Preliminary numerical study of flow and heat transfer characteristics in a simplified dual fluid reactor

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

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New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17

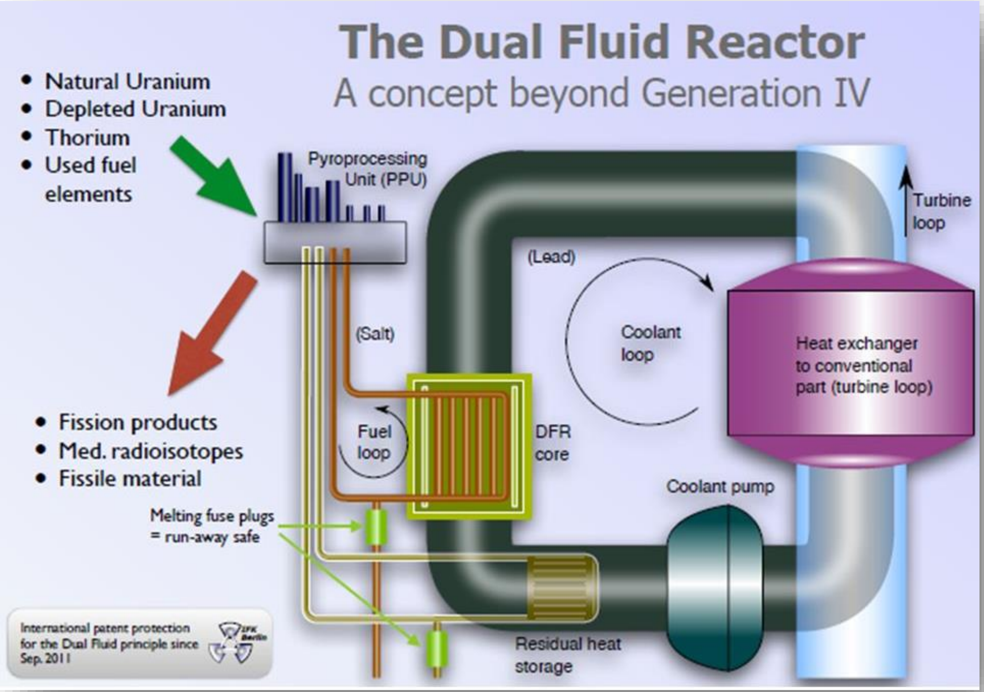
Outline

- Dual fluid reactor
- Mini-demonstrator of DFR
  - -Loops schematic design
  - -Core description
- CFD modeling of molten metals
  - - Liquid lead properties
  - - CFD modeling problem
  - - Operational conditions of MD
  - - K-omega SST model
- Towards k-omega SST model validation
  - - Tall facility experiment
  - - Simulation results
- Conclusions

A- Description of reactor mechanism

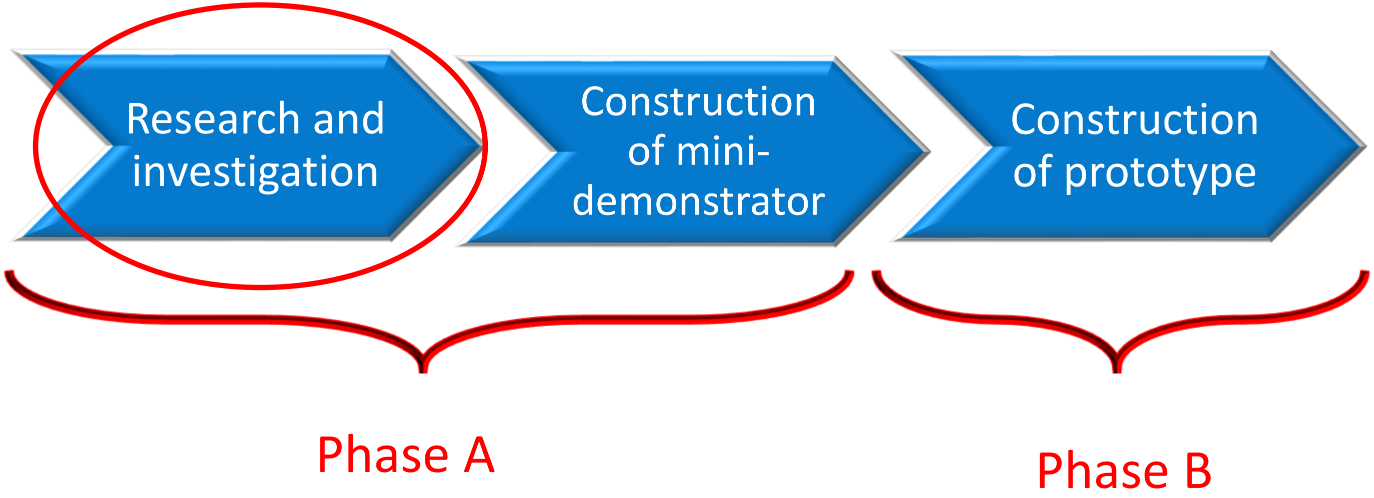
Fuel: Uranium- Chromium Eutectic loop.

Coolant: Molten Lead loop.



Dual fluid reactor (2)

B- Development sequence



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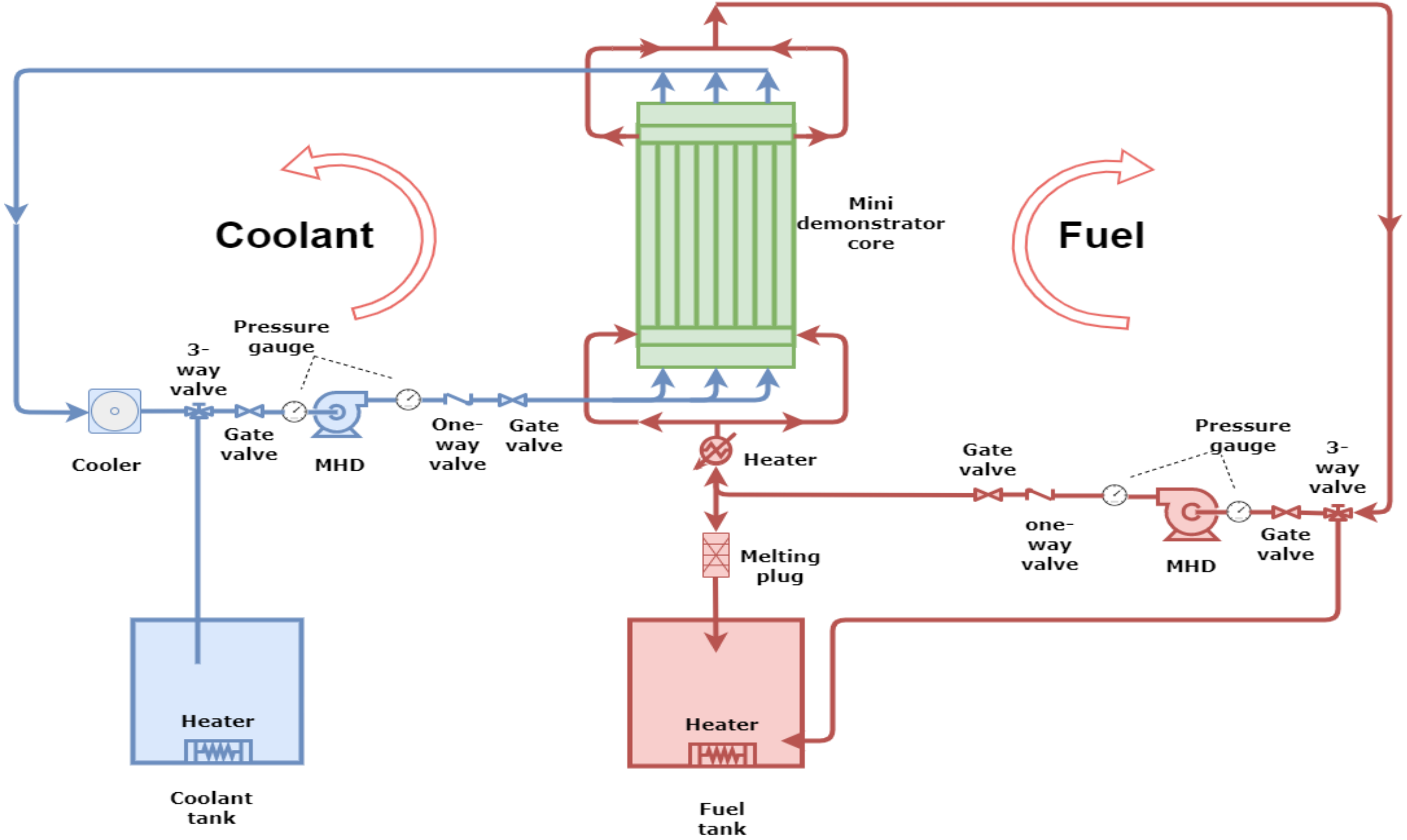
A- liquid lead – lead loops description



B- Core Description.

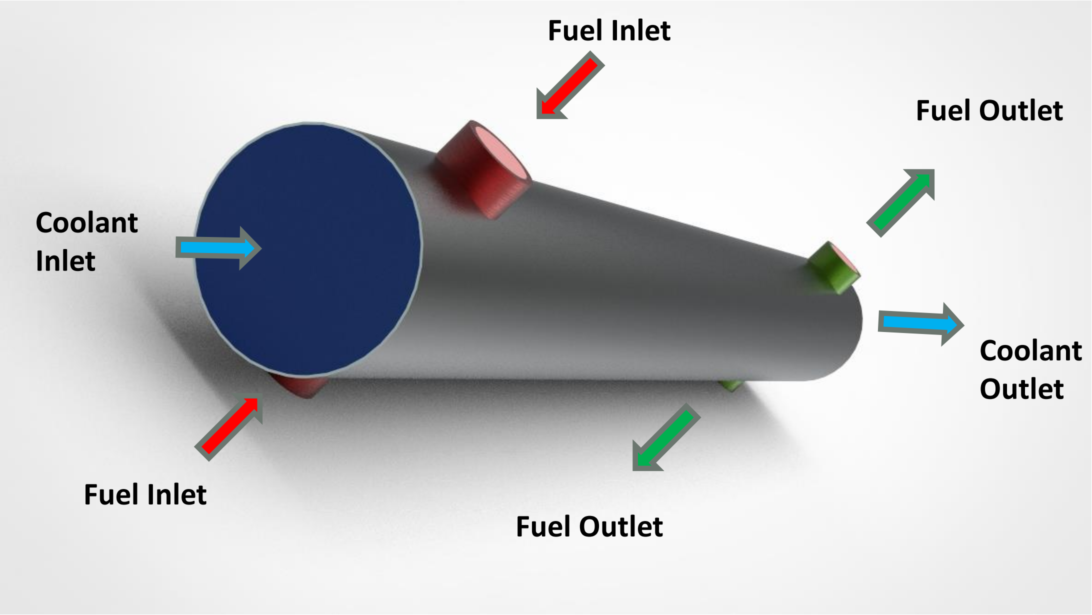
The mini-demonstrator core consists of:

- Two fuel Inlets and two fuel outlets, one coolant inlet and another outlet.

- 7 fuel pipes.

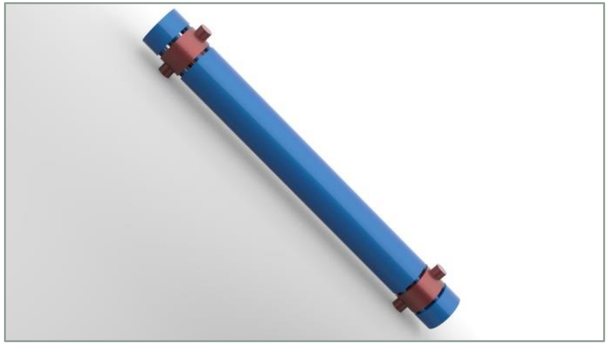
-12 coolant pipes on each side.

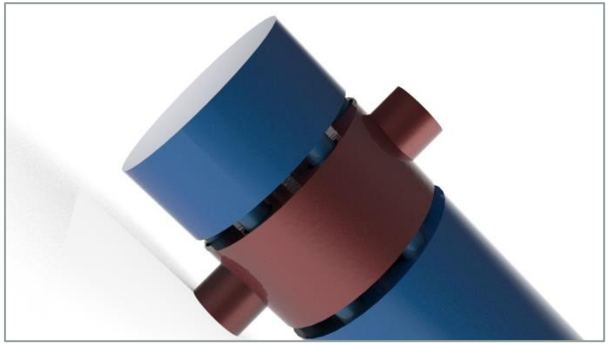
- Distribution zone and collection zone separated from the core by four separation discs.



B- Core Description (2)

Parameter	Values
Core zone inside Diameter D_{in} (mm)	130
Core zone Outside Diameter D_{out} (mm)	133
Core zone height H_{core} (mm)	880
Distribution zone D_{in} /H_{DZ} (mm)	130/70
Collection zone D_{in} /H_{CZ} (mm)	130/70
Number of fuel pipes	7
Fuel pin pitch (mm)	28
Outside/inside fuel tube diameter (mm)	23 / 19
Outside/inside large coolant tube diameter (mm)	23 / 19
Outside/inside Small coolant tube diameter (mm)	10 / 08



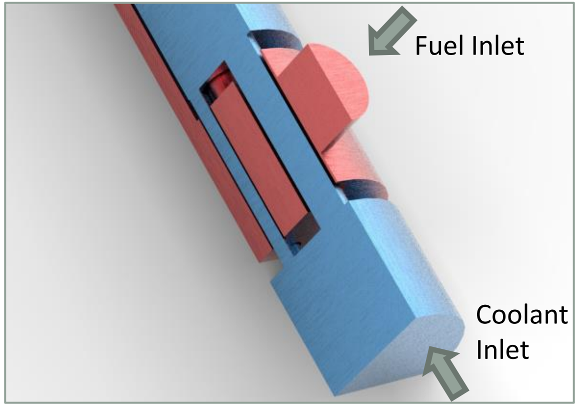


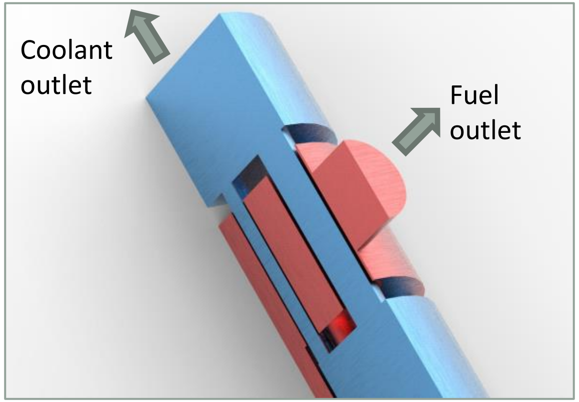
Mini-Demonstrator – cont.

B- Core Description (3)

The first figure *(up-right)* shows the collection zone; where the coolant is being collected from the pipes coming from the core to the outside of the MD. As well, fuel exits after collection from the fuel pipes.

- The second figure *(down-right)* explains the distribution zone where coolant and fuel find their ways to the core, fuel in pipes, and coolant filling the core.



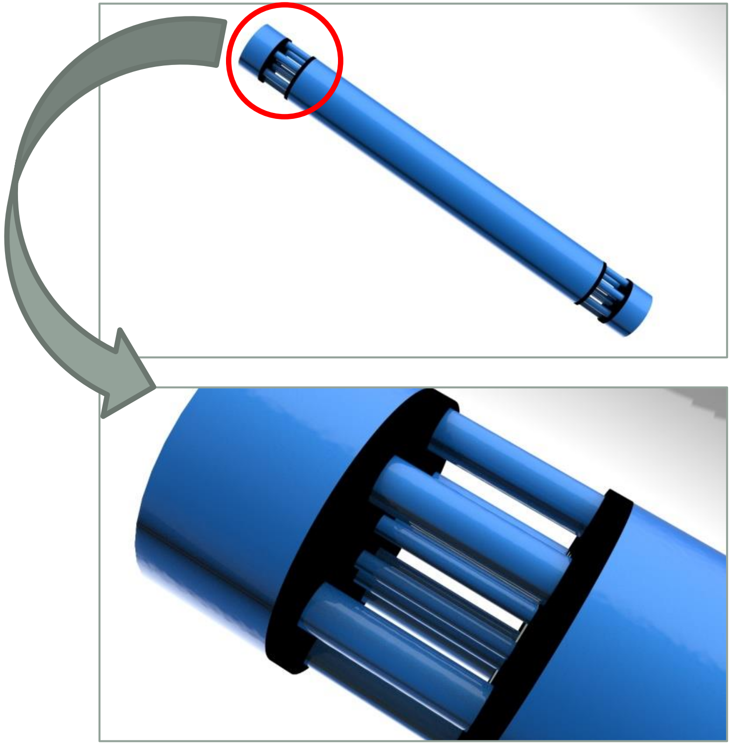


B- Core Description (4)

Coolant domain:

- Passes from the coolant inlet to the core.

- Coolant penetrates the distribution zone through 12 pipes (two different diameters)

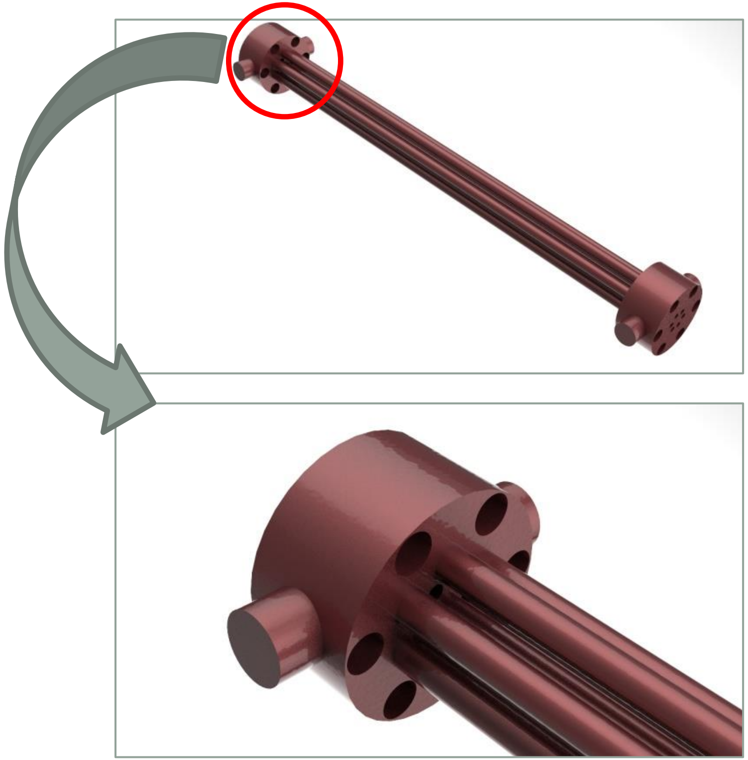


B- Core Description (4)

Fuel domain:

- Enters to the distribution zone directly.

- Go through the core in 7 pipes to the exit in the collection zone.



CFD modeling of molten metals (liquid lead)

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Molten lead properties *(Temperature rang 400-500 K)*

- High viscosity *(2.9 -2.3 *10-^{3} Pa.s).*
- High conductivity *(9-11 W/m.K).*
- High density *(>10,000 kg/m^{3}).*
- High Thermal diffusivity.
- Low momentum diffusivity.
- Relatively low melting point *(327 °C).*

Low Prandtl number!

CFD modeling of molten metals (liquid lead)

Are the current CFD models sufficient to model molten metals?

Not Exactly!

- The current RANS models, were not implemented for molten metal (very low Pr number fluids).
- Validation is essential!

CFD modeling of liquid lead in the MD

Operational conditions of mini-demonstrator

- Low inlet velocities (0.1 - 0.5 m/s)
- High Re (>15,000)
- Low Pr (<0.01)

CFD modeling of liquid lead in the MD

The Mini-demonstrator consists of:

- A distribution zone
- A collection zone
- Seven fuel pipes
- 24 coolant pipes

The complicated geometry results in low velocities but significant turbulence formed by strong mixing!

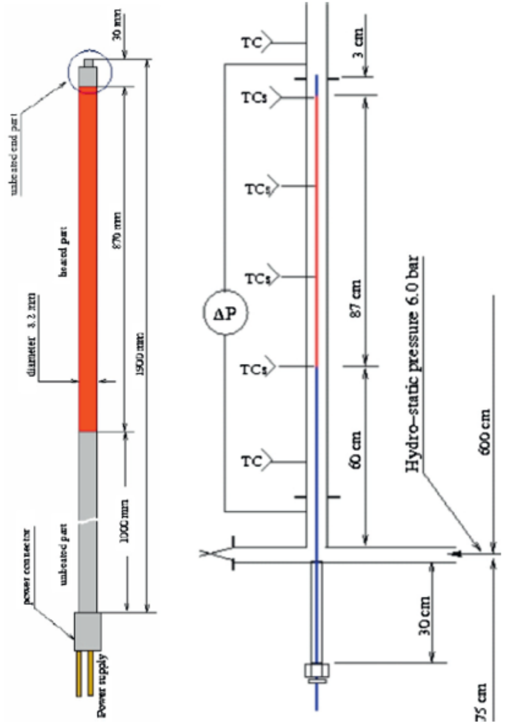
CFD modeling of liquid lead in the MD

Validation approach of K-omega SST model:

Tall facility *(KTH, Stockholm)*

Liquid lead bismuth eutectic running in an annulus cross section around a constant heat generation heater.

Source: Experimental and numerical study on lead–bismuth heat transfer in a fuel rod simulator.



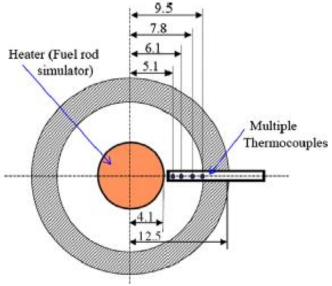
(a) Fuel rod simulator (b) Core simulator

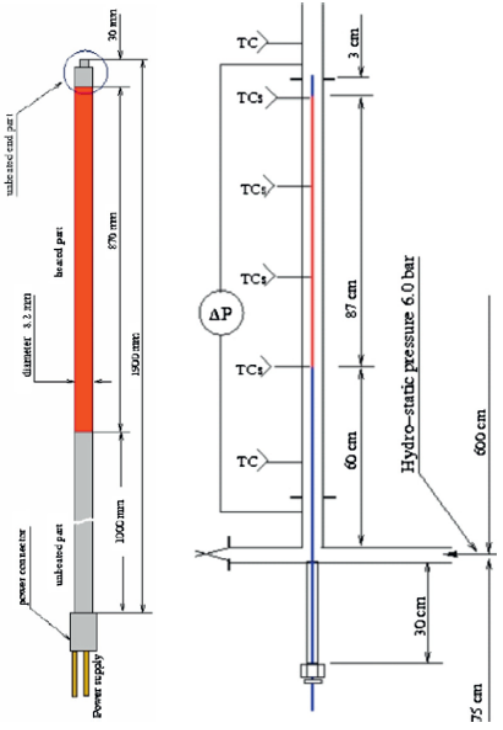
CFD modeling of liquid lead in the MD

Validation approach of K-omega SST model:

Tall facility *(KTH, Stockholm)*

- An experiment has been conducted to measure temperature in four levels of in the testing section.
- Each section has four thermocouples.





(a) Fuel rod simulator *(b) Core simulator*

Source: Experimental and numerical study on lead–bismuth heat transfer in a fuel rod simulator.

CFD modeling of liquid lead in the MD

Validation approach of K-omega SST model:

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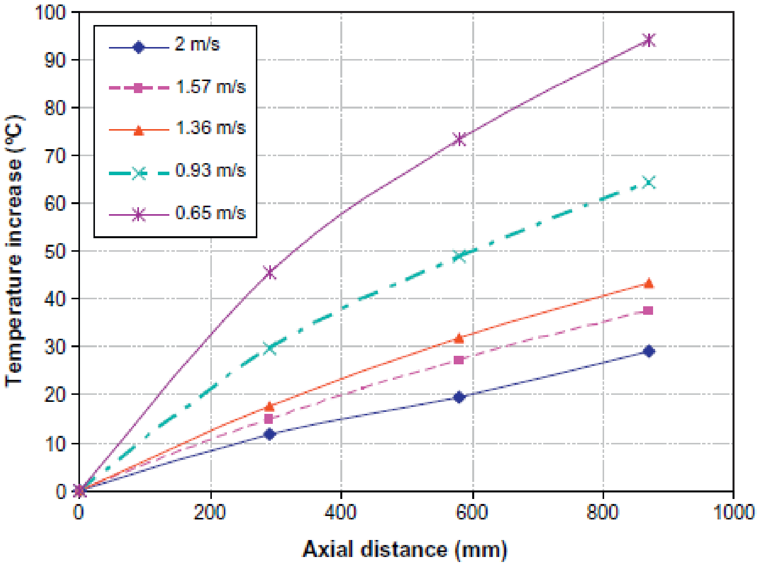


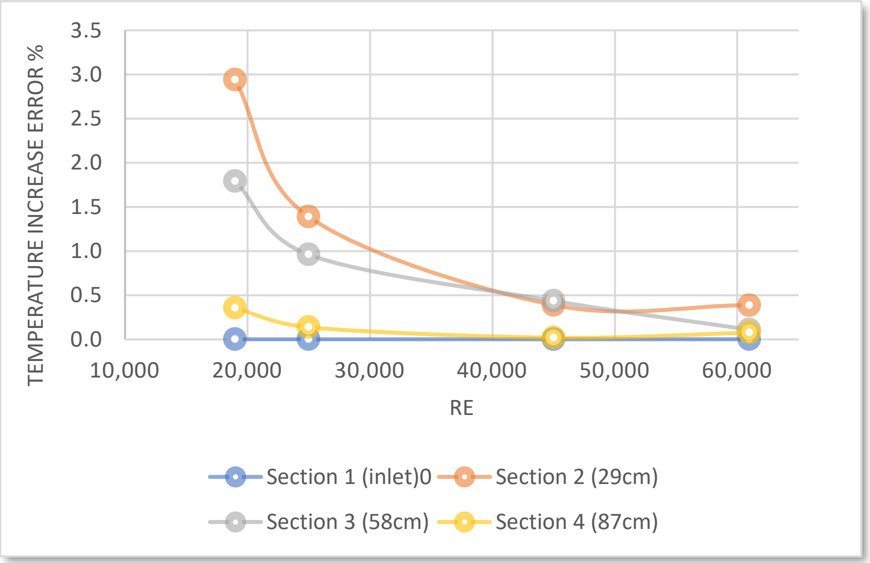
- Higher velocity
- Higher heat transfer rate
- Lower temperature!

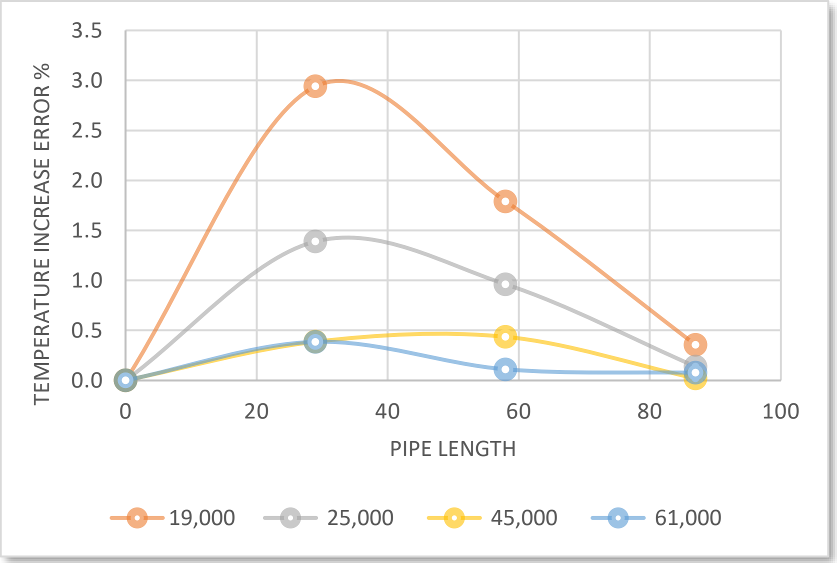
Source: Experimental and numerical study on lead–bismuth heat transfer in a fuel rod simulator.

CFD modeling of liquid lead in the MD

Validation approach of K-omega SST model:

Results

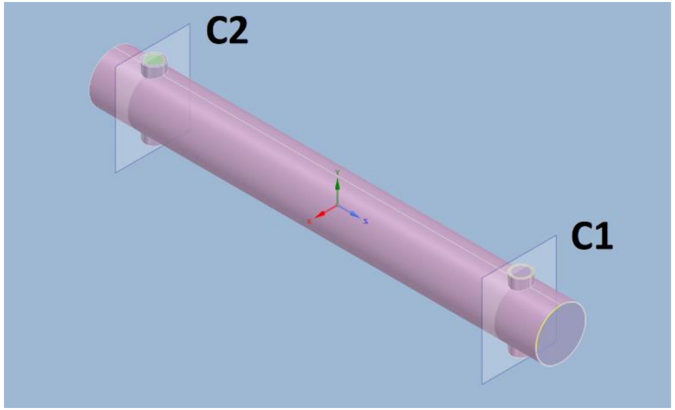


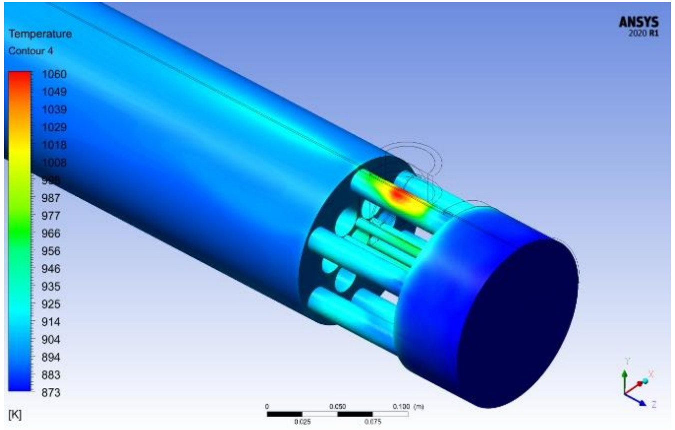


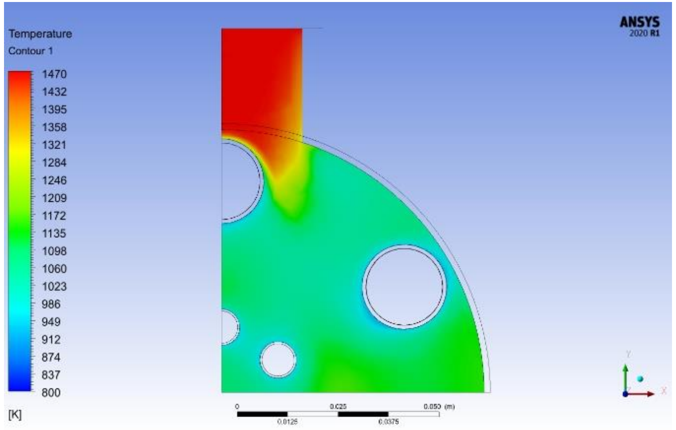
Examples of MD preliminary analysis observations

A **hot spot** has been observed in coolant pipe with temperature difference up to 130 degree.

Recommendation: hot spots should be avoided, adding more fuel inlets (not directly facing coolant pipes)







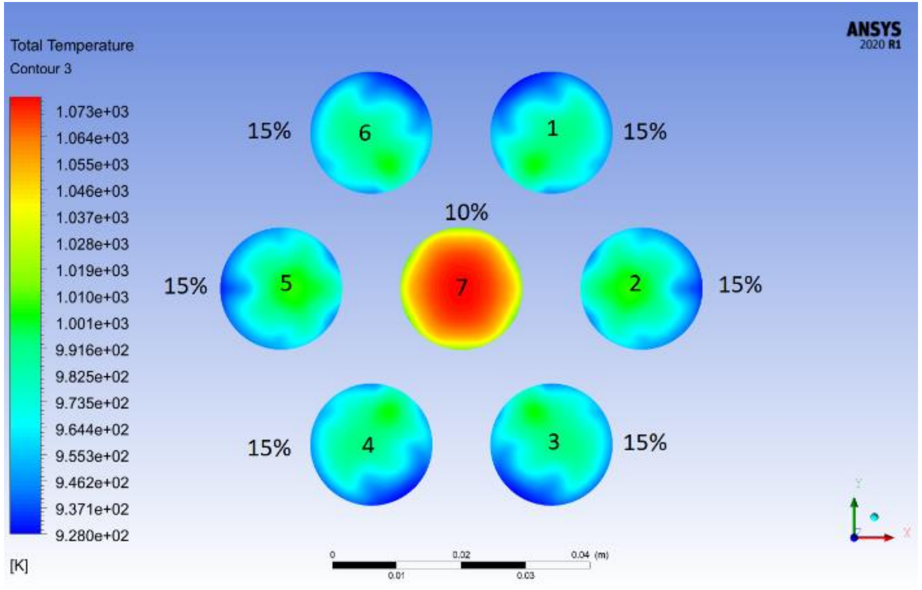
Examples of MD preliminary analysis observations

Heat transfer in the lateral fuel pipes are almost double the middle pipe.

Recommendation: high temperature difference in the core (non-homogeneous temperature distribution) should be decreased/controlled.

Increasing pitch and/or increase coolant mass flux.

Note: no heat generation, same inlet temperature.



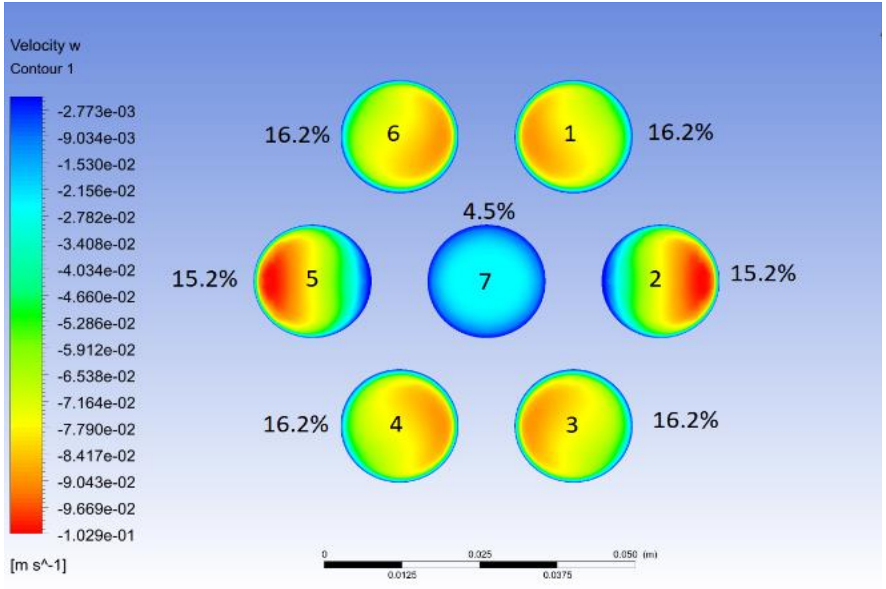
Temperature contours at inlet of fuel pipes and percentage of heat transfer in the pipe to total in core

Examples of MD preliminary analysis observations

Mass flow rate in lateral pipes are much higher than in the middle pipe.

Recommendation: fuel low mass flow rate should be avoided specially in high temperature pipes.

Testing different fuel inlet configurations in the distribution and collection zones (e.g. increase number of fuel inlets/outlets).



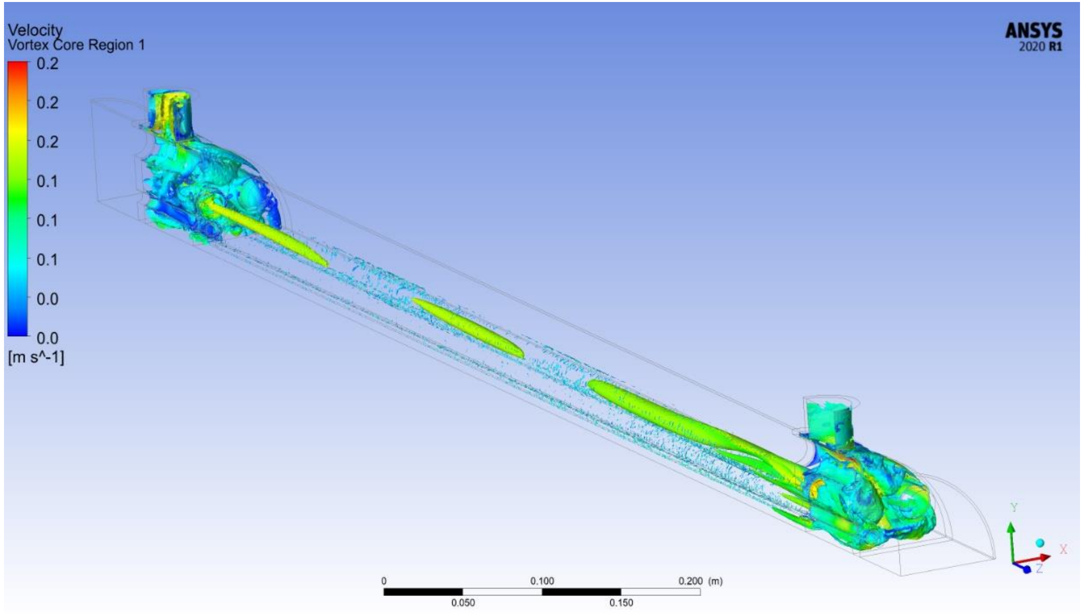
Velocity contours at inlet of the fuel pipes and percentages of mass flow rate in the pipe to total fuel flow in core

Examples of MD preliminary analysis observations

Swirling patterns have been observed in fuel pipes. Swirling may cause vibration and fatigue stresses on pipe structure.

Recommendation: The resulted vibration should be tested vs fuel/coolant velocities then the observed stresses should be compared to the material strength and design parameters.

If needed; turbulence stabilizers can be added (e.g. honeycombs)



Q-criterion level 0.0002 with variable velocity

Conclusions

- Although RANS models for low Pr number and high Re number flows may result in over or under predictions of heat transfer parameters, some can be reliable after validation in similar conditions.

- K-omega SST model showed a fairly acceptable accuracy when compared to experiment and can be considered reliable for low Pr number flows modeling to some extend. However, more validation is definitely required.

- Flow and heat transfer optimization based on comprehensive CFD analyses may be necessary for both the MD and DFR designs.

Thank you for attention

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