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Heat Transfer Characteristics of liquid metal Fast reactors

Presented By

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Presentation Outline

- **Introduction**
- **Objective**
- **Numerical Simulation**
- **Results and discussion**
- **Conclusions and recommendation for future work**

Introduction

- From thermal hydraulic points of view, the research gaps and modelling challenges in LMFR are mainly related to two points.
- First, the heat transfer characteristic of liquid metal is clearly different from that of the conventional fluids (air and water) because of its very low value of Prandtl number.
- Second, the special pool-type design causes the thermal hydraulic phenomena like natural circulation and stratification to have a great impact on LMFR

Introduction

- The limited benchmarking data for LMFR is due to the difficulties associated with measuring of the fluid velocity and temperature fields in liquid metal.
- Thermal hydraulic characteristics of liquid metal are an important area of research because it’s the main working fluid for breeder reactor, nuclear reactor that produces more fissionable material than it consumes to generate nuclear energy
- The fundamental value of nuclear energy in the long term may not be fully employed unless more reserves of natural uranium are found or until significant progress is conducted for effective using of uranium
- Many of the present issues that face the nuclear industry require extended and reliable knowledge of the characteristics of turbulent flow and heat transfer in liquid metals

Introduction

- **Diffusion in fluid and solids**
- $v = \frac{\mu}{\rho}$**, Is the kinematic viscosity**
- **is also known as momentum diffusivity. It has the same units as thermal diffusivity**
- **It can be used to calculate the speed that momentum (rather than heat) diffuses through a fluid**
- $Speed\ of\ heat\ diffusion\ in\ solid$

$$U = \frac{\alpha}{L}$$

- $Speed\ of\ momentum\ diffusion\ in\ fluid$

$$U = \frac{v}{L}$$

- **Liquid metal the working fluids in LMFR has low momentum diffusivity and high thermal diffusivity**

Objective

- Liquid metal diffuses heat rapid than momentum

- With the increased computational resources, three-dimensional Computational Fluid Dynamics (CFD) simulations allow adequate details about the heat transfer characteristics of liquid metals

Objective(cont.)

- In the present work, a full three-dimensional CFD study is conducted for 5x5 vertical rods bundle cooled with liquid lead as coolant.

- The wire wrap spacer in LMFR acts as a momentum exchange promoter in addition to its main function for keeping the inter-rods spacing for the fuel bundle.

- Wire wrap spacer with twisting pitches ratios of 5, 10, 20, 30, and 40 of the rod diameters are considered in this work

Numerical Simulation

Model Assumption

- **The flow is 3-dimensional.**
- **The flow is incompressible, steady and turbulent.**
- **The thermo-physical properties are constant except for the liquid lead which is specified as a function of temperature.**
- **The effect of radiation and natural convection is negligible.**

Numerical Simulation (cont.)

Mathematical Model Overview

Governing Equations	liquid lead Properties	Sub-Models
➢ Continuity ➢ Momentum ➢ Energy	1. ρ 2. μ 3. K 4. C_P	1. Turbulence Modeling (K-ε Model and (SST) k–ω model) 2. Near-Wall Treatment (Enhanced Wall Treatment) 3. Reactor point kinetics model

Numerical Simulation (cont.)

Mathematical Model Overview

Table 1 Simulation domain parameters and boundary conditions

Physical domain boundary conditions	• **Mass flow inlet boundary condition at inlet to the bundle** • **Pressure outlet at bundle outlet** • **Wall (No slip conditions) at all other boundary of the simulation domain.**
Wire wrap spacer pitch	5d, 10 d, 20 d, 30 d, and 40 d. where d is the rods diameter
bundle power	16 KW, Chopped cosine shape distribution
Inlet mass flow rate	5.6 kg/s
Liquid lead inlet temperature	693 K

Numerical Simulation (cont.)

Mathematical Model Overview

Liquid lead thermophysical properties used in the model

Property	Correlation	Applicable range
ρ	$11441 - 1.2795T$	$600 < T < 1500$
C_p	$176.2 - 4.923x10^{-2}T$ $+ 1.544x10^{-5}T^2$ $- 1.524x10^{-6}T^{-2}$	$600 < T < 1500$
k	$9.2 + 0.011T$	$600 < T < 1300$
μ	$4.55x\ 10^{-4}e^{1069/T}$	$600 < T < 1473$

The average heat transfer coefficient of the rods bundle is calculated as follows

$h=qA(Tave-Tin)$

where q is the bundle power, $Tave$ is the average rods bundle temperature computed from the simulation results.

Numerical Simulation (cont.)

Governing Equations

- **Based on mentioned assumption the governing equations takes the following form:**

- **Mass Conservation Equation:** $\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho V_i)=0$

- **Momentum Conservation Equation:**

$$\frac{\partial}{\partial t}(\rho V_i)+\frac{\partial}{\partial x_j}(\rho V_i V_j) = -\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}$$

- **Energy Conservation Equation:**

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}[V_i(\rho E+p)] = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+\frac{\partial}{\partial x_i}(\tau_{ij}V_i)+S_h$$

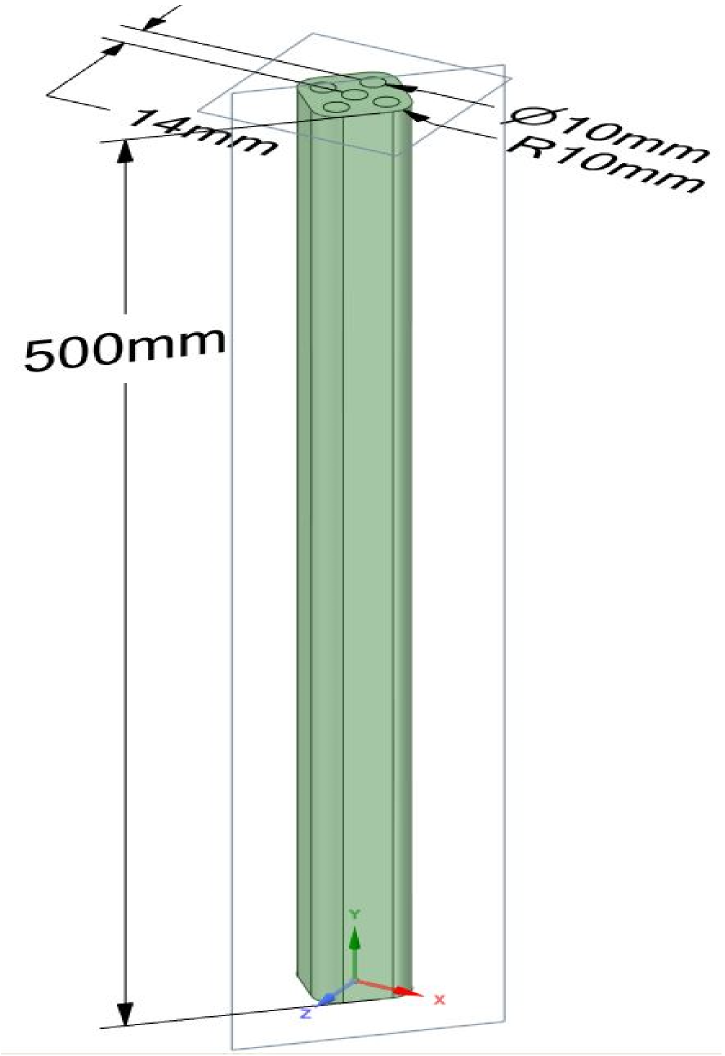
Numerical Simulation (cont.)

Turbulence model

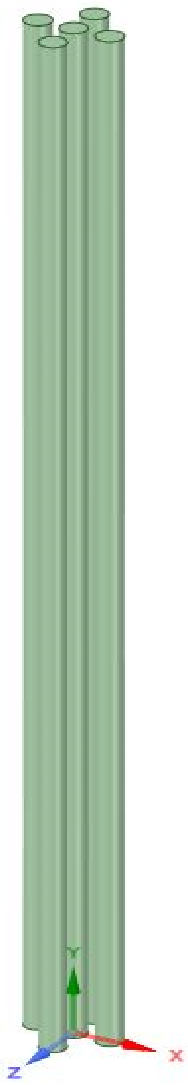
- The shear-stress transport (SST) k–ω model with the transitional flows option active is used for turbulence modeling during transient.

- The (SST) k–ω model has basically the same formulation as the standard k-ω model but it includes blending function to activate and take the advantage of the k-ω model in the near wall region or the transformed k-ε away from the wall region. In addition the definition of turbulent viscosity is modified to account for the transport of the turbulent shear stress.

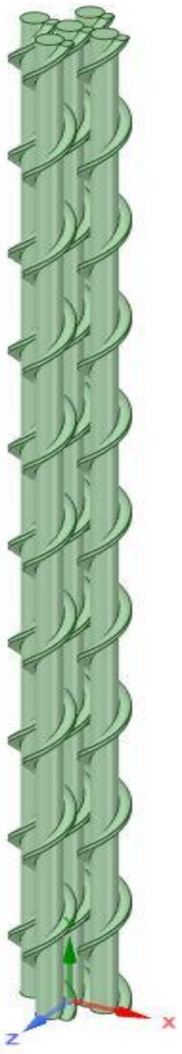
Physical Model Geometry



a) 3D view of the test section

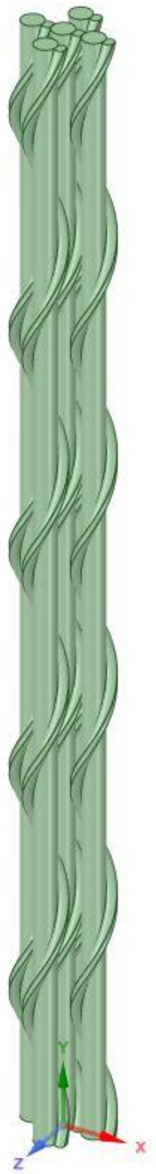


b) smooth rods



c) Wire wrap
pitch of 5d

Physical Model Geometry



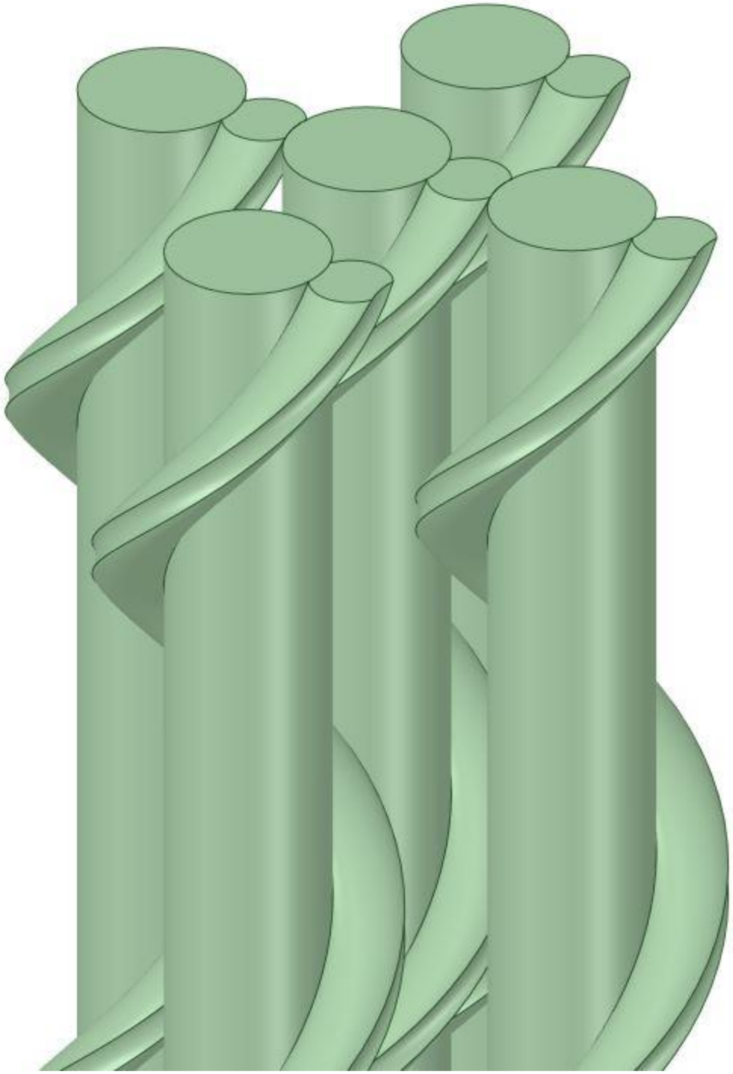
d) Wire wrap pitch of 10 d

e) Wire wrap pitch of 20 d

f) Wire wrap pitch of 30 d

g) Wire wrap pitch of 40 d

Physical Model Geometry



d) Zoom view of the rods bundle

MESH SENSITIVITY

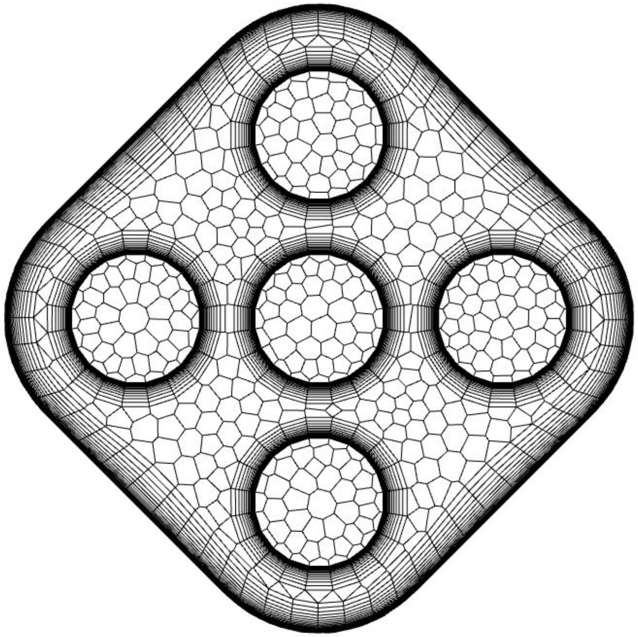
In this work to get numerical results that are independent of the grid density, the numerical study is conducted with different mesh densities. When the number of nodes increased from 1898572 to 2747858 a deviation of about 1 % in bundle maximum temperature is obtained. Whereas, when the number of nodes increases from 2747858 to 3702215, only 0.01% variation in bundle maximum temperatures is obtained. The case with nodes number of 3875496 is examined to be within Y+ of the order of 1 to accommodate the flow and temperature fine gradients in the vicinity of the rods surface. A polyhedral mesh is generated with inflation layers on the rods surface for all cases. Starting with course mesh, the simulation is conducted in FLUENT. Then, the Y+ values on the clad surfaces are checked. If Y+ values are greater than 1, a new fine mesh is generated and solved in ANSYS FLUENT and Y+ is checked again. This cycle is repeated until the final acceptable mesh is approved.

Mesh characteristics

a) 3 D mesh view of the smooth bundle

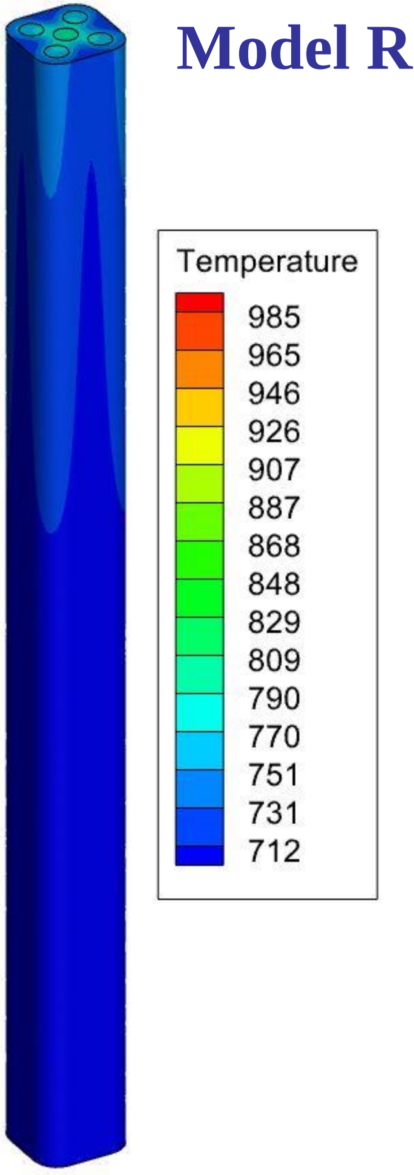
b) Cross sectional elevation mesh view of the bundle pitch 5d

Mesh characteristics

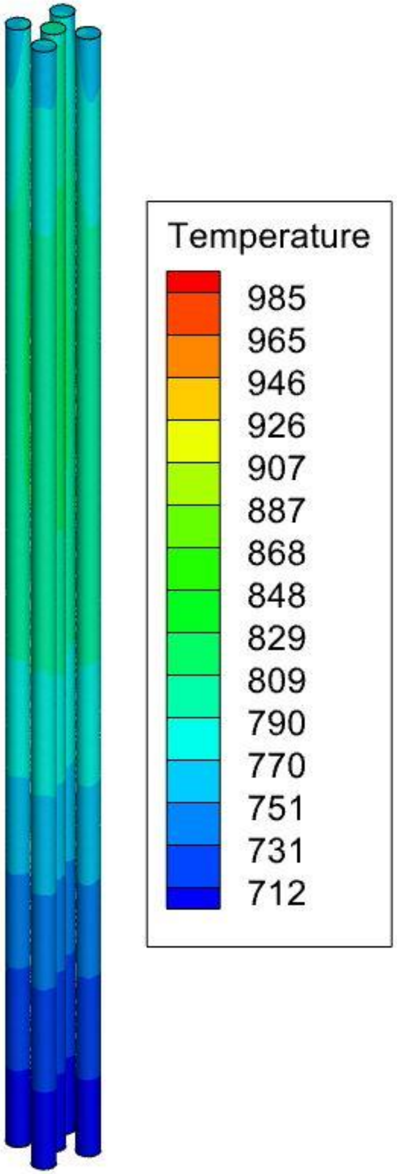


a) Plane sectional mesh view of the smooth bundle

Model Results

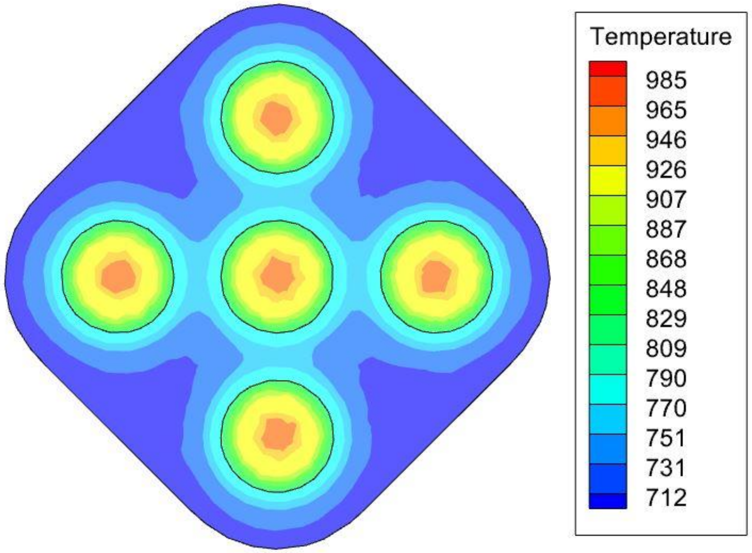


a) 3D temperature contour for smooth bundle



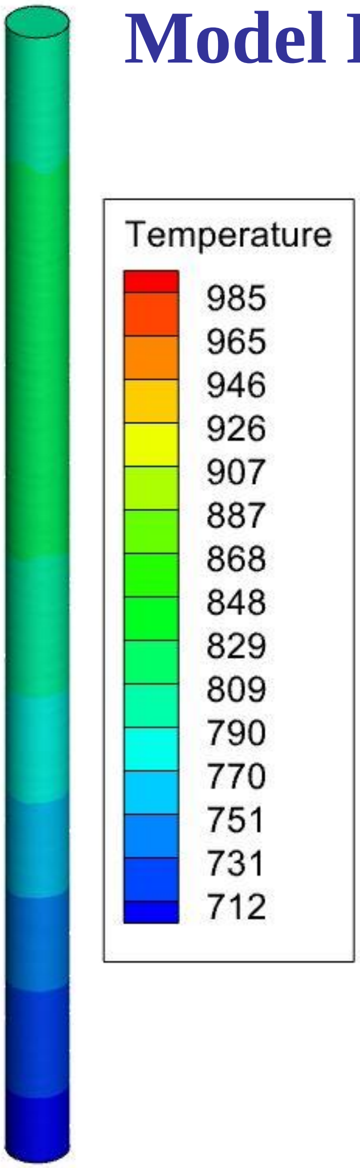
b) 3D temperature contour for smooth rods

Model Results

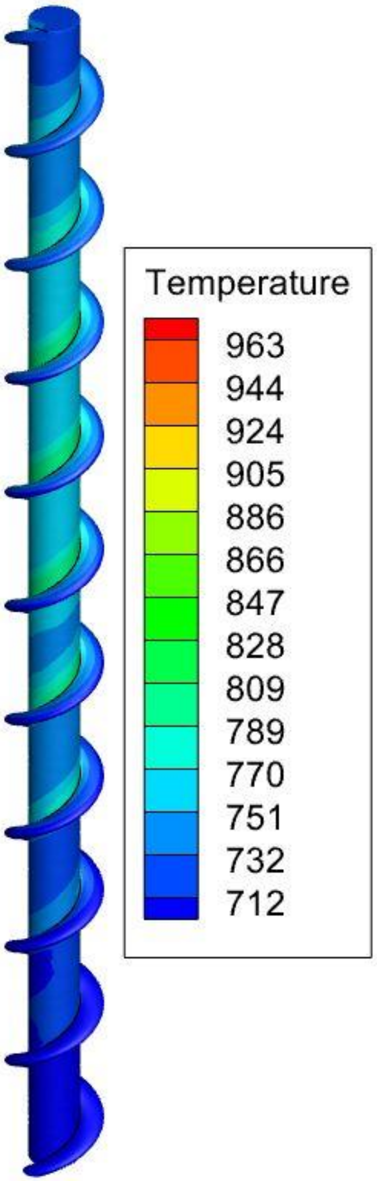


a) Plane sectional temperature contour at mid-height of the smooth bundle

Model Results

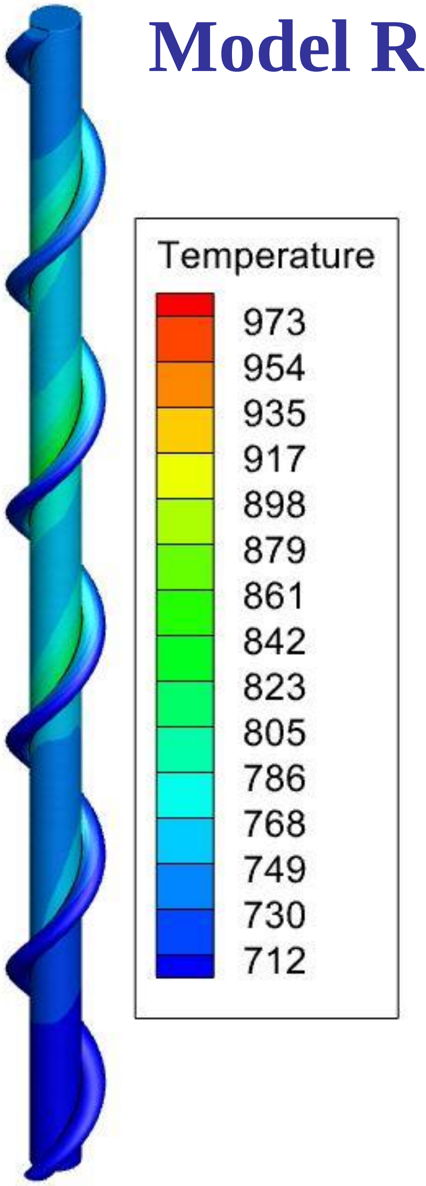


a) Smooth rod

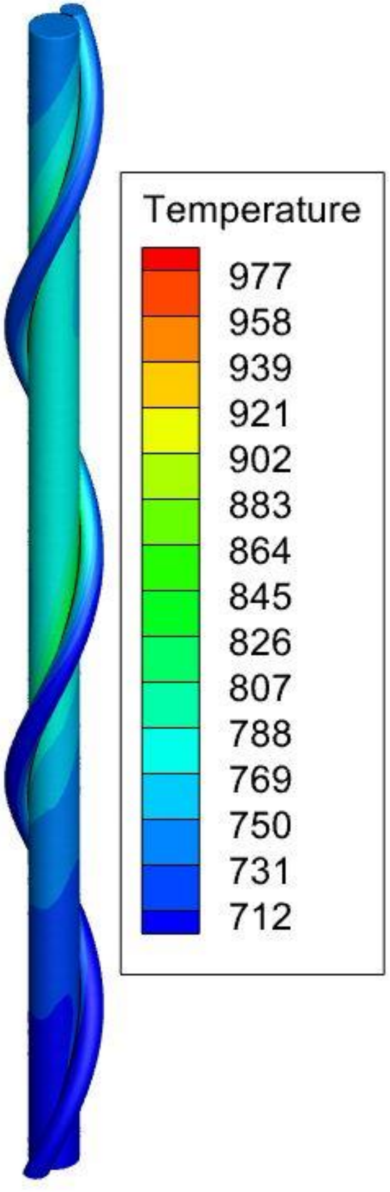


b) Wire wrap pitch of 5 d

Model Results

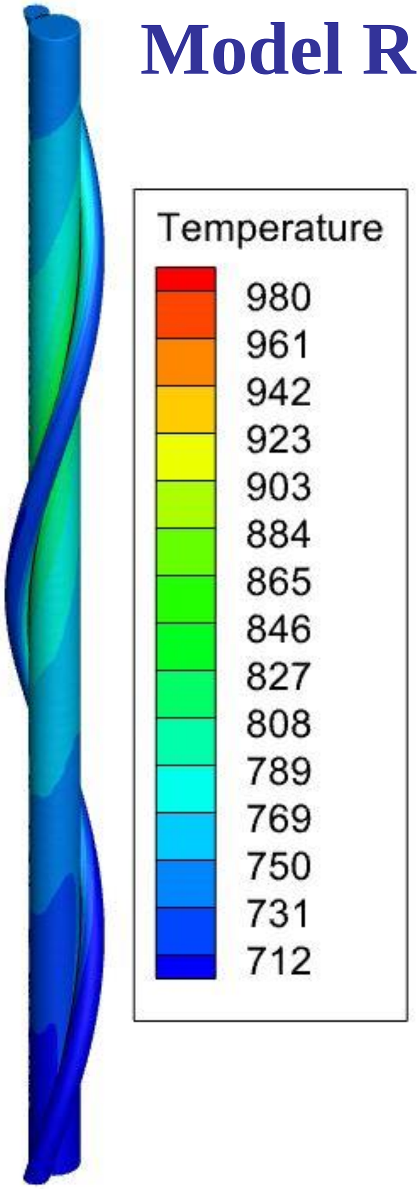


a) Wire wrap pitch of 10 d

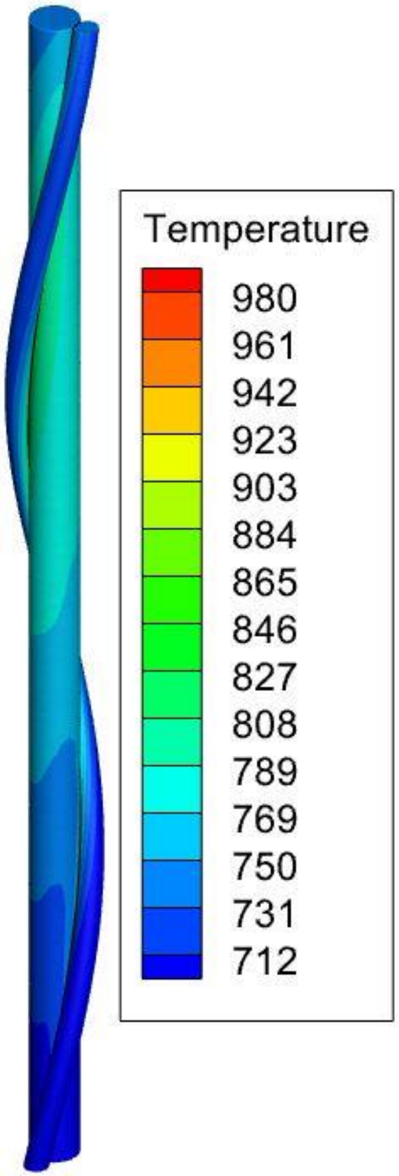


b) Wire wrap pitch 20 d

Model Results



a) Wire wrap pitch 30 d



b) Wire wrap pitch 40 d

Model Results

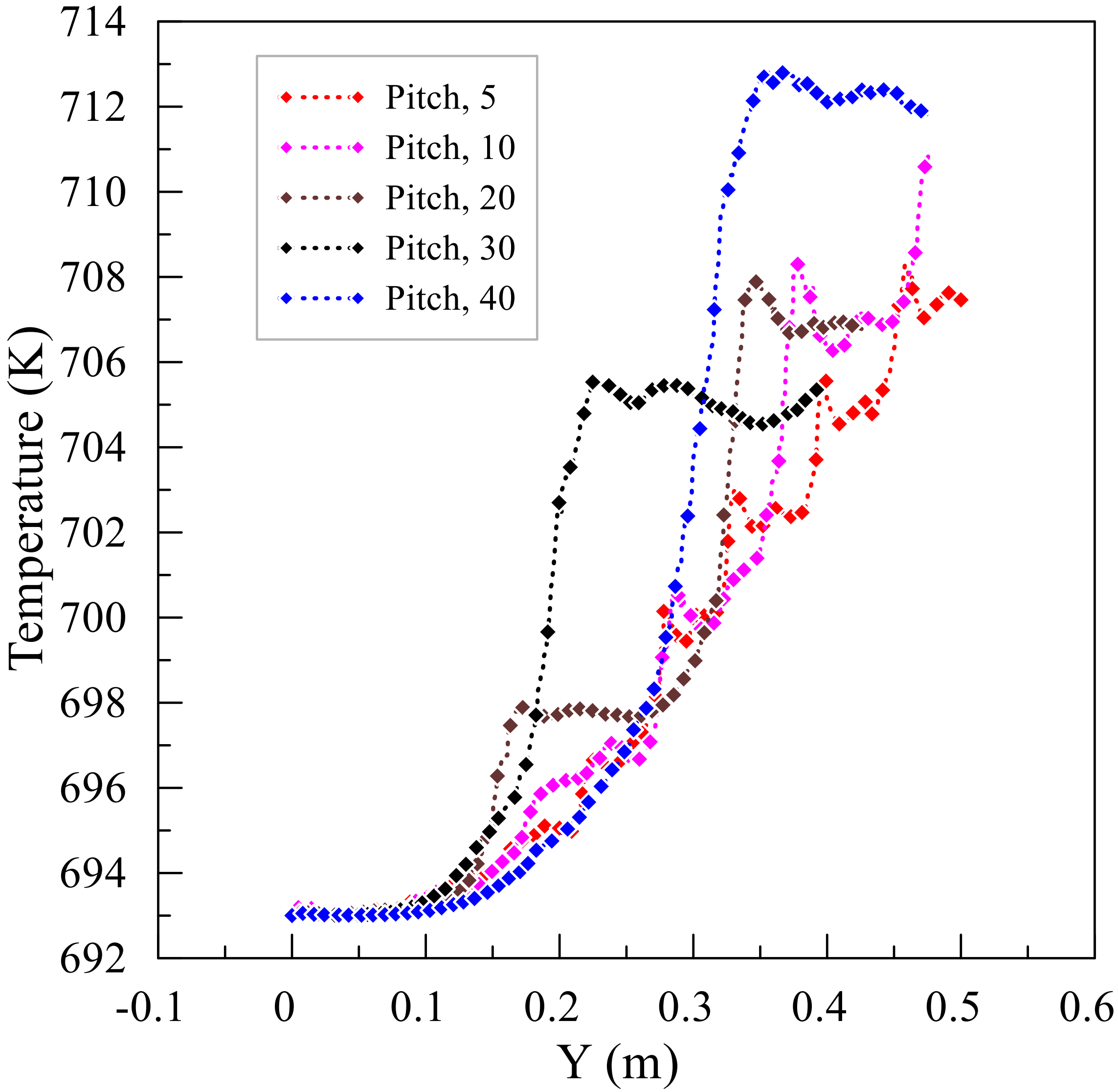


Fig. 5 rod surface temperature for central bundle rod at different wire wrap pitching

Model Results

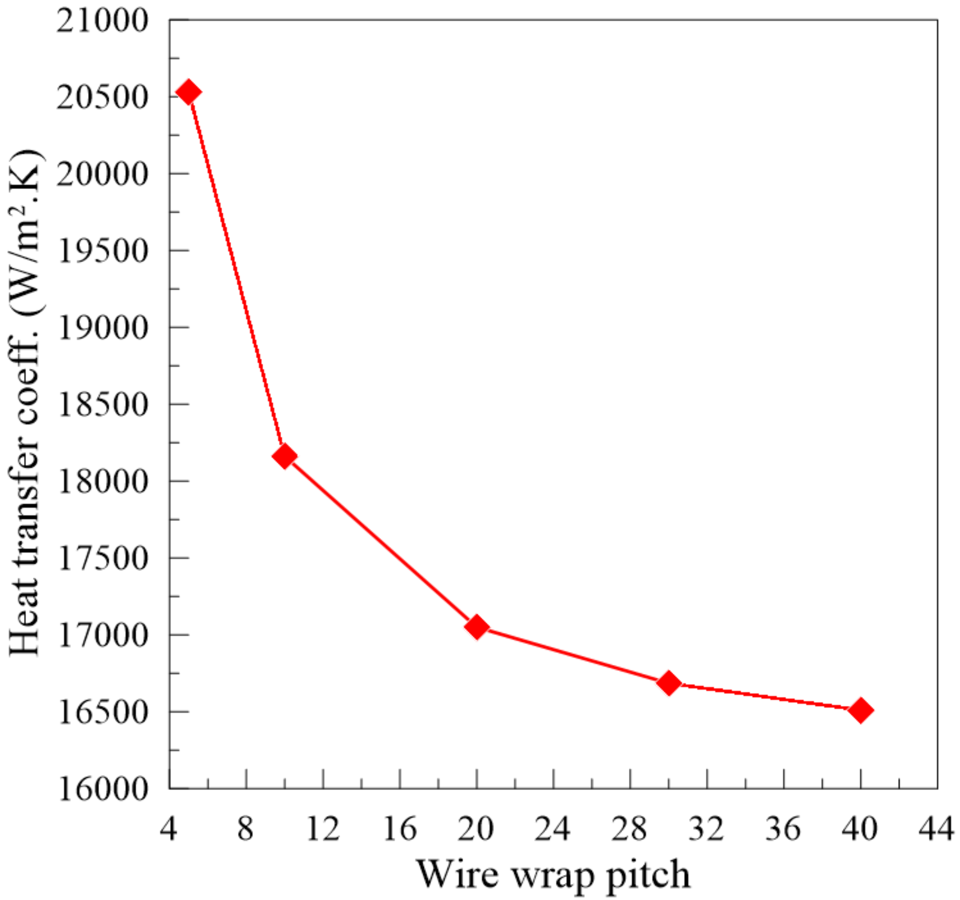


Fig. 6 variation of average Nusselt number for different wire wrap pitching

Model Results

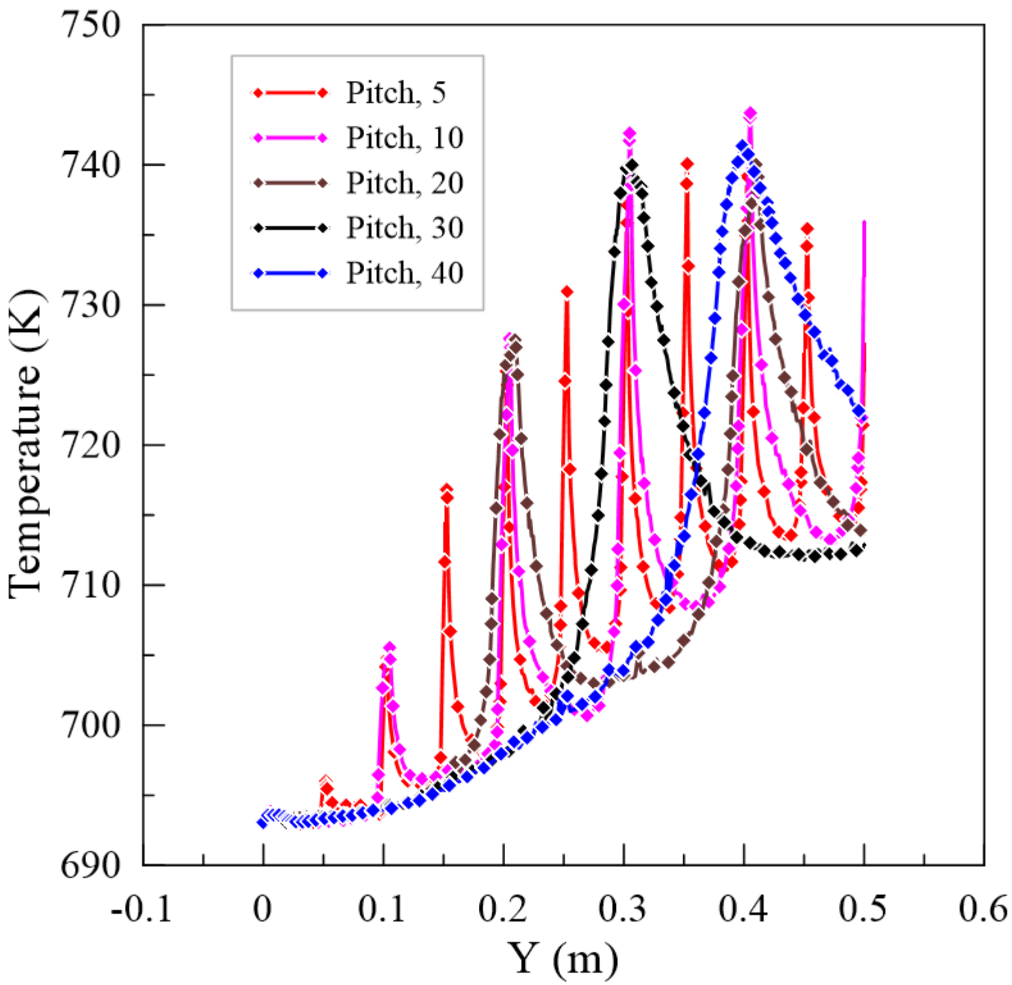


Fig. 7 variation coolant temperature in the middle coolant gap of the central rod of the bundle

Model Results

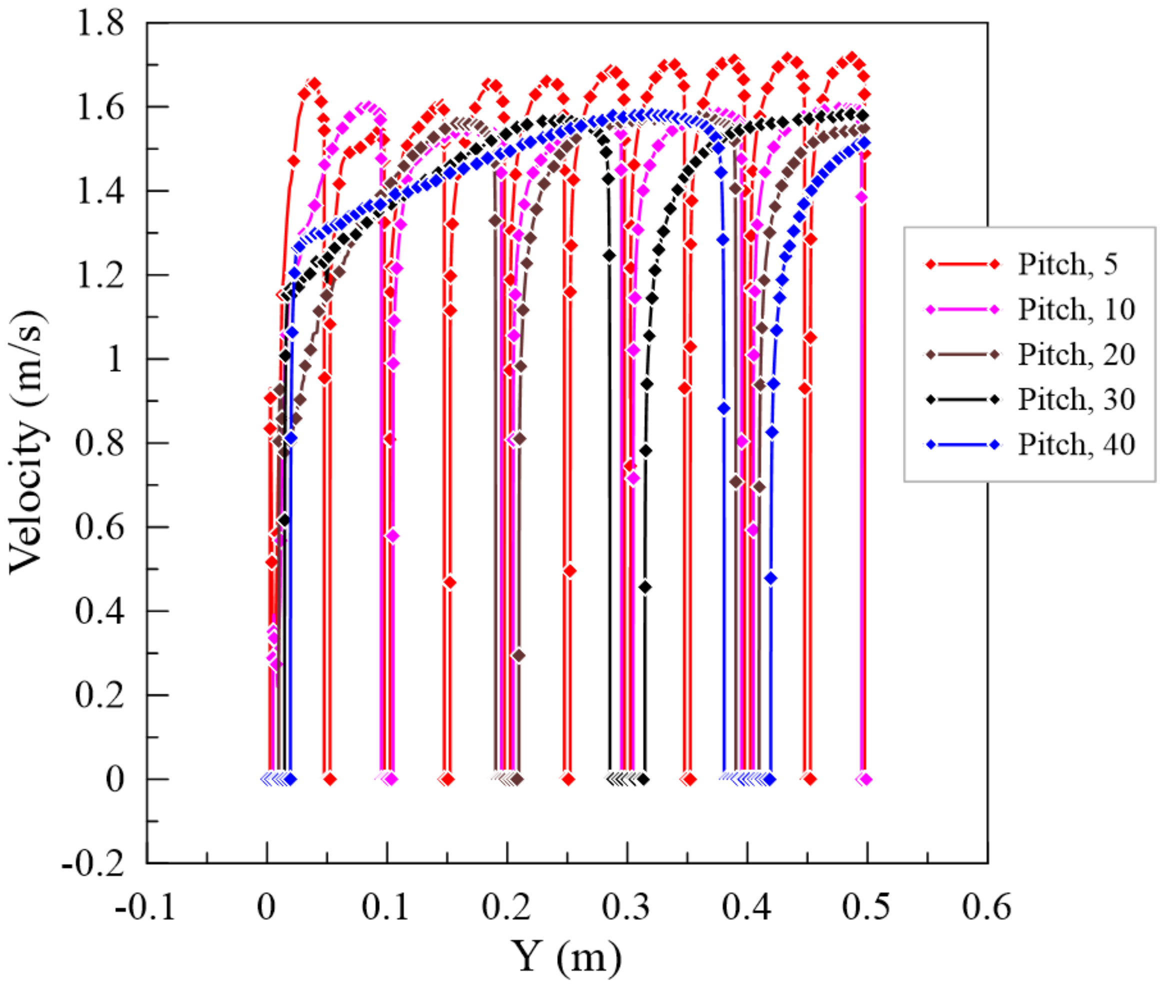


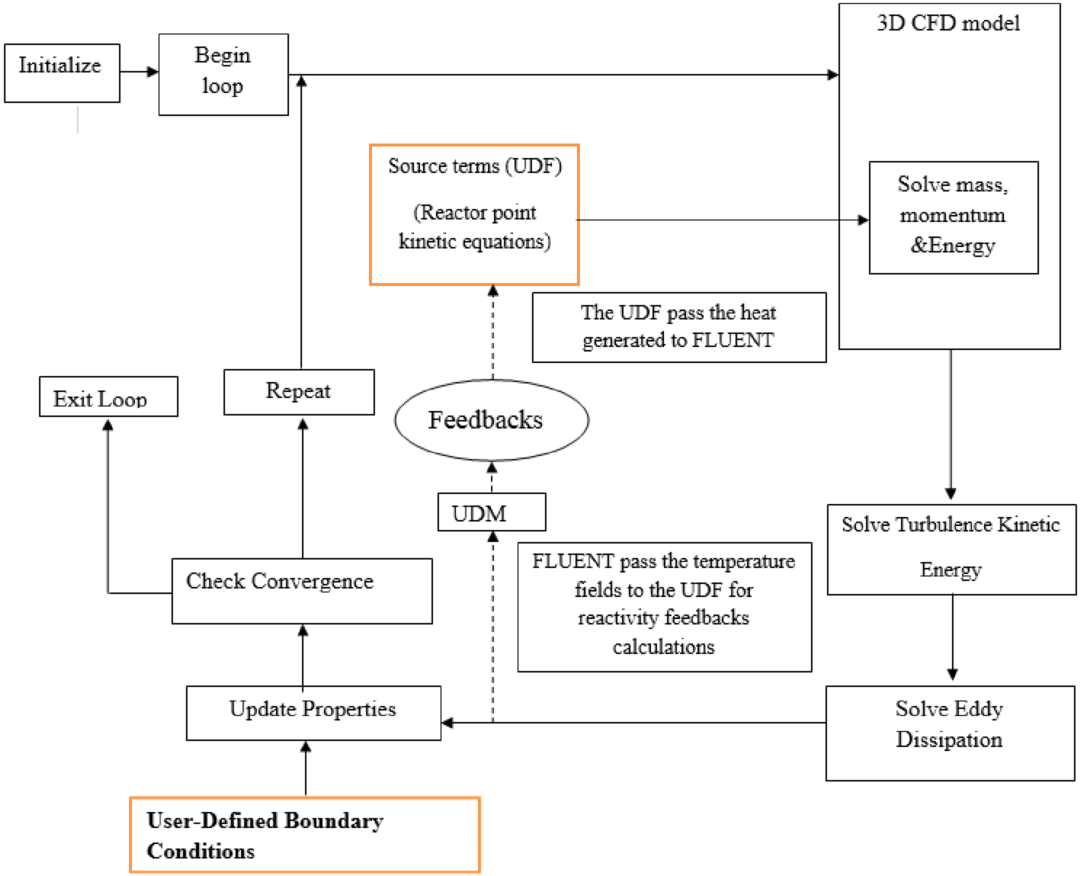
Fig. 8 variation coolant velocity in the middle coolant gap of the central rod of the bundle for different wire wrap pitching

CONCLUSION

This study presents the results of three-dimensional parametric computations of turbulent flow and heat transfer of liquid metal for longitudinal flow through bundle with wire wrap spacer at different twisting pitches. The wire twisting pitch plays a significant role on the heat transfer characteristics of LMFR. The low momentum diffusivity of liquid metal makes it inevitable to use turbulent and momentum mixing capabilities. The effect of decreasing the wire twist pitch act to increase the momentum exchange between the boundary layer flow of the liquid lead and the bulk flow and therefore the heat transfer coefficient increases. Therefore, the rods pitch act on the same way to the enhance the overall heat transfer coefficient. Slight increase of temperature in wake region of the wire is detected and reported. So, he wires act as a momentum exchange promoter in addition to its main function for keeping the inter rod spacing for the bundle.

Future work

CFD Codes can be customized to work with coupled neutronic and thermal hydraulics problems



Thank you