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Thermal Analysis of Mullite Coated Diesel Engine Cylinder Head Using 3-D Finite Element Method

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Abstract*— In this study, thermal analysis is investigated on a conventional (uncoated) cylinder head of diesel engine, made of cast iron in previous stage. Then the thermal analysis is performed on cylinder head, coated with $3Al_2O_3.2SiO_2$ (mullite) (Al_2O_3= 60%, SiO_2= 40%) material by means of using a commercial code, namely ANSYS. Finally, the temperature distributions are compared with each other. Heat transfer models have been developed for cylinder head with and without thermal insulation coating, which is incorporated in the simulated program. Gas wall heat transfer calculations are based on Annand's heat transfer model for IC engines. The effect of coating on the thermal behavior of the cylinder head is investigated using finite element analysis. It has been shown that the maximum surface temperature of the coated cylinder head with low thermal conductivity mullite material is improved approximately by 22-38%.

Index Terms—**Mullite; Low heat rejection; Annand's model**

I. INTRODUCTION

Ceramics have a higher thermal durability than metals; therefore it is usually not necessary to cool them as fast as metals. Low thermal conductivity ceramics can be used to control temperature distribution and heat flow in a structure [1-2]. Thermal barrier coatings (TBC) provide the potential for higher thermal efficiencies of the engine, improved combustion and reduced emissions. In addition, ceramics show better wear characteristics than conventional materials. Lower heat rejection from combustion chamber through thermally insulated components causes an increase in available energy that would increase the in-cylinder work and the amount of energy carried by the exhaust gases, which could be also utilized [3-4]. A major breakthrough in diesel engine technology has been achieved by the pioneering work done by Kamo and Bryzik [5-6]. Kamo and Bryzik used thermally insulating materials such as silicon nitride for insulting different surfaces of combustion chamber. An improvement of 7% in the performance was observed [7]. Sekar and Kemo [8] developed an adiabatic engine for passenger cars and reported an improvement in performance to the maximum extent of 12%. The experimental results of Morel et al. [9] indicate that the higher temperatures of the insulated engine cause reduction in the in-cylinder heat rejection, which is in accordance with the conventional knowledge of convective heat transfer. Woschni et al. [10] state that 5% of the input fuel energy cannot be accounted for which is of the order of the expected improvements. Havstad et al. [11] developed a semi-adiabatic diesel engine and reported an improvement ranging from 5 to 9% in ISFC, about 30% reduction in the in-cylinder heat rejection. Prasad et al. [12] used thermally insulating material, namely partially stabilized zirconia (PSZ), on the piston crown face and reported a 19% reduction in heat loss through the piston. Among possible alternative materials, one of the most promising is mullite. Mullite is an important ceramic material because of its low density, high thermal stability, stability in severe chemical environments, low thermal conductivity and favorable strength and creep behavior. It is a compound of SiO_2 and Al_2O_3 with composition $3Al_2O_3.2SiO_2$. Compared with YSZ, mullite has a much lower thermal expansion coefficient and higher thermal conductivity, and is much more oxygen-resistant than YSZ. For the applications such as diesel engines where the surface temperatures are lower than those encountered in gas turbines and where the temperature variations across the coating are large, mullite is an excellent alternative to zirconia as a TBC material. Engine tests performed with both materials show that the life of the mullite coating in the engine is significantly longer than that of zirconia.[13] Above 1273 K, the thermal cycling life of mullite coating is much shorter than that of YSZ.[14] Mullite coating crystallizes at 1023–1273 K, accompanied by a volume contraction, causing cracking and de-bonding. Mullite has excellent thermo-mechanical behavior; however its low thermal expansion coefficient creates a large mismatch with the substrate. To overcome this problem, a 150 µm thickness of NiCrAlY bond coat was used.

Table 1: Material properties of Cylinder head, Mullite and Bond coat

Material	Thermal Conductivity [W/m^{0}c]	Thermal expansion 10-6[1/^{0}c]	Density [Kg/m^3]
Cast iron	55	10	7920
Mullite	3.3	5.3	2800
NiCrAlY	16.1	12	7870

Material	Specific Heat [J/Kg^{0}c]	Poisson's ratio	Young's modulus [GPa]
Cast iron	456	0.3	110-140
Mullite	1260	0.25	21
NiCrAlY	764	0.27	90

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This paper investigates the temperature distribution using 3-D Finite Element Modeling of cylinder head of diesel engine with and without mullite coating.

II. THERMAL ANALYSIS USING FINITE ELEMENT METHOD

For thermal analysis the thermal circuit resistance model for heat transfer is prepared for cylinder head with and without ceramic coating.

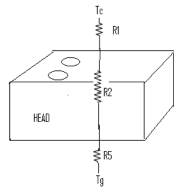

Fig 1

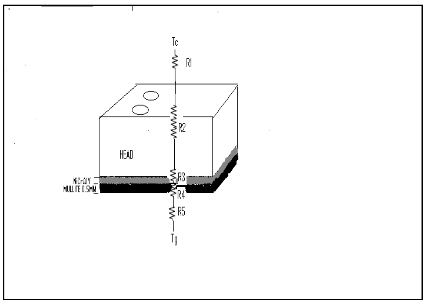

Fig 2

Figure 1 and 2 shows the thermal circuit resistance model for heat transfer from cylinder head (R1: water-jacket resistance, R2: block resistance, R3: bond coat resistance, R4: ceramic coating resistance, R5: cylinder hot gases resistance) The CAD modeling of cylinder head have been done with Pro/Engineer software and the finite element thermal analysis has been done using ANSYS thermal simulation software. Figure 3 and 4 shows 3D CAD model of conventional cylinder head and mullite coated cylinder head.

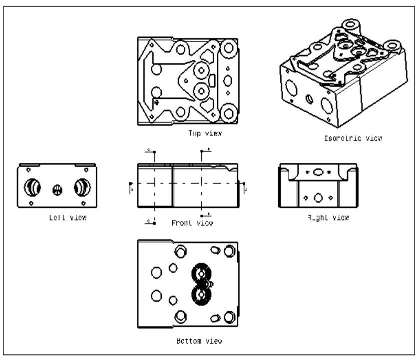

Fig 3 Drafting of Engine Head

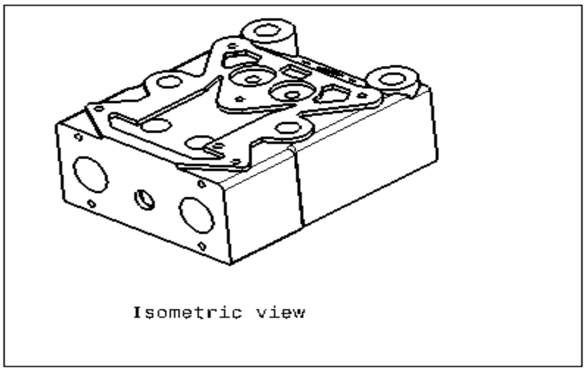

Fig. 4 Isometric View of Engine Head

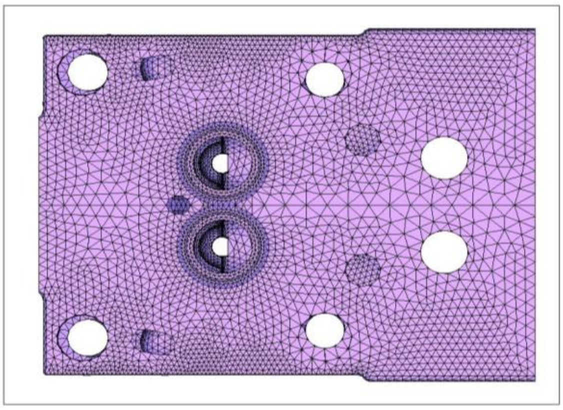

Fig. 5 Meshed model of engine cylinder Head

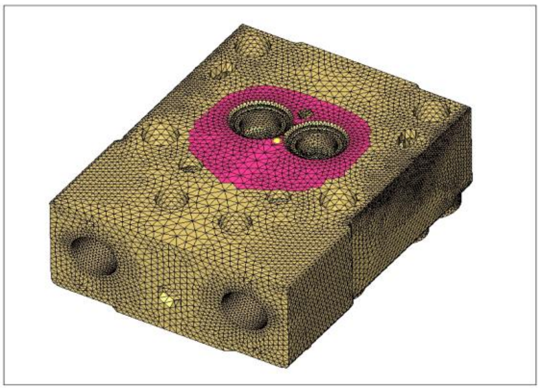

Fig.6 Meshed model of mullite coated engine Cylinder head

ANSYS simulation software has been used for analysis of the parts. By using this advanced module of ANSYS, engineers can easily evaluate product performance by simulating the behaviors of parts and assembly product in thermal loading condition. ANSYS simulation module can perform steady state and transient analysis of a thermal problem. The steady state thermal analysis is used to calculate thermal response to heat loads subject to prescribed temperatures and/or convection conditions. Steady thermal analyses assume a steady state for all thermal loads and boundary conditions. This Characteristic is used to test the temperature distribution on cylinder head surface. Transient thermal analysis is used to calculate thermal

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responses over the period of time and therefore it is used to estimate the cooling time. In this investigation, the thermal analysis for both conventional cylinder head and coated cylinder head were carried out. In the analysis, required parameters are peak temperature of cylinder hot gases which was 1630 K for conventional cylinder head and 1710 K for ceramic coated cylinder head; type of element (linear tetrahedrons, automatic mesh generation) and the number of node were 48349, 80140 and 43215, 71772 for conventional and coated cylinder head respectively as shown in Fig. 5 and 6. For boundary condition, the convective heat transfer coefficient of cylinder gases, which is a function of temperature, is calculated by Annand's heat transfer model. The convective heat transfer coefficient of cylinder gases at peak temperature is calculated as 2430 W/m^2K and 2800 W/m^2K respectively for convectional diesel engine and mullite coated diesel engine has been applied in the surface cylinder head. The heat flux due to coolant is taken into consideration. The wall coolant heat transfer coefficient is 5700 W/m^2K.

III. RESULTS AND DISCUSSIONS

The table 2 gives the values of heat at the maximum temperature node over the cylinder head assembly on conventional and mullite-coated cylinder head.

Table 2 Temperature of Combustion Chamber Vs maximum heat on Cylinder head

Temp of the Combustion Chamber(K)	Max heat on conventional cylinder head (W)	Max heat on the cylinder head with mullite coating (W)
980	8310	12326
1080	12550	15363
1180	12736	18672
1280	13778	20990

The table 2 shows that with increasing temperature in the combustion chamber, the maximum heat on the cylinder head is also increasing. It is seen that for a mullite-coated engine, the maximum heat at the cylinder head assembly node is around 25%-40% higher than the conventional engine. This is due to the maximum amount of heat-released causes the increase in temperature due to very hot operating condition of mullite-coated engine. Further, the maximum temperature value is determined as 978°C at the tip of conventional cylinder head. The maximum temperature value of mullite coated cylinder head is determined as 1064°C at the top verge of the cylinder head. This is due to effect of mullite coating; heat free flow path is restricted, which leads to increase in cylinder head temperature of mullite-coated engine. Fig.7 shows the comparison of simulation result of cylinder gas temperature as a function of crank angle for conventional and mullite coated engines with 0.5 mm mullite coating on combustion chamber. The predicted value peak cylinder gas temperature in the case of mullite coated engine is higher by about 13%, than conventional engine. It is evident from figure that, the gas temperature is much higher during the later part of the expansion stroke in case of mullite coated engine. The maximum amount of heat is released during this stroke, which causes to increase temperature due to very hot operating condition of mullite coated engine. Further, it is due to effect of insulation coating, heat free flow path is restricted, which leads to increase in gas temperature of mullite coated engine.

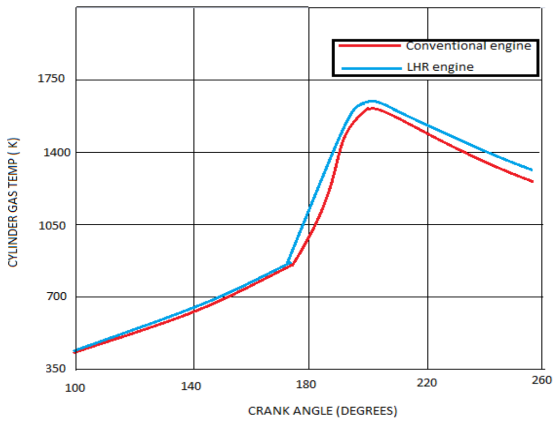

Fig 7: Crank Angle Vs Cylinder Gas Temperature

IV. CONCLUSION

The maximum surface temperature of the coated cylinder head with mullite material, which has low thermal conductivity, is improved approximately 22-38%. This result shows the reduction in the cooling load of system. According to the software simulations conducted in this project, it has been concluded that by using mullite coating for cast iron cylinder head increases the temperature of the combustion chamber of the engine and the thermal strength of the base metal. Finally the combustion chamber temperature also increases the thermal efficiency of the engine.

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