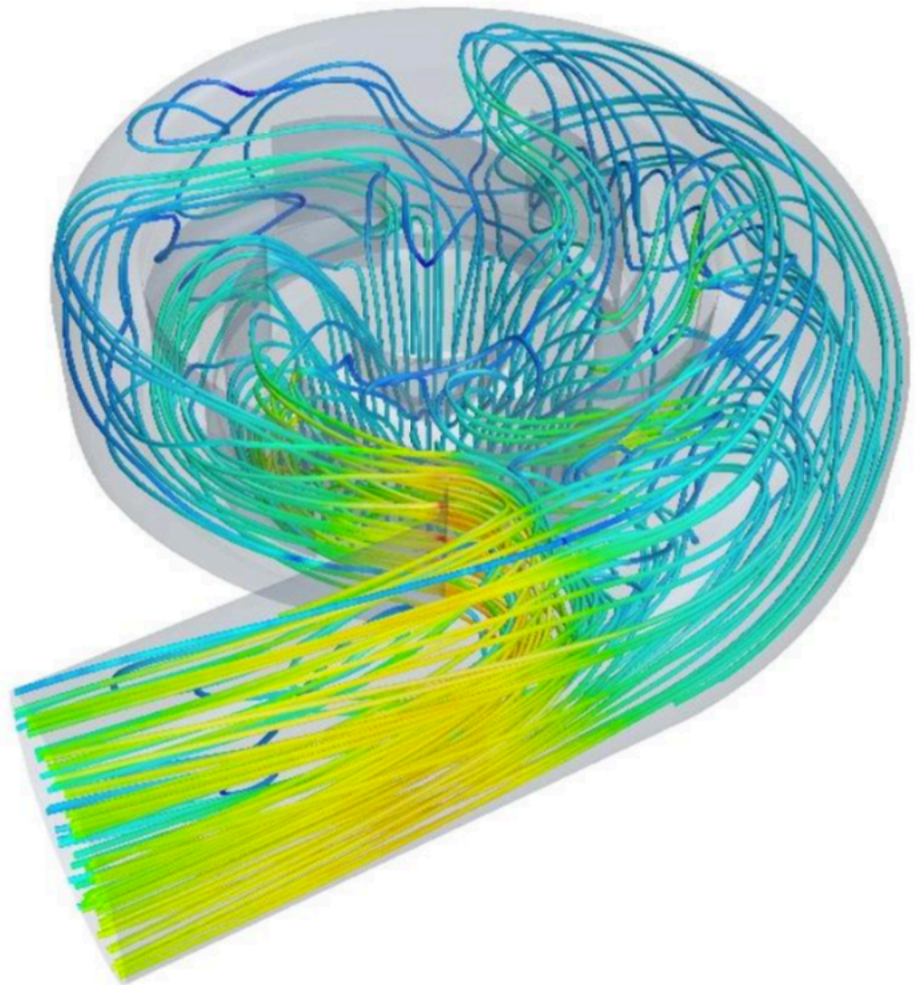
Thermal hydraulics of liquid metals



Janne Wallenius, Alejandría Pérez

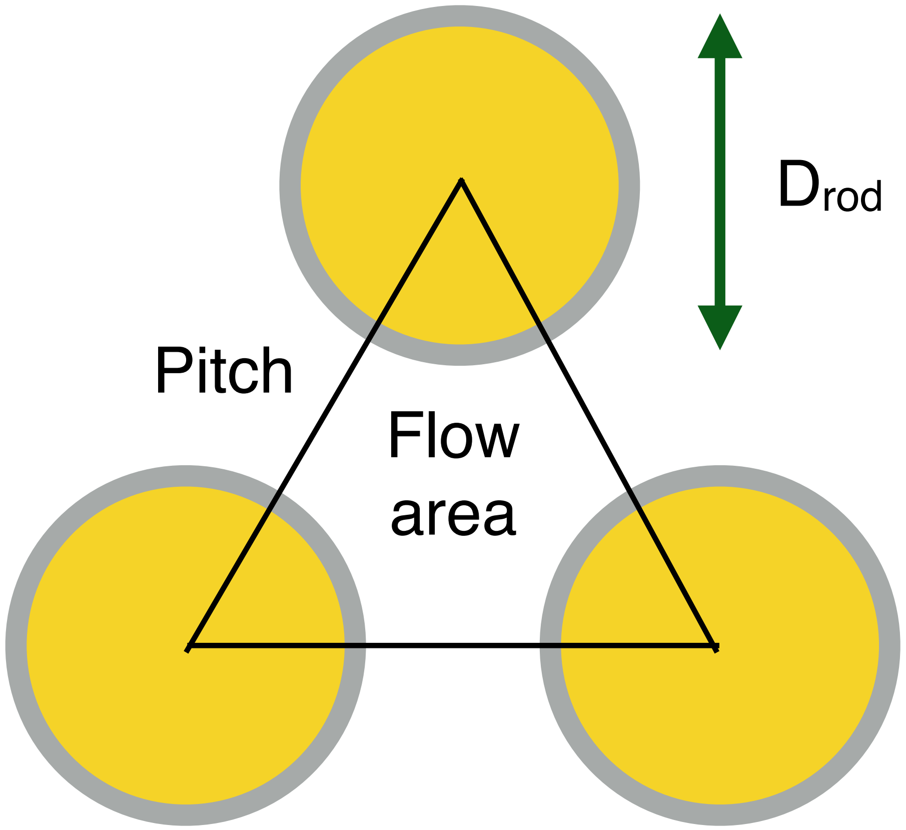
Nuclear Engineering, KTH

Intended learning outcomes

- After this meeting and home assignment you will be able to

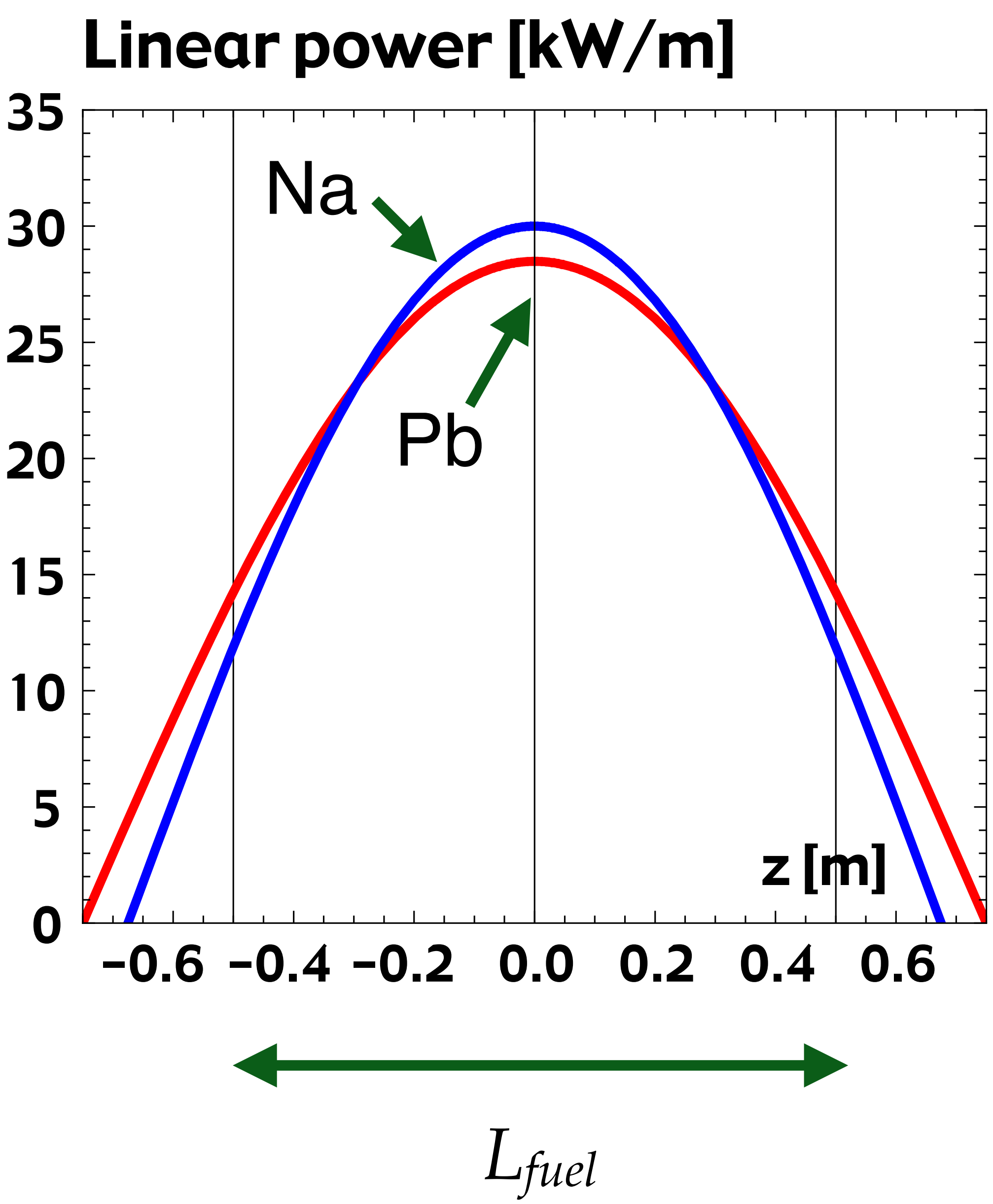
- Calculate coolant and clad temperatures in liquid metal cooled reactors.
- Evaluate the impact of coolant velocity and pin pitch on pressure drop.
- Estimate natural convection flow velocity in liquid metal cooled reactors.

Fast neutron reactor geometry



- Hexagonal geometry (triangular unit cell) standard choice for fast neutron reactors
- Close packing, minimises leakage
- In hexagonal geometry, one coolant channel transports heat from half a pin.
- Square lattice suggested for some lead cooled reactors (BREST, ELSY)

Axial power profile



- Axial power distribution in fast reactors well described by cosine function (away from control rods).

$$\chi(z) = \chi_{max} \cos\left(\frac{\pi z}{L_0}\right)$$

- Extrapolation length in Na: L_0 =1.35 L_{fuel}
- Peaking factor: χ_{max}/χ_{ave}
- Axial peaking factor: ≈ 1.26
- Extrapolation length in Pb: L_0 =1.50 L_{fuel}
- Axial peaking factor: ≈ 1.20

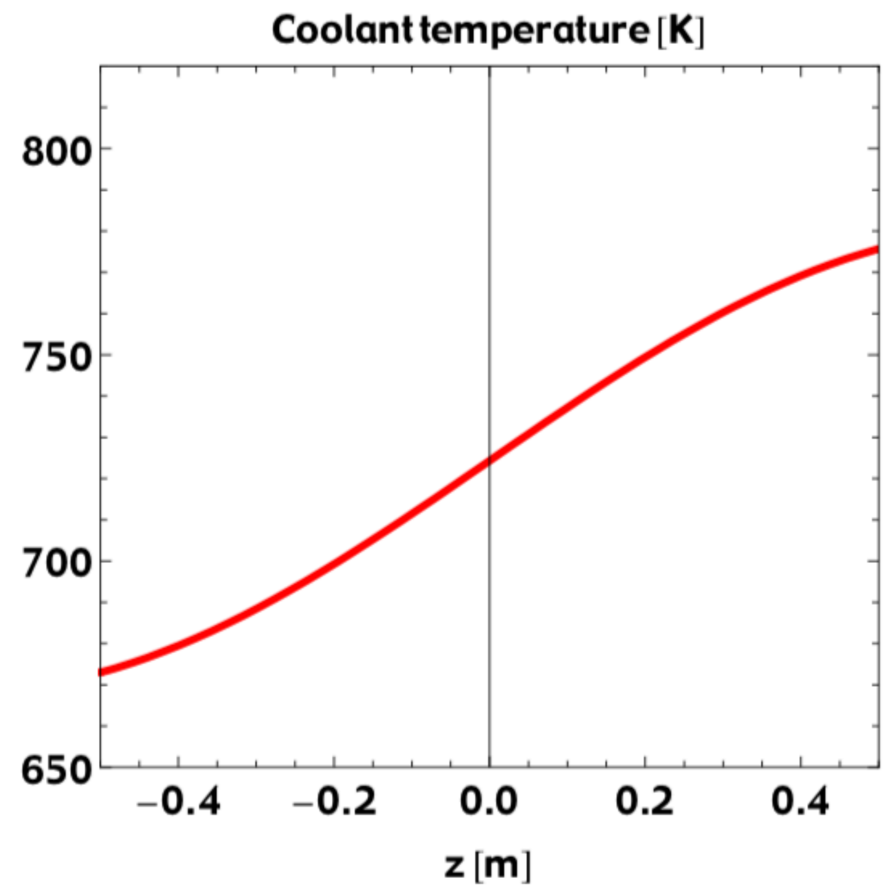
Coolant temperature

- Half the linear power is removed by one coolant channel:

$$T(z) = T_{in} + \frac{1}{\dot{m}} \int_{-L/2}^{z} \frac{\chi(z)}{2c_p} dz$$

- Mass flow is a constant, determined e.g. by density and velocity at the inlet of the coolant channel.

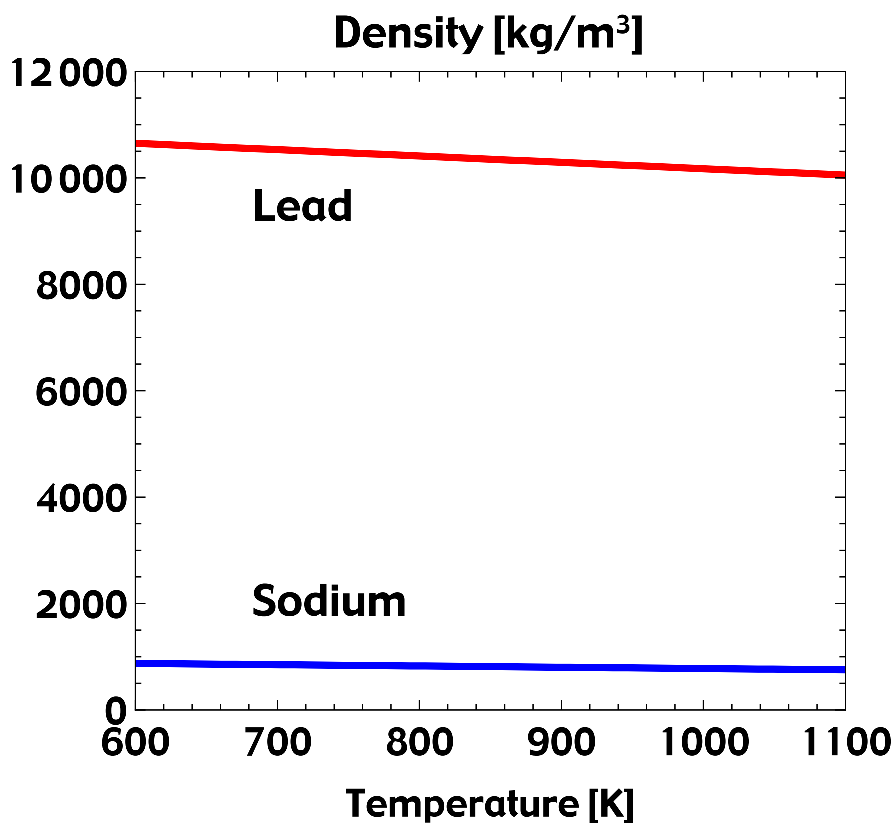
- To perform analytical integration, we may approximate c_p with its value at the inlet

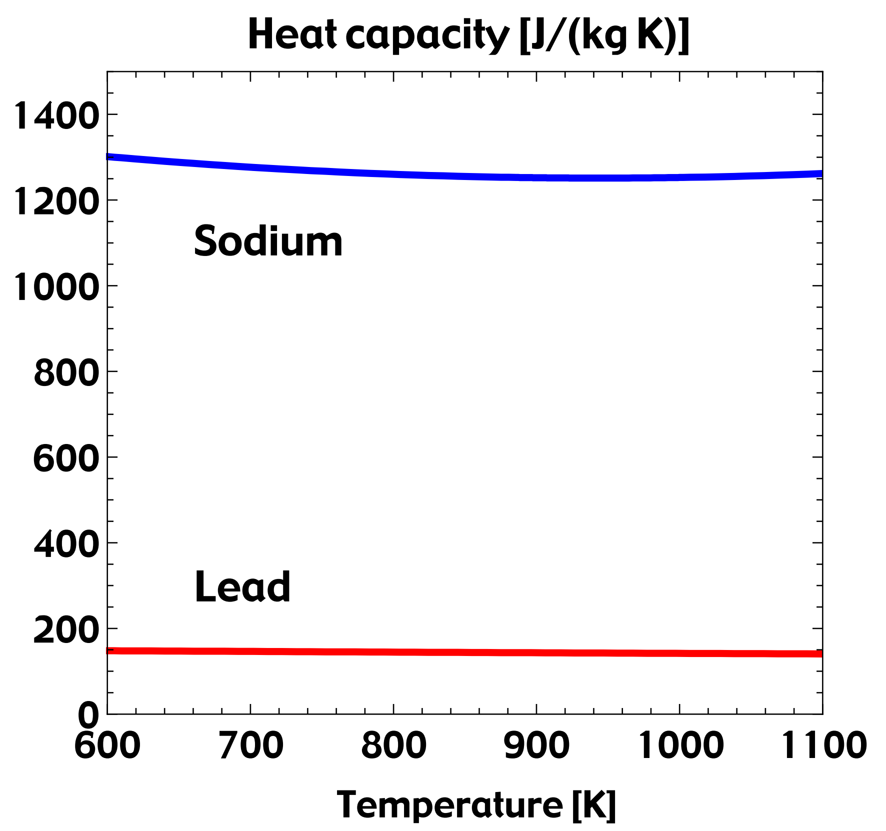


$$T(z) = T_{in} + \frac{L_{fuel}\chi_{ave}}{4\rho_{in}v_{in}A_{flow}c_p}\left(1 + \frac{\sin(\pi z/L_0)}{\sin(\pi L_{fuel}/(2L_0))}\right)$$

Physical properties

- The density of liquid lead is one order of magnitude higher than the density of liquid sodium.
- The opposite holds for the respective specific heat capacity
- The product of density and heat capacity is ≈ 40% higher for lead.





Density

- Sodium density as function of temperature:

$$\rho_{Na}(T) = 1012 - 0.2205T - 1.923 \times 10^{-5}T^2 + 5.637 \times 10^{-9}T^3$$

- Lead density as function of temperature (LBE handbook):

$$\rho_{Pb}(T) = 11441 - 1.2795T$$

- Relative expansion of Na larger than for Pb (2.2% vs 1.1% for $\Delta T = 100$ K)
- Absolute expansion of Pb larger than for Na (130 kg/m^3 vs 22 kg/m^3 for $\Delta T = 100$ K)

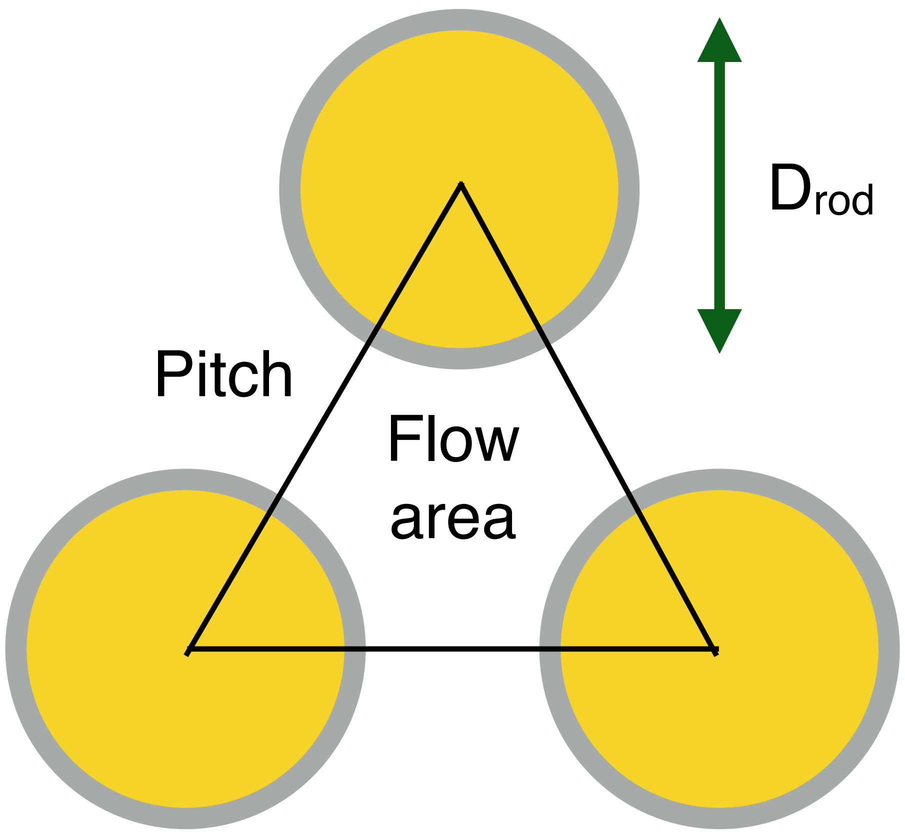
Velocity limitation

- Upper limit for sodium velocity: 7-9 m/s
- Limiting phenomenon: mechanical vibration of fuel assembly
- In lead-bismuth cooled reactors using un-protected stainless steels, velocity is limited to 1.8-1.9 m/s by erosion of protective oxide film on steel surfaces
- In lead-cooled reactors using alumina or silica protected steel surfaces, velocity is limited to < 2 m/s by desire to obtain a pressure drop small enough to remove decay heat by natural convection.

$$\Delta T_{cool} = \frac{Q}{\dot{m} c_p} = \frac{Q}{\rho v A_{flow} c_p}$$

- Coolant flow area in lead must be ≈ 3 times larger than in sodium to achieve the same heat removal rate!

Coolant channel dimensions



$$A_{flow} = P^2\frac{\sqrt{3}}{4} - D^2\frac{\pi}{8}$$

$$\Delta T = \frac{L_{fuel}\chi_{ave}}{2\rho_{in}v_{in}A_{flow}c_p}$$

- Typical design parameters
- Cladding diameter: D_{rod} = 10 mm
- Average linear power: $\chi_{ave} =$ 30 kW/m
- Fuel column height: L_{fuel} =1.0 m
- Sodium velocity: v_{Na} = 8.0 m/s
- ΔT_{Na} = 100 K –> Pitch = ? mm
- Lead velocity: v_{Pb} = 1.5 m/s
- ΔT_{Pb} = 100 K –> Pitch = ? mm

Clad temperature

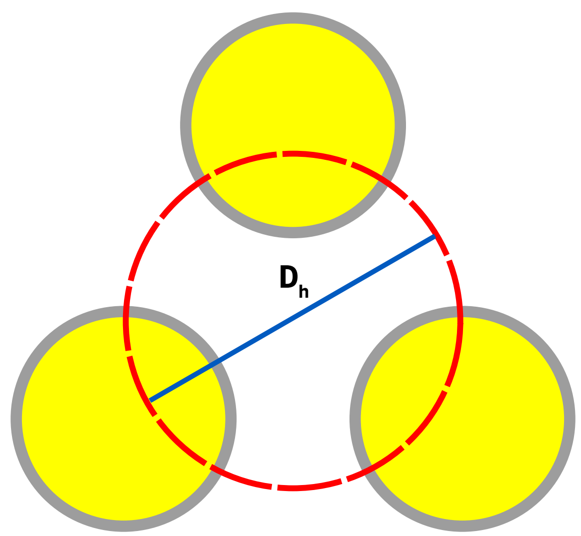
- Heat transfer from fuel clad to bulk coolant leads to temperature difference:

$$h\left(T_{surf} - T_{cool}\right) = \frac{\chi(z)}{\pi D} \qquad\qquad h = \frac{Nu \times k}{D_h}$$

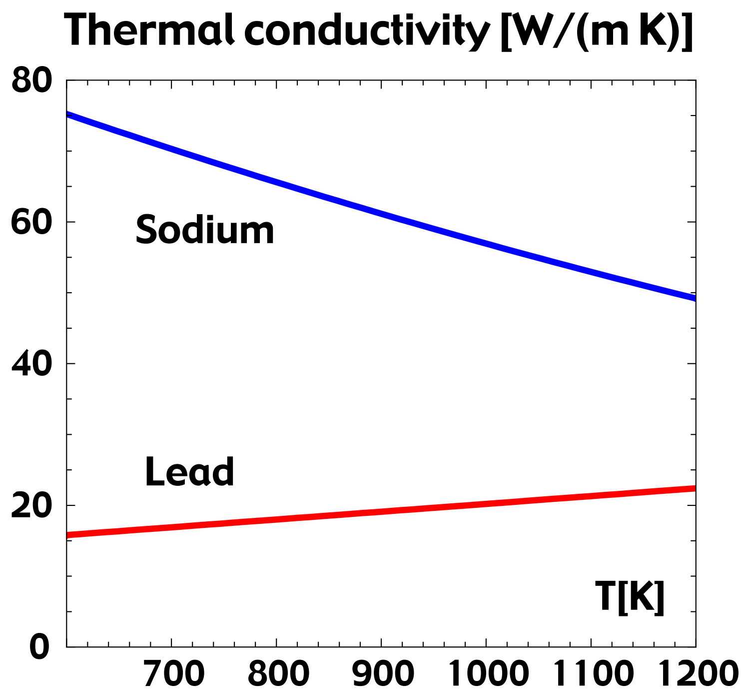
- The heat transfer coefficient depends on thermal conductivity of coolant, on the dimensionless Nusselt number and on the so called hydraulic diameter:

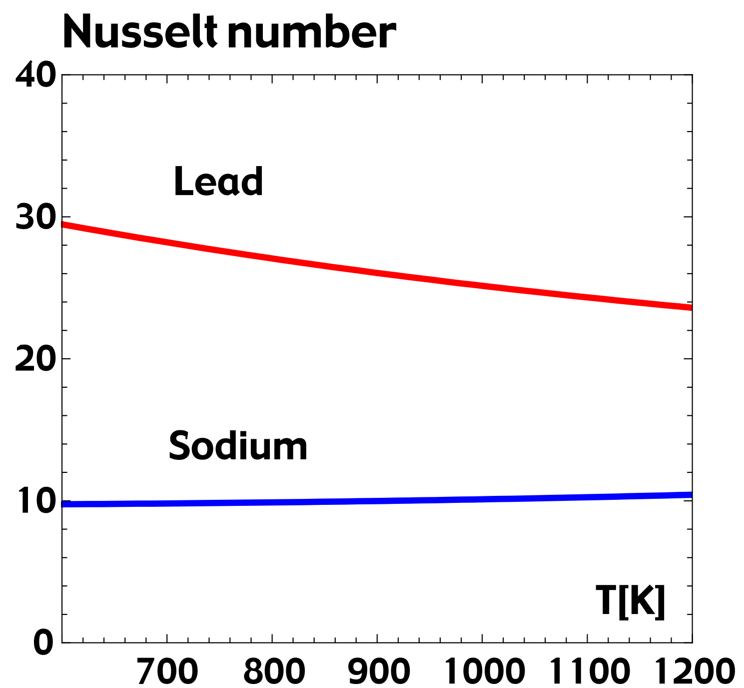
$$D_h = \frac{4A_{flow}}{P_{wet}}$$

$$P_{wet} = \frac{1}{2}\pi D$$



Physical properties





- Thermal conductivity of sodium is larger than for lead

$$k_{Na}(T) = 109.7 - 0.0645T + 1.173\times 10^{-5} T^2$$

$$k_{Pb}(T) = 9.2 + 0.011T$$

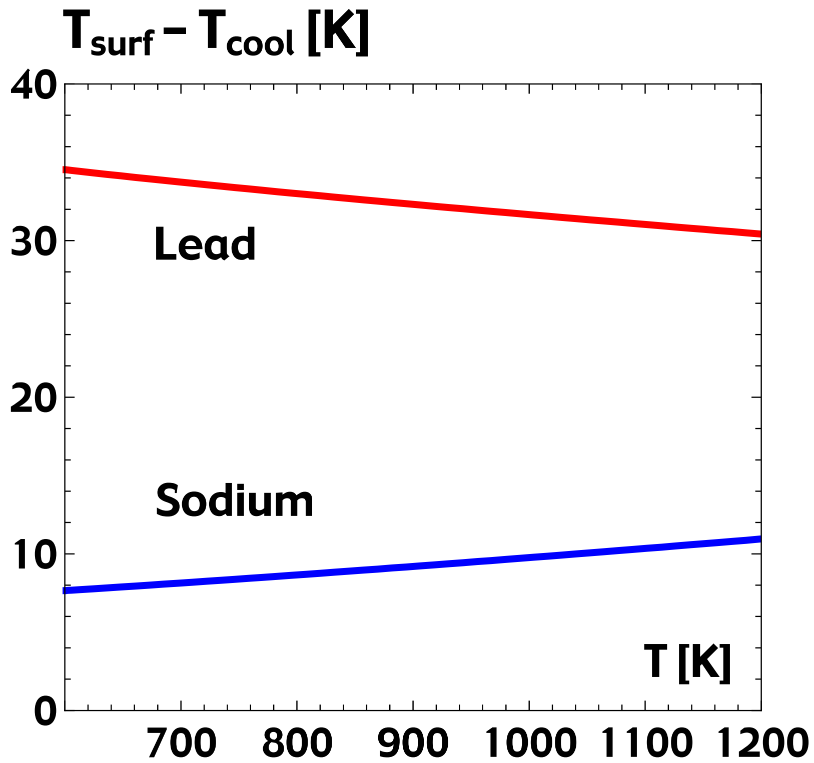
- Nusselt number depends on density, heat capacity, velocity, geometry and thermal conductivity.

$$Nu = 0.047(1 - e^{-3.8(P/D-1)})(Pe^{0.77} + 250)$$

$$Pe = \frac{\rho C_p v D_h}{k}$$

- Reference configuration: $Nu(\mathrm{Pb}) > Nu(\mathrm{Na})$

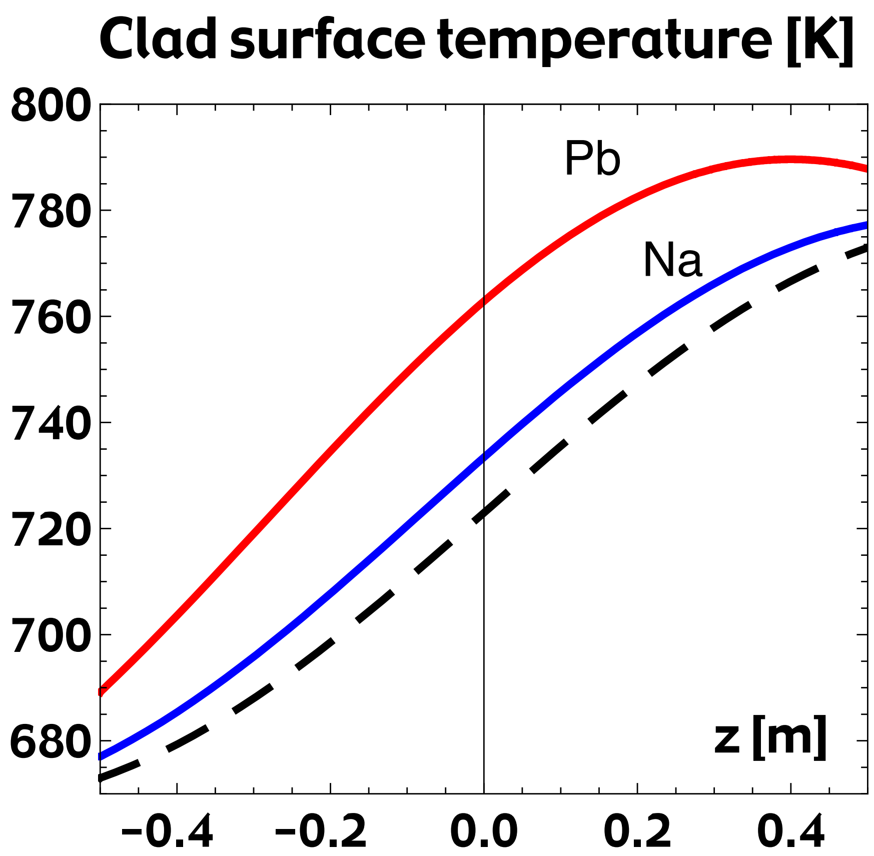
Temperature difference



$$\Delta T(z) = \frac{\chi(z)}{\pi D_{rod}} \frac{D_h}{Nu \times k} \qquad D_h = \frac{4A_{flow}}{P_{wet}}$$

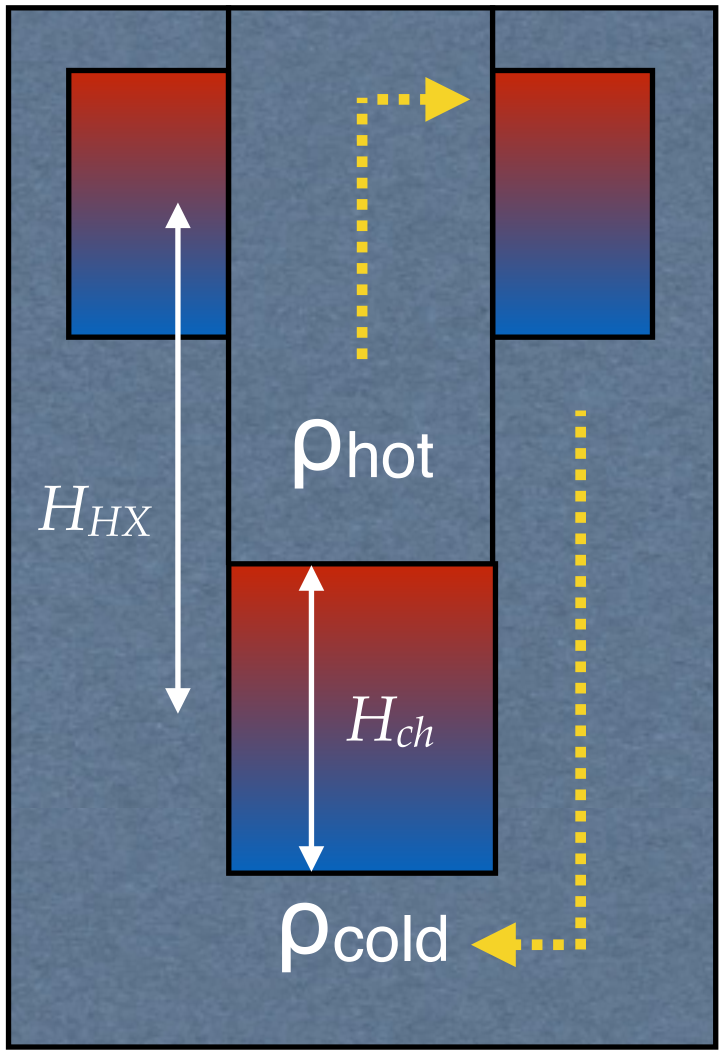
- $Nu\ x\ k$ ~ same for lead and sodium
- D_h ~ 3 times larger for lead
- For same bulk coolant temperature, temperature difference between clad and coolant several times larger in lead

Cladding temperatures



- Due to larger hydraulic diameter, cladding temperatures are significantly higher with lead coolant, even if bulk coolant temperature is the same.
- Maximum cladding temperature is located below the top of the fuel column.

Natural circulation



- Hot coolant above core has lower density than cold coolant at the outlet of the heat exchanger
- Buoyancy pressure head:

$$P_b = gH_{HX}(\rho_{cold} - \rho_{hot})$$

- For fully established natural convection, buoyancy pressure equals pressure losses in core and heat exchanger.
- Pressure drop is proportional to coolant velocity square, e.g. for the channel friction pressure drop:

$$\Delta P_{ch} = f\frac{H_{ch}\rho v^2}{2D_h} = f\frac{H_{ch}\dot{m}^2}{2D_h\rho A_{flow}^2}$$

Volumetric expansion & buoyancy pressure head

$$P_b = gH_{HX}(\rho_{cold} - \rho_{hot})$$

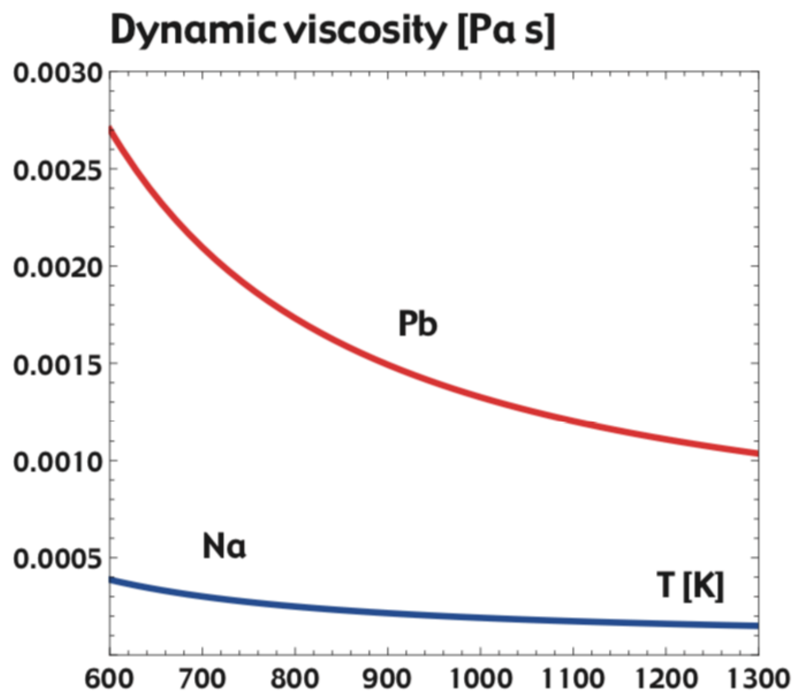
$$\rho_{Na}(T) = 1012 - 0.2205T - 1.923 \times 10^{-5}T^2 + 5.637 \times 10^{-9}T^3$$

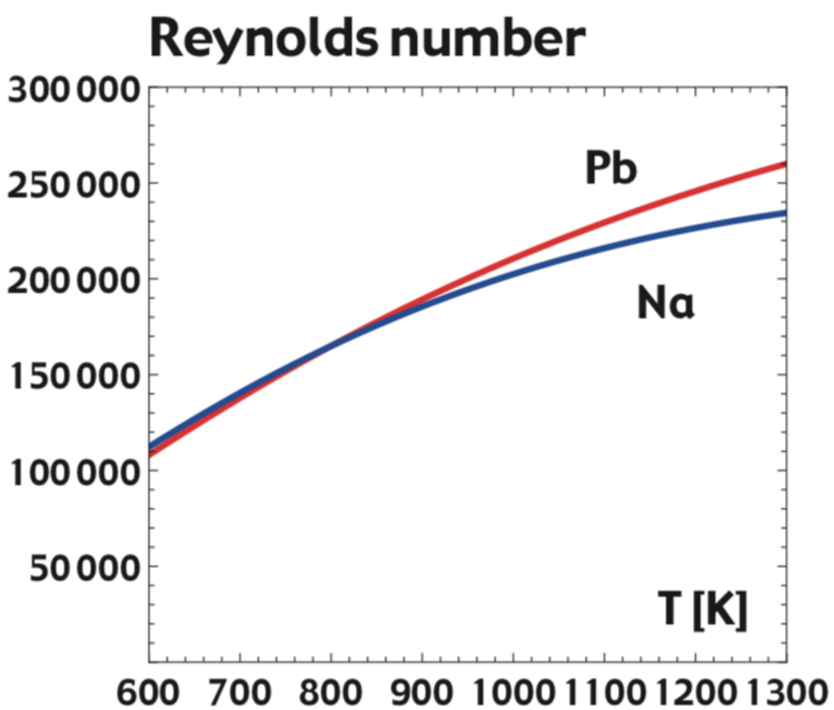
$$\rho_{Pb}(T) = 11441 - 1.2795T$$

$$\Delta T = 100K \rightarrow \Delta\rho_{Na} \simeq 22kg/m^3, \Delta\rho_{Pb} \simeq 128kg/m^3$$

- More than five times higher pressure head in a lead-cooled reactor
- Attainable buoyancy pressure head ≈ 1 kPa/m elevation of steam generator in a liquid lead cooled reactor

Channel pressure drop





$$\Delta P_{ch} = f\,\frac{H_{ch}\rho v^2}{2D_h} = f\,\frac{H_{ch}\dot{m}^2}{2D_h\rho A_{flow}^2}$$

$$f = \frac{0.316}{Re^{0.25}}, \quad Re = \frac{\rho v D_h}{\mu}$$

- Reynolds numbers, hence friction factors are similar for typical geometries of Na and Pb cooled reactors.

Coolant	Na	Pb
ρ	1	12
v^2	1	0.05
D_h	1	3
ΔP_{ch}	1	0.2

Home assignment 3

- Calculate the pin pitch required to keep the maximum fuel cladding temperature in the hottest rod below T = 820 K in sodium and lead, assuming
- D_{rod} = 10.0 mm, L_{fuel} = 100 cm.
- v_{Pb} = 1.5 m/s, v_{Na} = 8.0 m/s
- Pin **average** linear power density χ_{ave}= 20 kW/m
- Core inlet temperature of 670 K (remains constant during the transient)
- Calculate the heat transfer coefficient at the begin and end of fuel rod
- Calculate the vertical elevation of the decay heat removal heat exchanger (H_{HX}) required for the cladding of the hottest rod to survive an unprotected loss of flow accident (ULOF) with lead and sodium coolants, assuming
- H_{ch} = 150 cm, $\mu_{Pb}(T) = 4.55 \times 10^{-4} \exp(1069/T)$ $\mu_{Na}(T) = \exp\left(-6.4406 - 0.3958\ ln(T) + \frac{556.835}{T}\right)$
- Decay heat average linear power density = 1.5 kW/m
- $\Delta T_{coolant}$ = 100 K, over core during natural convection conditions.
- Total pressure drop in system = 2 ΔP_{ch}