HEAT TRANSFER ANALYSIS IN A LOW HEAT REJECTION DI DIESEL ENGINE

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Abstract

Compression Ignition engines are nowadays becoming essential because of their fuel economy and efficiency. In the recent trends, ceramic coating over the cylinder head, valves and the piston top surfaces are provided for thermal insulation. These thermal barrier coatings reduce the heat transfer from the combustion chamber to the cooling jackets and to the surroundings. This paper investigates the the temperature distribution over the cylinder head, valves and the piston resulting from coating those using Partially Stabilized Zirconia (PSZ) as a thermal barrier coatings. This analysis is based on the fact that coating thickness affects the heat transfer and temperature distribution in the cylinder head and piston. A 3-D Finite Element Analysis (FEA) using ANSYS is performed to evaluate the temperature distributions over the cylinder head, inlet valve, exhaust valve and the piston. Based on the analysis, it can be concluded that a coating of PSZ over the combustion chamber increases the temperature over the combustion chamber and reduces the heat rejection to the surrounding.

Keywords: Thermal barrier coatings, PSZ, Temperature distribution.

I. INTRODUCTION

The diesel engine with its combustion chamber walls insulated by ceramics is referred to as Low Heat-Rejection (LHR) engine. The LHR engine has been conceived basically to improve fuel economy by eliminating the conventional cooling system and converting part of the increased exhaust energy into shaft work using the turbocharged system. In LHR engine the combustion chamber is insulated with high temperature materials which makes the engine operate at hotter environment with less heat transfer. The components that are normally insulated include piston, cylinder head, valves, cylinder liner and exhaust ports. This has two important purposes—to reduce the size of coolant system & to increase the exhaust energy available for turbo charging and thereby increasing power and efficiency. It is expected that additional power and improved efficiency is possible with engine insulated because thermal energy that is normally lost to the cooling water and exhaust gas is converted to useful power through the use of turbo machinery and high temperature materials. Thermal barrier insulation of the combustion chamber is done by coating it with ceramics. Partially stabilized zirconia and aluminium titanate are used for coating. The coating is mainly done by plasma spraying. The changes in the combustion process due to insulation also affect exhaust emissions. Higher gas temperatures are supposed to reduce the concentration of incomplete combustion at the expense of increase in oxides of nitrogen.

II. BOUNDARY CONDITIONS

For the analysis; a single cylinder, water cooled, constant speed DI diesel engine is considered. The cylinder head is made out of cast-iron, valves are made out of hardened steel and the piston is made out of aluminium-silicon alloy. A coating of PSZ is applied over them to study the heat transfer and the temperature distribution. Over the surface of the combustion chamber, the heat transfer is found out using Annand's equation.

$$h_{\text{inner}} = a \times (k/B) \times \text{Re}^{0.7} + C/(T_g - T_w) \times ((0.01 \times T_g)^4 - (0.01 \times T_w)^4)$$

kcal/hr m^2 K Where, $a = 0.35$ to 0.8 increasing with increased engine speeds

$B =$ bore of the cylinder (m)

$C =$ 2.81 for CI engines

$k =$ thermal conductivity of the gas in kcal/hr m^2 K

$Re = B \times C_m/v$, where, $Cm =$ mean piston speed (m/sec) and $v =$ dynamic viscosity of the gas (m^2/s)

$T_g =$ working fluid temperature (K)

$T_w =$ maximum wall temperature (K)

Over the outside surface of the cylinder head, assuming air flows at the sides, the heat transfer is found out using the condition of free convection.

Assuming turbulent flow,

$10^{-4} < Gr\ X\ Pr < 10^{-9}$, the Nusselt number is given by,

$$Nu = 0.59 \times (Gr\ X\ Pr)^{0.25}$$

Also, $Nu = h_{outer} \times l/k$. Using this, {$h_{outer}$ can be determined.

Where, $Gr =$ Grash of number $= g \times \beta \times \Delta T \times l^3\ v^2$

$Pr =$ Prandtl number $= \mu \times Cp/k$

$g =$ acceleration due to gravity (m^2/sec)

$\beta =$ constant $= 1/T\ (K^{-1})$

$\Delta T =$ Bulk temperature inside combustion chamber-temperature of the air (K)

$l =$ length over which air passes over the combustion chamber (m)

$\mu =$ kinematic viscosity (N m/sec)

$Cp =$ specific heat of the gas (KJ/kg K)

$k =$ thermal conductivity of the gas (W/m K)

Over the surfaces of the valves, the heat transfer is found out using the condition of free convection by assuming constant wall temperature and flow over longitudinal cylinder body,

$$Nu = 0.48\ X\ (Gr\ X\ Pr)^{0.25} = h_{outer} \times l/k$$

The flow over the cooling jacket pipes is found out using the condition of forced convection as the water is supplied by means of an external source namely the pump.

$$Nu = 0.023\ X\ Re_B^{0.8}\ X\ Pr^{0.4} = h_{cooling} \times B/k_{water}$$

Where, $Re_B =$ Reynolds number which can be calculated by calculating the discharge.

It is to be noted that the fluid properties are to be evaluated at the bulk mean fluid temperature.

III. THERMAL ANALYSIS USING ANSYS

A **thermal analysis** calculates the temperature distribution and related thermal quantities in a system or component. A thermal analysis is performed using ANSYS to find out the temperature distribution around the cylinder head, inlet valve, exhaust valve and the piston as individual components. The element used is SOLID90 which is a 3-D eight node thermal element. The element has 20 nodes with a single degree of freedom, temperature, at each node. The 20-node elements have compatible temperature shapes and are well suited to model curved boundaries. Results indicated that the heat is more concentrated near the combustion chamber surfaces in a low heat rejection engine than in an ordinary engine and the temperature in the vicinity of the combustion chamber is more near the low thermal conductivity region i.e. the coated region. Also a thermal analysis is performed on the cylinder head assembly and the piston for a coated engine and an ordinary one over the combustion chamber temperature range of 973 K to 1273 K in increments of 100 K.

The Fig 1(a), Fig 1(b), Fig 2(a) and Fig 2(b) illustrate the temperature distribution over the cylinder head. As seen in the figures it can be concluded that the maximum temperature in a LHR engine (1104 K) is more than that of a conventional engine (1007 K). The region of maximum temperature (as shown by red) is more distributed near the exhaust valve region in a ordinary engine while in a LHR engine, the maximum temperature region is fully distributed throughout the coated region (around the bore). This indicates that the more heat is contained around the combustion chamber top surface in a LHR engine. It can also be seen that the temperature on the outer surface of the head is almost at atmospheric temperature in a LHR engine while the temperature on an ordinary engine is higher. It can be concluded that in a LHR engine, less amount of heat is rejected to the atmosphere because of the presence of a low thermal conductivity ceramic coating which almost reduces the heat loss to the atmosphere and to the cooling jackets.

The Fig 3(a) and Fig 3(b) depicts the temperature distribution around the ordinary inlet valve and a coated one. It can be seen that the temperature is more for a coated one (1032 K) than the ordinary valve (998 K) and is more densely concentrated over the entire valve face in a LHR engine. Fig 4(a) and Fig 4(b) illustrates the temperature distribution around the conventional piston and a coated one. As in the case of an ordinary piston (made of Aluminum has higher conductivity), the heat transfer rate is higher from the crown to the side wall, but gradually reduced in the skirt region due to the presence of rings. An analysis is done to compare the temperature distribution for four different combustion chamber temperatures over the piston assembly. In the case of LHR engine, it can be seen that heat is more concentrated near the crown and the bowl region and very little amount of heat is transferred to the side walls. Also an analysis is done to compare the temperature distribution for four different combustion chamber temperatures over the head assembly. It can be seen that with increasing temperature, in both the cases, the maximum temperature also increases and is higher for an LHR engine. Again, the outside temperature is almost same as that of the atmosphere in a LHR engine compared to an ordinary one where the surface temperature is still higher.

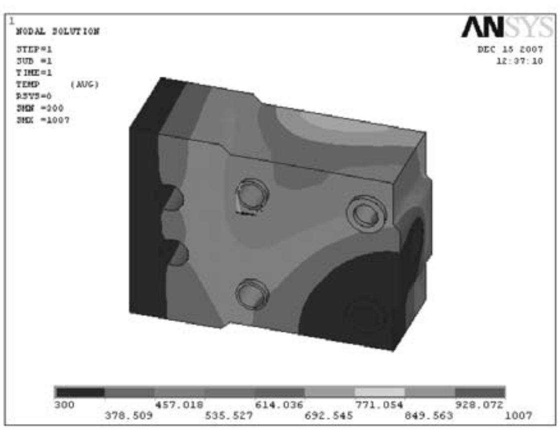

Fig 1 (a) Ordinary cylinder head

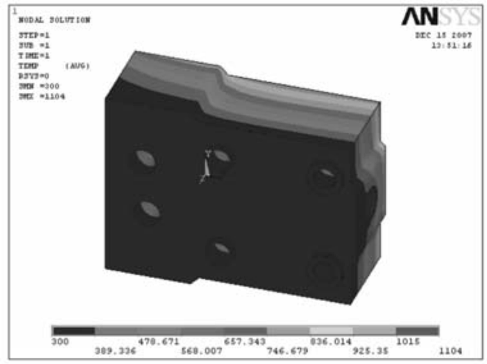

Fig 1 (b) Coated cylinder head

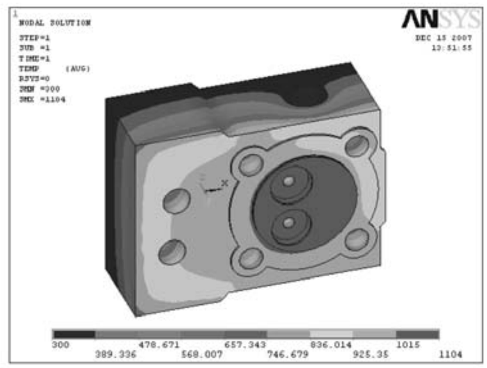

Fig 2 (a) Ordinary cylinder head

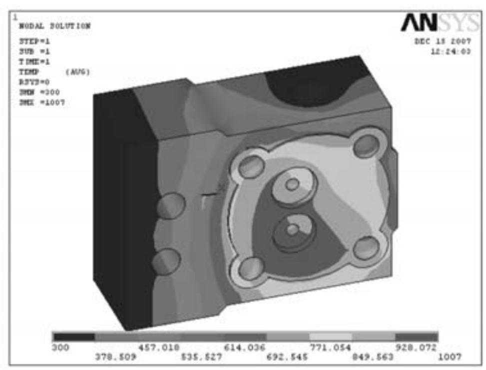

Fig 2 (b) Coated cylinder head

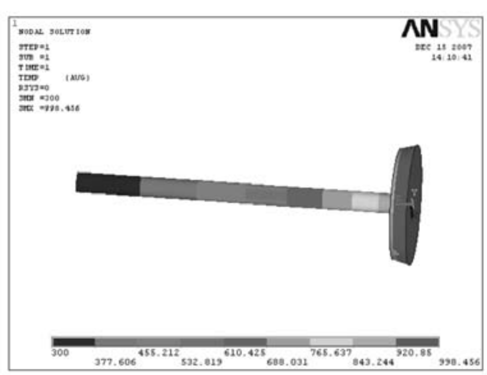

Fig 3 (a) ordinary inlet valve

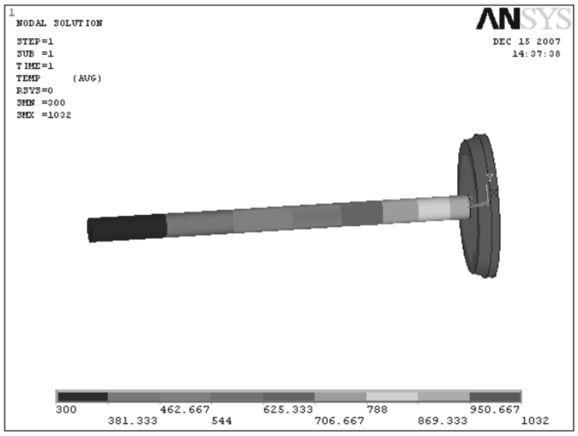

Fig 3 (b) coated inlet valve

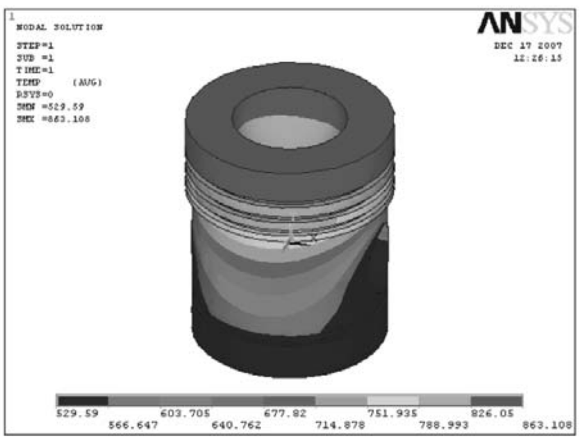

Fig 4 (a) Ordinary piston

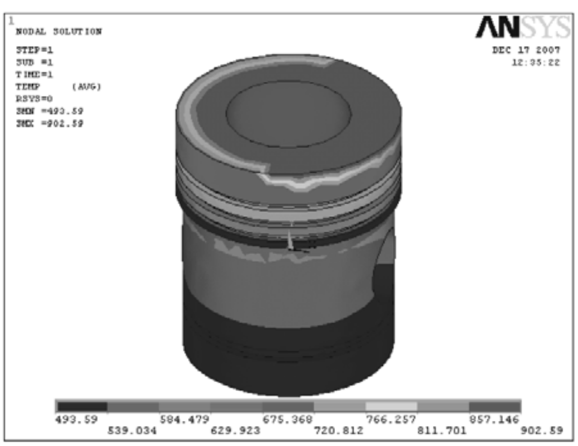

Fig 4 (b) Coated piston

IV. DISCUSSIONS

Table 1 Maximum Heat at the nodes for the cylinder head.

Temp of the combustion chamber (*K*)	Max heat on the cylinder head without coating (*W*)	Max heat on the cylinder head with coating (*W*)
973	8283	12456
1073	12606	15463
1173	12836	18752
1273	13679	20898

The table 1 gives the values of heat at the maximum temperature node over the cylinder head assembly and the Fig 6.34 below 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 coated engine, the maximum heat at the cylinder head assembly node is around 25%-40% higher than the ordinary engine.

Table 2 Maximum Temperature in the Piston

Temp of the combustion chamber (*K*)	Max temp of the piston without coating (*K*)	Max temp of the piston with coating (*K*)
973	778.178	876.337
1073	863.108	902.59
1173	956.089	1023
1273	1043	1084

The table 2 gives the values of maximum temperature over the piston shows that with increasing temperature in the combustion chamber, the maximum crown temperature on the piston is also increasing and so does the heat transfer to the side walls; but due to the presence of rings over the piston groove, the heat transfer drops below the skirt region. It is seen that for a coated engine, very less heat is transferred below the crown due to the ceramic barrier, which indicates more heat is retained over the crown and the bowl and hence very less heat is transferred below the grooves (skirt region).

V. CONCLUSIONS

Based on the results of the thermal analysis carried out in ANSYS, the following conclusions are drawn.

1. The temperature distribution in the cylinder head is higher in a low heat rejection engine than the conventional one and the zone of maximum temperature is more widely spread around the bore as compared to that of a conventional one, where it is more distributed near the exhaust valve. The heat rejection to the atmosphere is reduced in a LHR engine. The temperature distribution over the inlet and the exhaust valves indicates that the valve face heats up more in a LHR engine than the conventional engine. This indicates that the heat carried away the exhaust gases are retained by the coating in the combustion chamber.
2. The results indicate that with increase in combustion wall temperature, the maximum temperature over the head assembly and the maximum heat at the nodal point also increase for a LHR engine and is higher than that of the conventional diesel engine.
3. The analysis results on the conventional piston indicate that the maximum temperature occurs over the crown and spreads up to the ring belt whereas for the coated piston, the maximum temperature occurs over the crown and the bowl region and very less heat is transferred to the side walls up to the crown. In this case also, with increase in combustion chamber temperature, the maximum temperature over the piston and the maximum heat at the nodal point increase for a LHR engine and is higher than that of the base line engine.

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