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Improving heat transfer in an air-cooled engine by redesigning the fins

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Heat transfer modelling and simulation were carried out in a single-cylinder, four-stroke, air-cooled engine to evaluate the heat transfer rate of the engine block. The modelling studies of cylinders with different numbers of fins and different geometry were performed using the SolidWorks computer platform. The tested components were made of 6063-T6 aluminium alloy castings. The simulation concerned different numbers of fins as well as changing the geometry of fins with circular and rectangular perforations. The results of the studies showed the possibility of improving the power to mass ratio for cylinder efficiency and heat transfer rate. It was shown that a large number of fins leads to an increased heat transfer rate, but it affects the overall engine efficiency due to the increase in the total engine mass. Circular perforation is a better design solution than rectangular perforated fins with the same cross-section. Circular perforation provides a lower engine cylinder mass and gives more than 4 % better heat transfer rate. The perforation size was tested using circular perforations with a diameter of 7.14 mm, 8.5 mm and 10 mm. With a 7.14 mm diameter perforation, the heat transfer rate increases slightly compared to the other tested ones, while a 10 mm diameter perforation provides the best mass reduction.

Key words: *engine cylinder fins, circular and rectangular perforate, heat transfer rate*

1. Introduction

Studies of small combustion engines used in 2/3-wheeled vehicles concern various aspects, but in their nature, they concern the same issues as studies of engines of passenger cars or trucks. A study is still underway to improve the efficiency of this heat machine. Among a lot of projects, one can, of course, find those that concern ecology, when, for example, the researchers attempted to identify exhaust emissions from small engines in laboratory conditions [28]. There are works on improving the design, such as [20], in which the authors introduced a floating cylinder liner and assessed the tribological effects. Many works concern heat exchange in motorcycle engines – this is also the case with this article.

One way to remove heat from an internal combustion engine is to use an air-cooling system. Such systems are most often used in 2/3-wheeled vehicles, and these are the dominant means of transport in some countries. In Africa alone, there are over 27 million registered two-wheeled vehicles [17, 18]. If we add that 80% of them are used for commercial purposes, then all work on air cooling systems in internal combustion engines gains not only a scientific dimension (work on energy and the system's efficiency), but also sociological and economic significance [15]. In this system, the fins play a fundamental role. The geometry, number of fins, their size and the material from which they are made determine the system's efficiency, which translates into the engine's overall efficiency. These parameters can be modified, but it should be noted that some features are mutually exclusive, hence the attempt to verify selected factors in this paper.

The number, size and geometry of the fins pose difficulties in operating with large or excessive fin thicknesses. Increasing the fin thickness can increase the engine mass and increase its overall size. This can affect the engine performance, especially in applications where mass is critical, such as small, air-cooled engines, automotive, including those built with the rightsizing concept. This paper compromises the heat dissipation advantage because, on the one hand, the fin thickness is increased, but to minimize the mass, perforation of the fins with different spacing is introduced.

2. Related work

2.1. General view of cylinder fins

About 70% of burned fuel is evacuated from the engine to prevent any failure [3]. The cylinder fins, which constitute the engine cooling system, contribute to the acceleration of heat transfer to the environment, which causes a change in the engine's thermal load [5]. The improvement of the thermal characteristics of the engine cylinder can be achieved by expanding the surface of the fins [6], changing their shape, changing the material composition, and changing the geometry of the fins [26]. For example, in the project described in the article [3], during modelling of the engine cylinder heat. The cylinder and fins were made of different materials. The high suitability of cast iron for increasing the heat transfer rate was demonstrated. The fins were made with cylindrical perforation of 4 mm diameter and groove width of 2.5 mm. The modelling concerned a single-cylinder motorcycle engine with a capacity of 100 cm^3. In other research, a numerical analysis was performed for the different profiles with the aluminum material [23]. In the paper [22] an analytical approach was used to determine the temperature distribution for different fin lengths and different materials. The heat transfer rates for different fin materials were simulated during steady-state engine operation for each compression stroke separately. Equations for temperature distribution and heat transfer are provided for circular convective-radiative porous fins. Four distinct shapes – rectangular, convex, triangular, and exponential are considered with variable thickness [11]. The performance of each perforation shape – circular, rectangular, triangular, and non-perforated fins is assessed using forced convection heat transfer [14]. CFD analysis was used to validate the results. Rectangular and triangular fin geometry was analysed, and the best solution was the result of ambient conditions. In the next research work [25], a simulation platform was developed to predict and optimize the thermal efficiency of a two-stroke spark-ignition engine. In this case, the fins had circular, axial and triangular geometry [9]. The material properties of the engine block were also changed. For a better understanding of heat dissipation through the engine cooling system fins, it is important to assess what is happening inside the cylinder. In [21], a simulated thermal analysis of air spreading inside the engine cylinder was performed. Air is the so-called invisible working medium [19] that has an important impact on the rate of heat dissipation. The analysis showed a high significance of air movement inside the cylinder on external heat transfer to the atmosphere and, thus, cooling of the cylinder surface. In the article [9], the importance of computer modelling of cooling mechanisms in the combustion engine was once again emphasized. Studies indicated the possibility of increasing the efficiency and durability of the engine thanks to appropriate simulation at the design stage and during optimization of the cylinder head and block fins. The determinant in this respect is mainly the evaluation of the engine cooling process, especially during air cooling. Heat is conducted through the engine parts and dissipated to the atmospheric air through the fin surfaces. The above-mentioned article showed that insufficient heat removal from the engine would lead to the occurrence of high thermal stresses and a decrease in the overall efficiency of the engine [31]. During the tests, the fins were modified in various respects. The results of heat transfer through the existing fins and modified fins were compared also in the paper [12]. A significant increase in heat transfer was observed using modified fins. A methodology for optimizing heat transfer [13] and fin efficiency was proposed [8]. It is known that the fin area can be enlarged to increase the heat transfer rate [30], which makes the design of an engine as a structurally complex machine quite difficult. In the paper [24], ANSYS software was used to analyse the thermal properties of cylinder fins of different geometry, materials, and thicknesses. The temperatures and other thermal parameters, which are boundary conditions that change with time, are found using transient thermal analysis. Material issues are important aspects of considering the thermal loads of the engine. For example, in [3, 5] the heat transfer coefficient of a square engine with fins made of aluminum and magnesium alloys was studied. Geometrically, these were round or rectangular fins with fin thicknesses of 2 mm and 3 mm. It was found that the round fin made of an aluminum alloy showed a higher heat transfer rate than the magnesium alloy.

2.2. Number of fins effect on air-cooled cylinder

Another important element in analysing the heat transfer rate in an air-cooled engine is the number of fins. The number of fins varies depending on the change in fin pitch or the distance between each fin. In one of the projects, the influence of the number of fins on heat transfer was assessed. It was six fins with a 7 mm fin pitch, and in the second variant, there were five fins with a 10 mm pitch. The maximum heat transfer value was obtained with a 10 mm pitch. The heat transfer contour tests were carried out at a speed of 60 km/h [29]. During other experiments, this time using a wind tunnel, experimental cylinders with different numbers and different pitches of fins were tested. The temperatures inside the cylinder, on the surface of the fins and in the area between them were recorded [27]. Interesting results were described in [32]. It was shown that when the cylinder had many fins and too narrow a spacing between the fins at lower wind speeds, the heat release from the cylinder was not improved because the air had greater difficulty flowing through the smaller spaces between the fins. This caused an increase in the temperature between the fins and reduced the heat transfer rate. In other experiments, the changes in the number of fins with their different shapes were studied. In the paper [10], the research covered circular, triangular, and parabolic fins to define the most favourable shape and number of fins for heat dissipation in a two-wheeled vehicle. Similar work was carried out for different types of fin arrangement geometry (circular, triangular and parabolic) [16]. The optimization was performed on models of existing engines with different fin arrangements.

2.3. Effect of perforate on cylinder fins

In addition to the material issues, the number of fins and the spacing between them, as well as the fin perforation, can play an important role in heat transfer. Among the many studies on this topic, interesting works are in the papers [1, 3], where the aims of the research were to evaluate the effect of different fin perforation shapes on the heat transfer rate. In these experiments, different perforation geometries were used, including round, rectangular, triangular, and non-perforated fins. Circular perforations are added to heat exchangers to investigate how various geometrical and operational aspects affect the heat exchanger's flow fields and thermal properties [2]. The comparative thermal performances of circular and elliptical pin fin heat sinks are presented [7].

According to the research reports, non-perforated fins showed the lowest heat transfer rate, while round perforations provided the highest heat transfer rate, followed by rectangular and triangular perforations. The authors of the studies [14] reached similar conclusions. An important research element is the configuration of the fin pitch with perforation to increase the heat exchange efficiency. Mutual relations can improve the air mixing that causes turbulence, thus increasing the convective heat transfer coefficient and facilitating more efficient heat exchange. Such studies were performed and described in [16].

The cooling efficiency of the perforated-finned heat sink (PFHS) was studied by forcing heat exchange for the laminar convection mode. One of such experiments was devoted to the article [29]. In another paper [1], it was shown that with the increase in the number of perforations, which is associated with a decrease in their dimensions, the thermal boundary layer is more frequently interrupted, which affects the change in the heat exchange rate [4]. The authors of the work [12] reached similar conclusions. In another work [6], it was directly shown that the hole size and the gap between the perforations are optimal for obtaining the highest heat exchange rates at constant porosity.

3. Methodology

3.1. Modelling and boundary conditions.

The paper describes the design and simulation of the cylinder fins of a four-stroke single-cylinder engine for three cases of engine thermal load evaluation. The first part is the modelling of the cylinder fins of a 250 cm^3 single-cylinder air-cooled gasoline engine. The basic dimensions of the fins are as follows: thickness 2.5 mm, width 10 mm. It was designed and simulated for 9 fins with a spacing of 8 mm. The second approach was to design the fins of the same size by increasing the number of fins to 10 and 12 while reducing the spacing to 7 mm and 6 mm, respectively, to improve the heat exchange surface. Finally, circular and rectangular perforation shapes will be inserted into the fins, 8 for each fin, to minimize the mass of the engine cylinder and improve heat exchange. The simulation was carried out in all stages using SolidWorks software.

3.2. Engine parameters and material properties

The specification of the basic geometric dimensions of the tested engine, with a special description of dimensions of the cylinder fins, is included in Table 1. Next, Table 2 presents the material properties of the preferred material in the tests, which is the 6063-T6 aluminium alloy. The material was selected after a previous thermal evaluation of this alloy, indicating the most favourable thermal conductivity to obtain high thermal efficiency of the cylinder fins.

Table 1. Single cylinder air cooled engine

Engine parameters	Value	Unit
Bore diameter	50	mm
Stroke length	70	mm
Fin thickness	2.5	mm
Fin width	10	mm
Fins spacing	8	mm
Cylinder wall thickness	4	mm
Number of fins		–

Table 2. Physical properties of aluminium alloy 6063-T6

Properties	Value	Unit
Poisson's Ratio	0.33	–
Shear Modulus	$2.58e^{+10}$	N/m^2
Mass Density	2700	kg/m^3
Tensile Strength	$2.40e^{+8}$	N/m^2
Yield Strength	$2.15e^{+8}$	N/m^2
Thermal Expansion Coefficient	$2.34e^{-5}$	K^{-1}
Thermal Conductivity	209	$W/(m \cdot K)$
Specific Heat	900	$J/(kg \cdot K)$

3.3. Modelling of single cylinder

In this chapter, a design description of a single-cylinder, four-stroke air-cooled engine is presented, along with the modelling method using SolidWorks software. By introducing appropriate boundary conditions for the temperature inside the cylinder and convection on the cylinder fin, the thermal performance of the cylinder material made of aluminium alloy 6063-T6 is studied – Fig. 1 and Fig. 2.

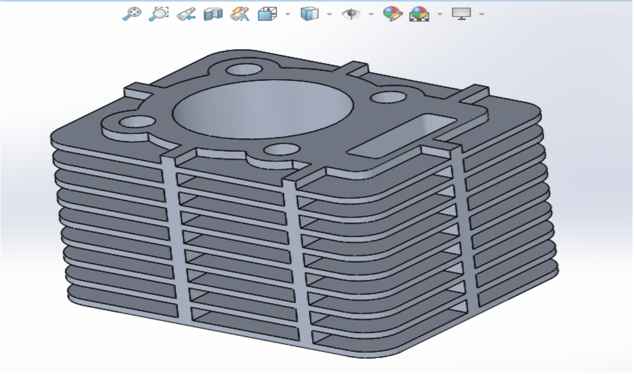


Fig. 1. Modelling of air-cooled engine cylinder

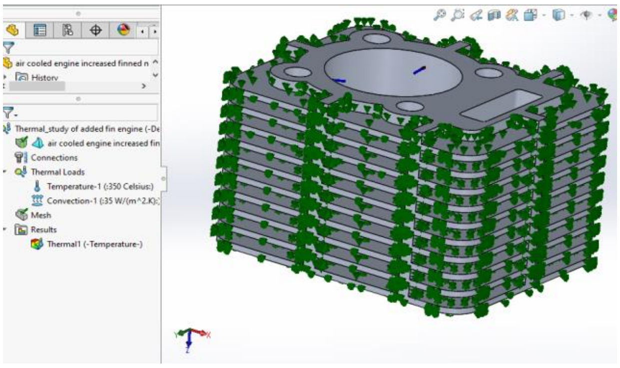


Fig. 2. Boundary conditions applied on existing cylinder fins

4. Results and discussion

4.1. Effect of stroke length – general view

The maximum temperature created on the piston head during the combustion process dissipated through the cylinder bore thickness to the outer to the tip of the cylinder fins. The heat transfer process occurs in all cylinder bodies and it slightly decreases as the piston moves from the top dead centre to the bottom dead centre as well as from the inner to outer surface. As is seen in Fig. 3, the maximum temperature is created inside the top dead center and the minimum temperature is in the outer part of the bottom dead center. This indicates that the heat transfer in single-cylinder air-cooled engines can also be affected by stroke length in addition to cylinder fin geometry.

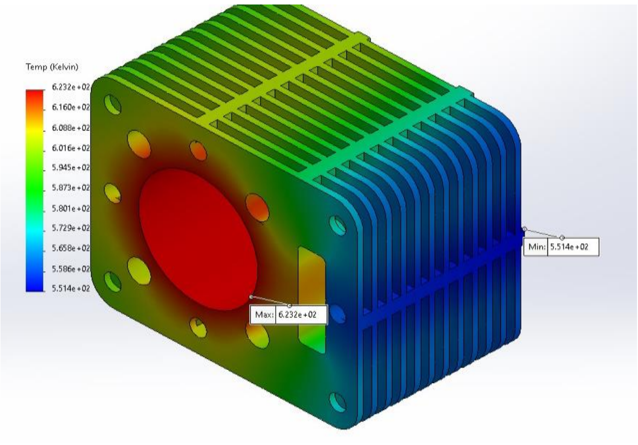
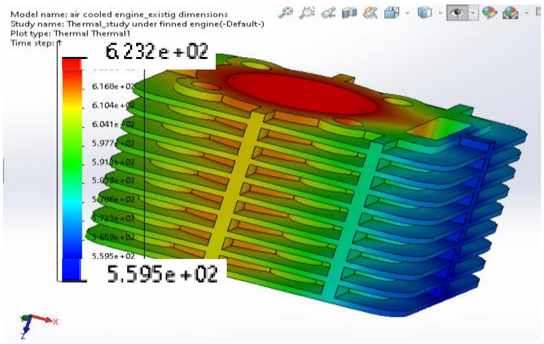


Fig. 3. Heat flow process in air cooled engine cylinder

4.2. Effect of number of fins on engine mass and thermal engine performance

In Figure 4, one can observe the results of the simulation of the thermal performance of the tested engine for a different number of fins and spacing between each fin.

Accordingly, in Fig. 4a – 9 fins separated by 8 mm were modelled and simulated, in which the maximum temperature is 623.2 K and the minimum 559.5 K. In Figure 4b there is an image of the simulation for ten fins with a spacing of 7 mm, and in the case of Fig. 4c there are 12 fins and a spacing of 6 mm between fins. Detailed descriptions of the obtained results for each simulation are given in Table 3. Each value is discussed below the table to make and analysis of thermal performance with a reduction in engine mass.



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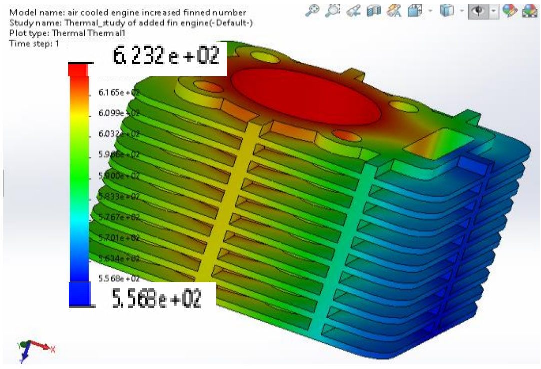
Time step: 1

a) 9 fins by 8 mm spacing



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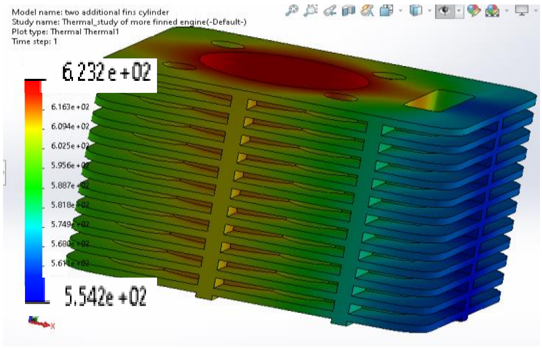
Time step: 1

b) 10 fins by 7 mm spacing



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Study name: Thermal_study of more finned engine(-Default-)
Plot type: Thermal Thermal1
Time step: 1

c) 12 fins by 6 mm spacing

Fig. 4. Spacing and number of cylinder fins on thermal performance

Table 3. Simulation results for different number and spacing of fins

Case	Temperature values, K			Cylinder mass, kg
	Max.	Min.	Change	
a	623.2	559.5	63.7	0.89
b	623.2	556.8	66.4	0.92
c	623.2	554.2	69.0	0.96

The fins on the engine cylinder are designed to dissipate heat generated during the combustion process, ensuring that the optimum operating temperature is maintained. The heat transfer rate is influenced by various factors, which were mentioned in the first part of the paper. In this part of the paper, a different number of engine cylinder fins in the same engine geometry is considered, while the spacing changes with the increase of the number of fins. By maintaining the existing geometric dimensions of the cylinder and engine fins and changing the number of fins and their spacing, the above-mentioned results were obtained – Fig. 4 and Table 4. With the increase in the number of fins, the temperature change increases because the addition of fins increases the heat dissipation area on the fins. It is obvious that the maximum cross-sectional area can increase the engine's heat dissipation capacity, especially under high load or high temperature operating conditions, while the mass of the cylinder increases with the addition of mass on the cylinder. This addition of mass has a negative effect on the power-to-weight ratio, which requires that the most advantageous solution be selected from those tested, i.e., to select the number of fins with the best reduction in engine mass.

The analysis of the results for three test conditions, where the number of fins was changed from 9, through 10 to 12, is presented in Fig. 5. It follows that the temperature change in the case of 12-cylinder fins is greater than in the other cases, which helps to achieve the maximum rate of heat exchange between the cylinder and the environment.

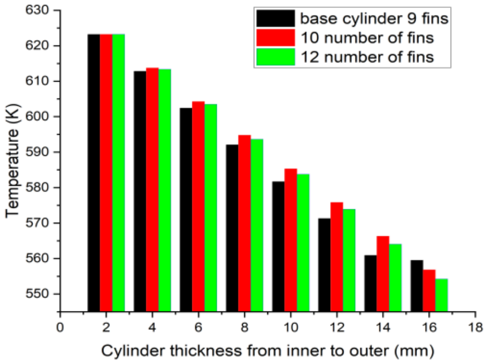
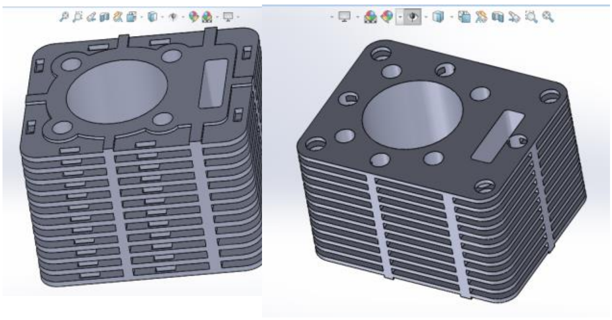


Fig. 5. Effects of number of fins on temperature change

In the next evaluation, it should be pointed out that by modifying the base engine by introducing ten fins and a 7 mm spacing, heat dissipation improved by 4.23%. Adding material increased the engine mass by 2.74%. In turn, 12 fins with a 6 mm spacing improved heat dissipation by 8.32% but increased the engine mass by 8.23%. More cylinder fins can also affect heat transfer efficiency and overall cooling efficiency, as resistance to heat flow and the inability to cope with increased heat dissipation increase.

4.3. Effect of perforate shapes on cylinder fins

In this part of the paper, the modelling of heat dissipation from the engine cylinder in the case of perforated fins is considered. Rectangular perforate shapes, as in case (a) in Fig. 6, and cylindrical arrangement of perforations, as in the other case – Fig. 6b, were assessed. The simulation results concern the analysis of heat dissipation, the overall engine performance, and the efficiency of its cooling system.



a) rectangular 4×10 mm; b) circular D = 7.14 mm

Fig. 6. Modelling of rectangular and circular perforate shapes

Figures 7 and 8 show the simulation results of rectangular and circular perforation shapes of cylindrical fins with the same surface area and the same entire engine geometry. For example, the simulation was carried out for 12 fins and a spacing of 6 mm. Then, rectangular and circular perforations were made, and the simulation results are described in Table 4.

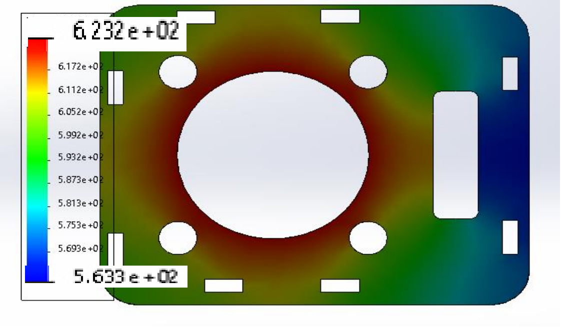


Fig. 7. Simulation result of rectangular perforate

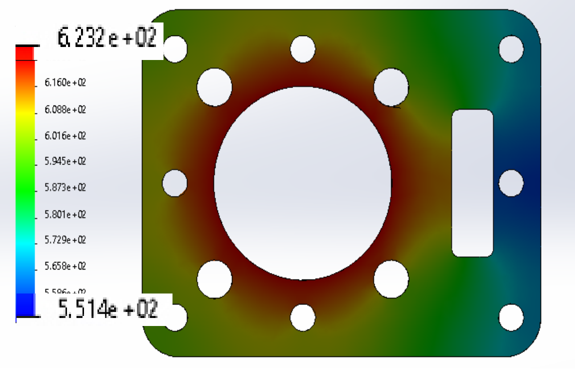


Fig. 8. Simulation result of circular perforate

Table 4. Compression result of circular and rectangular perforate on cylinder fin

s/n	Cylinder fins geometry	Temperature value, K			Cylinder mass, kg
		Max.	Min.	D/c	
1	12 fins with 6 mm spacing	623.2	554.2	69	0.960
2	If rectangular (10×4) mm perforate	623.2	563.3	59.9	0.940
3	If circular perforate (D = 7.14 mm)	623.2	551.4	71.8	0.926

The rectangular perforation reduces the engine cylinder weight from 0.960 to 0.940 kg and minimizes heat dissipation by more than 13% compared to the case without perforation, which is not beneficial. In the case of round perforated fins, the engine cylinder weight is further reduced from 0.960 to 0.926 kg, which is about 3.5% mass reduction, and in addition, the heat dissipation is greater by 4% than the case of the unperforated cylinder. This perforation arrangement is preferred for the engine operating at maximum temperature because the heat transfer rate is maximum. As the minimum temperature decreases, the temperature change increases by increasing the heat transfer rate.

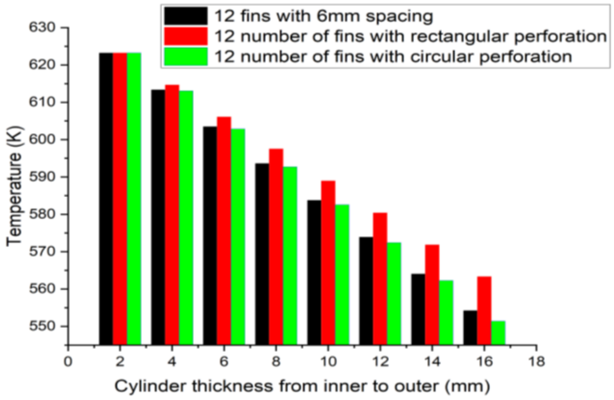


Fig. 9. Effect of perforation shapes

A perforated engine cylinder of different shapes can have different effects on the heat transfer rate of the engine cylinder. This is because removing some mass from the engine cylinder rib removes the cross-sectional area, which increases the heat transfer rate. In turn, removing mass along the length of the rib does not affect the heat transfer rate. Thus, in assessing the thermal characteristics of the engine, it is necessary to consider not only the perforation area but also the direction of the axis of the shape of the perforated system from the maximum temperature. In the case of rectangular perforation, only 4 mm length from centre to outer surface is perforated, whereas in case of perforation with circular geometry, 7 mm is perforated. Hence, as indicated in Fig. 9, circular perforation removes more material along the length, which lowers the temperatures to improve the heat transfer coefficient, while the area under both shapes is the same. So, circular perforation is preferable to increase the heat transfer coefficient for the same cross-sectional area as rectangular cylindrical perforated fins. This means that the area of a circular cross-section, which is the same as a rectangular cross-section, can dissipate the same heat but slightly resist the heat transfer flow.

The conclusions drawn from the previous considerations about the dominance of the circular perforation of the fins due to the high heat transfer rate and lower mass should be further analysed in terms of the geometry of this circular perforated element to see the effect of the circular fin diameter on the heat transfer rate. The simulation results are demonstrated in Fig. 10 and 11 and tabulated in Table 5.

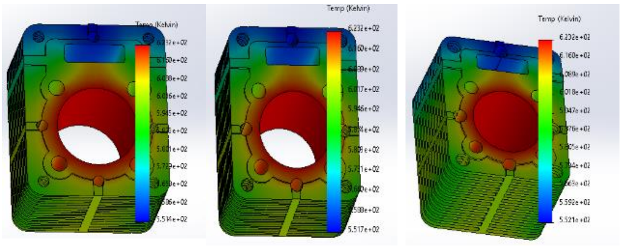


Fig. 10. Simulation result of different diameter of circular fins

Table 5. Effect of different diameter of circular perforate fins on heat transfer and overall mass of cylinder

s/n	Cylinder circular fins geometry	Temperature value, K			Cylinder mass, kg
		Max.	Min.	D/c	
1	7.14 mm	623.2	551.4	71.8	0.926
2	8.50 mm	623.2	551.7	71.5	0.910
3	10.00 mm	623.2	552.1	71.1	0.890

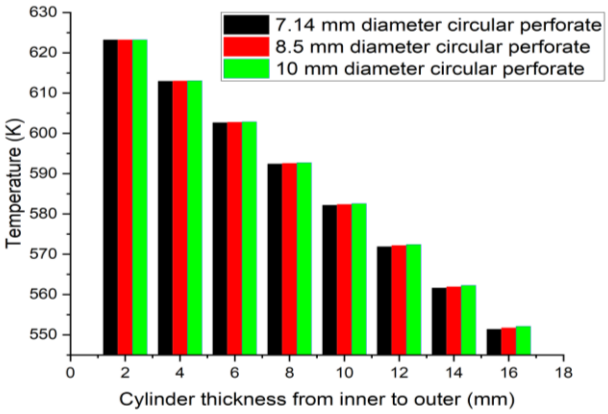


Fig. 11. Effect of perforation diameter

A large diameter perforation indicates the removal of a large mass from the cylinder fins, which leads to a minimization of the cylinder mass. At the same time, it is the removal of a large cross-section. Since the surface area is directly proportional to the heat transfer rate, the removal of a large cross-section reduces the heat transfer rate since the temperature difference between the maximum and minimum temperatures is reduced.

Thus, comparing the results obtained with the 8.5 mm and 10 mm circular perforations with those for the 7.14 mm diameter fins, the 8.5 mm circular perforation shows a lower heat transfer coefficient efficiency than the 7.14 mm diameter fins by 0.05% while achieving a better weight reduction of 1.65%. The 10 mm circular perforation shows a lower heat transfer coefficient efficiency than the 7.14 mm diameter fins by 0.17% while achieving a better weight reduction of 3.85%.

Conclusions

The article is part of the discussion on the thermal characteristics of an air-cooled engine when the cooling system design is changed. The paper describes the research on the effect of different numbers of fins and their geometrically varied perforations in a single-cylinder four-stroke engine. The following conclusions were obtained:

- With the increase in the number of fins, the temperature change increases because adding fins increases the heat dissipation area on the fins.
- 12 fins with a 6 mm spacing between them improves heat dissipation by over 8.3%, while the cylinder mass increases by about 7.8% compared to 9 fins and an 8 mm spacing, which constituted the base engine.
- The amount of heat dissipated by circular perforation is about 4% greater than in the case of non-perforated fins.
- Circular perforation of fins for the same cross-sectional area is more efficient in heat exchange than rectangular perforation.
- A fin with a high heat exchange rate is suitable for an engine operating at maximum temperature.
- A 7.14 mm diameter circular hole improves the heat transfer coefficient by almost 0.2% while adding 3.9% mass to the engine cylinder compared to 10 mm diameter circular perforated fins.

The work contributes scientific elements to the development of the discipline of mechanical engineering and thermodynamics and may have its application significance.

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Nomenclature

CFD	computational fluid dynamics
IC	internal combustion engine
PFHS	perforated-finned heat sink
SI	spark ignition

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