On the design of an air-cooling system of an IC engine block made from sheet metal

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Abstract. The cast and machined automotive cylinder block and the cylinder head serve to locate and hold the combustion cylinders in place, provide for cooling channels for the combustion cylinders and damp out vibrations, besides housing allied components needed for combustion. In the present work, the authors attempt to redesign the cooling system of the engine block for manufacture from sheet metal, and reduce its weight. It is proposed to have an air-cooling system around each of the combustion cylinders using a finned cooling cylinder rotating concentric with respect to the combustion cylinder with a coolant occupying the annular gap between the combustion cylinder and the cooling cylinder. The peculiar design enables hotter air to enter the combustion cylinder thereby increasing the expected thermal efficiency and power output, besides enhancing the quality of air-fuel mixing. Manufacture of the engine block from sheet metal involves embossing flow channels into thin sheets for the coolant, or machining such channels in thick sheets, folding them over, brazing the flat surfaces between channels and brazing the fin to the periphery of the cooling cylinder.

1. Introduction
A conventional IC engine involves manufacturing processes like casting and forging which are known to be environment unfriendly. Moreover, an engine block is a rather heavy casting providing great opportunity for light weighting. Besides, it needs to be machined subsequent to casting. Functionally, an engine block primarily houses the combustion cylinders, provides passages for circulation of the cooling fluid, and damps out the vibrations.

If a light weight structure constructed from alternate form of raw material using an alternate manufacturing route, serves the above-mentioned functionalities, then it might be possible to effectively reduce the weight of the engine. A light weight IC engine would also lead to benefits downstream, like lighter engine cradle and engine mounts.

This subject has not been touched upon by literature published in recent times, except for the ones by Date et. Al. [1-3] and Mahadevan [4], who proposed measures to manufacture the reciprocating components of the IC Engine (piston [1], connecting rod [3]), and transmission components like gears [2]. Water cooled light weight engine block for manufacture using sheet metal was designed by Basunathe [5]. Automotive cooling system component interactions have been documented by Walters [6], and studies on light weighting especially by material substitution (use of light-weight materials) for manufacture of automobile components were reported by Cole et. Al [7]. Materials and manufacturing processes used to make a cylinder block were reported by Nguyen [8]. Earlier, L. M. Taylor [9] had made attempts to make the engine block out of sheet metal. Taylor constructed the
cylinder block from tubing and sheet metal, joining parts by oven brazing. However, one is unable to find research-based documentation on the design and manufacture of a lightweight engine block using sheet metal. Of late, Dhonde [10] has made an attempt to design an IC engine block out of sheet metal.

The present work is about lightweighting of an air-cooled engine block of an automobile, by redesigning the cooling system, for manufacture using sheet metal. Designing a cooling system compatible with multi-cylinder IC engines presents many challenges. The design challenges and how they can possibly be met using a novel design of an air-cooled engine block are discussed in the sections that follow.

2. Design of a sheet metal engine block

2.1. Engine parameters

The total power of a four-stroke engine generated by a four in-line cylinder configuration used in this study, was assumed to be about 100 kW. Each cylinder was considered to have an inner diameter of the liner equal to 80mm. Assuming a thermal efficiency of 34% and assuming that 33% of the total heat is carried away by the cooling system, the remaining 33% is carried away by the exhaust gases. Taking this into account, each cylinder would need a cooling system to dissipate an average of 7.5 kW of power. Heat transfer considerations apart from lightweighting should therefore maximise the dissipation of heat for efficient cooling of the engine.

Consistent with the above, the peak cylinder liner temperature was estimated to be about 812 deg. C and the peak pressure of combustion was estimated to reach about 7 MPa. At these temperatures and pressures, the yield strength of the liner material should be at least 300 MPa at 812 deg. C. These values relate to a typical engine available in the laboratory.

2.2. Design requirements

In order to make the engine block manufacturable using sheet metal, it needs to be redesigned. Especially, the method of providing for cooling of the cylinders will have to change, since the current design is meant to be made by casting, and cannot be made from sheet metal, the way it is. To redesign the engine block, the functionalities of the conventional engine block, which is usually made as an aluminium casting, need to be achieved by design from sheet metal. No changes in the combustion parameters are envisaged as a consequence of the engine block being re-designed. Thus the process of generation of power in the engine cylinders remains unchanged, though the means of cooling and methods of performing the functions of the engine block would change as the engine block gets redesigned for manufacture using sheet metal. The major functions of the engine block are listed below:

a. The combustion cylinders need to be housed in the cylinder block, being held at a certain distance from each other.
b. Provision for cooling of the combustion cylinders should be made
c. Engine vibrations should be damped out
d. Adequate support for mounting allied parts should be available.

2.3. Design Concept

This may be achieved using sheet metal of different thicknesses, in the following manner:

a. The combustion cylinders are supported between two thick parallel plates. The cylinders are firmly held in position by the flanged plates.
b. Each combustion cylinder has around it a concentric cooling cylinder with fins. There is an annular gap between the combustion cylinder and the cooling cylinder. A certain quantity of thermal fluid (like Therminol XP) fills the annular gap. Cooling channels in the fins meant to dissipate heat open into the annular gap and the thermal fluid is circulated in these channels by natural convection (Figure 3).
c. The annular fluid also serves to damp the vibrations in each of the cylinders of the engine.
d. The chamber made from sheet metal that serves as the engine block would provide adequate opportunity to support/mounting of allied parts.

2.3.1. Thermal considerations for the engine block. Figure 1(a-c) shows the schematic arrangement of the engine block made from sheet metal. Figure 1(a) shows the arrangement of cylinders in a trapezoidal enclosure relative to the direction of movement of the vehicle, i.e., direction of entry of air into the engine, and the way the general features of the engine block would look from the top. The direction of reciprocation of the piston is perpendicular to the plane of paper in Figure 1(a). The trapezoidal shaped sheet metal chamber has two parts, the lower part that admits ambient air as the vehicle moves and the top part that has the inlet and outlet ports and corresponding ducts to and from these ports (Figure. 1a). The cylinders are closer to the larger side of the trapezium, and so are the inlet and outlet ports. The cylinders are arranged in line along the width of the vehicle, with the crank shaft running along the width of the vehicle (perpendicular to the plane of paper in Figure 1b). This figure also shows a schematic of engine action together with the engine combustion cylinder, cooling cylinder and the engine block. The path of air entering the lower half, acquiring heat from the cooling fins that dissipate heat from the combustion cylinders to the ambient air (Figure 1(b)). The heated air would try to expand, but is instead compressed by the tapering section (Figure 1(a)), thereby increasing its velocity.

The incoming air will invariably carry dust particles along. As the air initially collides with the fins, part of the dust particles would get removed. Those smaller ones which enter the trapezoidal section of the sheet metal engine block would get removed as the hot air, at a high velocity, would collide with the wall at the back requiring the air to make a 180 degrees turn before entering into the inlet port of the combustion cylinder in the upper part of the cylinder block (Figure 1(b)). Thus the high velocity air entering the cylinders may be expected to generate a mild supercharging effect. This way, part of the heat lost from the engine may be returned to the combustion cylinders. The extra air that does not get into the cylinders is used for scavenging the exhaust gases preventing them from crossing over to the inlet port side.

The engine cooling (and preheating of incoming air) is achieved by the finned cooling cylinders running concentric with the combustion cylinders (Figure 1(c)) The finned cylinders of a multiple in-line cylinder engine determine the power dissipated to the cooling air, and are made from sheet metal. Adequate number of fins and fin area must be available for efficient dissipation of heat as shown schematically in Figure 1(c). In this work, to account for adverse conditions, the maximum temperature of ambient air has been assumed to be 60 deg. C, which is higher than the temperatures seen by most Indian cities during peak summer. The objective here is to admit hotter air into the combustion cylinders thereby increasing the Carnot efficiency.

The loss of volumetric efficiency due to expansion of the hot air is compensated by the tapered geometry of the cylinder block. The angle of taper therefore is a very important design parameter. This way the velocity of air entering the cylinder may be expected to increase. Heated air would have a natural tendency to rise and will get into the upper part of the cylinder block, where a suction stroke would do the rest. In an engine operating at 6000 rpm, 3000 suction strokes per minute would be expected. Under these conditions, the cylinder liner would be at 812 deg C for total heat generation of about 25 KW. The temperature of the Therminol fluid in the fins would be expected to reach 107 deg C for an average air velocity of 10m/s (driving speed of about 40 kmph). In the worst case scenario, wherein the driving speeds of 10-15 km/hr at full power can be attained, the temperatures attained by the therminol fluid are of the order of 280 deg C, with the fluid circulating through the channels by natural convection. This is much below its maximum operating temperature of 315 deg C. These temperatures will influence the material selection for manufacturing, the design of the fins, and the manufacturing processes themselves.

The cooling system illustrated in Figure 1(a-c) is self-regulating. That is, when the vehicle is moving at a high speed, more heat is generated in the combustion cylinders and incoming air meets the fins at a greater velocity enhancing the rotational speed of the finned cooling cylinder. This would lead to turbulence in the coolant reservoir and enhance the heat transfer coefficient. Hence greater power generation is matched by more effective cooling from air flowing over the fins. In all the calculations,
it is assumed that only the fin area will dissipate heat to the incoming air. The area of the engine block itself that might dissipate considerable amount of heat has not been taken into consideration at this time. Hence the sheet metal engine block will further augment the heat carried by the air into the engine.
The air, after changing direction gets into the inlet of the cylinder, while some of it moves over to the exhaust side facilitating scavenging. The flue gases of all cylinders therefore enter a common line (perpendicular to the plane of paper in Figure 1(b)) and are discharged via an exhaust pipe.

The radius of curvature of the fin and the length of the fin (angle subtended by the fin at the centre of curvature, Figure 2), was also studied. Number of fins can go upto eight, exceeding which the cooling effect drops. Similarly, excessive curvature of the fin also restricts its utility. Hence the light curvature is applied through a subtended angle of 10 degrees (i.e., ‘angle of curvature’ = 10 deg.).

Based on simulations, eight fins were found to have the maximum dissipation of heat. Figure 3 shows a schematic view of a combustion cylinder with a concentric cooling cylinder on which one fin is shown to conceptually illustrate the features to enhance the cooling system. The fluid flows into the fin from a constant fluid filled annular gap between the combustion and cooling cylinders that serves as a reservoir of thermal fluid. Figure 3 shows the various features of the cooling fin with a network of horizontal and vertical cooling channels for flow of the thermal fluid.

The flow of the fluid through the channels made in the fins experiences inertia forces in terms of the centrifugal force (created by rotation of the cooling cylinder as the air enters the trapezoidal engine.
chamber), in addition to natural convection. At slow speeds natural convection would dominate, while at higher speeds, the flow of fluid would depend largely on the centrifugal force resulting from the speed of rotation of the cooling cylinder. Thus the effect of natural convection on circulation of the cooling fluid is relatively small at high speeds.

The new design of the cylinder block does not interfere with the combustion inside the automotive cylinders per se, but provides a framework to dissipate the heat to the incoming air and use hotter air for combustion in the combustion cylinders.

2.3.2. Aerodynamic loading on the sheet metal fins. The aerodynamic load on account of the air flow impinging on the fin is rather small, and does not cause any significant bending moment. A typical velocity is assumed to be 50 kmph for city driving conditions. For highway driving conditions, and no rotation of the finned cylinder, the bending stress on the fin corresponding to 120 kmph works out to about 132.5 kpa for a fin thickness of 10 mm. If the sheet thickness is reduced to 0.5 mm and cooling fluid is circulated through cooling channels embossed in the fin, the section modulus of the fin can be increased significantly. Even in the absence of any such stiffening features, the bending stress increases to 53 MPa.

![Diagram of a fin, attached to a finned cylinder concentric with the combustion cylinder](image)

**Figure 3.** Schematic of the arrangement of a fin, attached to a finned cylinder concentric with the combustion cylinder (a) with parallel flow channels (b) with horizontal and vertical channels. The centre-to-centre distance between the vertical channels is about 17 mm.

3. Manufacture of the sheet metal Engine block

3.1. Material for manufacture

The fins would have to be made from conducting metallic sheets with the fluid passages embossed into the fins to facilitate circulation of the fluid, as well as impart a mild curvature as shown in Figure 2. The material for manufacture of the finned cylinder should have good thermal conductivity and weldability, together with moderate degree of ductility. Given the temperatures seen by the 4 wheeler engines, using aluminium alloys will be risky as they will soften at the temperatures they will get heated to. Hence a medium carbon steel will be advisable as it will have adequate strength at the operating temperature, good ductility, and good weldability from a manufacturing standpoint. The stress of 53 MPa is rather small for any significant deflection of the fin which may be made from Al 5083 alloy or Al 6061 alloy. Besides, both have very good weldability as well. However, aluminium
alloys will be suitable at these stress levels only if the fins are effectively cooled by circulation of the thermal fluid.

3.2. Manufacture of the finned cylinder
The fins could be made by making the channels (by machining, as in the present case described in Figure 4) or by embossing if the sheet is thin enough, for the thermal fluid to flow through, bending of sheet metal at the two ends (Figure 4(a)) and folding them over at the line of bend to bring together the two halves of the fin (Figure 4(b)), which will involve a hairpin bend. In order to retain the overall shape of the fins, furnace brazing of the fins would be more practicable to prevent leakage of the fluid.

![Figure 4. (a) Two halves of the fin embossed on a single sheet to be folded(bent at 180deg) along the bend line (b) The fin after bending, showing end openings of the cooling channel and the radiused (base) flange to enable brazing onto the finned cooling cylinder.](image)

The base of the fin would be shaped as shown in Figure 4(b). This will enable assembly of the fin onto the outer surface of the finned cooling cylinder by brazing or similar technique. For better heat transfer, brazing the bottom of the fin with the outer surface of the cooling (finned) cylinder would be recommended. This will also strengthen the joint between the fin and the cylinder, making it leak proof. Pins may be inserted through the holes in the cylinder and those serving as openings for cooling channels to align these during brazing. The pins can be removed after the fins have been brazed to the cooling cylinder. In such an event, relatively smaller sheet thickness would be adequate. For instance, a thickness of 3mm would be enough for sufficient stiffness of the aluminium fin.

The cooling cylinder may be made from an aluminium sheet about 5-6 mm thick. The reservoir of thermal fluid would then be bounded by the outer surface of the combustion cylinder, the inner surface of the cooling cylinder and the thickness of the top and bottom plates, (which would be of the order of 10mm or so) and top and bottom seals.

3.3. Manufacture of trapezoidal engine chamber
The trapezoidal engine chamber is manufacturable by joining sheets/plates of suitable sizes. Two thick trapezoidal parallel plates, with flanged holes in one plate (equal to the number of cylinders) aligned with the corresponding flanged hole in the other plate, enable proper alignment of the combustion cylinder consisting of a liner inside it. The combustion cylinders could then be welded to the flanges in the parallel plates.

A negative (compressive) contact pressure can be generated between the combustion cylinder and the liner by subjecting the combination to high internal pressure (as in hydroforming) so as to cause a
sufficiently high elastic contact pressure. At the combustion temperature the contact pressure could be partly relieved due to heat, but then the liner will develop only small tensile stresses.

Such a design holds promise due to a significant weight reduction (at least 20-30%) in addition to eliminating the radiator and the cooling circuit not being required any more.

4. Conclusions
A design and manufacturing scheme for manufacturing the engine block from sheet metal has been suggested. The functionalities of the cast engine block can be achieved by a sheet metal engine block re-designed for the purpose.

Following differences from the conventional engine block are noteworthy:

a. A separate coolant pump is not required. Coolant is circulated by natural convection, saving power needed to drive the coolant pump
b. A separate radiator is not required as the function is performed by the finned cooling cylinder made from sheet metal
c. No machining of the engine block is involved
d. The redesigned cooling system uses wrought elements which would have a greater strength/weight ratio compared to the cast elements
e. A number of expensive manufacturing processes typically associated with the conventional engine block would get eliminated.

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