Thermal Analysis of Thermal Barrier Coatings in IC Engines

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Abstract— In the internal combustion engine, most of the heat generated during combustion process is absorbed by the piston by the direct heat loss. The application of thermal barrier coatings helps to reduce these thermal losses. This research investigates the effect of thermal barrier coating on heat transfer characteristics of IC engine. Four different materials are used as coating material and analysed using Finite Element Analysis under transient thermal conditions. Comparative studies are made on the parameters of heat flux, temperature vs time plot.

Keywords: Engine Combustion, Efficiency, Thermal Barrier Coating

I. INTRODUCTION

The Cylinder is the one of the major components in Engine, which is subjected to high temperature variations and thermal stresses. To cool the cylinder, fins are provided on the surface of the cylinder to increase the rate of heat transfer rate. Fins are Basically Mechanical structures which are used to cool various structures via the process of convection and conduction. Extended fins are well known for enhancing the heat transfer in IC engines. The construction of air-cooling system is very simpler. Therefore, it is important for an air-cooled engine to utilize the fins effectively to obtain uniform temperature in the Engine cylinder.

II. LITERATURE REVIEW

The overall efficiency of the internal combustion engine is only about 40% - 42%. This efficiency has to be improved to save fuel energy and oils. In recent days, there is a maximum demand for fuels and oils leads to higher cost and non-availability. This demand can be reduced by improving the efficiency of the internal combustion engine which is challenge for the engineers [1-2]. The heat energy generated in the internal combustion engine can be increased by reducing the direct heat dissipation to surroundings by coating the combustion chamber with low heat dissipating ceramic materials. The ceramic materials are having less thermal conductivity, low coefficient of thermal expansion and good wear resistance. Few ceramic materials can be used as thermal barrier coating materials to increase the temperature in the combustion chamber. This high temperature will helps in burning the un-burnt gases, minimizes the pollutants and reduces the utilization of fuels [3]. Many researchers were studiedthe influence of thermal barrier coating materials in improving the thermal efficiency of the internal combustion engines with declined pollutants and some of the literatures were reviewed.

G Sivakumar et al., [4] have reviewed many papers relating to the coating materials used in internal combustion engine to improve the thermal efficiency.

J.Rajasekaran et al., [5] were studied the influence of thermal barrier coating in the SI engine. The result shows that the break power increases in coated engine as compared to the un-coated engine. The thermal efficiency of the SI engine enhances as compared to uncoated SI engine reported by many researchers.

III. OBJECTIVE

The objective of the research is to investigate the effects of thermal barrier coating on heat transfer characteristics of IC engine cylinder using different types of coatings using Finite Element Analysis software.

IV. RESEARCH METHODOLOGY

The CAD model is developed using Creo 2.0 software which is sketch based, feature based parametric 3D modelling software developed by PTC. The software exhibits bi-directional associativity and parent child relationship.

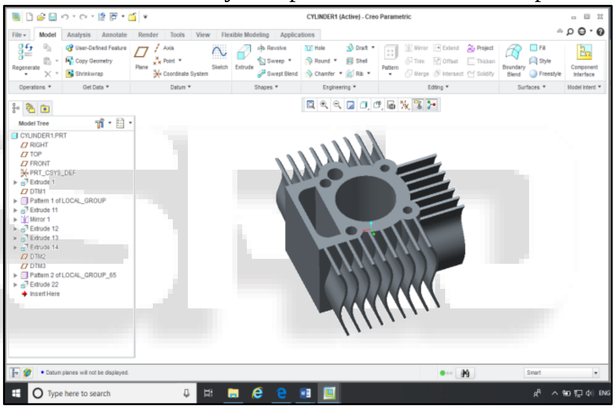

Fig. 1: CAD model of IC engine

The CAD model of IC engine is developed using extrude, sketch and pattern tool. Datum features like planes are also required. The CAD model developed in Creo 2.0 is converted into. iges format which is imported in ANSYS design modeler. The CAD model imported is checked for hard edges and cleanup operation is performed before its sent for meshing.

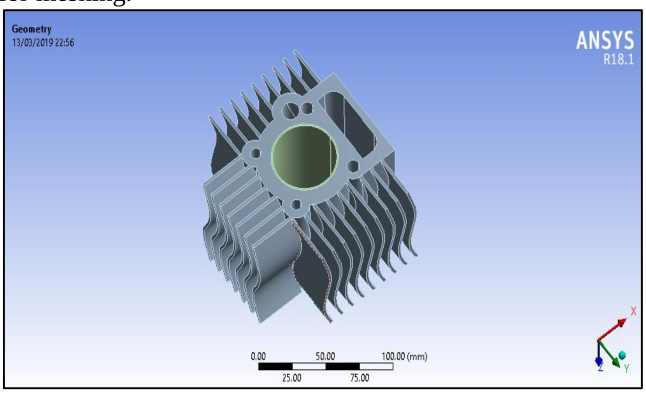

Fig. 2: Imported CAD model in ANSYS design modeler

The CAD model imported is meshed in ANSYS mesher using tetrahedral elements. The tetrahedral elements are selected due to complex geometry. The size function is set to fine and inflation normal.

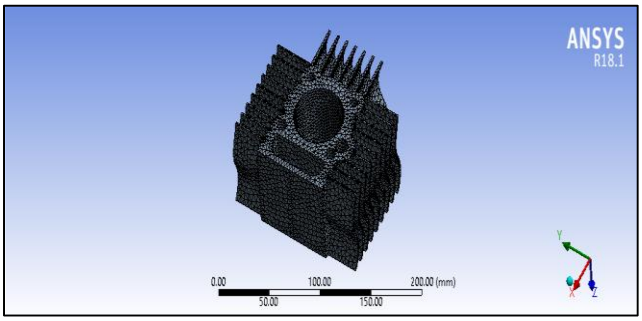

Fig. 3: Meshed CAD model in ANSYS

The number of modes generated is 115917 and number of elements generated is 64614.After meshing the model is applied with thermal loads. The inner cylinder surface is applied with temperature of 673K and remaining outer surfaces are applied with convection coefficient of 29.54 W/m^2 K. The remaining surfaces are kept insulated as shown in figure 4 below.

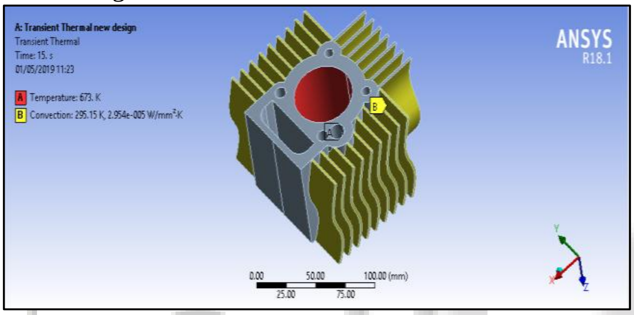

Fig. 4: Loads and Boundary Conditions

In this stage software carries out matrix formulations, matrix multiplications and inversions. The local stiffness matrix is formulated and added to form global stiffness matrix. The ansys solver report is shown in next section.

V. RESULTS AND DISCUSSION

The first analysis is conducted using Aluminium alloy material.The temperature plot, vector plot and heat flux plot are generated as discussed in next section.

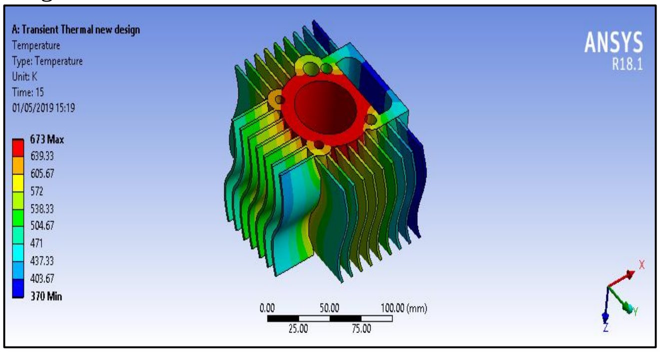

Fig. 5: Temperature plot using Aluminium Alloy

The temperature distribution plot of engine cylinder without coating material is shown in figure 5 above. The temperature is highest in engine cylinder portion and reduces as towards fin which dissipated heat generated. The transient analysis is conducted for 15 counter seconds.

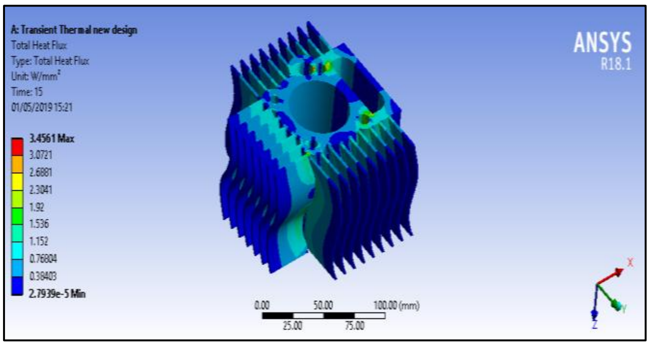

Fig. 6: Total heat flux using Aluminium Alloy

The heat flux plot of engine cylinder using aluminium alloy is shown in figure 6 above. The maximum magnitude of heat flux generated is 3.456 W/mm^2.

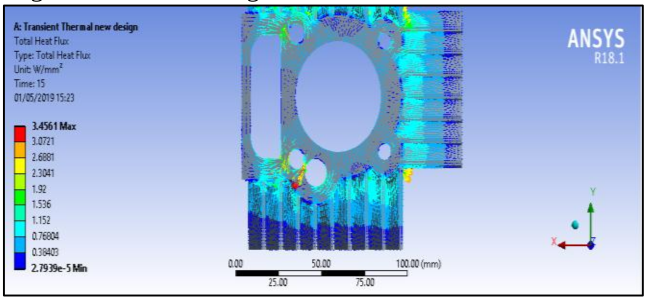

Fig. 7: Total heat flux using Aluminium Alloy

As heat flux is vector quantity it is represented using arrows. The vector plot shows direction of heat flow from within engine cylinder to outer surface and dissipating through fins as shown in figure 5.5 below. The temperature probe at a point is shown by figure 7below. The time of analysis ranges from 0 to 15 secs. The curve shows quadratic behavior with temperature rising from 433K to 639K in 15 secs.

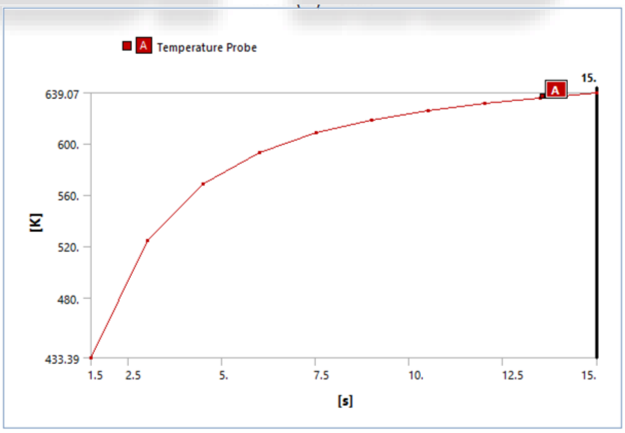

Fig. 8: Temperature vs time plot

The heat flux value initially higher with magnitude of 7.328 W/m^2 K gradually decreases with time due to decrease in thermal gradient as can be seen from figure 9 below.

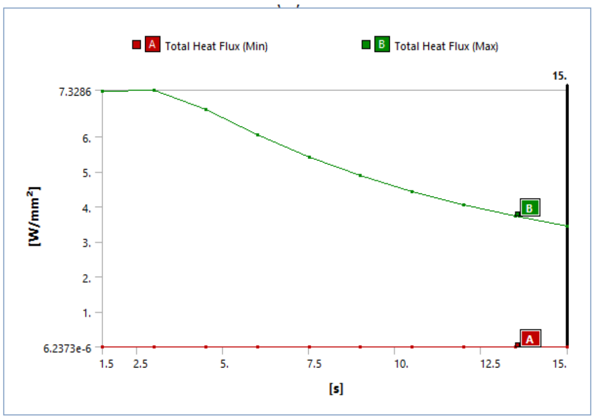

Fig. 9: Total heat flux vs time plot

The further analysis is conducted to analyse the affect of coating on inner wall of engine cylinder as shown in figure 10 below.

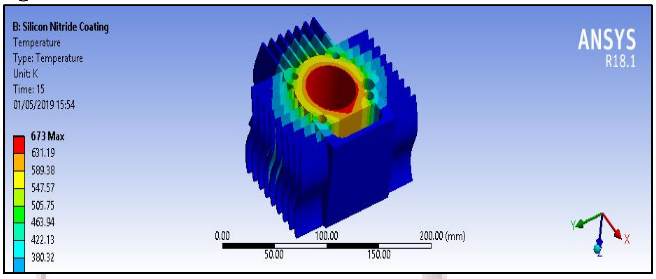

Fig. 10: Temperature plot using silicon nitride coating on inner wall

The temperature distribution plot of engine cylinder with silicon nitride coating material is shown in figure 10 above. The temperature is highest in engine cylinder portion and reduces as towards fin which dissipated heat generated. The transient analysis is conducted for 15 counter seconds

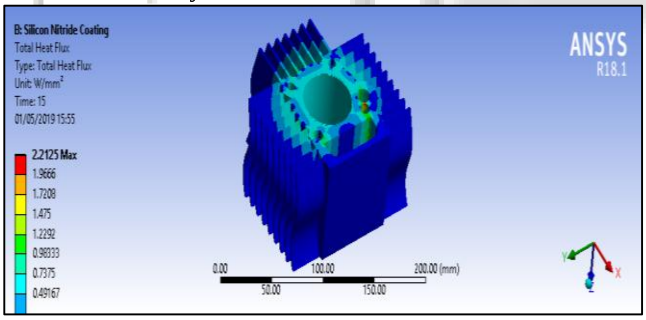

Fig. 11: Thermal flux plot using silicon nitride coating on inner wall

The heat flux plot of engine cylinder using aluminium alloy is shown in figure 11 above. The maximum magnitude of heat flux generated is 2.212 W/mm^2.

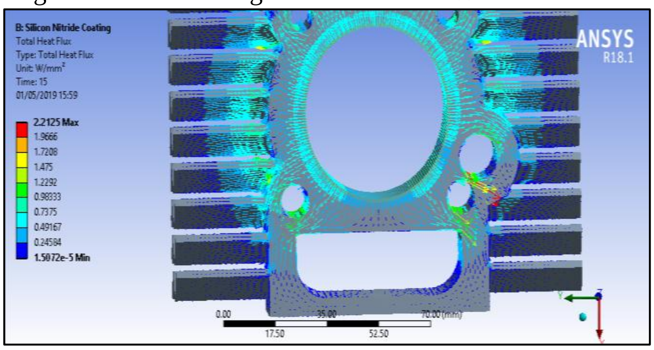

Fig. 12: Vector plot of heat flux using silicon nitride coating

As heat flux is vector quantity it is represented using arrows. The vector plot shows direction of heat flow from within engine cylinder to outer surface and dissipating through fins as shown in figure 5.10 above. The temperature probe at a point is shown by figure 13 below. The time of analysis ranges from 0 to 15 secs. The curve shows quadratic behaviour with temperature rising from 321.2K to 520.57K in 15 secs.

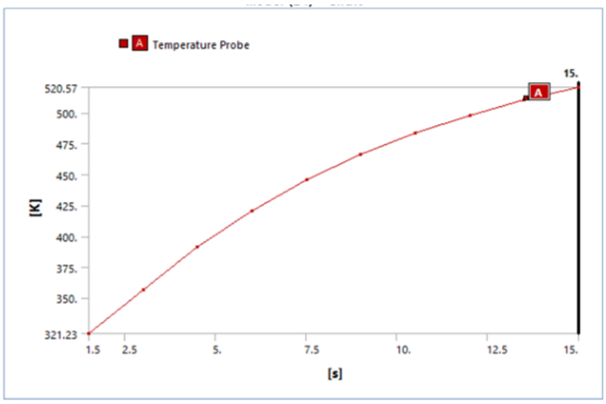

Fig. 13: Temperature probe using silicon nitride coating

The heat flux value initially higher with magnitude of 2.69 W/m^{2}K gradually decreases with time due to decrease in thermal gradient as can be seen from figure 14 below.

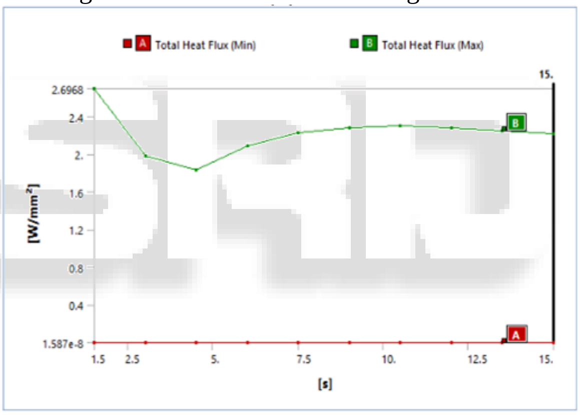

Fig. 14: Total heat flux using silicon nitride coating

The further analysis is conducted to analyse the effect of coating on inner wall of engine cylinder using Aluminium Nitride coating material. The coating material is to act as thermal barrier to achieve better efficiency and heat retention.

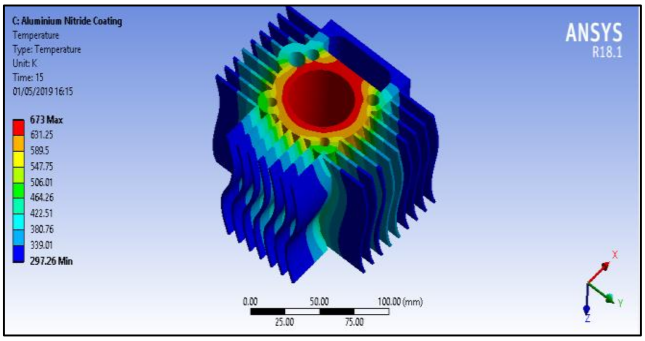

Fig. 15: Temperature plot using silicon nitride coating on inner wall

The temperature distribution plot of engine cylinder with aluminium nitride coating material is shown in figure 15 above. The temperature is highest in engine cylinder portion and reduces as towards fin which dissipated heat generated. The transient analysis is conducted for 15 counter seconds

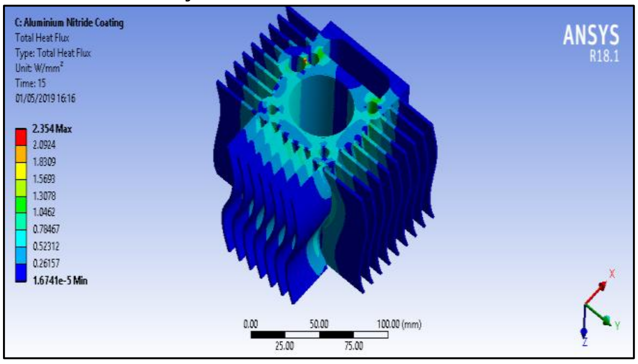

Fig. 16: Thermal flux plot using silicon nitride coating on inner wall

The heat flux plot of engine cylinder using aluminium nitride coating is shown in figure 16 above. The maximum magnitude of heat flux generated is 2.35 W/mm^2.

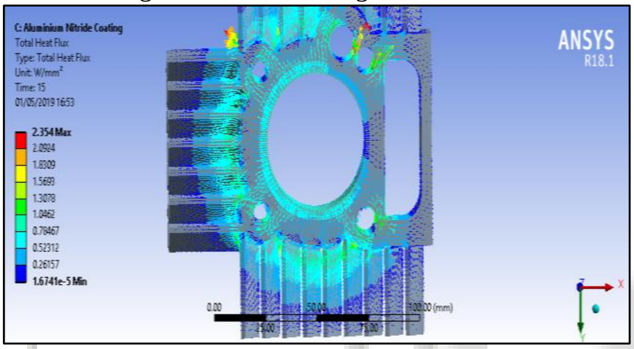

Fig. 17: Thermal flux plot using silicon nitride coating on inner wall

As heat flux is vector quantity it is represented using arrows. The vector plot shows direction of heat flow from within engine cylinder to outer surface and dissipating through fins as shown in figure 17above. The temperature probe at a point is shown by figure 18 below. The time of analysis ranges from 0 to 15 secs. The curve shows quadratic behaviour with temperature rising from 339.23K to 564.09 K in 15 secs.

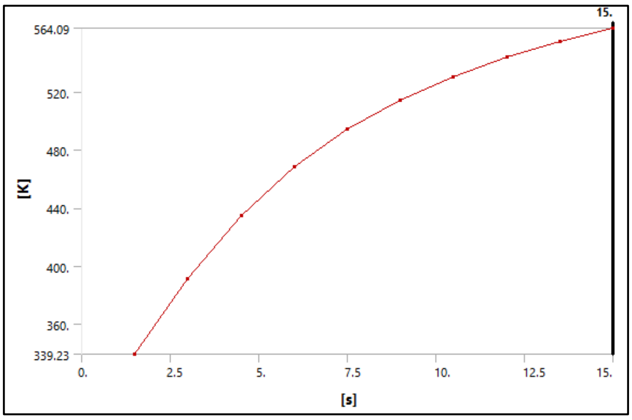

Fig. 18: Temperature probe using aluminium nitride coating

The heat flux value initially higher with magnitude of 2.35 W/m^2 K gradually decreases with time due to decrease in thermal gradient as can be seen from figure 19 below.

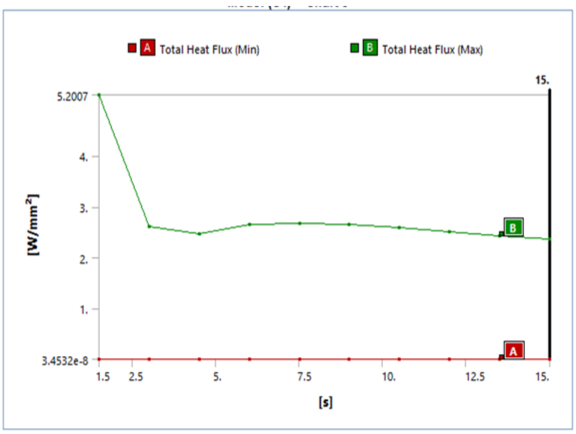

Fig. 19: Total heat flux using aluminium nitride coating

The further analysis is conducted to analyse the effect of coating on inner wall of engine cylinder using ceramic 8D coating material. The coating material is to act as thermal barrier to achieve better efficiency and heat retention.

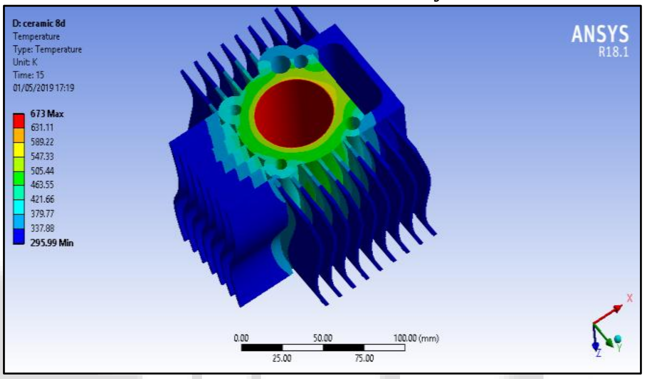

Fig. 20: Temperature plot using ceramic 8D coating on inner wall

The temperature distribution plot of engine cylinder with silicon nitride coating material is shown in figure 20 above. The temperature is highest in engine cylinder portion and reduces as towards fin which dissipated heat generated. The transient analysis is conducted for 15 counter seconds

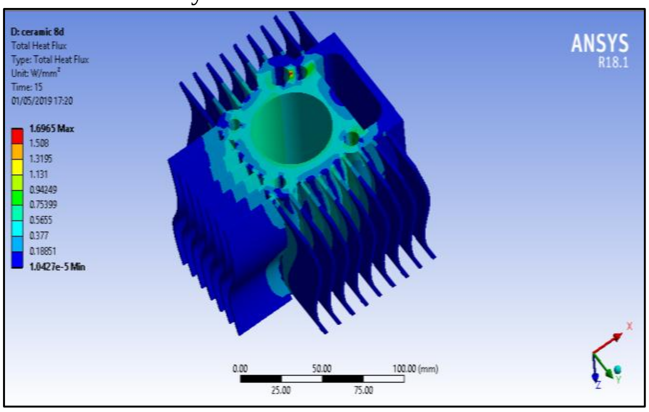

Fig. 21: Thermal flux plot using ceramic 8D coating on inner wall

The heat flux plot of engine cylinder using aluminium alloy is shown in figure 21 above. The maximum magnitude of heat flux generated is 1.69 W/mm^2.

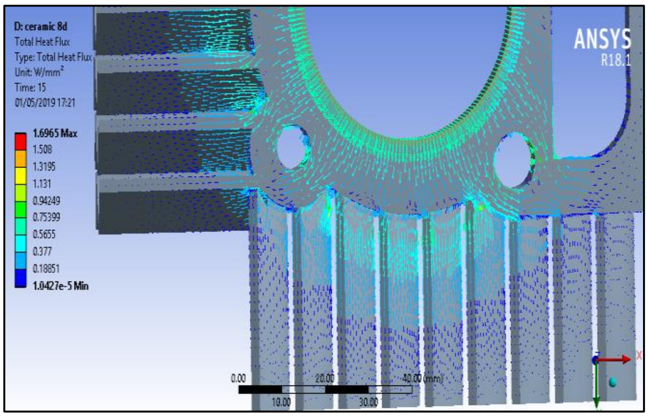

Fig. 22: Thermal flux plot using ceramic 8D coating on inner wall

As heat flux is vector quantity it is represented using arrows. The vector plot shows direction of heat flow from within engine cylinder to outer surface and dissipating through fins as shown in figure 22 above. The temperature probe at a point is shown by figure 23 below. The time of analysis ranges from 0 to 15 secs. The curve shows quadratic behaviour with temperature rising from 306.18K to 444.71 K in 15 secs.

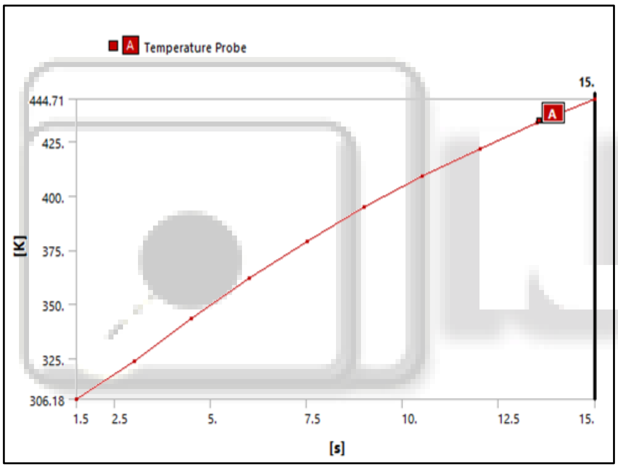

Fig. 23: Temperature vs time plot using ceramic 8D coating on inner wall

The heat flux value initially higher with magnitude of 1.69 W/mm^2 K gradually decreases with time due to decrease in thermal gradient as can be seen from figure 24 below.

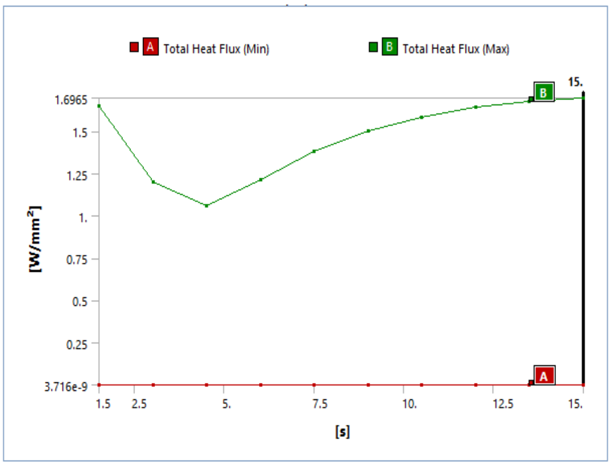

Fig. 24: Thermal Flux plot

Material	Total Heat Flux (W/mm^2)
Aluminium Alloy	7.32
Silicon Nitride Coating	2.69
Aluminium Nitride Coating	2.35
Ceramic 8D	1.69

Table 1: Total Heat Flux using different materials

The heat flux comparison shows that engine cylinder without coating material loses its heat in maximum magnitude with heat flux of 7.32 W/mm^2. The use of coating material reduces heat loss and act as thermal barrier. The heat flux using ceramic 8D material is lowest and hence is best coating material to act as thermal barrier.

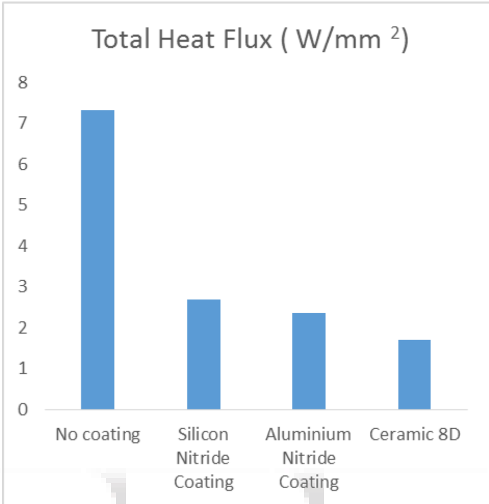

Fig. 25: Thermal Flux comparison using different materials

The thermal flux is maximum in engine without coating thereby heat loss is maximum with magnitude of 7.32 W/mm^2. Application of silicon nitride coating has reduced thermal flux to 2.69 W/mm^2 and with aluminium nitride is 2.35 W/mm^2. The minimum heat loss is with ceramic 8D material with magnitude of 1.69 W/mm^2.

Material	Maximum Temperature(K)
No coating	639.07
Silicon Nitride Coating	520.5
Aluminium Nitride Coating	564.09
Ceramic 8D	444.7

Table 2: Maximum temperature attained

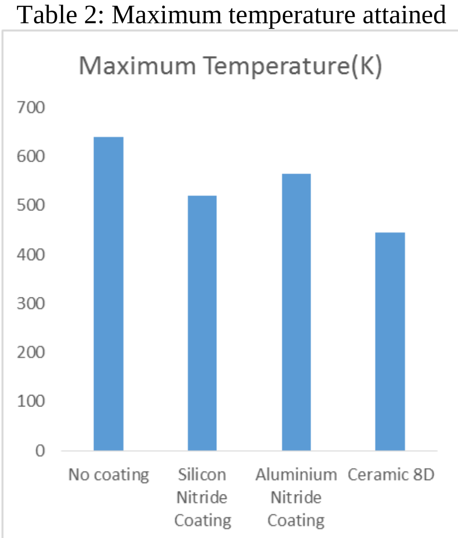

Fig. 26: Maximum temperature comparison using different materials

Applying probe at outer point of engine cylinder for temperature determination, the maximum temperature is attained when coating material is not used with magnitude of 639.07K. Application of coating material has provided thermal barrier and reduced maximum temperature attained outside engine cylinder. The lowest temperature is attained using ceramic 8D material with magnitude of 444.7K.

VI. CONCLUSION

Thermal analysis of IC engine cylinder is conducted using ANSYS software to determine the effect of coating materials on improving thermal barrier properties which would improve efficiency of IC engine. The detailed conclusion are:

1) Application of coating materials have reduced heat loss to a considerable extent
2) Applying probe at outer point of engine cylinder for temperature determination, the maximum temperature is attained when coating material is not used with magnitude of 639.07K.
3) Application of coating material has provided thermal barrier and reduced maximum temperature attained outside engine cylinder. The lowest temperature is attained using ceramic 8D material with magnitude of 444.7K.
4) The thermal flux is maximum in engine without coating thereby heat loss is maximum with magnitude of 7.32 W/mm^2.
5) Application of silicon nitride coating has reduced thermal flux to 2.69 W/mm^2 and with aluminium nitride is 2.35 W/mm^2.
6) The minimum heat loss is with ceramic 8D material with magnitude of 1.69 W/mm^2.

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