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DESIGN OF CUSTOMIZED MODULAR CYLINDER HEAD FOR SI-ENGINE

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ABSTRACT

This paper proposed the design of modular cylinder head for a 150 cc racing motorcycle engine which provides the flexibility to change the internal architecture and use different components in the cylinder head to achieve the desired engine performance. Unconventional production method using CNC machining is the preferred approach because of lower per unit cost. The objective was to design a light weight cylinder head suitable for low-medium volume production using CNC machining and also prevent localized overheating of hotspots on the cylinder head. This was achieved by varying the local thickness of the cylinder head and directing more coolant by providing channels to the hotspots. In addition the heat transfer from the exhaust gas is minimized by shortening the exhaust manifold. By managing cylinder head cooling, it is possible to minimize the weight of the cylinder head and the size of the cooling system to reduce the overall engine weight. The cylinder head is divided into three parts consisting of the cylinder head cover, the valvetrain housing and the combustion chamber housing. The detailed design was then done and finalized. The computational work of stress and thermal analysis was done on ANSYS.

Keywords: cylinder head, SI-engine, modular design, stress analysis.

INTRODUCTION

An internal combustion engine is a device that converts chemical energy (fuel) to heat energy (combustion of fuel) to pressure energy (pressure forcing the piston down) to mechanical energy (movement of piston) [1-6]. Throughout these conversions process, it is desirable to maximize the efficiency of these conversions. All this is done within the engine itself, hence the name internal combustion engine. There are generally two types of internal combustion engine; spark ignition engines also known as Otto, gasoline or petrol engines, and compression ignition engines also known as a diesel engine [7-12]. The high energy density of the fuel used and the simplicity, ruggedness and high power to weight ratio of the internal combustion engine secured its wide application in the transportation (land, sea and air) and power generation sector. This project is focused on a new approach to designing and manufacturing cylinder heads for a low volume production using CNC machining instead of the conventional method like die and sand casting. As the cylinder head will be CNC machined, it will be designed with varying thickness with channels to direct more coolant to the hotspots such as the valve seat, valve stem and sparkplug. This will minimize the temperature variation over the cylinder head. The above approach will include bolting and sealing the 3 major parts of the cylinder head to the cylinder block. The placement of inlet and outlet of the coolant will be controlled by the packaging of the engine. CFD analysis will not be part of the scope of this project.

Research or racing engines are usually manufactured in small volume with faster turnaround and frequent modification [13-19]. The conventional manufacturing methods are not cost effective and require longer lead time. With the conventional casting technique, it is difficult to precisely control the dimensions and finishing of the internal features in the cylinder head. Polishing is needed to get the desired surface quality therefore incurring additional cost. The conventional method of die of sand casting of a cylinder head limits its design. The designer has to consider the design of the cast itself as it has to use cores to produce the cavities in the cylinder head. As a result, the conventional design of a cylinder head has a cooling system that overall cool the cylinder head in general areas and does not concentrate on the hotspots. This includes the exhaust manifolds which have to be avoided as it puts the heat that is supposed to be rejected by the exhaust back into the cooling system. The objective was:

1) Design a modular cylinder head that is light weight and can be manufactured using CNC machining
2) Prevent localized overheating and minimize temperature variation over the cylinder head achieved by varying the local thickness of the cylinder head and directing more coolant by providing channels to the hotspots.

METHODOLOGY

This modular cylinder head has 3 parts. Part 1 is the bottom most part which includes the upper section of the combustion chamber. This is the most critical part of the cylinder head. All of the thermal stresses originate from this part because of the combustion that takes place in the combustion chamber. The majority of the mechanical stress is also applied to this part because of the pressure from the combustion. Part 1 also houses the

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intake and exhaust ports, valve seats and valves. As majority of heat is dispersed from the components of this part, the cooling channel is located solely in this part as well. On top of Part 1 sits Part 2. This is also known as the valvetrain housing. The valve train which includes camshaft, spring, key, retainer and valveguide are all housed in Part 2. The lubrication oil for the valvetrain components is contained Part 2 as well. Part 3 is the cover for Part 2. This avoids spillage of the lubrication oil to the engine compartment.

Preliminary design stage

To start off the design process, a drawing of the cross-section of the cylinder head was produced and scaled 1 to 1. The drawings were then used to produce a cardboard model of the cylinder head. This cardboard model was used to decide the placement of the components inside the cylinder head such as the intake and exhaust ports, inlet and outlet of the cooling channels and where exactly to divide the cylinder head into two parts. This is called packaging and any adjustments on the positions of the component can easily be made with the cardboard model. The cardboard model produced is shown in Figure-1.

Figure-1. Cardboard model produced.

3D model of cylinder head

After the packaging was finalized, the first version of the cylinder head was created in Solidworks. Iterations were done where adjustments and modifications were made to improve the design. The final design was obtained after 19 iterations and is shown in Figure-2.

It is important to choose the right combustion chamber profile as it will affect many factors of the combustion. The profile of the combustion chamber can affect the swirling and mixing of the air-fuel mixture, the combustion propagation and the heat loss among other things. The pent roof design has 2 flat slanting surfaces on either side much like a roof. These flat surfaces must be wide enough to fit in the intake and exhaust valves. The angle of these flat surfaces also matters as it affects the swirling of the air-fuel mixture in the chamber. The best angle for a pent roof profile is 7° (degrees) and this value was used in this design. A cross-section of the combustion chamber profile is shown in Figure-3.

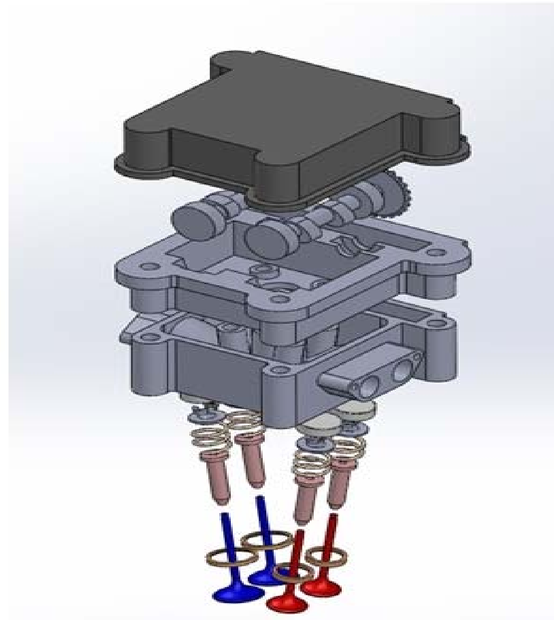

Figure-2. Exploded view for final design of assembly.

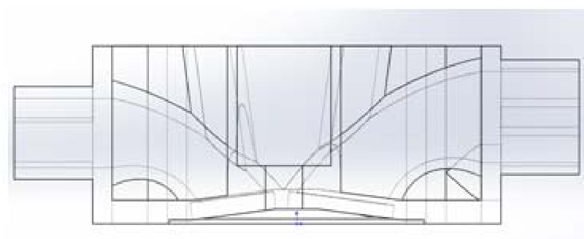

Figure-3. Cross-section of combustion chamber profile.

The cooling of this cylinder head is an important aspect of the design. Without the cooling system, the cylinder head would overheat and fail due to structural failure. This design of the cylinder head uses a liquid-cooling system. The main part of the cooling system is the cavity in Part 1 as shown in Figure-4.

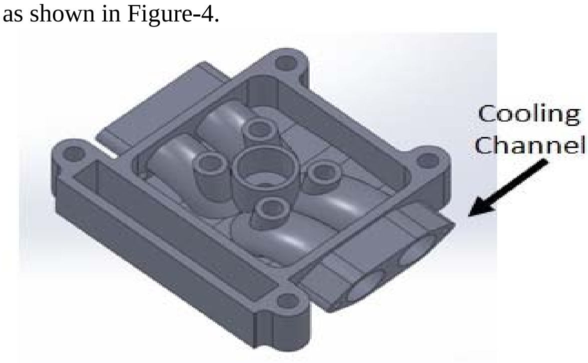

Figure-4. Cooling channel located in Part 1.

Part 2 is the valvetrain housing. This part houses the valvetrain which includes various components such as valves, springs, retainer, key and camshaft. Part 2 is

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secured to the rest of the assembly and the engine block by 4 bolts. The bolt holes were designed to align perfectly to Part 1. Figure-5 shows the design of the valvetrain housing also known as Part 2.

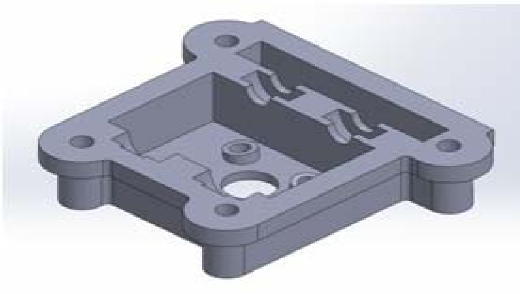

Figure-5. 3D model of Part 2.

Finite element analysis

The type of elements used for this model is tetrahedral. This type of element was used because of the complexity of the geometry. The resulting mesh generated produced 95,449 nodes and 53,685 elements with a minimum edge length of 7.1797×10-5m. The main parameters for this simple analysis were the thermal and mechanical load and how it affects the stress patterns of the design. Only Part 1 was analyzed as that is where the majority of the thermal load is located and it is the critical part of the cylinder head. The effect of vibrations and flow were removed from this simple analysis. Thermal parameters that were present in this analysis are the temperature distribution resulting from the combustion of the fuel, the exhaust gases, surrounding air and the cooling effect of the coolant. The relevant thermal parameters of the analysis were taken from Li et al. [20] and it is shown in Table-1.

The mechanical parameters includes 2 elements which are the mechanical forces acting on the part and the mechanical constrains. The mechanical forces comprises of the pressure caused by the combustion. The maximum brake mean effective pressure (bmep) for a small spark-ignition engine is 10 atm which is 1013.25 kPa according to Heywood [21]. This pressure was applied on the surface of the combustion chamber. The mechanical constrains for this analysis includes the modeling of bolts. Appropriate constrains were put in place.

Table-1. Thermal parameters of analysis [20].

Location	Thermal Coefficient, $\alpha \cdot W/(m^2 \cdot K)$	Temperature, K
Upper & side surface	23	293
Intake channel surfaces	350	335
Exhaust channel surfaces	650	973
Combustion chamber surfaces	1000	1200
Cooling channel surfaces	3000	353

RESULTS AND DISCUSSIONS

The analysis was done in ANSYS Workbench 14.0. There are two parts of this analysis. The first part is the thermal analysis and the latter is the mechanical analysis. The thermal analysis was done to obtain the temperature distribution by applying thermal parameters to the part. This temperature distribution resulted in a thermal load. Mechanical analysis was done on top of the thermal load and the resultant stress pattern was product of the compounding of thermal and mechanical load. ANSYS Mechanical was used to run this analysis and resultant stress patterns were obtained.

Temperature distribution

The thermal analysis was done to get the temperature distribution of the part under working conditions. The thermal parameters are shown in Table-1. Figure-6 shows the resultant temperature distribution of Part 1.

The lowest temperature on the cylinder head which is at the intake manifold with a magnitude of 353 K and highest temperature is 525 K, located at exhaust manifold. This is because the exhaust gases product of the combustion is very hot. After every cycle, the exhaust gases are pushed out of the cylinder through the exhaust manifold. Each second only takes a fraction of a second thus the exhaust manifold is almost constantly exposed to hot exhaust gases, bringing the temperature up.

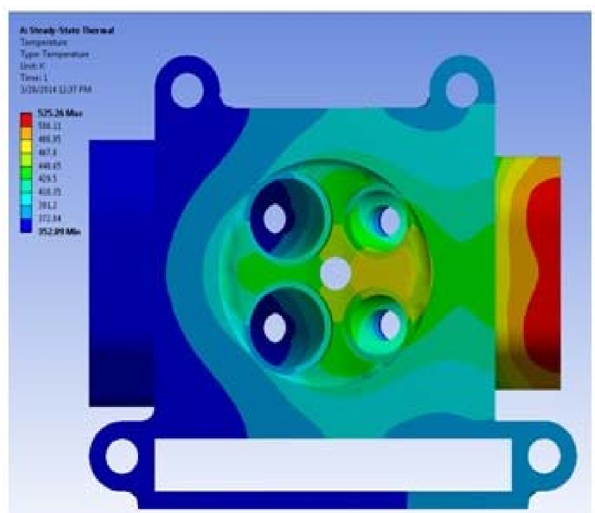

Figure-6. Temperature distribution over combustion chamber.

Thermal and mechanical stress

The presence of the temperature distribution affects the resultant stress thus the stress analysis was done by using the data of the thermal analysis as its input. In addition to temperature distribution, mechanical load was also applied to the relevant areas. The Von-mises stress patterns are shown in Figure-7.

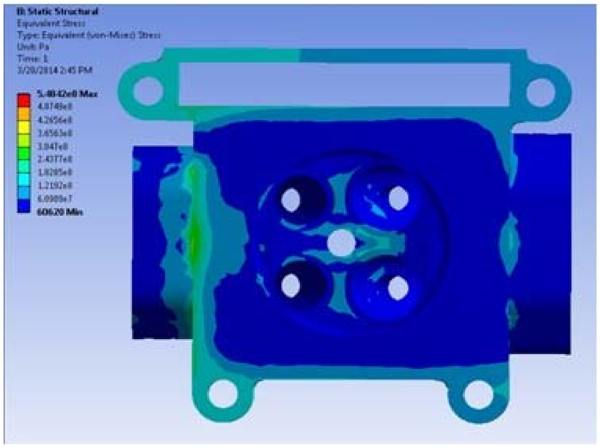

Figure-7. Equivalent stress over combustion chamber.

The lowest magnitude of stress on the cylinder head which is at top of the valve guide insert with a magnitude of 606 Pa. This is because in this analysis, this valve guide insert was not constrained. The highest stress on the cylinder head is 548 MPa and is located at inlet of the cooling system which is located next to the exhaust port Figure-8 shows the location with the highest stress. Even through the magnitude of the highest stress is quite high, it is a localized stress. This localized stress will dissipate under working conditions as the material would relax gradually.

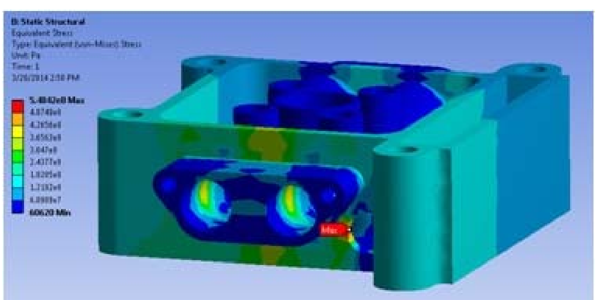

Figure-8. Location of maximum stress on the cylinder head.

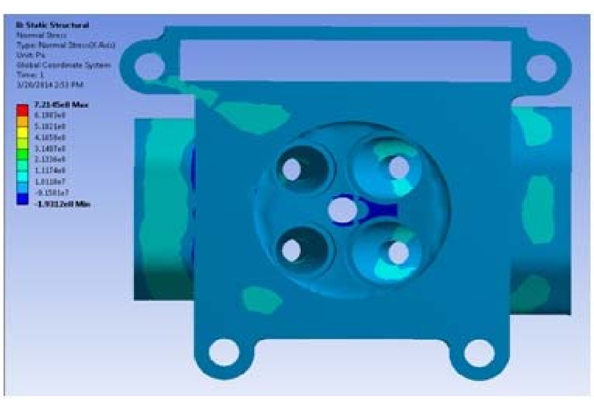

Figure-9. Normal stress over combustion chamber.

Figure-9 shows normal stress on Part 1. This normal stress shows the stress applied on the part without the input of constrains where else the Von-Mises stress is the resultant stress of the whole system. It is also observed that the maximum normal stress on the cylinder head is 721MPa. This maximum stress is located at the meeting point of the valve guide insert and the spark plug insert. The magnitude of the maximum stress is quite high but it is a localized stress that cover a very small portion, this stress will relax during working conditions. The maximum stress has a positive magnitude indicating a tension force is acting on the part, pulling the guide insert and the spark plug insert away from each other.

CONCLUSIONS

The objective stated that the cylinder head cooling system has to be designed to prevent localized overheating or hotspots and minimize temperature variation on the cylinder head. This was done by directing more coolant to the hotspots by providing channels to the affected areas. A detailed design was carried out for all components including cooling system channels. Solid Works was used to produce the 3D digital model of the cylinder head, and ANSYS was used to do the thermal and stress analysis. A finite element analysis was then done to check the thermal and mechanical stresses under operating engine loads. Preliminary optimization of the design was done based on the results of the analysis, by managing material thickness and components to make it lighter. It was found that the magnitude and concentration of temperature at the combustion chamber is lower than that of previous studies. The structural stress resulting from the thermal and mechanical load is mostly localized including the maximum stress. This localized stress will relax itself during working conditions. This is a long term project which must be completed up to the T0 prototype to validate the results of the finite element analysis. The modular design enables the module to be modified for improvement to be manufactured using CNC machining. This approach reduces the cost of engine development. Another approach is to use the emerging 3D printing manufacturing technology.

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