MINIATURISED CYLINDER HEAD PRODUCTION BY RAPID PROTOTYPING

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Abstract. *This work shows the development of the design and manufacturing of a very small engine, namely its head. The engine works under the 4-stroke cycle, therefore having a very complex cylinder head, housing the camshaft, valves and its auxiliaries (seats, guides, springs), spark plug, inlet and exhaust passages and a coolant chamber. The geometries, both inner and outer are highly intricate which makes the production of such a part a very difficult job. In addition, when the engine is very small, as it is the case of this engine, all dimensions are miniaturized therefore making it extremely difficult to design, cast and finish. The cooling chamber, in particular, has a critical inner core removal problem due to reduced accessibility, imposing casting limitations. The cores place also a problem of air and gas removal during metal filling and solidification. Rapid prototyping may be the only solution to build the cores, and may help in the design and manufacturing phases of the casting tools. 3D printing with a plaster based material as a rapid prototyping technique presents itself as a tool to drastically reduce the design-development-casting process effort and time cycle. This technique enables the designer to obtain new moulds for castings on the shortest time possible, following redesign and new casting simulations. This paper illustrates the various tasks involved in the design and development stages leading to the production of a running prototype of the cylinder head for this small engine.*

Keywords: *Engine design; Casting design; Rapid Prototyping; 3D printing; Casting simulation*

1. INTRODUCTION

Different rapid prototyping techniques were applied to the development and manufacture of a cylinder head to be used on a small engine intended for a fuel consumption marathon. The various stages of development are herein presented and discussed.

The design should incorporate various characteristics and features intended to maximise the efficiency of the engine. The head should be of the hemispherical type with two inclined valves, and should have squish area, OHC, a sufficiently large volume coolant chamber and a swirl producing inlet passage. All this should be included in a 10x10x14 cm envelope.

The first designs and models produced by rapid prototyping explored the design features, such as the design constrains and potential for miniaturization and manufacture. Later, various features were optimized in terms of operation (swirl generation, pressure loss) and in terms of manufacture (mould production, wall thickness, casting behaviour and machining).

The final design combines the required levels of swirl generation (by the inlet track) and coolant volume, with the potential of manufacture of a very complex component with sufficient precision.

Some of the various interim design changes and optimisations are described, which led to the final specification.

1.1. Shell Eco-Marathon

An international competition for fuel consumption is organised every year by Shell, called Eco-Marathon. This year, 2009, the race comprised 8 laps to the Lausitzring track (near Berlin, Germany) totalling slightly less than 30 km at an average speed of 30 km/h with minimum fuel consumption. The University of Minho participated in this event for 4 years with its car, EconomicUM (Figure 1). A new engine (UMotor, Figure 2) is being developed for this car and it is part of this development that is reported here.

Figure 1. EconomicUM

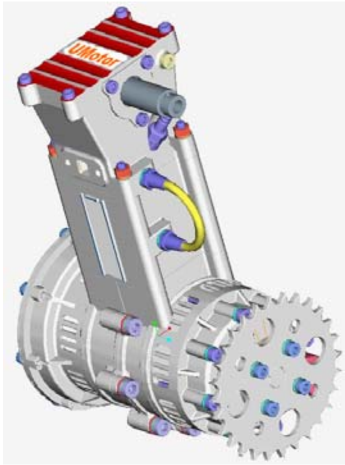

Figure 2. UMotor

The main aim of this engine is efficiency, so it should run at relatively low speeds, should have low mechanical losses and high compression ratio and should work at a specified temperature. To enhance indicated efficiency the combustion should be very fast, so a high turbulence is necessary prior to ignition. This turbulence helps to enhance mixture preparation but also it helps the development of fast burn rates. In I. C. engines there are two forms of turbulence: tumble and swirl. As tumble is usually created in pent roof 4-valve heads and the present engine is a 2-valve design, swirl is used, being created by the intake port design. This design can be done studying the flow inside the cylinder during the intake and compression stroke, using fluid dynamics. In this case, the softwares GAMBIT/FLUENT were used to optimise the design. Furthermore a high swirl is usually not desired, as the kinetic energy for the flow is obtained at the expense of a reduced volumetric efficiency (Stone, 1989). However, this engine has, intentionally, very low volumetric efficiency, in order to work under the over-expanded cycle, so this constrain is not too relevant.

1.2. Creation of swirl

The idea of a helical port is that the air is brought in rotation prior to entering the cylinder, namely in the inlet port. The rotation is achieved by forcing the air flow around the valve stem, so that there is an angular momentum created about the cylinder axis when the charge enters the cylinder. Helical ports normally have a higher discharge coefficient than direct ports if the swirl levels are equivalent (Heywood, 1988). Another advantage of helical ports is that they are not that sensitive to misplacements that may occur in casting. Also, a helical port produces better swirl than a direct port. This is the swirl producing design established for this engine.

2. CREATION OF A SUITABLE INTAKE DESIGN

The head was decided to be produced by casting, as its intricate design rendered it impossible to be produced by other methods such as machining. The material used for the cores and the moulds is to be produced by rapid prototyping There are some restrictions to this process:

- It is impossible to produce very sharp angles.
- It is impossible to have undercuts, as it would not be possible to open the moulds.

To design the intake three software packages were used:

- CAD software: Solid Works
- Meshing software: Gambit
- Modelling software: Fluent

2.1. Specifications and constrains

The cylinder capacity lies between 20 and 25 cm^3 and the flow was modelled for an engine speed of 4000 rpm, with valve lifts of 1.5 mm, 2.0 mm and 2.5 mm. There are some restrictions on the design of the inlet track:
:

1- The casting restrictions apply.
2- There is a limit to the thickness of the walls.
3- The fuel should be injected towards the inlet valve, impacting over its back. As the inlet is curved to create swirl, care must be taken to allow a straight path from the injector to the valve.

4- Care must be taken to reduce pressure losses within the helical duct. This was a problem in an earlier design for this engine.

A previous head design had been designed, produced by rapid prototyping and tested using FLUENT. Results from this early design can be seen in Figure 3. The major problems were the huge pressure loss created by this passage, there was no clear path from injector to valve and the problematic shape for manufacture.

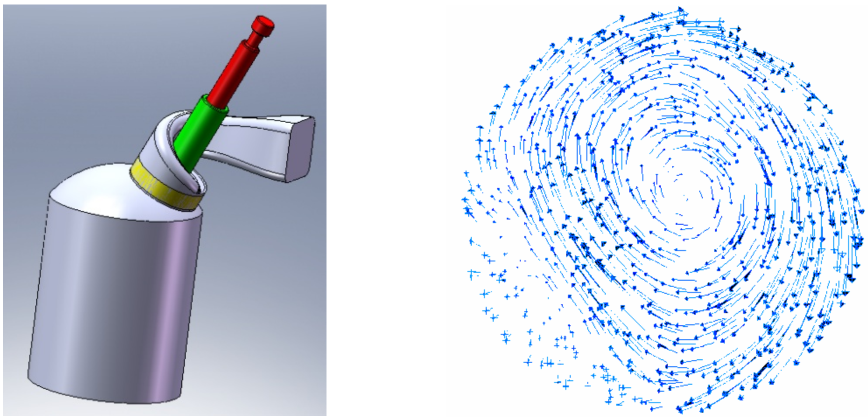

Figure 3. Initial inlet passage design and produced swirl inside the cylinder

2.2. Development of the intake design

Although that earlier head has been designed and produced by rapid prototyping techniques, it was decided to create a totally new design. Figure 4 shows the base design of the hemispherical combustion chamber and the valve seat. From this base, elements such as valve seat and inlet passage were added.

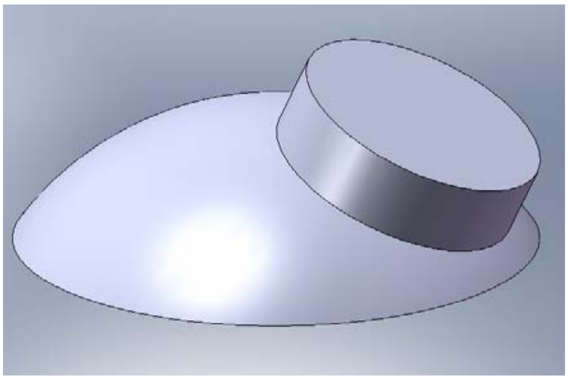

Figure 4. Basic design of the hemispherical combustion chamber and the valve seat

On the final (sixth) geometry the optimisation of the intake design was applied (Coene, 2008), in terms of design for manufacturing and to enhance swirl. Four views of this geometry can be seen in Figure 5. This head had all the required characteristics, high swirl production (Figure 6), a straight path from injector to valve and it could be produced using rapid prototyping techniques and aluminium casting.

2.3. Cylinder head making

A cylinder head (Figure 7) was designed to incorporate the specific inlet port, coolant chamber, housing the camshaft, valves and its auxiliaries (seats, guides and springs), spark plug and exhaust passage. The overall engine case is to be made from aluminum. The material choice affects the manufacture of the component, since in addition to fulfilling service requirements it must simultaneously satisfy production feasibility. Casting is usually the correct natural choice to produce a single or a few functional metallic components having intricate geometry for it is versatile, allows design freedom at have low cost (Dickens et al, 1995).

The geometries in this model, both inner and outer, are highly intricate which makes the production of such a part a very difficult job. In addition, because the engine is very small, all dimensions are miniaturized therefore making it extremely difficult to design, cast and finish. The cooling chamber, in particular, has a critical inner core making problem due to the complexity of its shape and the reduced accessibility, imposing casting limitations. To overcame core making difficulties, rapid prototype technologies provide a method of production that is very convenient for use when single or a few components are to be manufactured (Saraiva et al., 2002). The pattern is not but the CAD model itself, and a virtual model of the cores and the cavity may be built. The entire mould can then be produced using adequate Rapid Prototyping equipment and techniques. 3D printing technology was decided to be used, for it is available and cost effective. The material chosen was a plaster based Z Corporation powder, the ZP®131.

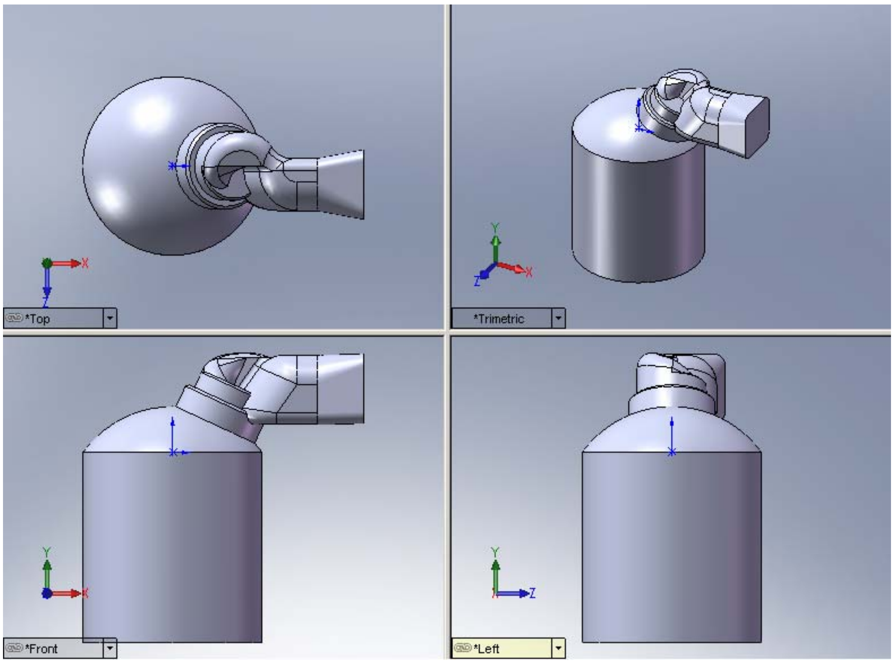

Figure 5. Final geometry

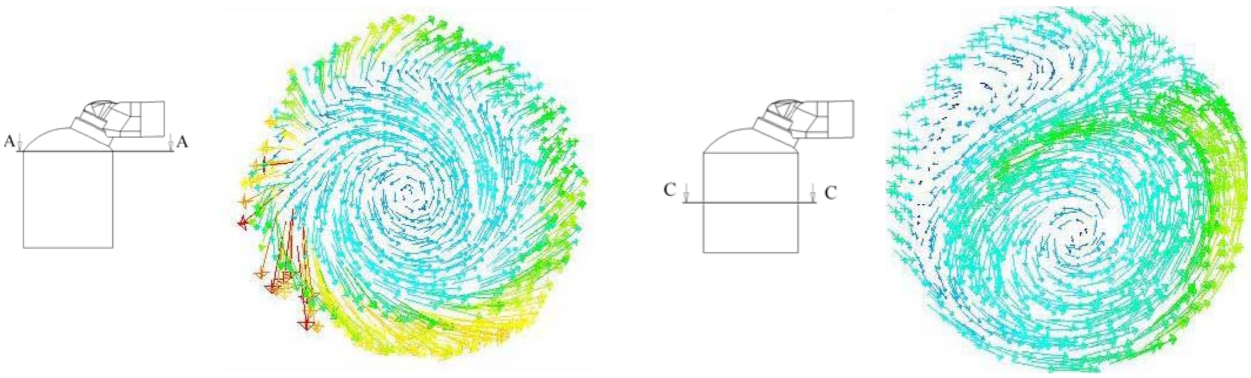

Figure 6. Final geometry with FLUENT (swirl) results at two locations of the cylinder

On this initial design, the inner core of the coolant passage (Figure 8) had to be removed through small (8 mm diameter) holes highlighted in green on (Figure 7), making the removal very difficult. The second design corrected this situation, having a bigger hole (21 mm diameter) on the top of the coolant chamber for easier inner core removal (Figure 9). An effective produced gas removal during pouring operation is expected to be incorporated in this design, in order to obtain sound castings.

Casting accuracy is not enough for a functional model; subsequent machining is then needed to obtain some of the desired features of a particular part (Barbosa, J. et al, 1999). The features requiring more accuracy are then machined to fulfill design requirements. NC machining provides that accuracy, as long as the cutting tool can reach the area to machine. Nevertheless some features must be good enough for acceptance in as cast condition, eventually suffering hand finishing operations, as it is the case of the inlet and exhaust channels.

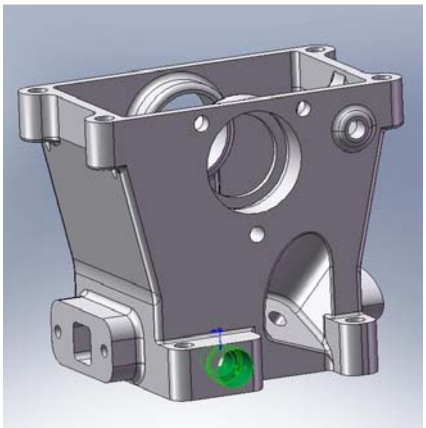

Figure 7. Design #1

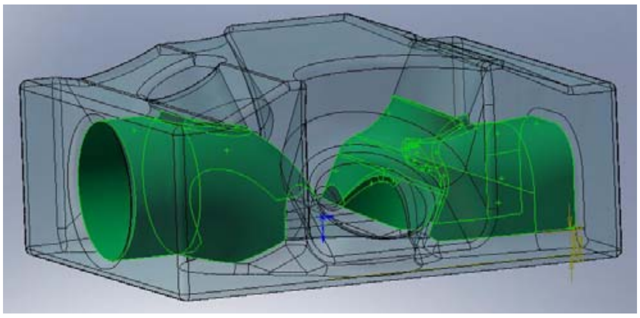

Figure 8. Coolant chamber with inlet (right) and exhaust (left) ports highlighted

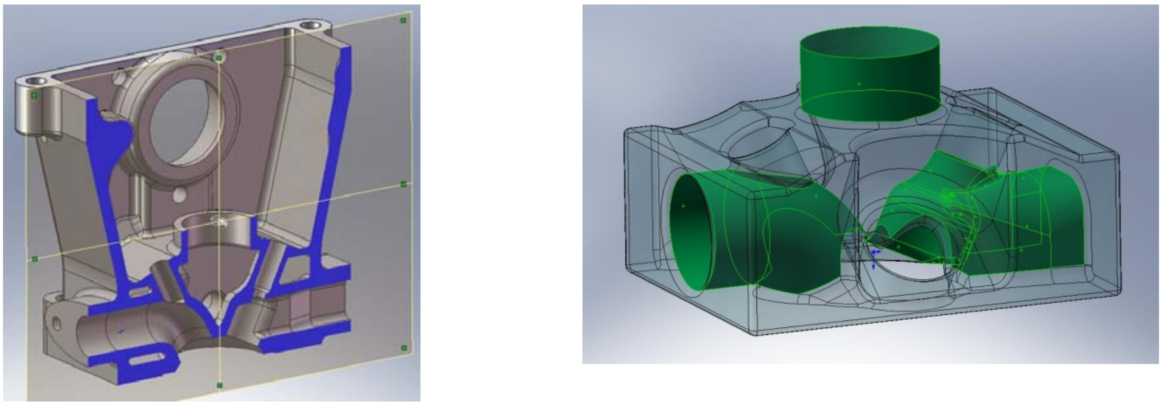

Figure 9. Design #2 - Half cut cylinder head (left) and coolant chamber (right)

2.5. Mould assembly

From the CAD model (Figure 7), models of the mould and core were made. These mould and core models were used to produce the plaster base plaster the ZP®131, using Z Corporation 301 Plus printer machine. Although rapid prototyping techniques allow the entire set to be made in one piece avoiding assembling problems, it is difficult to remove the non agglomerated plaster dust from the inside of the mould due to the complex shape of the part. The mould was then produced by assembling the cavity and cores made separately. The molten metal will then be poured through adequate channels built in the mould.

However complex, the inner core (shaping the combustion chamber, the inlet and exhaust passages and the valve and injector seats), was made in only one part as shown in Figure 10.

Figure 10. Combustion chamber, inlet and exhaust passages inner core (note the swirl geometry)

Figure 11 presents the aspect of the mould assembly, before the inner core being mounted. The image shows that that each components of the mould was divided into two sub-components. This allows easy dust removal, eventual printing defects correction and an easy assembling operation. The outer case of the mold includes the pouring basin, the sprue and the runner to provide a molten metal path to the cavity. The complex shape of the coolant chamber core can be seen. It must also be noticed that the upper core, which originates the cylinder head top chamber for housing the camshaft and valves, is hollow to facilitate not only the removal of the air trapped inside the mould cavity, but also the exhaust of the gases produced by the combustion of organic components present in the mould and cores material.

Figure 12 presents the full mould assembly ready for metal pouring. Four top orifices can be seen, that were built to serve as a way out for the air and gases from the cavity.

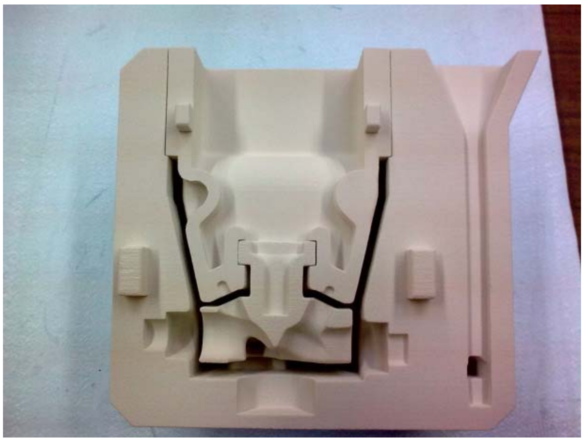

Figure 11. Half assembled mould showing coolant chamber and top chamber cores, the pouring basin, the sprue and the runner entrance

Figure 12. Fully assembled mould ready for metal pouring

2.4. Casting simulation

NovaCast®, a foundry simulation software, was used to predict the solidification behaviour of the cylinder head.

The geometry used in the simulations was the geometry depicted in Figure 7, and for the mould a surrounding box mould was assumed for simulation purposes (see Figure 13).

It must also be noticed that although for the metal the characteristics are already well known, (the aluminium alloy chosen is widely used in casting industry), for the mould the data used to make the simulations had to be introduced in the software data base, and a calibration has to be done to obtain realistic results from the numerical simulation.

The simulations were made using soundness casting parameters like the ultimate solidification time, the metal pressure and velocity in the moulds or Niyama's criteria, to predict the possible occurrence of shrinkage or bubble formation in the cast part. Figure 13 depicts an example of the numerical results obtained.

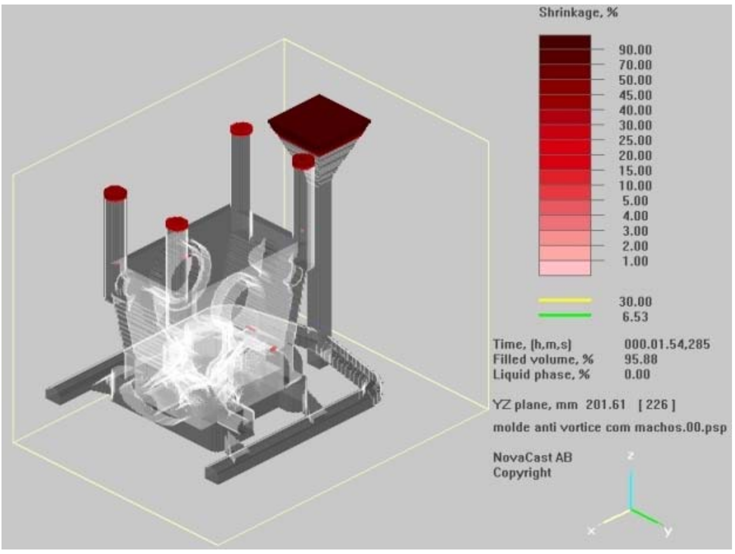

Figure 13. NovaCast® shrinkage prediction

2.5. Actual Casting Results

The mould assembly of Figure 12 was used to produce an actual casting prototype of the cylinder head. The part obtained showed a large hole defect in the massive wall near the cooling fluid entrance, as depicted in Figure 14 (left) From the image it may be concluded that three different reasons joined together to produce that defect:

- the local massive wall kept the metal molten longer than the rest of the part;
- the position of the ingate contributed to worsen this effect because the continuous passage of hot molten metal during the mould filling increased the local temperature;
- the narrow orifices of this design didn’t facilitate de inside air and gases removal, that managed to force a passage through the liquid metal to get out.

To verify the interior soundness of the cat part the metallic prototype was cut trough a plane containing the axes of the inlet and exhaust valves. In Figure 14 (right) three defects occurring in the sectioned area can be seen:

A – a shrinkage of the massive wall of the intake duct where it intersects the outer case;
B – a broken core happened maybe either during filling operation or the final assembling, due to the slenderness of that particular core;
C – a hole resulting from incomplete mould filling, due perhaps to a very thin local wall or to the pressure of the gases forcing a way out.

The results so far obtained led to the conclusion that a different design should be produced in order to obtain a successful cast part. Next paragraph presents the new design proposal that is now under production.

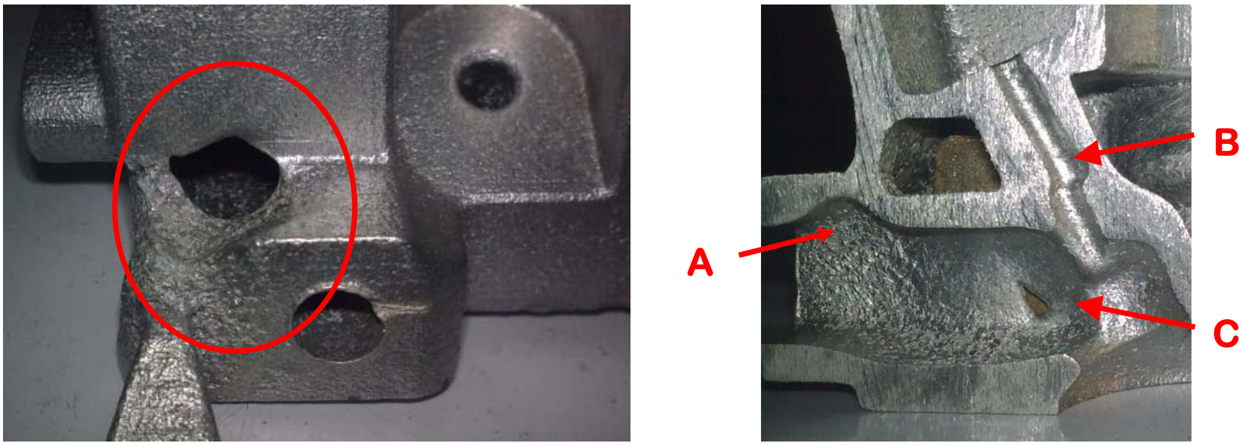

Figure 14. Shrinkage defects surrounding massive regions of the part

3. MODIFYED CASTING DESIGN

New moulds and cores are going to be produced incorporating design improvements to minimize casting defects.
In Figure 15 some of the present state of the cylinder head design is shown. The modifications include:
- the top surface is now open to easy air and gases removal during actual casting, and core removal afterwards ;
- a more generous coolant chamber created to increase thermal inertia, also helps in guaranteeing uniform wall thickness highly recommended for casting reasons;
- the enlarged top camera room will also facilitate the ulterior machining access to the valve guide drills.

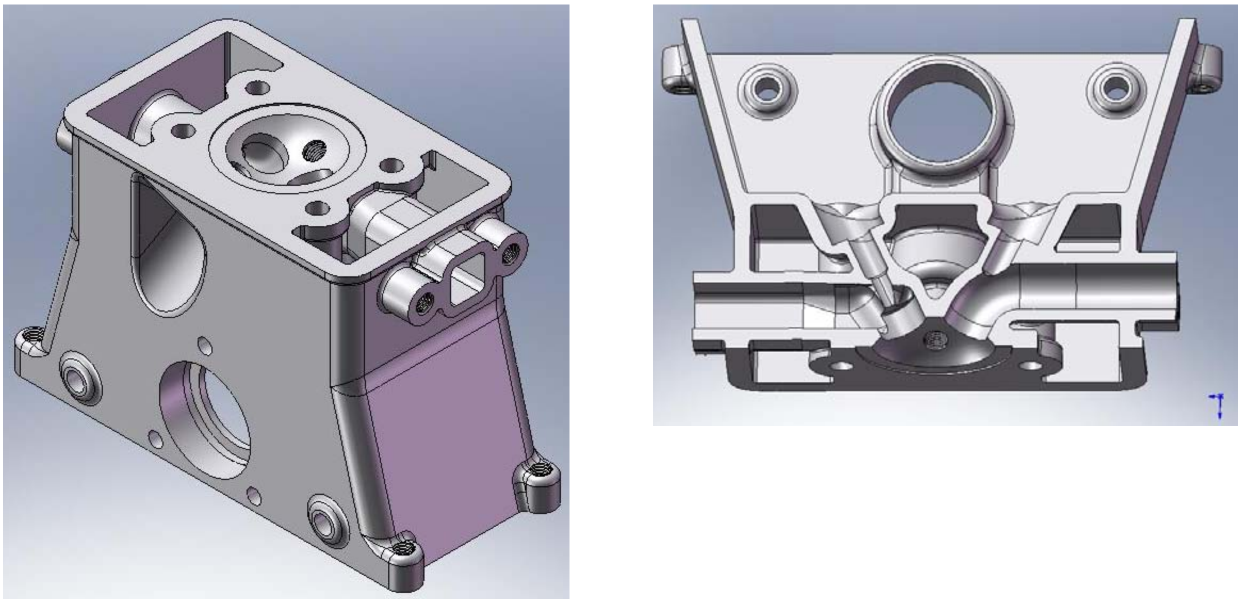

Figure 15. Design #3 – Bottom isometric view (left) and half cut showing the new coolant chamber (right)

New moulds and cores are now being obtained from virtual model shown in Figure 15. The entire process will be repeated to obtain an actual functional part.

4. CONCLUDING REMARKS

A special purpose internal combustion engine was designed using CAD techniques. This is one of a kind engine, designed for a specific aim (minimal fuel consumption). The head was designed with intense swirl production by means of a specific intake geometry. The geometry was optimized using CFD (FLUENT) modeling.

Rapid Prototypes have been produced, allowing early improvements on the design, enabling a fast final design.

The use of Rapid Prototyping in the production of the casting moulds and cores made it easier to implement the design changes in the actual manufactured components. Modifications of the design are easily introduced into the actual parts.

A metal prototype was obtained by direct pouring molten aluminum into a plaster moulds directly obtained by 3D printing rapid prototyping.

The encountered defects led to an improved design which is now under production.

4. ACKNOWLEDGEMENTS

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