W02

An average small car engine consumes 5 liters of diesel per 100 km of driving. Now, let's consider a scenario where we have a car traveling at an average speed of 60 km/h. During this operation, the car's engine generates an average of 21 kW of heat. Diesel has an LHV of 35.8 MJ per liter.

The outer surface of an engine is located in an area where oil leakage can occur, and if the leaked oil comes into contact with a hot surface having a temperature above its autoignition temperature, it can ignite spontaneously, posing a fire hazard. To address this concern, engineers have designed an engine cover made of an aluminum plate with a thickness of 2 cm and a thermal conductivity of 237 W/mK.

The inner surface of the engine cover, which is exposed to hot air, maintains a temperature of 330 ^{o}C. To prevent fire risks in the event of an oil leak onto the engine cover, a layer of thermal barrier coating (TBC) with a thermal conductivity of 1.1 W/mK is applied to the outer surface of the engine cover.

For this analysis, we consider the engine's surface area to be 1.1 m^2. The application of the TBC acts as a thermal insulator, reducing the rate of heat transfer from the hot inner surface to the outer surface of the engine cover. This insulation layer helps in lowering the temperature of the outer surface, thereby minimizing the risk of oil autoignition and potential fire hazards.

By implementing this thermal barrier coating, engineers aim to enhance the safety and reliability of the engine while ensuring optimal performance even in challenging operating conditions.

a Give the definition of efficiency.

b What is the efficiency of the car engine? State the assumptions that are made.

c Provide a sketch of the thermal network. Include all known temperatures, resistances, and the direction of the flow of heat. Explain each component.

d Determine the heat flux through the wall of the engine.

e Would a TBC layer of 8 mm in thickness be sufficient to keep the engine cover surface below the autoignition temperature of 200 °C to prevent fire hazards?

f Determine the temperature at the interface between the aluminium and TBC layer.

g Give a sketch of the temperature profile inside the layers of the car engine.

Note: Clearly indicate the change in temperature in the axial direction, the change in slope at the interface. Lastly, indicate the numerical value of the temperature at the interface

Solution W02

a Give the definition of efficiency.

$$\eta = \frac{\text{useful work}}{\text{input energy}} \cdot 100\ \%$$

(1) Correct definition

b What is the efficiency of the car engine? State the assumptions that are made.

It is assumed that:

- all energy not being lost is used for power generation.

(0.5) Correct assumption

The consumption of diesel per unit of time can be calculated by the rate of diesel consumption per km (=5 per 100 km) and knowing the average velocity (=60 km per h):

$$\dot{V}_{\text{diesel}} = \frac{5}{100} \cdot 60 = 3\ \text{L/h} = 8.33 \cdot 10^{-4}\ \text{L/s}$$

(0.5) Correct calculation of diesel consumption per unit of time

The heat generated from combustion is calculated as:

$$\dot{E}_{\text{combustion}} = \text{LHV}_{\text{diesel}} \cdot \dot{V}_{\text{diesel}} = \left(35.8 \cdot 10^{6}\right) \cdot \left(8.3 \cdot 10^{-4}\right) = 29.83\ \text{kW}$$

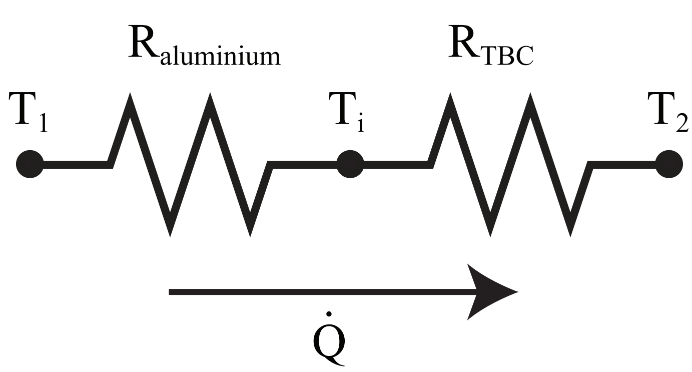
(0.5) Correct calculation of generation of heat

This yields an efficiency of:

$$\eta = \frac{\text{useful work}}{\text{input energy}} \cdot 100\ \% = \frac{\dot{E}_{\text{combustion}} - \dot{Q}}{\dot{E}_{\text{combustion}}} \cdot 100\ \% = \frac{29.83 - 21}{29.83} \cdot 100\ \% = 29.6\ \%$$

(0.5) Correct calculation of efficiency

c Provide a sketch of the thermal network. Include all known temperatures, resistances, and the direction of the flow of heat. Explain each component.



(1) Correct sketch

- T_1: Temperature at the interface between the aluminium and hot air inside the motor. Known to be 330$^{\text{o}}$C.
- T_{I}: Temperature at the interface between the aluminium and TBC. Not known yet.
- T_2: Temperature at the interface between the TBC and cold air outside. Not known yet.
- $R_{\text{aluminium}}$: Thermal resistance induced by the aluminium layer due to conductive heat transfer. Not known yet.
- R_{TBC}: Thermal resistance induced by the TBC layer due to conductive heat transfer. Not known yet.
- $\dot{Q}$: Rate of heat transfer from the inside of the engine to the outside. Known to be 21 kW.

(1) Correct explanation of all components, (-0.5) per missing

d Determine the heat flux through the wall of the engine.

The heat flux is defined to be:

$$\dot{q}'' = \frac{\dot{Q}}{A} = \frac{21.000}{1.1} = 19.09\ \text{kW/m}^2$$

(1) Correct calculation of heat flux

e Would a TBC layer of 8 mm in thickness be sufficient to keep the engine cover surface below the autoignition temperature of 200 °C to prevent fire hazards?

To determine whether a TBC layer of 8 mm in thickness is sufficient to keep the engine cover surface below the autoignition temperature of 200 °C to prevent fire hazards it should be validated that $T_2 < 200\ ^{o}$C.

First, all thermal resistances should be determined:

$$R_{\text{aluminium}} = \frac{x_{\text{aluminium}}}{k_{\text{aluminium}} \cdot A} = \frac{0.02}{237 \cdot 1.1} = 7.67 \cdot 10^{-5}\ \text{K/W}$$

$$R_{\text{TBC}} = \frac{x_{\text{TBC}}}{k_{\text{TBC}} \cdot A} = \frac{0.008}{1.1 \cdot 1.1} = 6.61 \cdot 10^{-3}\ \text{K/W}$$

(0.5) Correct calculation of conductive resistance

As the resistances stand in series, the total thermal resistance can be calculated as:

$$R_{\text{total}} = R_{\text{aluminium}} + R_{\text{TBC}} = \left(7.67 \cdot 10^{-5}\right) + \left(6.61 \cdot 10^{-3}\right) = 6.69 \cdot 10^{-3}\ \text{K/W}$$

(0.5) Correct calculation of total resistance

From the thermal resistance theorem, it is known that:

$$\dot{Q} = \frac{T_1 - T_2}{R_{\text{total}}}$$

So:

$$\rightarrow T_2 = T_1 - \dot{Q} \cdot R_{\text{total}} = 330 - 21.000 \cdot \left(6.69 \cdot 10^{-3}\right) = 189.55\ ^{o}\text{C}$$

(0.5) Correct calculation of T_2

So yes, a TBC layer of 8 mm in thickness is sufficient to keep the engine cover surface below the autoignition temperature.

f Determine the temperature at the interface between the aluminium and TBC layer. From the thermal resistance theorem, it is known that:

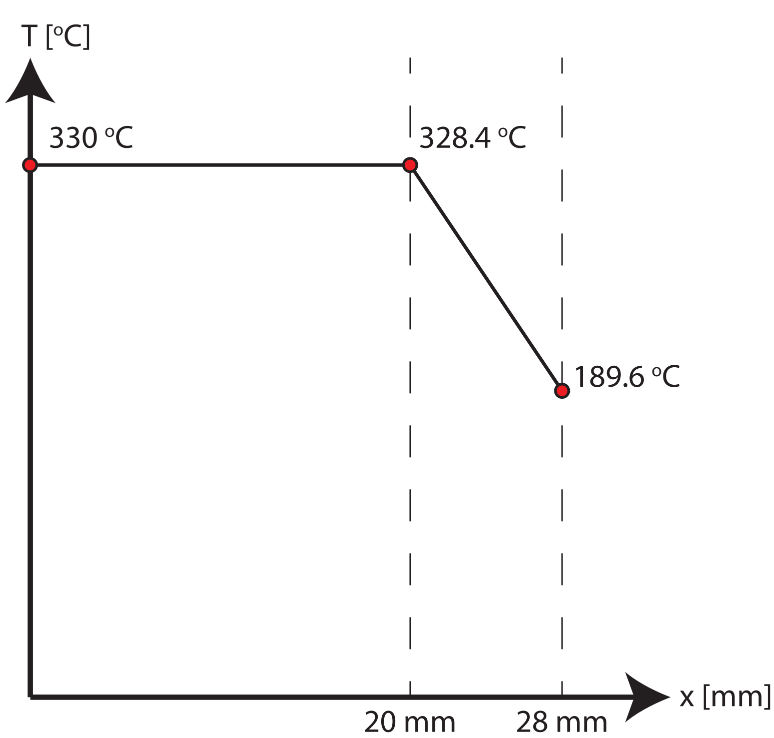
$$\dot{Q} = \frac{T_1 - T_{\text{i}}}{R_{\text{aluminium}}}$$

So:

$$\rightarrow T_{\text{i}} = T_1 - \dot{Q} \cdot R_{\text{aluminium}} = 330 - 21.000 \cdot \left(7.67 \cdot 10^{-5}\right) = 328.39\ ^{o}\text{C}$$

(0.5) Correct calculation of T_{i}

g Give a sketch of the temperature profile inside the layers of the car engine.



The temperature drop in the second layer is bigger than the temperature drop in the first layer.

Both lines should be straight.

The gradient of the second layer should be steeper than the gradient of the first layer at the intersection.

All temperatures should be at the correct location.

(2) For all correct criteria, (-0.5) per missing criteria