



**University of  
Nottingham**

UK | CHINA | MALAYSIA

# **Advanced propulsion systems MMME4066**

## **Coolant system and heat rejection**

**Antonino La Rocca**

**Professor in Applied Thermofluids and Propulsion systems**

**Coates Office C39**

**Email: [antonino.larocca@nottingham.ac.uk](mailto:antonino.larocca@nottingham.ac.uk)**



1. Introduction to coolant systems
2. Heat transfer
3. Conduction through the walls
4. Worked examples
5. Thermostat and coolant pump
6. Worked example



1. Introduction to coolant systems
2. Heat transfer
3. Conduction through the walls
4. Worked examples

# Why does an engine need to be cooled?

Principally to limit the operating temperature of engine parts to values consistent with durability and integrity requirements. Typically this requires temperatures to be  $<200^{\circ}\text{C}$ .

Compare this to temperatures of gases in the cylinder:

Towards the end of the compression stroke, the charge temperature is typically 600K in an SI engine and 675K in a diesel

After charge combustion, early in the expansion stroke the products of combustion have a temperature typically 2000- 2500K

During the exhaust stroke, the charge (exhaust) gas temperatures vary typically between 500K (idling) to  $\sim 1300\text{K}$  (full load)

## Exhaust side of a high performance engine

This is hot and a lot more the 200C!

Cast iron and steel can be exposed to higher temperatures...but not in the engine core!



# What are the consequences of overheating?

- anomalous combustion events such as pre-ignition and engine knock
- oxidation of lubricant films and poor lubrication of the piston-liner interface



# What are the consequences of overheating?

- damage to the edges of the piston and exhaust valve seats
- distortion of the engine block and head, seizure of the engine



HT necessarily limits the operating temperature of the engine cylinder head and block, protecting against distortion or damage of components, and also limits the operating temperature of the lubricating oil, extending life and maintaining lubricant properties.

In addition heat transfer affects engine performance and efficiency in other both good and bad ways:

## **Bad:**

- Reduces the net heat released due to combustion (the net value is the difference between chemical energy released and the heat transfer to the walls)
- Reduces thermodynamic efficiency because the heat losses in the expansion stroke reduce work transfer.

## **Good:**

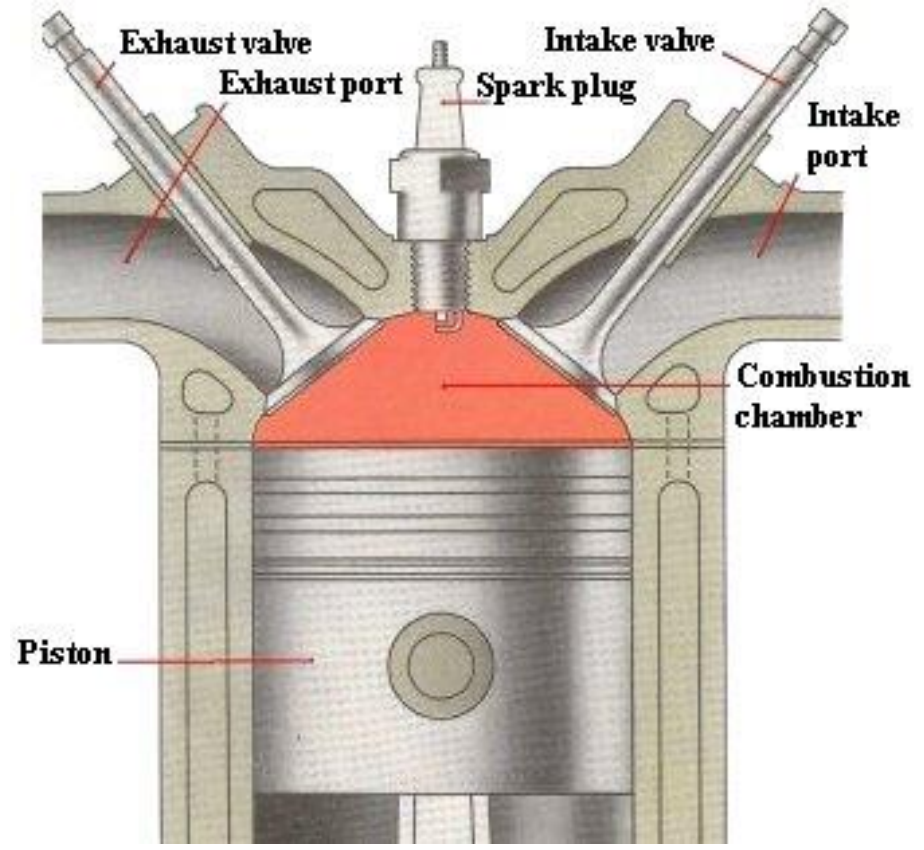
- Restricts the possibility of hot spots which may cause combustion anomalies such as premature ignition (by acting as an igniter) or knock ( uncontrolled combustion of the last parts of the mixture to burn)
- Restricts the formation of nitrogen oxides, which are a regulated pollutant

HTR cylinder walls and exhaust port of similar magnitude.

HTR to the walls are highest during combustion

Substantial HT from gas to valve during the exhaust process

HTR through intake port is small



**Conduction:**  $\dot{Q}'' = -k \frac{\Delta T}{\Delta x}$  through cylinder head, walls and piston

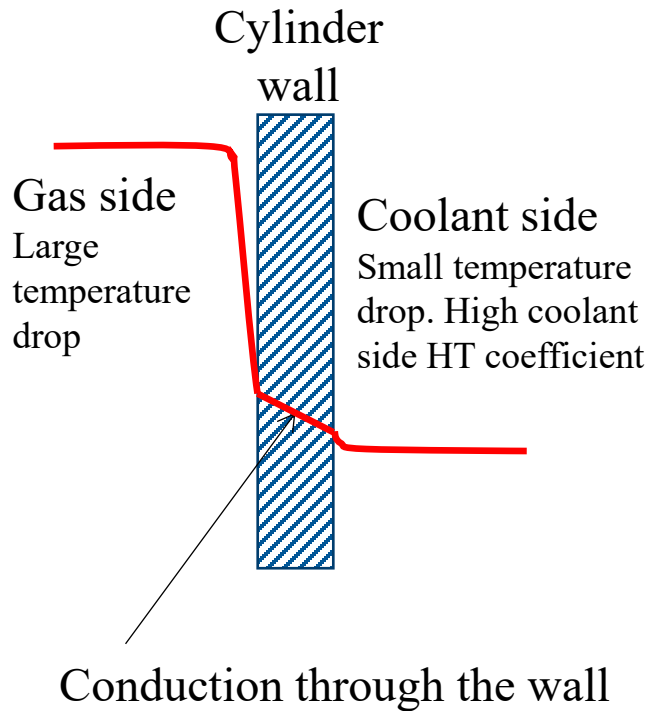
**Convection: (forced)**  $\dot{Q}'' = h\Delta T$  between gasses and cylinder head, walls and piston. Then again forced convection from cylinder walls to coolant

**Radiation:**  $\dot{Q}'' = \sigma(T_1^4 - T_2^4)$  from high temperature gasses and flame to cylinder

Boltzmann constant  $\sigma = 5.67 \times 10^{-8} W/m^2 K^4$

# Worked example

Estimate the surface temperature of the cylinder liner of a cast iron block for a location where the gas to surface heat transfer rate is  $1250\text{kW/m}^2$  if the wall thickness from surface to coolant passage is  $6\text{mm}$ , the thermal conductivity is  $60\text{W/m}^2\text{K}$  and the coolant temperature is  $85^\circ\text{C}$

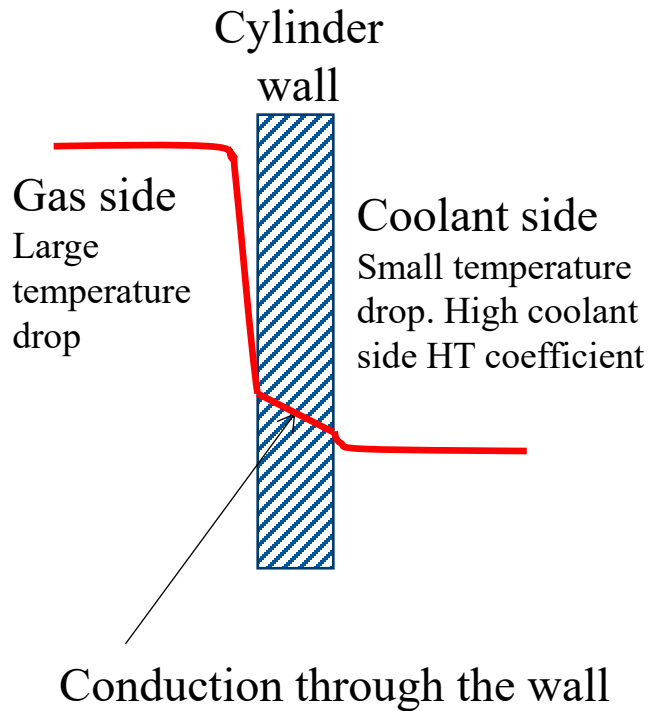


Conduction through the wall:

$$\dot{Q}'' = -k \frac{\Delta T}{\Delta x}$$

# Worked example

Estimate the surface temperature of the cylinder liner of a cast iron block for a location where the gas to surface heat transfer rate is  $1250\text{kW/m}^2$  if the wall thickness from surface to coolant passage is  $6\text{mm}$ , the thermal conductivity is  $60\text{W/m}^2\text{K}$  and the coolant temperature is  $85^\circ\text{C}$



Conduction through the wall:

$$\dot{Q}'' = -k \frac{\Delta T}{\Delta x} = -k \frac{(T_c - T_g)}{\Delta x}$$

$$T_c - T_g = -\dot{Q}'' \frac{\Delta x}{k}$$

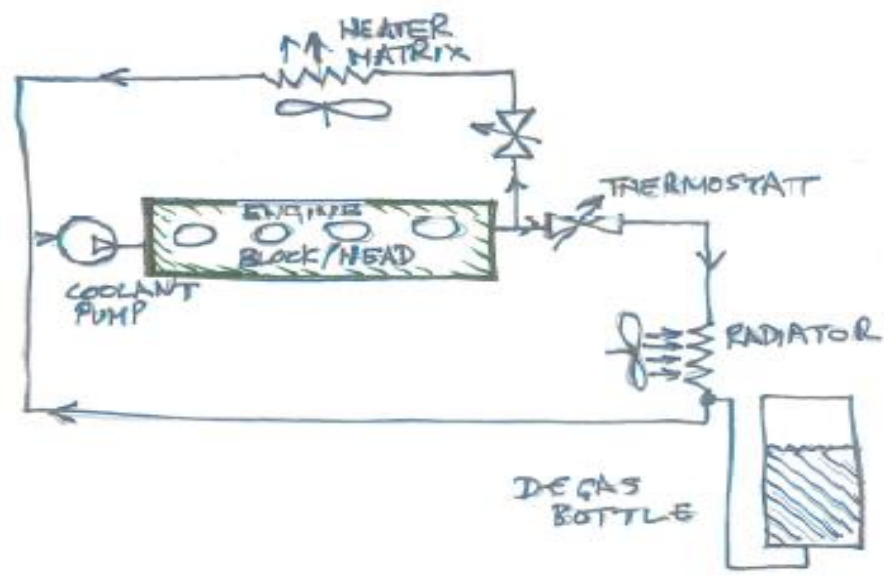
$$T_c - T_g = -1250 \times 10^3 \frac{6 \times 10^{-3}}{60} = -125$$

Surface temperature on gas side

$$T_g = 125 + 85 = 210^\circ\text{C}$$

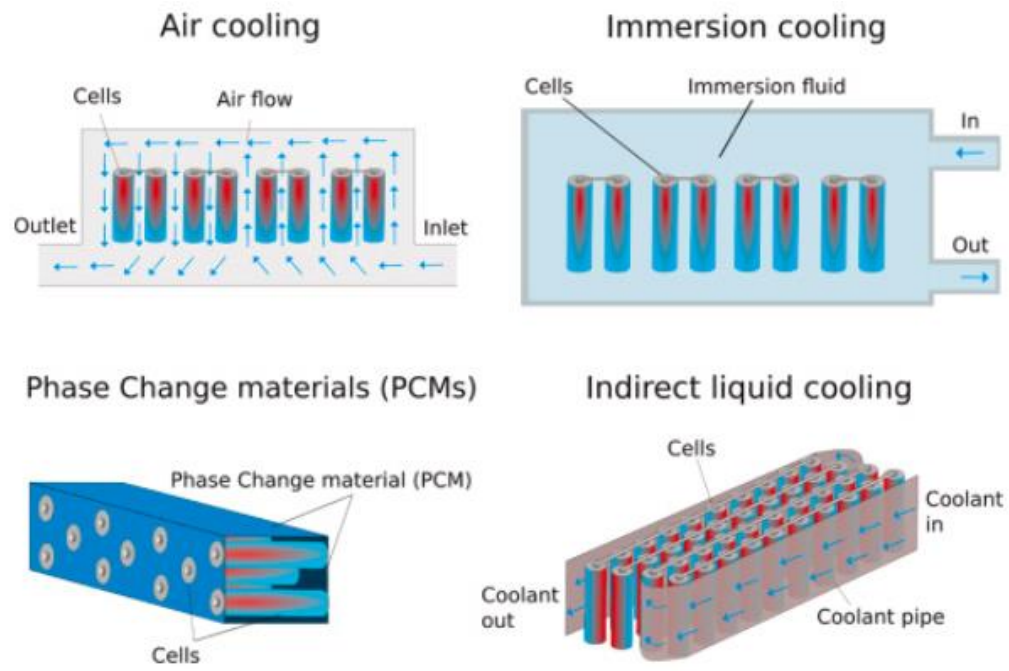
# Coolant system

Designed to absorb peak rate of heat rejected. Ensure engine does not overheat



Basic cooling system  
Coolant circulates around a closed system  
Receives heat from a engine/gas/structure  
Transports it to the radiator  
Heat is rejected to air  
Thermostat opens at  $\sim 85^{\circ}\text{C}$ , trend is to raise this to 90- 100C

# Coolant system relevant to electric vehicles



Download : [Download high-res image \(492KB\)](#)

Download : [Download full-size image](#)

Relevant to BEV too. Battery thermal management systems are critical for high performance electric vehicles, where the ability to remove heat and homogenise temperature distributions in single cells and packs

<https://doi.org/10.1016/j.jpowsour.2022.231094>

Fast charging responsible for thermal load on the battery –

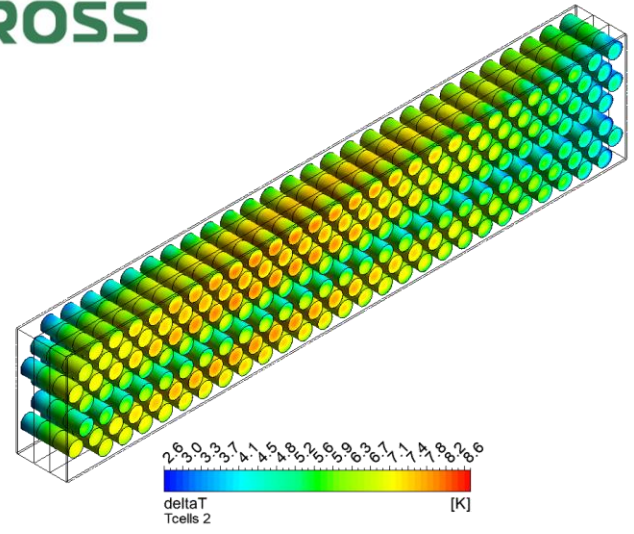
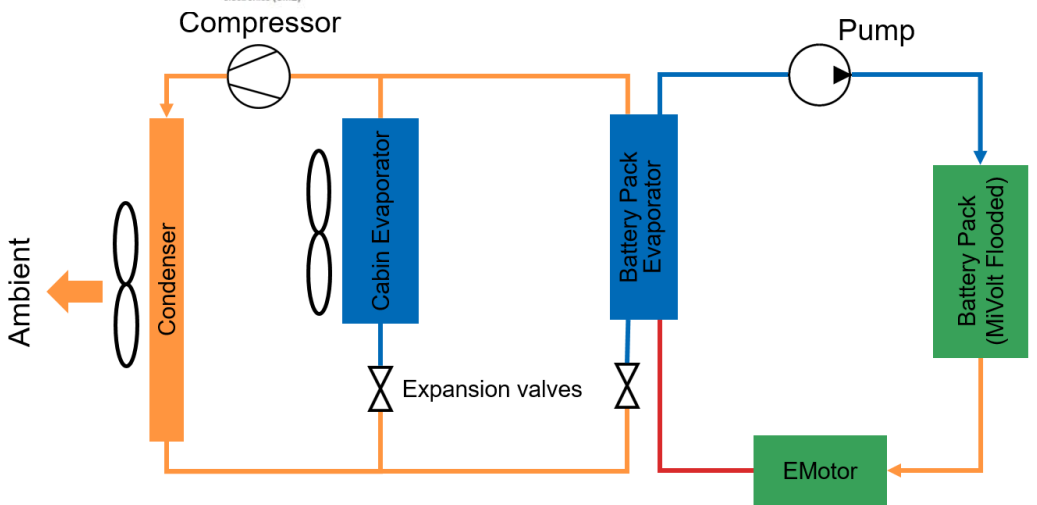
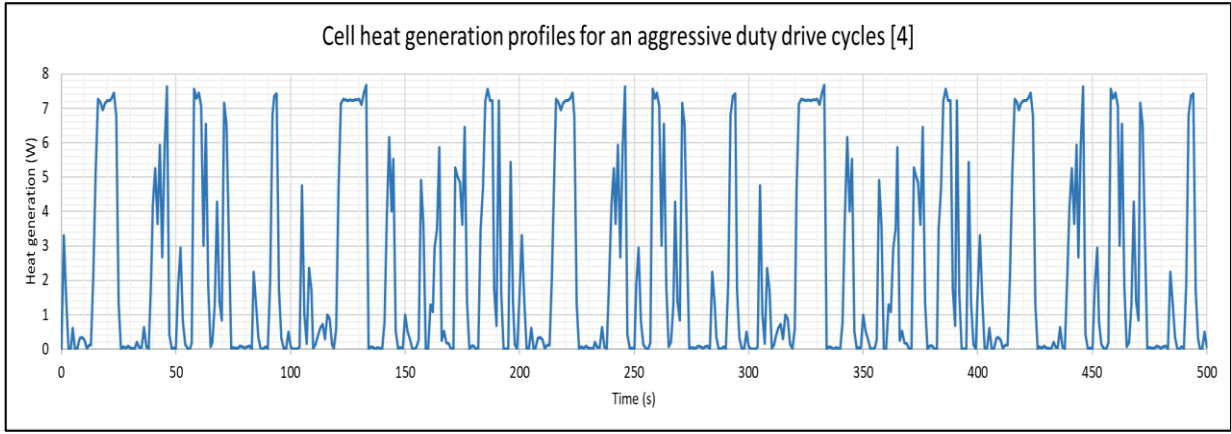
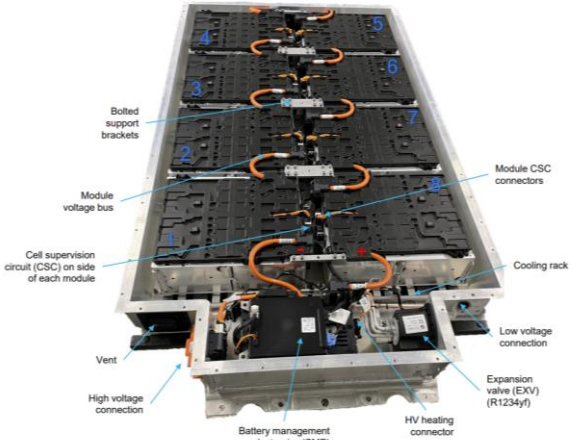
Charging at 1C means the battery is fully charged in 1 hours  
 For a 50Wh battery @ 1C Power input is  $50\text{kwh}/1\text{h} = 50\text{kW}$   
 Charging at 2C means the battery is fully charged in 0.5 hours  
 For a 50Wh battery @ 2C Power input is  $50\text{kwh}/0.5\text{h} = 100\text{kW}$

during fast charging battery needs cooling!

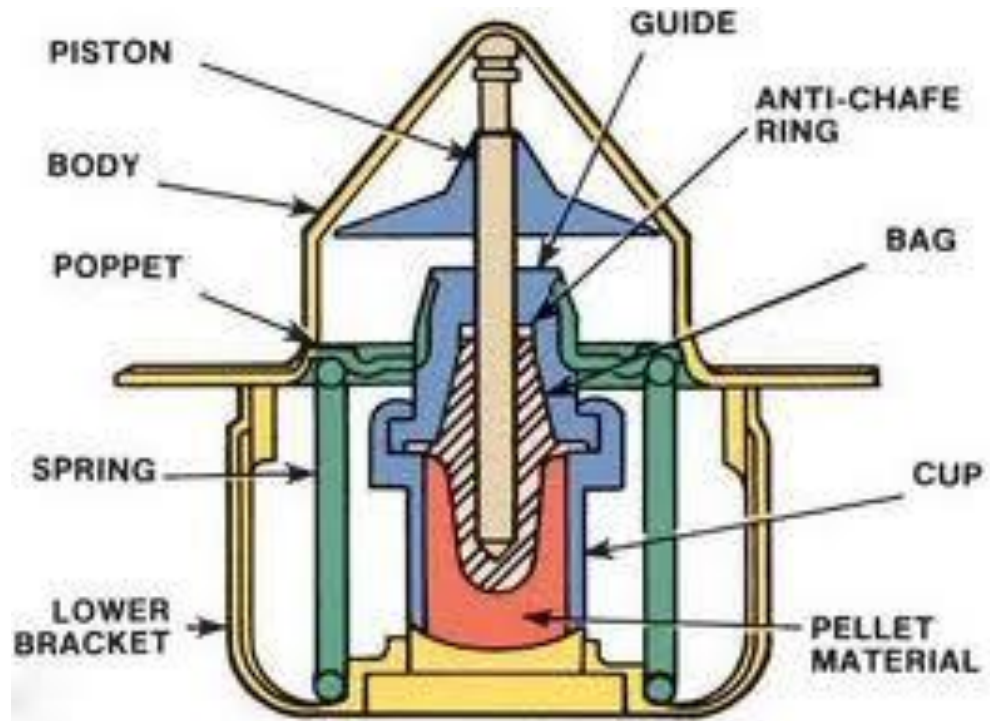
# EU Albatross project at UoN looked at battery thermal management for fast charging



FRONT OF VEHICLE



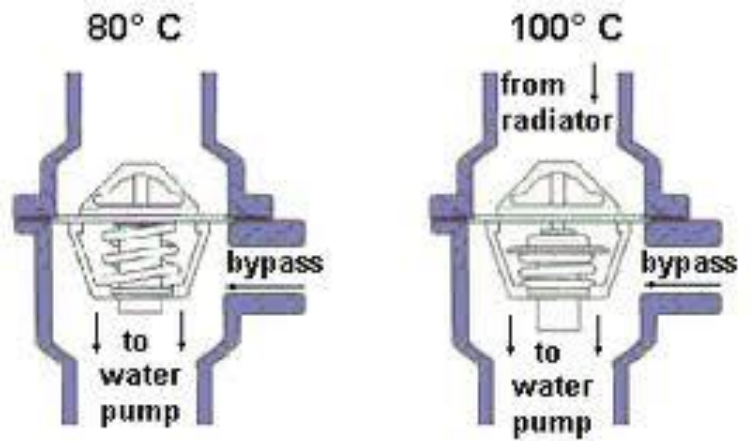
# Wax Thermostat



As the engine heats up, the **wax** melts and expands.

The sealed chamber operates a rod which opens a valve when the operating temperature is exceeded.

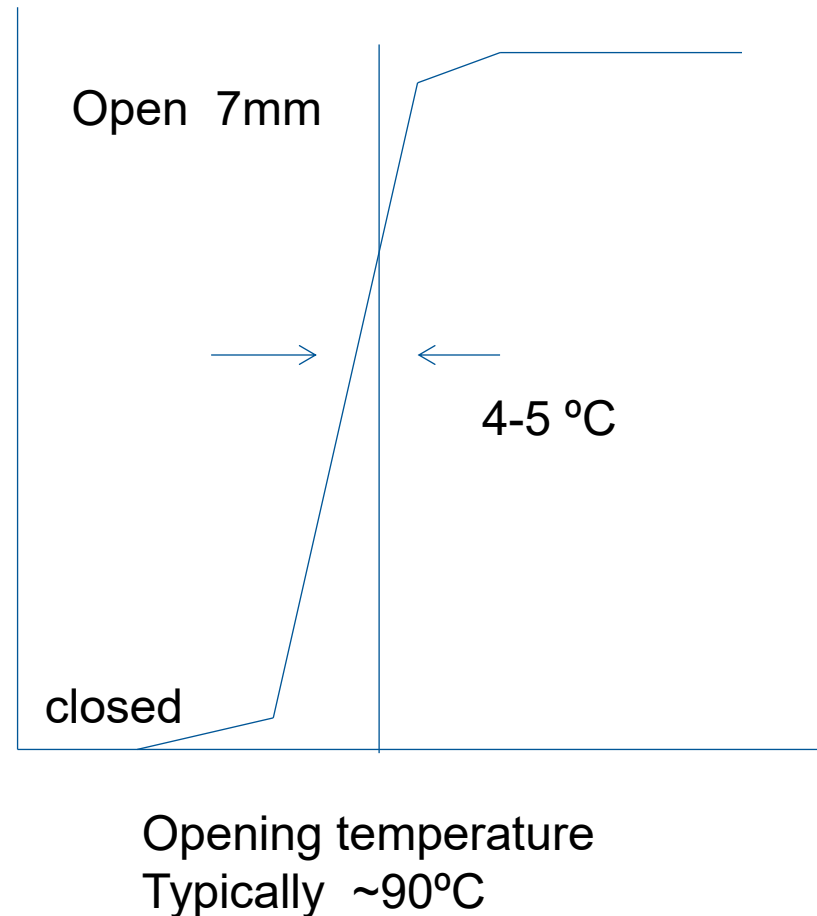
When the wax melts, it expands significantly and pushes the rod out of the cylinder, opening the valve.



The **thermostat** stays closed until the coolant temperature reaches the nominal **thermostat** opening temperature.

# Wax Thermostat

- Wax pellet has an expansion coefficient of 14-16%
- Opening 6-7mm from fully closed to fully open
- This is progressive across a defined temperature range of typically a few degrees Centigrade
- This 'sharp' response means the thermostat regulates coolant temperature by allowing more or less coolant to flow through the radiator loop



- Simple vane pump
- Usually driven off the crankshaft by a belt drive to the front pulley
- Specific work input to the impeller to circulate the coolant:

$$\Delta p / \rho \text{ (kJ/kg)}$$





## Worked example

The heat rejected to the coolant across a 4-cylinder spark ignition engine at full power output is approximately 23kW while the rubbing friction losses are 7kW. There is not no cabin heating.

Calculate the required power input to the pump if the pressure rise across the pump is 1 bar and temperature drop across the radiator is not to exceed 10deg C.

$$\text{Total heat rejected to the coolant} = \dot{Q}_T + \dot{W}_{friction} = 30kW$$

In the example, the engine rejects approximately 30kW to coolant, and under steady operating conditions and no cabin heating, it must reject this in the radiator.

If the temperature drop across the radiator is not to exceed 10deg C, what rate of coolant circulation is required and what is the required power input to the pump if the pressure rise across the pump is 1 bar?

This is a typical question arising from considering what the coolant circuit must deliver:

The temperature drop of the coolant passing through the radiator will be equal to the temperature rise of the coolant when it circulates through the engine: we don't want large temperature gradients in the engine

The coolant pump must provide a pressure rise equal to the pressure drop around the circuit (across the thermostat, the radiator, any restrictions within the engine, losses in pipework)

$$\text{Total heat rejected to the coolant} = \dot{Q}_T + \dot{W}_{friction} = 30.05 \text{ kW}$$

30 kW to be rejected in radiator, with 10deg C temperature drop.

Steady flow energy equation:

$$\dot{m} c_p \Delta T = \text{heat rejection} = 30 \text{ kW}$$

$c_p$  for coolant is 4.2 kJ/kgK

$$\dot{m} = 30 \times 10^3 / 4.2 \times 10^3 \times 10 = 0.71 \text{ kg / s}$$



## Calculate the pump input power

System pressure drop is 1bar; circulation rate is 0.71 kg/s.

$$\text{Specific pump work} = \Delta p / \rho = 1 \times 10^5 / 1000 = 100 J / kg$$

$$\text{Pump power} = \dot{m} \times \Delta p / \rho = 0.71 \times 100 = 71 \text{ watts}$$

## If cooling a battery then ....

A cylindrical battery has a 30Ah capacity and an internal resistance of 0.5 Ohm. If discharging at 4C, then calculate the heat rejected by the cell.

At a C rate of 1 a fully charged battery with a capacity of 30Ah can provide 30A for one hour

C rate of four the current is  $30 \times 4 = 120\text{A}$

Heat generated is  $Q = I^2 \times R = \dots\dots$

So depending on how many cells you have in your battery pack you'll know how much heat needs to be removed

Describe the benefits of electrification of engine accessories in the combustion engine powertrain with regard to a more efficient mobility and CO<sub>2</sub> reduction.

[8]

A possible answer:

Electric actuators enable faster and more precise control. Electrification of engine accessories provides off-loading and supports the engine.

When uncoupled from belt drive, mechanical losses are eliminated reducing fuel consumption and results in a CO<sub>2</sub> reduction. Energy for electric accessories can be produced by means of recuperation.

In addition they operate independently of engine speed and therefore can be designed purely based on specific requirements. E.g. an electric cooling pump can be designed to help during engine's warmup phase

1)

(a) Explain briefly:

- i) The difference between gross and net values of indicated work.
- ii) The difference between net indicated work and brake work.

[6]

(b) A four cylinder engine runs on a liquid fuel which has a lower heating value  $Q_{LHV}$  of 43 MJ/kg and a density  $\rho$  of 790 kg/m<sup>3</sup>. The engine runs at 4000 rev/min and produces a gross indicated power output of 50kW.

i) If fuel conversion efficiency was 100%, what would be the values of gross indicated specific fuel consumption, the rate of engine fuel consumption and the volume of fuel consumed per cycle per cylinder?

[15]

ii) The actual gross indicated specific fuel consumption is 190g/kW-h and actual combustion efficiency is 98.6%. Calculate the gross indicated thermal efficiency and the fuel conversion efficiency of the engine.

[12]

(a) Explain briefly:

**The difference between gross and net values of indicated work:**

Indicated work is done by the cylinders content on the piston.

The gross value is indicated work done during the compression and power strokes.

The net value is indicated work done over the cycle.

The difference is the pumping work associated with gas exchange process (induction and exhaust).

**The difference between net indicated work and brake work:**

The difference between net indicated work and brake work is work required to drive ancillaries and overcome rubbing friction.

## Question 1 – past exam paper 2011-12

(b) A four cylinder engine runs on a liquid fuel which has a lower heating value  $Q_{LHV}$  of 43 MJ/kg and a density  $\rho$  of 790 kg/m<sup>3</sup>. The engine runs at 4000 rev/min and produces a gross indicated power output of 50kW.

indicated specific fuel consumption,  
the rate of engine fuel consumption  
volume of fuel consumed per cycle per cylinder

$$\eta_f = 1$$

$$Q_{LHV} = 43 \text{ MJ/kg}$$

$$isfc_g = \frac{1}{\eta_f Q_{LHV}} = \frac{1}{Q_{LHV}} = \frac{1}{43} \quad \text{kg/MJ} \quad \text{or} \quad \text{kg/MWs}$$

$$= \frac{1}{43} \times 10^3 \times 10^{-3} \quad \text{g/kWs} = \frac{60 \times 60}{43} \text{ g/kWh} = 83.7 \quad \text{g/kWh}$$



## Question 1 – past exam paper 2011-12

$$\dot{W}_{ig} = 50kW \quad \dot{m}_f = 83.7 \times 50 \text{ g/h} = 4185 \text{ g/h} = 1.1625 \text{ g/s}$$

$$N = 4000 \frac{\text{rev}}{\text{min}} \quad N \text{ cycles} = \frac{N}{2} = \frac{4000}{2 \times 60}$$

$$\text{Fuel per cylinder per cycle} = \frac{1.162 \times 120}{4000 \times 4} = 8.7 \times 10^{-3} \text{ g/cycle}$$

$$\text{volume of fuel consumed per cycle per cylinder} = \frac{8.7 \times 10^{-3}}{790 \times 10^3} = 11 \text{ mm}^3$$



## Question 1 – past exam paper 2011-12

the gross indicated thermal efficiency  
fuel conversion efficiency of the engine

$$isfc_g = \frac{1}{\eta_f Q_{LHV}} = \frac{1}{\eta_c \eta_{igth} \times Q_{LHV}}$$

$$\eta_{igth} = \frac{1}{\eta_c Q_{LHV} \times isfc_g} \quad \begin{array}{l} Q_{LHV} = 43 \times 10^6 \text{ J/kg} \\ \eta_c = 98.6\% = 0.986 \end{array}$$

$$isfc_g = \frac{190 \times 10^{-6}}{3600} \text{ kg/Ws} = \frac{190 \times 10^{-6}}{3600} \text{ kg/J} = 0.053 \times 10^{-6} \text{ kg/J}$$

$$\eta_{igth} = \frac{1}{\eta_c Q_{LHV} \times isfc_g} = \frac{1}{0.986 \times 43 \times 10^6 \times 0.053 \times 10^{-6}} = 44.5\%$$

$$\eta_f = 0.986 \times 0.445 = 43.8\%$$