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Heat Transfer Analysis of 70 kW Gray Cast Iron Alloy Engine Head

Su Yin Win*, Lwin Lwin Oo
Department of Mechanical Engineering, Technological University (Thanlyin), Yangon, Myanmar

ABSTRACT

Engine head is one of the most complicated parts of internal combustion engine. It is directly exposed to high combustion pressure and temperature. In this paper, engine head heat transfer rate for 70.4 kW diesel engine. The design engine head is made of gray cast iron alloy. The original engine head is made of aluminums alloy. The cast iron engine head can get over heat temperature because the thermal conductivity of cast iron is not as good as aluminium. So that it is necessary of increasing the cooling efficiency. In the engine heat transfer calculation, the heat fluxes from the engine head are calculated with vary engine speeds and water velocity and heat transfer analysis is required for the engine metal changing process.

Keywords : Heat Flux in Engine Head, Heat Flow to the Coolant, Heat Carried by the Exhaust Gas ,Thermal Stress, MATLAB Program

I. INTRODUCTION

Engine head is one of the most complicated parts of internal combustion engine. It is directly exposed to high combustion pressure and temperature. Heavy-duty diesel engine heads experience severe thermal and mechanical loading under both steady-state and transient engine operation [5]. Consequently, engine head design is very sophisticated as it needs to house cooling passages for ensuring compliance with thermal stresses, while providing sufficient mechanical strength to withstand combustion pressures, and yet accommodating intake and exhaust valves and ports, and the fuel injector.

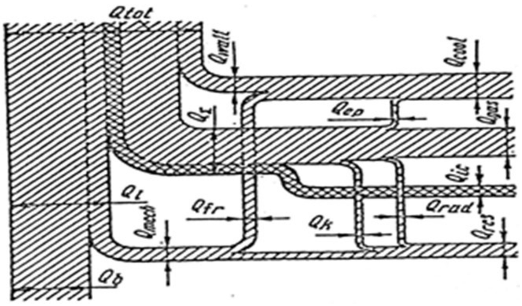


Figure 1 : Internal Heat Balance of the Engine

All internal combustion engine are equipped with some type of cooling system because of the high temperature they generate during operation [4]. Fig.1 shown of the internal heat balance of an engine.

Where,

Q_{tot} =Heat introduced into the engine with fuel

Q_i= Heat equivalent to the indicated work of the engine

Q_b = Heat equivalent to the brake work of the engine

Q_{wall} = Heat transferred to the internal cylinder wall

Q_{cool} = Heat rejected to the cooling medium

$Q_{\sum}$ = total heat contained in the exhaust gases

Q_{mech} = Heat equivalent to the work spent on friction and driving the auxiliary mechanisms

Q_{fr} = Heat transferred to the cooling medium owing to friction of the piston and its rings

Q_{ic} = Heat of the fuel owing to chemically incomplete combustion

Q_{res} = Residual term

Q_k = Heat corresponding to the kinetic energy of the exhaust gas

Q_{rad} = Heat lost result of radiation

Q_{ep} = Heat rejected by the spent gases to the cooling system in the exhaust pipe

Q_{gas} = Heat carried away from the engine with the exhaust gases

II. HEAT FLOW CALCULATION

The total amount of heat spent in one second is calculated

$$Q' = m_f' \times CV \quad (1)$$

where,

Q' = total amount of heat spent in one second

m_f' = fuel consumption per hour

CV = Calorific value of fuel =42 MJ/kg

$$m_f' = b.s.f.c \times Power \quad (2)$$

b.s.f.c = brake specific fuel consumption

$$Power = \frac{P_b \times V_s \times N}{2 \times 60} \quad (3)$$

where,

Pb = brake mean effective pressure

Vs = displacement volume

N = engine speed

$$V_s = \frac{\pi}{4} B^2 S \quad (4)$$

where, S = stroke length

B = cylinder diameter

The amount of heat flux various with engine speed are calculated by using from above equations. Prediction of 70.4 kW diesel engine heat transfer as the function of speed within (500 rpm to 5000 rpm) is shown in Fig 2.

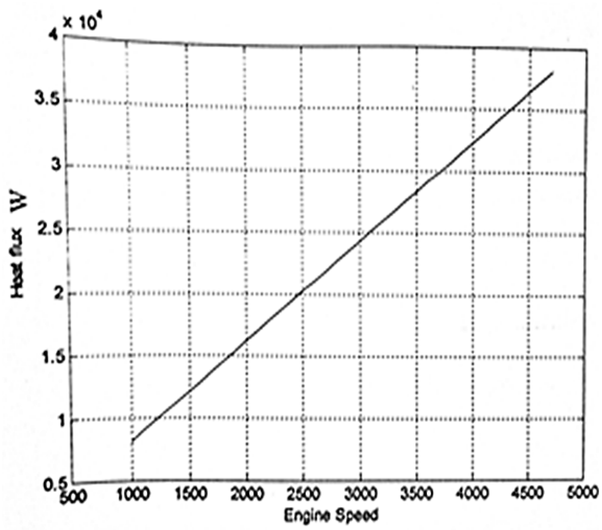


Figure 2 : Prediction of 70.4 kW gray cast iron diesel engine heat transfer as the function of speed[10]

III. STEADY STATE HEAT FLUX IN ENGINE

Local heat transfer rates are required for calculation thermal stresses. This is particular interest to designer of low heat rejection engines, as the thermal stresses in these engine are greater than in conventional engines due to higher wall temperature. In fact, a major problem with insulation coating is thermal stress due to the differential heating within the combustion chamber. Engine life cycle prediction is also effected by the local heat transfer rates.[9]

Different part of the engine operates at the different temperatures. The highest temperature values are at the center of piston crown. In the engine head the highest temperatures are occurs at the center of cylinder head and the cylinder wall near the cylinder head. In the engine head of exhaust channel, the exhaust gas temperature is also high.[9]

The heat transfer coefficient from the coolant to the metal of the tube α is determined.

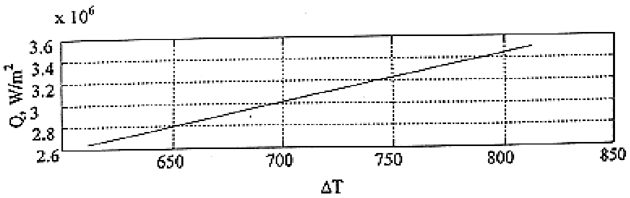
$$\alpha_1 = 60 + b_1\sqrt{V_w} \quad (5)$$

The heat rejected to the cooling medium is determined from the convection heat equation.

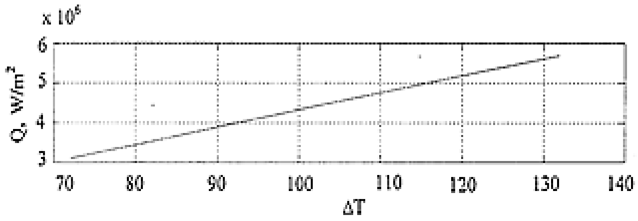
$$Q_{cool} = \alpha_1(T_w - T_{coolant}) \quad (6)$$

where, Q_{cool}= heat rejected to the cooling medium
T_w = surface temperature
$T_{coolant}$= Coolant temperature
α_1= convection heat transfer coefficient
b =30 for quite flow
= up to 60 for sharp turns and sudden change of velocity in the water jacket
The limit of α_1 is 2500 to 5000 W/m²℃.

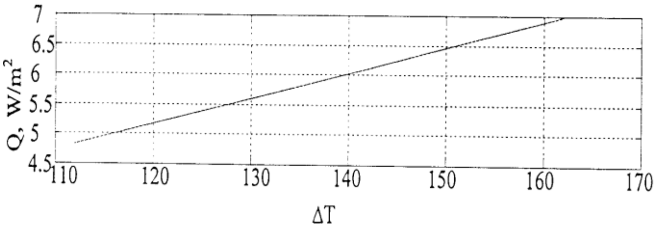
The mean temperature of the water coolant is 86 to 91˚C. For design purposes it is necessary to predict the local flows and to calculate the component temperature. By mean of an iterative processes it is then possible to modify the design unit, The temperature and the resulting thermal stresses are acceptable. The heat transfer process in an engine is however very complex. Firstly combustion in the diesel engine is homogeneous, and at any one time there are wide variation in gas temperature, through the charge. Secondly, radiation is an important contributor to heat flow, but there are wide variation in gas temperature , through the charge. Finally, there are considerable variation in the local velocity of the various portions of the charge. Fig. 3 a,b,c shows steady state heat flux at different location of engine head. The heat flux magnitude is the highest at the exhaust channel and centre of cylinder head is second position.



(a) At the Exhaust Channel



(b) At Cylinder Wall near the Cylinder Head



(c) At the Center of cylinder Head

Figure 3 : Steady state heat flux at different location[10]

IV. HEAT FLOW TO THE COOLANT WITH VARIOUS COOLANT VELOCITIES AND CARIOUS TEMPERATURE DIFFERENCE

The large majority of highly rated diesel engines employ liquids cooling. While teir may be special reasons for example in military engine, for using air cooling, the problem of cooling local regions with very high heat flows, the value bridges and adjacent to the injector make air cooling unattractive for highly rated engines. In the critical regions of the cylinder head, the heat flux vale are high, heat transfer is by means of nucleate boiling. Here, although the bulk temperature of the coolant is below its boiling, steam bubbles are formed at the metal and coolant interface. Heat transfer therefore involves the latent heat of the liquid and the very high rates of the heat transfer can occur without the large temperature steps that would be necessary with forced convection heat transfer. While boiling heat transfer has received considerable attention in recent years with resultant voluminous literature, the majority of this has involved chemically clean surfaces and chemically pure coolant. The coolant is water which may will be untreated and with appreciable quantities of hardness.

Under forced convection heat transfer condition and in the absent of a thermal barrier, heat transfer coefficients rising from about 4,000 to 12000 W/m2K are obtained as the water velocity rises from 0.25 to 1.0 m/s. For boiling heat transfer, it is appropriate to define the heat transfer by means of boiling potential that is the metal surface temperature mines the boiling temperature of the coolant.

It will be seen that in the boiling regime, increasing the coolant velocity only reduces the metal temperature if the velocity is raised sufficiently high to suppress the boiling and this is not normally feasible since the water pressure would be excessive and the pump power too high. Reduction in coolant temperature do not affect metal temperature and may indeed accentuate thermal stress problems in cylinder head since the outer restraining area of the cylinder head deck are cooled by force convection and will be reduced in temperature. An increase of coolant pressure gives a direct increase in metal temperature.

Also the amount of heat rejected to the cooling system is calculated from Eq(7) and result is shown in Fig .4.

$$Q_{cool} = C_w \times \Delta T \times \dot{m_w} \quad (7)$$

where, Q_{cool}= the amount heat to the cooling system

C_w=specific heat of water

=4.19 kJ/kg C

ΔT=temperature difference of coolant between engine outlet and inlet

=(7-11)

$\dot{m_w}$ = the amount of water pass through the engine

$$\dot{m_w} = \rho A V_w n \quad (8)$$

=(7-11)

$\dot{m_w}$ = the amount of water pass through the engine

$\dot{m_w} = \rho A V_w n$

where, ρ = density of coolant =998 kg/m³

A = Area of water jacket

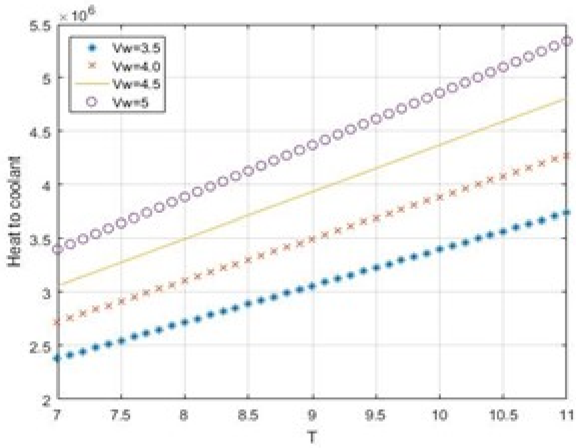
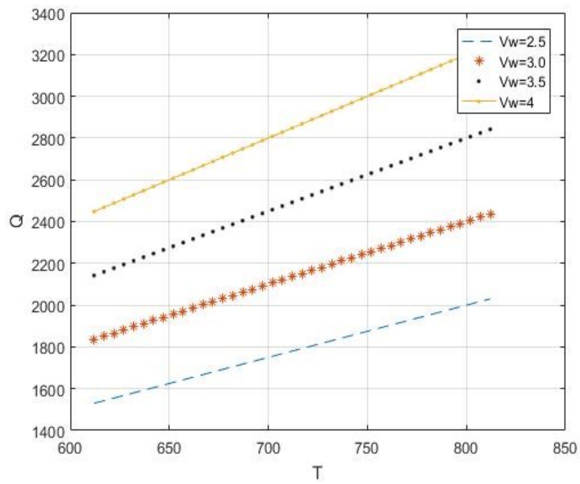
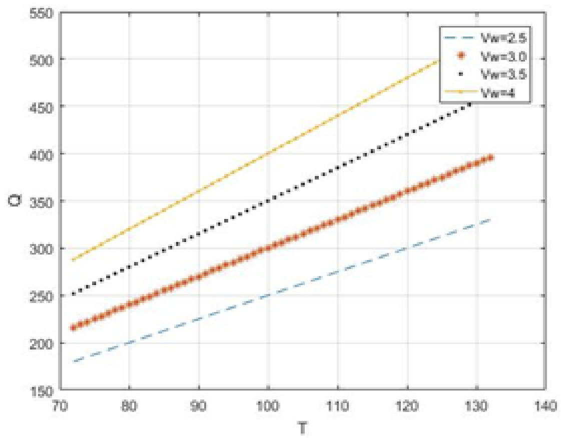


Figure 4 : Steady state heat flux at different location [10]

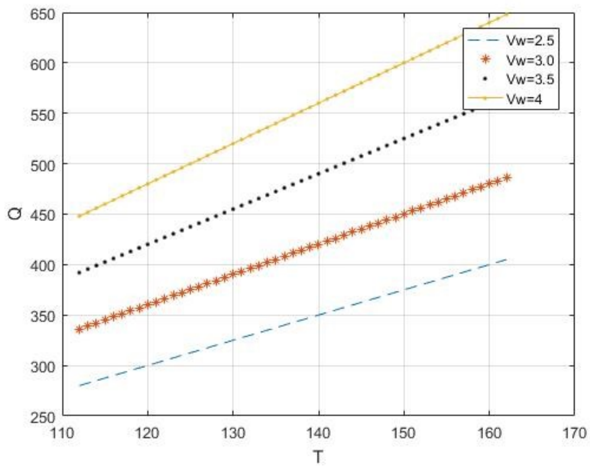
Heat transfer coefficient is rising as the water velocity rises. If the water velocity was changed, the heat flux at the engine head is also changed. These results were calculated by using equation (6) and water velocity was changed from 3.5 to 5 m/s. The results are shown in Fig . 5.



(a) At the Exhaust Channel



(b)At the Cylinder Wall Near the Cylinder



(c) At the Cylinder Head

Figure 5 : a,b,c are showed heat flux at the engine with various water velocities [10]

If the coolant velocity is low, the collapse of the bubbles can lead to cavitation erosion. At higher flow rates, nucleate boiling is suppressed. For flows over the range 1 to 3 m/s agreement between measurement and prediction is excellent. Coolant flow distribution has a major effect on the engine operating temperature, distribution for engine designs with no organized cooling within the cylinder head, it is often acceptable to specify coolant side heat transfer condition based on knowledge of the coolant properties and bulk flow rate.

V. HEAT ABSORBED AND TRANSFERRED BY THE ENGINE HEAD

The amount of heat absorbed by the engine head varying with the load from (11 to 19%) of the total heat supply with fuel.[3]From 11 to 37% of total heat absorbed by the engine head is transfer to the wall of the exhaust channel. [6] Fig.6 show the heat absorbed and transferred by the engine head.

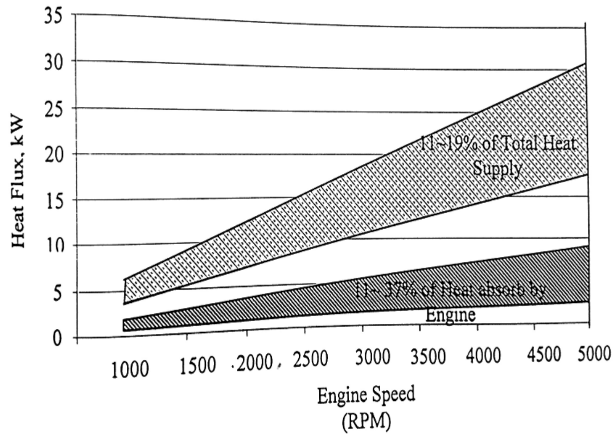


Figure 6 : Heat Absorbed and Transferred by the Engine Head[10]

VI. HEAT FLOW TO COOLANT

Water is very effective cooling media with a high enthalpy of vaporization, high specific heat capacity and high thermal conductivity. In the diesel engine (15 to 35%)of available heat of fuel is disposed to the cooling system. [7]The amount of heat to the coolant with varying mean piston speed are calculated following equation.

$$Q_{cool} = (15\ to\ 35)\%\ .\ CV \times b.s.f.c \times A_p \times P_b \times V_p \quad (9)$$

where,

Q_{cool}= heat flow to coolant , kW

A_p = piston cross section area

P_b = brake mean effective pressure

V_p = mean piston speed

= 3 to 4 m/s

$V_p = \frac{2LN}{60}$ (10)

$P_b \doteq P_i - P_{mech}$ (11)

$P_{mech}^{\cdot} = A + V_p . B$ (12)

where, Pi = indicated mean effective pressure

P_{mech}= mechanical losses

High speed diesel engine with divided combustion chamber, A= 0.105 and B= 0.0138 [1] and heat to the coolant with various mean piston speed result are shown in Figiure (7).

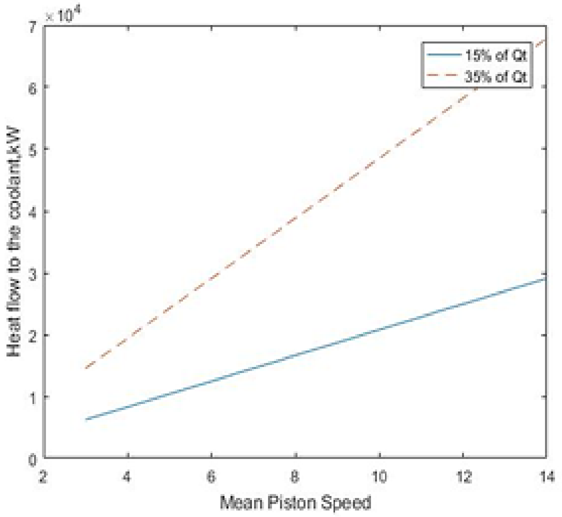


Figure 7: Heat to the Coolant with Various Mean Piston Speed[10]

VII. HEAT CARRIED AWAY FROM THE ENGINE WITH EXHAUST GAS

The heat carried away from the exhaust gas is determined following equation.

$Q_{gas} = \dot{m}_f[M_2(\mu C_p")t_{gas} - M_1(\mu C_p)t_0]$

(13)

Q_{gas} = 62.75 kW

= 41 % Q_t

where, μ = actual coefficient of molar charge

=1.045

M_1 = quantity of the fresh charge

= 0.6923 kmole

M_2 = mass of combustion product

=0.72512 kmole

$C_p"$ =specific heat at constant pressure of combustion product

=25.374 kJ/kmole℃

C_p = specific heat at constant pressure of fresh charge

=25.868 kJ/kmole℃

t_{gas} = exhaust gas temperature

= 914℃

t_0 = fresh charge temperature

=55℃

Q_{gas} =heat carried away from the engine with the exhaust gases.

VIII. THERMAL STRESS

Failure due to excessive thermal stress are one of the common causes of engine break down under highly rated condition. Under extreme condition as with burning exhaust valve following exhaust gas blow by or burning of piston crown or cylinder heads by contact with outflow jets from pre chamber type of combustion chamber or yet again as a result of detonation when a diesel engine is operated on gasoline, metal may actually be removed in quantities.

In considering materials for operation under conditions of thermal fatigue, it is important to remember that in the cylinder head, liner and piston crown one is not working between fixed temperature limits but with approximately fixed local heat fluxes. A reduction in thermal conductivity therefore increases the temperature limits and increases the peak thermal strain. The important method of reducing thermal stress is reduced the gas side temperature.

It is clear that important factor is the temperature drop through the metal and coolant interface, it can be done to improve the effectiveness of the cooling since nucleate boiling exists and as already show increase of coolant velocity or reduction in coolant temperature are ineffective.

Thermal stress in engine head is

$$\sigma th = \alpha E \Delta t / 2(1-\mu) \quad (14)$$

σth = thermal stress, kg/cm2
E = young' modulus, kg/m2
= 1.3×10-6kg/cm2
μ = Possion's ratio
= 0.25
Δt = maximum temperature different
α = coefficient of linear expansion per℃

For engine of medium size, the maximum temperature different was allowed between 55 to 62℃.[8] The results of thermal stress are shown Fig. 8.

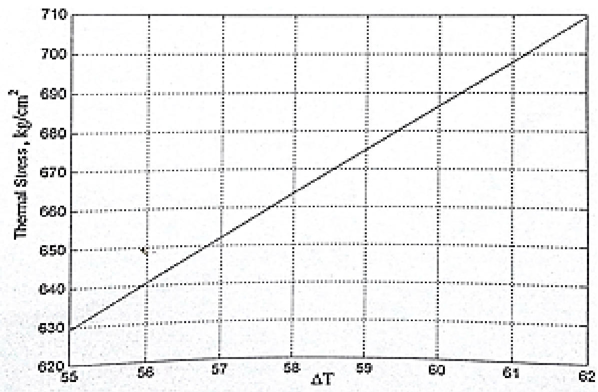


Figure 8 : Thermal strength of the engine head

IX. CONCLUSION

Heat transfer analysis to the engine head with various water velocity, water flow rate, water jacket average length and radiator of cooling system for 1974cc gray cast engine head were calculated. The design water velocity is 2.8m/s. The limit of water velocity is 2.5 to 3 m/s for diesel engine. The temperature of the coolant is 88.5 ° C The original engine head used in aluminum engine head can be released the amount of heat about 30.28 kW but the design radiator is rejected heat about 53.32 kW. The amount of heat introduced into the engine with fuel is 152.36 kW and the amount of heat rejected to the cooling system is 53.32 and the heat carries away from the engine with the exhaust gas is 41 % Qt . For diesel engine without super charging, Qgas is (25 to 45) % of Qt . The brake specific fuel consumption of the diesel engine is 13.06 kg/hr.

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