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Application of RELAP5-3D to Subchannel Analysis by Using the Experimental Data of NACIE-UP Facility

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Activity framework

- GEN IV Liquid Metal Fast Reactors (LMFR) aim at obtaining reliable fuel operations characterized by high-burnup and high-power density features;

- In such conditions, to perform an affordable core design, an effective thermal-hydraulic characterization of the fuel bundle at a subchannel level is needed.

- To fulfill this scope, two main approaches were followed throughout the last decades:

    1. Develop specific SubChannel Thermal-Hydraulic code (SCTH); SUPERENERGY II, MATRA-LMR, COBRA-LM for SFR and ANTEO+, SACOS-PB for LFR.
    2. Adopt full Computational Fluid Dynamics (CFD) codes.

Activity framework

➢ Both approaches are characterized by strengths and weaknesses.

SCTH	CFD
Approach	
1D conservation equations solved along flow direction. Mass, momentum and energy exchanges between adjacent subchannels considered by using ad-hoc constitutive relations.	3D conservative equations.
Strengths/Weaknesses	
✓ Fast-Running; Design Tool;	✓ Capability to simulate complex 3D T/H phenomena
✗ Needed to be upgraded any time pre-set features are breached; Limited domain (coupling required)	✗ High computational cost

Activity framework

➢ Within this framework, an alternative option can be represented by the adoption of a best-estimate System Thermal-Hydraulic (STH) code, used by following a ‘dedicated’ approach for subchannel analysis.

Feature	SCTH	CFD	STH
Assembly Geometry	Ad-hoc	Any	Any
Coolant type	Ad-hoc	Any	Any
Conservative Equations	1D + Constitutive Correlations	3D	1D/’3D’
Computational Cost	Very Low	High	Medium (Incr. from 1D to 3D)
3D T/H phenomena	Limited to core	Yes	Partial
Transient Analysis	Limited to core	Limited by computational time	Yes

Activity framework

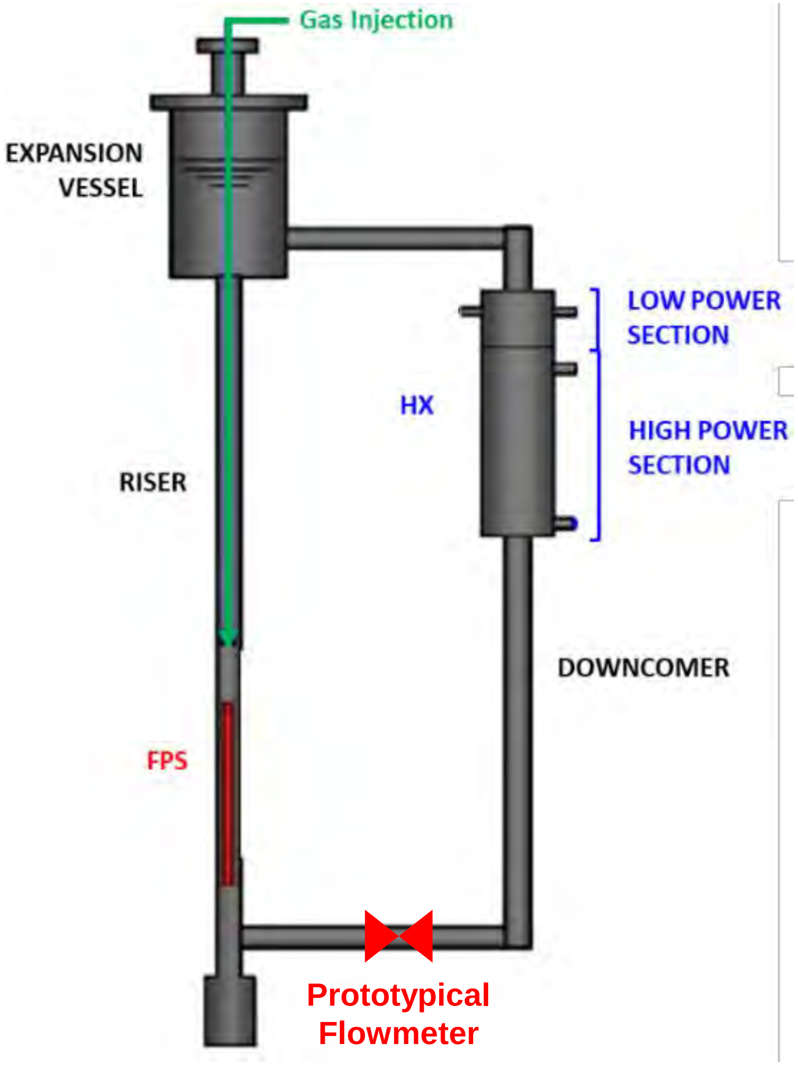
- Such approach related to STH codes was already adopted for subchannel analysis related to Sodium Fast Reactors (SFR), [Memmott et al., 2010].

- The aim of the presented work is extending its validity to Lead Fast Reactors (LFR); The selected STH code is RELAP5-3D©;

- The experimental data needed for the approach validation are derived from the test campaign performed in the last years at the NACIE-UP facility hosted in the ENEA research center of Brasimone.

- Using this alternative approach and validating it against experimental data has the goal to have a suitable code to investigate the LFR core transient behavior during operational and accidental conditions.

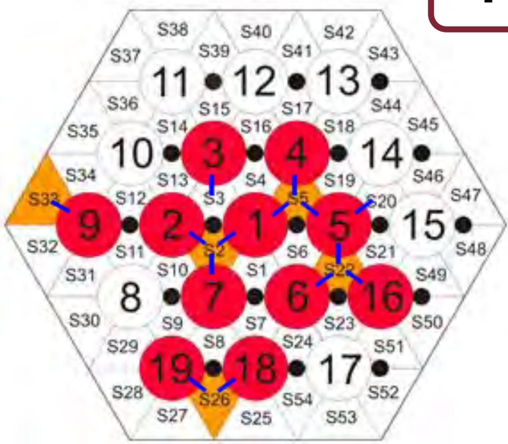
Overview of NACIE-UP facility



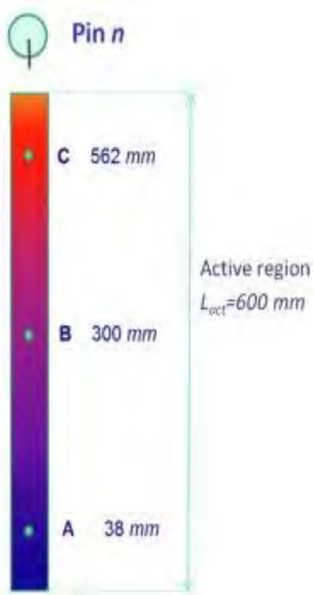
- Rectangular loop: height is nearly 8 m and horizontal pipelines are 2.4 m, [Di Piazza et al., 2019].
- FPS (simulating reactor core) is located at the riser bottom, while water/liquid metal heat exchanger (HX) at downcomer top, with a thermal center height difference of 5.5 m.
- LBE flow is gas-enhanced (Argon) during normal operations.
- Gas is introduced slightly above FPS exit and separated in the expansion vessel.
- Several thermocouples (TC) placed along the LM flow path to fully characterize the temperature field. A prototypical flowmeter is inserted in the lower horizontal pipe.

Overview of NACIE-UP facility

FPS

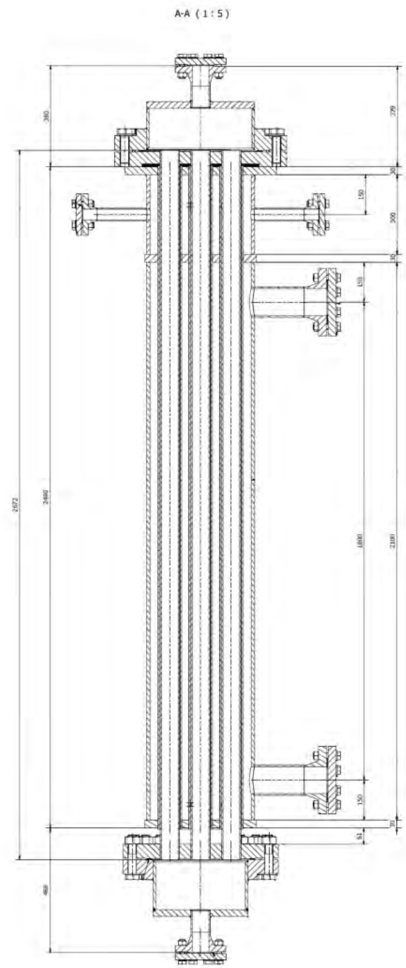


- Instr. pins
- Instr. sub-channels
- Wall-embedded TCs



FPS Parameter	Unit	Value
Max. Power	kW	235
Pin N°	-	19
Pin OD	mm	6.55
Pin pitch	mm	8.4
Wire OD	mm	1.75
Wire Pitch	mm	262
Tot. Length	mm	2000
Th. Length	mm	600
Hyd. Diam.	mm	3.84

HX



- Shell&Tubes configuration;
- 7 bayonet tubes;
- 300 mm active length low power section;
- 2100 mm active length high power section;

NACIE-UP test campaign

- During 2017 test campaign (Horizon 2020 SESAME project), 3 Fundamental Tests (FT) were performed at the facility to investigate the circuit T/H behavior associated to a low power and/or mass flow transient, [Di Piazza et al., 2019].
- In each FT, loop started from steady state conditions (Before Transient, BT). Then, a transition was imposed, either in terms of power or mass flow or both. When the system reached a new steady state (After Transient, AT), test was concluded.

FT1 (Gas Lift Transition)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	20	10
FPS Power	kW	50	
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^3h^{-1}	10	

FT2 (Power Transition)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	18	
FPS Power	kW	100	50
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^3h^{-1}	6.6	

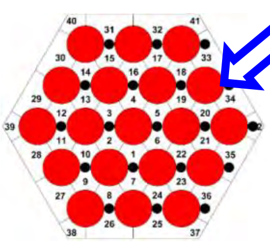
FT3 (Protected Loss of Flow Accident, PLOFA)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	20	0
FPS Power	kW	100	10
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^3h^{-1}	10	

NACIE-UP test campaign

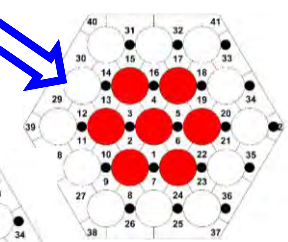
- During 2017 (Accordo di Programma - AdP), 3 tests (ADPs) were performed at the facility. They became the object of a IAEA Coordinate Research Project (CRP I31038) started in 2022 and still ongoing (2nd RCM Meeting in November 2023).

- In each test, loop started from steady state conditions (Before Transient, BT). Then, a transition was imposed, either in terms of power or mass flow or both. When the system reached a new steady state (After Transient, AT), test was concluded.

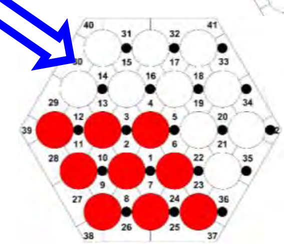
ADP10 (even pin power distribution)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	10	0
FPS Power	kW	30	
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^{3}h^{-1}	10	



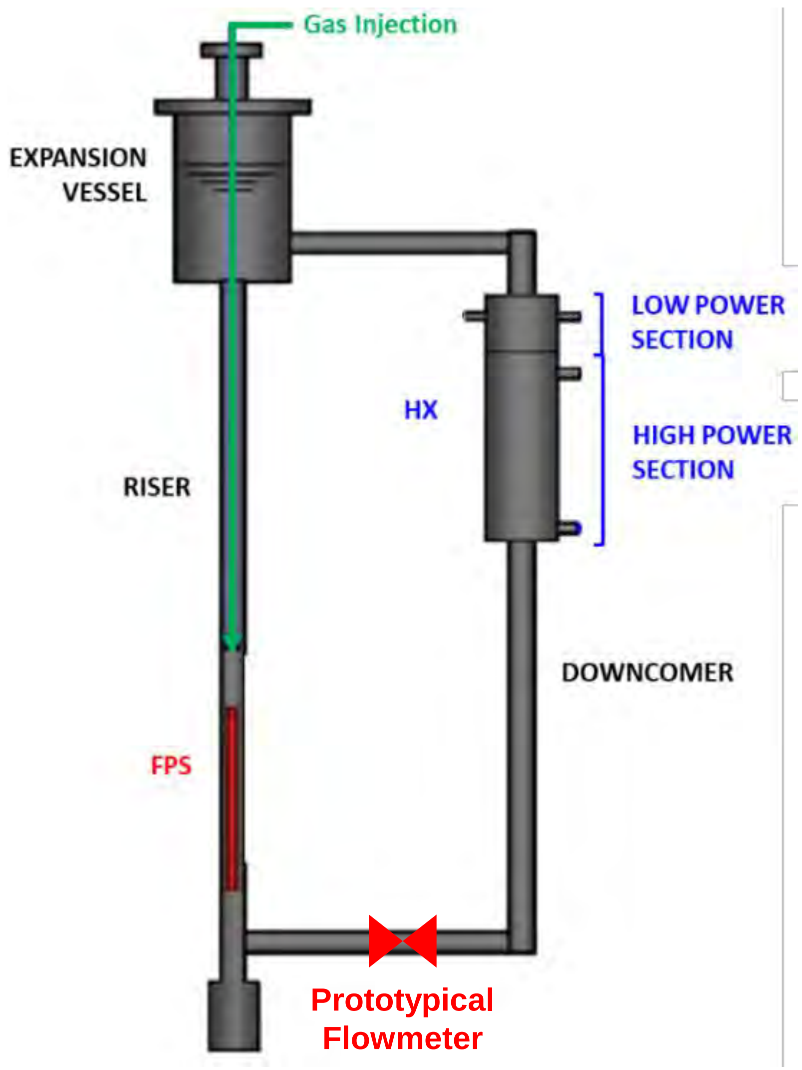
ADP06 (central pin power distribution)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	10	0
FPS Power	kW	30	
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^{3}h^{-1}	10	



ADP07 (dissymetrical pin power distribution)			
Parameter	Unit	BT	AT
Gas Flow	N l min^{-1}	10	0
FPS Power	kW	38	
HX Feedwater Flow (@ 443 K and 1.6 MPa)	m^{3}h^{-1}	10	



Overview of NACIE-UP facility



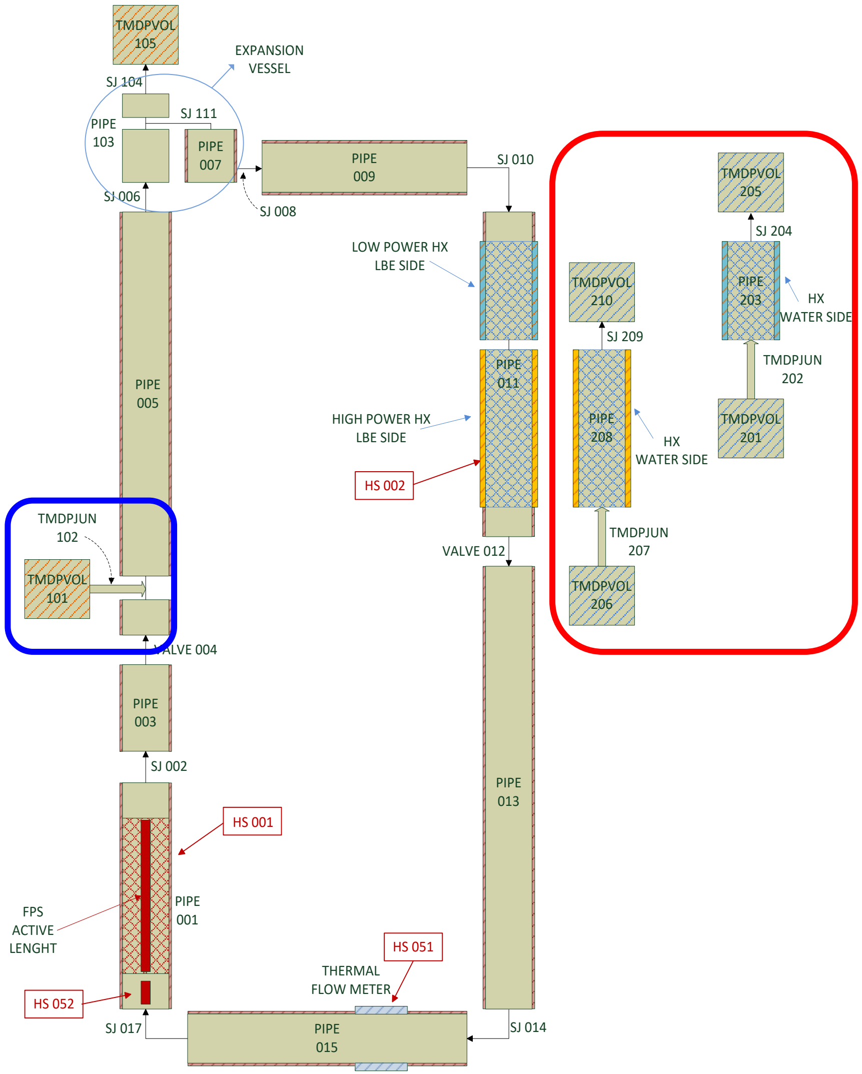
A **complete model of NACIE-UP primary circuit**, including all components, has been developed at NERG of Sapienza University of Rome by using the best-estimate system code **RELAP5-3D©**.

Multi-step (i.e., purpose) approach:

1. Simulating the loop transient behavior at a system level → FPS simulated with lumped parameters (WP1).
2. Understand in detail the transient behavior of the FPS → rest of the LBE loop simulated with BCs (WP3).
3. Simulation of the whole facility transient behavior (Input deck of Points 1 & 2 combined).
4. Perform UQ and SA (WP5).

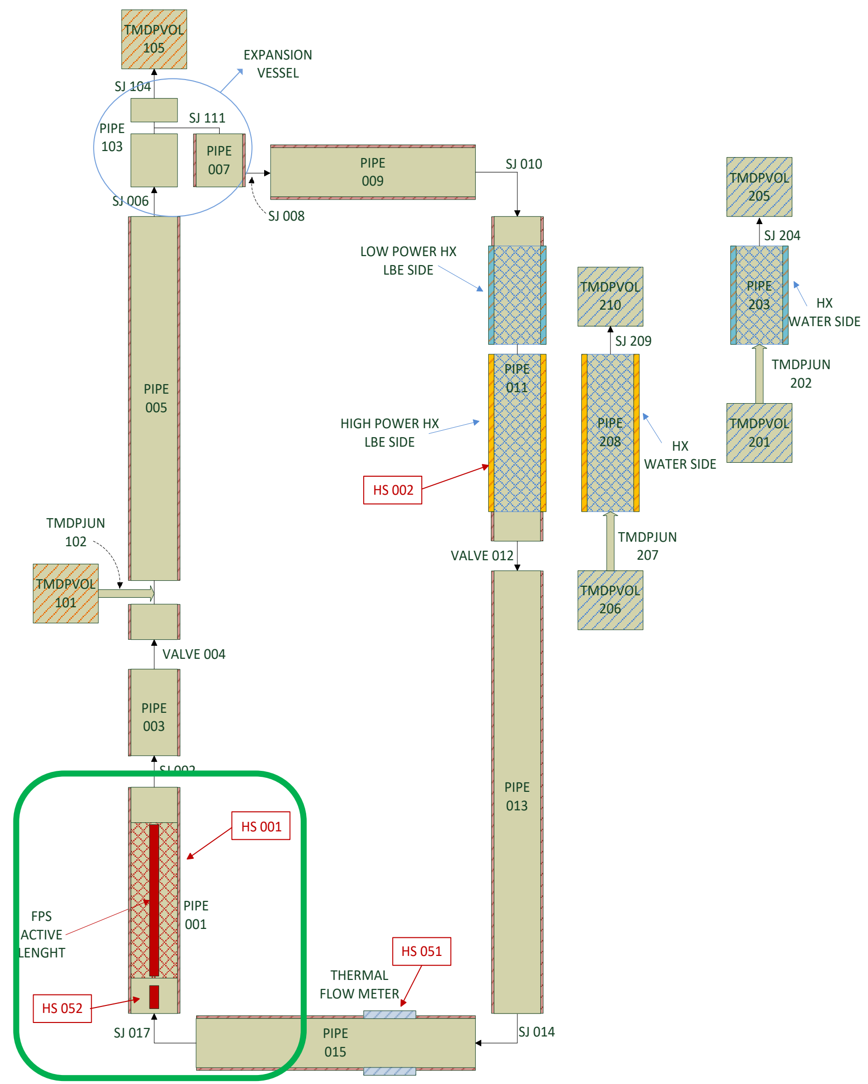
RELAP5-3D© Model

- RELAP5-3D© system thermal-hydraulic code (Version 4.3.4) was used.
- *Sliced nodalization technique* was adopted to properly evaluate the natural circulation.
- The *node-to-node ratio* was kept below 1.25 (more homogeneous mesh);
- All system components (pipeline and equipment) modelled with 1-D components.
- **Gas injection** modelled with imposed inlet boundary conditions (pressure, temperature and mass flow).
- Only **HX high power section secondary side** simulated. Water inlet conditions set as boundary conditions (pressure, temperature and mass flow).



RELAP5-3D© Model

- **FPBS** modelled with a single pipe using lumped parameters. Axial nodalization respects the instrumented elevations (Sections A, B and C).
- *Cheng & Todreas* correlation for wire-wrapped fuel bundle axial PDs.
- *Kazimi & Carelli* (Westinghouse) HTC correlation used within fuel bundle.
- *Seban & Shimazaki* HTC correlation used for primary circuit pipeline (heat losses) and for the HX primary side (LBE flows within tubes).
- *Dittus-Boelter* HTC correlation and *Inayatov multiplier* (i.e., p/d) adopted for secondary water flowing within HX shell.
- *Heat losses* considered. Boundary conditions applied on the insulator external surface (T_{air}=10 °C, HTC_{air}=3 $W/m^2 {*} K$).
- *Free surface* simulated within the expansion tank.



RELAP5-3D© Model

- The present work is focused on the evaluation of **RELAP5-3D© capability with respect to subchannel analysis**. For this, an input deck containing a dedicated FPS modelling was developed by DIAEE.

- Several aspects must be carefully taken into account: **i)** the FPS geometrical scheme; **ii)** the cross-flow model; **iii)** the wire-wrap induced turbulent mixing model; **iv)** the fluid conduction model, in both axial and radial directions.

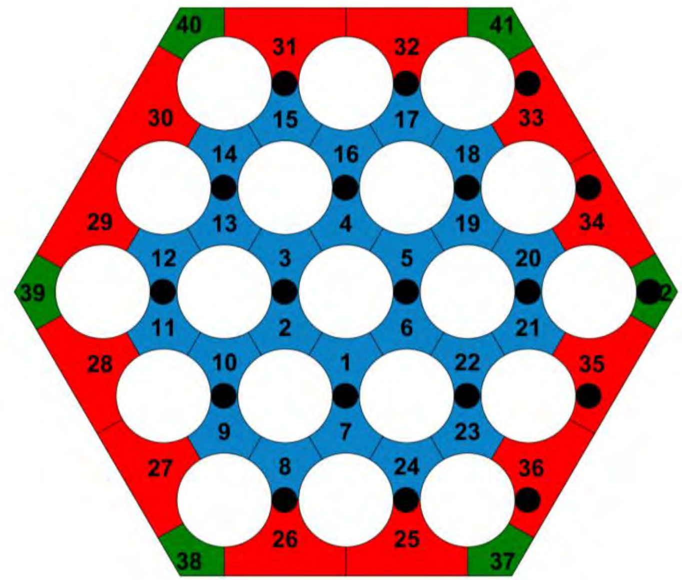
- **LBE inlet temperature (TP-101) and mass flow provided by benchmark specifications are used as boundary conditions.**

Input deck features
Subchannel by subchannel approach
Cheng-Todreas for fuel bundle pressure drops
Cross junctions among adjacent subchannels
Wire turbulent mixing
Fluid thermal conduction

RELAP5-3D© Model

Geometrical scheme

- FPS was divided into 42 subchannels, grouped in three main categories: interior (24, blue), edge (12, red) and corner (6, green).
- They are characterized by a different thermal-hydraulic behavior. For this, each channel was modelled with a dedicated pipe component.
- The axial discretization consists in **10 Control Volumes** (CVs) distributed between the entry non-active region (4), the active length (5) and the unheated exit region (1). **Δz~14 cm**.
- A total of **420 CVs** constitutes the FPS model.



Parameter	Unit	Interior	Edge	Corner
Number	-	24	12	6
Flow Area	m^2	1.2497E-05	2.4958E-05	9.1207E-06
Hyd. Diam.	m	3.8302E-03	4.6539E-03	3.5547E-03

- The flow areas and hydraulic diameters derive from **Cheng & Todreas model (1986)**.

RELAP5-3D© Model

Fuel Bundle Pressure Drops

- **<u>Cheng & Todreas (CT) 1986 detailed model</u>** for friction factor correlations was considered [Cheng et al., 1986].
- RELAP5-3D© gives the user the possibility to implement ad-hoc Re-dependent friction factor correlations (see aside).
- φ, A, B and C parameters were computed differentiated for each subchannel type, namely interior, edge and corner.

R5-3D© f correlations

Regime	Correlation
Laminar (Re < 2200)	$f_L = \frac{64}{Re\theta}$
Transition (2200 < Re < 3000)	$f = \left(3.75 - \frac{8250}{Re}\right)(f_{T,3000} - f_{L,2200}) + f_{L,2200}$
Turbulent (Re > 3000)	$\frac{1}{\sqrt{f_T}} = -2\log_{10}\left\{\frac{R}{3.7D_h} + \frac{2.51}{Re}\left[1.14 - 2\log_{10}\left(\frac{R}{D_h} + \frac{21.25}{Re^{0.9}}\right)\right]\right\}$ $f_T = A + BRe^{-C}$

Cross Junctions

- Hydraulic coupling between adjacent subchannels realized with multiple junctions (**<u>600 cross junctions</u>**). K-loss coefficients were evaluated by using ***<u>Idelchik hydraulic handbook</u>*** [Idelchik, 2003] and associated to cross junction components.

$$K = (z_p + 1) * A * \varphi * Re^{-0.27}$$

$$A = 3.2 + 0.66a_1$$

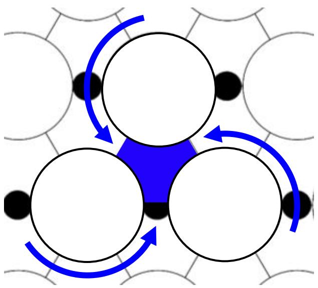
$$a_1 = (1.7 - \bar{s})^{1.5}$$

RELAP5-3D© Model

Wire Turbulent Mixing

- For an **inner channel, both** inflow and outflow contributions are present, proportional to axial mass flux. Since the inner channel mass flow is nearly the same, the net lateral flow is almost null. Wire turbulent mixing affects the energy but not the mass conservation equation.
- In the **edge region**, a swirl flow is experienced, circulating along the overall assembly-perimeter. Wire presence influences both the thermal and mass balances, flattening the temperature distribution in the assembly duct.
- Swirl flow power terms related were computed for each channel and axial location by using more than 1000 RELAP5-3D© control variables. **ε^* and C_{1L}** formulas are derived from **Cheng & Todreas (CT) 1986 detailed model**, as discussed in [Cheng et al., 1986]. Then, they are associated to the corresponding control volumes by means of ad hoc HSs (**420 in total**).

Interior Ch.

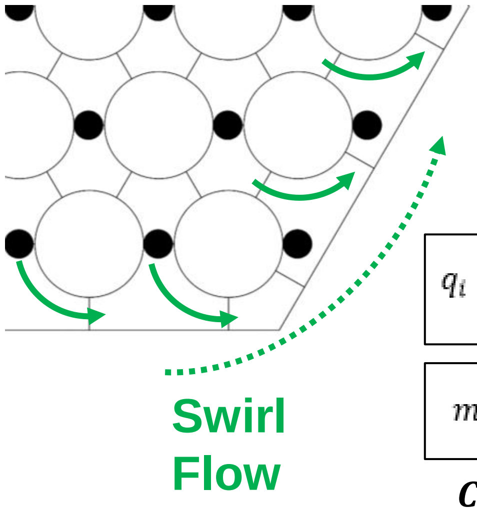


$$q_i = \sum_j m_{t,i} c_p (T_i - T_j)$$

$$m_t = \varepsilon^* G A_t$$

ε^* is the dimensionless effective eddy diffusivity

Edge/Corner Ch.



$$q_i = \sum_j m_{t,i} c_p (T_i - T_j)$$

$$m_t = C_{1L} v \rho A_t$$

C_{1L} is the edge transverse velocity ratio

RELAP5-3D© Model

Wire Turbulent Mixing

Interior Ch. → ε^* is the dimensionless effective eddy diffusivity

$$\varepsilon^* = C_m * \left[\frac{\left(\frac{\pi}{6}\right)\left((D + D_w) * D_w\right)}{\left(\frac{\sqrt{3}}{4}\right)P^2 - \left(\frac{\pi D_0^2}{8}\right)}\right]^{0.5} * tan\theta = \mathbf{0.011(L)/0.019(T)}$$

Edge/Corner Ch. → C_{1L} is the edge transverse velocity ratio

$$C_{1L} = C_s * \left[\frac{\left(\frac{\pi}{4}\right)\left((D + D_w) * D_w\right)}{P * \left(W - \left(\frac{D_0}{2}\right)\right) - \left(\frac{\pi D_0^2}{8}\right)}\right]^{0.5} * tan\theta = \mathbf{0.082(L)/0.149(T)}$$

C_m and C_s are Re-dependent. They have two different formulas for Laminar (L) & Turbulent (T) regions. In the transition region, they are interpolated.

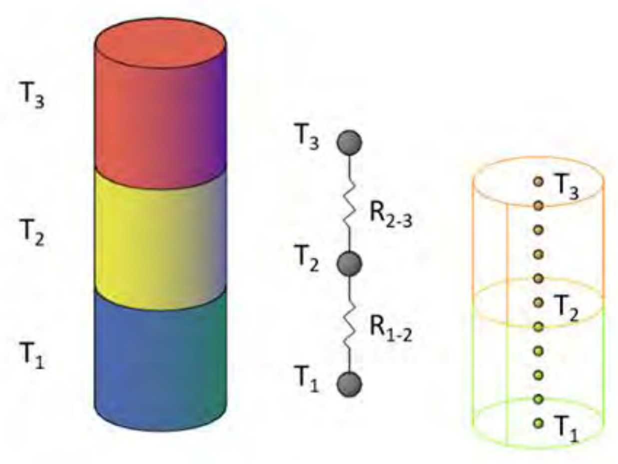
➢ Swirl parameters are derived from **Cheng & Todreas model (1986)** [Cheng et al., 1986].

$$cos\theta = \frac{H_w}{\sqrt{H_w^2 + \left(\pi(D_0 + D_w)\right)^2}}$$

RELAP5-3D© Model

Fluid Thermal Conduction

- Since originally developed for LWRs, RELAP5-3D© does not account for **fluid thermal conduction**. Nevertheless, such phenomenon could assume relevant effect in case of liquid metal.
- [Yoo et al., 2003] proposed to use a modified Peclet number, *Pe**, to predict the thermal conduction importance along fluid coordinates (radial and axial). It was proven that axial conduction presents negligible effects, while radial conduction could assume a moderate importance for low flow rate, typical of a loss of flow accident (FT2 and FT3).
- For this, axial conduction is neglected, and a radial conduction model is added to the subchannel nodalization in '**ftc**' input deck by means of specific heat structures (**600 in total**). They are characterized by: **i)** thickness equal to the bulk distance between connected volumes, **ii)** transvers heat transfer area (coherent with geometry), **iii)** fluid thermal conductivity (LBE in this case), **iv)** negligible heat capacity, and **v)** very high multiplicative factor to exclude convective thermal resistance.



Simulation Results

- To assess the RELAP5-3D© capabilities w.r.t. subchannel analysis, numerical outcomes must be compared with the experimental results. **Firstly, FTs transients were investigated (only FT1 is reported in the following)** [Ciurluini et al. 1, 2023] [Ciurluini et al. 2, 2023].

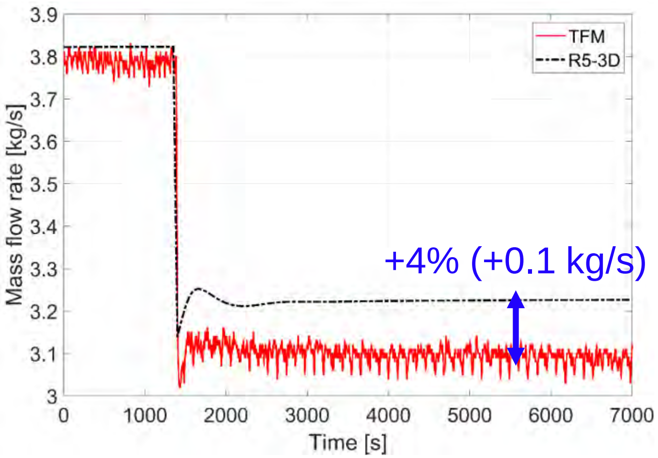
- Then, within the framework of the IAEA CRP, **ADP10, ADP06 and ADP07 transient were simulated**.

- For **LBE thermophysical properties**, it was adopted the ones recommended by the Organization for Economic Co-operation and Development – Nuclear Energy Agency [OECD/NEA, 2015]. They were implemented in RELAP5-3D© by DIAEE, [P. Balestra et al., 2016].

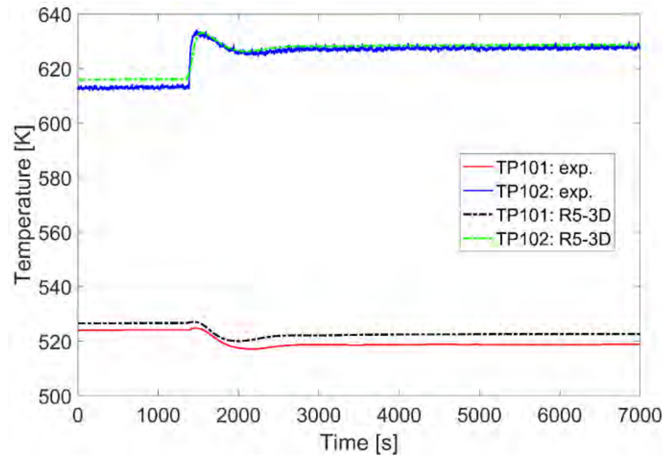
FT1 Simulation Results

- System scale behavior is the same for all input decks (‘**cmo**’, ‘**wtm**’, ‘**ftc**’), different only for subchannel modelling, influencing the mass flow/temperature distributions within FPS.

FPS LBE Mass Flow



FPS LBE In/Out Temp.

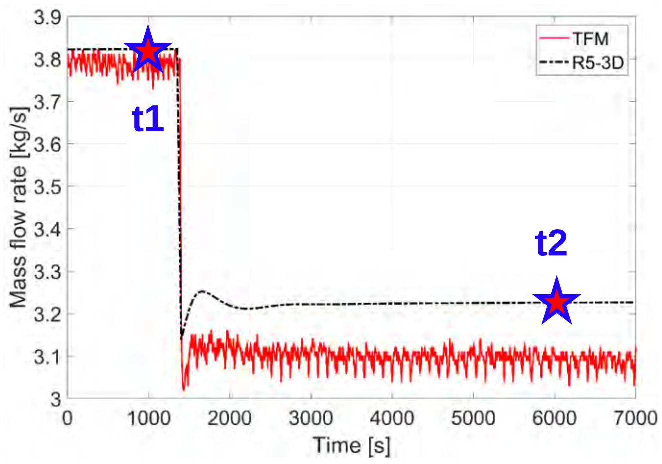


Considering the error related to prototypical flowmeter measurements (5-7%, [Di Piazza et al., 2019]), the code is able to well predict gas lift transient qualitatively and quantitatively.

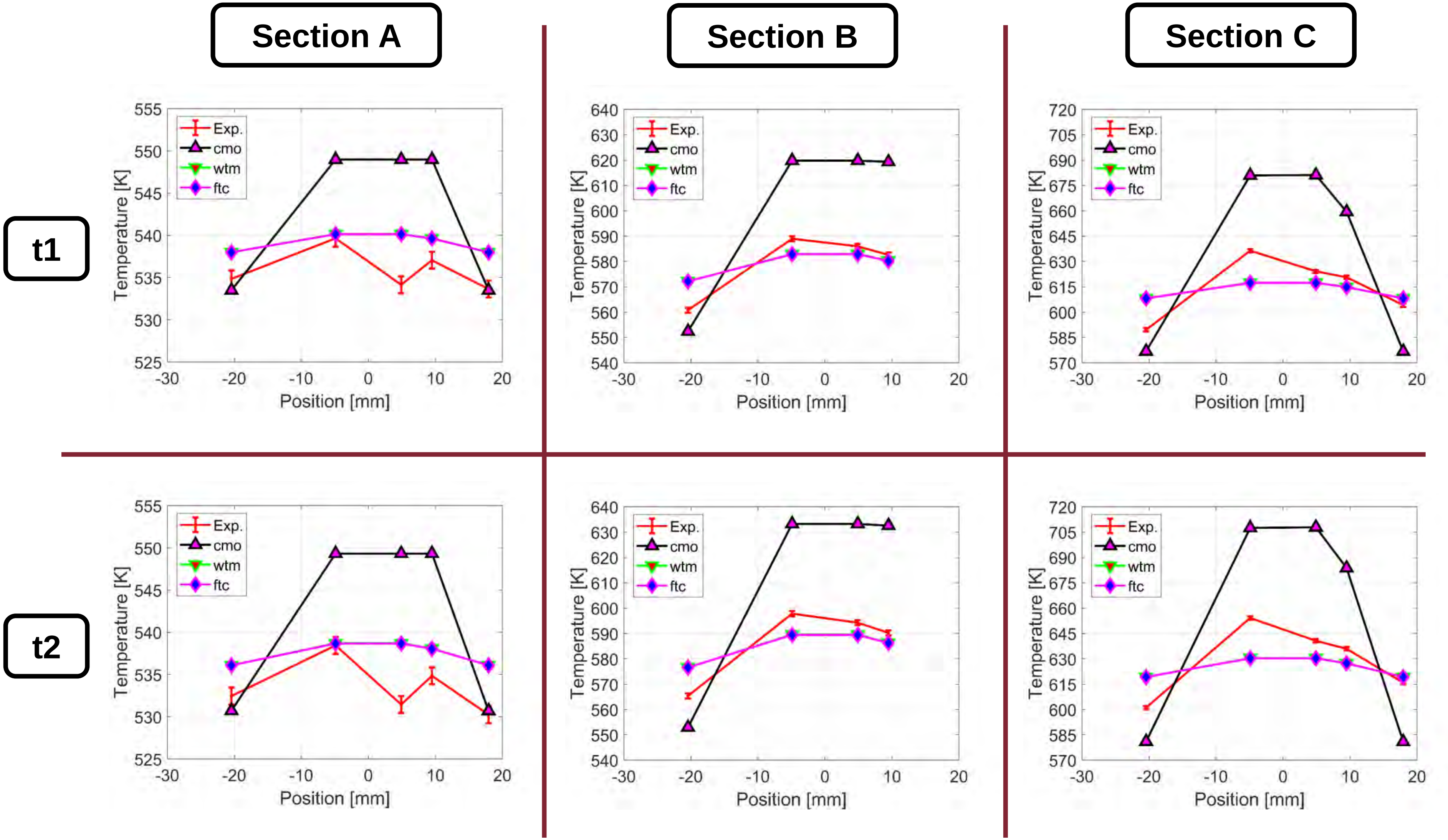
FT1 Simulation Results

- Focusing on the FPS modelling, The five instrumented channels are uniquely identified by their 'radial' position w.r.t the assembly center, assumed as zero.
- Test data plotted together with error bars representing the measurement uncertainty (±1 K).
- All the three axial locations equipped with thermocouples are considered (i.e. **sections A, B and C**). Regarding section B, the temperature reading related to channel 26 is not reported since the corresponding sensor is out-of-service during the test campaign.
- Comparison is performed by taking into account both pre (**t1**) and post (**t2**) transient steady state conditions, referring to 1000 and 6000 s.

Instrumented Channel [-]	Radial Position [mm]
29	-20.4
2	-4.9
5	4.9
22	9.5
26	17.9



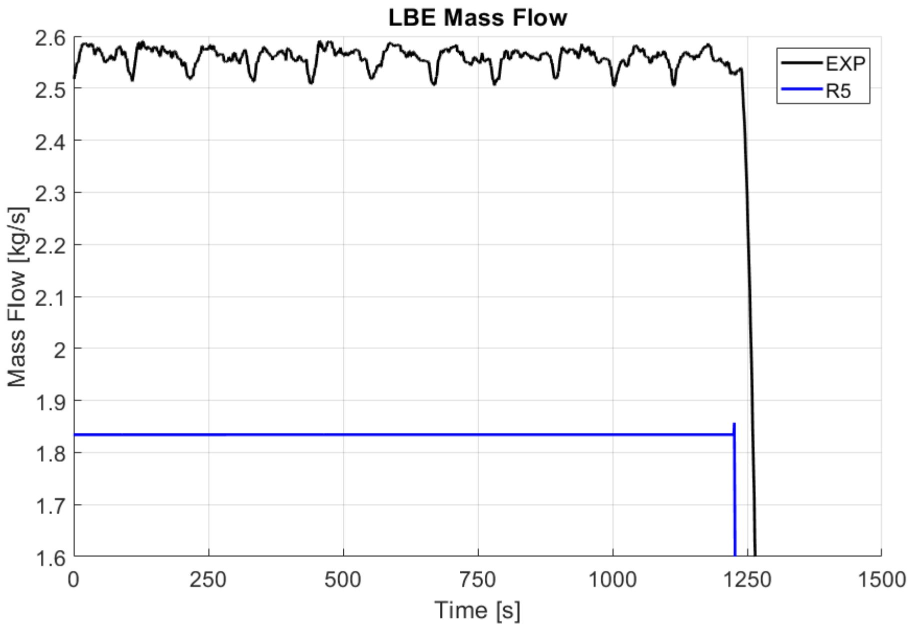
FT1 Simulation Results



ADP-10 Simulation Results

Preliminary Simulation

LBE mass flow at Beginning of Transient (BoT).



ADP-10 Simulation Results

Considerations

- At BoT, gas lift enhances LBE circulation. RELAP5-3D© underestimates this parameter.
- RELAP5-3D© calculates a lower average void fraction in the riser column (**0.020**) with respect to the experimental conditions.
- The latter can be estimated by using experimental measurements (P-103 and P-105) and the formula:

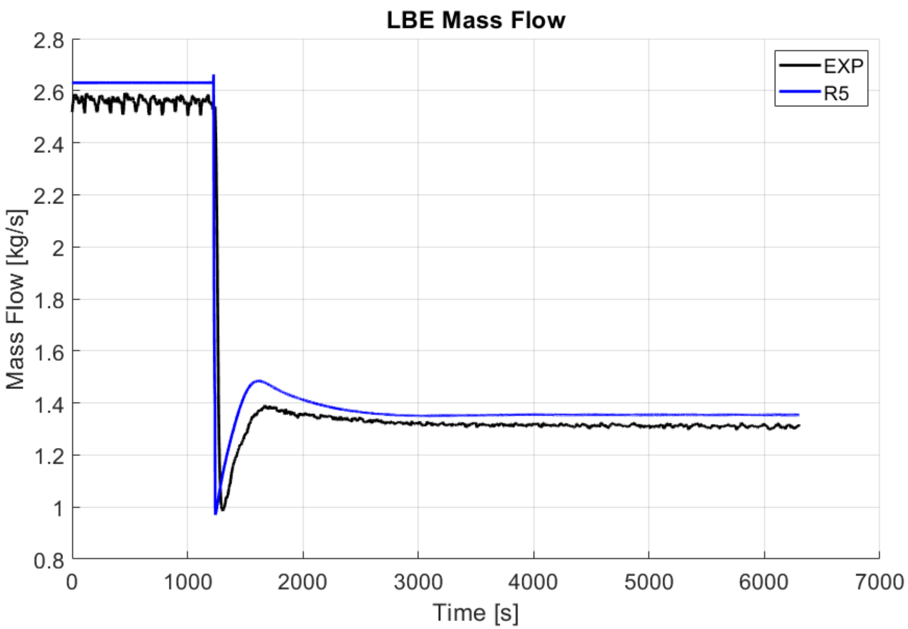
$$\alpha_{exp} = \frac{\rho_{LBE} - \rho_m}{\rho_{LBE} - \rho_{gas}} = 0.044 \quad with \quad \rho_m = \Delta p_{exp} / (g * \Delta h_{pressure\ taps})$$

- Thus, RELAP5-3D© underpredicts the gas lift. To properly simulate this phenomenon, gas inlet mass flow is increased, and the numerical simulations were repeated with this enhanced value.
- The reason why RELAP5-3D© is not able to properly predict the gas lift is that the correct free rise velocity correlation for bubbles in liquid metals is not implemented (water correlation is used).

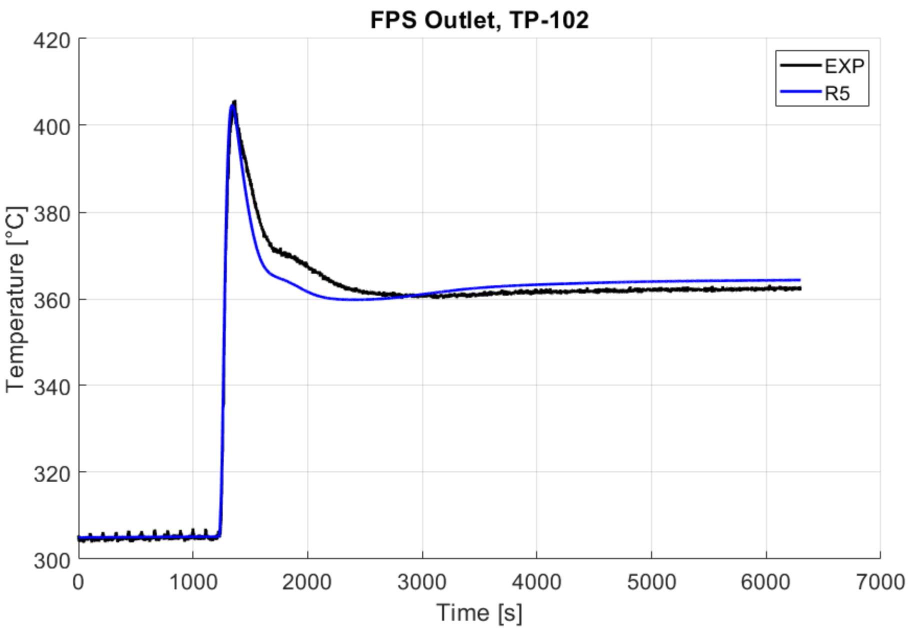
ADP-10 Simulation Results

New simulation

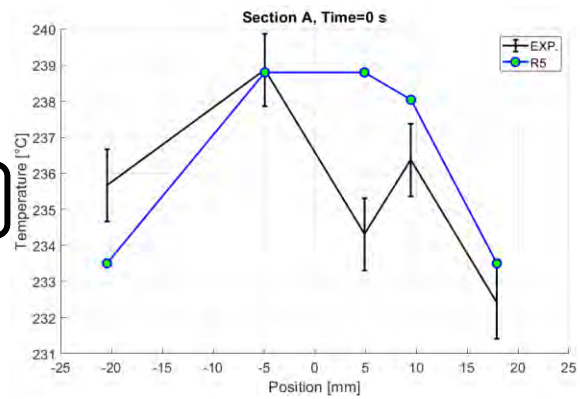
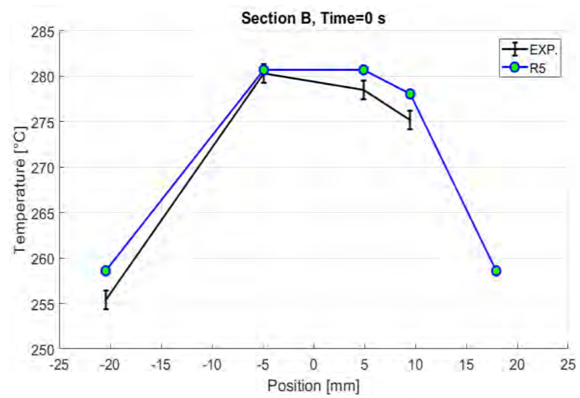
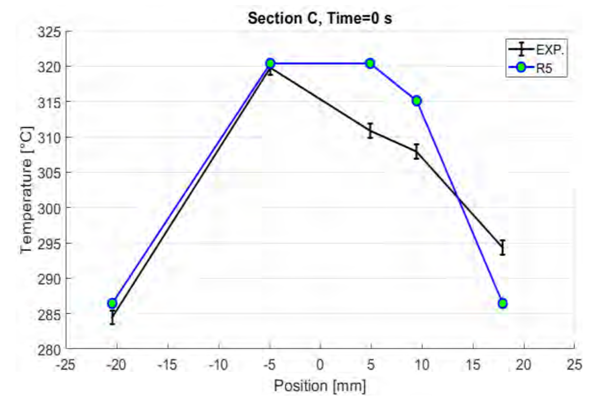
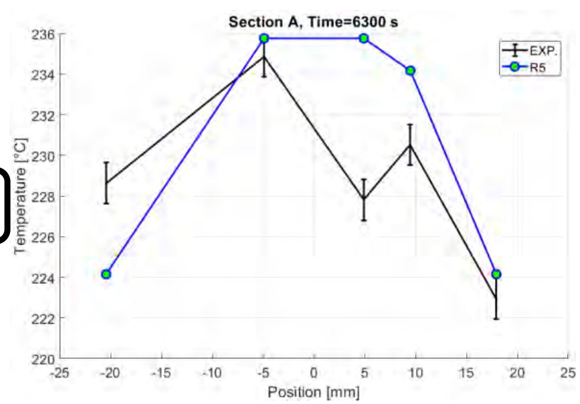
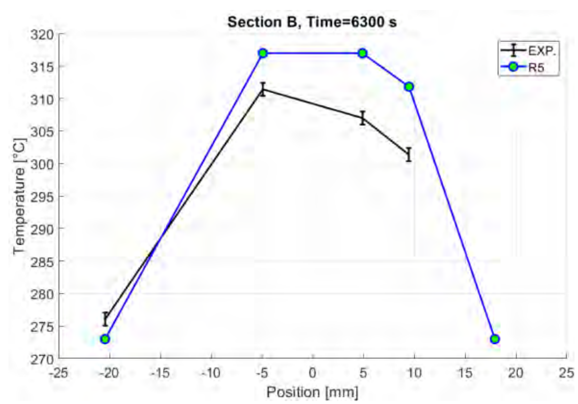
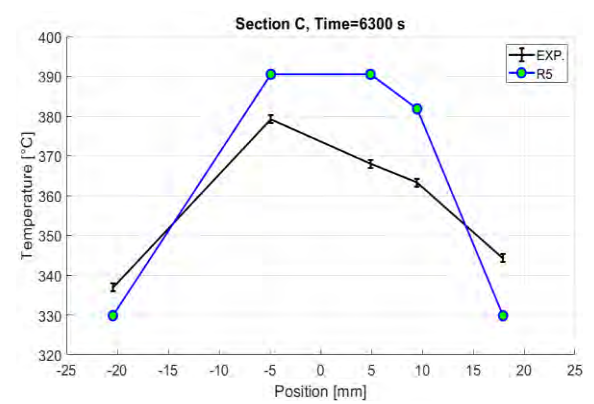
LBE mass flow



FPS Outlet Temperature

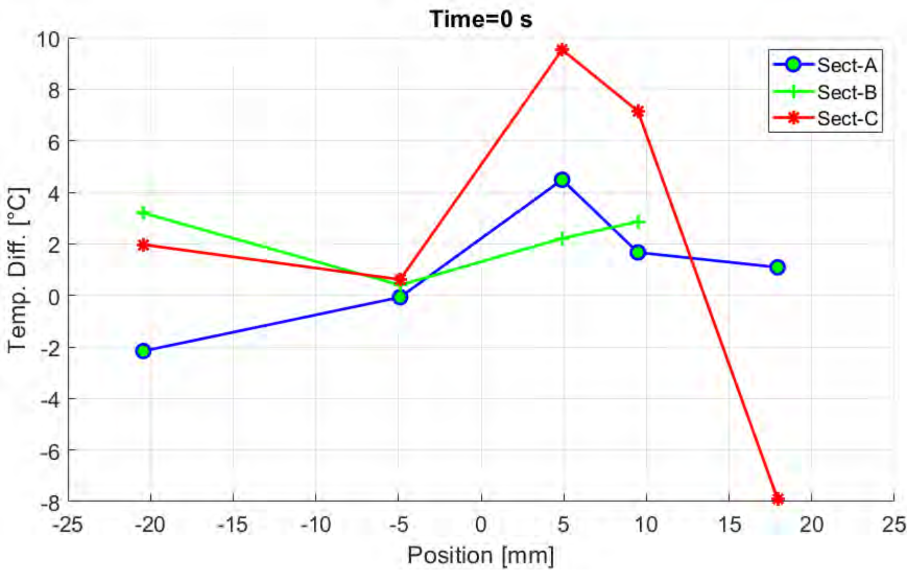


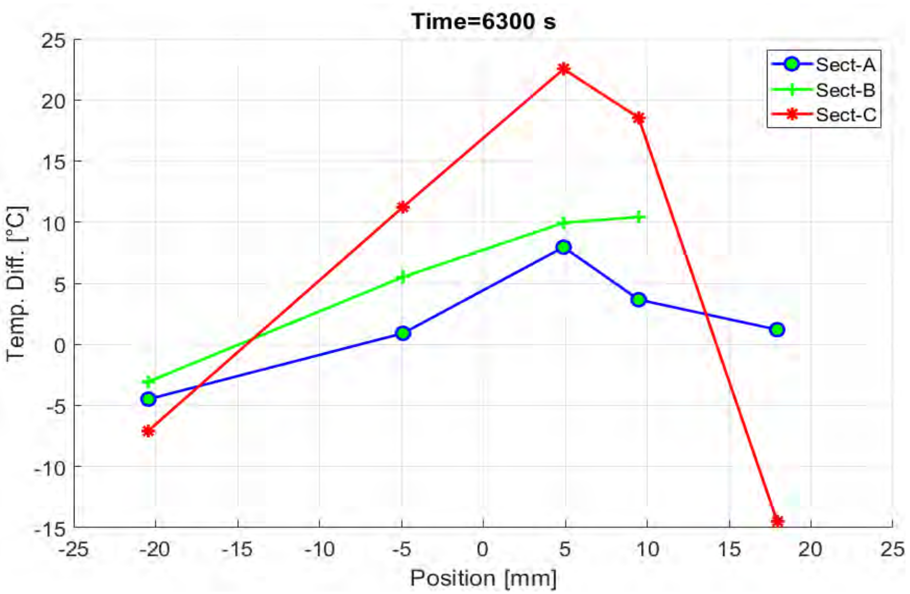
ADP10 – FPS Bulk Temperatures

	Section A	Section B	Section C
BoT			
EoT			

<u>The CH-26 Temp is not reported since the sensor is out-of-service</u>

ADP10 – FPS Bulk Temperatures



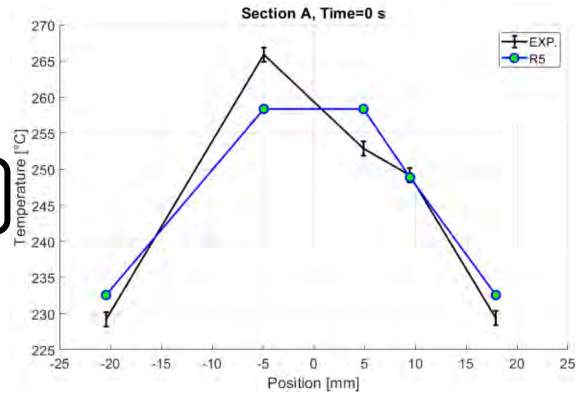


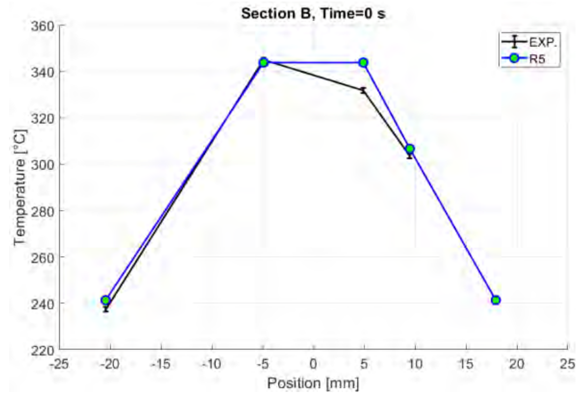
Max Δ (˚C)	BoT	EoT
Section A	-2/+4	-5/+8
Section B	0/+3	-3/+10
Section C	-8/+10	-15/+22

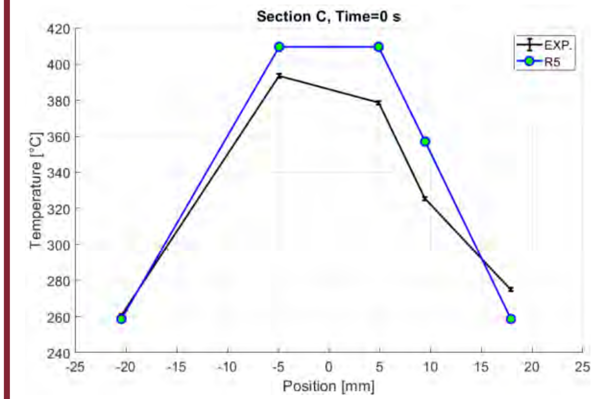
ADP06 – FPS Bulk Temperatures

Section A | **Section B** | **Section C**

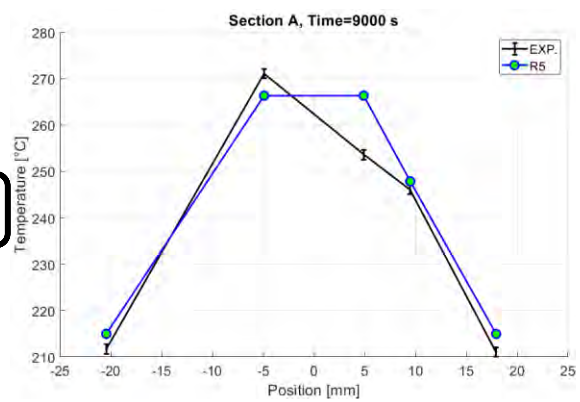
BoT

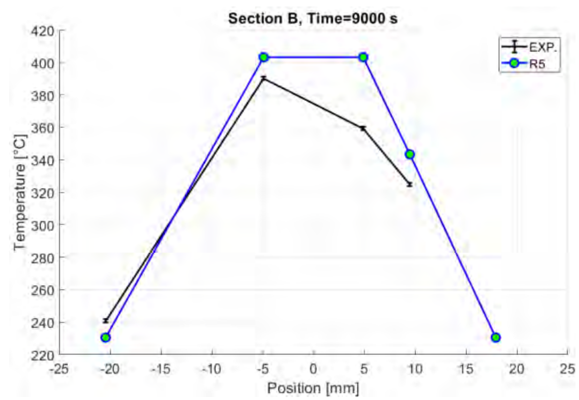


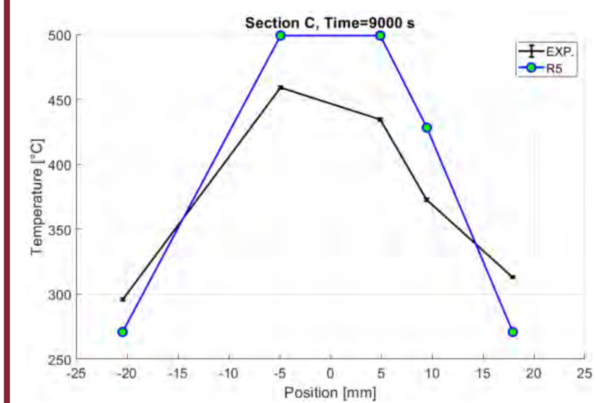




EoT

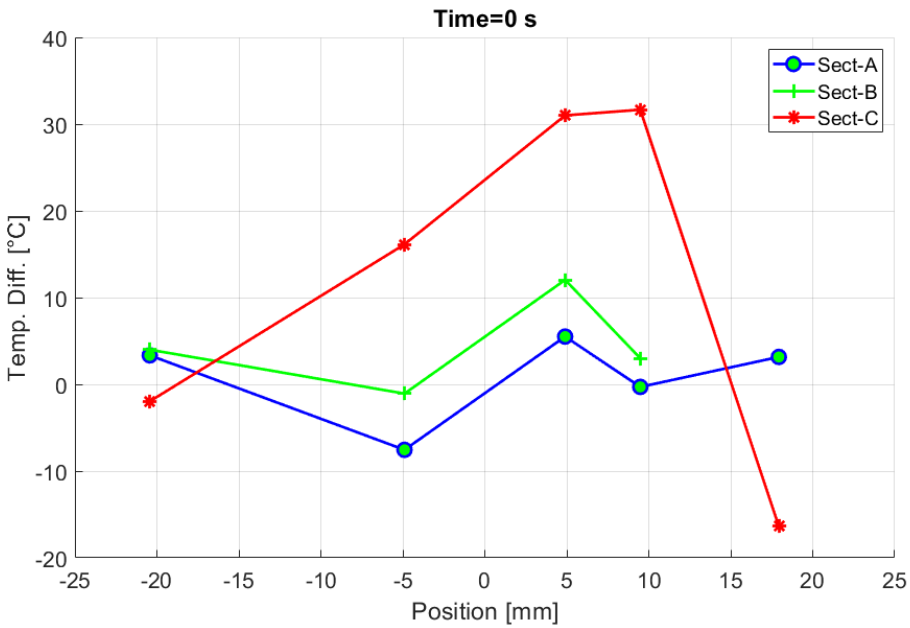


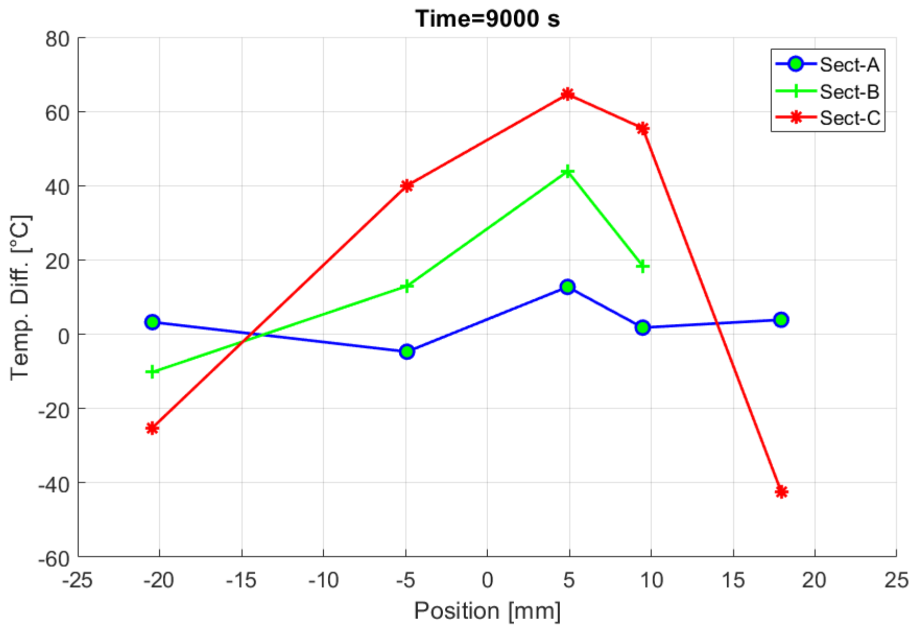




The CH-26 Temp is not reported since the sensor is out-of-service

ADP06 – FPS Bulk Temperatures





Max Δ (°C)	BoT	EoT
Section A	-7/+5	-5/+15
Section B	-0.5/+11	-10/+42
Section C	-18/+30	-40/+62

Conclusions

- Several FPS modelling were considered in order to separately evaluate the impact of different T/H phenomena (**cross-flow**, **wire turbulent mixing**, **fluid thermal conduction**) on the simulation results.
- Void fraction profile along the primary loop riser: i) impact on the LBE forced circulation @ BoT; ii) RELAP5-3D© capability to well simulate the gas lift.
- RELAP5-3D© predicts more peaked temperature distributions. Possible explanations: RELAP5-3D© underestimates the lateral energy transfer → Sensitivity on the C&T thermal energy exchange parameters (ε^* and C_{1L}).
- RELAP5-3D© predicts the same temperature for channels 2 & 5, as well as for channels 26 & 33 (i.e., symmetrical transversal temperature distribution). Although, the experimental data for them are quite different, showing an asymmetrical behavior. Possible explanation: dissymmetry can only be caused by the local effects induced by the wire rotation.

Conclusions (cont'd)

- Preliminary results showed that system codes are a possible alternative for subchannel analysis, even if a comparison with results coming from other approaches (SCTH, CFD) are needed.

- This approach is not suitable for design purposes and it is not able to catch 3D flow details, but it allows to investigate system behavior in transient and accidental conditions (**Deterministic Safety Analysis**), reducing computational time and avoiding coupling validation problem.

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Thanks for your attention

Any questions?