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Tubular Sodium Receivers

An investigation into the limits of using liquid sodium in tubular receivers

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Liquid sodium has a heat conductivity far superior to other common heat transfer fluid contenders, such as thermal oil or molten salt. Thermodynamic modelling [1] has observed that its use could increase the exergetic efficiency of tubular receivers by maintaining lower tube surface temperature while withstanding higher fluid outlet temperatures, potentially decreasing a receiver's size or improving it's performance.

Focus

Tubes are used extensively on high temperature solar receivers because they are good pressure vessels, the flow within them is well understood and individual tubes are allowed to thermally deform independent from one another. Optimisation of tubes for a specific fluid and receiver configuration requires an accurate understanding of loss mechanisms (radiation, convection, conduction and friction), an appreciation of the limits of the heat transfer fluid used (for example maximum temperature), and an awareness of the thermal elastic stress created from temperature gradients within the tube.

A close look at tube temperatures carrying liquid sodium [2] revealed that maximum tube temperatures are kept lower and higher solar fluxes would be permissible given that state-of-the-art tube materials increasingly lose resistance to thermal stress at temperatures above 600 °C. It was also found that tube efficiency – measured as the net heat flux transferred to the fluid divided by the heat flux incident on the tube's surface – was largely insensitive to a range of tube dimensions and flow velocities. Liquid sodium outperforms molten salt even at large tube diameters and low flow velocities when compared by this metric, as illustrated in Fig. 1.

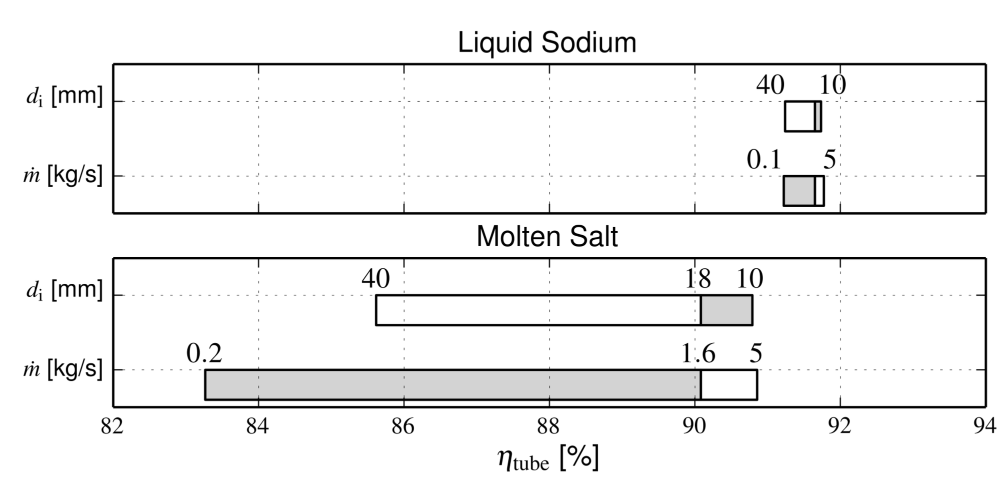


Figure 1: Tornado chart showing the dependency of Inconel® 625LCF tube efficiency on tube diameter d_i and mass flow $\dot{m}$ for liquid sodium and molten salt

The model has been further developed to calculate thermal-elastic stress and deformation of material. Following validation against established literature, component stresses in polar coordinates and how they relate to the common engineering quantity of "equivalent" or "von Mises" stress is illustrated in Fig. 2.

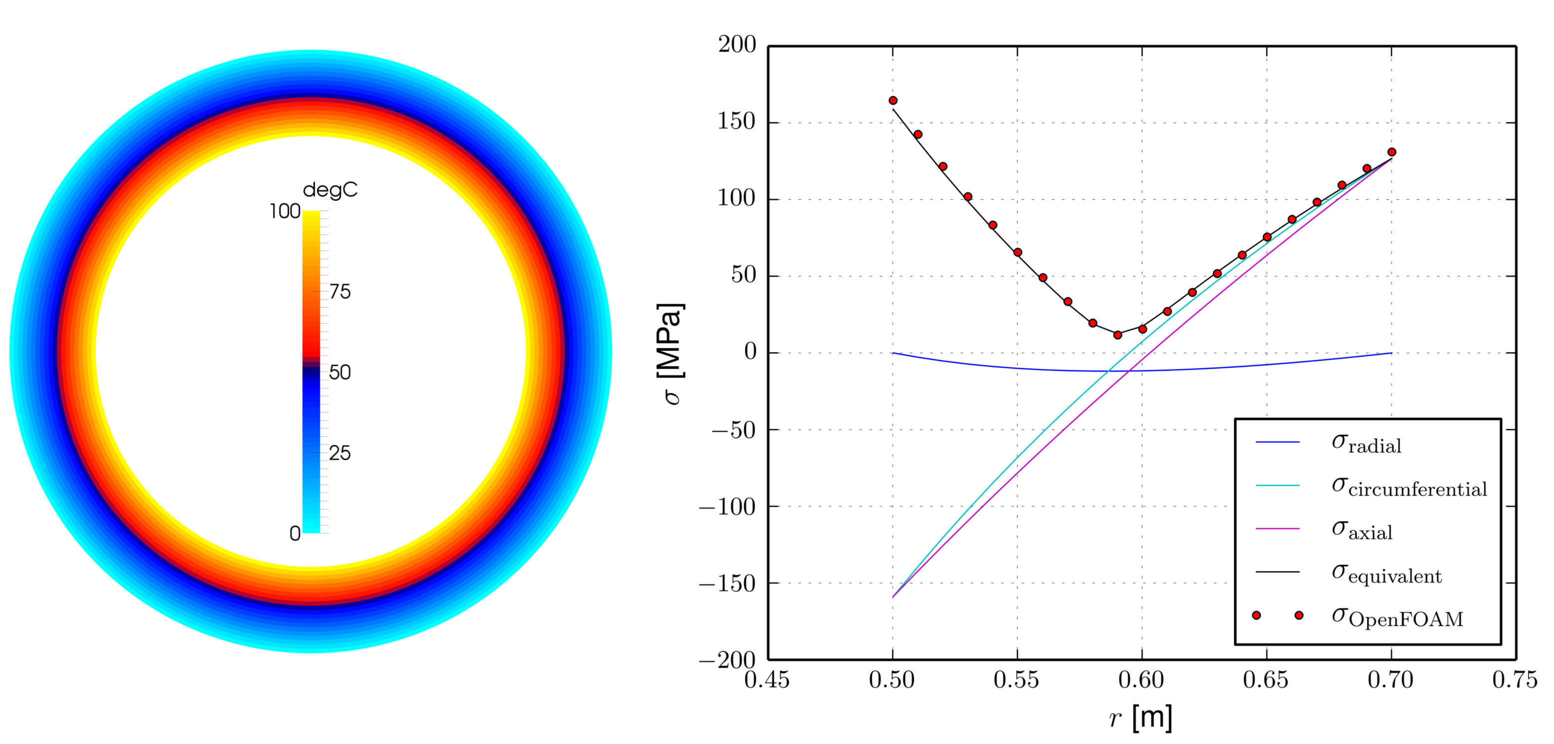
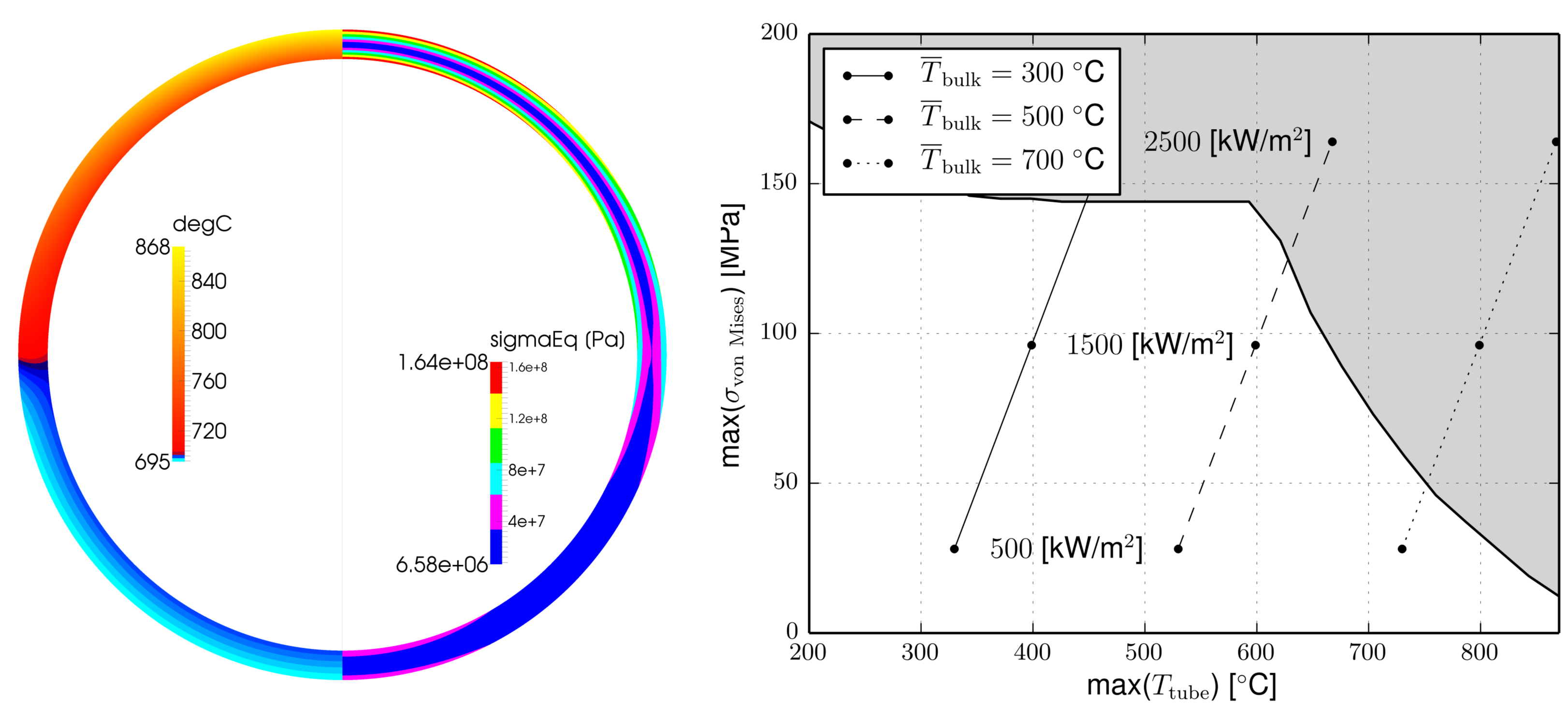


Figure 2: Validation of the Finite Volume Model (FVM) thermal-stress solver for a thick-walled tube with isothermally differing wall temperatures (shown left) and analytically obtained principal polar coordinate stress compared with values at discrete cell points from the OpenFOAM solver sampled radially (on the right); compressive is negative and tensile is positive

The common held knowledge that materials are stronger in compression as they are in tension does not apply here. High temperature alloys become increasingly ductile from 600 °C up to their workable limit around 900 °C, and as such succumb to creep-rupture and low-cycle fatigue in both compression and tension. In addition, it is apparent from Figs. 2 and 3(a) that compression on the hot side of the tube is almost equalled by tension on the cold side, and that peak stress occurs where the tube is most exposed to incident flux.



(a): Tube temperature (left) and equivalent stress (right) with a collimated heat flux of 2500 kW/m² and bulk sodium temperature 700 °C

(b): Peak equivalent stress versus peak tube temperature of a range of heat fluxes and bulk sodium temperatures; unshaded region is acceptable (ASME Code Case No. 2063)

Figure 3: Thermal stress in an exemplary length of 20mm Haynes® tube (1mm wall thickness) using liquid sodium as a heat transfer fluid

For the modelling presented in Fig. 3(b), it becomes apparent that tubular receiver design must carefully consider the fluid's path through regions of appropriate heat flux. Tubes with bulk fluid at temperatures below 500 °C can withstand flux as high as 2200 kW/m², but as bulk sodium temperatures rise above 500 °C flux needs to be continually decreased to around 800 kW/m² when bulk sodium temperature is 700 °C.

Outlook

The activities being pursued in parallel at present:

- Calorimetric measurements in laboratory experiments on tubes in the ANU's solar simulator circulated with liquid sodium.
- High performance computations using National Computational Infrastructure (NCI) at the ANU to validate Computational Fluid Dynamic modelling of liquid sodium (very low Prandtl Number). This will be coupled to the thermal-elastic model for the exploration of various receiver flow path configurations.
- Development of thermal-visco-elastic modelling to account for relaxation with time-series data from select manufacturers.
- Explorations in 1D steady-state/transient models of a tubular receiver under expected operating conditions to elicit the accumulation of fatigue and creep.

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