Lecture 1 of 4
(16:4)

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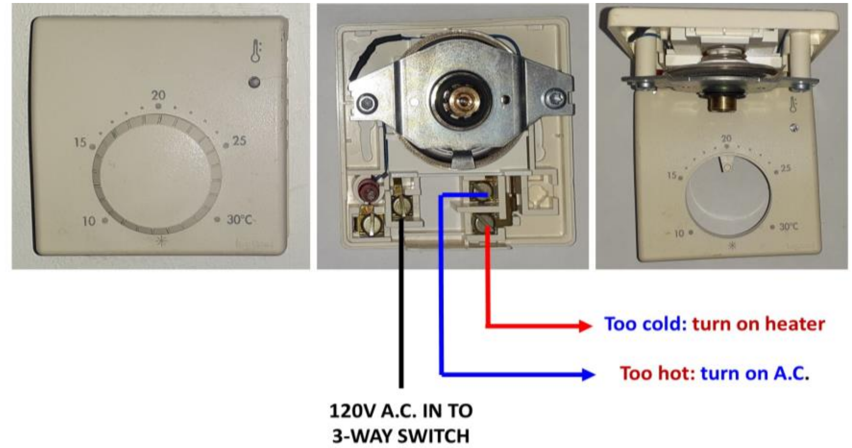
5.1 Some thermal regulation devices (1)

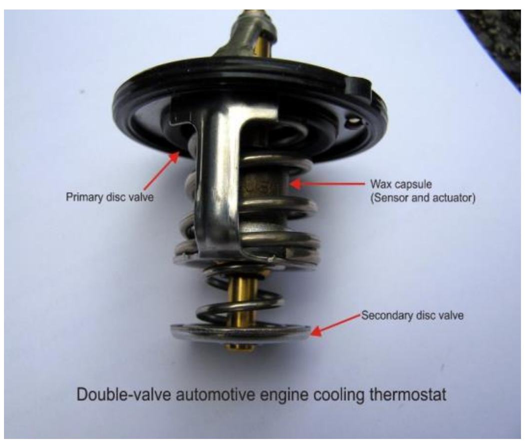
The humble room thermostat:

Bi-metallic strip electric witch actuator

Feedback:



slow, thru room air convection



The almost-as humble automobile radiator thermostat

Feedback:

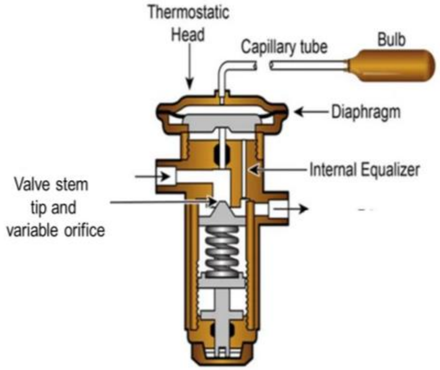
Fast, immersed, expanding wax plug capsule counteracts closure spring to increase coolant flow as engine warms up

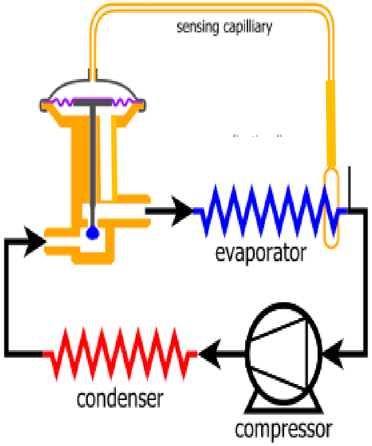
5.1 Some thermal regulation devices (2)

The water heating radiator thermostatic valve:

Feedback

Fast, immersed, expanding wax plug capsule closes valve orifice as set temperature is approached.





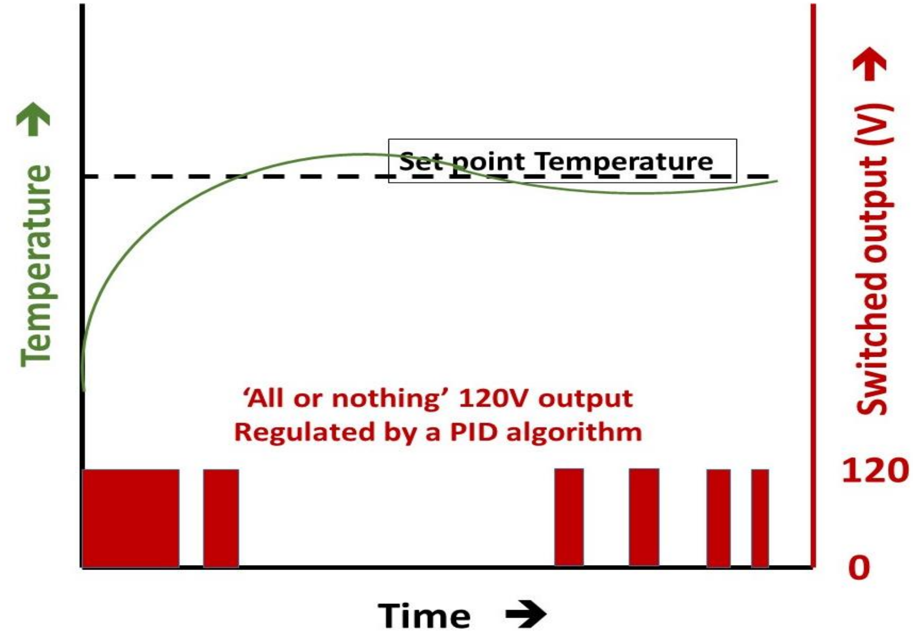
Vapor bulb-driven thermo-regulation valve.

Feedback:

Very Fast, Bulb usually clamped to a metal tube in a cooling circuit:

When sensed tube temp too high vapour expands (or evaporates), pushing on diaphragm, opening valve stem to let more coolant into the circuit.

5.1 Some thermal regulation techniques (1)



Inexpensive digital controller with NTC thermistor
& Pulse Width Modulated ("All or Nothing") relay output
driven by a PID (Proportional, Integral and Derivative algorithm)

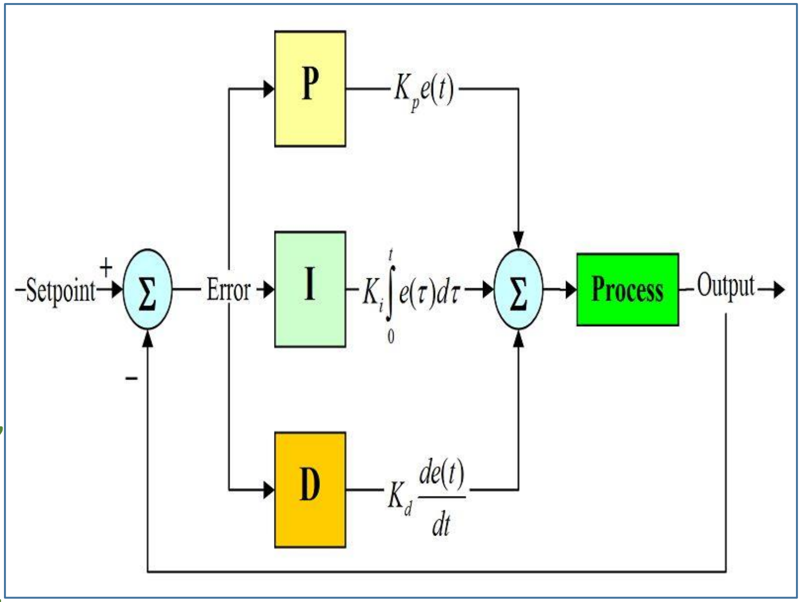
5.1 Proportional, Integral &Derivative Control (1)

$$u(t) = K_\mathrm{p} e(t) + K_\mathrm{i} \int_0^t e(\tau)\,\mathrm{d}\tau + K_\mathrm{d} \frac{\mathrm{d}e(t)}{\mathrm{d}t}$$

- Three correctional terms K_p, K_I and K_D : proportional, integral and differential gain: form the collective (time dependent) response $u_{(t)}$ of the control algorithm to differences $e_{(t)}$ between measured value of a <u>P</u>rocess <u>V</u>ariable & <u>S</u>et <u>P</u>oint to be maintained or reached;

  K_p, K_I & K_D are "tunable" parameters

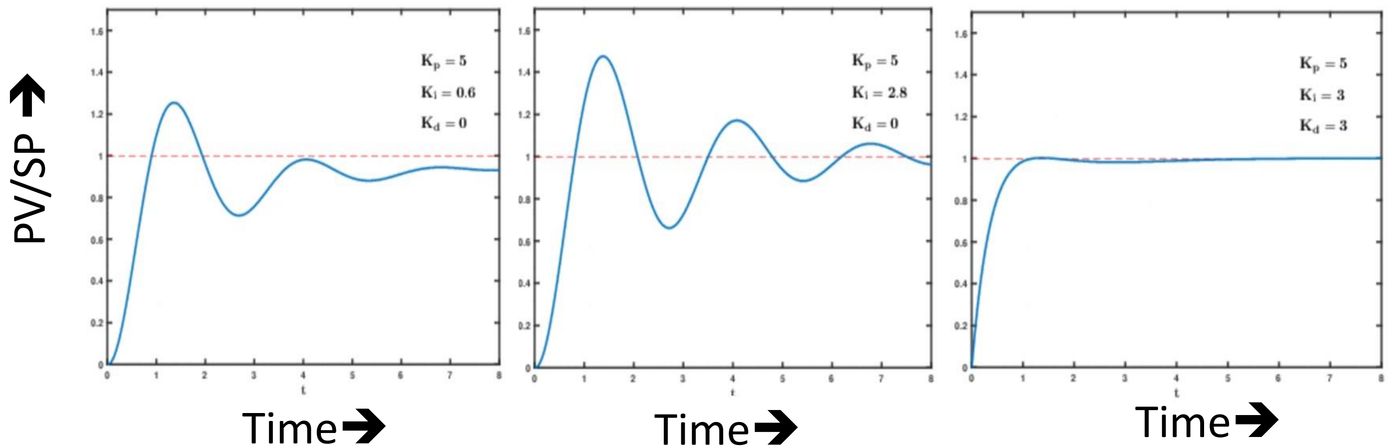
- t is the current time (or timestamp) of the measured ***PV*** at which $e_{(\tau)}$ is calculated.
- The variable t is the internal integration time which can take on values from a start time t of the most recent timestamp t.



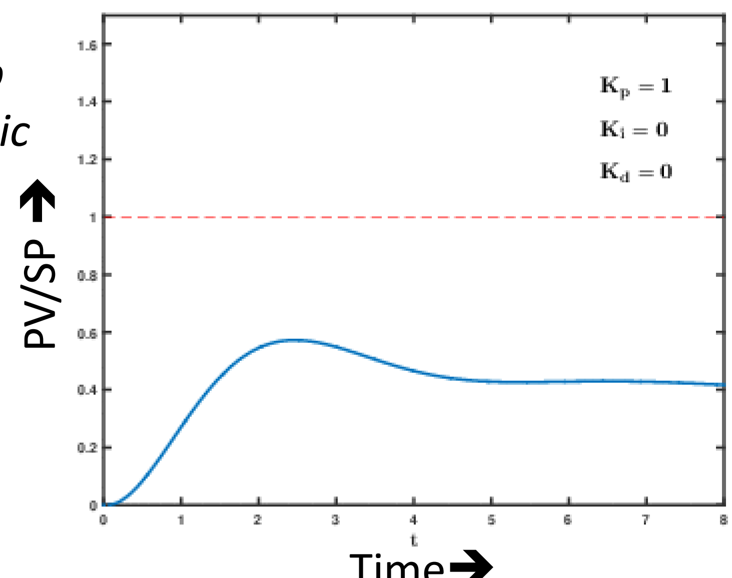
- A modern PID controller will contain a "learn mode" algorithm that will vary K_p, K_I & K_D to find the optimum combination. In doing so it will find the feedback characteristic (or "transfer function") of the system.

One such autotune is the Zeigler-Nicholls approach

5.1 Proportional, Integral &Derivative Control (2)



Screenshots (from https://en.wikipedia.org/wiki/File:PID_Compensation_Animated.gif)
*the time-dependent response of the measured value (blue curve) of a process variable (**PV**) following a step change in setpoint (**SP**) when regulated by an automatic learning-mode PID algorithm.*
***x-axis**: time (arbitrary units):*
***y axis**: measured value of the process value relative to the new set point (taken to be 1).*



5.2 Monophase liquid cooling (1)

SYSTEMS PACKAGING

Cooling a Superfast Computer

Heat is removed from the CRAY-2 supercomputer by a cooling fluid that flows over each component.

By Richard D. Danielson, 3M Commercial Chemicals Div., St. Paul, Minn., Nick Krajewski and Jerry Brost, Cray Research, Chippewa Falls, Wisc.

A new generation supercomputer, the CRAY-2, uses a novel approach to cooling which will very likely influence computer construction in the future. Made by Cray Research Inc., the supercomputer combines diminutive physical size with very high speed and memory capacity.

The new supercomputer is cooled by immersing the entire computer — power supplies, memory boards, logic circuits and main processors — in an inert, high-dielectric liquid bath. CRAY-2 works sit in a sealed 155-gal tank of 3M's Fluorinert perfluorocarbon, electronic liquid FC-77.

Supercomputer packaging

The CRAY-2 design makes use of significant technological innovations, with capabilities which are an order of magnitude greater than those of its predecessor. These include a clock cycle of 4.1 ns, four background processors for independent or combined tasking, high-speed local random-access memory of 256 million words, and an effective throughput six to 12 times that of the physically larger CRAY-1.

In dramatic counterpoint to its expanded speed and capacity, the CRAY-2 is only about half the size of Cray's earlier system, standing approximately 45-in. high with a diameter of less than 5 ft.

The CRAY-2's relatively small size is a necessity for its blazing speed. Signal propagation times from point-to-point within the system must be extremely short, or the exotic processor and memory circuits cannot do their job. But physical compactness creates enormous heat buildup problems. At very high computer speeds,

1. Circuit modules are immersed in a non-conductive, circulating, fluorocarbon liquid to remove heat from the CRAY-2 supercomputer. Transparent circuit module towers are in the foreground, while a coolant storage tower is in the background with cabinets containing pumps and heat exchangers on both sides.

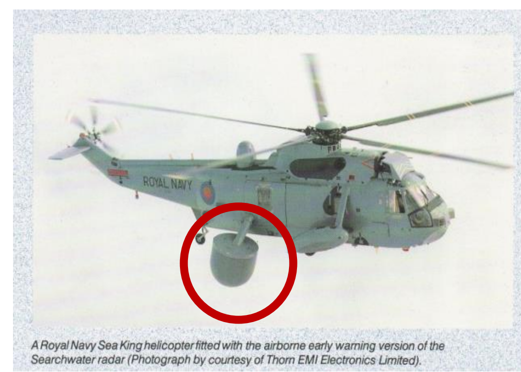
2. Cooling fluid *is pumped through the circuit module towers and heat exchangers.*

***A cold blast from the past**:*

Cray II supercomputer completely immersed in (electrically non-conductive) liquid coolant here 3M FC-77® fluorocarbon (weighs ~1.8 x H_2O)*

(See liquid pumps and fluorocarbon / water heat exchanger).

**Such fluorocarbon fluids have very high Global Warming Potential (GWP_{20y}: 5000-10000* CO_2) and are being progressively replaced with new compounds.*



A Royal Navy Sea King helicopter fitted with the airborne early warning version of the Searchwater radar (Photograph by courtesy of Thorn EMI Electronics Limited).

The military remain big users (e.g. radar systems)

5.2 Monophase liquid cooling (2)

Heat capacity, temperature rise *vs*. power & liquid flow rate

- A fluid will rise in temperature according to its mass, ***m*** (kg), the heat energy ***Q***, (Joules) absorbed, and its own heat capacity, ***C,*** expressed in units of $J.kg^{-1}.K^{-1}$;

- ***C*** relates the energy needed to raise 1kg of the fluid by 1 ˚C or 1 Kelvin (K);

- Let's consider a practical situation:
  We have a source of heat, ***P***, (Watts or $J.s^{-1}$) which we wish to evacuate using a cooling fluid, but what mass flow $\dot{m}$ ($kg.s^{-1}$) do we need, and by how much can we allow the temperature in the fluid itself to rise (***DT***, ˚C)?

- Liquid temperature rise is related to the absorbed power & liquid heat capacity via

$$DT = \frac{P}{C * \dot{m}}$$

5.2 Monophase liquid cooling (3)

Approximate heat capacity of some cooling fluids

[references refer to unit support notes]

Fluid (Gas)	C: J/(kg.°C)	Fluid (Liquid)	C: J/(kg.°C)
Air (20 ˚C, 1 bar)	1006 [2.1]	Mercury	126
Helium (20 ˚C, 1 bar)	5192 [2.1]	3M NOVEC® 649 (liq.) (20 ˚C)	1103 [2.2]
Hydrogen (20 ˚C, 1 bar)	14288 [2.1]	3M FC-72® (liq.) (25 ˚C)	1100 [2.3]
		Water (liq.)	4187 [2.1]

5.2 Monophase liquid cooling

Problem (1) – see also separate sheet:

A core processor chip in a PC dissipates 100W of heat. The user has attached a liquid-channel cooling block directly to it, through which coolant liquid can flow.

The user has a choice between water or a non-conductive modern liquid coolant with GWP=0 (3M NOVEC® 649 [2.2]). What is the mass flow $\dot{m}$ of (1) water and (2) 3M NOVEC® 649 needed to ensure that the coolant liquid temperature rise ***DT*** is limited to 10 ˚C?

5.2 Monophase liquid cooling (4)

In practice of course, heat must be channelled into a cooling fluid through adhesive or thermal grease and through the wall of the cooling block into the fluid.

All these materials have thermal resistances which stack up, resulting in a significant temperature offset between the dissipating structure and cooling fluid evacuating the heat.

5.2 Thermal Conductivity, thermal resistance – getting heat into a coolant

Thermal conductivity & resistance can be considered similarly to electrical conductivity & resistance, with expressions similar those derived from Ohm's law.

The temperature difference, ***δT*** (K) across a thermal interface (a good thermal conductor like a metal or a poor conductor like a foam insulator) of thickness ***l*** (m) when a power density of ***q*** ($W.m^{-2}$) is applied to one side is given by:

$$\delta T = \frac{q.l}{k}$$

where ***k*** is the thermal conductivity of the interface expressed in SI units of $W.m^{-1}.K^{-1}$

Alternatively the above equation can be expressed in terms of the thermal *resistance*, ***R*** (expressed in SI units of $m.K.W^{-1}$) of the interface as follows:

$$\delta T = q.\,R.\,l$$

This equation has a similar form to that of the expression linking the voltage drop, ***δV,*** along a wire of cross sectional area, ***a,*** and length, ***l,*** with its resistivity, ***r***, in Ohm-metres:

$$\delta V = \frac{I.r.l}{a}$$

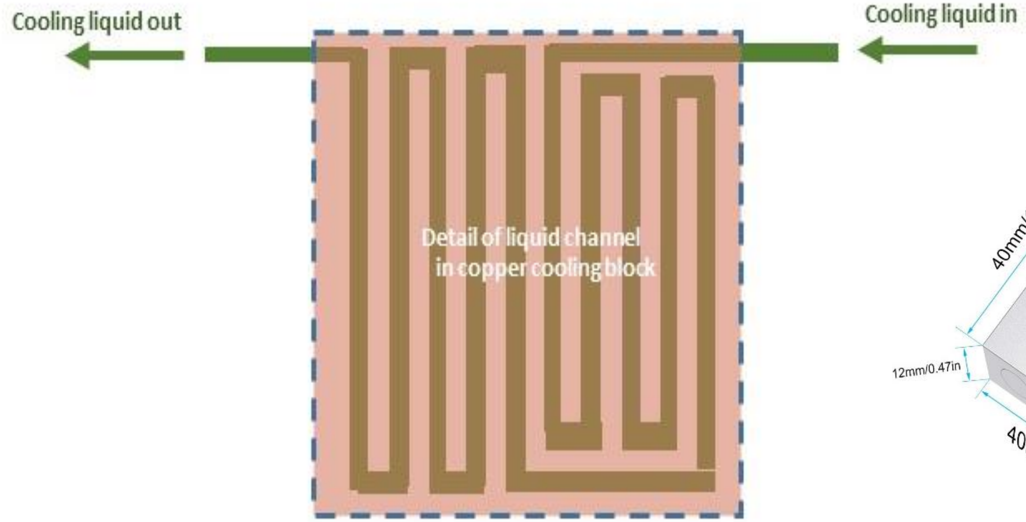
where (***I/a***) is the current flux, in $A.m^{-2}$, in direct analogy to ***q*** in $W.m^{-2}$

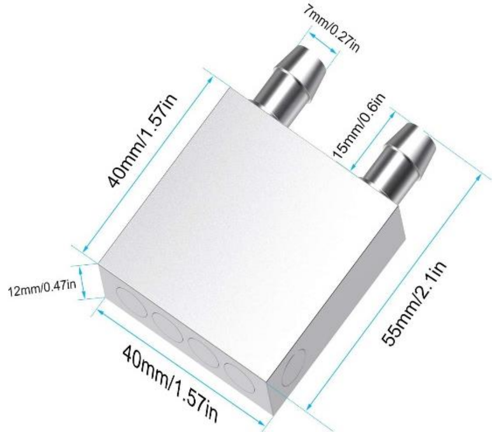
Approximate thermal conductivity of some common materials

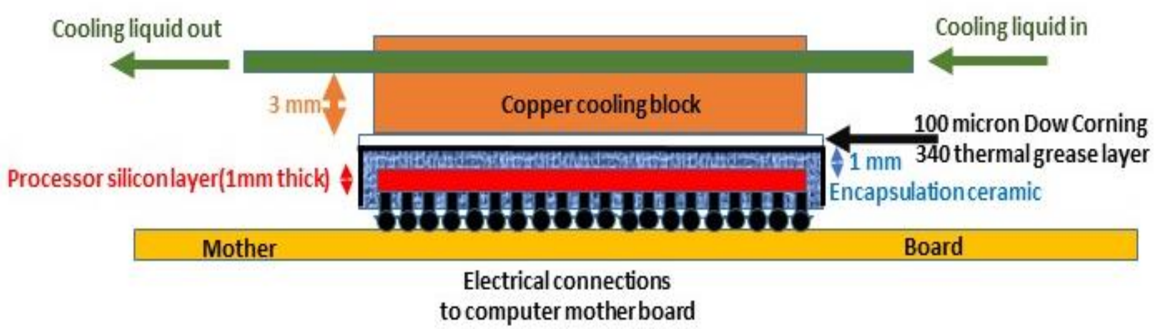
Material	Thermal Conductivity $W.m^{-1}.K^{-1}$	Application
Air (20 ˚C, 1 bar)	0.026??? [2.1]	Insulator
Aluminium	236	Good elec & heat conductor
Asbestos (200 ˚C)	0.21	Historic insulator (hazardous)
Beryllia (ceramic)	285 (room temp)	Heat spreader (hazardous)
Brass	109–160	Good elec & heat conductor
Copper	400	Very good elec & heat conductor, cooling systems
Cork	0.043	Insulator
Diamond (CVD wafer)	2300	Heat spreader
Dow Corning 340 heat conducting paste	0.67	Demountable thermal connection heat source ➔ heat sink
3M FC-72® (liq.) (25 ˚C)	0.06 [2.3]	Cooling liquid
Glass	0.935	
Glass Fiber (20 ˚C)	0.042	Insulator
Gold	312	Electrical connections
Graphite	151	Heat spreader
Lead	35	Electrical connections
Mica (50 ˚C)	0.43	Heat resistant Electrical Insulator
3M NOVEC® 649 (liq.) (25 ˚C)	0.06 [2.2]	Cooling liquid
Rockwool (20 ˚C)	0.034	Insulator
Silver	425	Very Good elec & heat conductor
Silicon	148-150	Active semiconductor
304, 316 Stainless Steel	14-18 (room temp)	Poor heat conductor (for a metal), cooling systems
STYCAST® 2850 (Emeron & Cuming)	1.02-1.68 [2.4]	Thermally conductive epoxy: permanent connection heat source ➔ heat sink
Urethane Foam (Rigid) (20 ˚C)	0.026	Insulator
Water (20˚ C)	0.613	Cooling liquid

5.2 Monophase cooling and conducting heat into a coolant (1)

Example from a common application: cooling a processor core with a liquid-channel block (plan and elevation views)



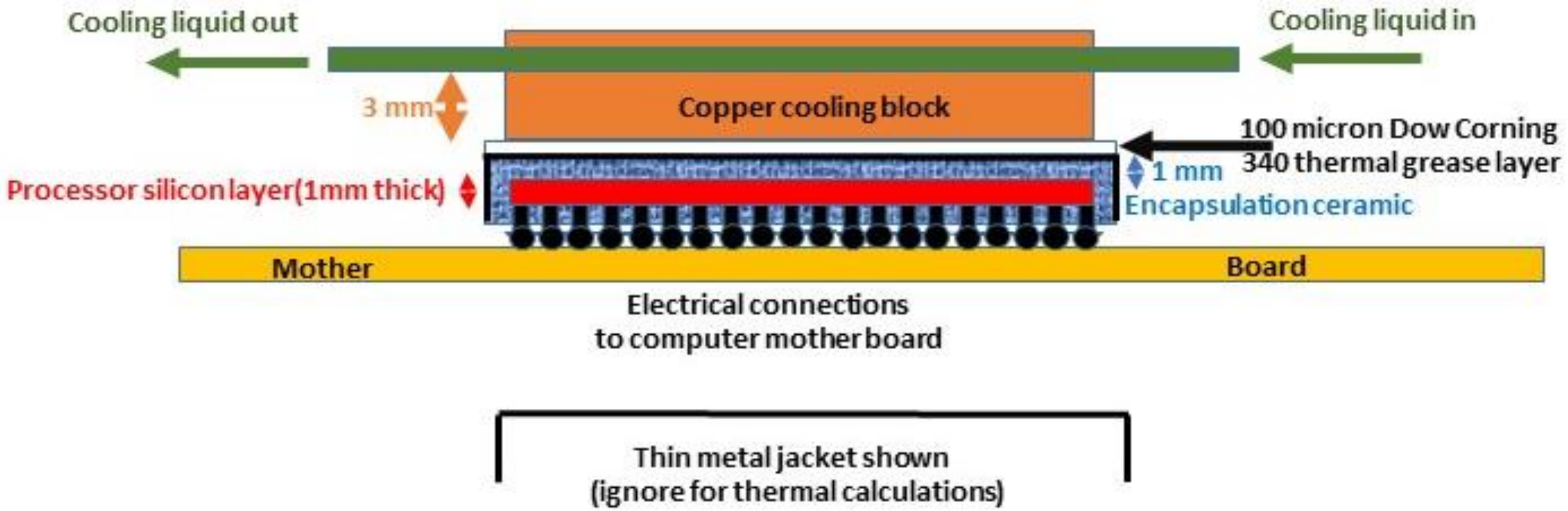




5.2 Monophase cooling and conducting heat into a coolant

Problem (2) – see also separate sheet:

A core processor chip in a PC dissipates 100W of heat and has a 4 x 4cm square profile. The user has attached a 4 x 4cm channelled copper block on top, through which liquid flows to cool the processor. The cooling block makes contact with a thin metal jacket on top of the chip through a 100 micron layer of Dow Corning 340 thermal-conductive grease.



The processor chip package itself is 3 mm thick in total (as illustrated), made from a 1 mm-thick active silicon layer centrally-sandwiched with 1 mm of ceramic encapsulant above & below it. The ceramic fill has a thermal conductivity of 200 $Wm^{-1}.K^{-1}$.

5.2 Monophase cooling and conducting heat into a coolant

Problem (2: cont) – see also separate sheet

Note: *the heat is dissipated in the doped semiconductor implanted into the surface of the active silicon layer* ***facing down*** *towards the connector to the mother board, and must first pass through 1 mm of silicon substrate in the opposite (up) direction on its way to the cooling block. Any heat loss by conduction through the connector pins to the mother board can be ignored. The very small thermal resistance of the thin topside metal jacket can also be neglected in the calculation; you can pretend that it isn't there.*

The heat from the chip can be thought of as passing through 1 mm of silicon and a further 1mm of ceramic before passing through a 100 micron (0.1 mm) thick layer of Dow Corning 340 thermal paste, and finally through the copper cooling block with an effective thickness of 3 mm before reaching the cooling liquid channel, as shown in the figure.

5.2 Monophase cooling and conducting heat into a coolant

Problem (2: cont) – see also separate sheet

For the first 4 questions you can consider that the coolant to enters the block 20 ˚C and leaves at 30 ˚C. The average temperature of the liquid in the cooling channel can thus be taken to be 25 ˚C.

What are the (progressively-increasing) temperatures on the following surfaces;

Q1: The surface of the copper block in contact with the top face of the Dow Corning 340 thermal grease film (**A**)?
(This is 3mm from the plane of the coolant channel)
Q2: The surface of the ceramic in contact with the bottom face of the 100 micron Dow Corning 340 thermal grease film (**B**)?
Q3: The hot (downfacing) side of the1 mm thick processor chip itself (**C**)?
Note: you have to consider the thermal resistance of two materials in series to get to this figure.
Q4: Which material contributes the biggest temperature difference (temperature difference across itself)?
Q5: What method would you use to reduce the contribution of this layer (mechanical solutions acceptable)?

Building on knowledge

Q6: The user has a choice between water or a non-conductive modern liquid coolant with GWP = 0 (3M NOVEC® 649 [2.2]), but the pump available can only circulate a maximum of 3 grams per second (a mass flow of 0.003 $kg.s^{-1}$) of any liquid. What is the input temperature of NOVEC 649 to the copper cooling block to maintain an average temperature in the block cooling channel of 25 ˚C? (Hint: this calculation uses the concept of coolant heat capacity and mass flow from the previous problem.