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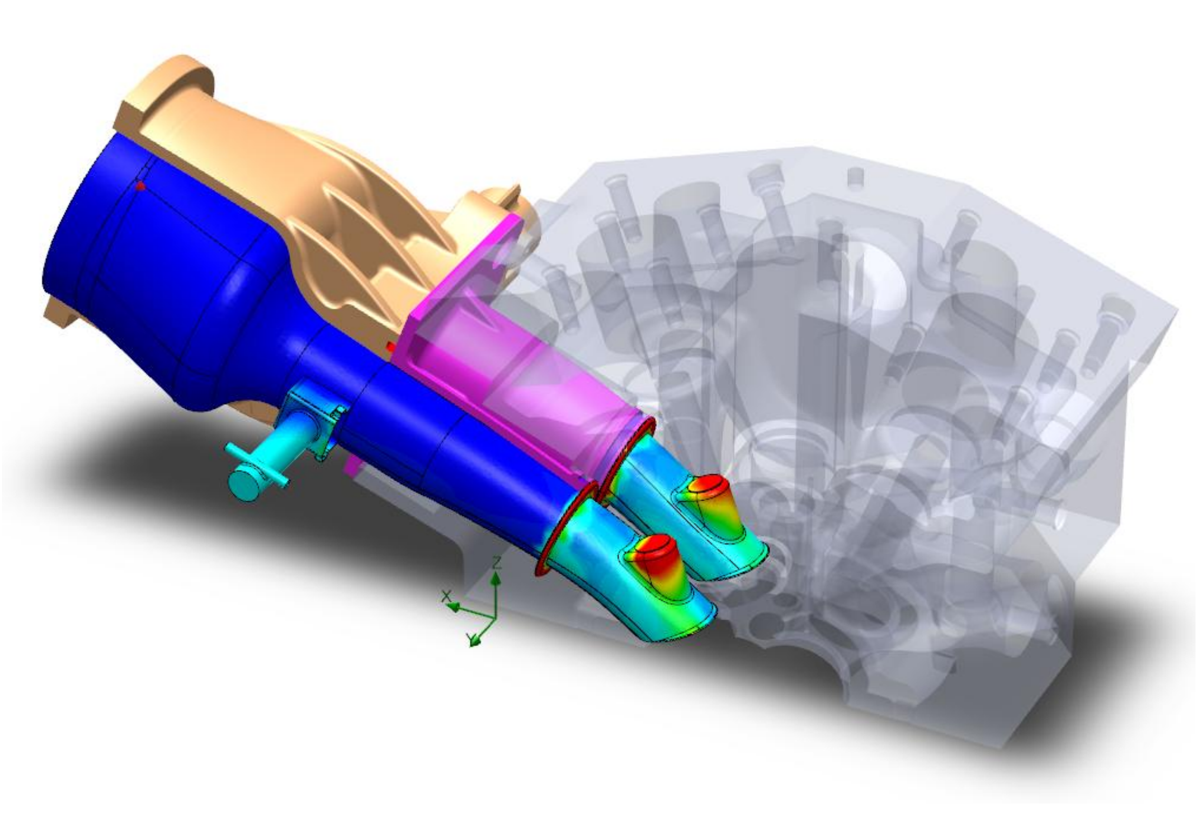

Intake Port Isolation for Direct Injected Turbo Charged Gasoline Engines

Master's Thesis in the Automotive Engineering programme

EMIL HÅKANSSON

Department of Applied Mechanics
Division of Combustion
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

This thesis work relates to an intended improvement of volumetric efficiency, particularly on lower engine speeds, in a direct injection turbo charged gasoline engine. It has been known for a long period of time that heat transfer rate in flow components, such as intake system can have considerable effects on mass flow and consequently volumetric efficiency. There are several ways to enhance the amount of air flowing thru an engine, such as increasing size of intake and exhaust geometries. The modification that will be implemented in this project is not supposed to increase the volume of air that will flow thru the engine, but to a certain extent increase the mass flow of it. This is achieved by decreased intake air temperature which results in increased density and hence increased mass flow of the incoming intake air charge. The area of investigation in this thesis project relates to the fact that heat builds up in the cylinder head and transfers to the intake ports surfaces making them very hot. The main objective is to study how a decreased temperature of the intake ports surfaces influences the temperature of the incoming intake air. To efficiently accomplish such a study, a technical solution which intends to reduce heat transfer to the intake ports surfaces must be developed and isolated intake ports are one example of such a solution. The expected outcome of this solution is that the surface temperatures in the intake ports will be reduced and consequently heat transfer to the incoming intake air charge is reduced to a certain extent.

The primary aim of the thesis project is to develop a technical solution that with a great amount prevent heat from transferring to the intake ports surfaces. The secondary aim of this study is to investigate how decreased surface temperature in the intake ports influences the incoming intake air charge temperature. Finally, the results will be compared against measured data, obtained from an identical standard single cylinder head.

The intention of reducing the surface temperature in the intake ports is to hopefully answer some questions such as were the highest amount of heat transfer occurs in the intake port, if it mostly occurs over the entire intake port or predominantly near the hot intake valves. The results from the GT-Power engine simulations showed that isolated intake ports obtained a reduced surface temperature in the intake ports. That substantially led to a decreased temperature of the incoming intake air, particularly on lower engine speeds. In the single cylinder experiments it was found that the isolated intake ports were a possible method to reduce the temperature of the incoming intake air. Thus, the result did not become as positive as was indicated from the results of the theoretical simulations. To conclude, the major drawback was experienced during experiment testing, there it was noticed that the standard intake ports did not heat the incoming intake air as much as was expected. This consequently resulted that the initial improvement potential of isolated intake ports influence on intake air was not as great as what is expected from the beginning of the thesis.

Contents

Preface

This study was successfully conducted at the division Engine Development and Combustion Efficiency at Volvo Cars Corp, Gothenburg, Sweden.

I would like to thank:

- My Volvo supervisors, Andreas Berntsson and Johan Lennblad at Volvo Cars for giving me guidelines and input how to successfully carry out this thesis work.

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- Roy Ekdahl at Volvo Cars, for doing the test experiments on the manufactured prototypes.

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Finally, I would like to thank all colleagues at Volvo Cars that in some way was involved in this thesis project and who gave me a warm welcome when I first arrived.

Gothenburg, June 2011

Emil Håkansson

Symbols & Abbreviations

V	$Volume\ [m^3]$
P	$Pressure\ [bar]$
T	$Temperature\ [\ K\ ]$
R	$Gas\ constant\ [\ \frac{kJ}{kg} K\ ]$
Nu	$Nusselt\ Number$
Re	$Reynolds\ Number$
$T_{1,2,3,4}$	$Fluid\ temperature\ at\ the\ four\ different\ strokes\ [\ K\ ]$
T_{in}	$Inlet\ temperature\ of\ the\ air\ [\ K\ ]$
T_{out}	$Outlet\ temperature\ of\ the\ air\ [\ K\ ]$
T_s	$Temperature\ of\ the\ cylinder\ head\ [\ K\ ]$
A_s	$Surface\ area\ of\ the\ intake\ port\ [m^2]$
A	$Area\ [m^2]$
C_p	$Specific\ heat\ constant\ of\ air\ [\ \frac{kJ}{kg} K\ ]$
C_v	$Specific\ heat\ [\ \frac{kJ}{kg} K\ ]$
L	$Lenght\ of\ the\ intake\ port\ [m]$
D_h	$Dynamic\ average\ diameter\ of\ the\ intake\ port\ [m]$
ρ	$Density\ [\ \frac{kg}{m^3}\ ]$
t	$Time\ [\ s\ ]$
h	$Heat\ transfer\ coefficient\ [\ \frac{W}{m^2}℃\ ]$
k	$Thermal\ conductivity\ constant$
q	$Heat\ flux\ [\ \frac{kJ}{kg}\ ]$
$q_{conduction}$	$Conductive\ heat\ flux\ [\ \frac{kJ}{kg}\ ]$
$q_{convection}$	$Convective\ heat\ flux\ [\ \frac{kJ}{kg}\ ]$

$q_{radiation}$ $Radiative\ heat\ flux\ [\frac{kJ}{kg}]$

ε $Emissivity$

σ $Stefan - Boltzmann\ Constant$

η_f $Fuel\ conversion\ efficiency$

f_{smooth} $Darcy - Weisbach\ friction\ factor\ for\ smooth\ pipes$

f_{rough} $Darcy - Weisbach\ friction\ factor\ for\ rough\ pipes$

$\dot{m}_a$ $Mass\ flow\ of\ the\ incoming\ air\ charge\ [\frac{kg}{s}]$

v $Velocity\ of\ the\ flow\ [\frac{m}{s}]$

ν $Viscosity\ of\ air\ [\frac{kg}{m\ s}]$

sfc $Specific\ fuel\ consumption\ [\frac{mg}{J}]$

Q_{HV} $Lower\ heat\ valve\ of\ specific\ fuel\ [\frac{MJ}{kg}]$

Pr $Prandelt\ number$

CFD $Computational\ fluid\ dynamic$

1 Introduction

The automotive industry has been rapidly expanded the last years due to higher expectations and demands for high performance vehicles with low fuel consumption and less emissions. Down-sizing of engine size combined with direct injection and turbo charging is seen by many vehicle manufactures as it is the most cost effective concept to reduce fuel consumption and thereby meeting the strict future CO_2 emission levels for gasoline engines. For these engines, heat transfer has a great effect on engine characteristics such as maximum load, thermal efficiency, combustion stability, emissions and response. Heat transfer has a specifically significant effect on volumetric efficiency, which is a measure how efficient an engine´s gasexchange process and understanding resulting change on the volumetric efficiency curve can help to identify when heat transfer is a problem. In order to stay competitive, car manufactures are forced to constantly develop new unique solutions which place their products in line with or ahead of their competitors. A project with the aim to isolate the intake ports is a perfect example of this, with the purpose of improving the potential of gasoline engines.

Based on several investigations on driving behavior it has been shown that daily drivers often operate on lower engine speeds and rarely uses the maximum capability of the engine. With a down-sized engine during normal cruising conditions on lower engine speeds it is common to experience a lack of engine power when giving the engine full throttle without a gear change. The most significant situation of this may occur while entering an inclined road with a low engine speed. In order to maintain a constant velocity during the entire slope, probably a down shift of a gear is required which will result in a higher engine speed and hence increased engine power. Since most drivers are operating on lower engine speeds, the drivability becomes extremely important in these regions. As one of the automotive companies goal is to deliver the feeling that the vehicle has a good acceleration potential on both lower and higher engine speeds. Since it is not a problem to generate great amount of engine power on higher engine speeds, the problematic areas is in the lower engine speed regions. Therefore the engine has to be able to provide sufficient power at lower engine speeds in order to avoid the possibility that their customers experience a lack of power when providing the engine with full throttle, which occurs when the gas pedal is in its maximum position. To efficiently accomplish this, a technical solution which intends to improve low end torque must be developed and isolated intake ports are one example of such a solution.

1.1 Background

This thesis project at Volvo Cars Corp. was requested by a division within the Powertrain Engineering department called Engine Efficiency and Combustion Development. The division is specialized on principles of internal combustion engines and amongst other things they focus on gasoline engines. In detail they are responsible for engine performance parameters and geometric aspects that comprise the gasexchange process in the engine. Therefore they are responsible for investigating new unique solutions and trends in the area of engine development. Many trends in engine development focus on boosting the specific engine power output, but the primary focus is to discover solutions that enhance volumetric efficiency of the engine. In spark ignited engines, the volumetric efficiency and subsequently airflow are the most influential engine performance parameters that affects the brake torque when the air-fuel ratio (AFR) is fixed. The design of the intake port is also a major factor that affects the volumetric efficiency of an engine, where abrupt contour changes provoke pressure drops which results in less air entering the cylinder. For example, over-sized intake and exhaust geometries tend to increase the airflow thru the engine. The modification that will be implemented in this project is not supposed to increase the volume of air that will flow thru the engine, but to a certain extent increase the mass flow of it. This is achieved by decreased intake air temperature which results in increased density and hence mass flow of the incoming air charge.

Volvo personnel have during engine rig testing on different intake port geometries noticed that if the in-contact area between the incoming air charge and the intake port was slightly increased, the amount of induced air per cycle was reduced, particularly on lower engine speeds. Since this is an important finding, it is needed to be exploited further to see if these phenomena can be reversed and used to improve the performance of gasoline engines. One explanation of this phenomenon could be that when a larger in-contact area was used, more heat was transferred to the incoming air charge which raised its temperature. This consequently results in a volume expansion of the air and therefore the quantity of air flowing thru the engine is decreased. This particular phenomenon is explained by the working gas law, which defines that cold air is denser than hot air, which means that colder air takes up less space since it is more compressed. To further investigate how intake air temperature is influenced by intake ports surfaces, a simplified heat transfer simulation was made with the engine simulation program GT-Power. In this simulation the intake ports heat transfer coefficient were set to zero, which means that no heat from the intake port walls was able to transfer to the incoming intake air charge. The result of this simulation is presented by the Brake-Torque graph in Figure 1, there it is indicated that the effects of isolated intake ports shows promising effects on output torque, particularly on lower engine speeds.

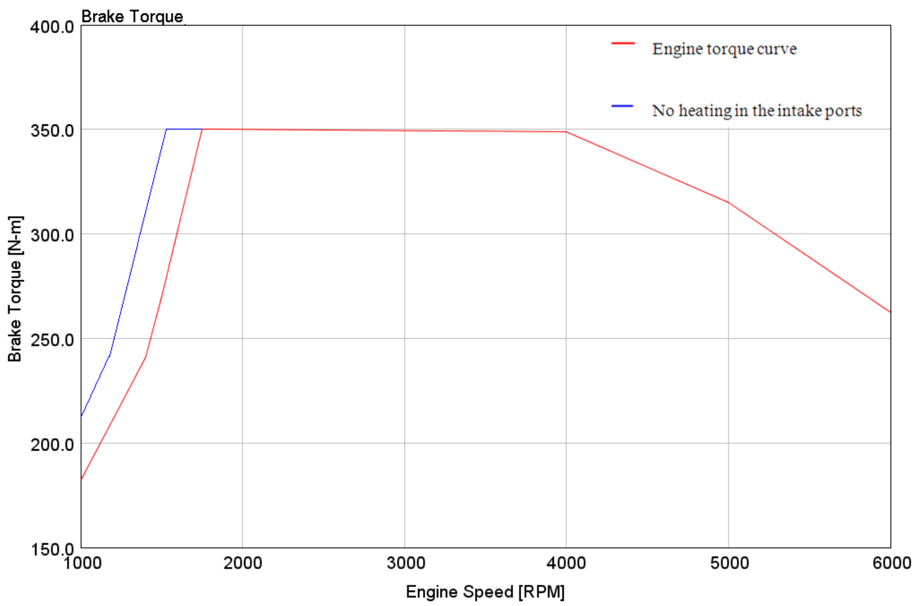

Figure 1. Effects of optimal isolated intake ports compared to standard intake port design.

Since the automotive industry is highly competitive there is always a need for new innovations to assure long term survival as a car manufacture. An interest of increasing brake torque on lower engine speeds has been on the agenda for the latest engine series. But this has been hard to accomplish since the knock phenomena has been a limiting factor. Therefore, with the intended effects of isolated intake ports the knock limit may be increased which gives the possibility to increase brake torque on lower engine speeds. These findings as previously described, initiated an interest of practically performing a investigation on the effects on isolated intake ports. Such a study can possibly verify and quantify the positive and negative effects of isolated intake ports. However, to setup the right conditions for such a study are challenging and will in many ways deviate from the more ideal conditions that is used in the theoretical simulations.

In an internal combustion engine heat is being added and removed all the time, heat is added during the combustion process and removed by the cooling system, and being radiated to surrounding components in the engine bay. The task in this thesis project relates to the fact that heat builds up in the cylinder head and transfers to the intake port surfaces making them very hot. As the intake air charge is traveling thru the hot intake port it may to a certain extent absorb heat making it warmer and hence less dense. The same concept can be found during a warm summer day at a standard home with an air conditioner that has an air duct going through a hot attic and into the air conditioned room. If the duct going through the hot attic is insulated, it means that cooler air can reach the room. The rate of heat transferring into the flowing air is obviously dependent on the amount of insulation material that is applied but it is also influenced by several other parameters. The parameter that has the most significant effect on heat transfer rate into a flowing fluid is the velocity of the flow, which is defined in Chapter 2, Section 2.3.2. Since moving air is not a good conductor of heat, a slower velocity of the flow means that there is more time for the walls to transfer heat to the flowing air. In real life situations it may occur when driving around in stop and go traffic, which corresponds to operations on lower engine speeds. This will occur since the air is moving slower in to the engine and the hot surrounding intake ports walls will tend to increase the temperature of the air which decreases the amount of oxygen entering the cylinders. This can be explained that the density of the air is being decreased by the temperature raise. This phenomenon may not be so pronounced at higher engine speeds since there is not enough time for the air to absorb any larger amount of heat, which is illustrated in Figure 2.

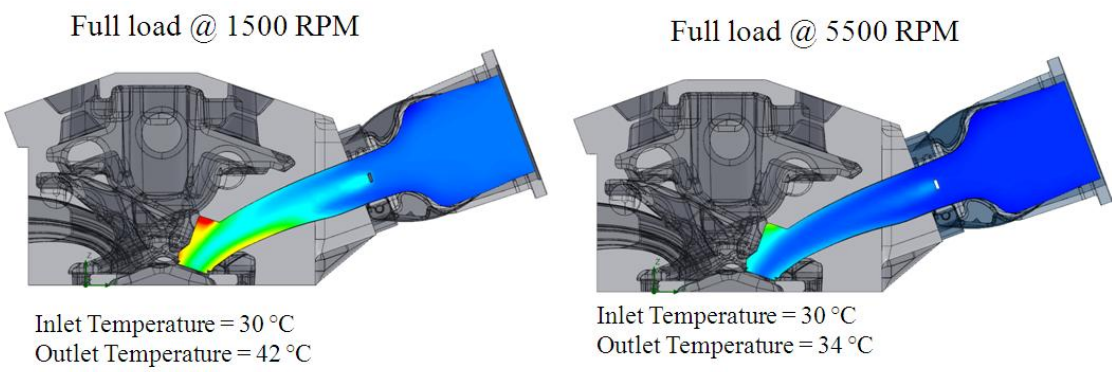

Figure 2. CFD simulations illustrate contour plots how intake air temperature is influence by the hot cylinder head on two different engine speeds.

In Figure 2 it is illustrated a comparison between two computational fluid dynamic (CFD) simulations which illustrates running conditions on 1500 rpm respective 5500 rpm. The result of these simulations illustrates that the intake air is heated more at lower rpm compared to higher rpm, which is indicated by the outlet temperature between the two simulations. Another example of this low versus high engine speed temperature influence phenomena may be to compare this with the event of moving a finger through a flame from a candle, where the skin can be compared to the flowing air charge in the intake port. Move the finger slowly and it will burn the skin, then move the finger fast and it won't feel anything. So, in order to increase the temperature of the air, it needs time to get heat soaked by the surrounding intake port walls and this may predominantly occur on lower engine speeds when the air is moving slower thru the intake port. These intake charge heating phenomena's and principles directly relates to the area of investigation for this thesis work.

1.2 Aim of study

The primary aim of the thesis project is to develop a technical solution that with a great amount prevent heat from transferring to the intake ports surfaces. The secondary aim of this study is to investigate how decreased surface temperature in the intake ports influences the incoming intake air charge temperature. Finally, the results will be compared against measured data, obtained from an identical standard single cylinder head.

1.3 Method of enquiry

The project will be pursued according to the block diagram in Figure 3, which will be more detailedly described in what follows.

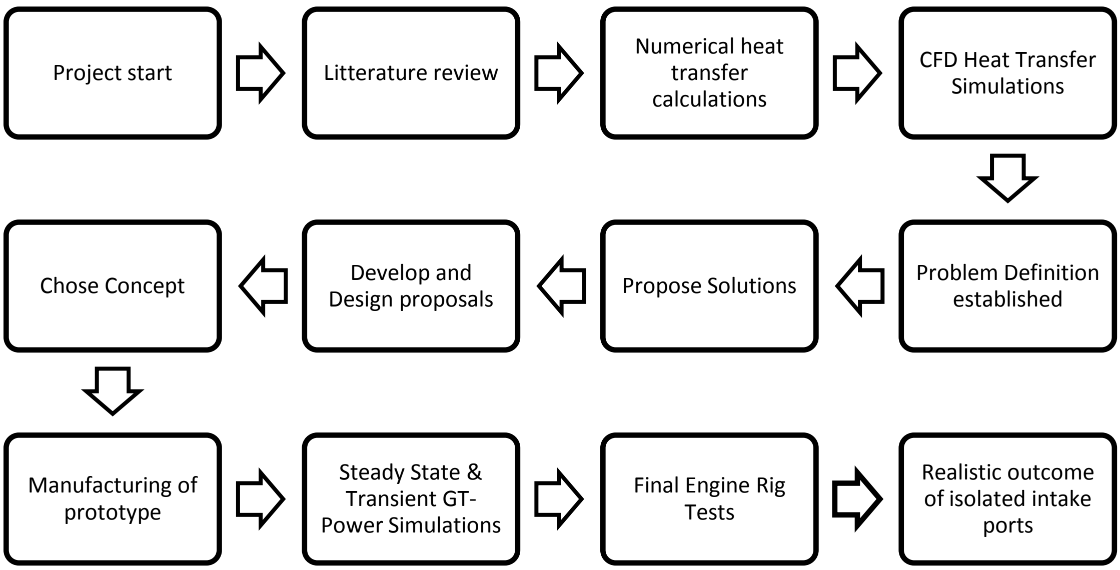

Figure 3. Illustrates the outline for this thesis work.

The first step of this thesis project will be to perform a comprehensive literature review on previous performed work within the area of investigation. Based on this review and investigation of numerical heat transfer formulas & steady-state CFD heat transfer simulations on the intake port process, the problem definition for this project can be determined to a certain extent. The next procedure is to propose technical solutions that achieve a reduction of intake port wall temperature and hence possibly reduce heat transfer to the incoming air charge. These proposals will be designed with Catia V5, using an already existing single-cylinder head model, which is illustrated in Figure 13. There are many ways to accomplish reduced heat transfer to the intake ports surfaces, but generally modifications to the intake ports are made in an existing cylinder head with the purpose of isolating the incoming air from the hot cylinder head. When suitable models have been developed, a simplified heat transfer analysis will show the most suitable proposal for this study. A prototype of this proposal will then be manufactured by an in-house workshop department within Volvo Cars. In a final procedure the effects of isolated intake ports will be simulated with the engine simulation software GT-power. These simulations will give a deeper knowledge about the area of investigation and an indication on the theoretical effects of isolated intake ports. When modifications to the existing cylinder head have been implemented, it will be tested in a running engine rig, which will be performed exclusively by Volvo employees. In order to evaluate the experiments outcome the results from the modified cylinder head will be compared with an identical cylinder head without isolated intake ports. This will eventually verify the realistic outcome of isolated intake ports. Therefore the main objective of this project is to create a solution that will decrease intake port walls temperature enough to see if it achieves a noticeable effect on incoming air temperature and hence low end torque.

1.4 Limitations

At start, this project did not have any strict boundaries for how the particular solution should be carried out. The creativity will therefore be the limiting factor of how a solution should be designed which effectively obtain reduced heat transfer from the cylinder head to the surfaces in the intake ports. Thus, one of the main criterions is that the chosen solution should be able to practically implement on an already existing single cylinder head. Therefore there are no intentions to manufacture a new specific cylinder head for this project. Instead the chosen solution will be implemented in an already existing cylinder head that has been used as a test engine for other projects. The geometric limitations where modification is allowed will be restricted where the surface of the intake ports begins and down thru the entire intake ports where the valves are located. Thus, integrated devices in the cylinder head will restrict the possibility of isolating the entire intake ports, which is illustrated in Figure 4, were the red dashed area approximately shows were modifications will be allowed.

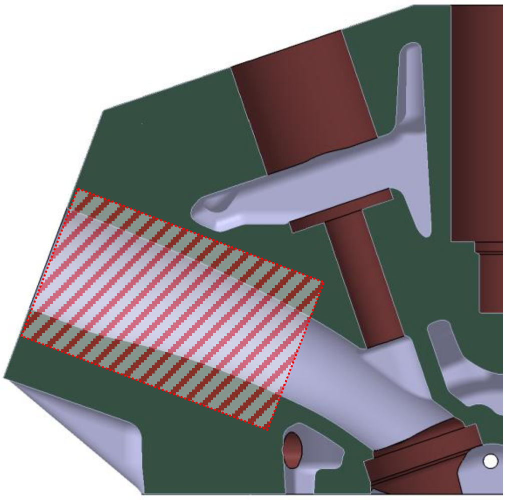

Figure 4. Illustrates a cross section thru the standard intake port were modifications is allowed.

As the main focus in this thesis will be on thermodynamic effects related to intake port geometry and intake air temperature, there will be no investigation on how isolated intake ports influence emissions. Since the shape of the intake port influences numerous of complex engine parameters, it is therefore determined that the port curvature of the proposed isolated intake ports solution must be identical to the standard design of the intake ports. This is necessary in order to achieve results that can be compared and evaluated against a cylinder head without isolated intake ports. Since this research is focused on computer aided design and heat transfer simulations of isolated intake ports, the production of the prototypes will be handled by Volvo´s in-house workshop. Finally, there will be no documentation in this report on how the test equipment is controlled or calibrated since the engine experiment rig tests will be performed by Volvo Employees.

2 Theory

The fundamental modes of heat transfer can be summarized as conduction, convection and radiation. Since heat is added and removed during the four strokes, transient heat transfer will occur and this means that the temperature within an object changes as a function of time. In this study, the dominant heat transfer phenomenon will be conduction and convection, since the temperatures in the area of investigation are relative low, the radiation effects are almost negligible. The conduction phenomena can be defined as heat transfer between solid bodies that is in physical contact. The convection principle can be defined as the transfer of heat from one place to another by the movement of liquids and gases. Since heat transfer is the primary focus in this thesis project, only equations that influences heat transfer will be described in this theory chapter.

2.1 Literature review

The area of heat transfer in intake systems has been investigated and presented by numerous authors in the past. However, the effects of heat transfer in the intake ports is an area with few published research investigations. This review will be focusing on publications made by Heywood (1988) and Graiff (1979) which is the inventor of Thermal Insulated Intake Ports. In both publications it is stated that a reduction of surface temperature in the intake port will result in positive effects on engine characteristics. However, they have different opinions on how fuel consumption is affected by decreased intake air temperature. Graiff (1979) claims that reduced fuel consumption are achieved by coating the intake port area of the engine with thermally insulation material. The solution is shown in Figure 5, were number 17 illustrates the thickness of the insulation material applied to the intake port walls.

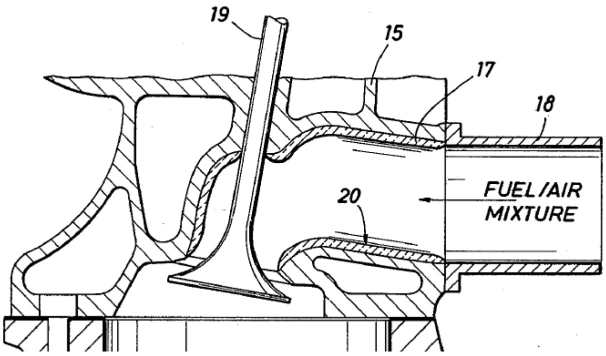

Figure 5. Illustrates thermally insulated intake ports.

Heywood is commenting this subject, by the following statement, “Charge heating in the manifold and cylinder has greater effect at lower speeds, due to longer gas residence times” and that “heat transfer to the inflowing charge reduces volumetric efficiency” , copied from Heywood (1988).

The engine used by Graiff (1979) in the thermally insulated intake ports study is not using a direct injection system and therefore it can not be 100% comparable with the engine setup which is used in this thesis where a direct injected engine is used. The statement made by Graiff (1979), that decreased fuel consumption is obtained by decreasing surface temperatures in the intake ports seems to be an unrealistic conclusion. Since the intake air temperature is intended to be decreased by reduced intake ports surface temperature, it results that the air gets denser and that the engine is required to inject more fuel per cycle in order to maintain the initial air-fuel ratio, otherwise the mixture gets leaner. Since more fuel is required to be injected, the fuel consumption is automatically increased. In Heywood (1988), it is stated that heating of the incoming air charge decrease volumetric efficiency on low engine speeds. This is the most logic conclusion of how wall temperature influences the incoming air charge. Since mass flow is increased by decreased wall temperature, it means that more air is forced in the engine and therefore the engine must inject more fuel in order to maintain a constant air/fuel ratio. Therefore the fuel consumption will be increased which also translated into a more powerful engine. The conclusion of this review is that the result of the insulated intake ports made by Graiff will not reduce fuel consumption in today's engines.

2.1.1 Existing solutions

During the literature review it was discovered that there is already two existing methods which is used to decrease peak temperatures during combustion in the combustion chambers. The first method is based on the principle of injecting water into the incoming air. This procedure decreases the temperature of incoming intake air and therefore reducing peak temperature during combustion. This directly translates to a decreased knock limit and reducing the amount of heat absorbed into the cylinder walls which also relates to reduced heat transfer losses. The effects of water injection may result in possibilities such as increased compression ratios or boost pressures.

Exhaust gas recirculation (EGR) is another method used to reduce peak temperatures in combustion chambers during combustion. It works by re-circulating a portion of exhaust gases back to the intake port. On the way back to the intake port the gases are cooled by an EGR intercooler. Thus, the main purpose of EGR is to reduce the amount of NO_x that is generated during the combustion process.

2.2 Expected outcome

The expected effects of isolated intake ports relate to the improvement of low-end torque output of given engine displacement by increasing the inlet air density. The primary outcome of this thesis project will specifically show to what degree the intake air temperature is decreased by reduced wall temperature in the intake ports. This will hopefully answer some important questions which is unknown, such as where main heat transfer occurs in the intake port, e.g. does it mostly occur near the intake valves or over the entire intake port. It has been known for a long period of time that heat transfer rate in flow components, such as intake system can have considerable effects on mass flow and volumetric efficiency. So, if a larger amount of heat transfer occurs in the intake system, it will heat the air and raising its temperature. A rule of thumb can be that the volumetric efficiency is proportional to average intake system fluid temperature and a 1% change in temperature will change the volumetric efficiency by roughly 1%. Thru literature review and ongoing discussion with Volvo employees an expected outcome of isolated intake ports can be formed, which is summarized in Figure 6.

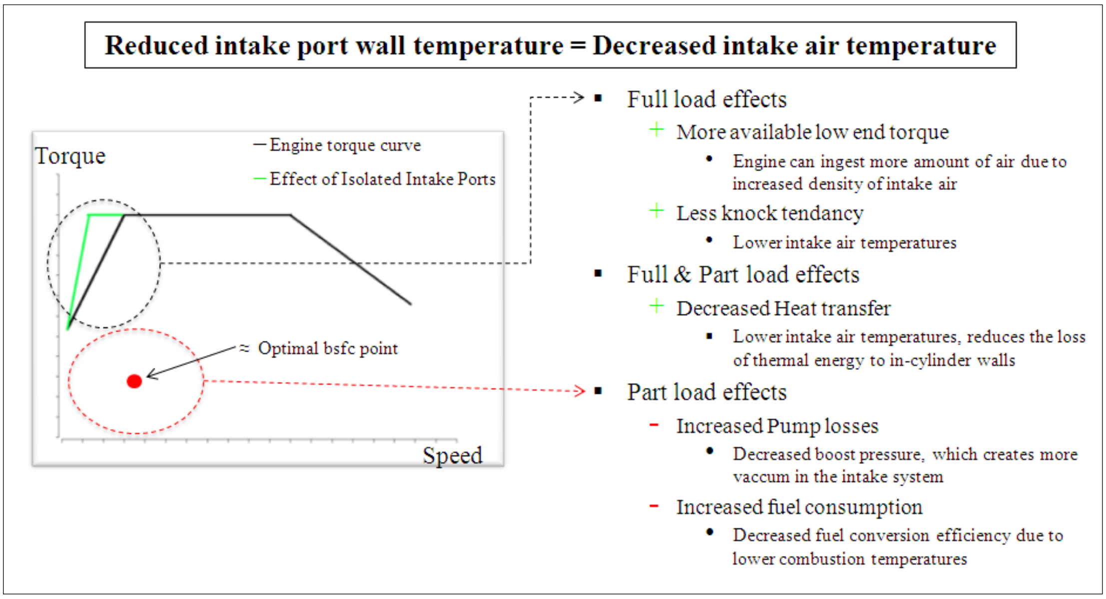

Figure 6. Illustrates the expected outcome of isolated intake ports.

According to Figure 6 the primary expected outcome of isolated intake ports is a reduction of surface temperature where the intake ports are isolated from the hot cylinder head. The effects of this may be that it prevents heat from transferring to the incoming intake air which decreases the temperature of it. This will consequently translate into an increased low end torque which results in increased acceleration capability on lower engine speeds.

2.2.1 Increased low end torque

One of the primary expected effects of isolated intake ports are increased low end torque, how this is obtained is summarized Figure 7 and will be further described in what follows.

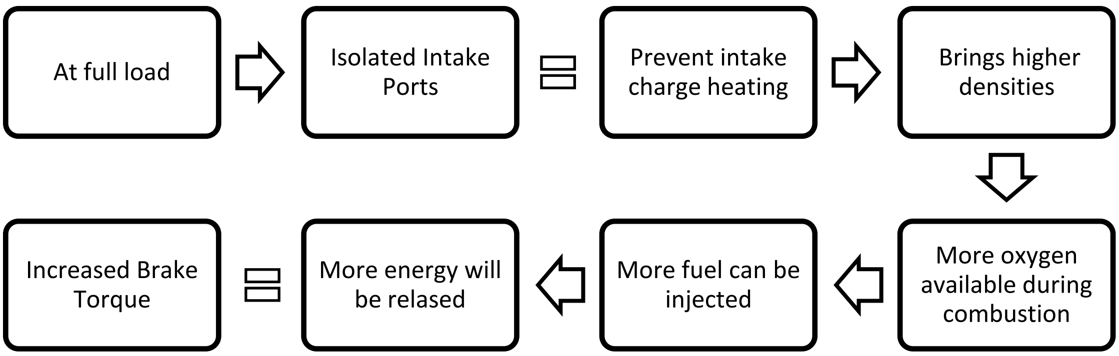

Figure 7. Illustrate how brake torque is expected to be amplified by isolated intake ports.

The intake port in an engine refers to the quantity of air an internal combustion engine can inhale per cycle. During the air charge time in the intake port, it picks up unwanted heat from the intake port walls, which increasing its volume and decreasing its density. Thus, a decreased surface temperature obtained by isolated intake ports may therefore prevent the air from getting heated. This will supply the engine with cooler air and the cooler the supply is, the better, since lower temperatures translate into higher densities. A higher density of the intake air means that it contains more oxygen per unit volume. This is important, since any amount of fuel injected into the combustion chamber of an engine requires a specific amount of air to burn efficiently. This amount is, in general, 14.7 parts of air and 1 part of fuel (air/fuel ratio), and is known as the "stoichiometric ratio", or lambda 1. Therefore, the more air that is ingested into the engine, results that more fuel in injected per cycle, which releases more energy and hence translates directly into more output torque.

2.2.2 Less engine knock tendency

It is commonly know that heat transfer in the intake system raising the temperature of the incoming intake air charge. As engine speed decreases, each four stroke cycle takes longer time due to fewer revolutions per minute. This result that the hot combustion gases travels slower out from the engine and therefore the hot gases increases heat transfer to in-cylinder walls due to the longer gas residence times. Higher in-cylinder temperatures substantially increase the risk of pre-detonation of left over end gases, which also are known as Knock. It is an undesirable combustion phenomenon which is created by a spontaneous ignition of a portion of end gases (unburned mixtures). As the flame from the spark plug propagates across the combustion chamber, the end gases ahead of the flame are compressed, causing an increased temperature and density of the end gas. During the compression of the end gases, they undergoes a chemical reaction and the product of these reactions will auto ignite and release a large part of its energy. When this occur the end gases burns rapidly and sharp metallic sounds appears which is called knocking. So if the intake charge temperature is increased, it automatically means that the in-cylinder combustion temperature increases as well as the risk of knocking. If the air is cooler prior the compression stroke, it will have positive effects on in-cylinder heat losses. One reason for this is that lower intake air temperatures decreases peak temperatures during combustion, which therefore reduces overall heat transfer to the in-cylinder walls and automatically reduce heat losses during each four stroke cycle. Therefore an intake air charge with lower temperature sustains a decreased risk of engine knock, which is shortly illustrated in Figure 8.

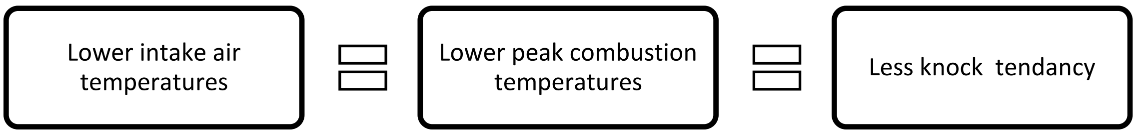

Figure 8. Effect of decreased intake temperature on knock.

2.2.3 Higher Pump-losses

Power is needed to create a flow thru the engine and this power is a loss which can be called pumping loss. This loss can be defined as the required work to move air in and out of the engine. In Figure 9 it is summarized how higher pump losses is obtained by a decreased intake air temperature. How this in detail occurs will be further described in what follows.

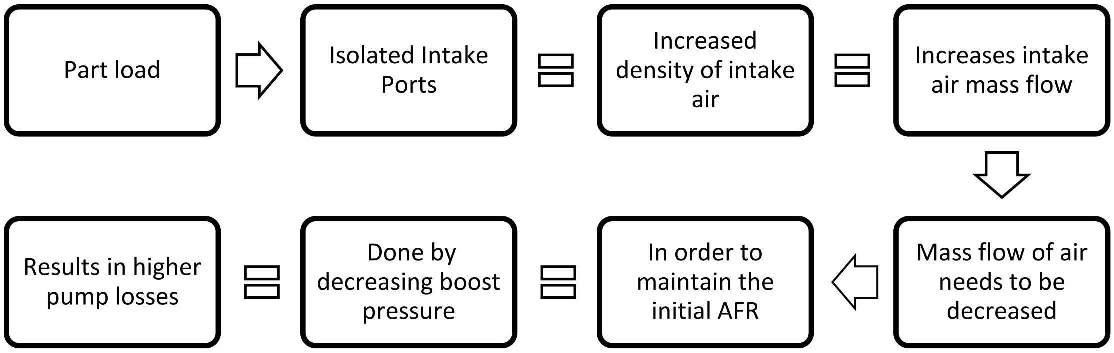

Figure 9. Illustrate the negative effects of isolated intake ports on part open throttle.

Pump losses is created during the intake and exhaust stroke as the piston is being acted upon by the intake manifold under pressure and the exhaust systems backpressure. These strokes is therefore resisting the motion of the crankshaft and hence absorbing power. The amount of pump losses that occurs is dependent on engine load and speed. The intake pumping losses varies with the amount of available air in the intake system which is controlled by the throttle. So, when the throttle is wide open, the resistance to inhale air is minimal which results in minimal pump losses. At a partly open throttle the pumping losses tends to be significantly higher due to less available air in the intake system. A decreased intake air temperature translates to higher density levels, which results that more mass will be induced per cycle. At any load point it is crucial that the right amount of air is delivered to the engine in order to maintain a specific air/fuel ratio. Therefore when the flowing air mass is increased by decreased intake temperatures, the amount of air needs to be decreased in order to maintain a fixed air-fuel ratio, which may occur with isolated intake ports. This can easily be done by decreasing the boost pressure that is produced by the turbo charger. The decreased boost pressure will result in less air entering the engine and by doing this the increased vacuum effect during the intake stroke will result that more power is required to inhale fresh intake air charge into the cylinders, since there will be less available air in the intake system. Pump losses directly relate to the mechanical efficiency of the engine since pumping losses is the required work to move air in and out of the cylinders. Thus, a decreased boost pressure will not be required at a wide open throttle, since the engine wants to inhale as much air as possible at this throttle position and therefore pump losses predominantly will occur at part load areas.

2.2.3.1 Reduce pumping losses

Since pumping losses is expected to be increased with isolated intake port, it has been determined that a solution should be designed to decrease pump losses. In many race cars applications it is a common procedure to position the throttle directly on the cylinder head were the intake ports begins, which is referred as “direct throttle” in what follows. This is mostly done to enhance the response time of the engine. Thus, in theory it is also possible that this solution obtains reduced pumping losses, since the throttling volume of air is reduced by moving the throttle closer to the intake valves. Since no investigation on Volvo has been performed on the effect of reduced pumping losses with a throttle that is mounted directly on the cylinder head, it is determined to design a direct throttle that is directly mounted on the cylinder head. This will show if a direct throttle offers any improvement in the aspect of pump losses. A very simplified expected outcome of a direct throttle is illustrated in Figure 10.

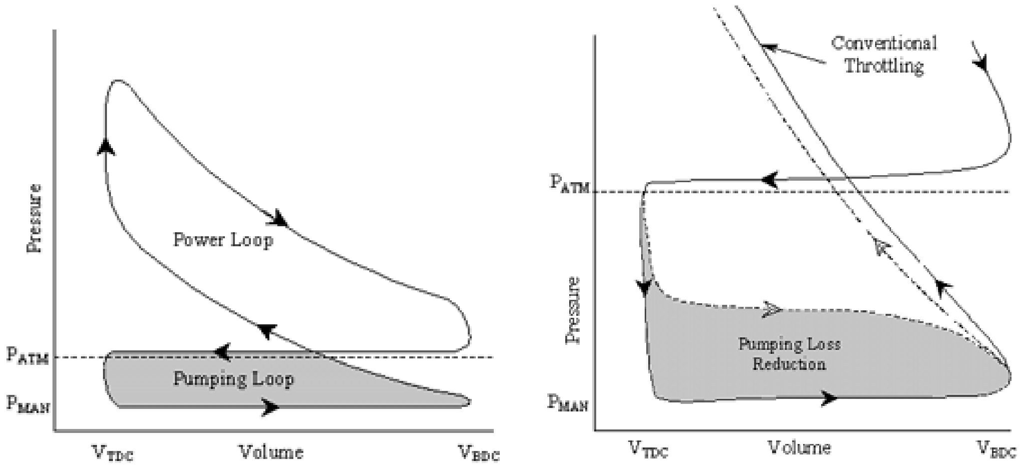

Figure 10. Illustrates in theory how pumping losses may be decreased with a direct throttle.

2.2.4 Increased fuel consumption

In an internal gasoline combustion engine the fuel conversion efficiency defines how efficiently fuel is converted into usable energy. This means that increased fuel consumption decreases the fuel conversion efficiency, which is defined in equation (1), where sfc is equal to the specific fuel consumption and Q_{hv} is the lower heat value for a specific fuel.

$$\eta_f = \frac{1}{sfc\ Q_{HV}} \qquad (1)$$

The fuel conversion efficiency is also a function of the fluid temperatures for the different strokes and therefore intake air temperature will be an influencing parameter. According to equation (2), a decreased intake air temperature (T_1) results in a decreased fuel conversion efficiency, where, $T_{1,2,3,4}$ is equal to the fluid temperatures for the four different strokes.

$$\eta_f = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \qquad (2)$$

This can be explained that lower intake air temperatures translates to lower combustion temperatures and since hot air enhances fuel vaporization and mixing, a decreased intake charge temperature will decreased thermal efficiency of the combustion process. Since it is expected that isolated intake port will obtain a decreased intake air temperature, it automatically translate to increased fuel consumption according to equation (1) and (2).

2.3 Investigation of heat transfer equations

2.3.1 Working gas law

The expected effects of isolated intake ports are primarily based on the working gas law. It defines that a temperature reduction is increasing the density of a fluid or gas, which is defined by equation (3), where ρ is equal to the density, P is the pressure, T is the temperature and R is the gas constant.

$$\rho = \frac{P}{T\,R} \tag{3}$$

This means that a warmer intake air temperature provides less oxygen to the combustion process per cycle. Hence, a colder intake air temperature means that more oxygen can be delivered to the engine since the air is denser. The conclusion of this equation is that a decreased temperature by 10℃ means an increased air density of 3.57%.

2.3.2 Influence of intake port wall temperature

The following formulas will illustrate a steady-state flow in a simplified straight intake port, which is illustrated in Figure 11. The purpose of these equations is to investigate which are the most influential parameters that affect the intake air temperature in the hot intake ports and to get a deeper knowledge on how the intake charge heating affects the outlet temperatures.

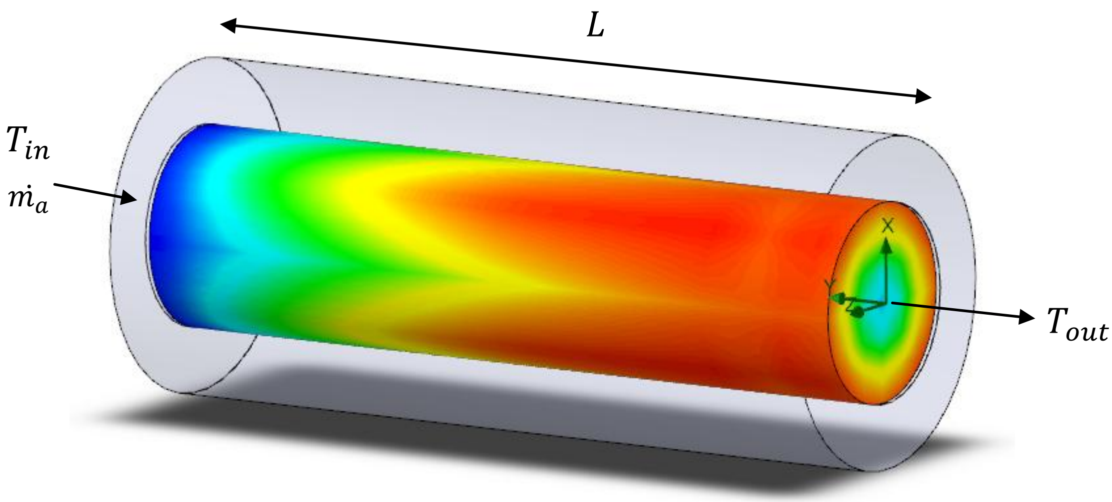

Figure 11. Illustrate how the flowing intake air is influenced by the hot surfaces in a simplified straight intake port.

In Figure 11, $\dot{m}_a$ is equal to the inlet mass flow of the incoming air charge, T_{in} is the inlet temperature, T_{out} is the outlet temperature, D_h is the average hydraulic diameter and L is the length of the intake port.

The first step is to study if the flow is turbulent or laminar, which will be indicated by the Reynolds number (Re), which is shown in equation (4), where v is equal to the velocity of the flow and ν is the viscosity of the gas. A reynolds number higher than 4000 indicates that the flow is turbulent, which will occur at higher velocities such as in the intake port that is studied.

$$Re = \frac{v\, D_h}{\nu} \tag{4}$$

Since the flow will be turbulent, the Nusselt number for turbulent flow is determined in equation (5), where $f_{rough} = 4\, f_{smooth}$, f_{smooth} is equal to $(0.790\ln(Re) - 1.64)$, and Pr is the Prandtl number.

$$Nu = 0.125\, f_{rough} Re\, Pr^{1/3} \tag{5}$$

In equation (6), the intake port heat transfer coefficient is determined, where k is defined as the thermal conductivity constant.

$$h = \frac{k}{D_h} Nu \tag{6}$$

By using equation equations (1)-(6), equation (7) can be derived. This equation shows how the intake air temperature is influenced by the hot intake port surfaces, where T_s is equal to the surface temperature of the intake ports, A_s is the surface area of the intake port and C_p is the specific heat constant at constant pressure.

$$T_{out} = T_s - (T_s - T_{in})e^{(-h\, A_s/\dot{m}_a C_p)} \tag{7}$$

The conclusion of equation (7) is that the most influential parameters that affect heat transfer rate in a pipe with a flowing fluid or gas, with constant surface temperature, are the velocity of the flow and thermal conductivity constant. Other parameters that affects heat transfer rate are for example the roughness of the surface and the curvature of the pipe.

2.4 GT–Power

In GT-power the internal heat transfer coefficient, the predicted fluid temperature and the internal wall temperature are used to calculate the total heat transfer. Intake system heat transfer to the incoming fluid is usually described by steady, turbulent pipe flow. In GT-Power the pipe and flow-split temperatures are calculated using an built in wall temperature solver module that takes into account material properties for different temperatures such as conductivity, density and specific heat.

The wall temperature solver module uses equations from the discretized energy conservation, using a finite volume method. When a pipe with different layers is modeled such as isolated intake ports, each of the wall layers are divided into pipe subvolumes and are used as control volumes for the energy equation. Heat transfer across the radial direction, thru the volumes, is calculated using a resistance to conductive heat transfer, as well as radiation between the surfaces on either side. In the axial direction conductive heat transfer is calculated using a wall connection solver module, which takes into account the areas that is in physical contact. The wall temperature can be solved with either a steady-state or transient simulation. When a steady-state simulation is requested, the heat transfer code tries to reach the final steady-state wall temperature as quickly as possible, so that a fully warmed system may be simulated in only a few cycles. This simulation mode will be used when generating the engine brake torque versus engine speed plot. If warm-up characteristics of a system are being studied, the transient heat transfer mode is used. This mode will be used when simulating the effects of isolated intake ports on engine response time. How isolated intake ports are modeled and simulated in GT-Power will be further explained in the Chapter 3.

The equations in what follows will show the most generalized equations that GT-Power uses during heat transfer simulations in pipes and flow-splits. These equations are based on the conservation of energy formula, which is defined in equation (8), where C_v is equal to the specific heat constant at constant volume, q is the heat flux, ρ is the density, T is the temperature, t is the time and V is equal to the volume.

$$\int \frac{\partial(\rho C_v T)}{\partial t} dV = \int (-\nabla^\circ q) dV \tag{8}$$

By integration of equation (8), equation (9) is derived, where q is the heat flux at the different faces which is defined in equation (10), (11) and (12).

$$\rho C_v \frac{\Delta T}{\Delta t} = \sum_{faces} -qA \tag{9}$$

In equation (10), heat flux is due to conduction, where k is equal to the thermal conductivity and T is the nodal temperatures.

$$q_{conduction} = -k \nabla T \tag{10}$$

In equation (11), heat flux is due to radiation, where ε is equal to the surface emissivity, σ is the Stefan-Boltzmann constant and T is the surface temperatures.

$$q_{radiation} = -\varepsilon\, \sigma(T_1^4 - T_2^4) \tag{11}$$

In equation (12), heat flux is due to convection at internal flow conditions, where h is the heat transfer coefficient for internal flow, T_g is the gas or fluid temperature and T_w is the temperature at the wall.

$$q_{convection} = h_{internal} \left(T_g - T_w\right) \tag{12}$$

In equation (13), heat transfer coefficient for external flow is defined, where Nu is equal to $0.5 + 0.10(Rayleigh\ Number)^{\frac{1}{3}}$, k is the thermal conductivity of the fluid and D is the diameter of the pipe.

$$h_{external} = max \left(\frac{Nu\, k}{D}\right) \tag{13}$$

3 Methodology

The main purpose of this project is to develop a technical solution that reduces heat transfer from the hot cylinder head to surfaces in the intake port. This can be executed in numerous ways, such as either isolating or insulating the intake ports from the cylinder head. The first possible method is based on the principle of insulating the intake ports, which is accomplished by applying a surface coating material with insulating properties on to the surfaces in the intake ports, such an example is illustrated in Figure 12, where the purple area corresponds to intended thickness of the insulating material.

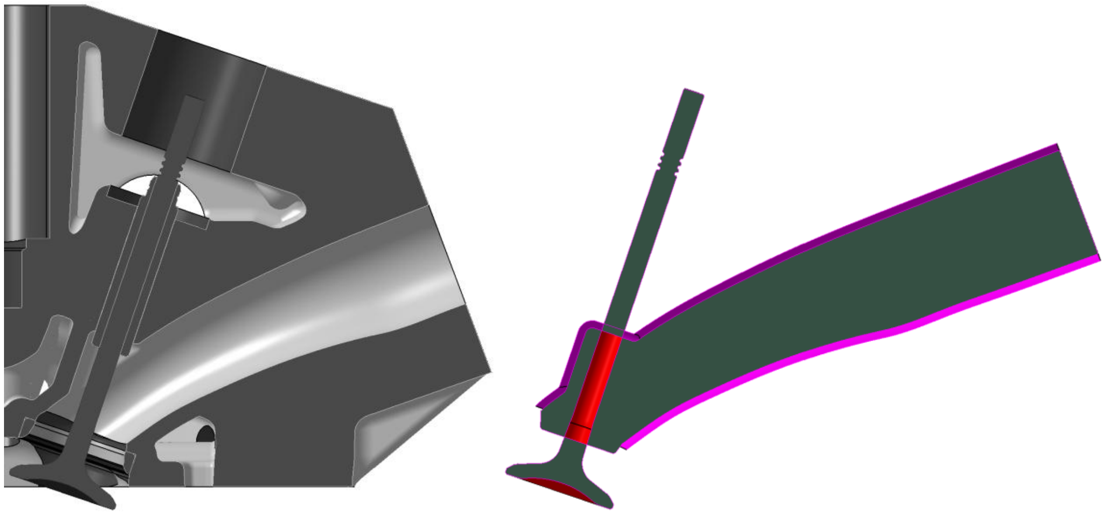

Figure 12. Illustrates the principle of insulated intake ports.

This method is based on the same principle that was described in the literature review. The main advantage with this solution is that it gives the possibility to cover the entire intake port. Thus, this solution is complicated to implement in a manufacturing point of view, since it is necessary to remove material in the intake ports with the same amount as the thickness of the insulating material that is intended to be applied. Therefore it is required to use an advanced milling machine since the curvature of the intake ports is complexly designed. Since an insulating solution will be in physical contact with the cylinder head it will be hard to reduce a great amount of heat that transfers to the intake port surfaces. Thus, is it possible but it would be necessary to use a really thick coating or an insulating material which has an extremely low thermal conductivity constant. Since it is hard achieve a thick coating, an insulation solution will probably have small effect on low operating temperatures such as in the intake port and it is instead more suitable for insulating application in high temperatures area such as exhaust system regions. It is therefore concluded that insulated intake ports are not the most suitable application to reduce surface temperatures in the intake ports.

The other possible solution is based on the principle of isolating the intake ports from the hot cylinder head. This will be done by removing a part of the intake ports in the cylinder head and replacing it with an insert that is replicating the shape and geometry of the intake port part that has been removed. So a part of the intake port will be separated from the hot cylinder head and this is executed by removing material from the cylinder head and replacing it with a technical solution that actively or passively decreases heat transfer to the surfaces in the intake ports. This method will be explained further in what follows, since it will be implemented in this project.

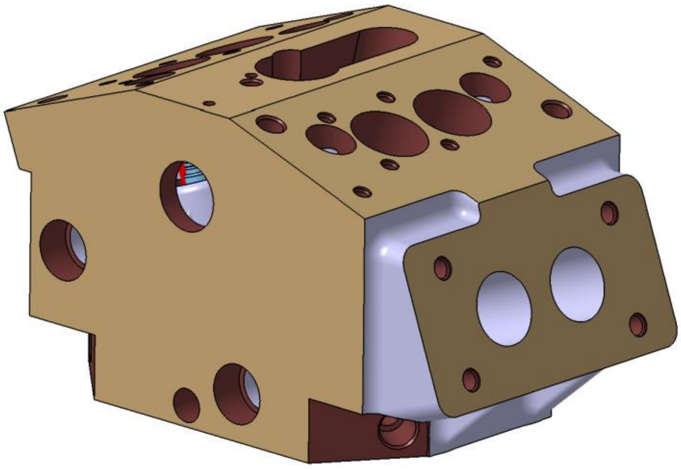

Figure 13. Illustrates the standard design of the single cylinder head that will be used during the design process.

When virtually designing and assembling engines there are always challenges with packaging of new components. It was therefore a challenge to remove material in the cylinder head without interfering with other integrated devices such as water channels, oil core and screw holes etc, which is illustrated in Figure 13, were the grey material represents the intake ports. Since the cylinder head is exposed by high temperatures created by friction and combustion, material properties such as thermal conductivity, specific heat constant, melt temperature and resistance to thermal shock needs to be taking into account when choosing material for the insert that is replacing the removed part of the standard intake ports. The intake port insert should also be designed so easy changes of material could be possible as material selection evolve over time with new technology. Since the turbo charger pushes pressurized air thru the intake ports, it is therefore crucial to ensure that the incoming air is sealed from the surrounding ambient air where the transition between the insert and the cylinder head is located. So the chosen solution must properly seal in order to avoid leakage which otherwise leads to misleading results which cannot be compared with data obtained from a standard cylinder head.

3.1 Design process

During the product development process in this project, Catia V5 was used for designing isolated intake port proposals. Since aluminum is an extremely good transmitter of heat, a goal was to remove as much material as possible around the intake ports and replacing it with material that is a poor transmitter of heat, which corresponds to a material with low thermal conductivity. Therefore isolated intake ports will build on the principle of removing material around the intake ports in the cylinder head, which is shown in Figure 4. The first step in the design process was to investigate how much space there was available around the intake ports in the cylinder head. This will determine how much material that is possible to remove and also how much of the entire intake ports that is possible to isolate. This was investigated using an existing 3D cylinder head model to investigate how near water channels, oil core and other devices were located in comparison to the intake ports, which is illustrated in Figure 14.

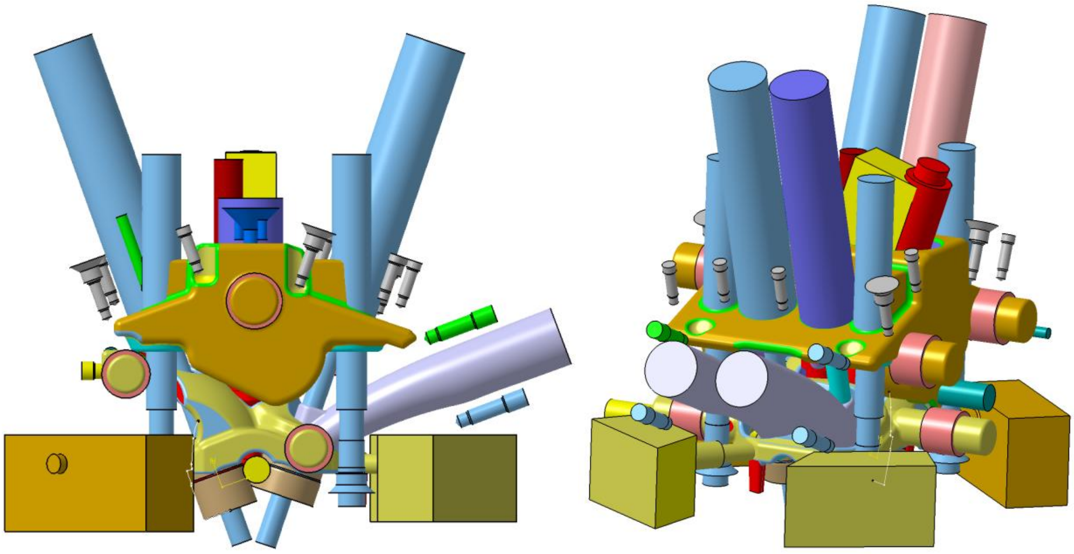

Figure 14. Illustrates all integrated devices in the cylinder head.

When investigating different types of surface reducing methods it was discovered that there were two possible procedures that could be implemented using the idée of isolated intake ports. The first isolation method is based on a solution that actively cools the walls in the intake ports using the principle of forced cooling. This solution is intended to cool down the insert that is replacing the part of the intake port that has been removed. This will be achieved using a thermoelectric element called Peltier. These elements are for example commonly used in small refrigerator and in electronic cooling applications. A Peltier element is a semi-conductor and builds on the principle of converting current & voltage into a temperature difference between its two sides. One side of the Peltier element is cold and the other is hot. The amount of produced energy is controlled by the current via a voltage regulator. In order to efficiently use the Peltier element to cool down the insert as much as possible, the warm side of the element must be cooled down as well. It may be solved by using a heat sink application that transfers away the heat by convection and radiation. So, the intention of this method is that the Peltier element will be mounted on the insert and consequently reduce surface temperature of the insert by forced cooling. One example of such a setup is illustrated in Figure 15.

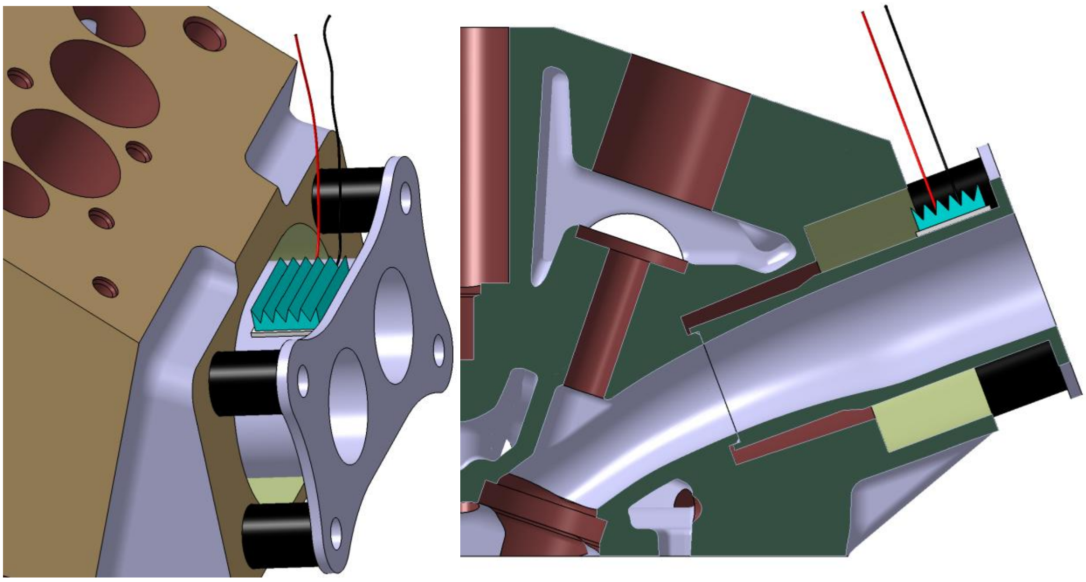

Figure 15. Illustrates the principle of Peltier element cooled intake ports.

An insert material with high thermal conductivity is preferred for this application, since it will therefore lead the cool medium thru the insert more efficiently and therefore decrease surface temperature of the intake ports to a greater extent. A perfect example for such a material is aluminum, which has a high thermal conductivity constant. This solution would be perfect for study purpose, which means that it will definitely give information about how intake port walls temperature affects intake air temperature. Since the solution will be using the principle of forced cooling, it will therefore be possible to control the amount of energy that is produced by the Peltier element, this translates to the fact that the surface temperature of the intake ports can be regulated. The conclusion of this solution is that it may not be a realistic solution for commercial usage, since a Peltier element is expensive and consumes energy. This is the main reasons why this solution will not be implemented in this project.

The other method is based on the principle of using a technical solution that passively reduces heat transfer between the hot cylinder head and the intake ports surfaces. This was done by thermally separating a part of the intake port from the cylinder head, which is illustrated in Figure 16.

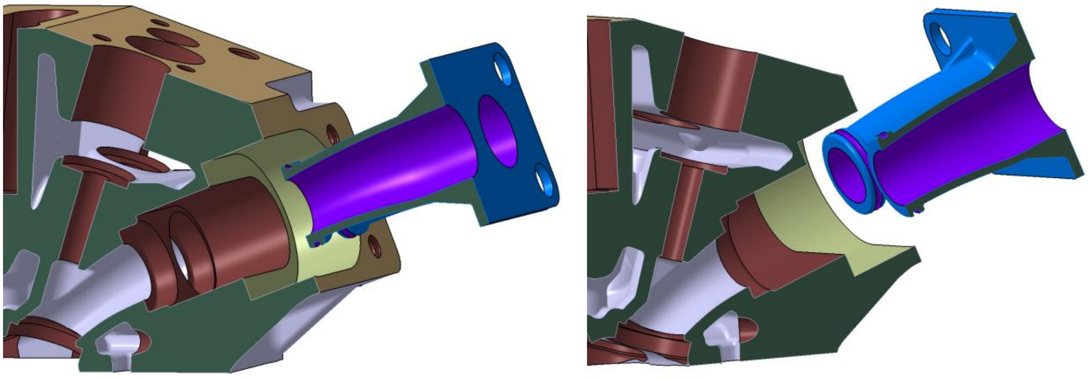

Figure 16. Illustrates the chosen concept for practical implementation of isolated intake ports.

By replacing a part of the aluminum intake port with an insert that has lower thermal conductivity compared to the aluminum intake ports, wall temperatures compared to the standard design will be reduced. The possibility of removing material around the intake port the whole way down to the intake valves was limited by integrated devices within the cylinder head such as water channels that were located near the intake valves, which is seen in Figure 14. The insert will have the same shape as the part of the standard intake port that has been removed, as been seen in Figure 17. Another goal when designing the insert was to minimize the in-contact area between the cylinder head and the insert. This is done with the purpose of minimize thermal conduction, where the two materials are in physical contact. This will occur at two locations and the first is thru the rubber sealing that will be mounted on the insert, which is seen in Figure 19. Thus, conduction will not occur in the bottom of the insert, since there is an air pocket between the end of the insert and the cylinder head, which is also seen in Figure 19. The other location where conduction will occur is where the insert is mounted on the outside surface of the cylinder head.

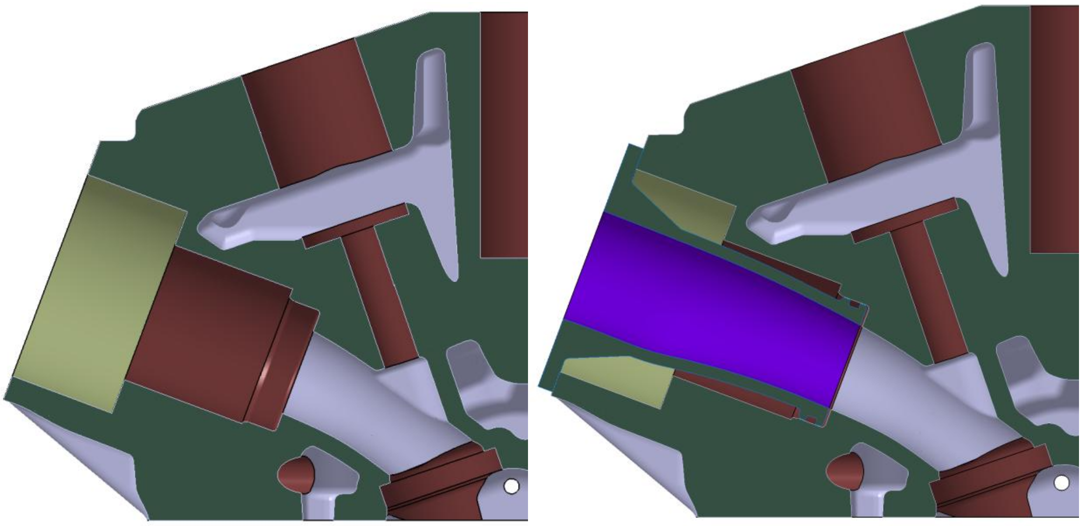

Figure 17. Illustrates how the plastic insert is mounted in the modified cylinder head.

Since the goal was to remove as much aluminum material as possible from the cylinder head and due to the fact that the insert was designed with a pipe thickness of 3.5mm, it resulted that the insert did not cover the entire volume of removed cylinder head material, which is seen in Figure 17 and 18. This gave the possibility to decreased heat transfer to the intake port surface even further by insulating the left over space. But, it was thru heat transfer calculations concluded that stand still air was the most appropriate insulating method for the left over space, which has been created between the insert and the cylinder where material has been removed. The air will therefore work as a thermal barrier and hence reduce surface temperature at the insert even further.

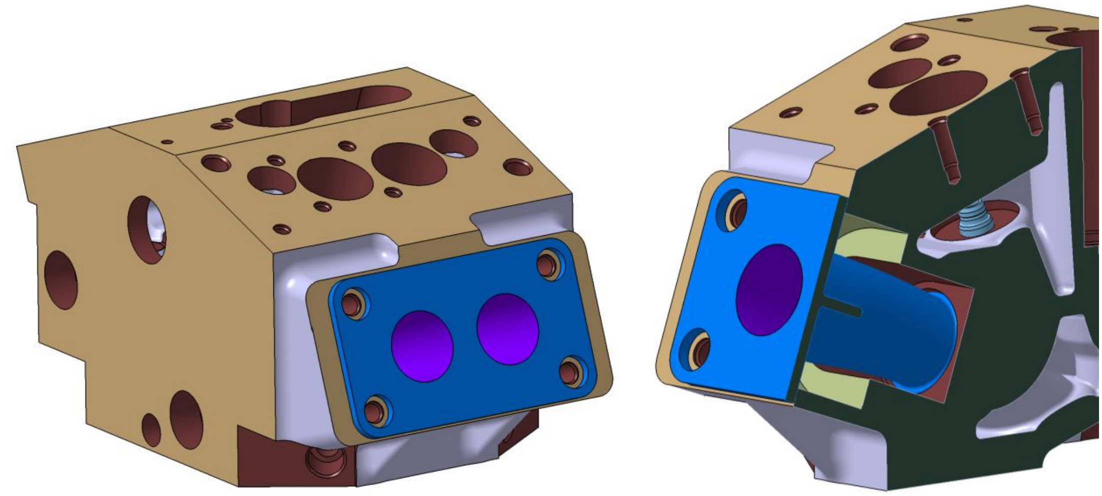

Figure 18. Illustrates the modified cylinder head with the plastic insert mounted.

As the average temperature of the cylinder head is approximate 95℃, material selection for the insert was needed to be considered. The insert was manufactured with a Free Form Fabrication (FFF) method at Volvo's in-house workshop facility. The workshop had two materials that were available for this manufacturing technique. For this application it is preferred to find a material that has desired properties such as resistant to high temperatures and low thermal conductivity, which means that the materials ability to conduct heat is poor. The two available materials were pure polyamide and polyamide with a mixture of 30% glass fiber. The variant with 30% glass fiber mixture finally became the chosen material to use, since it had the most desired properties for this application, such as melt temperature at 150℃ and a thermal conductivity constant of 0.144, this is a great difference compared to the standard intake ports were Aluminum has thermal conductivity constant of 244.

Since the intake port will be separated in two parts, the connection between the two needs to have a smooth transition. This is required to reduce the chance of interrupting the flow pattern so pressure losses and turbulence will occur in this region. Therefore a guiding system in the bottom of the cylinder head has been designed, which will ensure that the plastic insert will be positioned in the right place, which is seen in Figure 17, 18 and 19. In this transition area it is also crucial that there are no leakage of the incoming air since the turbo charger is pushing pressurized air thru the intake ports. This may occur if there is no sealing solution installed. Therefore the insert will be designed with a sealing solution, which will ensure perfect sealing, which is seen in Figure 18. Since the plastic material will be expanded when it is exposed by the high temperatures from the cylinder head, a radial sealing is preferred. By using this method the sealing can slide in the axial direction as the plastic insert expands due to temperature variations, which is illustrated in Figure 19.

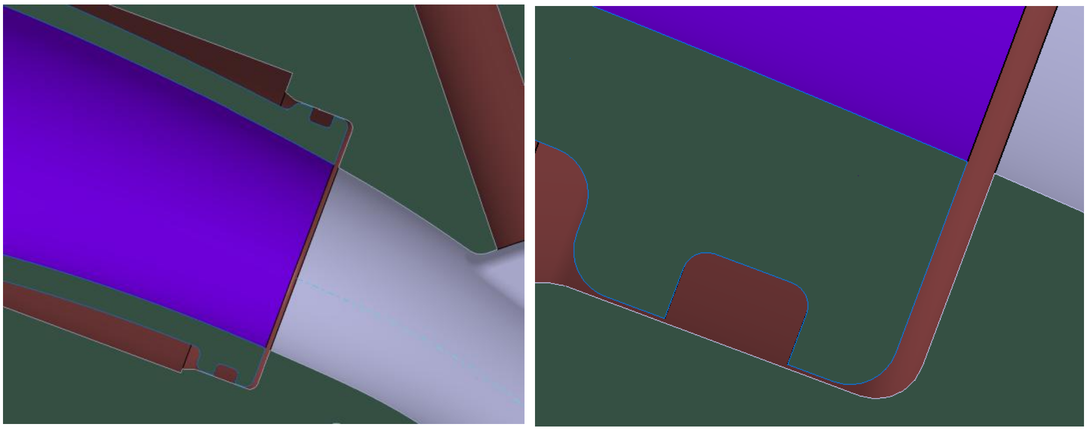

Figure 19. Illustrates how the rubber sealing will be mounted and that it ensure no leakage.

3.2 GT-Power

Since it was not the intension to create a new engine model from scratch, the simulations was directly performed on an already existing multi-cylinder engine model developed by Volvo. Since it was not possible to isolate the entire intake ports, the first adjustment in the engine model, was to separate each intake port into two pipes so it corresponds to the isolated intake ports, which is illustrated within the red-dashed lines in Figure 20.

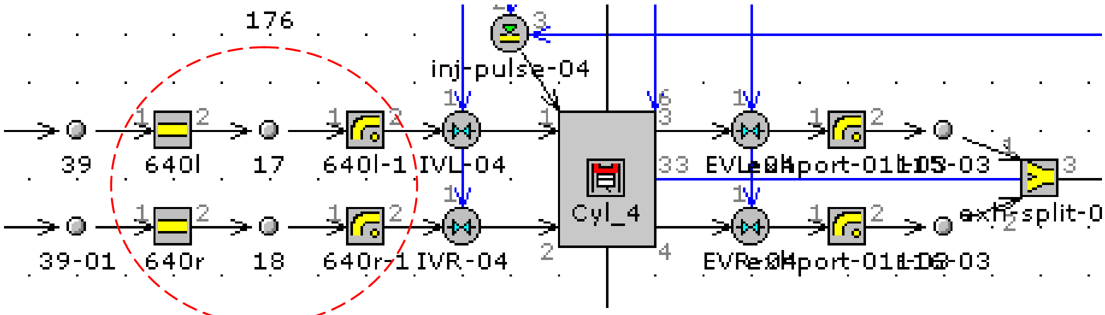

Figure 20. Illustrates how the intake ports, at one cylinder, are split into two parts.

The first part of the intake ports (640 l/r) will replicate the geometries of the developed plastic insert that has been designed in Catia. Since the plastic insert will be surrounded by air space and aluminum material within the cylinder head, it is necessary implement different layers around the intake ports. This is because convection and radiation will occur between the different layers, which are illustrated in Figure 21, where layer 1 is corresponds to the plastic insert, layers 2 is the air gap and layer 3 is the cylinder head.

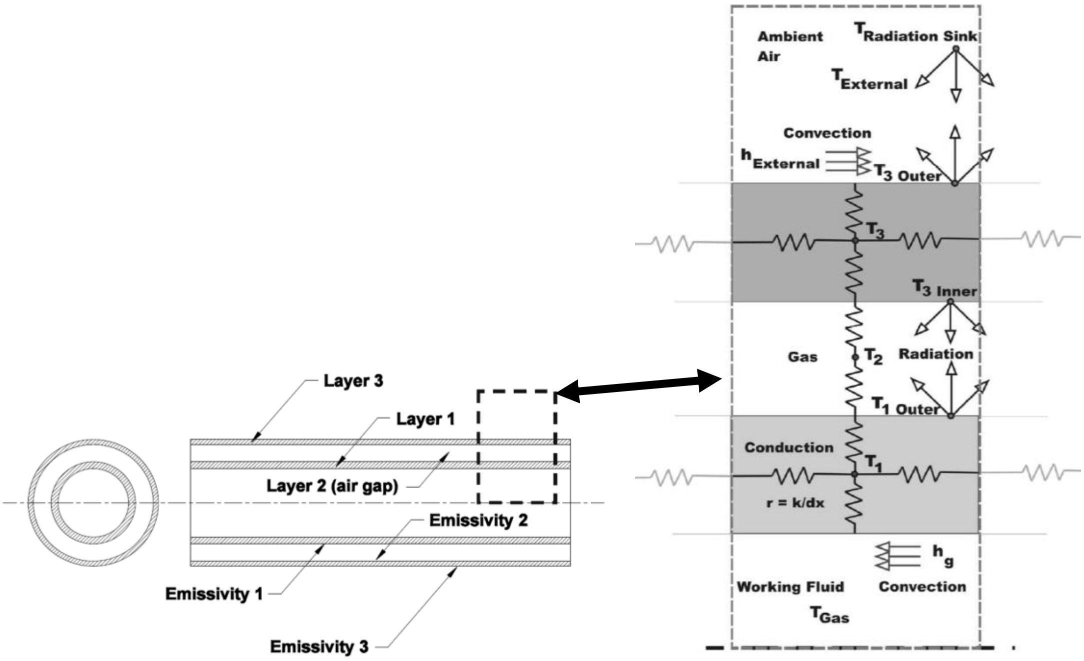

Figure 21. Shows a generalized geometry on how isolated intake ports are modelled in GT-Power and which are the basic heat transfer phenomena's that occurs between the different layers.

The isolated intake ports will be modeled using a built in module in GT-Power, called "Wall Temperature Solver", where each wall layer is described with a column of data. The first column represents the inside layer and the last column the external layer. Each row is representing material properties for each layer. This makes it easier to model a pipe with an air gap, which will be implemented in the isolated intake ports, which is seen in Figure 22. For surface emissivity, the factor has been set to zero, since the radiation effects will be negligible as explained previous in the report.

Attribute	Unit	Layer1	Layer2	Layer3
Surface Emissivity		0	0	0
Layer Thickness	mm	3.5	5	5
Layer Material Object		PolyamideFFF	air-matl	aluminum

Figure 22. Illustrates how isolated intake port is modelled in the engine model.

Since it was not possible to isolate the entire intake ports, the last part of the intake ports will be modeled as the standard aluminum intake ports, which is illustrated in Figure 23.

Attribute	Unit	Layer1
Surface Emissivity		0
Layer Thickness	mm	5
Layer Material Object		aluminum

Figure 23. Illustrates how the standard intake ports are modelled.

Since the plastic insert will be in physical contact with the cylinder head, heat conduction between these two materials must be taken into account when performing the final simulations. This was done using a “Heat Conduction Flange” module where the in-contact areas between the two objects are defined. This allows heat transfer across adjacent components surfaces and further making the simulations more comparable to the realistic experiments. In order to improve the accuracy of the simulations even further, it is crucial that the simulation and experiment testing use almost exact the same ambient conditions. This is necessary because mass flow rate is proportional to intake density, which is proportional to pressure and inversely proportional to temperature.

To investigate the main effects of isolated intake ports in GT-Power, four plots were generated. The first and most important is the steady-state Torque vs. engine speed plot, which will illustrates the effects of isolated intake ports on low end torque. Another important aspect to investigate is if isolated intake ports obtain an improved response time of the engine. This will be done by plotting the Torque versus time plot, which will simulate how long time it takes to reach a maximum torque from 50Nm. The knock phenomenon is also another important factor that is interesting to investigate. This will be done by plotting the temperature of the unburned zone during combustion and comparing it with standard design without isolated intake ports. This will show if there becomes a temperature difference between the two setup´s. Since the intended effect of isolated intake ports is a decreased intake air temperature, the outlet temperature of the plastic insert will be compared against the temperature at the standard intake ports.

3.3 CFD Boundary Conditions

The boundary conditions for the CFD simulations are mainly based on steady-state turbulent flow, where heat transfer via radiation, convection and conduction is activated. Many parameters will not be explained in this section, but the most important parameters are defined in what’s follows. The plastic insert is modeled with the material properties of Polyamide (30% glass fiber). The initial temperature of the intake air is set to 20℃ , the surrounding ambient air temperature is set to 20℃, the temperature of the cylinder head is set to 95℃, the roughness for all surfaces is set to $14\mu m$, inlet mass flow corresponding 1500 rpm is set to 0.01 kg/s, the outlet static pressure is set to 225kPa, the swirl intensity of the flow is set to one and the emissivity constant for aluminum is set to 0.11.

3.4 Experiment testing

In order to be able to evaluate the effects of isolated intake ports compared to an identical cylinder head without isolated intake ports, it is required to perform tests on both setups. Since it is in the greatest interest to see the effects of isolated intake ports on both high and low loads, two different tests was performed on both cylinder heads. In the first test, the engine was run thru an engine mini-map, which means that the engine was run in pre-defined load/speed operating points on part loads. Therefore the outcome of this test will only show the effects of isolated intake ports on part loads. The pre-defined operating point in this mini-map is illustrated in Figure 24.

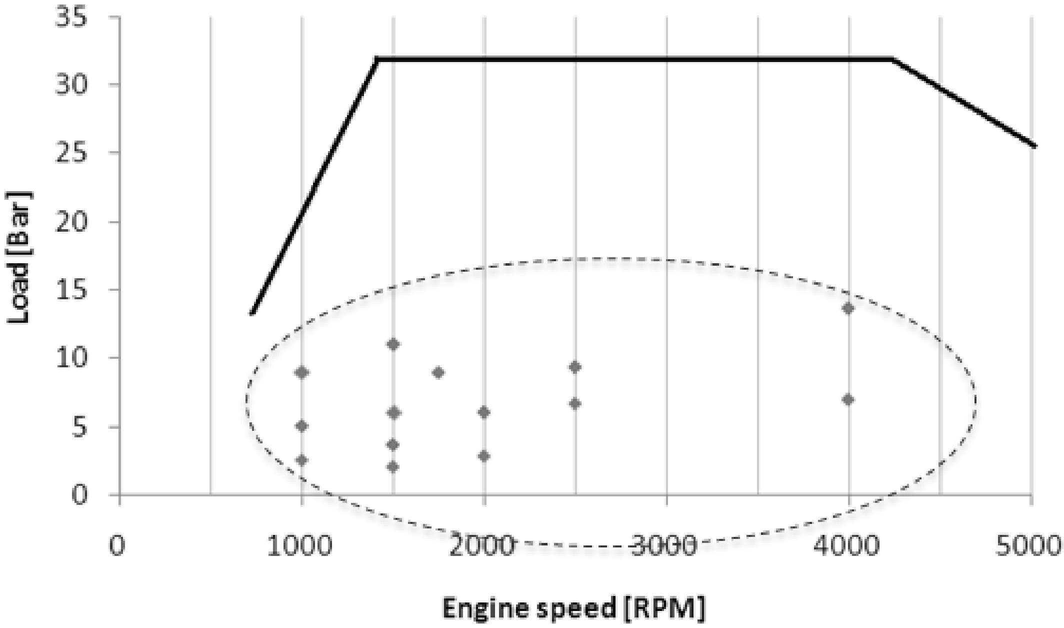

Figure 24. Illustrate which operating point that is tested in the mini map.

In the second test the engine was run at full loads between 1500 rpm to 6000 rpm. This test will verify the effects of isolated intake ports on full load. All tests were done by Volvo personnel at the engine research laboratory where intake air temperature was compared between the two different setups using a thermo element that measured the temperature at three different positions in the intake port, which is illustrated in Figure 25. Then the temperatures between the two cylinder-heads were compared, which will indicate if isolated intake ports obtain a reduced intake air temperature.

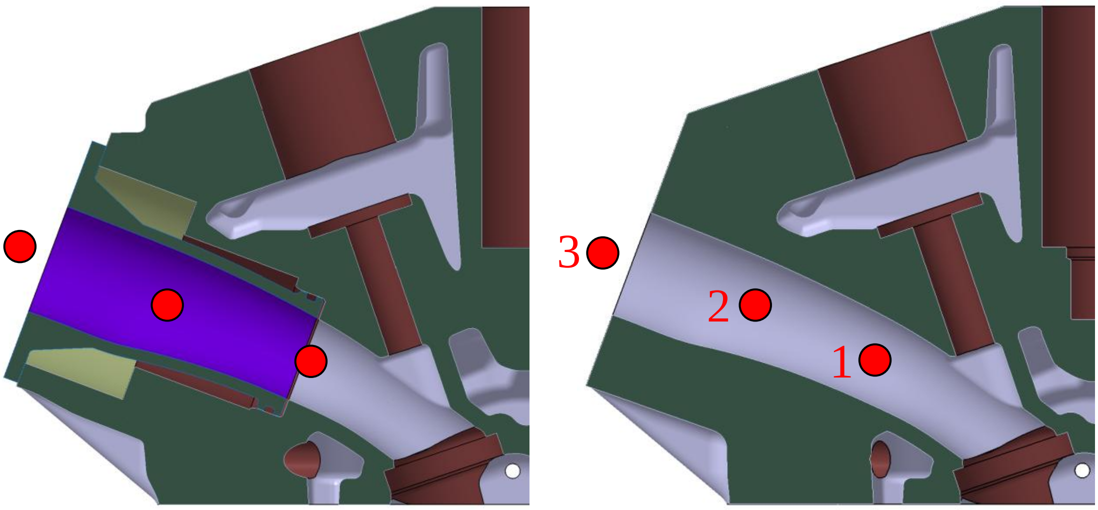

Figure 25. Illustrates were the intake air is measured at three different positions in the port.

3.5 Direct Throttle

Since this thesis project is based on the investigation of isolated intake ports, the design process of the direct throttle solution will not be described. Instead the final Direct Throttle solution is directly presented in Figure 26 and it was manufactured by Volvo´s in-house workshop.

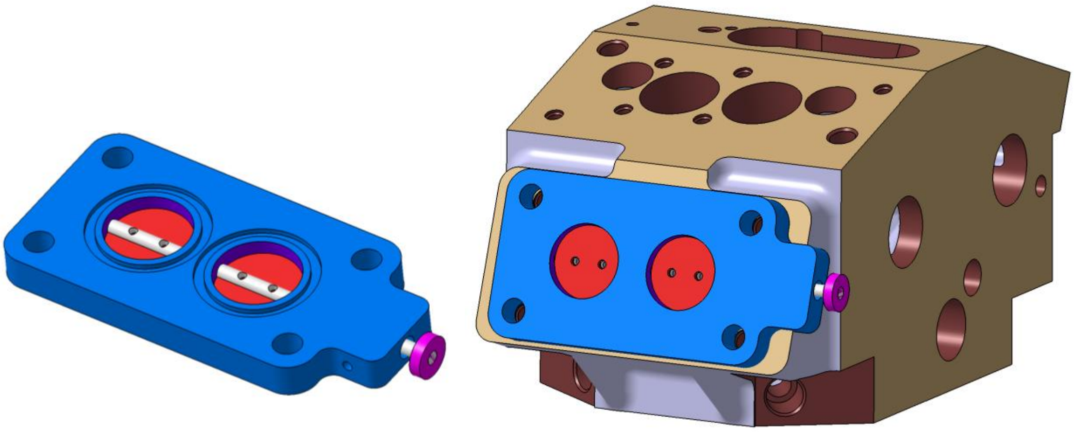

Figure 26. Illustrates how the direct throttle is designed and mounted on the cylinder head.

4 Results

4.1 GT-Power

The first generated result was the steady-state brake torque versus engine speed plot, which is illustrated in Figure 27. In this graph it is seen that isolated intake ports generated an increased low end torque, by approximately 10Nm.

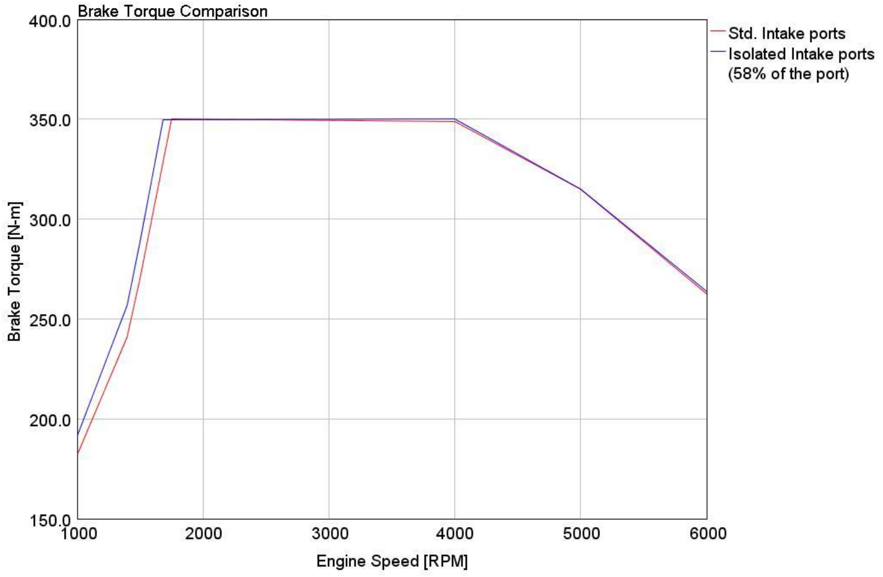

Figure 27. Illustrates the effects of isolated intake ports on engine torque compared to standard intake ports.

Since the goal was to reduce heat transfer to incoming intake air, an interesting simulation parameter to investigate is the outlet temperature where the plastic insert ends. In Figure 28 it is shown that the intake air temperature at the plastic insert outlet is decreased by average 11°C between 1250 rpm to 2100 rpm compared to the standard intake ports, where the outlet temperature corresponds to position 1 in Figure 25.

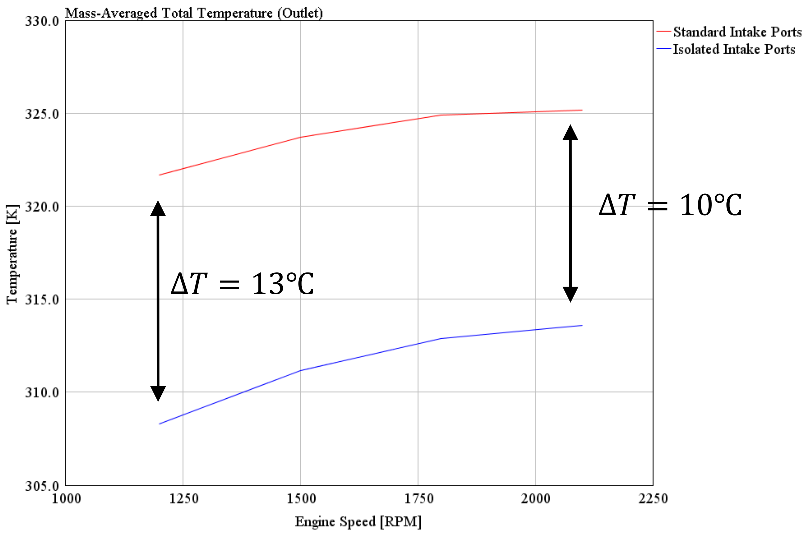

Figure 28. Illustrates the mass-average intake air temperature at the outlet of the isolated insert.

In Figure 29, the plot illustrates how response time of the engine was improved by isolated intake ports. The plot contains a comparison between standard intake ports, optimal isolated intake ports and the isolated intake ports. The results show that isolated intake ports improve the response time of engine compared to standard design.

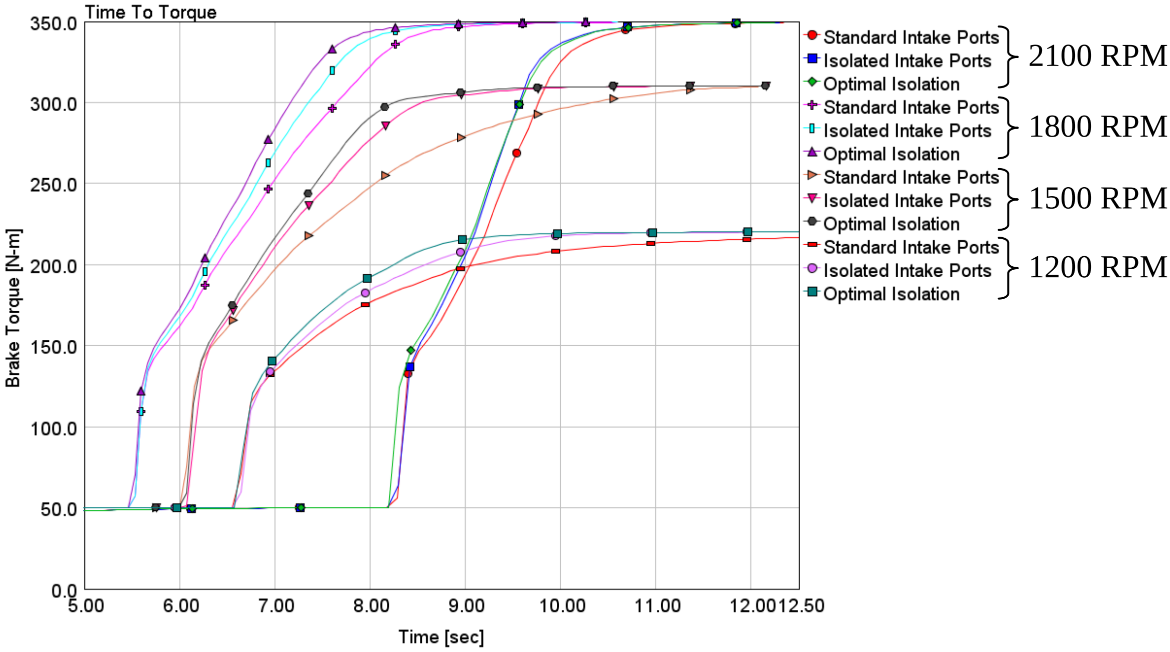

Figure 29. Illustrates the response test simulation on four different engine speeds.

The last result is based on the investigation of how knock is influenced by isolated intake ports, which are done by plotting the unburned zone temperature versus crank angle degrees during combustion. The result of this investigation showed that the temperature was approximately reduced by 13℃ at the unburned zone, which is illustrated in Figure 30 and 31 and consequently decreases the risk of engine knock.

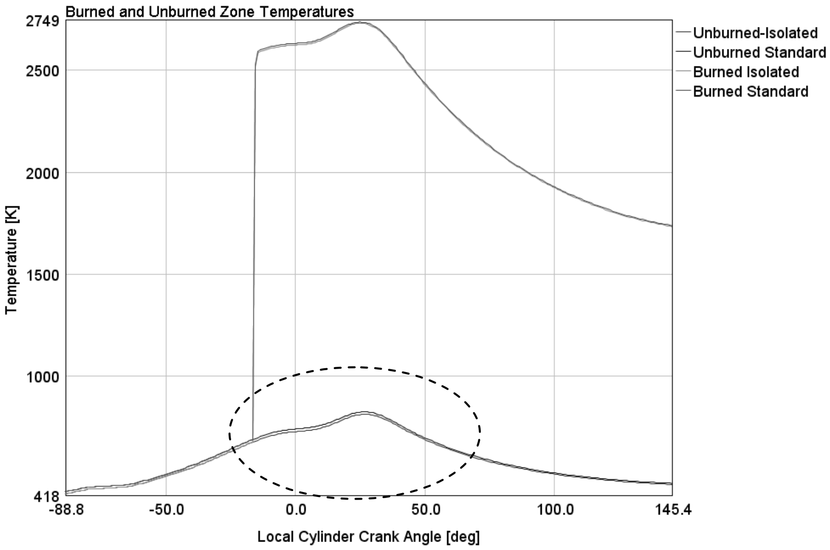

Figure 30. Illustrates the Unburned and Burned zones during combustion at full load, were the dashed area show the zoomed in area in Figure 28.

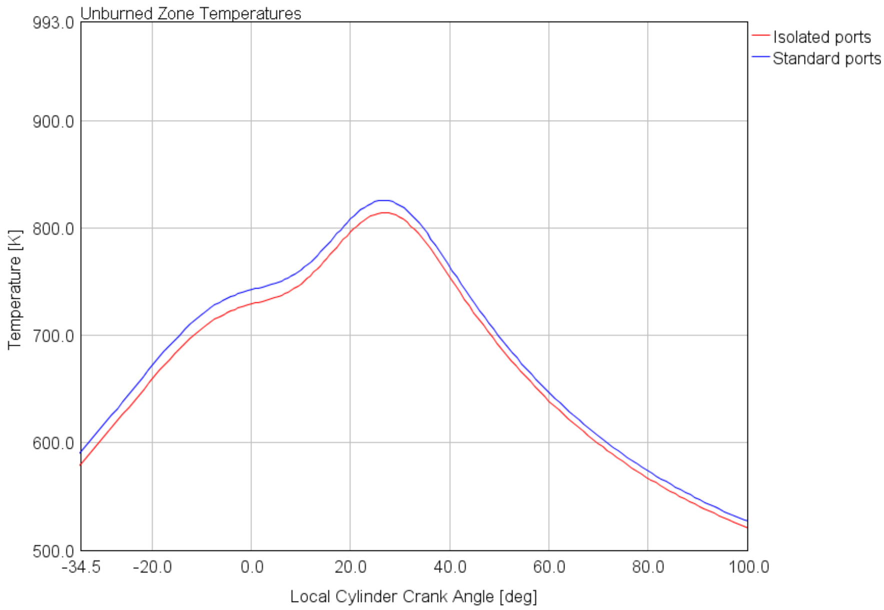

Figure 31. Illustrates the effects of isolated intake ports on temperature at the unburned zone.

4.2 CFD

4.2.1 Standard Intake Ports

In Figure 32 it is illustrated how the incoming intake air is heated by the standard intake ports. The inlet temperature is set to 30℃ and the outlet temperature became 42℃. This means that the incoming intake air temperature is heated by 12℃ during its travel in the intake ports.

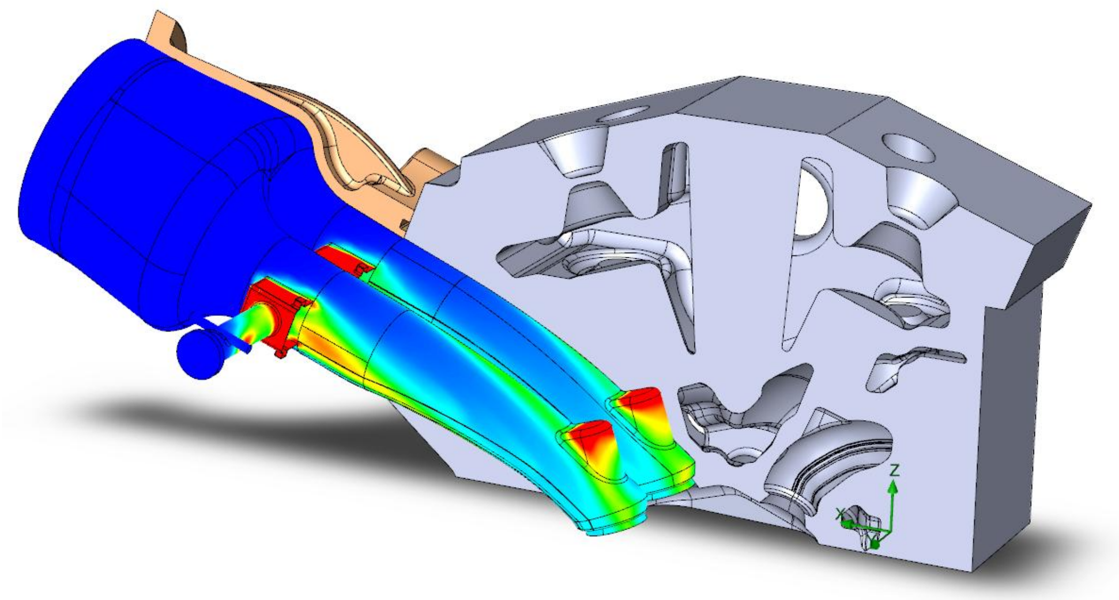

Figure 32. Illustrates how the incoming intake air temperatures are influenced by the standard intake ports.

4.2.2 Isolate Intake Ports

In Figures 33, 34 and 35 it is illustrated how incoming intake air is heated with isolated intake ports. The inlet temperature is set to 30°C and the simulations calculated an outlet temperature of 36°C, which means that isolated intake ports generated a temperature reduction of 6°C, compared to the standard intake ports.

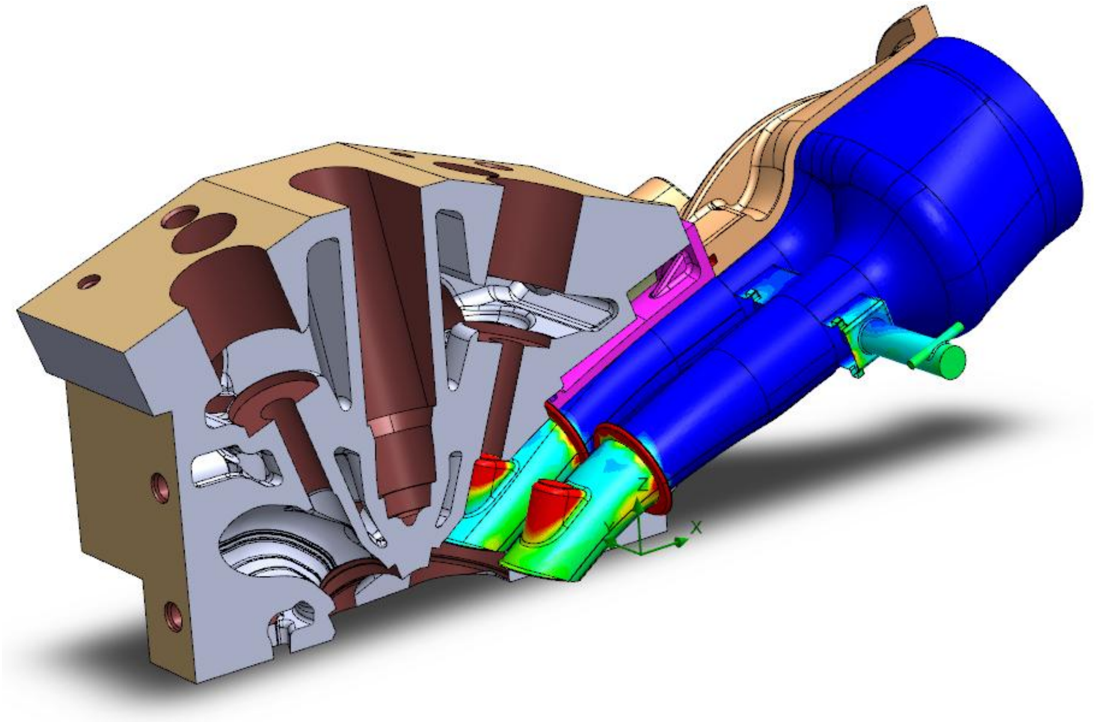

Figure 33. Illustrates how the incoming air is heated with isolated intake ports.

In Figure 34 it is also seen that heat transfer via conduction mainly occurs where the insert transitions over to the standard intake port. The figure also illustrates that there almost no heat transfer to the incoming intake air charge over the isolated part of the intake ports.

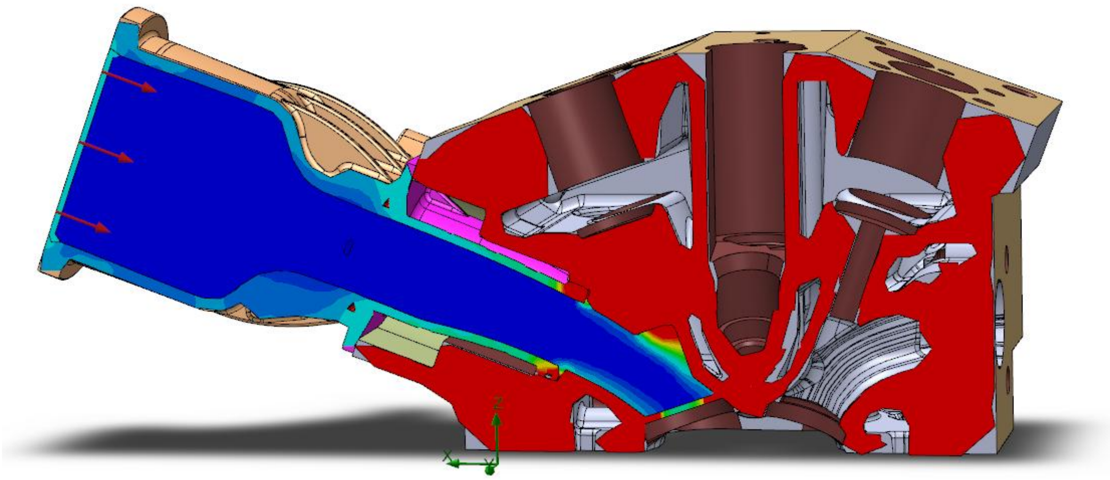

Figure 34. Illustrates how the heat is transferred thru solid bodies into the incoming intake air with isolated intake ports.

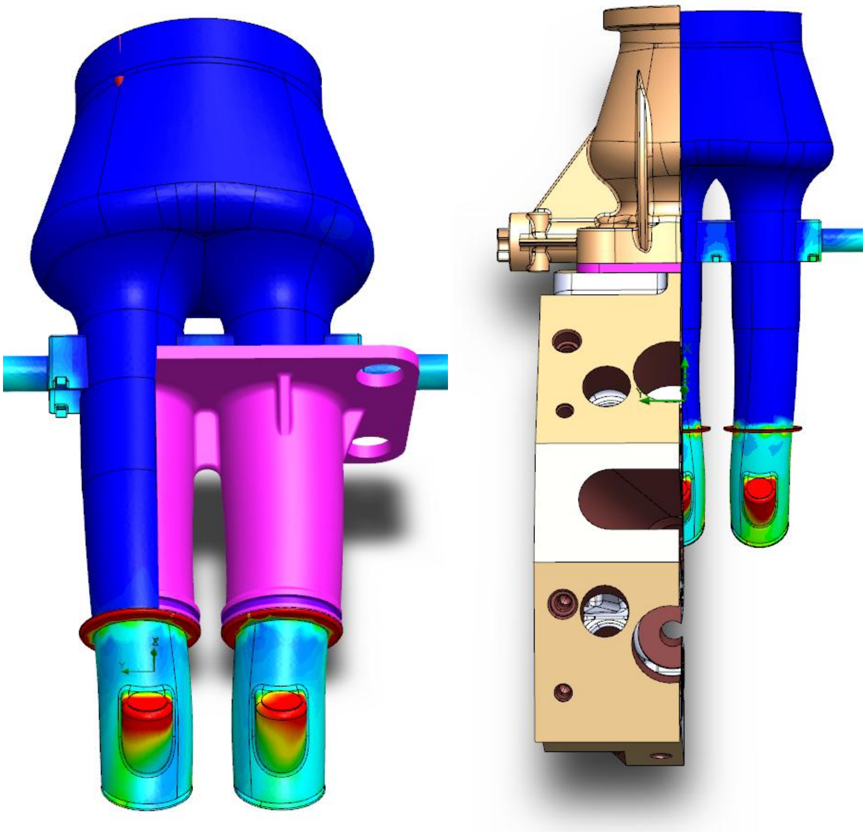

Figure 35. Illustrates how the heat is transferred thru solid bodies into the incoming intake air with isolated intake ports.

4.3 Experiment testing

In order to evaluate the realistic outcome of isolated intake port it is neccessary to test this modified single cylinder head in a running engine bench were intresting parameters is captured. The experiment testings contained a full load testing, which means that the engine is operating with wide open throttle at engine speeds from 1500 to 5000 rpm. In the other experiment the engine operated in a mini-map with different operating points on part load, which is shown in shown in Figure 23.

4.3.1 Full load testing

The first performed experiments was the full load testing. Since the intended improving effect of isolated intake ports is expected to be on lower engine speeds, focus will be concentrated to this area, which is between 1500 rpm to 3000 rpm. The outcome of these experiments is shown in Table 1, where T(3), T(2) and T(1) corresponds to where the intake air temperature is measured, which is illustrated in Figure 25. The most significant changes are the average reduced intake air temperature with 4.2 °C and volumetric efficiency which is in average increased with 3%.

Table 1. Shows the final results from the full load experiments.

Full Load Testing

	Isolated Intake Ports							
	NMEP	Speed_Dyno	Voleff	T(3)	T(2)	T(1)	Airflow_V	Airflow_M
	-	-	-	-	-	-	-	-
	bar	min^-1	-	°C	°C	°C	l/s	g/s
	19,067	1500,46	1,605	32,4	32,3	34,1	6,562	11,879
	19,266	1998,43	1,529	32,5	33,2	34,8	8,325	15,098
	18,815	2498,59	1,467	32,7	32,8	34,7	9,973	18,116
	17,735	2997,6	1,35	32,9	32,5	34,6	10,998	20,016
Average	18,7195		1,48775			34,55	8,9645	16,27725
	Standard Intake Ports							
	NMEP	Speed_Dyno	Voleff	T(3)	T(2)	T(1)	Airflow_V	Airflow_M
	-	-	-	-	-	-	-	-
	Bar	min^-1	-	°C	°C	°C	l/s	g/s
	19,084	1502,41	1,58	32,3	36,4	38,7	6,461	11,67
	18,969	2002,84	1,471	32,5	36,5	39	8,306	14,968
	18,671	2503,19	1,433	32,8	35,5	38,8	9,781	17,669
	17,666	3003,12	1,343	32,8	35,1	38,3	10,93	19,868
Average	18,5975		1,45675			38,7	8,8695	16,04375

4.3.2 Engine mini-map testing

The most important parameters from the mini-map experiments are shown in Figure 36 and 37, where number 1, 2 and 3 corresponds to the measurement positions in Figure 25. The results from this mini-map test shows that the isolated intake ports generates the most significant reduction of intake air temperature at operating points (5 bar/1000 Rpm), (9 bar/1000 Rpm), (4 bar/1500 Rpm) and (6 bar/1500 Rpm).

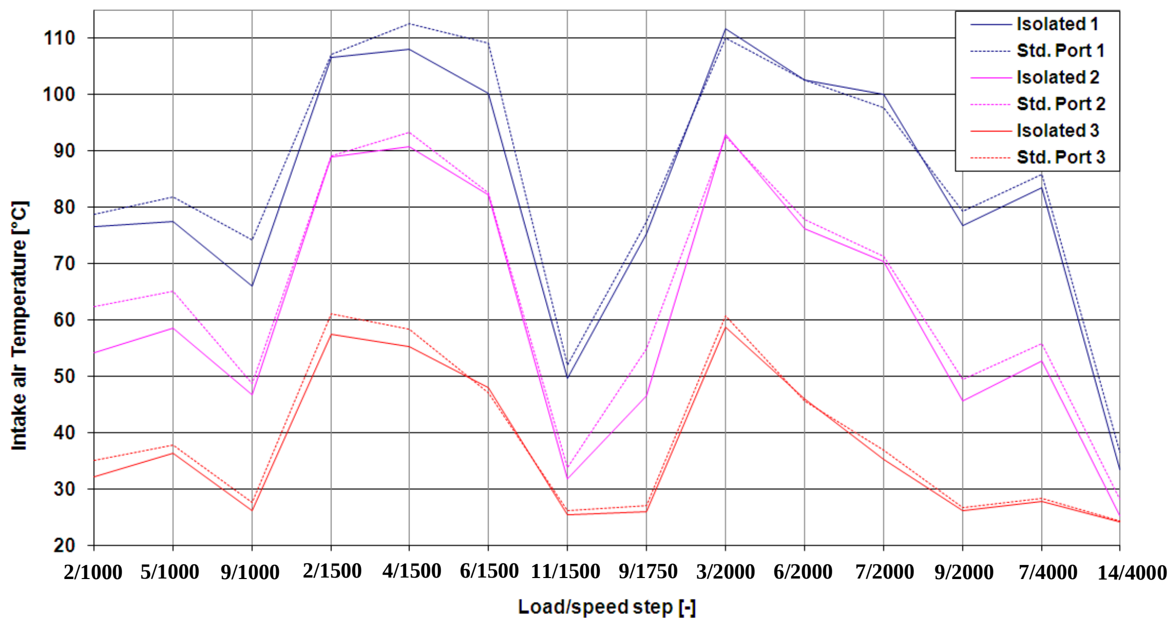

Figure 36. Illustrates the intake temperature at the different operating points from the mini-map.

In Figure 37, it is seen that the fuel consumption is increased with isolated intake ports, predominaly at lower engine speeds.

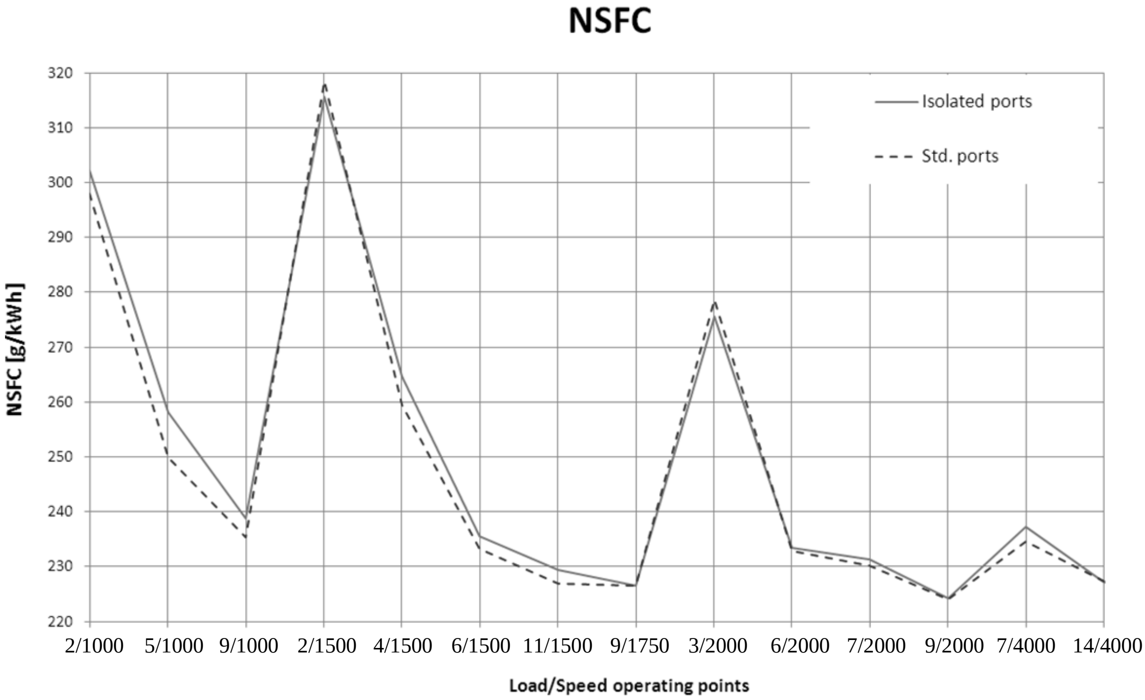

Figure 37. Illustrates the fuel consumption at the operating points from the mini map.

4.4 Direct Throttle

The outcome from the experiments with a throttle directly mounted on the cylinder head did not end up as expected. The pump losses were instead increased with this solution, which is seen in Table 2, were only one operating point is presented since the pump losses was increased on all operating points with direct throttle.

Table 2. Illustrates the pump losses from one operating load/speed point.

Standard		
	PMEP - bar	T(3) - °C
1000/5.0	-0,347	84,8

Direct Throttle		
	PMEP - Bar	T(3) - °C
1000/5.0	-0,4385	75,0

5 Discussion

The simulation results ended up as the predicted expected outcome of isolated intake ports. The heating of the intake air by the surfaces in the intake ports did have effect on the mass flow. Since the density of the air was increased and more mass admitted to the engine, the volumetric efficiency was increased. The heating effects did have more effect at lower engine speeds and therefore it acted to tilt the volumetric efficiency curve. This resulted that the combustion process was provided with more oxygen, which gives the possibility to inject more fuel per cycle. The effects of this result in a more powerful engine without increasing its size, particularly at lower engine speeds. The response time plot, Figure 29, indicates that there occurs an error at 1500 rpm, since the improvement is too great to be realistic. Since the engine model used at these simulations was a research model, it may be that the turbo was not 100% calibrated to the particular engine model. Since the results from the simulations shows that cooler intake air charge at lower engine speeds is sustained by isolated intake ports, it directly translates to less tendency of knocking at theses speeds. Since knock is a limiting parameter for several performance parameters it gives the opportunity to optimize the engine even further. As the fuel conversion efficiency was decreased by the lowering of combustion temperature, a way to equalize the negative effects of isolated intake ports may be to increase the combustion temperature, which can be done in several ways, which is illustrated in Figure 38.

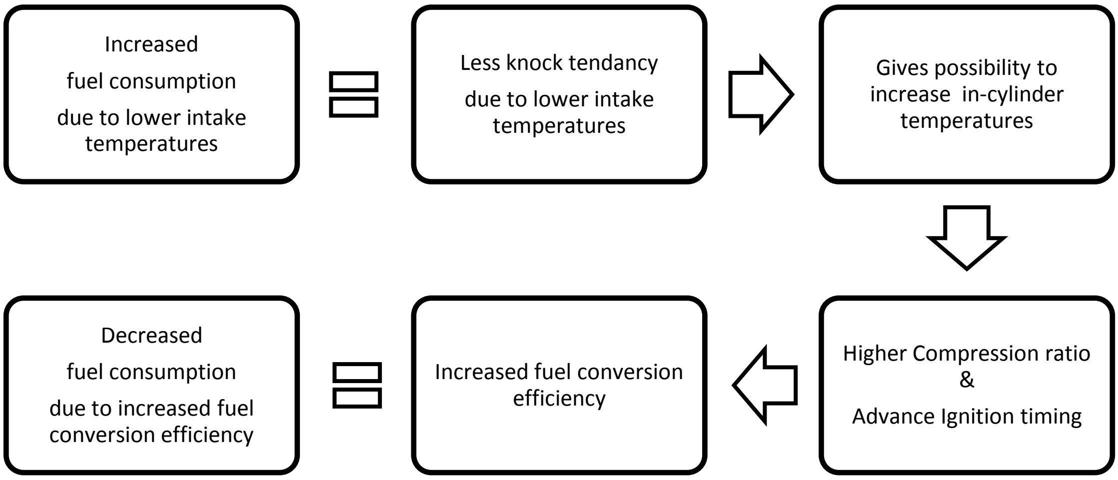

Figure 38. How to equalize the negative effects of isolated intake ports.

One method may be to increase compression ratio so the engine produces higher in-cylinder pressure which leads to higher combustion temperature. Higher temperatures during the combustion stroke translate directly into increased fuel conversion efficiency. So, intake port isolation combined with increased compression ratio can possibly equalize the negative effects of colder intake air since knock limits compression ratio, which influences power and efficiency. Another method would be to increase boost pressure at low engine speeds, thus this method will not decrease fuel consumption, instead increase the output torque even further. Heat soak of the intake charge can cause the ignition timing to be backed down, either through the intake air temperature sensor, or through the knock control. Therefore a higher resistance to knock gives the possibility to optimize ignition timing even further.

MBT is the timing which give the maximum brake torque for given engine. Timing which is advanced or retarded from this optimal timing point results in lower output torque. This optimum timing will depend on flame development, propagation and length of flame, which contra depends on engine design, fuel quality, air temperature etc. A lower intake air temperature will therefore give the possibility to advance the timing even further since it is limited by the knock. The most suitable method that could be used to equalize the negative effects should have the possibility to be varied with engine speed. As compression ratio is a constant parameter it may be preferred to try the method of changing boost pressure or ignition timing first, since the boost pressure and ignition timing can easily be varied compared to compression ratio which is constant. Although there is variable compression ratio system available on the market, but Volvo has decided to not implement such system on their engines.

In the experiments it is seen that the fuel consumption was increased which was expected. This occurs mostly at lower engine speeds were isolated intake ports predominantly influence the intake air temperature. Since the results from the full load theoretical engine simulation showed a decreased outlet temperature at the plastic insert by average 11°C. It may be summarized that the realistic experiments did not fall out as what expected, since the temperature at the full load testing was only decreased by 4.2°C. One explanation of this may be that the engine model was not calibrated enough and therefore parameters which influence heat transfer in the intake ports may be wrongly adjusted. Another interesting phenomenon that occurred at the experiment testing of the direct throttle was that the intake air temperature was decreased. This could be explained that the amounts of backflow of the hot combustion gases were restricted by the throttle from traveling backwards thru the intake system and therefore heating the intake air even further. So, if the intake valve closing occurs earlier, the amount of backflow will decreased and consequently decreased intake air temperature. Since the theoretical simulations and the realistic experiments deviated in the amount as it did, it may be in the greatest interest for Volvo to investigate why this deviation occurs. In GT-Power there is parameter which is multiply additional heat transfer to the intake air temperatures during its travel thru the intake port. This value is for example used to take into account the hot intake valves and stems. If this parameter is increased it enhances heat transfer between the intake air gas and the intake port surfaces. The recommended value is typically set to 1.0, thus in the Volvo engine model it was set to 1.35. This may be an explanation why the results from the simulations compared to the realistic experiments deviated in the amount what they did.

According to the performed CFD simulations at 1500 rpm, the intake air temperature was only raised by 12°C during its travel thru the standard intake ports. At the same engine speed with isolated intake ports it is calculated that the temperature is reduced by 5°C compared to the standard intake ports. The results from these CFD simulations almost correspond to the outcome of the realistic experiments. Thus, they can not be fully compared to the realistic experiments, since the CFD simulations is using steady-state flow and in the realistic case it occur transient flow since intake air pulsating back and forth in the intake ports as the intake valves open and closes.

6 Conclusion

In engine development there is always pros and cons with different methods or new solutions. An understanding of the effects that a single component has on the results is important when determining the cause of differences between measured and predicted results. When evaluating new solutions, it is almost a standard procedure that the theoretical simulations deviates in comparison to the realistic results and the investigation of isolated intake ports proved such a thing. In this study the theoretical GT-Power simulations indicated promising results. Thus, the major drawback was experienced during experiment testing, there it was noticed that the standard intake ports did not heat the incoming intake air as much as was expected. This consequently resulted that the initial improvement potential of isolated intake ports influence on intake air was not as great as what is expected from the beginning of the thesis. The conclusion of this is that the internal thermodynamic involvement in intake ports is counter intuitive and complex. Thus, successfully investigation of new unique engine solutions requires both running engine rig tests and engine simulations.

For future studies in the area of investigation it may be recommended to use transient CFD simulations where boundary conditions for the cycle are applied from a 1D cycle engine simulation model, such as GT-Power. Since the results from the direct throttle testing ended up as it did, it may be good idea to investigate the influence of backflow on intake air temperature. With variable valve timing the amount of backflow can be decreased by closing the intake valves earlier. This may result that less combustion gases travels up thru the intake system and hence translates into lower intake air temperature. Since it is the aim to inhale as cold intake air as possible on high load and as warm air as possible on low loads. So a suggestion may be to decrease the amount of backflow on high loads in order to decrease heating of the intake air temperature. Since the intake air temperature was not reduced in the amount as what was indicated from the GT-Power simulations, a suggestion may be to investigate the intake port heat transfer multiplier. This parameter is defining additional heat transfer rate between the intake air fluid and the intake port surfaces. According to the outcome of the experiments, this multiplying parameter is probably defined with a too high value. The recommendation is to use the data obtained from the realistic experiments and iterate a new value for this parameter.

In this thesis project it is shown that heat transfer rate in the intake port is influenced by many complex parameters. According to the results, the most influential parameters of intake charge heating is the backflow and the hot surfaces around the intake valves. To conclude, analysis of complex system such intake ports takes place in different levels from receiving control of a single component to the final control of the complete engine.

7 References

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