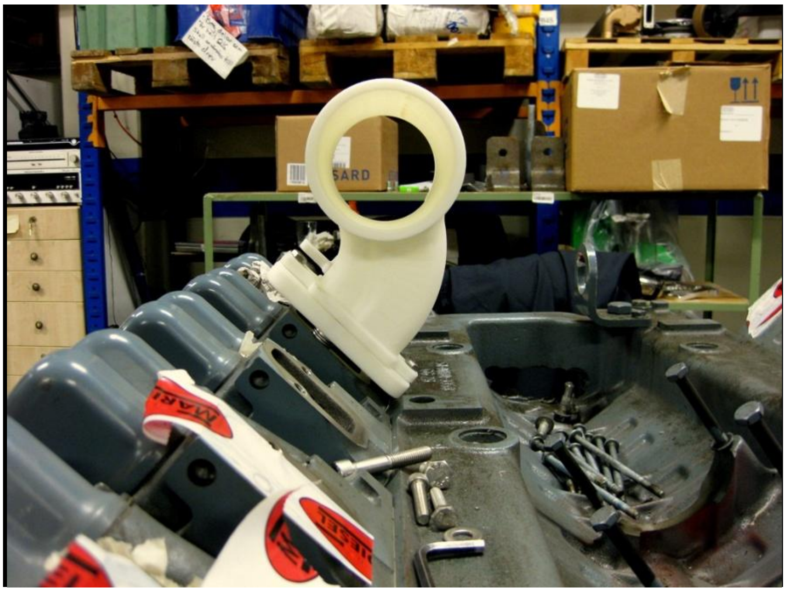


Figure 10-13 - The rapid prototype model of the Budget Viper intake manifold

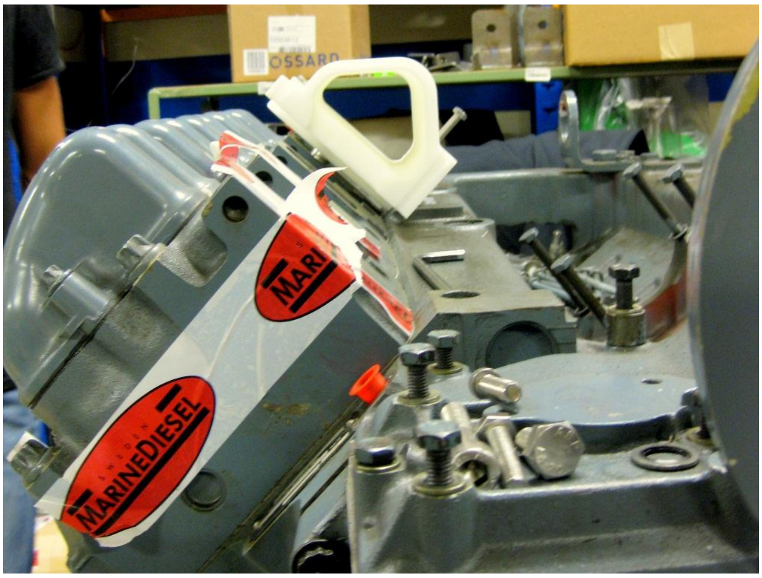


Figure 10-14 - The rapid prototype model of the Rocket Sled intake manifold

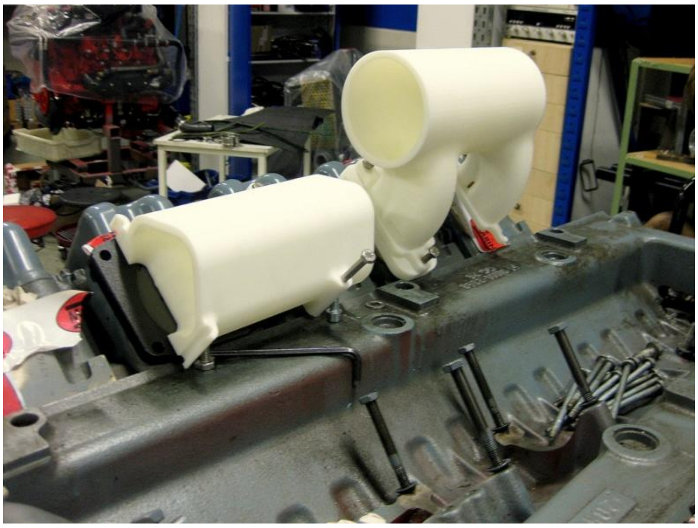


Figure 10-15 - Both concepts assembled to the engine

The port interface and attachments to the cylinder head did not match perfectly with the rapid prototype. This made it hard to attach the adapter to the cylinder head. This was however deemed to be due to the method used when measuring the engine parts. The precision when using rulers and so on is not as exact as for example a lasers scan. The attachment of the adapters must hence be slightly adjusted in order to make it fit perfectly on the cylinder head. As it is now, it is not possible to assemble due to clash with the engine block.

The edges of the Rocket Sled ports might be a bit too sharp to be able to cast. The face of the port that is to connect to the adapter will however be machined after casting to enable a tight seal to the adapter. This means that some extra material will be needed at that face when casting the intake manifold. This might be enough to solve this problem. Both of the concepts do not seem to interfere with other subsystems as long as adjustments are made to the adapter.

## 10.4 Material

The material used in both concepts is an aluminum alloy that is used as standard for these kinds of applications on MarineDiesel. The material is considered to be well suited for complicated, thin walled, casted constructions that are to withstand inner pressure. The material does also have good mechanical properties and good resistance to corrosion. Since the material has been used earlier by MarineDiesel with good results no further research have been done to find other suitable materials.

## 10.5 Discussion and recommendations

The concepts made in this report are not ready for production and should not be. The focus has been set on creating flexible feasible concepts that are possible to manufacture when adapted to future requirements in order to create the best possible prerequisites for MarineDiesel to implement in the project. If decisions are made to be final early in the project, necessary changes can later on require extensive rework. It is better in this case to create flexible solutions and make the final decisions as late as possible.

The manual measurements performed early in the project are carefully made and good for concept studies but will not be exact enough to meet later requirements concerning alignment and tolerances. Hence a laser scan of chosen components or design straight from drawings must be made to consider this issue. As the measurements are inaccurate all CAD models needs to be re-made. The CAD-models and documentation will be used as guidelines when MarineDiesel continues to work with the project.

The theoretical research and the pre concept generation research proved to be satisfying. The initial design and testing on the concepts gave very good results. The drawbacks stated in the OEM manifold evaluation conclusion were all considered and strongly improved. No extensive re-design was needed as the concepts showed expected flow results.

The simulation conditions are corresponding to full speed, thus when most mass flow needs to be delivered. The future charge pressure is unknown, as well the back pressure in the cylinder during the intake sequence. According to calculations 4,815 bar absolute pressure (3,815 relative pressure between manifold and cylinder) has been used to verify the flow capabilities and none of the manifolds tested have had any difficulties to deliver sufficient mass flow. If the volumetric efficiency is higher than 0.85 the needed charge pressure is lower. A well designed air intake system reduces the magnitude of the charge pressure. The flow simulations and analyzes made are considered to be sufficient at MarineDiesel to verify the capabilities of the intake manifold.

An unexpected result of the concept evaluation is that the Budget Viper that where designed to be a performance intake performed worse than the compact Rocket Sled manifold in the deliverability of mass flow during one intake sequence simulation. The simulations where performed several times to verify the results and a short analysis to understand why this occurred were also performed. During this analysis the Budget Viper were also simulated with shorter runners which gave a better result than the long. The result of this analysis implies that long runners hinder flow but caters for a more even flow. The concepts chosen have however both performed more than well and no adjustments were made to the concepts.

The cylinder heads may have to be replaced for instance due to unsatisfying flow capabilities through the valves. If MarineDiesel chooses to change the cylinder heads the concepts are still useable. Our recommendation is in that case to change the port profile and the bolt pattern. This could eliminate the need for adapters, thus the concept could be assembled directly to the new cylinder heads. The adapters are now used to change the bolt pattern as the present short distance between the hole and the port is not making room for bolts outside the flow path (wall thickness would be to thin if the bolts were to be placed e.g. by the side of the runner in the Budget Viper concept). Both intake manifold concepts could be used together with new cylinder heads. The use of adapters allows however the design of the manifolds to be both compact and flow efficient.

The OEM manifold has been tested and evaluated. In Chapter 6.3 conclusions can be found regarding the OEM design and flow capabilities. According to calculations and testing the OEM would be able to deliver sufficient flow in spite of the drawbacks found. This implies that MarineDiesel could use the existing manifolds for physical testing up to 1800 hp. If the OEM manifold performs as expected it could be used as a final solution later on. If replacing the intake manifold concepts the OEM manifold is in fact compatible with both suggested air intake system concepts. The overall design and performance is not as good as for the two new concepts, but the solution is feasible as long as upstream connection(s) could be accomplished. However, if new cylinder heads are to be made, our suggestion is to not use the OEM due to the complicated design and its inferior flow.

The Computer aided design has been made with Solid Works software. It is very important when using CAD for design to make simple and stable models. The dimensions and features should be sketched and connected to parts of the model that is more or less set, thus where the risk for changes to occur is relatively low. Redesign due to a wrongly defined CAD model consumes time and energy. Much time has been spent with CAD and many models have been made to end up with the two final concepts chosen.

In design there are many options to consider and interdependencies between them. A small change in one feature could result in the need for a change in one other. When there are few facts stated and few requirements to follow, thus many uncertainties, it is hard to make final decisions and find a best solution. The solutions presented in this report are designed from the prerequisites given and are fulfilling the existing requirements. MarineDiesel now has two different intake manifold concepts with associated air intake systems to aid their future decision-making. The design choices made for the Budget Viper and Rocket Sled should be visible in the report so that the concepts could be verified by the reader. As mentioned, new requirements will arise, and the flexibility built in the concepts can easily be utilized and hopefully bring a final solution mostly based on the findings stated in this master thesis report.

# List of References

## Books

Bell, C. (1997). *Maximum Boost.* Cambridge, USA: Bently Publishers.

Bergström, K. (1987). *Förbränningsmotorteknik.* Göteborg, Sweden: Institutionen för Förbränningsmotorteknik Chalmers Tekniska Högskola.

Ferguson, C. R., & Kirkpatrick, A. T. (2001). *Internal combustion engines.* New York: John Wiley & Sons.

Fleming, J. (2000). *Complete guide to diesel marine engines.* Enola, Pennylvania: Bristol fashion publications.

MacInnes, H. (1984). *Turbochargers.* New York, USA: The Berkely publishing group.

Miller, D. S. (1990). *Internal flow systems.* Houston, Texas: Gulf publishing company.

Ulrich, K. T., & Eppinger, S. D. (2008). *Product Design and Development - fourth edition.* New York, NY, USA: McGraw-Hill Companies, Inc.

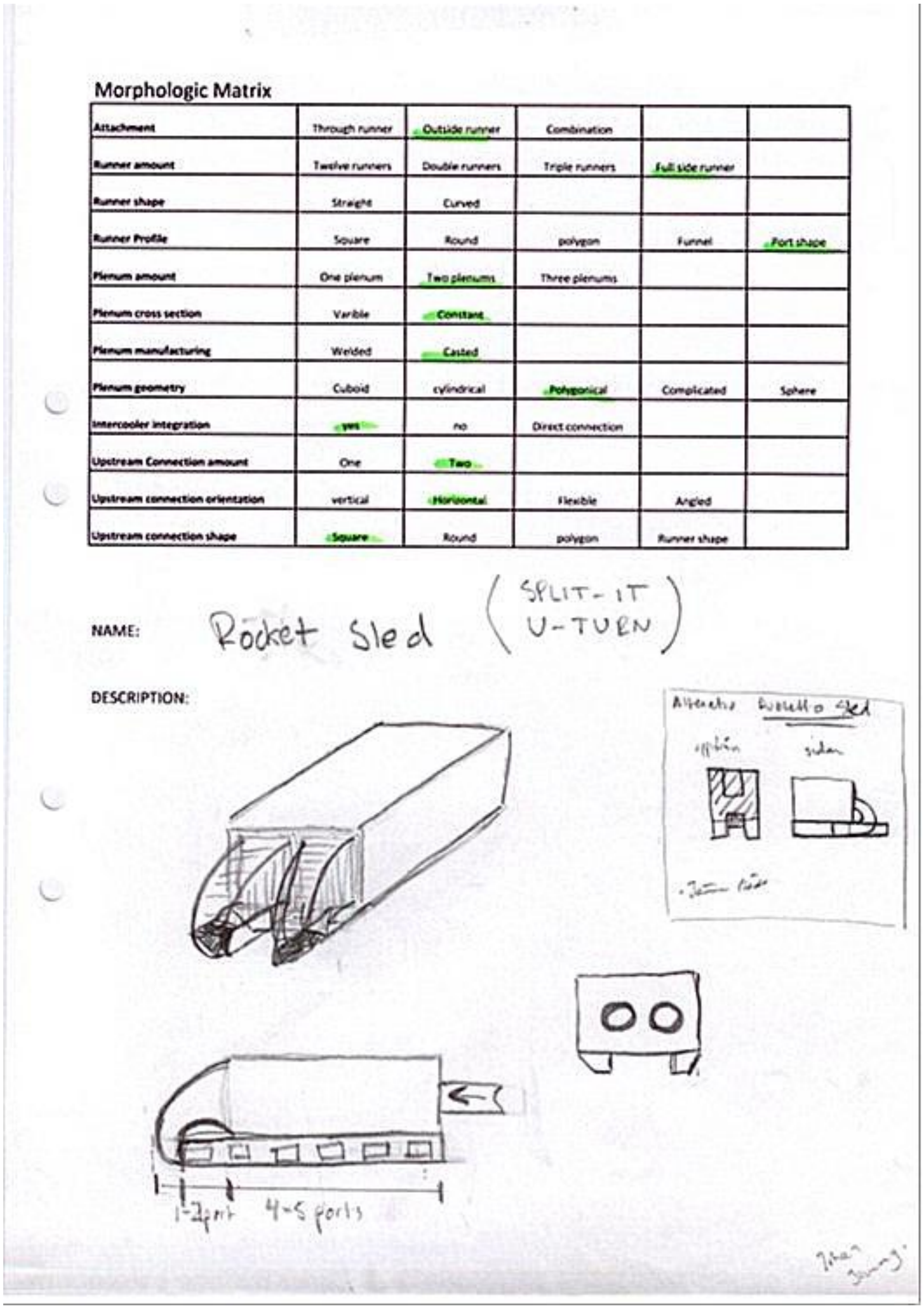
Zander, L. (2007). *Internal Combustion Engine Gasexchange & Boosting.* Stockholm: Lennarth Zander and Jure Förlag AB.

## Web References

1. Liquid to air intercooler systems. http://www.bellintercoolers.com. (18 may 2011)

# Appendix A – Example of Morphological Paper for Concept Generation

Below you can see the concept Rocket sled. The reason for the two names within brackets is that Split It and U-turn has been combined into this concept. The sketch is very simple but should try, together with the marked matrix, to make the concept understandable. Dubletto is a similar concept that could be used with the overlaying intercooler. Dubletto has though its own morphological paper.



Morphologic Matrix

| | | | | | |
|---|---|---|---|---|---|
| **Attachment** | Through runner | Outside runner | Combination | | |
| **Runner amount** | Twelve runners | Double runners | Triple runners | Full side runner | |
| **Runner shape** | Straight | Curved | | | |
| **Runner Profile** | Square | Round | polygon | Funnel | Port shape |
| **Plenum amount** | One plenum | Two plenums | Three plenums | | |
| **Plenum cross section** | Varible | Constant | | | |
| **Plenum manufacturing** | Welded | Casted | | | |
| **Plenum geometry** | Cuboid | cylindrical | Polygonical | Complicated | Sphere |
| **Intercooler integration** | yes | no | Direct connection | | |
| **Upstream Connection amount** | One | Two | | | |
| **Upstream connection orientation** | vertical | Horizontal | Flexible | Angled | |
| **Upstream connection shape** | Square | Round | polygon | Runner shape | |

NAME: Rocket Sled (SPLIT-IT U-TURN)

DESCRIPTION:

# Appendix B – List of Requirements

This appendix includes the list of requirements for the new concepts.

| **List of requirements** | **Demand/Wish** | **Target value** | **Unit** | **Verification method** |
|---|---|---|---|---|
| **Performance** | | | | |
| Total mass flow | D | >1,947 | kg/s | simulation/test |
| Mass flow to valve/cylinder during intake | D | > 0,973 | kg/s | simulation/test |
| Manifold pressure resistance | D | withstand inner over pressure at 4,8 bar | bar | testing |
| Air temperature resistance | D | > 250 | ºC | material properties |
| Max Outer surface temp | D | 60 | ºC | measurements |
| Leakage | D | none at 4,8 bar | | testing |
| **Material properties** | | | | |
| Corrosion resistance | D | good | | material properties |
| Standards | W | use standard material for purpose | | material properties |
| **Geometrical constraints** | | | | |
| Outer surface cavities | W | NONE | pcs | verification of CAD model |
| Plenum volume | W | 11,0-15,4 (50-70% of $V_{D)}$ | $Dm^3$ | measurement of CAD model |
| **Features** | | | | |
| Temperature sensor | D | Allow for temperature sensor | | verification of CAD model |
| Pressure sensor | D | Allow for pressure sensor | | verification of CAD model |
| **Attachments to engine** | | | | |
| Use standars fasteners | W | M8 bolts | | verification of CAD model |
| **Other** | | | | |
| Maintenance | W | None | | |
| Service life | D | > 1000 (more than engine life) | hours | fatigue calculations |

# Appendix C – Creative Papers

This appendix shows the so called creative papers that where created in the research phase and then used in the concept generation phase to stimulate the creativity.

# Attachment to cylinder head

V-band clamps

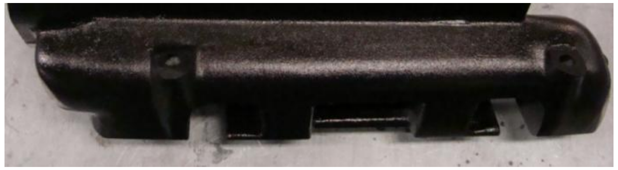
Glue

Rope

- How many bolts is needed?
- Where should they be placed?
- Need of gasket?
- Other fastening methods – dependent of cylinder head
- Make sure there is room for the fastener
- Must be adapted to cylinder head
- Heat expansion
- No leakage

Bolt straight through manifold

Bolts outside of manifold



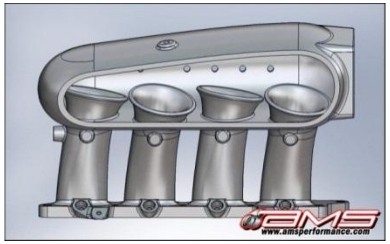
Big bolt around port

# Runners

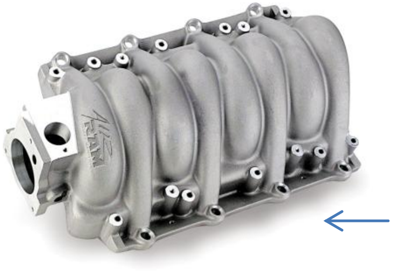
Direct contact to plenum

Molded

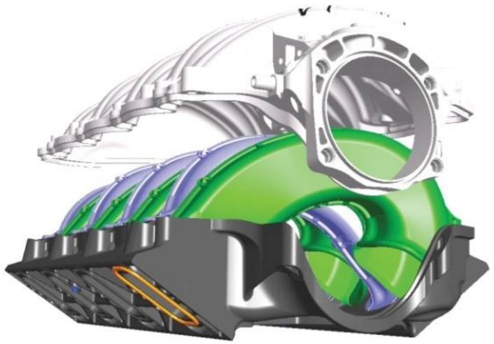
As pipes



“Overlying”



Integrated kind of



- No sharp corners
- Flow should be even to all ports – symmetry in runners is good ie equal length.
- Round pipes or square pipes etc.
- Rubber, plastic or other alternative materials?
- Should they go one and one or two and two etc?
- Connection to plenum is of great importance
- Length of runners
- Long is good for turbos
- Runner inlet geometry
- “Overlying” or “underlying”

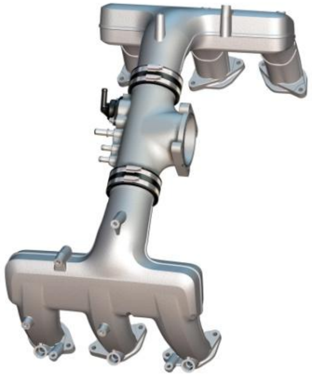
# Upstream connection

Koppling,Uppåt

Koppling, bakåt

Vridbar, runtom

Vridbar, uppåt



- Flexible/Turnable connection (not pre-defined direction)
- Attachment of pipe that resists high pressure and temperature.
- Hose clamp for soft pipe
- Expected turbo and air filter position (backwards?)
- V-band clamp
- Water Connections for Intercooler
- Turbo outlet temperature expansion
- Screw joint
- Stud and nut
- Bolt and washer
- No leakage

# Plenum

Variable cross section

- One plenum for each side?
- Connector between plenums
- Placement and size of connector
- Symmetry of sides
- Inner surace and geometry
- Inner guidance of air flow
- 50-70 % of engine displacement volume, 11-15,4 L
- Integrated intercooler
- Sensor placement
- Streamlined
- Isolation from engine?
- Variable cross section