A Novel Approach to Investigation of Axial Fluid Conduction Effect in Low Prandtl Number Fluids

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Outline

1. Introduction
2. Theoretical Backgrounds
3. Analysis to examine the effect of axial fluid conduction
4. Results and Discussions
5. Summary & Conclusions

Introduction

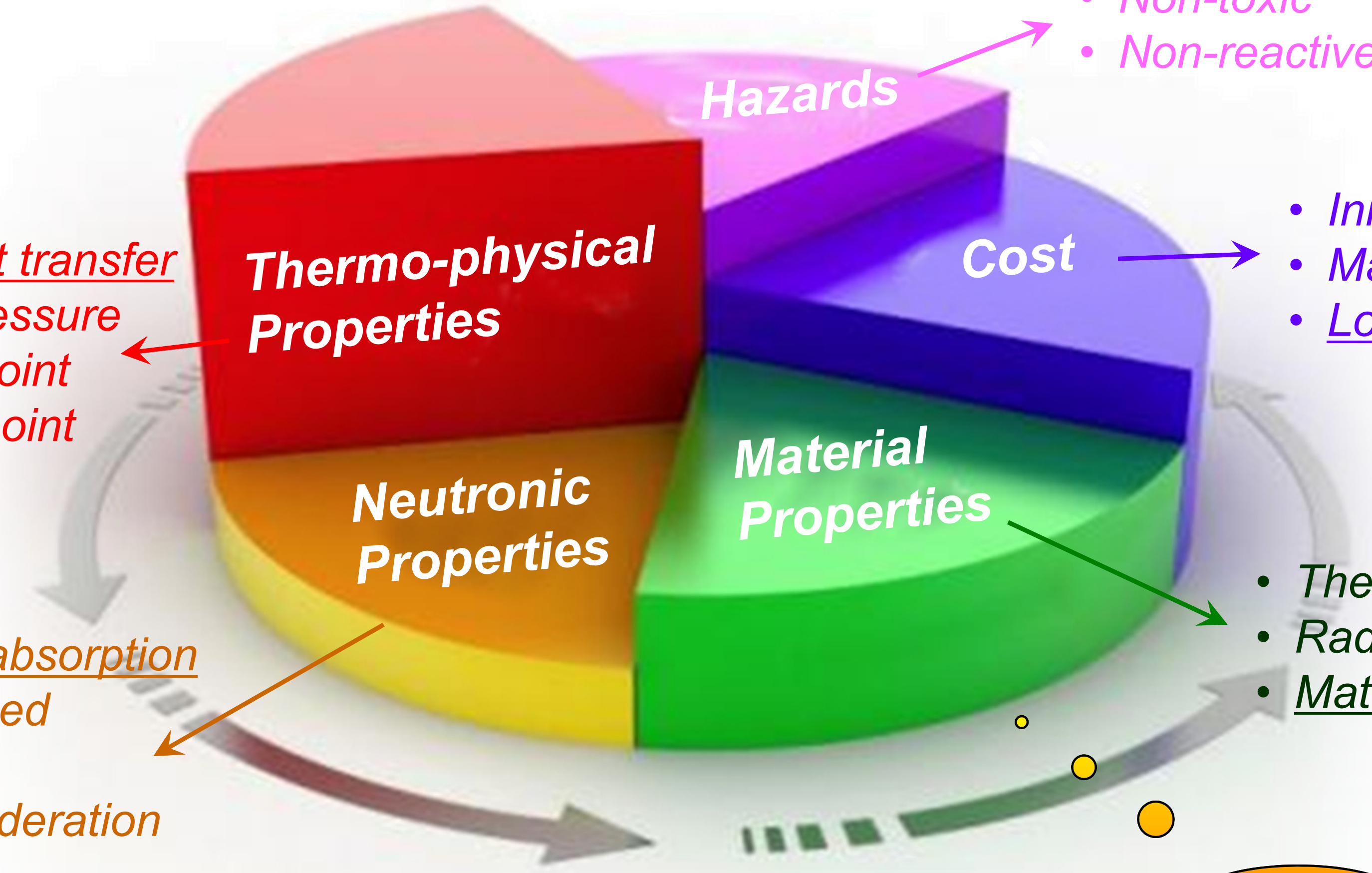
❑ Coolant Criteria for FR application

– In accordance with Generation-IV goals

- *Non-toxic*
- *Non-reactive*

- *Initial inventory*
- *Make up inventory*
- *Low pumping power*

- *Excellent heat transfer*
- *Low vapor pressure*
- *High boiling point*
- *Low melting point*



- *Thermal stability*
- *Radiation stability*
- *Material compatibility*

- *Low neutron absorption*
- *Minimal induced radioactivity*
- *Negligible moderation*

Thermo-physical and thermal-hydraulic properties of sodium are superior to lead or helium

Support Passive Safety

Introduction

* Sodium Thermal-hydraulic Integral Effect Test Loop

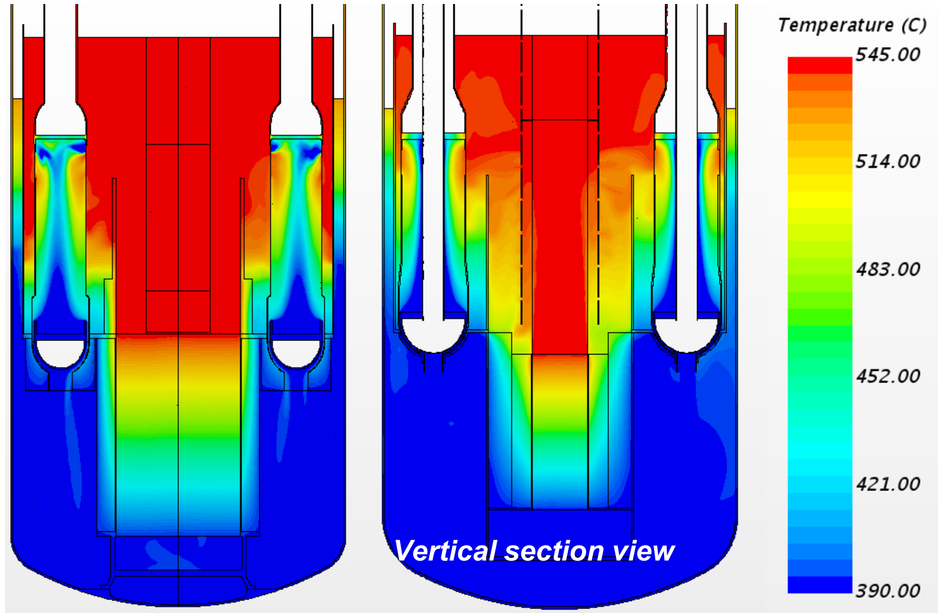
❑ Motive of work

– Design of scaled-down thermal-hydraulic test section, such as STELLA-2*

- Height reduction corresponding to power scale
  - ✓ Scale ratio (Height: 1/5, Volume: 1/125)
- Preservation of general arrangement of Rx. Internals, key components, and independent sodium loops

– Need of thermal designers' understanding

- Proper application ways for liquid metals
- Basic nature of liquid metal fluids distinguished from that of ordinary water in thermal-hydraulic aspects

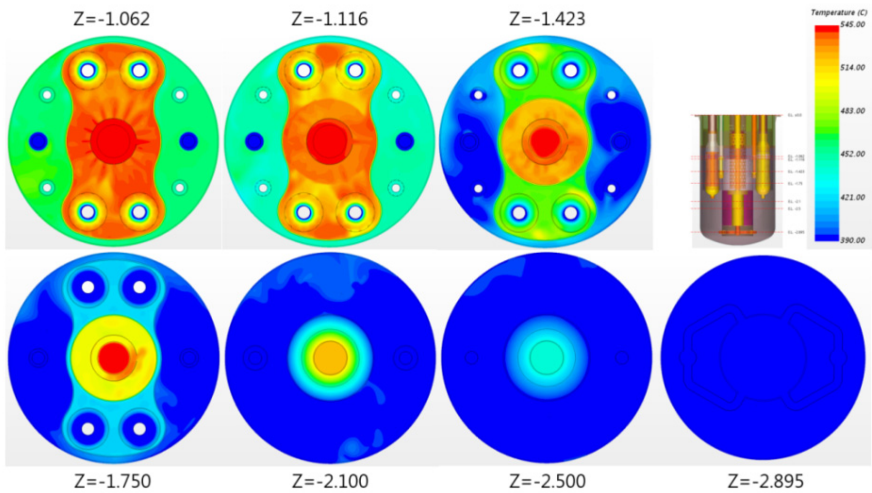


< Examples: Comparison of sodium temperature distributions >
- Prototype vs. Scaled-down test section -

❑ Objectives

– To investigate axial fluid conduction effect in all kinds of thermal system design process as they have not done before in ordinary water system

– To validate conventional scaling design methodologies for thermal-hydraulic systems using low Prandtl number fluids (e.g. Liquid metals)



Horizontal section view

Theoretical Backgrounds

- **Proper design of thermal system dealing with low Prandtl number fluids**
  - Need of understanding of basic nature of fluid properties distinguished from those of ordinary water
    - Ratio of energy transfer through momentum vs. through thermal diffusion: Prandtl number
- **Thermal-hydraulic applications dealing with**
  - Higher Prandtl number fluids than ordinary water
    - Magnitude of longitudinal convection is much larger than that of fluid conduction along with flow
      - ✓ Axial fluid conduction along with flow stream can be negligible
  - Highly conductive fluids like liquid metals
    - Prandtl number becomes quite low
      - ✓ due to high thermal conductivity
    - Thickness of the thermal boundary layer is significantly larger than the hydrodynamic one
      - ✓ Mechanism of conduction heat transfer dominates over that of momentum transfer
      - ✓ Thermal diffusion would be an effective mode of heat transfer *(Less effect of viscosity on heat transfer coefficient)*

$$Pr = \frac{Momentum\ Diffusivity}{Heat\ Diffusivity} = \frac{\nu}{\alpha} = \frac{(\frac{\mu}{\rho})}{(\frac{k}{\rho c_p})} = \frac{c_p \mu}{k}$$

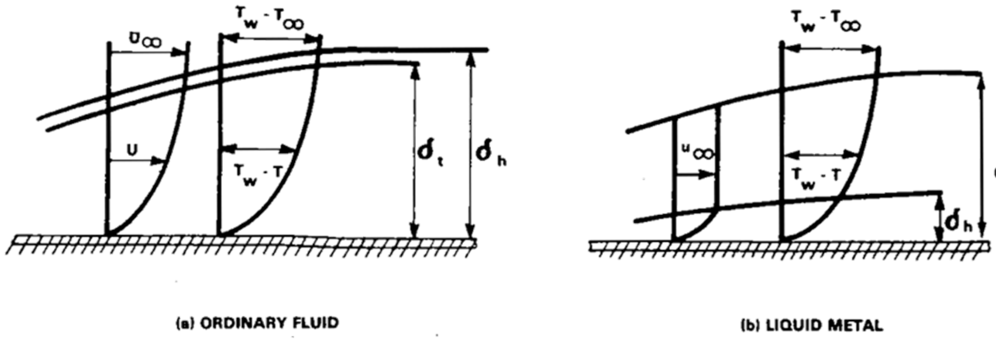


FIGURE 9-15. Comparison of thermal (δ_t) and hydrodynamic (δ_h) boundary layers for ordinary fluids vs liquid metals.

✓ ***Source:*** *Thomas H. Fanning, "Fast Reactor Coolant Options," Fast Reactor Short Course, Purdue Univ., Mar.26-27, 2013*

Theoretical Backgrounds

❑ What about the application fields of liquid metal fluids

- Axial fluid conduction along with flow direction can be negligible or not?
  - It totally depends on flow conditions
- Judgment criterion on this concern can be theoretically defined as a ratio of axial fluid conduction term over that of convection: e.g. Peclet #

❑ Equation of energy for axial flow in cylindrical coordinates (r,θ,z)

$$\rho c_p V_z \frac{\partial T}{\partial z} = k\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + k\frac{\partial^2 T}{\partial z^2} - \mu\left(\frac{\partial V_z}{\partial r}\right)^2 + G$$

- *Uniform heat generation source or sink* (G)
- *Heat source from viscous dissipation* ($\mu\left(\frac{\partial V_z}{\partial r}\right)^2$)
- *Axial fluid conduction* ($k\frac{\partial^2 T}{\partial z^2}$)

– Ratio of 'order of magnitude' of $\left(k\frac{\partial^2 T}{\partial z^2}\right)$ and $\left(\rho c_p \vec{V}_z \ldots\right)$

$$\frac{k/L}{\rho c_p \vec{V}_z / L} \cong \frac{k}{\rho c_p V} \equiv \frac{1}{Pe} \quad \Leftarrow \quad \left(Pe = Re \cdot Pr = \frac{\rho c_p V}{k}\right)$$

$$\frac{axial\ \ fluid\ \ conduction}{axial\ \ convection} = \frac{1}{Pe} = \frac{1}{Peclet\ \ number}$$

❑ Effect of axial fluid conduction

- Generally negligible for '$Pe \geq 100$'
- Should be examined in the range of '$0 \leq Pe \leq 100$'
- For liquid metals, the laminar flow would occur generally at 'Pe < 100 or less'
- Axial fluid conduction term should be considered for such thermal systems

Theoretical Backgrounds

❑ How to be applied to scaling design methodology in thermal-hydraulic systems

– Scaling design criteria on thermal-fluidic system with taking into account of axial fluid conduction

- **Step 1**: Dimensionless conservation equations (Ref.: [Ishii et al., 1986] & [Yoon et al., 2001])

$$\rho c_p\left(\frac{\partial T_i}{\partial t}+u_i\frac{\partial T_i}{\partial x}\right)=q_i \qquad \frac{\partial T_i^*}{\partial t^*}+u_i^*\frac{\partial T_i^*}{\partial x^*}=\frac{q_i l_o}{\rho c_p u_o \Delta T_o}$$

- **Step 2**: Non-dimensionalize energy conserv'n equ'n after adding axial fluid conduction term on it

$$\rho c_p\left(\frac{\partial T_i}{\partial t}+u_i\frac{\partial T_i}{\partial x}\right)=q_i+k\frac{\partial^2 T_i}{\partial x^2}$$

$$u_i^*=u_i/u_o,\quad x_i^*=x_i/l_o,\quad t_i^*=t\cdot\left(u_o/l_o\right),\quad T_i^*=T_i/\Delta T_o$$

u_o : *steady − state velocity* ΔT_o : *max. temperature difference*

$$\frac{\partial T_i^*}{\partial t^*}+u_i^*\frac{\partial T_i^*}{\partial x^*}=\frac{q_i l_o}{\rho c_p u_o \Delta T_o}+k\cdot\frac{l_o}{\rho c_p u_o \Delta T_o}\frac{\Delta T_o}{l_o^2}\cdot\frac{\partial T_i^{*2}}{\partial x^{*2}}=\frac{q_i l_o}{\rho c_p u_o \Delta T_o}+\underbrace{\frac{1}{Re\cdot Pr}\cdot\frac{\partial T_i^{*2}}{\partial x^{*2}}}_{\text{Axial fluid conduction}}$$

- **Step 3**: Obtain scaling design criteria with axial fluid conduction term → $(Re\cdot Pr)_R\equiv Pe_R=1$
  - ✓ To preserve overall TH behaviors of the prototype even in a scaled-down thermal system

❑ For extension of the theoretical results to the practical application case

– Need of actual criteria to disregard axial fluid conduction effect in very low *Pr* # fluids

– Further investigations on laminar flow cases with liquid metal cooling system

Thermal flow system for CFD analysis

❑ Objectives

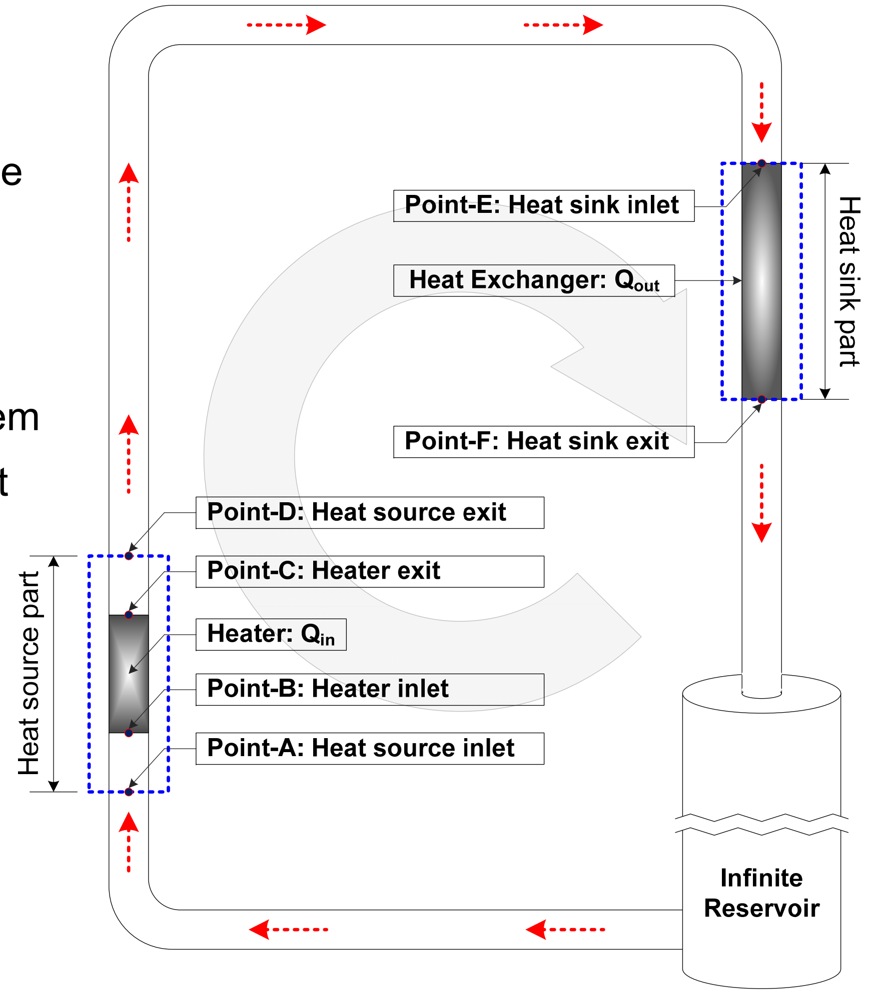
- To examine the practical effect of axial fluid conduction in a low Prandtl number fluid along the flow direction
- To obtain judgment criteria to disregard axial fluid conduction effect with respect to flow conditions

❑ Postulated thermal flow system for CFD analysis

- A closed loop piping system with a simplified geometry
  - Circular-shape & cross-sectional area without flow area change (for simplicity of the analysis)
- System including uniform heat source and sink terms
  - Thermal behaviors coupled with flow conditions
- Employing a postulated reservoir with infinite volume in the system
  - For a proper control of the boundary conditions at the inlet part of the heat source
  - To examine meaningful transient effect of fluid conduction along the backward direction

❑ Domain for CFD analysis

- Entire flow region in all loop piping system
  - To obtain flow distributions
  - To obtain temperature profiles along the flow direction
- Heat loss through pipe wall in radial direction: N/A

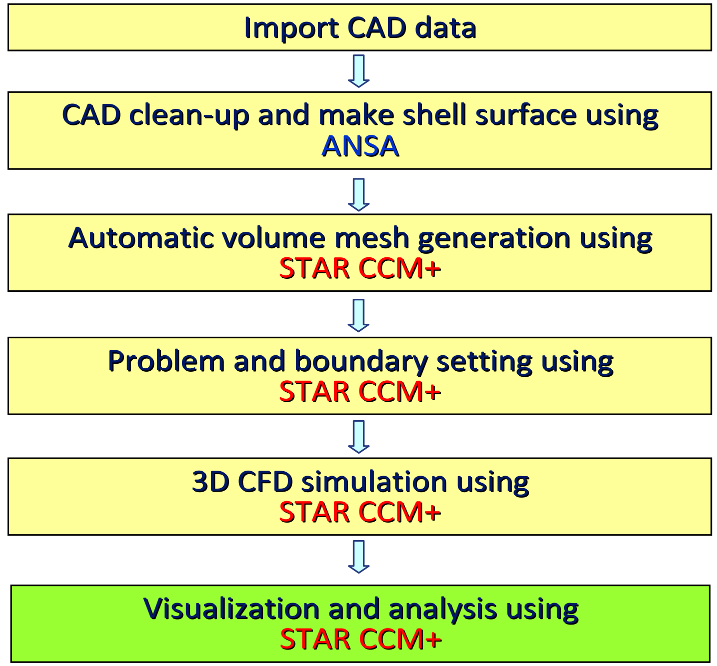


< Schematic of the postulated closed loop system >

Evaluation by CFD Analysis

❑ Simulation Conditions

- Implemented software
  - Mesh generation and solving: STAR CCM+
  - CAD repair and shell surface generation
  - Mesh generation and solving: STAR-CCM+ V11
- Unsteady-state calculation
  - till after reaching steady-state condition
- Laminar flow
- Mesh type : Polyhedral Mesh
- Number of volume cells: ~ 120,000
- CHT (Conjugate Heat Transfer)
  - Not considered
- Polynomial density
- Parallel processing



Boundary Conditions	
Heat source & sink	427 W (equivalent)
Inlet / outlet fluid temp. (^{o}C)*	545.0 / 390.0
Wall conditions	No-slip, Adiabatic
Geometry of loop piping system	2.0 m long & 1.5 in (ID)

** Operating conditions in STELLA-2*

Cases for Sensitivity Analysis

- **Boundary conditions for the CFD analysis to examine axial fluid conduction effect**
  - Total seven cases of postulated fluids with respect to the variations of Prandtl numbers
    - Seven different thermal conductivities were assigned to each postulated fluid
  - Reference fluid (Case: 1k)
    - Basically liquid sodium (primary coolant of SFRs as well as any sodium test sections)
  - Thermal conductivities of the other six fluids: set to have different thermal conductivities

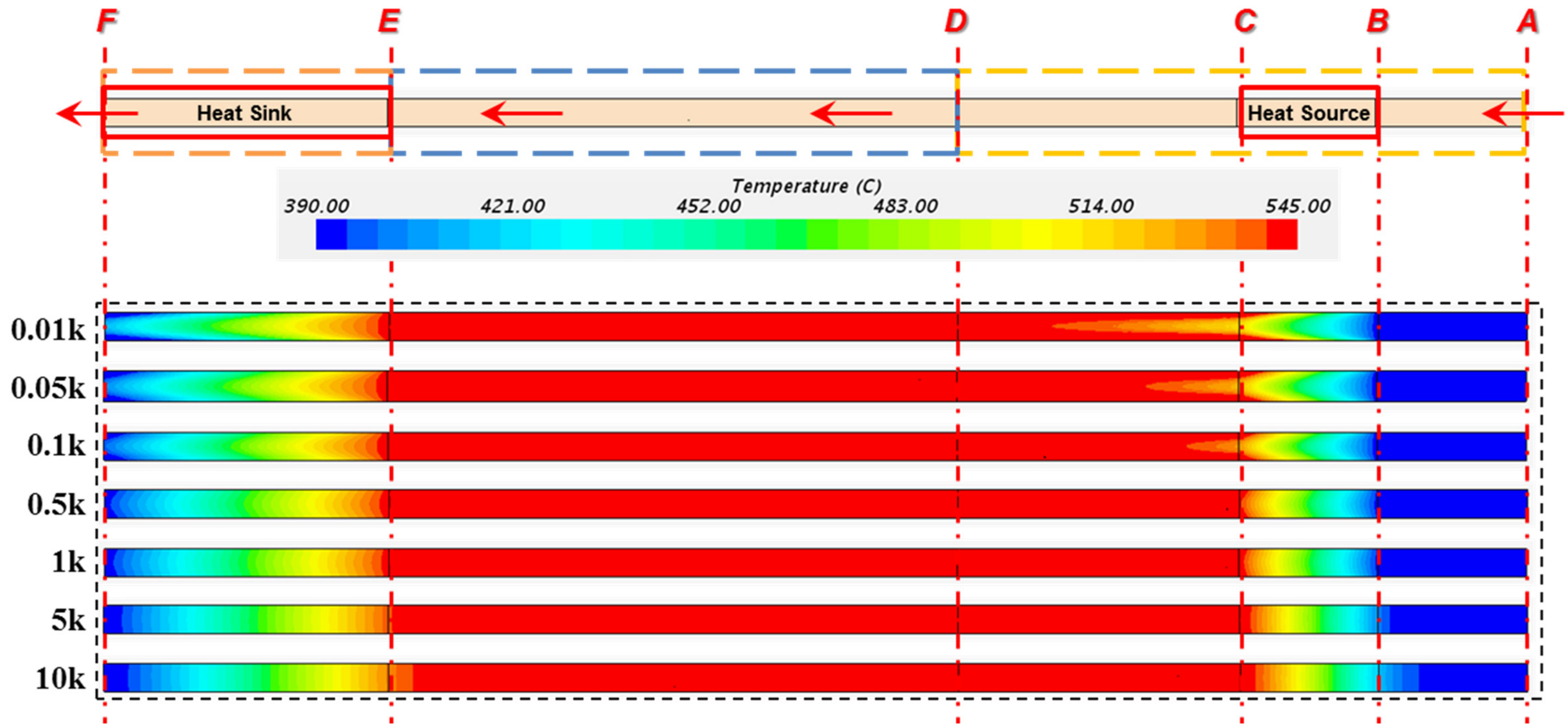
Case ID	Descriptions
0.01k	**1% of the ref. thermal conductivity for liquid sodium** ***(Corresponding to that of ordinary water)***
0.05k	**5% of the reference thermal conductivity for liquid sodium**
0.1k	**10% of the reference thermal conductivity for liquid sodium**
0.5k	**50% of the reference thermal conductivity for liquid sodium**
1k	**Reference thermal conductivity for liquid sodium**
5k	**5 times of the reference thermal conductivity for liquid sodium**
10k	**10 times of the reference thermal conductivity for liquid sodium**

Super conductive fluid

  - Flow rate conditions: ranged from 1% to 10% of the nominal flowrate (1%, 4%, 7%, and 10%)
    - For very low flow conditions that potential effect of axial fluid conduction could be easily seen
    - Reynolds numbers in all test cases were carefully considered as well to check the flow regimes of extreme conditions ***(at STELLA-2 design conditions)***

Results of CFD Analysis (1/4)

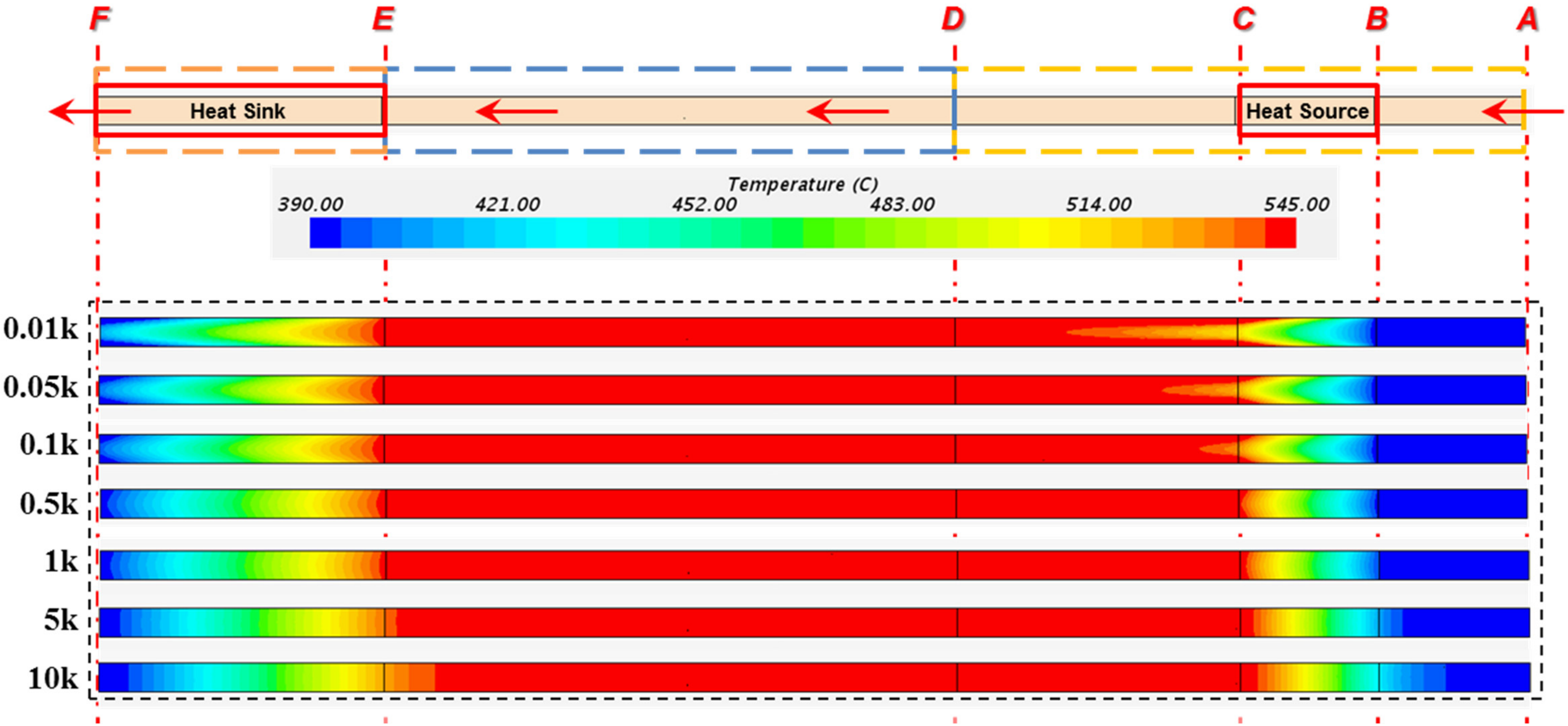
- **Conditions of each examination case**
  - **10%** flow rate to the nominal
  - Reynolds number: ~ 2,410



(a) Flow conditions: 10% flow rate to the nominal (Reynolds number ~ 2,410)

Results of CFD Analysis (2/4)

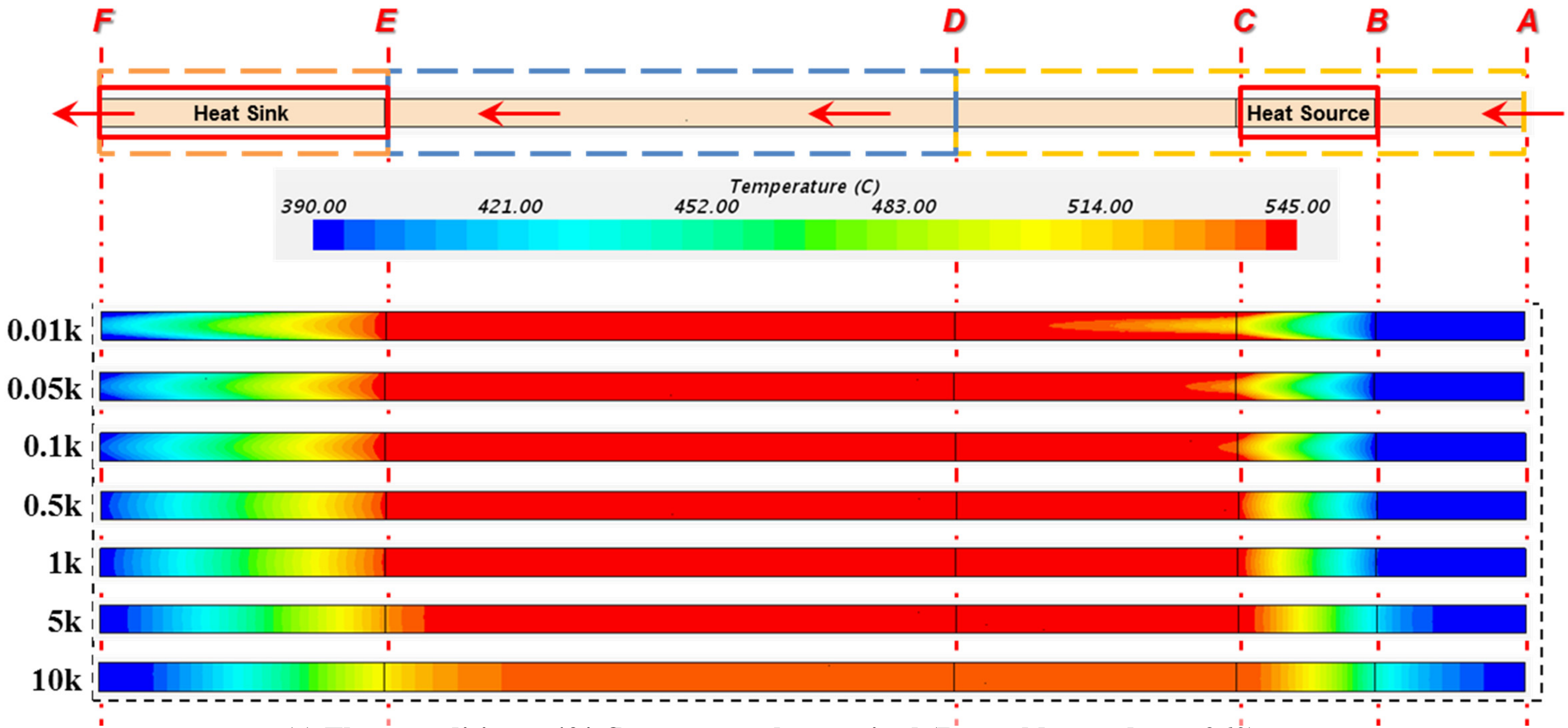
- **Conditions of each examination case**
  - 7% flow rate to the nominal
  - Reynolds number: ~ 1,690



(b) Flow conditions: 7% flow rate to the nominal (Reynolds number ~ 1,690)

Results of CFD Analysis (3/4)

- **Conditions of each examination case**
  - **4%** flow rate to the nominal
  - Reynolds number: ~ 964

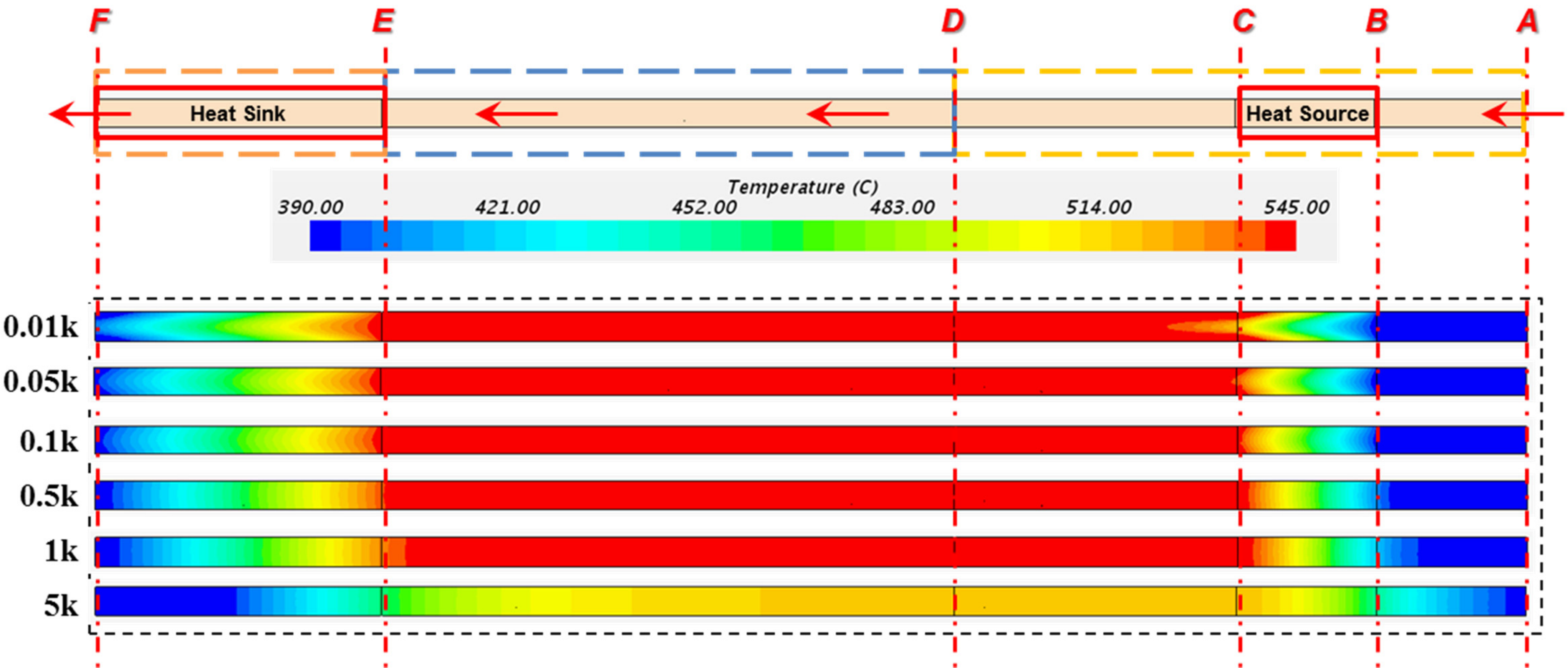


(c) Flow conditions: 4% flow rate to the nominal (Reynolds number ~ 960)

Results of CFD Analysis (4/4)

❑ **Conditions of each examination case**

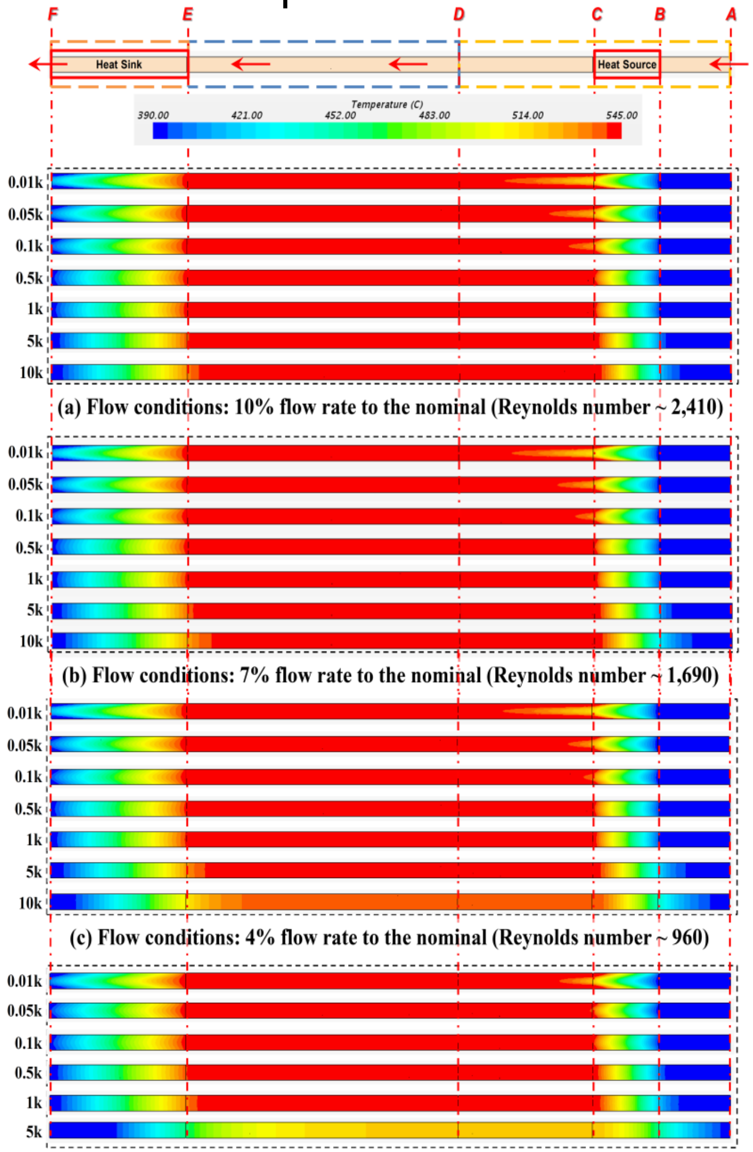
- **1%** flow rate to the nominal
- Reynolds number: ~ 241



(d) Flow conditions: 1% flow rate to the nominal (Reynolds number ~ 240)

Review of CFD Analysis Results

❑ **Quantification of axial fluid conduction effect** with respect to test conditions



(a) Flow conditions: 10% flow rate to the nominal (Reynolds number ~ 2,410)

(b) Flow conditions: 7% flow rate to the nominal (Reynolds number ~ 1,690)

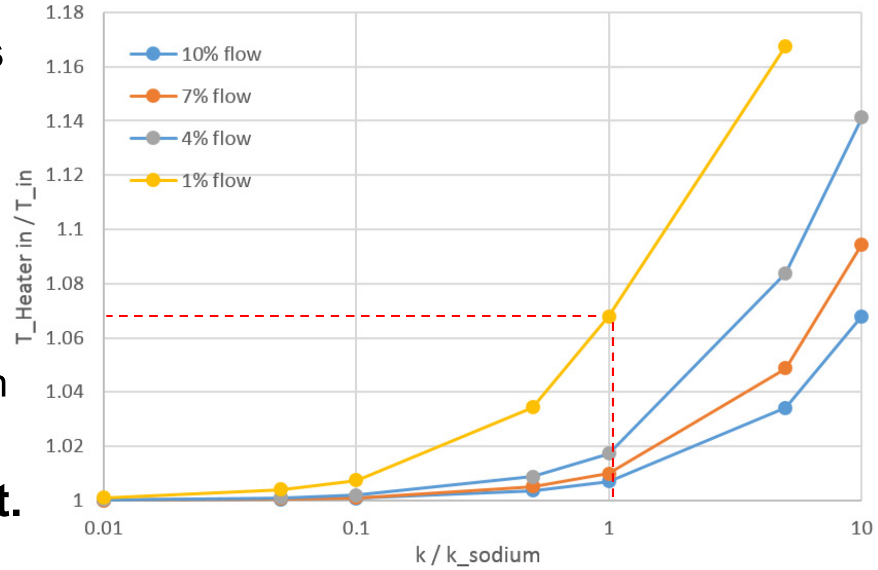
(c) Flow conditions: 4% flow rate to the nominal (Reynolds number ~ 960)

(d) Flow conditions: 1% flow rate to the nominal (Reynolds number ~ 240)

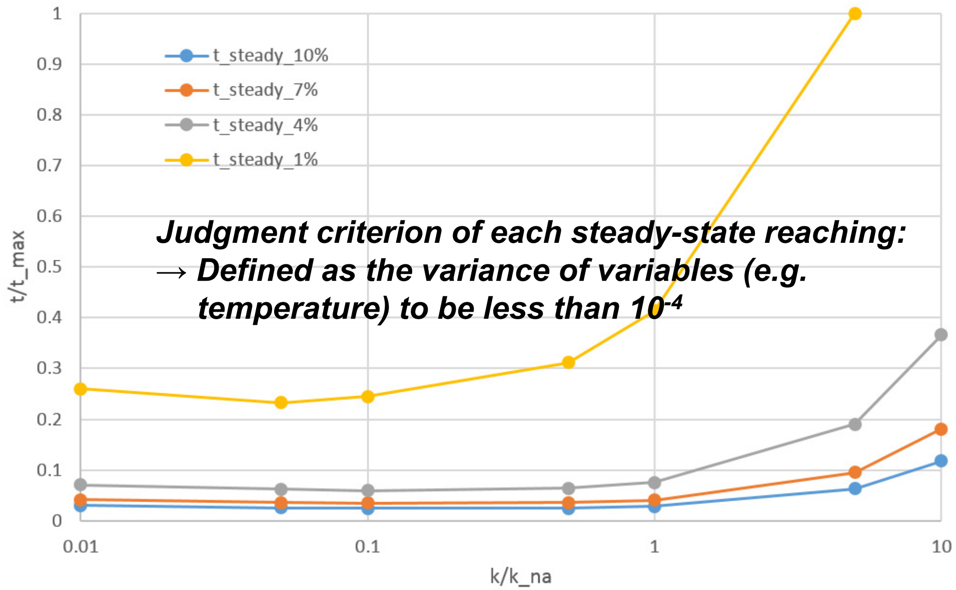
Flow conditions	Ratio of thermal conductivities (k/k_{Ref}, %)	1% (0.01k)	5% (0.05k)	10% (0.1k)	50% (0.5k)	100% (1k)	500% (5k)	1000% (10k)
1% flow rate to the nominal	***Re number***	**241**	**241**	**241**	**241**	**241**	**241**	**241**
	Pr number	0.4941	0.0988	0.0494	0.0099	0.0049	0.0010	0.0005
	Pe number	119.5	23.8	11.9	2.4	1.2	0.2	0.1
	$T_{heater,in}$	390.4	391.6	392.9	403.4	416.5	455.3	N/A
	$T_{heater,ex}$	544.6	544.1	543.6	538.5	532.0	459.4	N/A
4% flow rate to the nominal	***Re number***	**964**	**964**	**964**	**964**	**964**	**964**	**964**
	Pr number	0.4941	0.0988	0.0494	0.0099	0.0049	0.0010	0.0005
	Pe number	476.2	95.2	47.6	9.5	4.8	1.0	0.5
	$T_{heater,in}$	390.0	390.4	390.8	393.5	396.8	422.7	445.1
	$T_{heater,ex}$	544.9	544.8	544.6	543.3	541.6	528.4	507.7
7% flow rate to the nominal (Nominal case)	***Re number***	**1686**	**1686**	**1686**	**1686**	**1686**	**1686**	**1686**
	Pr number	0.4941	0.0988	0.0494	0.0099	0.0049	0.0010	0.0005
	Pe number	833.3	166.7	83.3	16.7	8.3	1.7	0.8
	$T_{heater,in}$	390.1	390.2	390.4	392.0	394.0	409.0	426.8
	$T_{heater,ex}$	545.0	544.9	544.8	544.0	543.0	535.6	525.8
10% flow rate to the nominal	***Re number***	**2409**	**2409**	**2409**	**2409**	**2409**	**2409**	**2409**
	Pr number	0.4941	0.0988	0.0494	0.0099	0.0049	0.0010	0.0005
	Pe number	1190.5	238.1	119.0	23.8	11.9	2.4	1.2
	$T_{heater,in}$	390.0	390.2	390.3	391.4	392.8	403.3	416.5
	$T_{heater,ex}$	545.0	544.9	544.9	544.3	543.6	538.4	531.8

Quantification of CFD Analysis Results

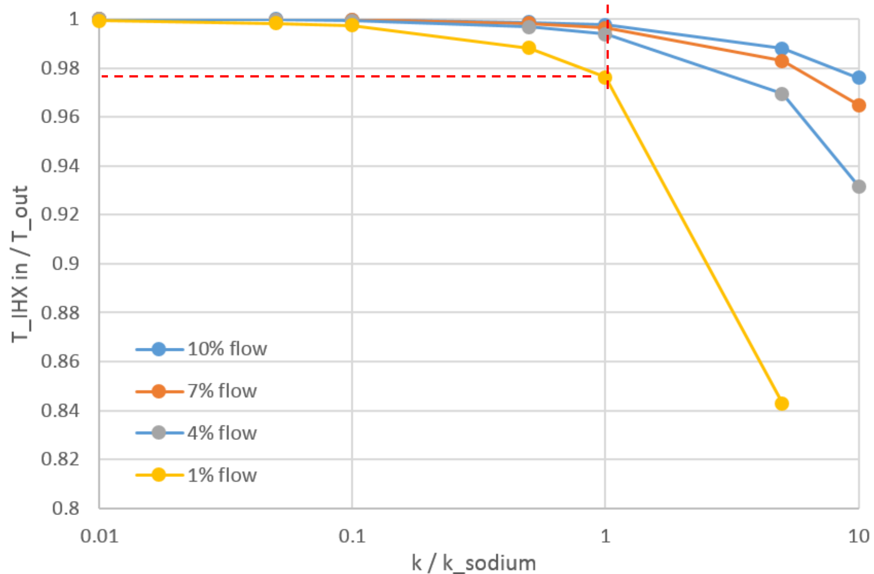
- **Ratio variation for mass-flow-averaged temperatures**
  - At the heater inlet to the ideal temperature
    - ~7% deviation at its maximum (sodium)
  - At the heat sink inlet to the heater exit temperature
    - ~3% deviation at its maximum (sodium)
  - Strong forward/backward heat transfer along the flow stream in super-conductive fluids more than 1k
- **Need of more physical times taking for reaching st.st.**
  - Due to unexpected heat dissipation from the heat source/sink



Variation of temperature ratios at the heater inlet (point-B) to the heater source part (point-A, ideal)



Comparison of normalized physical times taking for each steady-state reaching



Variation of temperature ratios at the heat sink inlet (point-E) to the heat source exit (point-D)

Summary and Conclusions

❑ A noble approach to CFD analysis

- For the purpose of examining the axial fluid conduction effect
- For the cases limited in highly conductive laminar flow

❑ Major findings obtained from the present study

- Obvious effect on axial fluid conduction in very low Prandtl number fluids
  - Totally dependent on the conditions of fluid flow and its thermal properties
- Stronger effect on axial fluid conduction along the flow stream
  - In lower Reynolds number flows and lower Prandtl number fluids (*i.e. higher k*)
- Weaker effect on it and to be negligible of axial fluid conduction in thermal designing process
  - Only for the fluids having its thermal conductivity of less than or similar to that of liquid sodium
  - Otherwise,
    - ✓ System designers should take into account the effect of axial fluid conduction in all kinds of thermal system design process as they have not done before in ordinary water system
- When system designers make choice of working fluids except ordinary water coolant
  - They should take into account the basic nature of Prandtl numbers of working fluids for appropriate system design

Thank you for your attention

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< References >

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