ANS Winter Meeting & Expo

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Thermal Stratification Analysis for Sodium-cooled Fast Reactors: Development of the 1-D System Model

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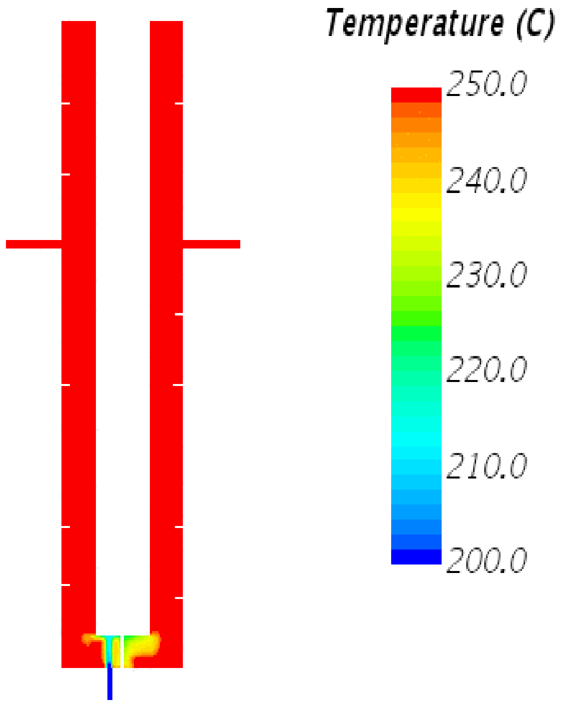
Thermal stratification in nuclear systems

- Thermal stratification
  - Formation of stratified layers of coolant with a large temperature gradient
- Nuclear systems involved
  - High-Temperature Gas-Cooled Reactors (HTGR)
  - Small-Modular Boiling-Water Reactors (SMBWR)
  - **Pool-type Sodium-Cooled Fast Reactors (SFR)**
  - ...
- Concerns
  - Leads to neutronic and thermal-hydraulic instabilities
  - Causes thermal fatigue crack growth
  - **Impedes natural circulation**



Existing methodologies

- 0-D methods
  - System-analysis codes such as: RELAP5, SAS4A/SASSYS-1, DYN2B, CATHARE, ATHLET, Super-COPD, …
  - Fast running
  - Poor predictions for the transients
- 2-D and 3-D methods
  - CFD codes such as: STAR-CCM+, STAR-CD, Fluent, CFX, AQUA, …
  - Accurate predictions
  - Computationally expensive and time consuming
- 1-D methods
  - BMIX ++ (Zhao, 2003)
  - 1-D scalar transport model (Wilson and Bindra, 2018)

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Objective

To develop an advanced physics-based data-driven 1-D thermal stratification model, which can be implemented into system-analysis codes.

Project collaborators

NEUP Nuclear Energy University Program
U.S. Department of Energy

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Guidance →

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Validation

Design

Validation

Verification

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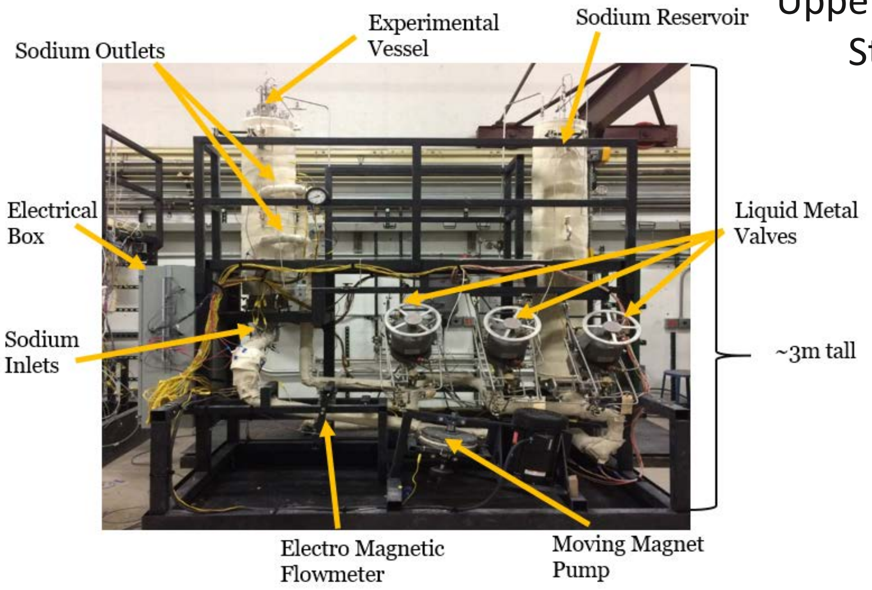
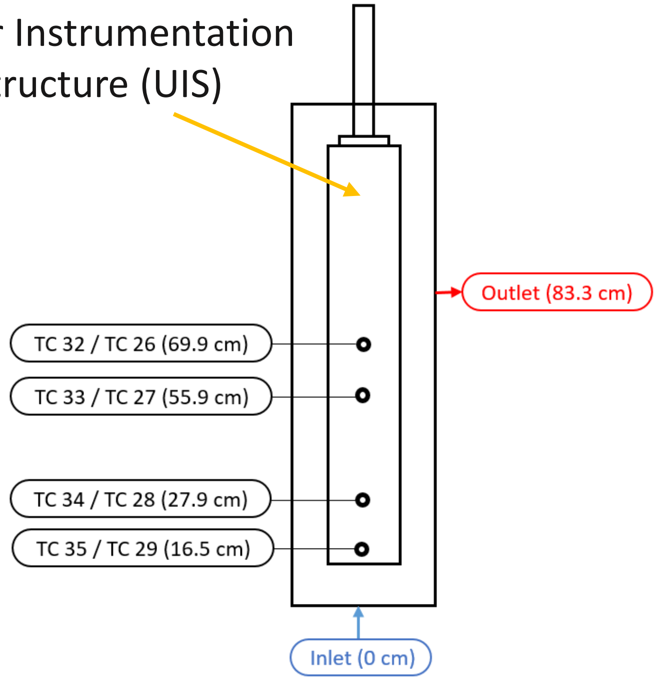
Liangyu Xu
Emilio Baglietto

Experimental setting and CFD calculation





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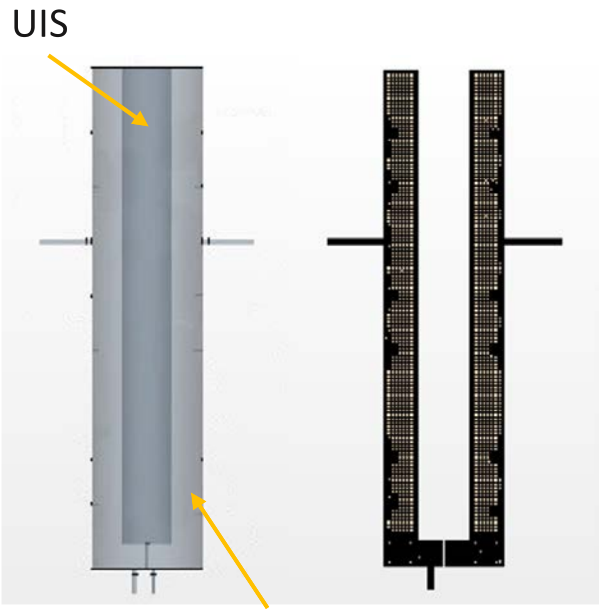
The Thermal Stratification Experimental Facility (TSTF)

Experimental setting



Massachusetts Institute of Technology

CFD model

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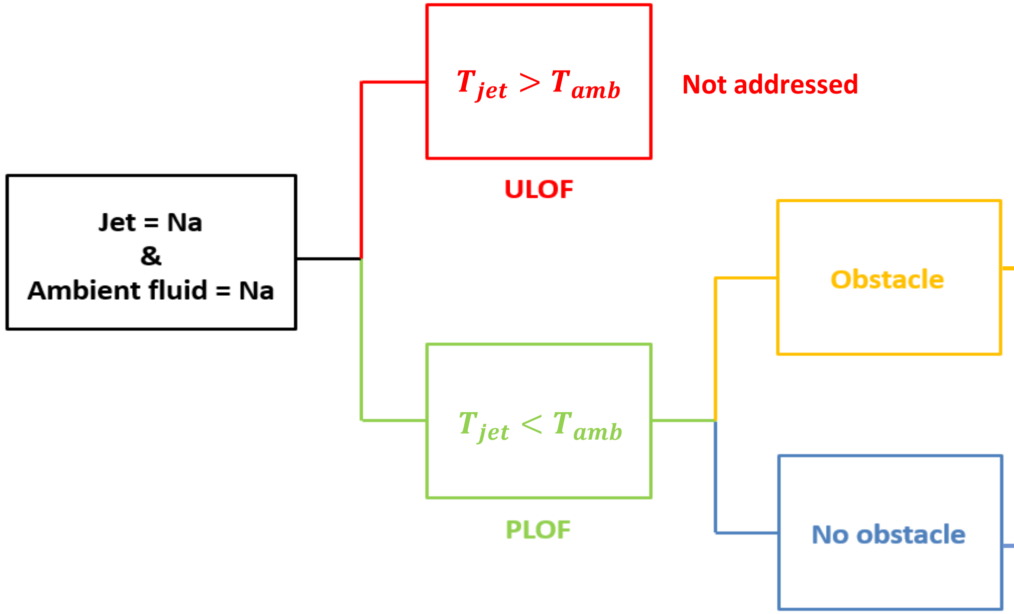
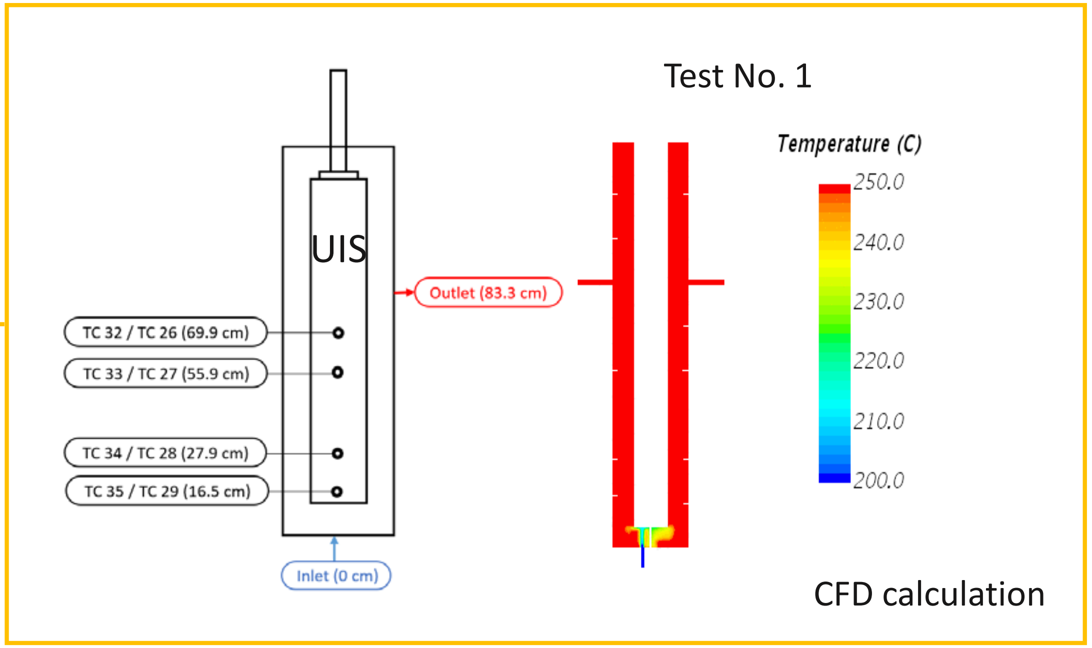
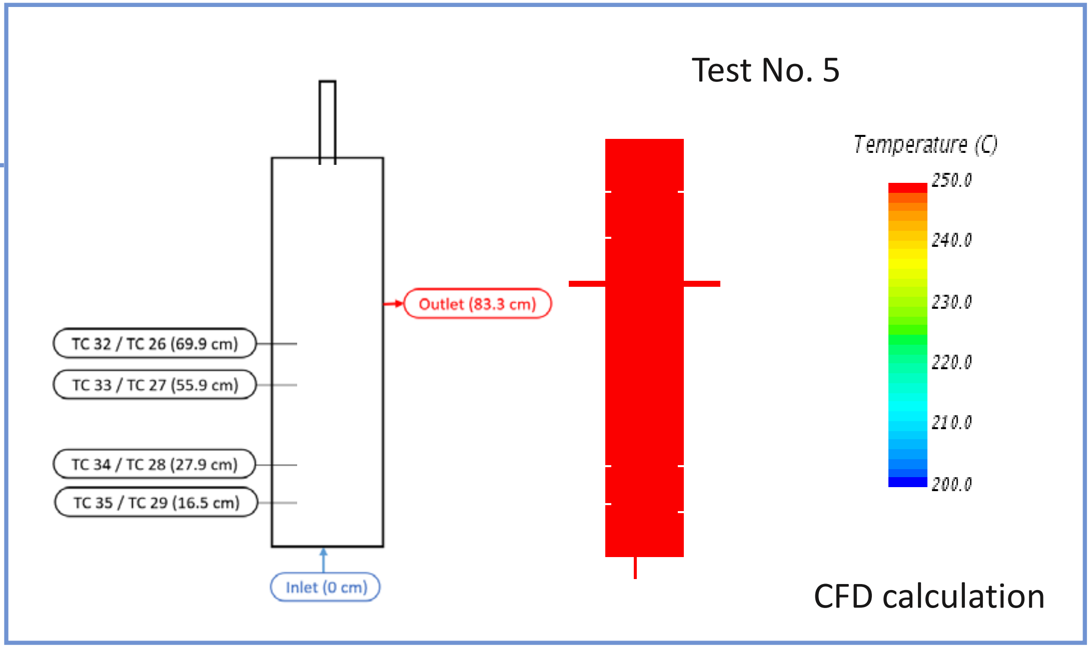
Flow conditions considered







Test No.	Inlet T (℃)	Initial T (℃)	Flow rate (gpm)	Flow rate (L/s)	
1	200	250	6	0.38	With UIS
2	200	250	10	0.63	
3	200	225	10	0.63	
4	200	300	1.5	0.09	Without UIS
5	200	250	3	0.19	
6	200	300	3	0.19	
7	200	250	10	0.63	
8	200	300	10	0.63	

Governing equations

(Peterson, 1994)

$$A_{amb}(z)\frac{\partial \rho_{amb}}{\partial t}+\frac{\partial(\rho_{amb}Q_{amb})}{\partial z}=\sum_{k=1}^{N_{jet}}\rho_k Q'_k \ (conservation\ of\ mass)$$

$$\frac{\partial P_{amb}}{\partial z}=-\rho_{amb}g\ (conservation\ of\ momentum)$$

$$A_{amb}(z)\frac{\partial(\rho_{amb}h_{amb})}{\partial t}+\frac{\partial(\rho_{amb}h_{amb}Q_{amb})}{\partial z}-A_{amb}(z)\frac{\partial}{\partial z}\left(k_{amb}\frac{\partial T_{amb}}{\partial z}\right)=\sum_{k=1}^{N_{jet}}\rho_k h_k Q'_k \ (conservation\ of\ energy)$$

By combining the mass and the energy equations

$$\rho_{amb}c_p\frac{\partial T_{amb}}{\partial t}+\rho_{sf}c_p\bar{u}_z\frac{\partial T_{amb}}{\partial z}-\frac{\partial}{\partial z}\left(k_{amb}\frac{\partial T_{amb}}{\partial z}\right)=\frac{1}{A_{amb}(z)}\sum_{k=1}^{N_{jet}}(\rho Q')_k\,(h_k-h_{amb})$$

By approximating $dh=c_p dT$ and $\Delta h=c_p\Delta T$ when $T_{jet}\approx T_{amb}$

$$\rho_{amb}c_p\frac{\partial T_{amb}}{\partial t}+\rho_{sf}c_p\bar{u}_z\frac{\partial T_{amb}}{\partial z}-\frac{\partial}{\partial z}\left(k_{amb}\frac{\partial T_{amb}}{\partial z}\right)=\frac{N_{jet}}{A_{amb}}c_{p,jet}\rho_{jet}Q'_{jet}(T_{jet}-T_{amb})$$

only parameter requiring additional closure relations

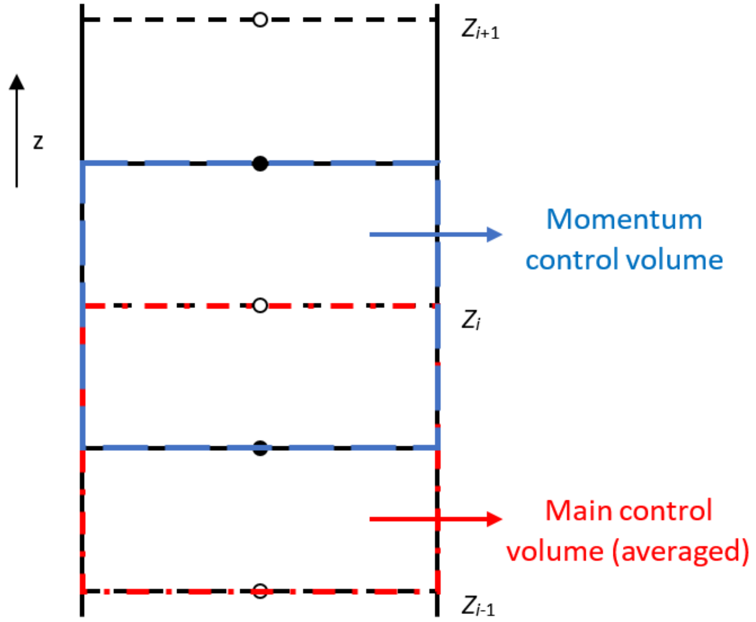
Discretization

$$\rho_{amb} c_p \frac{\partial T_{amb}}{\partial t} + \rho_{sf} c_p \bar{u}_z \frac{\partial T_{amb}}{\partial z} - \frac{\partial}{\partial z}\left(k_{amb} \frac{\partial T_{amb}}{\partial z}\right) = \frac{N_{jet}}{A_{amb}} c_{p,jet} \rho_{jet} Q'_{jet}(T_{jet} - T_{amb})$$

- standard staggered scheme
- semi-implicit approach for the temporal derivative
- first-order upwind scheme for the first order spatial derivative
- second-order central difference scheme for the second order spatial derivative

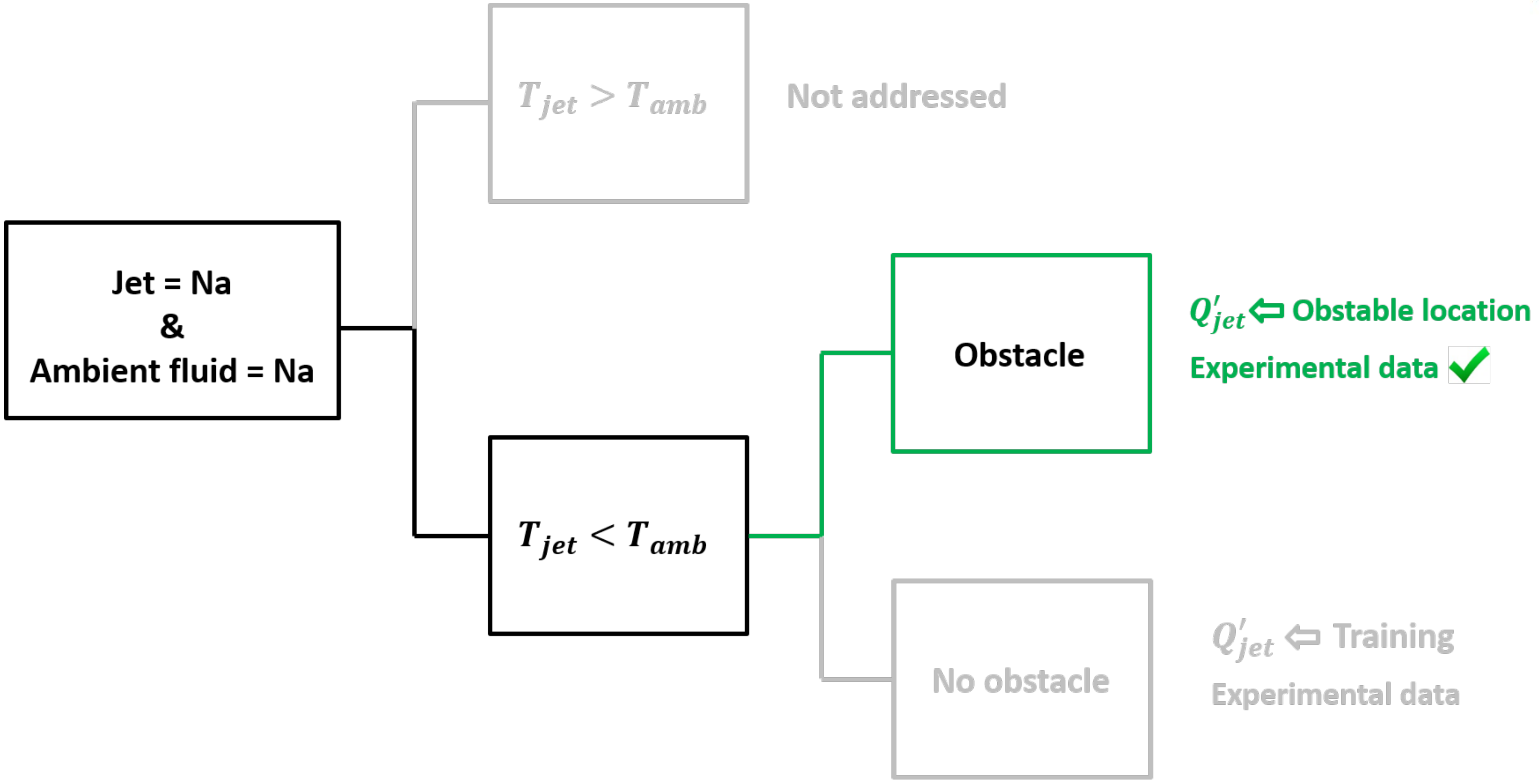
$$\rho_i^n c_{p,i}^n \frac{T_i^{n+1} - T_i^n}{\Delta t_n} + \rho_i^n c_{p,i}^n \bar{u}_{z,i}^n \frac{T_i^{n+1} - T_{i-1}^{n+1}}{\Delta z_i} - \frac{2}{\Delta z_i} k_i^n \left[\frac{T_{i+1}^{n+1} - T_i^{n+1}}{\Delta z_{i+1} + \Delta z_i} - \frac{T_i^{n+1} - T_{i-1}^{n+1}}{\Delta z_i + \Delta z_{i-1}}\right] = \frac{N_{jet}}{A_{sf}} c_{p,jet} \rho_{jet} Q'_{jet,i}(T_{jet} - T_i^n)$$

- Initial condition: Uniform T_{sf}
- Neumann boundary conditions: $T_0 = T_1$ and $T_{N+1} = T_N$
- Sensitivity analysis: Δt and Δz



Staggered scheme

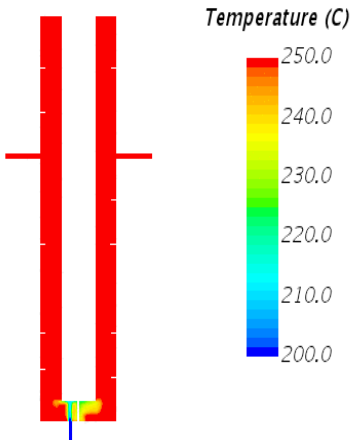
Flow conditions considered

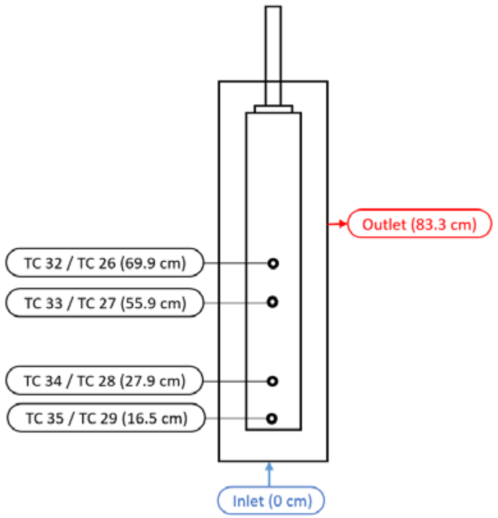


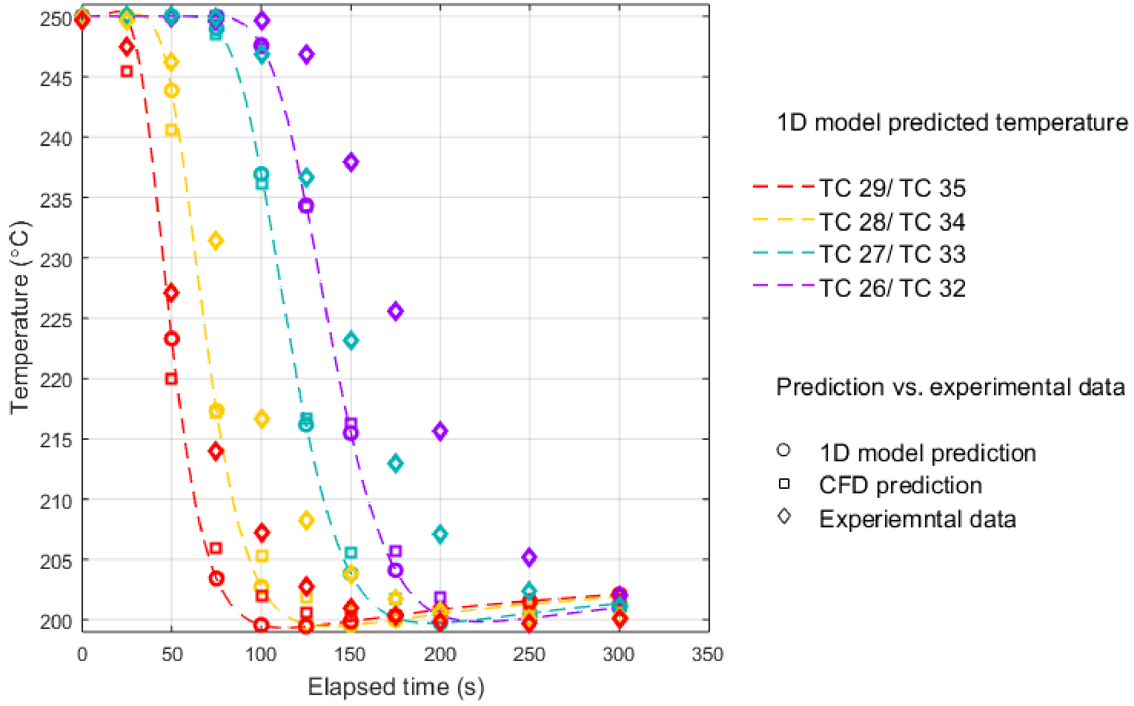
$T_{jet} < T_{amb}$ with UIS: Exp. data vs. predictions

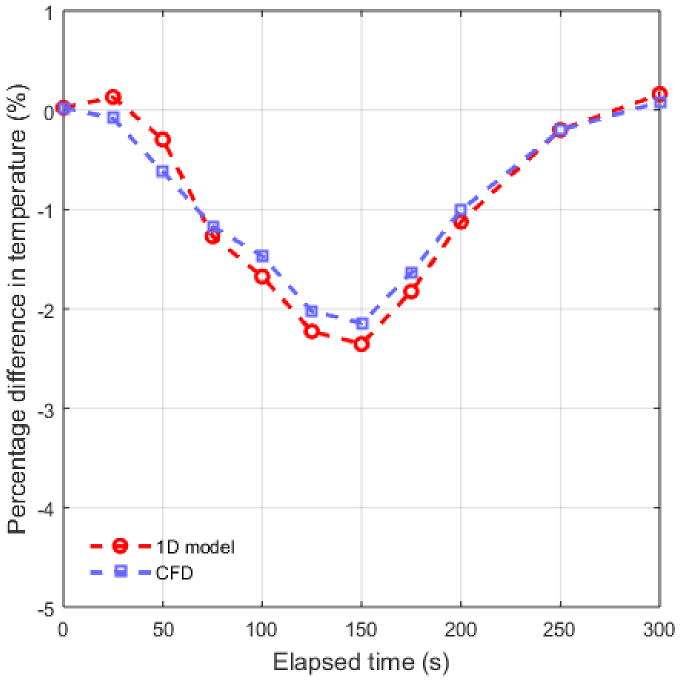
- Model for Q'_{jet}
  - $L_{jet} = z_{UIS}$
  - $Q'_{jet} = Q_{jet}/N_{jet}\,L_{jet}$

Test #1
$T_{jet} = 200°C$
$T_{amb} = 250°C$
$U_{jet} = 1\ m/s$









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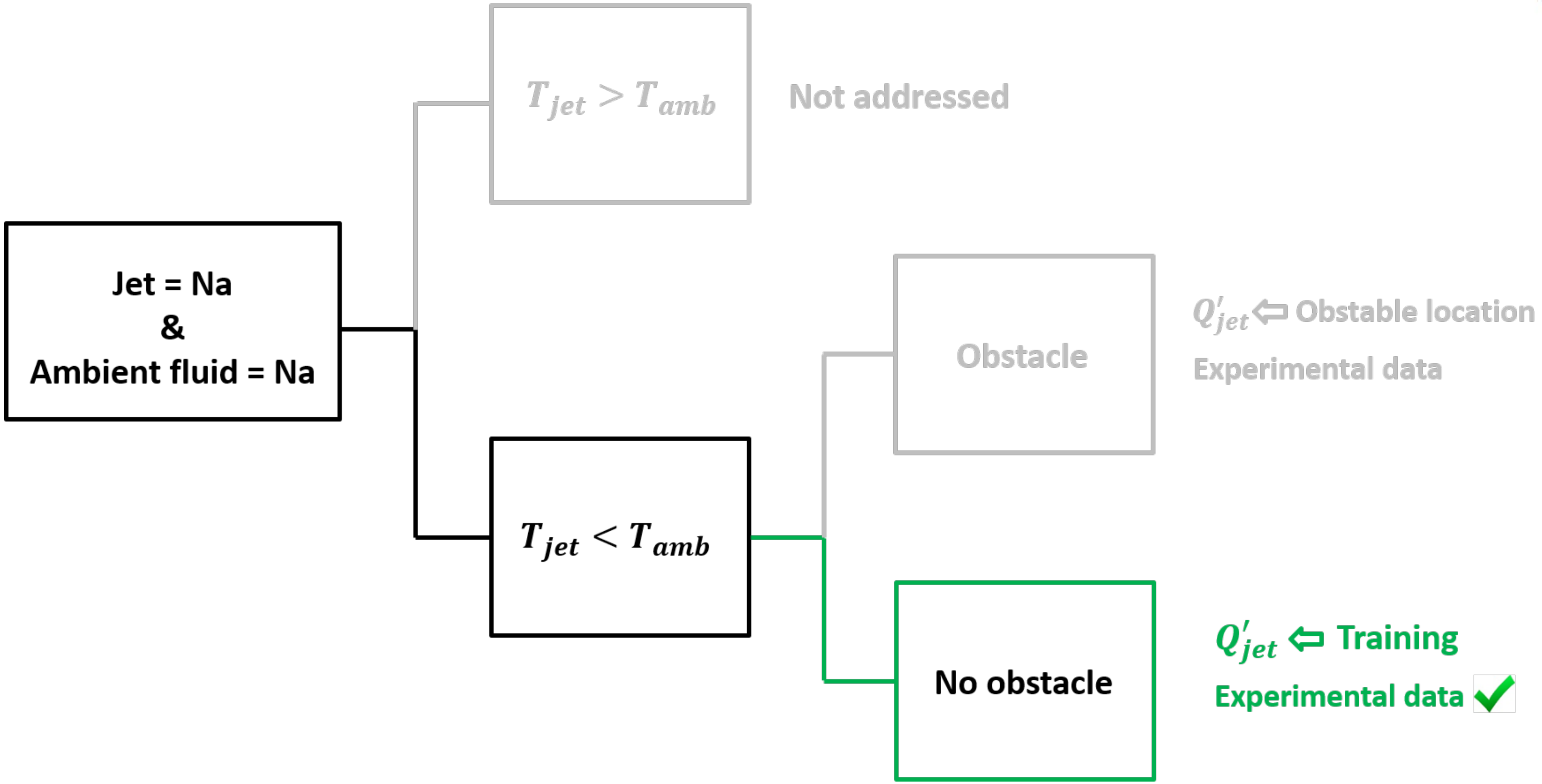
Flow conditions considered



$T_{jet} < T_{amb}$ without UIS: model for Q'_{jet}

$$\boldsymbol{stopping\ force\ F = F_D + F_g}$$

$$F_D = -C_D \rho_{sf} A_{jet} v_{jet}^2 \qquad F_g = -(\rho_{jet} - \rho_{sf}) V_{jet}$$

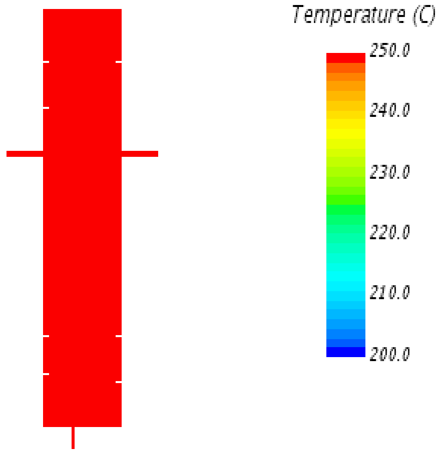
For a hypothetical cylindrical jet with a length L

$$\frac{dv_{jet}}{dt} = \frac{F_D + F_g}{\rho_{jet} A_{jet} L_{jet}} = -\left(\frac{C_D}{L_{jet}} \frac{v^2 \rho_{sf}}{\rho_{jet}} + \frac{\rho_{jet} - \rho_{sf}}{\rho_{jet}}\right)$$

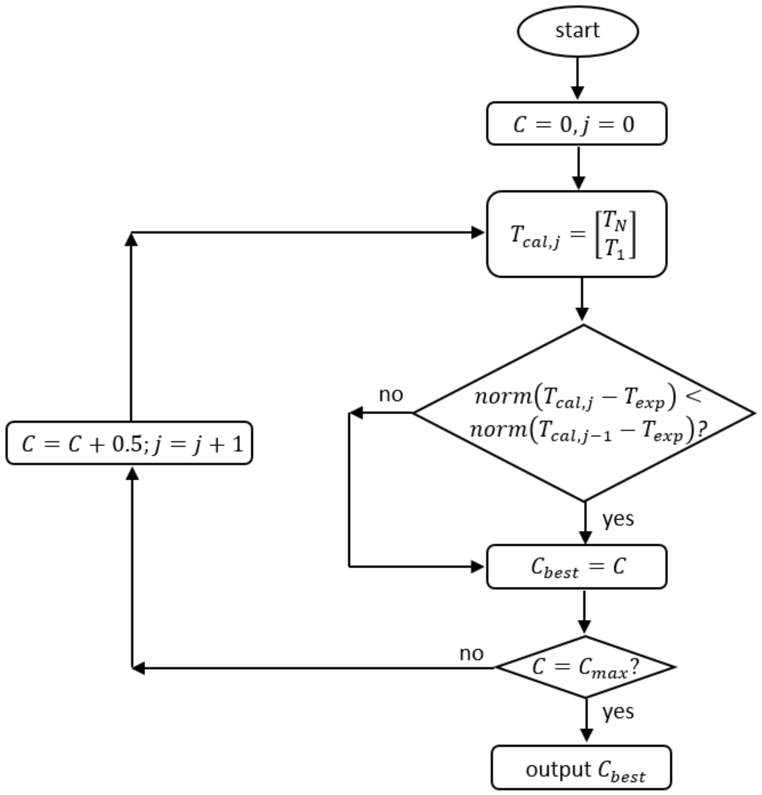
$$dv_{jet} = -\left(C \frac{v^2 \rho_{sf}}{\rho_{jet}} + \frac{\rho_{jet} - \rho_{sf}}{\rho_{jet}}\right) dt$$

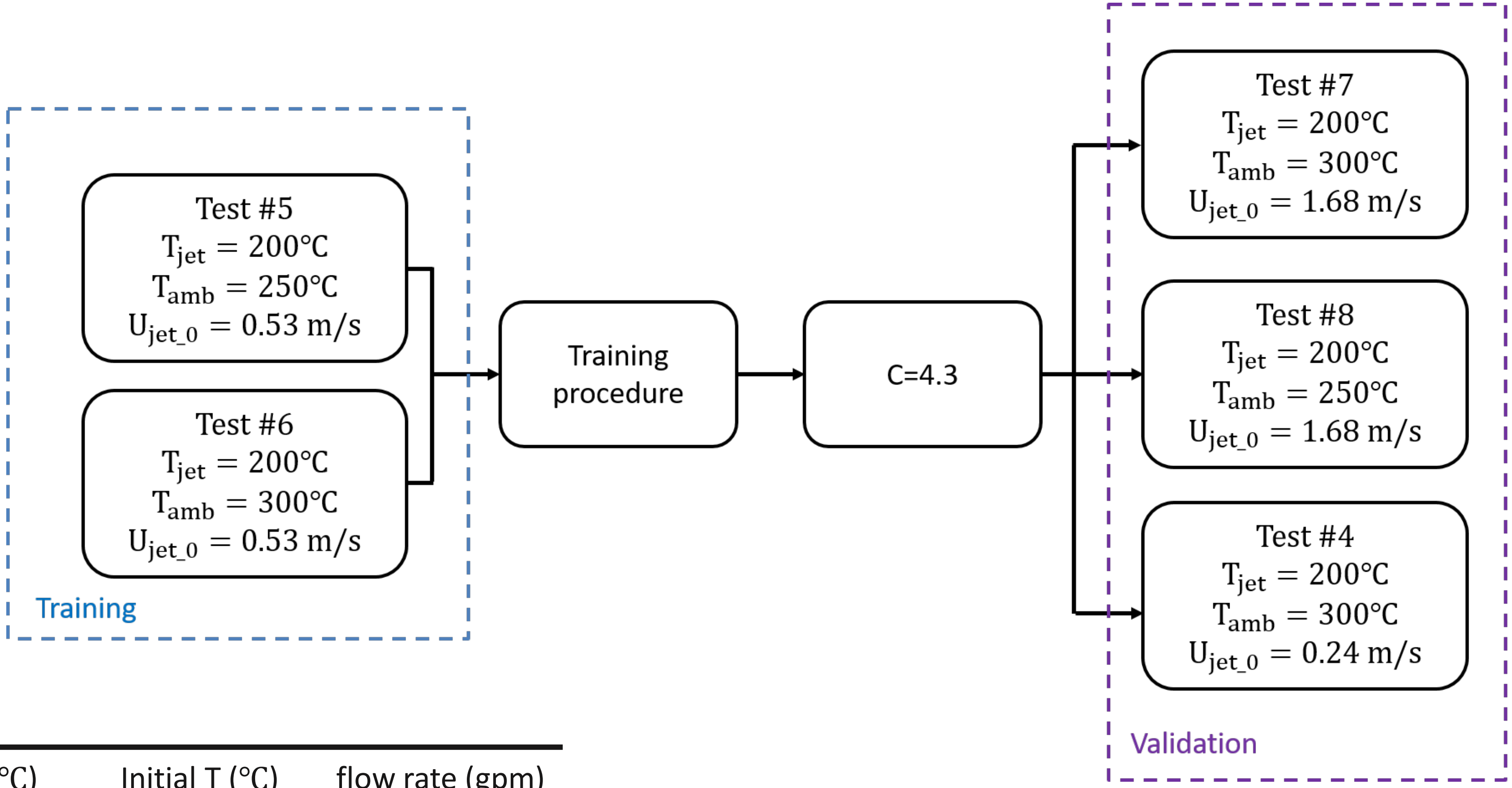
only parameter to be determined

$$\boldsymbol{maximum\ height\ of\ the\ jet \rightarrow Q'_{jet}}$$



$T_{jet} < T_{amb}$ without UIS: training procedure





	Test No.	Inlet T (°C)	Initial T (°C)	flow rate (gpm)
Validation	4	200	300	1.5
Training	5	200	250	3
	6	200	300	3
Validation	7	200	300	10
	8	200	250	10

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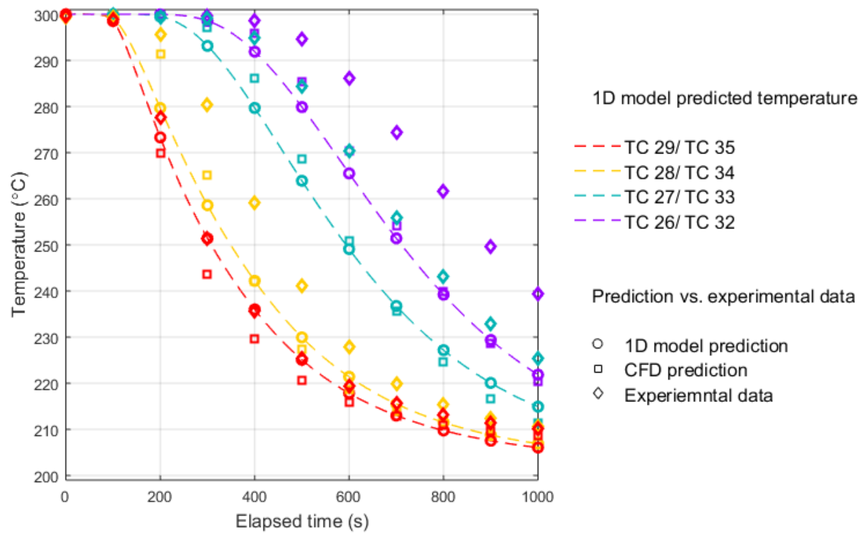
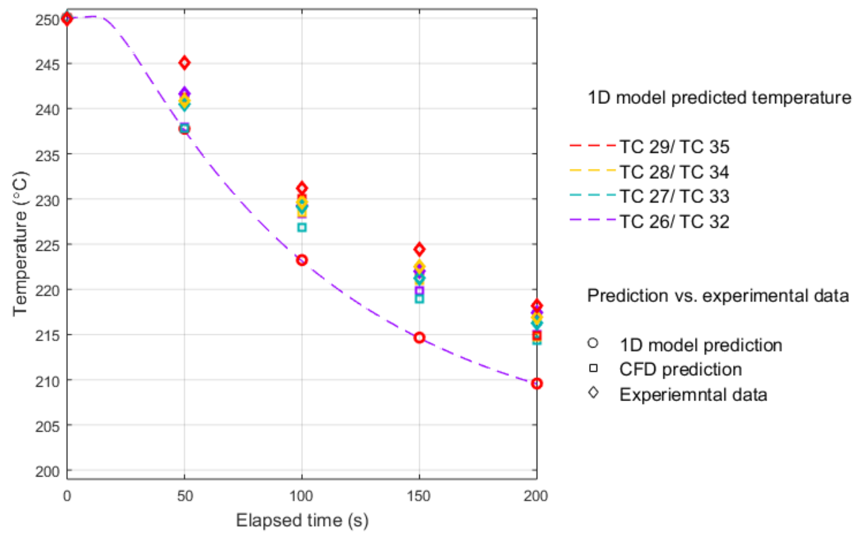
$T_{jet} < T_{amb}$ without UIS: results

Test #4
$T_{jet} = 200°C$
$T_{amb} = 300°C$
$U_{jet} = 0.24\ m/s$



Test #7
$T_{jet} = 200°C$
$T_{amb} = 300°C$
$U_{jet} = 1.68\ m/s$



	Test No.	Inlet T (°C)	Initial T (°C)	flow rate (gpm)
Validation	4	200	300	1.5
Training	5	200	250	3
	6	200	300	3
Validation	7	200	300	10
	8	200	250	10

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Comparison of model accuracy

Test No.	Inlet T (°C)	Initial T (°C)	ΔT (°C)	Flow rate (gpm)	Max error 1D (°C)
1	200	250	-50	6	-21
2	200	250	-50	10	-20.5
3	200	225	-25	10	-9.6
4	200	300	-100	1.5	-23
5	200	250	-50	3	-10.4
6	200	300	-100	3	-26.2
7	200	250	-50	10	-7.8
8	200	300	-100	10	-12.1

With UIS (tests 1–3)

No UIS (tests 4–8)

Validation (test 4)

Training (tests 5–6)

Validation (tests 7–8)

Summary and …

- 1-D system-level model for the prediction of the thermal stratification in the pool-type SFRs
- Flow conditions considered: $T_{jet} < T_{amb}$
  - With UIS
  - Without UIS
- Performance of 1-D model $\sim$ CFD calculation
- Non-negligible discrepancies between predictions and measurement

Future work

- To improve the 1-D model by removing some approximations and assumptions

Acknowledgement

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NEUP Nuclear Energy University Program

U.S. Department of Energy

References

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- Wilson, G. and Bindra, H., 2018. Thermal stratification and mixing in SFR plena using a one-dimensional scalar transport model. American Nuclear Society 2018 winter meeting.
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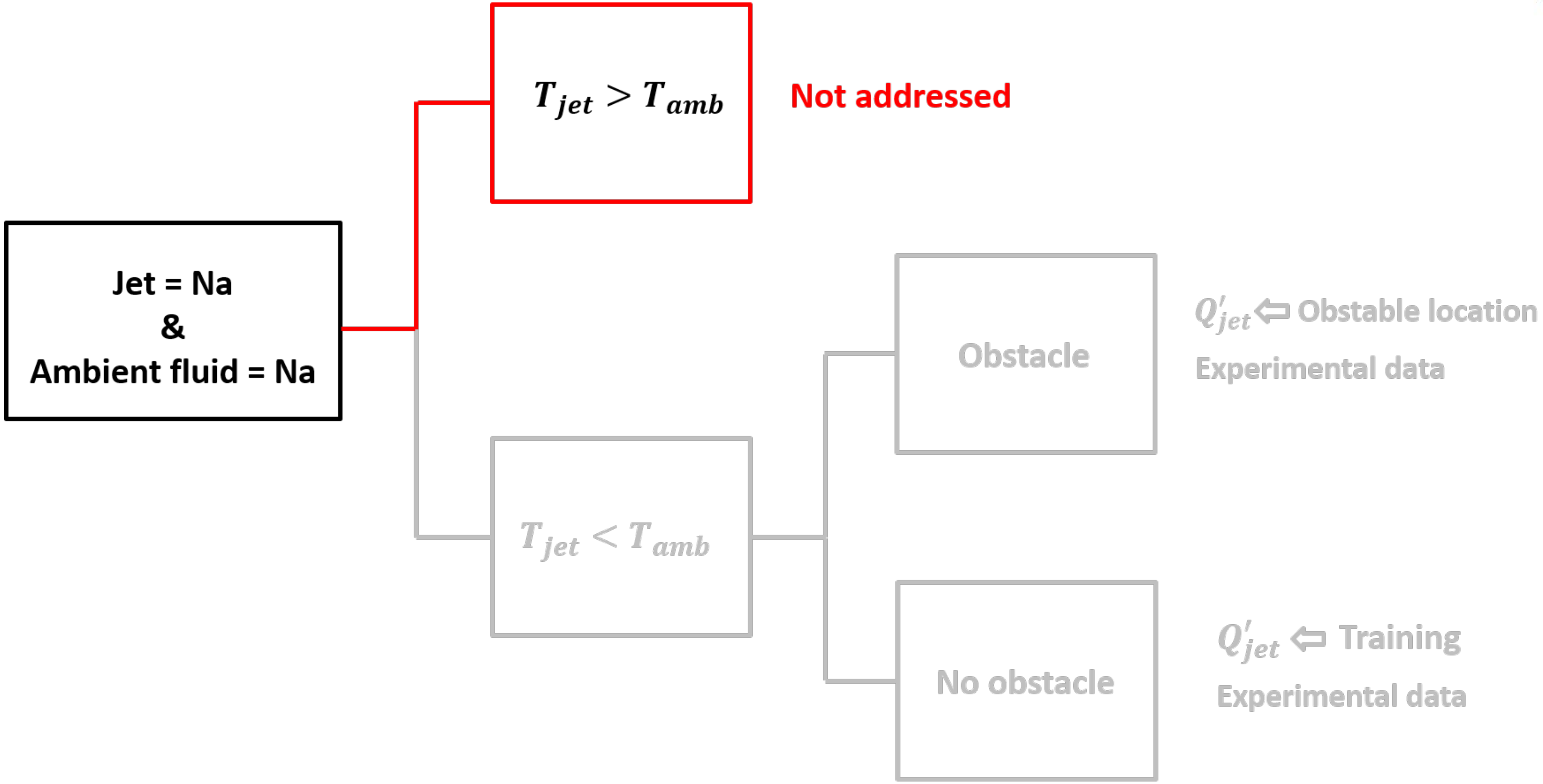
Backup slides

Flow conditions considered



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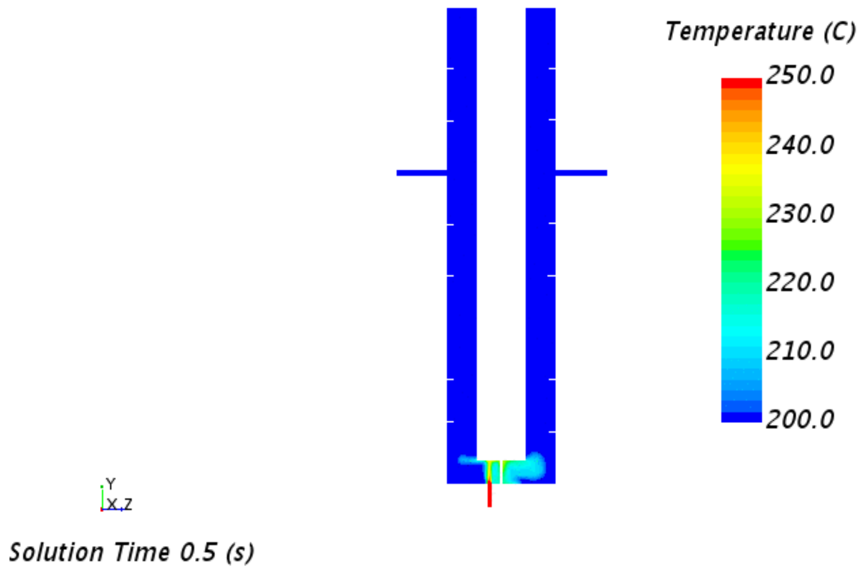
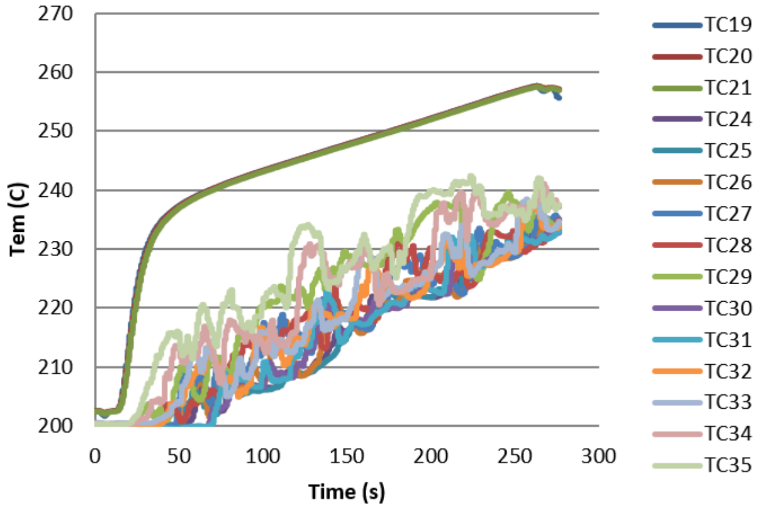
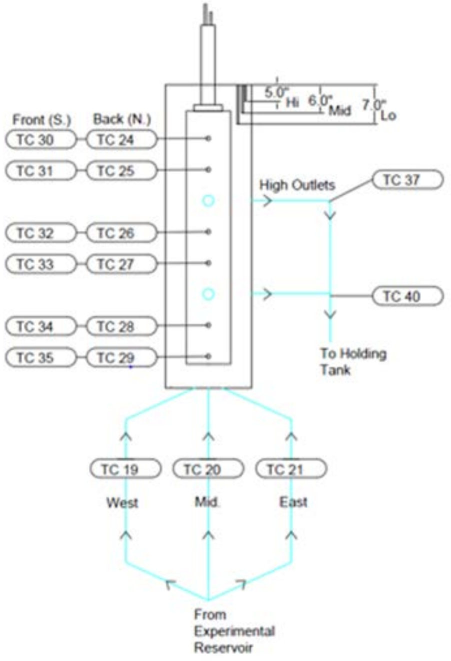
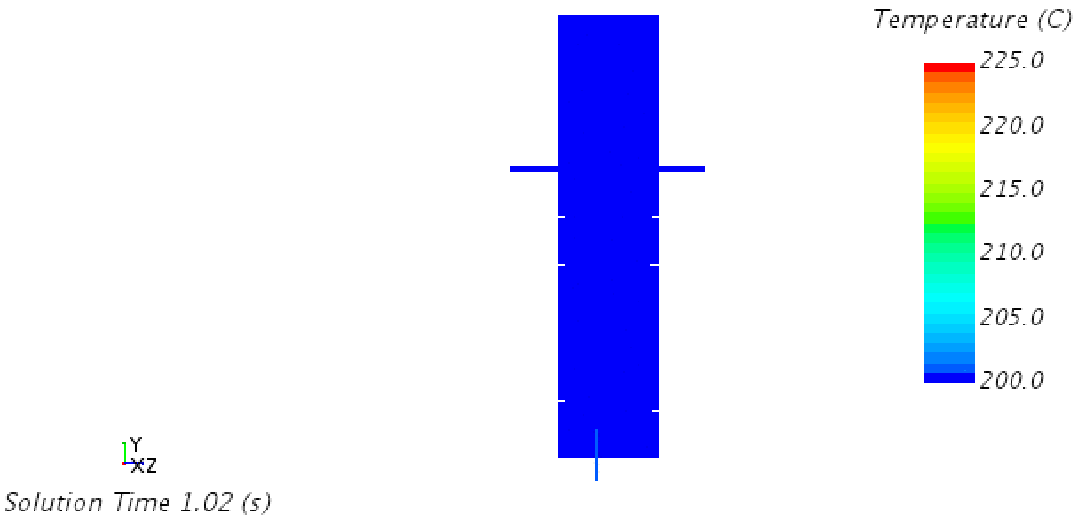
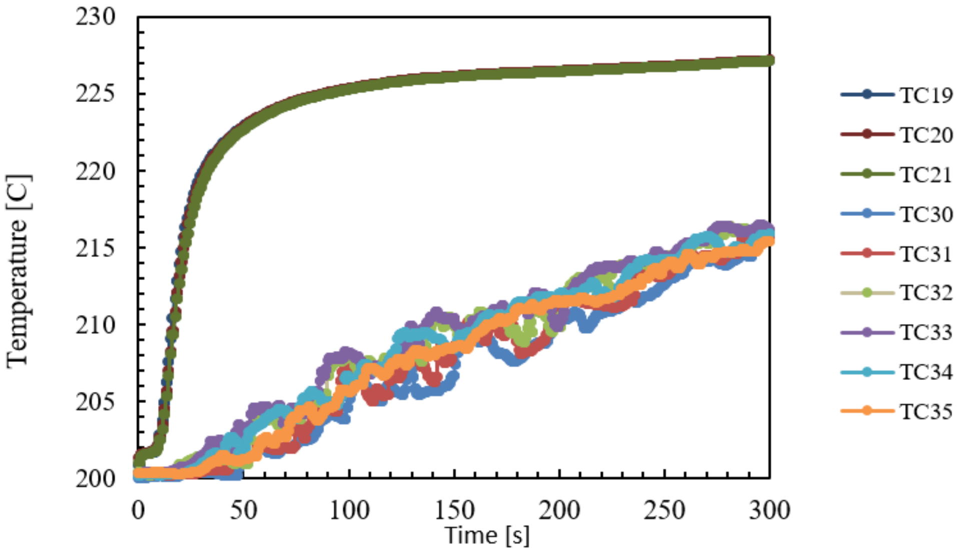
$T_{jet} > T_{amb}$:











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