MARMARA UNIVERSITY
FACULTY OF ENGINEERING

ADAPTATION OF EXISTING ENGINES FOR HYDROGEN INTERNAL COMBUSTION

Mahmoud ELOBEIDY # 150419543

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Department of Mechanical Engineering

Supervisor
Prof. Dr. Mustafa YILMAZ

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Adaptation of Existing Engines for Hydrogen Internal Combustion

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Mahmoud ELOBEIDY

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Signature of Author(s) ....

Department of Mechanical Engineering

Certified By ....

Project Supervisor, Department of Mechanical Engineering

Accepted By..

Head of the Department of Mechanical Engineering

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June, 2023 Mahmoud ELOBEIDY

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ABSTRACT

Adaptation of Existing Engines for Hydrogen Internal Combustion

In order to successfully cope with the trend of mitigating climate change we Have be able to achieve the highest CO_2 emission reduction. Alternatives to hydrocarbon fuels can significantly contribute towards this goal and save the earth. Hydrogen, one of these alternatives, is a carbon-free fuel and could help end our dependence on fossil fuels towards minimizing the CO_2 emission. Hydrogen-powered internal combustion engines with near-zero emissions are an attractive automotive solution. The structure of hydrogen-fueled engine is almost the same as for conventional internal combustion engine. However, modifications are required to this engine to be adapted to hydrogen as fuel and to overcome numerous challenges. Hydrogen has a small quench distance, which is much shorter than that of gasoline, making flame to travel closer to the cylinder walls than that of gasoline before it extinguishes. Short quenching distance and high burning velocity of hydrogen make chamber walls hotter. Furthermore, the small quench distance of hydrogen makes it easier to escape the intake valve when it is closed, causing backfire. The objective of this project is to modifying the existing gasoline internal combustion engine to be adapted to hydrogen fuel and to overcome significant problems caused by the low quench distance and higher burning velocity of hydrogen. In this project the cooling system for the hydrogen internal combustion engine was improved through more control of the coolant flow velocity in the water jacket. The centrifugal water pump is driven by an electric motor, instead of the engine crankshaft as with the traditional gasoline engine. This modification can improve engine cooling control and capacity. Seat with width of 1.5mm of the intake valve in the traditional gasoline engine was increased to 2.0mm to reduce hydrogen leakage under the same seating pressure, which was restored by reducing the valve spring length. Finally, two small exhaust valves replaced the large exhaust valve in the traditional gasoline engine to improve cooling in the combustion chamber.

SYMBOLS

°C : degree Celsius

$CO2$: carbon dioxide

H_2 : hydrogen

K : heat transfer coefficient;

N_2 : nitrogen

NOx : oxides of nitrogen

O_2 : oxygen

t : shear modulus

T_1 : absolute initial temperature

T_2 : absolute final temperature

T_{f1} , T_{f2} : the temperatures of fluids between which the heat exchange takes place

$V1/V2$: the compression ratio

α_a , α_b : convection film coefficients of the inner and outer wall surfaces

γ : ratio of specific heats

η_{th} : theoretical thermodynamic efficiency

ABBREVIATIONS

BDC : bottom dead center
COP21: Conference of the Parties 21
COP26: Conference of the Parties 26
EU : European Union
F : force
IC : internal combustion
IMEP : indicated mean effective pressure
In : inch
km : kilometer
Lb : pound
mm : millimeter
N : newton
OP : open pressure
ppm : part per million
RPM : revolutions per minute
SP : seat pressure
TDC : top dead center
VSR : valve spring rate

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1. INTRODUCTION

Global energy-related carbon dioxide emissions rose by 6% in 2021 to 36.3 billion tones, their highest ever level, according to a released new International Energy Agency's analysis (IEA, 2022). The global average atmospheric carbon dioxide was 414.72 parts per million in 2021, setting a new record high despite the continued economic drag from the COVID-19 pandemic. In fact, the jump of 2.58 ppm over 2021 amounts tied for 5th-highest annual increase in the record (Lindsey, 2022).

Carbon dioxide concentrations are rising mostly because of the fossil fuels that people are burning for energy. Since the middle of the 20th century, annual emissions from burning fossil fuels have increased every decade, from an average of 3 billion tons of carbon (11 billion tons of carbon dioxide) a year in the 1960s to 9.5 billion tons of carbon (35 billion tons of carbon dioxide) per year in the 2010s, according to the Global Carbon Update 2021 (Lindsey, 2022). Today, internal combustion engines using fossil fuels generate about 25% of the world's power and they are responsible for about 17% of the world's greenhouse gas emissions, while producing other main pollutant emissions such as carbon monoxide and carbon dioxide, which have strong negative impact on air quality in urban spaces (Reitz, et al., 2020). In order to successfully cope with the trend of mitigating climate change as outlined in the recommendations of Paris (COP21) and Glasgow (COP26) Climate Agreements, propulsion technologies must be able to achieve the highest CO_2 reduction, within very short time scales (Onorati et al., 2022).

There is a breakthrough internal combustion engines technology to enable a significant reduction of harmful emissions and dependence on fossil fuel. While petrol and diesel may be on the road to nowhere, alternative fuels could come to the fore to give combustion engines a new lease of life. This could mean a hydrogen-burning future (Scoltock, 2022). Hydrogen is a carbon-free fuel and could help end our dependence on fossil fuels towards achieving zero net greenhouse gas emissions. At the same time, Hydrogen could be produced from diverse domestic resources. Hydrogen, as a fuel for internal combustion engines, can significantly contribute to alternative, environmentally friendly road mobility solutions, including meeting the EU's 2050 CO2 neutrality targets (Berry et al., 1996; Hydrogen Central, 2022).

Hydrogen as an energy carrier and main fuel is a promising option due to its carbon-free content, wide flammability limits and fast flame speeds. For spark-ignited internal combustion engines, utilizing hydrogen direct injection has been proven to achieve high engine power output and efficiency with low emissions (Yip et al., 2019). Hydrogen-powered internal combustion engines with near-zero emissions and higher efficiency than diesel engines are an attractive automotive solution. This solution also takes significant advantage of the mature internal combustion engines design (Stepien, 2021). The hydrogen internal combustion engine offers the opportunity to achieve similar performance and comfort characteristics as a conventional gasoline fueled engine. These hydrogen engines burn fuel in the same manner that gasoline engines do. The efficiency of a hydrogen combustion engine can be similar to that of a traditional combustion engine (Berckmuller, 2003; Hydrogen Central, 2022).

However, investigating the potential of hydrogen as a fuel began 30 years ago research interest in hydrogen internal combustion engines has started gaining momentum again, owing to the vast investment plans into hydrogen infrastructures across the globe. The cumulative investments in renewable hydrogen in the EU alone are expected to be in the range of EUR 180-470 billion by 2050, as set out by the European Commission (European Commission, 2020; Babayev et al., 2022). Now, hydrogen combustion, either via gas or liquid, is emerging as one of the most promising options in this respect. Airbus is exploring the technology's potential in preparation for its zero-emission aircraft programme (Airbus, 2020).

The structure of hydrogen-fueled engines is almost the same as for conventional internal combustion engines. However, modifications are required to this engine to be adapted to hydrogen as fuel. At this stage of development, hydrogen-powered internal combustion engines still need to overcome numerous challenges. There are still-unsolved problems related to the using of hydrogen combustion engine (Stepien, 2021). Various modifications to these engines are required due to hydrogen's properties (Akal et al., 2020).

2. RESEARCH PROBLEM

Hydrogen has a small quenching distance of merely 0.64 mm, which is much shorter than that of gasoline (2.0 mm). The quenching distance is the distance within which the flame is quenched near the inner wall of the cylinder. In other words, it is the distance between the cylinder walls and the maximum point the combustion flames reach (Gutkowski and Parra-Santos, 2014). Because of the small quenching distance of hydrogen, flames travel closer to the cylinder wall than other fuels before they extinguish (Benim and Pfeiffelmann, 2019).

Small quenching distance helps spread out the fuel to burn better. However, it can cause other problems. Small quenching distance causes flames to be closer to the cylinder wall before they are extinguished compared to other fuels. This has a considerable impact on the heat transfer through the walls (Korn, 2020). Small quenching distance of hydrogen make Heat transfer from burning gas to the cylinder wall in a hydrogen combustion Engine higher than that with gasoline engine. Consequently, walls of combustion chambers are heated more when hydrogen is used as a fuel.

The smaller quenching distance of hydrogen can also increase the tendency for backfire since the flame from a hydrogen-air mixture more readily passes a closed intake valve, than a hydrocarbon-air flame. In other words, a lower quenching distance of hydrogen might create a backfire because the hydrogen can fit between the valve and the combustion chamber more easily. Frequent backfire can occur in inlet port fuel injection hydrogen internal combustion engine. Hydrogen tends to backfire, especially since it may escape through a closed intake valve (Stepien, 2021). Backfire of hydrogen-fueled internal combustion engines limits the hydrogen fuel applications and drops the power output (Li et al., 2021). It should be noted also that utilizing hydrogen in internal combustion engines may induce safety concerns. These issues require special measures in the design (Yip et al., 2019)

The hydrogen flame ignites and burns quickly and is therefore relatively short-lived (Aleiferis and Rosati, 2012). The burning velocity of hydrogen is very high. The burning velocity of hydrogen is 265-325 cm./sec. versus 37-45 cm./sec. of that of gasoline. Burning velocity is the speed at which a flame front propagates relative to the unburned gas (Edmondson and Heap, 1971). The higher burning velocity of hydrogen is the main cause of the fast combustion in chamber (Rogstadkjernet, 2004). The short duration of the hydrogen combustion process leads to an increased heat emission and hence, to a higher amount of heat across the walls of the combustion n chamber compared to hydrocarbon Combustion engine (Nickl et al., 2022). The short duration of the combustion process and higher burning velocity of hydrogen cause heat transfer from burning gas to the cylinder wall in a hydrogen combustion engine to be higher than that with gasoline engine.

The theoretical adiabatic flame temperatures of hydrogen is 2254°C, while it is 2138°C for gasoline. The adiabatic flame temperature is the temperature reached by a flame under ideal conditions. In other words, it is an upper bound of the temperature that is reached in the combustion chamber (Turns, 2011). But we have to keep in mind that the closer flame, is the more heat transfer to chamber wall.

3. IC ENGINE DEFINITIONS

An internal combustion engine is a type of heat engine that converts the energy from the combustion of a fuel into mechanical energy. This process occurs when a fuel is burned with an oxidizer, typically air, inside a combustion chamber that is part of the engine's working fluid flow system. The expansion of high-pressure and high-temperature gases resulting from the combustion process exerts force on a component of the engine, such as a piston, turbine blade, rotor, or nozzle. This force causes the component to move a certain distance, converting the chemical energy of the fuel into kinetic energy, which can then be used to power machines or vehicles. Internal combustion engines are used in a variety of applications where the weight or size of the engine is a significant factor, and they have largely replaced external combustion engines in these contexts.

3.1 Working Principles

A four-stroke internal combustion engine is one in which the piston completes four distinct movements or "strokes" during one full rotation of the crankshaft. These strokes are:

1. Intake: Also known as induction or suction. The intake stroke starts at the top dead center (TDC) and ends at the bottom dead center (BDC). During this stroke, the intake valve is open and the piston moves downward, creating a vacuum that sucks in an air-fuel mixture into the cylinder.

2. Compression: The compression stroke begins at BDC, immediately after the intake stroke, and ends at TDC. During this stroke, the intake and exhaust valves are closed, and the piston compresses the air-fuel mixture in preparation for ignition during the power stroke.

3. Combustion or Power: Also known as power or ignition. At the beginning of the second revolution of the four-stroke cycle, the crankshaft has completed a full 360-degree rotation. At the top dead center (TDC) of the compression stroke, the compressed air-fuel mixture is ignited by a spark plug in a gasoline engine or by heat generated by high compression in a diesel engine. The resulting explosion forces the piston back down to BDC, producing mechanical work that turns the crankshaft.

4. Exhaust: Also known as outlet. During the exhaust stroke, the piston moves from BDC back to TDC while the exhaust valve is open, expelling the spent air-fuel mixture out of the cylinder.

3.2. Two Stroke IC Engine

A two-stroke engine is a type of internal combustion engine that completes a power cycle with only two movements of the piston, one up and one down, during a single crankshaft revolution. In contrast, a four-stroke engine requires four movements of the piston to complete a power cycle, occurring over two crankshaft revolutions. In a two-stroke engine, the combustion stroke and the compression stroke overlap, with the intake and exhaust functions occurring simultaneously. This allows the two-stroke engine to have a simpler design and fewer moving parts compared to a four-stroke engine, but it also makes it less efficient and more polluting.

During the compression stroke of an internal combustion engine, the inlet valve opens to allow an air-fuel mixture to enter the combustion chamber. The piston then moves upwards, compressing the mixture. At the end of the compression stroke, a spark plug ignites the mixture, starting the power stroke.

During the power stroke, the ignited fuel burns, producing hot gases that exert pressure on the piston. The piston moves downward as it pushes against the crankshaft, converting the chemical energy of the fuel into mechanical energy. As the piston moves downward, some of the heat from the burning fuel is exhausted through the exhaust valve. The power stroke is the main source of mechanical work in the engine, and it occurs during the second revolution of the four-stroke cycle.

3.3 Types of Injections

There are several injection strategies that can be used in an internal combustion engine to deliver fuel to the combustion chamber. Some common strategies include:

1. Direct injection: In this strategy, fuel is injected directly into the combustion chamber, where it mixes with the incoming air and is ignited by a spark plug. Direct injection allows for more precise control of the fuel-to-air ratio and can improve the efficiency of the engine by allowing a leaner fuel-to-air ratio to be used.

2. Port injection: In this strategy, fuel is injected into the intake port, where it mixes with the incoming air before entering the combustion chamber. Port injection is less precise than direct injection and may not allow for as lean a fuel-to-air ratio, but it is simpler and less expensive to implement.

3. Carburetion: This is a older method of fuel injection where the fuel is mixed with incoming air in a carburetor before entering the engine. Carburetors are not as precise as modern fuel injection systems and are not commonly used in modern engines.

4. Multi-point injection: In this strategy, fuel is injected at multiple points in the intake system, rather than just at a single point. This can help to more evenly distribute the fuel-to-air mixture and improve combustion.

3.4 Inlet Radius and Volumetric Efficiency

The inlet radius of an engine refers to the curvature of the inlet port, which is the opening through which air and fuel enter the engine. The radius of the inlet port can affect the flow of air and fuel into the engine, and thus can have an impact on the performance and efficiency of the engine.

The volumetric efficiency of an engine is a measure of how effectively the engine is able to draw in a charge of air and fuel. A higher volumetric efficiency means that the engine is able to draw in a greater mass of air and fuel per unit of time, resulting in more power and potentially better fuel efficiency.

The inlet radius can have an effect on the volumetric efficiency of the engine. A larger inlet radius can allow for more airflow, which can increase the volumetric efficiency. However, a larger inlet radius can also create more turbulence, which can reduce the efficiency of the flow and decrease the volumetric efficiency. A smaller inlet radius can reduce airflow, but may also create a smoother, more streamlined flow, which can improve the volumetric efficiency. The optimal inlet radius will depend on the specific design and operating conditions of the engine.

3.5 Engine Speed

Engine speed, also known as engine RPM (revolutions per minute), refers to the rotational speed of an engine's crankshaft. It is a measure of how fast the crankshaft is turning and is usually expressed in units of RPM. The engine speed is an important factor in determining the performance and efficiency of an engine, as it affects the rate at which the engine is able to produce power and the fuel consumption of the engine.

In a piston engine, the speed of the crankshaft is directly related to the speed of the pistons, which move up and down in the cylinders as the crankshaft turns. As the crankshaft turns, it drives the connecting rods, which are attached to the pistons, causing the pistons to move up and down in the cylinders. The movement of the pistons is what converts the energy of the burning fuel into mechanical work, which is used to turn the crankshaft.

In general, a higher engine speed will result in higher power output, but it will also typically result in higher fuel consumption. The optimal engine speed will depend on the specific design and operating conditions of the engine.

3.6 Compression Ratio

Compression ratio is a measure of the ratio of the volume of the combustion chamber when the piston is at the bottom of its stroke (BDC) to the volume of the combustion chamber when the piston is at the top of its stroke (TDC). It is expressed as a ratio, such as 8:1, which means that the volume of the combustion chamber at BDC is 1/8th the volume at TDC.

The compression ratio of an engine has a significant effect on the performance and efficiency of the engine. A higher compression ratio means that the fuel-to-air mixture in the combustion chamber is more highly compressed, which can lead to a more efficient burn and higher power output. However, a higher compression ratio also increases the risk of knocking or pre-ignition, which can damage the engine.

The in-cylinder pressure (IMEP) is a measure of the pressure in the combustion chamber during the combustion process. It is affected by the compression ratio of the engine, with a higher compression ratio resulting in a higher IMEP.

NOx (oxides of nitrogen) emissions are pollutants that are formed during the combustion process in internal combustion engines. They are formed when nitrogen in the air reacts with oxygen at high temperatures. The compression ratio of an engine can have an impact on NOx emissions, with a higher compression ratio typically resulting in higher NOx emissions.

4. HYDROGEN ENGINE SPECIFICATIONS AND RELATED EQUATIONS

4.1. Autoignition Temperature

Hydrogen has a relatively high autoignition temperature. This has important implications when a hydrogen-air mixture is compressed. In fact, the autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio. The temperature rise is shown by the equation:

$$T_2=T_1(V_1/V_2)^{\gamma-1}$$

where:

$V1/V2$ = the compression ratio

T_1 = absolute initial temperature

T_2 = absolute final temperature

γ = ratio of specific heats

Hydrogen has high flame speed at stoichiometric ratios. Under these conditions, the hydrogen flame speed is nearly an order of magnitude higher (faster) than that of gasoline. This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle. At leaner mixtures, however, the flame velocity decreases significantly.

Hydrogen has very high diffusivity. This ability to disperse in air is considerably greater than gasoline. This facilitates the formation of a uniform mixture of fuel and air.

Hydrogen has very low density. This results in two problems when used in an internal combustion engine. The energy density of a hydrogen-air mixture, and hence the power output, is reduced.

The theoretical or stoichiometric combustion of hydrogen and oxygen is given as:

$2H_2 + O_2 = 2H_2O$

Moles of H_2 for complete combustion = 2 moles

Moles of O_2 for complete combustion = 1 mole

Because air is used as the oxidizer instead oxygen, the nitro-gen in the air needs to be included in the calculation:

Moles of N_2 in air = Moles of O_2 x (79% N2 in air / 21% O_2 in air)

= 1 mole of O_2 x (79% N_2 in air / 21% O_2 in air)

= 3.762 moles N_2

Number of moles of air = Moles of O_2 + moles of N_2

= 1 + 3.762

= 4.762 moles of air

Weight of O_2 = 1 mole of O_2 x 32 g/mole

= 32 g

Weight of N_2 = 3.762 moles of N_2 x 28 g/mole

= 105.33 g

Weight of air = weight of O_2 + weight of N (1)

= 32g + 105.33 g

= 137.33 g

Weight of H_2 = 2 moles of H_2 x 2 g/mole

= 4 g

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

A/F based on mass = mass of air/mass of fuel

= 137.33 g / 4 g

= 34.33:1

A/F based on volume = volume (moles) of air/volume (moles) of fuel

= 4.762 / 2

= 2.4:1

The percent of the combustion chamber occupied by hydro-gen for a stoichiometric mixture:

% H_2 = volume (moles) of H_2/total volume (2)

= volume H_2/(volume air + volume of H_2)

= 2 / (4.762 + 2)

= 29.6%

As these calculations show, the stoichiometric or chemically correct A/F ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This means that for complete combustion, 34 pounds of air are required for every pound of hydrogen. This is much higher than the 14.7:1 A/F ratio re-quired for gasoline.

Since hydrogen is a gaseous fuel at ambient conditions it displaces more of the combustion chamber than a liquid fuel. Consequently, less of the combustion chamber can be occupied by air. At stoichiometric conditions, hydrogen dis-places about 30% of the combustion chamber, compared to about 1 to 2% for gasoline.

Because of hydrogen's wide range of flammability, hydrogen engines can run on A/F ratios of anywhere from 34:1 (stoichiometric) to 180:1. The A/F ratio can also be ex-pressed in terms of equivalence ratio, denoted by phi (Φ). Phi is equal to the stoichiometric A/F ratio divided by the actual A/F ratio. For a stoichiometric mixture, the actual A/F ratio is equal to the stoichiometric A/F ratio and thus the phi equals unity (one). For lean A/F ratios, phi will be a value less than one. For example, a phi of 0.5 means that there is only enough fuel available in the mixture to oxidize with half of the air available. Another way of saying this is that there is twice as much air available for combustion than is theoretically required.

The simplest method of delivering fuel to a hydrogen engine is by way of a carburetor or central injection system. The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. At this point conditions are much less severe and the probability for premature ignition is reduced. In port injection, the air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. Since less gas (hydrogen or air) is in the manifold at any one time, any pre-ignition is less severe. The inlet supply pressure for port injection tends to be higher than for carbureted or central injection systems, but less than for direct injection systems. More sophisticated hydrogen engines use direct injection into the combustion cylinder during the compression stroke. In direct injection, the intake valve is closed when the fuel is injected, completely avoiding premature ignition during the intake stroke. Consequently, the engine cannot backfire into the intake manifold. The power output of a direct injected hydrogen engine is 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor.

Due to hydrogen's low ignition energy limit, igniting hydro-gen is easy and gasoline ignition systems can be used. At very lean air/fuel ratios (130:1 to 180:1) the flame velocity is reduced considerably and the use of a dual spark plug system is preferred.

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the specific-heat ratio of the fuel as shown in the equation:

$$\eta_{th}=1-[1/(V_1/V_2)^{\gamma-1}]$$

where:

V_1/V_2 = the compression ratio
γ = ratio of specific heats
η_{th} = theoretical thermodynamic efficiency

The specific-heat ratio is related to the fuel's molecular structure. The less complex the molecular structure, the higher the specific-heat ratio. Hydrogen (γ = 1.4) has a much simpler molecular structure than gasoline and therefore its specific-heat ratio is higher than that of conventional gasoline (γ = 1.1) (Energy.Gov, 2014).

4.2. Heat Transfer and Cooling the Engine

The amount of heat transferred from cylinder walls is calculated through using either Woschni expression or Annand and Hohenberg expression (Sanli et al., 2008; Binti Zakaria, 2012).

The heat flow, transferred through a solid cylindrical wall, separating two fluids with different temperatures, is calculated by the following formula in the simplest case:

$q = K \times (T_{f1} - T_{f2})$;

K - heat transfer coefficient;

T_{f1} , T_{f2} - are the temperatures of fluids between which the heat exchange takes place.

The heat transfer coefficient k depends on the physical properties of the heat carrier, the flow regime and the thermal conductivity of the solid wall. The heat transfer coefficient of a cylindrical wall, referred to the length of the pipe, can be expressed in terms of the convection film coefficients of the wall surfaces:

$$K = \pi / [(1 / \alpha_a * D_1) + (1 / 2\lambda) * Ln(D_2 / D_1) + (1 / \alpha_b * D_2)];$$

α_a , α_b - convection film coefficients of the inner and outer wall surfaces;

λ - wall heat transfer coefficient;

D_1 - inner diameter;

D_2 - outer diameter.

In this calculation, heat transfer through a tube of length L, with inner diameter D_1, outer diameter D_2, and with wall thermal conductivity λ is considered. The tube wall separates a fluid A with a temperature T_{fa} and a fluid B with a temperature T_{fb}. For the calculation, the convection film coefficients α_a, α_b should also be specified, which can be calculated in this Section.

As a result of calculations, the temperatures of the wall surfaces T_{wa}, T_{wb}, power P and heat flow Q, transmitted through the wall, and also heat transfer coefficient of the wall K, calculated relative to the pipe length, are determined.

An electric water pump is a consideration to feature advanced thermal management system engineering. Centrifugal pumps that are driven by electric motors are used with very large traditional engines.

The energy in 2.2 pounds (1 kilogram) of hydrogen gas is about the same as the energy in 1 gallon (6.2 pounds, 2.8 kilograms) of gasoline.

Hydrogen has a low volumetric energy density (US Department of Energy, 2023a).

4.3. Intake Valve

A valve spring rate is the amount of pressure needed to compress the valve spring. Valve springs are used in internal combustion engines and come in various load ratings. The load rating is how much pressure it takes to compress the spring by 1 inch. Most valve springs are rated at a maximum pressure and are measured in pounds per square inch (PSI)

Enter the open pressure, seat pressure, and the lift height into the calculator to determine the valve spring rate.

Valve Spring Rate Formula:

The following equation is used to calculate the Valve Spring Rate.

$VSR=(OP-SP)/L$

Where VSR is the valve spring rate (lbs/in)

OP is the open pressure (lbs)

SP is the seat pressure (lbs)

L is the lift (in)

To calculate a valve spring rate, subtract the seat pressure from the open pressure, then divide by the lift.

4.5. Coil (Conical) Spring Force Calculator

A coil spring force is a type of mechanical force that works in conjunction with a conical coil and can be used to exert a force on an object. It is typically used in electronic devices, such as clocks and wristwatches, to help them keep track of time.

Enter the diameter of the spring wire, the mean coil radius, and the shear modulus into the calculator to determine the conical spring force.

F = pi/16 * d^3 / r * t

Where F is the force (N)

d is the diameter of the wire (m)

r is the mean radius of the coil (m)

t is the shear modulus of the material (Pa)

Spring Force:

A spring force is a restoring force provided by a physical spring, a helical spring, or a torsion spring. The restoring force provided by the spring is proportional to the displacement of the elastic element. It always acts in the direction that tends to restore the equilibrium position of the body. In other words, this means that when you apply a force to compress or stretch a spring, it pushes back against that external force with a restoring force (the amount of which depends on how much the spring has been compressed or stretched).

Enter the spring constant and the displacement into the calculator to determine the spring force.

The following equation is used to calculate the Spring Force.

Fs = k*x

Where Fs is the spring force (N)

k is the spring constant (N/m)

x is the displacement of the spring (m)

The displacement is the distance of compression or tension

To calculate the spring force, simply multiply the spring constant by the displacement

A spring constant is a measure of a spring's ability to resist compression and elongation. The higher the spring constant, the harder it is to compress or stretch it.

Calculate the spring constant of a spring using Hooke's Law. Enter the spring displacement and force on the spring to calculate the spring constant. (Also known as spring rate calculator). This calculator can also determine the force or displacement given the spring constant and other variable.

The following is Hooke's law formula for determining the spring constant of a spring:

$F=-k*x$

Where F is the force (N)

k is the spring constant (N/m)

x is the displacement (m) (positive for displacement, negative for compression)

To calculate a spring constant, divide the spring force by the spring displacement.

Every 0.015 in. reduction of spring length increases seat pressure by 3.8 lbs,

Seating pressure drops as seat width increases.

The most important factors in designing a valve spring are going to be rate, free standing length (FL), coil bind (solid height), and stress. The amount of wire in the spring determines the rate (less wire = higher rate = higher stress), so wire Ø, coil count, and spring Ø are the dimensional factors that will effect rate.

Rate and free standing length, when combined with valve stem length, will allow to calculate seat pressure. To increase seat pressure, we can increase free standing length or rate. Maximum valve lift is advised to be some number (say .050") over solid height of the spring. Solid height is simply coil count wire Ø. Increasing wire Ø would increase spring rate and therefore seat pressure, but also increase solid height, limiting valve lift. Wire Ø is calculated to the fourth power in the spring rate equation, so seat pressure would increase exponentially as the valve lift decreased.

A common way to increase seat pressure for the springs we have to install a shim between the cam lobe and spring body. Doing so will increase seat pressure by some number of lbs, and will also decrease valve lift. Now say you wanted to increase your seat pressure to 30 lbs. To do so, we install a .100" shim somewhere between the end of the spring and the cam lobe. This lowers the installed length of the spring to .700", giving you the 30 lb seat pressure that we are looking for, but it also reduces the amount of travel between the installed length and solid height to .400", leaving with a theoretical maximum valve lift of .399" (Lucifer, 2016).

4.6. Exhaust Valve

Certain higher performance engines need higher temperature-capable valve materials due to increased exhaust gas temperatures, higher exhaust flow rates, higher cylinder pressures, and/or modified valve timings (target temperatures are exceeding current 760oC with the potential to reach higher temperature) (Muralidharan, 2013).

Valve stainless steel that had been modified in its chemical composition, is the most popular material used for commercial valve making. Exhaust valve is made of austenitic stainless-steel alloys, 21-4N (21% chromium).

The properties that contribute to the use of hydrogen as a combustible fuel are the wide range of flammability, low ignition energy, small quenching distance, high autoignition temperature, high flame speed at stoichiometric ratios, high diffusivity and very low density.

5. HYDROGEN STORAGE

Hydrogen has the highest energy per mass of any fuel. However, its low ambient temperature density results in a low energy per unit volume. As a result, hydrogen needs special storage methods that have potential for higher energy density. That is to say, hydrogen has a high energy per mass, but a low energy per volume, so it needs higher storage space. This makes hydrogen storage a key enabling technology for the advancement of using hydrogen as a fuel (US Department of Energy, 2023b).

Hydrogen can be stored physically as a gas or a liquid, or chemically in solid materials (US Department of Energy, 2023b). For many years hydrogen has been stored as compressed gas or cryogenic liquid, and transported as such in cylinders, tubes, and cryogenic tanks for use in industry (Air Liquide, 2023).

Hydrogen is the lightest gas in the entire Universe. One liter of this gas weighs only 90 mg under normal atmospheric pressure, which means that it is 11 times lighter than the air. A volume of around 11 m3 is needed to store just 1 kg of hydrogen, which is the quantity needed to drive 100 km. For this reason, hydrogen density must be increased either through high-pressure storage in the gaseous form or very low temperature storage in the liquid form. The easiest way to decrease the volume of a gas, at constant temperatures, is to increase its pressure (Air Liquide, 2023).

Hydrogen tanks are used for hydrogen storage in fuel cell vehicles. Storage of hydrogen as a gas typically requires high-pressure tanks (5,000–10,000 psi) (US Department of Energy, 2023b). Compressed hydrogen is a storage form whereby hydrogen gas is kept under pressures to increase the storage density. This system has begun to be used in the design of Honda and Nissan. Today, most car manufacturers have used the solution that consists in storing hydrogen in the gaseous form, at high pressure. This technology enables to store enough hydrogen to allow a car to run about 550 km between fill-ups (Air Liquide, 2023).

For storing maximum hydrogen in a restricted volume, it is needed to convert hydrogen gas to liquid hydrogen by cooling it to a very low temperature. Hydrogen turns into a liquid when it is cooled to a temperature below -252,87 °C. At -252.87°C and 1.013 bar, liquid hydrogen has a density of close to 71 kg/m3. At this pressure, 5 kg of hydrogen can be stored in a 75-liter tank. In order to maintain liquid hydrogen at this temperature, tanks must be perfectly isolated (Air Liquide, 2023). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Liquid hydrogen tanks were designed for BMW cars (US Department of Energy, 2023b).

A hydrogen tank is used for hydrogen storage. There are two main varieties of hydrogen fuel tanks. The most common hydrogen fuel tank for cars, trucks, buses and other vehicles is the compressed hydrogen gas tank. Almost all car manufacturers have chosen to fuel their cars with compressed hydrogen gas. BMW is one exception, with their dual fuel "Hydrogen 7 automobile" that uses cryogenic hydrogen and gasoline. Therefore, most hydrogen fueling stations currently dispense compressed hydrogen and only a few carry cryogenic liquid hydrogen. (AFC TCP, 2023).

Tank material could be steel/aluminum, Aluminum with filament windings such as glass fiber/aramid or carbon fiber around the metal cylinder, composite material, fiberglass/aramid or carbon fiber with a metal liner (aluminum or steel) or composite such of carbon fiber with a polymer liner (thermoplastic) (Hua, 2010). Compressed hydrogen fuel tanks are now made of carbon fiber composites or carbon fiber and metal alloys and composites. The inner line of the tank is a high-molecular weight polymer that serves as a hydrogen gas permeation barrier. The outer shell is placed on the tank for impact and damage resistance. A pressure regulator and an in-tank gas temperature sensor are located in the tank's interior in order to monitor the pressure and temperature during the gas-filling process. Generally, the storage tanks in cars must withstand high pressures and be able to store hydrogen without any leakage. Several car manufacturers today use compressed hydrogen tanks in their cars, which are capable of 350 and 700 bars, depending on the automotive type (light duty/heavy duty) (AFC TCP, 2023).

6. HYDROGEN SAFETY

Some skeptics point to hydrogen's safety issues as a potential deal-breaker to its more widespread use (Tae, 2021). It is true that hydrogen used as fuel is a very flammable gas and can cause fires and explosions if it is not handled properly. In addition, hydrogen fires are invisible (US Department of Labor, 2023).

In fact, all fuels have some degree of danger associated with them. On the other hand, a number of hydrogen's properties make it safer to handle and use than the fuels commonly used today. For example, hydrogen is non-toxic. In addition, because hydrogen is much lighter than air, it dissipates rapidly when it is released, allowing for relatively rapid dispersal of the fuel in case of a leak (US Department of Energy, 2023c).

Some other properties of hydrogen require additional engineering controls to enable its safe use. Specifically, hydrogen has a wide range of flammable concentrations in air and lower ignition energy than gasoline or natural gas, which means it can ignite more easily. Consequently, adequate ventilation and leak detection are important elements in the design of safe hydrogen systems. Because hydrogen burns with a nearly invisible flame, special flame detectors are required (US Department of Energy, 2023c). Because some metals can become brittle when exposed to hydrogen, selecting appropriate materials is important to the design of safe hydrogen systems. In addition to designing safety features into hydrogen systems, training in safe hydrogen handling practices is a key element for ensuring the safe use of hydrogen (US Department of Energy, 2023c). Hydrogen cars' storage tanks should also be subject to rigid testing standards, such as exposure to extreme temperatures and pressures, before they can be deployed (Tae, 2021).

To evaluate hydrogen's safety, it must be compared to that of other conventional fuels like gasoline, propane, and diesel. While no fuel is 100 percent safe, hydrogen has been shown to be safer than conventional fuels in a multitude of aspects. Hydrogen is not toxic, unlike conventional fuels. On the other hand, many conventional fuels are toxic or contain toxic substances, including powerful carcinogens. Moreover, when it comes to vehicles that run on hydrogen fuel, hydrogen produces only water, while vehicle combustion of conventional fuels generates harmful air pollution. A hydrogen leak or spill will not contaminate the environment or threaten the health of humans or wildlife, but fossil fuels can pose significant health and ecological threats when leaked, spilled, or combusted. Unlike actual explosives, pure hydrogen cannot explode. The risk comes when it hits the air. For hydrogen to cause an explosion, oxygen needs to be present. Hydrogen has a higher oxygen requirement for explosion than fossil fuels. It can be explosive with oxygen concentrations between 18 and 59 percent while gasoline can be explosive at oxygen concentrations between 1 and 3 percent. This means that gasoline has greater risk for explosion than hydrogen (Tae, 2021).

Again, all fuels have some degree of danger associated with them. The safe use of any fuel focuses on preventing situations where the three combustion factors including ignition source (spark or heat), oxidant (air), and fuel, are present. With a thorough understanding of fuel properties, it is possible to design fuel systems with appropriate engineering controls and establish guidelines to enable the safe handling and use of a fuel (US Department of Energy, 2023c).

Although there has been a lot of recent hype around hydrogen, it is not a new technology. Industry has been using hydrogen in rocket fuel, oil refineries, and fertilizer production for the past 40 years, more than enough time for scientists and engineers to develop and adopt robust safety protocols (Tae, 2021).

It is concluded that hydrogen is safer than conventional fuels. However, safety measures should continue to be prioritized that should make it safer to handle than conventional fuels like gasoline and diesel when handled responsibly (Tae, 2021). As more and more hydrogen demonstrations get underway, its safety record can grow and build confidence that it can be more trusted as safer by users (US Department of Labor, 2023c).

7. OBJECTIVES

The objective of this project is to modifying the existing gasoline internal combustion engines to be adapted to hydrogen fuel and to overcome significant problems caused by the low quench distance and higher burning velocity of hydrogen in the combustion chamber. The modifications of the existing gasoline internal combustion engines to be adapted to hydrogen fuel are to improve the cooling system and modify the intake and the exhaust valves. A better cooling system for hydrogen combustion engine was proposed to overcome the effect of higher heating caused by burning the hydrogen and transferred to the chamber wall. For better cooling, a modification in the exhaust from combustion chamber was planned. On the other hand, hydrogen escapes through the intake valve was dealt with.

8. MATERIALS AND METHODS

Before suggestion of improved modifications of the hydrogen engine the detailed specifications of the hydrogen as a fuel and the engine itself were studied.

Mazda L engine was the base engine for modifications.

Drawings were done using Soildworks Soft wear.

Thermo-dynamic Analysis

Thermo-dynamic Analysis was done according to Pulkrabek (2003).

Assuming that hydrogen act as an ideal gas:

Bore of Engine [m] (B) = 0.089

Stroke of Engine [m] (L) = 0.1

Length of Engine Connecting Rod [m] (l) = 0.132

Cross Sectional Piston Area (A_P)

$A_p = (\pi/4)*B^2 = 6.22*10^{-3}$

Compression Ratio (C_r) = 9.7

Number of Cylinders (N_cyl) = 4

Displaced Volume Of Engine [m^3]

$V_d = N_{cyl}*A_p*L = 2.488*10^{-3}$

For one cylinder(V_d) = $6.2211*10^{-4}$

Calculates Clearance Volume [m^3]

$V_{TDC} = (V_d/(C\_r-1))/N_{cyl} = 7.15*10^{-5}$

For one cylinder (V_{TDC})

First Attempt

State1

Assumed T_1 = 77 C = 350 K

Atm = P_1 = 100 KPa

$V_1 = V_d + V_{TDC} = 2.56*10^{-3}$

For one cylinder (V_1) = $6.936 *10^{-4}$ (m^3)

Mass of gas mixture [kg]

$m_{mix} = P_1V_1/RT_1 = 2.55*10^{-3}$ kg 2.548494664*10^{-3} (R=0.287kJ/kg-K)

For one cylinder (m_{mix}) = $6.905*10^{-4}$ kg

State 2

Specific heat capacity (k) = 1.4

A/F = 34:1

$P_2 = P_1(C\_r)^k$ = 2407 kPa

$T_2 = T_1(C\_r)^{k-1}$ = 868.5 K =596C

$V_2 = m_{mix}*(RT_2/P_2) = 7.15*10^{-5} = V_{TDC}$

Assuming Exhaust residuals is 0

Mass of air (m_a) = (34/35) ($6.905*10^{-4}$) = $6.7*10^{-4}$ kg

Mass of fuel (m_f) = (1/35) ($6.905*10^{-4}$) = 1.97 $*10^{-5}$ kg

State 3

Heat added during one cycle

$Q_{in} = m_f * Q_{hv} * \eta_c = m_{mix} * C_v(T_3-T_2)$

η_c= combustion efficiency assumed to be 98%

C_v = 0.821 kJ/kh-K

lower heating value (Q_{hv}) = 120210 kJ/kg

solving for T_3 :

T_3 = 4962.3 K 4689 C

$V_3 = V_2 = 7.15*10^{-5}$

For constant volume:

$P_3 = P_2(T_3/T_2)$ = 13752 kPa which is max pressure reached

State 4

$T_4 = T_3(1/C\_r)^{k-1}$ = 2000 K

$P_4 = P_3(1/C\_r)^k = 571$ kPa

$V_4 = m_{mix} * R * T_4 / P_4 = 6.936 *10^{-4} = V_1$

Work process is assumed to be isentropic

$W_{34} = mR(T_4\text{-}T_3)/(1\text{-}k) = 1.4676$ kJ

Work absorbed during compression

$W_{12} = mR(T_2\text{-}T_1)/(1\text{-}k) = -0.257$ kJ

Net indicated work (W_{net}) = $W_{12}+W_{34} = 1.211$ kJ

imep = $W_{net}/(V_1\text{-}V_2) = 1946.6$ kPa

Second Attempt

Assuming that hydrogen act as an ideal gas:

Bore of Engine [m] (B) = 0.089

Stroke of Engine [m] (L) = 0.1

Length of Engine Connecting Rod [m] (l) = 0.132

Cross Sectional Piston Area (A_P)

$A_p = (\pi/4)*B^2 = 6.22*10^{-3}$

Compression Ratio (C_r) = 9.7

Number of Cylinders (N_{cyl}) = 4

Displaced Volume Of Engine [m^3]

$V_d = N_{cyl}*A_p*L = 2.488*10^{-3}$

For one cylinder(V_d) = $6.2211*10^{-4}$

Calculates Clearance Volume [m^3]

$V_{TDC} = (V_d/(C\_r\text{-}1))/N_{cyl} = 7.15*10^{-5}$

For one cylinder (V_{TDC})

State1

Assumed $T_1 = 77$ C = 350 K

Atm = $P_1 = 100$ KPa

$V_1 = V_d + V_{TDC} = 2.56*10^{-3}$

For one cylinder (V_1) = $6.936 *10^{-4}$ (m^3)

Mass of gas mixture [kg]

$m_{mix} = P_1V_1/RT_1 = 2.55*10^{-3}$ kg (R=0.287kJ/kg-K)

For one cylinder (m_{mix}) = $6.905*10^{-4}$ kg

State 2

Specific heat capacity (k) = 1.4

A/F = 59:1

$P_2 = P_1(C\_r)^k$ = 2407 kPa

$T_2 = T_1(C\_r)^{k-1}$ = 868.5 K =596C

$V_2 = m_{mix}*(RT_2/P_2) = 7.15*10^{-5} = V_{TDC}$

Assuming Exhaust residuals is 0

Mass of air (m_a) = (59/60) ($6.905*10^{-4}$) = $6.79*10^{-4}$ kg

Mass of fuel (m_f) = (1/60) ($6.905*10^{-4}$) = 1.15 $*10^{-5}$ kg

State 3

Heat added during one cycle

$Q_{in} = m_f * Q_{hv} * \eta_c = m_{mix}*C_v(T_3-T_2)$

η_c= combustion efficiency assumed to be 98%

C_v = 0.821 kJ/kh-K

lower heating value (Q_{hv}) = 120210 kJ/kg

solving for T_3 :

T_3 = 3260 K 2987 C

$V_3 = V_2=7.15*10^{-5}$

For constant volume:

$P_3 = P_2(T_3/T_2)$ = 9035 kPa which is max pressure reached

State 4

$T_4 = T_3(1/C\_r)^{k-1}$ = 1313.7 K

$P_4 = P_3(1/C\_r)^k$ = 375.4 kPa

$V_4 = m_{mix} * R * T_4 / P_4 = 6.936 *10^{-4} = V_1$

Work process is assumed to be isentropic

$W_{34} = mR(T_4-T_3)/(1-k) = 0.964$ kJ

Work absorbed during compression

$W_{12} = mR(T_2-T_1)/(1-k) = -0.257$ kJ

Net indicated work (W_{net}) = $W_{12}+W_{34} = 0.707$ kJ

imep = $W_{net}/(V_1-V_2) = 1136$ kPa

Third Attempt

Assuming that hydrogen act as an ideal gas:

Bore of Engine [m] (B) = 0.089

Stroke of Engine [m] (L) = 0.1

Length of Engine Connecting Rod [m] (l) = 0.132

Cross Sectional Piston Area (A_P)

$A_p = (\pi/4)*B^2 = 6.22*10^{-3}$

Compression Ratio (C_r) = 9.7

Number of Cylinders (N_{cyl}) = 4

Displaced Volume Of Engine [m^3]

$V_d = N_{cyl}*A_p*L = 2.488*10^{-3}$

For one cylinder(V_d) = $6.2211*10^{-4}$

Calculates Clearance Volume [m^3]

For one cylinder (V_{TDC})

$V_{TDC} = (V_d/(C\_r-1))/N_{cyl} = 7.15*10^{-5}$

State1

Assumed T1 = 77 C = 350 K

Atm = P_1 = 100 KPa

$V_1 = V_d + V_{TDC} = 2.56*10^{-3}$

For one cylinder (V1) = $6.936*10^{-4}$ (m^3)

Mass of gas mixture [kg]

$m_{mix} = P_1V_1/RT_1 = 2.55*10^{-3}$ kg

(R=0.287kJ/kg-K)

For one cylinder (m_{mix}) = $6.905*10^{-4}$ kg

State 2

Specific heat capacity (k) = 1.4

A/F = 49:1

$P_2 = P1(C\_r)^k = 2407$ kPa

$T_2 = T_1(C\_r)^{k-1} = 868.5$ K =596C

$V_2 = m_{mix}*(RT2/P2) = 7.15*10^{\wedge-5} = V_{TDC}$

Assuming Exhaust residuals is 0

Mass of air (m_a) = (49/50) ($6.905*10^{-4}$) = $6.767*10^{-4}$ kg

Mass of fuel (m_f) = (1/50) ($6.905*10^{-4}$) = 1.381 $*10^{-5}$ kg

State 3

Heat added during one cycle

$Q_{in} = m_f * Q_{hv} * \eta_c = m_{mix}*C_v(T_3-T_2)$

η_c= combustion efficiency assumed to be 98%

C_v = 0.821 kJ/kh-K

lower heating value (Q_{hv}) = 120210 kJ/kg

solving for T_3 :

T_3 = 3738 K 3465 C

$V_3 = V_2 = 7.15*10^{-5}$ m^3

For constant volume:

$P_3 = P_2(T_3/T_2)$ = 10360 kPa which is max pressure reached

State 4

$T_4 = T_3(1/C\_r)^{k-1} = 1506$ K

$P_4 = P_3(1/C\_r)^k = 430$ kPa

$V_4 = m_{mix} * R * T_4 / P_4 = 6.936 *10^{-4} = V_1$

Work process is assumed to be isentropic

$W_{34} = mR(T_4-T_3)/(1-k) = 1.106$ kJ

Work absorbed during compression

$W_{12} = mR(T_2-T_1)/(1-k) = -0.257$ kJ

Net indicated work (W_{net}) = $W_{12}+W_{34} = 0.849$ kJ

imep = $W_{net}/(V_1-V_2) = 1364$ kPa

indicated power $\dot{W}_i = [W_{net} * N / n] * N_{cyl}$

where

N is rev/sec

n is rev/cycle

At 4000 rpm

$\dot{W}_i = 113.2$ kW

Calculating friction mean effective pressure by using the bellow formula for simplicity

fmep (obtained from Blair) Based On Displacement, RPM

if V_d>500*10^{-6} fmep=(100000+350*L*RPM)*10^{-3}

if V_d<500*10^{-6}

fmep=(100000+100*(500-V_d*10^{-6})+350*L*RPM)*10$^{-3;}$

$V_d = 2.488*10^{-3}$

L = 0.1

fmep = 290 kPa

bmep = imep – fmep = 1074 kPa

bmep is brake mean effective pressure

imep is indicated mean effective pressure

(W_b) brake work = (bmep / imep) * W_{net} = 0.668 kJ

($\dot{W}_b$) brake power = [W_b* N / n] * N_{cyl} = 89 kW

Modeling the engine using single zone modeling

It was decided that we will use 49:1 air fuel ratio. As observed when the air fuel ratio is increase the output work is decreased however when the air fuel ratio is decreased the temperature inside the chamber increases significantly. We should optimize the air fuel ratio with talking into consideration the in chamber temperature and power output of the engine.

Table 1. Under normal atmospheric conditions and by assuming that hydrogen acts as an ideal gas and maximum combustion efficiency of 95%, the below table was obtained.

Revolutions per minute (RPM)	Indicated power (kW)	Brake power (kW)	Friction loss (kW)
4000	62.41	42.5	19.91
5000	85.38	56.87	28.51
6000	109.2	70.58	38.62
7000	132.5	82.46	50.04

9. RESULTS AND DISCUSSION

9.1 Redesign the Cooling System

In this project the cooling system for the hydrogen internal combustion engine was optimized through controlling the coolant flow velocity in the water jacket. The centrifugal water pump is driven by an electric motor, instead of the engine crankshaft as with the traditional gasoline engine. This modification can improve engine cooling control and capacity.

The electric centrifugal pump can enable us to manage the coolant flow rate, through allowing to choose the desired coolant flow rate regardless of the engine speed. An electrically driven pump substitutes the standard crank-shaft driven one for the management of the coolant flow rate is independent of engine speed (Falbo, 2021).

The flow of the fluid and its heat transfer directly affect the cooling performance of an engine (Gholinia et al., 2018). The main heat comes from cylinder side walls where they are the closest to combustion chamber area. The amount of heat transferred from cylinder walls is important to determine overall performance, size and cooling capacity needed for a specific internal combustion engine (Sanli et al., 2008; Binti Zakaria, 2012).

In general, getting an internal combustion engine to run on hydrogen is not difficult. Getting an internal combustion engine to run well, however, is more of a challenge (Energy.Gov, 2014). Engine cooling is most critical for an internal combustion hydrogen engine. Engine cycle thermal efficiency needs to be improved for this engine. Improving cooling circuit efficiency could be done by optimizing the coolant flow velocity in the water jacket (Liu et al., 2022).

Conventional cooling has been applied in automotive industry for ages and it is still the option for major car makers on cooling solutions for their product. A water jacket is a structure that allows water to pass through a cylinder block in the internal combustion engine. The cooling system of an engine depends on circulating coolant by the water pump in the water jacket, formed in the cylinder block and the cylinder head of the engine. The coolant is circulated to water jacket around the combustion chamber area by motion of centrifugal water pump which is directly driven by the engine. The coolant is passed through the radiator where it is cooled by air drawn through the radiator by fan and by air draft due to forward motion of the vehicle. A thermostat is used to control the temperature required for cooling.

A water pump is required to circulate the coolant throughout the engine. The pump is directly coupled to the engine crankshaft and thus its speed and output pressure is directly proportional to the engine's speed. The pump flow increases as the engine speed increased. In other words, water pump performance is dependent on the engine speed (Henry, 2001). This means that, for the same pressure and as the engine speed goes up, flow rate increases but at a lower rate than engine speed rate. This is the fact that the pump power is limited and that its efficiency decreases at the high-speed end due to increased losses (Lehner, 2001; Binti Zakaria, 2012).

A cooling system should be at place and it will act as a load on the engine. After calculating the required power for cooling the chamber. It should be added to the friction loss which will give us a lower Brake power.

9.2 Redesign the Intake Valve

Seat with width of 1.5mm of the intake valve in the traditional gasoline engine was increased to 2.0mm. In the traditional gasoline engine, leakage at the seat allows hydrogen to pass when the valve is closed. Increasing seat width could reduce hydrogen leakage at the same seating pressure. Sufficient seating pressure is required to ensure that the valve is held closed firmly in one motion.

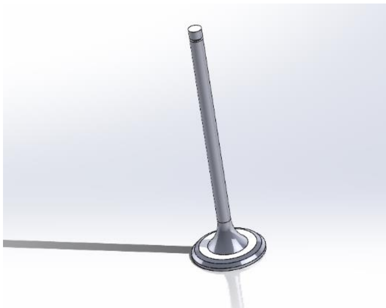

Figure 1. Seat width of the intake valve was increased to 2.0mm from 1.5mm in the traditional gasoline engine.

A shim was suggested to be installed between the cam lobe and spring body to reduce the length of the spring. The reduction in the spring length leads to increasing the seat pressure and compensate the drop in this pressure occurred as a result of increasing seat width. Thus, the seat pressure will be returned 120 lbs again. Valve seating pressure is the amount of force that the valve spring exerts in the area of contact between the valve face and seat. Proper seating pressure is critical for tight shut-off.

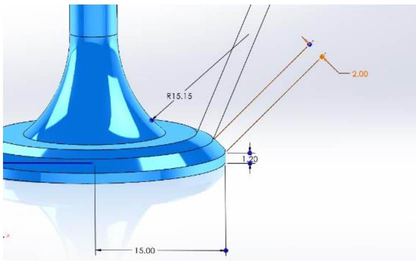

Figure 2. Head of the modified intake valve with its parameters.

Hydrogen's small quenching distance means that hydrogen can more readily get past a nearly closed intake valve (Rosati and Aleiferis, 2009; Ramadhas, 2016). To ensure proper seating and sealing of the valve in a hydrogen engine, width of the valve seat needs to be increased. However, we have to keep in mind that seating pressure drops as seat width increases (Scharff, 1990). In this project, the seat width was increased to improve seating and sealing while the intake valve is closed.

Generally, the ideal seat width for traditional automotive engines is 1.5mm for intake valves (Monroe, 1987). Because of their lower operating temperatures, intake valves are typically made of materials such as chrome, nickel, or tungsten steel (Edwards, 2022). Valve seat width and point of contact on the valve face is very important for proper sealing. If seat is uneven, compression leakage will result. Widening seat reduces seat pressure. Too low seat pressure per area unit causes leakage. Valve springs have 2 important pressure specs, seat pressure and open pressure. Seat pressure is the force holding the valves closed at zero lift. While, open pressure is the force pushing up on the valve at max lift. In other words, seat pressure is the pressure the valve spring places on the valve when it is in closed position. Open pressure is the spring pressure that forces the valve to close after the rocker arm pushes it open during the combustion cycle.

It is important getting the correct amount of spring pressure. Insufficient or excessive pressure will cause engine performance to suffer, along with the possibility of damage occurring, which can be severe. Spring rates are listed in terms of pounds per inch, which simply means that the rating number associated with a particular spring is the force that is necessary to compress the spring one inch. Generally, 130-145 lbs. on the seat with an open of around 350-360 lbs. should be adequate (Mavrigian, 2015; Allen, 2017).

The sealing surface is the most critical working surface of the intake valve of the internal combustion engine. Seating of the valve face to the valve seat is what provides the seal for the valve against combustion pressure. The most critical sealing surface in the valve is between the seat and the cylinder head when the valve is closed (Edwards, 2022). Valve seat width and point of contact on the valve face is very important for proper sealing. The valve has to contact the face over the entire circumference of the seat, and the seat must be with the proper width all the way around. Seat width determines the amount of valve face that contact with the seat and consequently determines the coefficient conductivity of the valve (Schwaner, 1991).

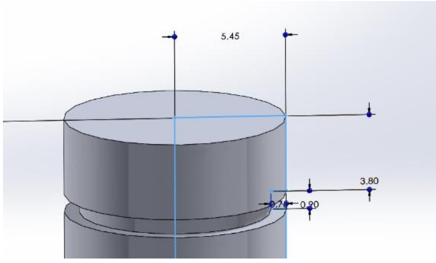

Figure 3. Other parameters of the modified intake valve.

9.3 Redesign the Exhaust Valve

In this project two small exhaust valves were used for the hydrogen engine instead of one large valve in the traditional gasoline engine. The head diameter of the each of the new exhaust valves is 20mm with seat width of 2.4mm.

Typically, the exhaust valve is of one-piece design. However, using two small exhaust valves with hydrogen engine instead of one large valve helps in cooling through improve the airflow out of the engine.

Two exhaust valves were found to minimize the intensity of hot-spots in the combustion chamber, thereby avoiding too high combustion temperatures. The two exhaust valves should run cool, since not only are they individually smaller in size with shorter heat flow paths, but also their settings are better spaced for more uniform cooling (Nunney, 2016).

Figure 4. Two small exhaust valves were used for the hydrogen engine instead of one large valve in the traditional gasoline engine.

Two valves engine heads were recommended to reduce the temperature in hydrogen engine as well as with traditional engine (Erdemir, 2000; Berckmuller et al., 2003;

Stepien, 2021).

The ideal seat width of the exhaust valve for automotive engines is 2.4mm with head diameter of 34mm. The exhaust valve has to withstand much higher temperatures than the intake valve so it is usually made of a stronger high temperature alloy. Titanium valves tend to hold more heat than stainless steel valves so they require upgrading the seats to some type of copper alloy. Copper provides good thermal conductivity to pull heat out of the valve when the valve is closed (Carleyon, 2017).

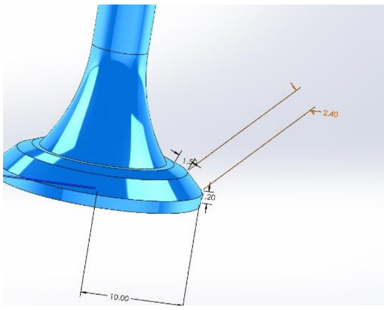

Figure 5. The head diameter of the each of the new exhaust valves is 20mm with seat width of 2.4mm.

10. CONCLUSION

During the course of this project detailed specifications of the hydrogen as a fuel and the engine itself were studied. Shortcomings of the hydrogen as a fuel for the traditional engine were identified. Three modifications in the traditional gasoline engine were suggested to be adapted for hydrogen.

In this project the cooling system for the hydrogen internal combustion engine was improved through controlling the coolant flow velocity in the water jacket. The centrifugal water pump is driven by an electric motor, instead of the engine crankshaft as with the traditional gasoline engine. This modification can improve engine cooling control and capacity.

Seat with width of 1.5mm of the intake valve in the traditional gasoline engine was increased to 2.0mm. Increasing seat width could reduce hydrogen leakage at the same seating pressure. Sufficient seating pressure is required to ensure that the valve is held closed firmly in one motion. A shim was suggested to be installed between the cam lobe and spring body to reduce the length of the spring. The reduction in the spring length leads to increasing the seat pressure and compensate the drop in this pressure occurred as a result of increasing seat width.

Two small exhaust valves were used for the hydrogen engine instead of one large valve in the traditional gasoline engine. The head diameter of the each of the new exhaust valves is 20mm with seat width of 2.4mm.

The next step in this project is applying the suggested modifications by an automobile factory that is interested with hydrogen engine.

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