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SUBCHANNEL MODELLING CAPABILITIES OF RELAP5-3D© FOR WIRE-SPACED FUEL PIN BUNDLE

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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

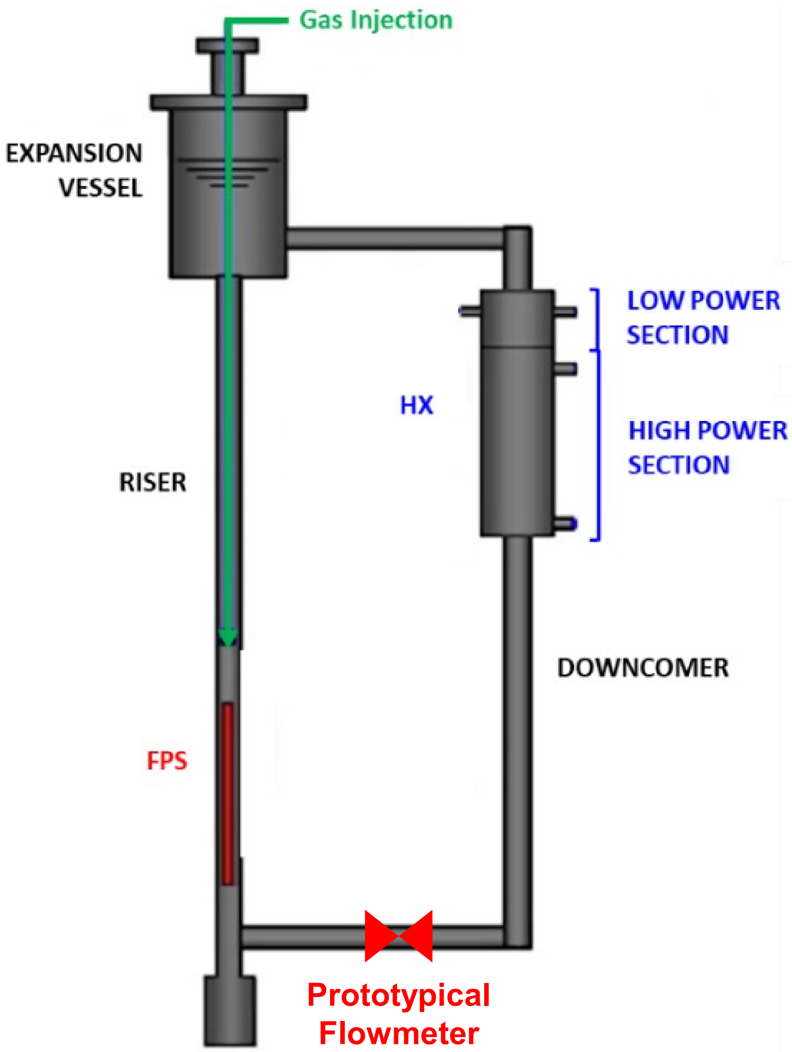
- Within this framework, an alternative option can be represented by the adoption of a best-estimate System Thermal-Hydraulic (STH) code, used by following a 'dedicated' approach for subchannel analysis.

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.

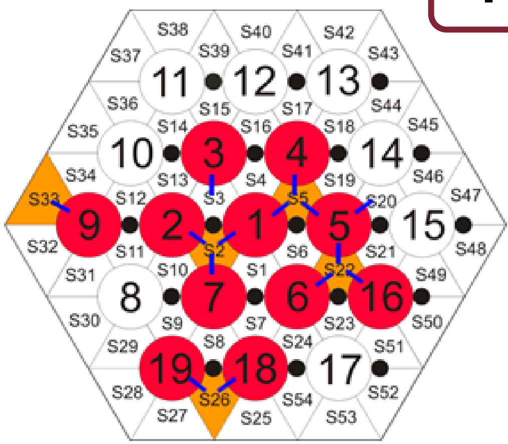
Overview of NACIE-UP facility



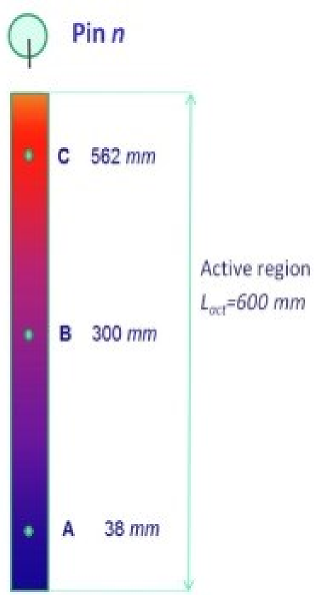
- Rectangular loop: height is nearly 8 m and horizontal pipelines are 2.4 m, [Di Piazza et al., 2019].
- FPS (simulating reactor core) is located at the riser bottom, while water/liquid metal heat exchanger (HX) at downcomer top, with a thermal center height difference of 5.5 m.
- LBE flow is gas-enhanced (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

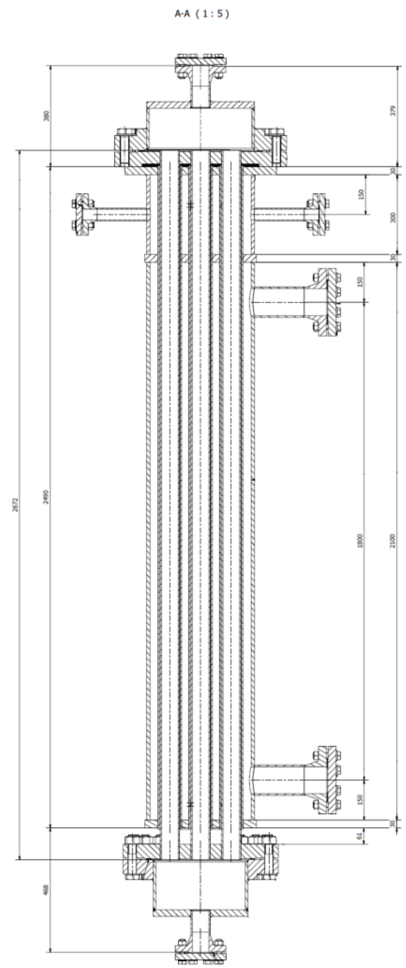


- Instr. pins
- Instr. sub-channels
- Wall-embedded TCs



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

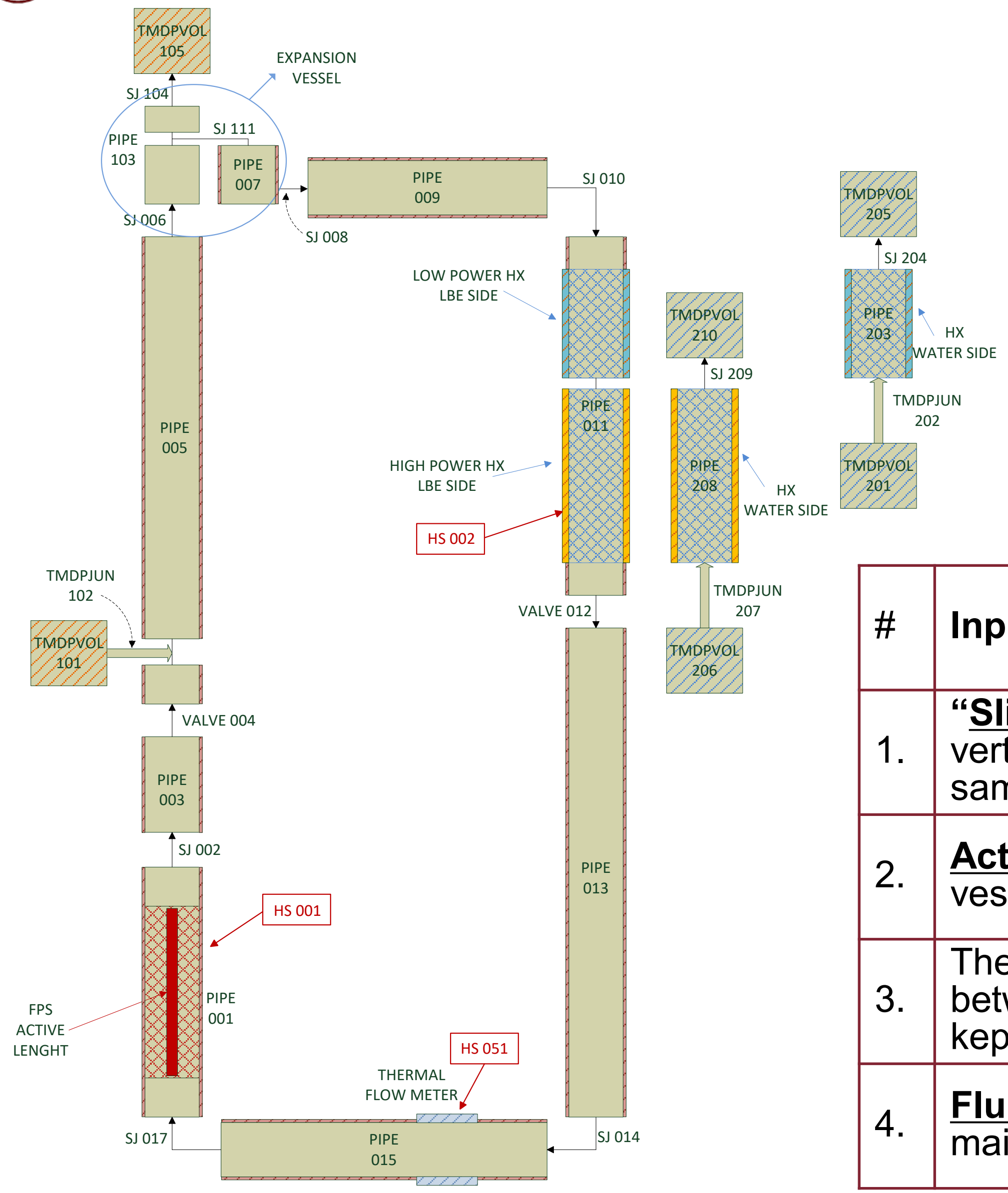
- During 2017 test campaign (Horizon 2020 SESAME project), 3 Fundamental Tests (FT) were performed at the facility to investigate the circuit T/H behavior associated to a low power and/or mass flow transient, [Di Piazza et al., 2019].
- In each FT, loop started from steady state conditions (Before Transient, 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	

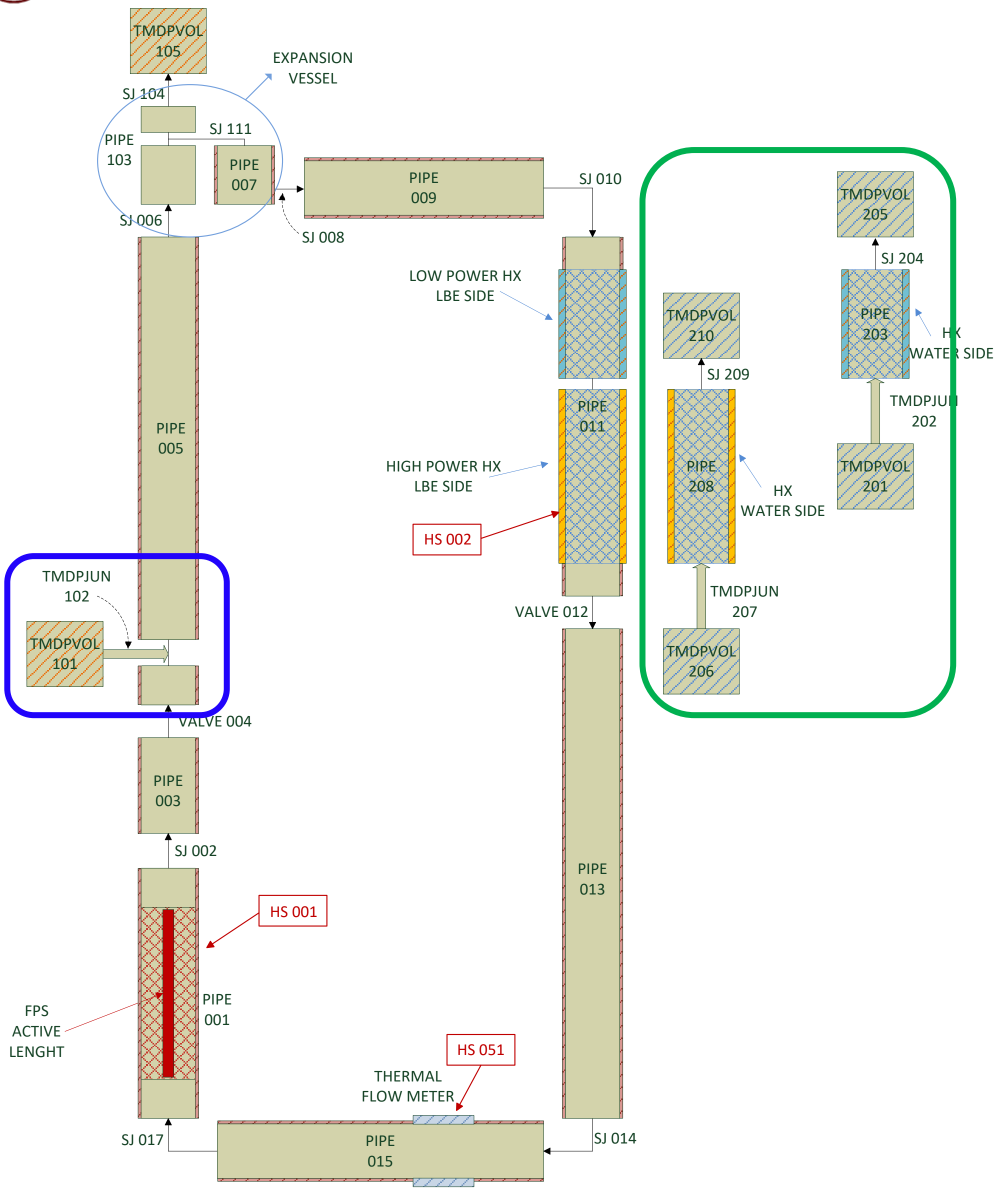
RELAP5-3D© Model



In the last years, a **complete model of NACIE-UP primary circuit**, including all components, was developed at DIAEE of Sapienza University of Rome by using best estimate system code **RELAP5-3D©**. The aim is simulating the loop transient behavior at a system level, [N. Forgione et al., 2019].

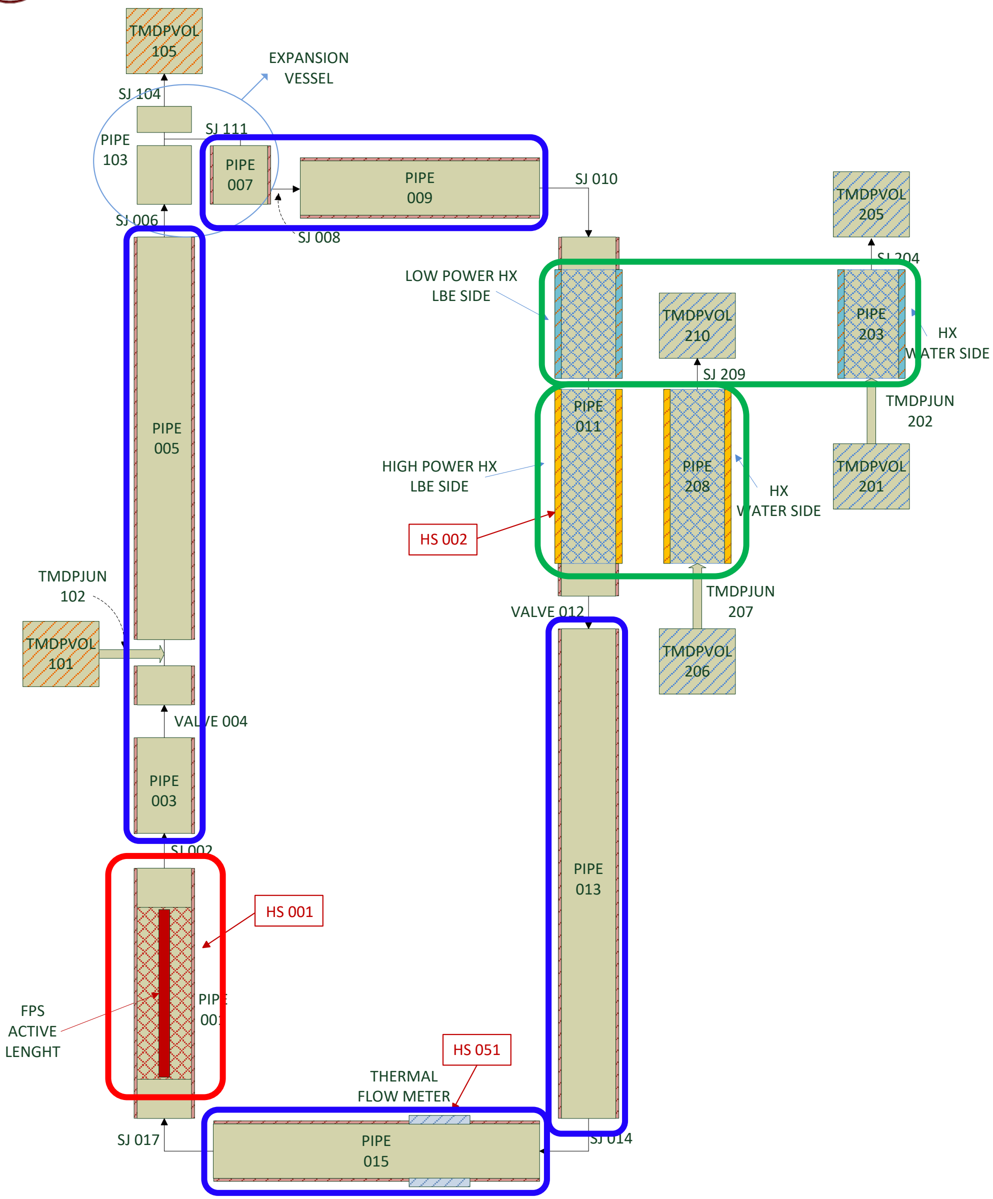
#	Input Deck Features
1.	"**Slice nodalization technique**", ensuring the same vertical mesh to system components situated at the same height.
2.	**Actual design elevations** maintained for all the vessel equipment and piping.
3.	The **node-to-node ratio**, defined as the ratio between the length of two adjacent control volumes, kept below 1.25.
4.	**Fluid and material inventories** rigorously maintained for involved systems.

RELAP5-3D© Model



- TMDPVOL 101 and TMDPJUN 102 simulate the **argon injection system** while TMDPVOL 105 assures the outlet of the gas;
- TMDPVOL 201 and TMDPJUN 202 fix the **water conditions** requested at the HX low power section inlet, while the time dependent volume 205 represents the water outlet. The same nodalization is used for HX high power section secondary side, by using TMDPVOL 206, TMDPJUN 207 and TMDPVOL 210.

RELAP5-3D© Model



Heat Structures (HS) are used to simulate:

- The power produced within FPS pins.
  - Power was axially distributed according to active zone vertical nodalization. A small fraction (8%) is associated to the 'theoretically unheated entry region.
  - Westinghouse correlation is used for fuel bundle to better match experimental data, [Di Piazza et al., 2019].
- The thermal coupling between LBE (primary side) and water (secondary side) within the HX.
  - Westinghouse correlation is used for tube bundle.
  - Reference powder thermal properties are considered, [Di Piazza et al., 2019].
- The heat losses towards the external environment.
  - Constant environment temperature (285 K) and HTC (3 $Wm^{-2}K^{-1}$) are imposed as BCs on the HS external surface.
  - Seban-Shimazaki correlation is used for LBE HTC.

RELAP5-3D© Model

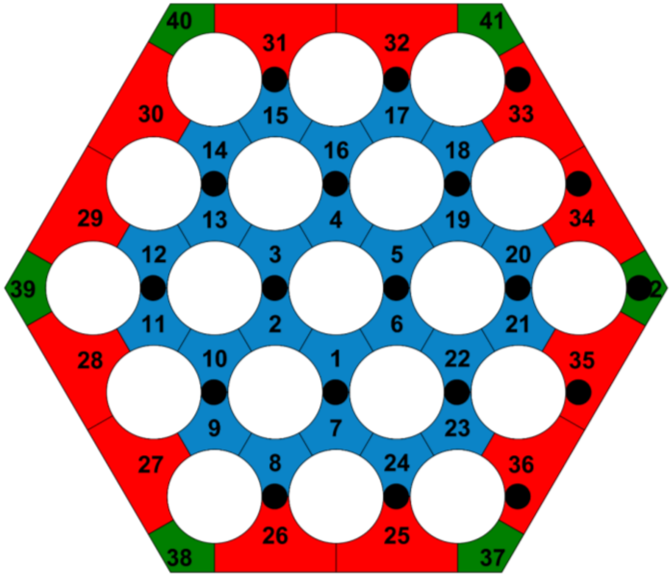
- The present work is focused on the evaluation of **RELAP5-3D© capability with respect to subchannel analysis**. For this, the previous input deck developed by DIAEE, was improved by adding a dedicated FPS modelling.
- Considering the lessons learned from [Memmott et al., 2010], several aspects must 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.
- To separately evaluate their impact on the simulation outcomes three different FPS models, labelled '**cmo**', '**wtm**' and '**ftc**', were tested against experimental results.

Input deck features	cmo	wtm	ftc
Subchannel by subchannel approach	yes	yes	yes
Cheng-Todreas for fuel bundle pressure drops	yes	yes	yes
Cross junctions among adjacent subchannels	yes	yes	yes
Wire turbulent mixing	no	yes	yes
Fluid thermal conduction	no	no	yes

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).
- A total of **420 CVs** constitutes the FPS model.



Fuel Bundle Pressure Drops

- Cheng & Todreas (CT) 1986 detailed model for friction factor correlations was considered.
- RELAP5-3D© gives the user the possibility to implement ad-hoc Re-dependent friction factor correlations (see aside); for more info about the implementation refer to [V. Narcisi et al., 2021].
- 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)	$f_L = \frac{64}{Re\vartheta}$
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

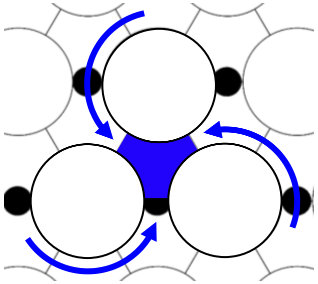
- Hydraulic coupling between adjacent subchannels realized with multiple junctions (for a total of **600 cross junctions**).
- In '**cmo**', wire turbulent mixing is ignored. Mass transfer depends on pressure gradient and hydraulic resistance only.
- K-loss coefficients were evaluated by using *Idelchik* hydraulic handbook and associated to cross junction components, see [V. Narcisi et al., 2019] for further details.

RELAP5-3D© Model

Wire Turbulent Mixing

- Lateral mass flow balance for an **inner channel** consists of inflow and outflow contributions, proportional to the axial mass flux in the related subchannel. Since the inner channel mass flow is nearly the same, the net lateral flow is almost null. Thus, <u>the wire turbulent mixing affects the energy but not the mass conservation equation</u>.
- In the **edge region**, a swirl flow is experienced, circulating along the overall assembly-perimeter. Thus, <u>wire presence influences both the thermal and mass balances</u>, flattening the temperature distribution in the assembly duct.
- Power terms related to swirl flow were computed for each channel (inner/outer) and axial location thanks to **more than 1000 RELAP5-3D© control variables** (‘**wtm**’ input deck). **Formulas are derived from [Memmott et al., 2010]**. Then, they are associated to the corresponding control volumes by means of ad hoc HSs (**420 in total**).

Interior Ch.

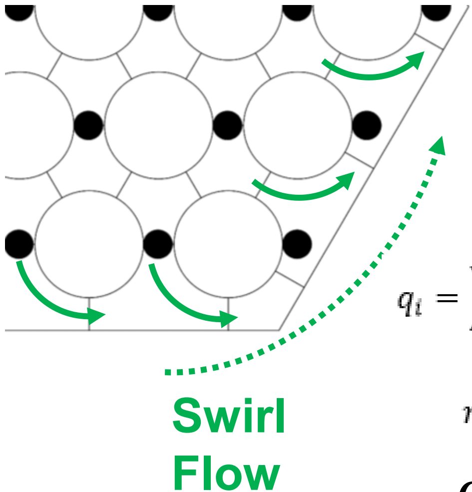


$$q_i = \sum_j m_{t,i} c_p (T_i - T_j)$$

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

ε^* is the dimensionless effective eddy diffusivity

Edge/Corner Ch.



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

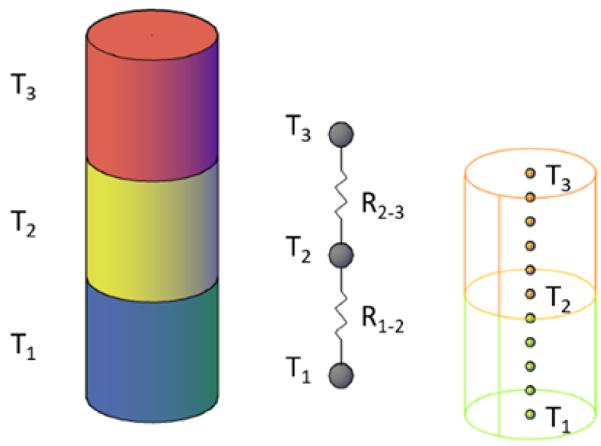
$$m_t = C_{1L} v \rho A_t$$

C_{1L} is the edge transverse velocity ratio

RELAP5-3D© Model

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, FT1 transient was selected**.

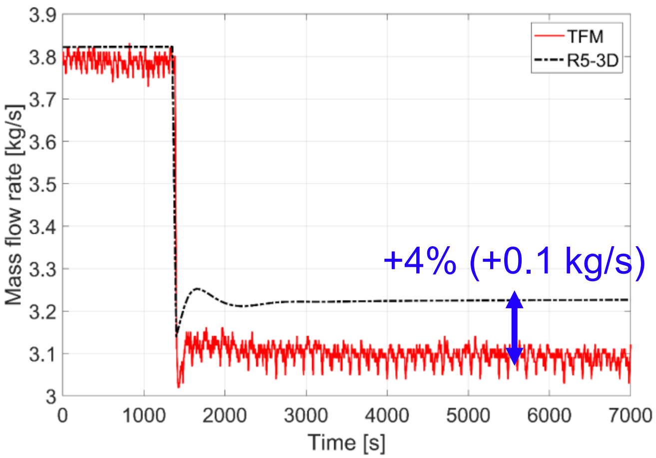
- Calculations were run with a **time step of 10^{-3} s**, after time step sensitivity. Lower time steps had negligible effects on the results, while for higher ones Courant limit was exceeded.

- For **LBE thermophysical properties**, it was adopted the ones recommended by the Organization for Economic Co-operation and Development – Nuclear Energy Agency (OECD/NEA, [8]). They were implemented in RELAP5-3D© by DIAEE, [P. Balestra et al., 2016].

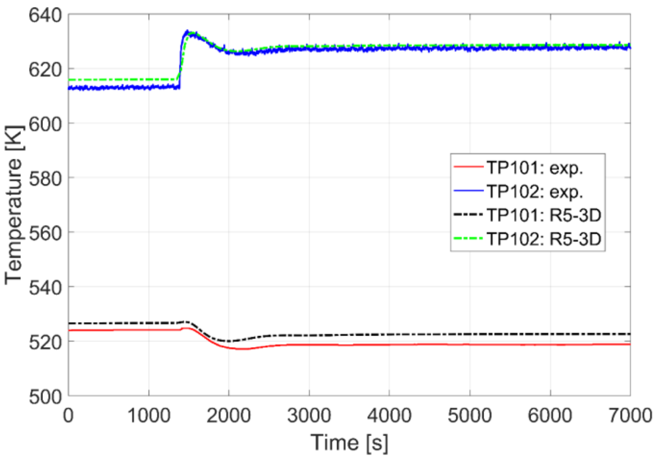
Simulation Results

- A detailed system scale analysis is out of scope for the present work. Only FPS principal FOMs are reported to demonstrate the code is able to provide FPS inlet conditions consistent with experimental data.
- 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.

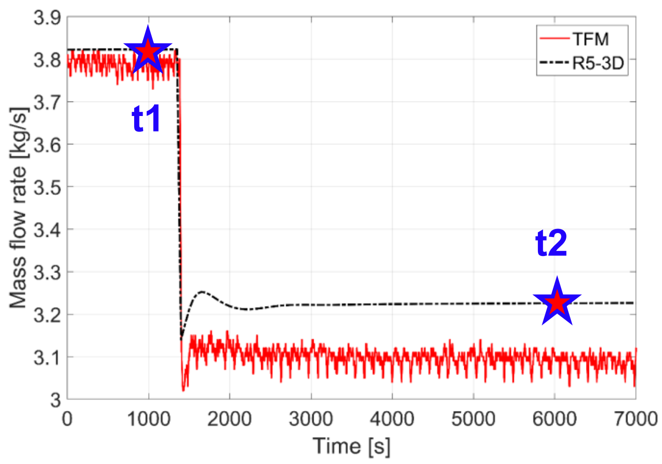


Considering the error related to prototypical flowmeter measurements (5-7%, [Di Piazza et al., 2019]), the code is able to well predict gas lift transient qualitatively and quantitatively.

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



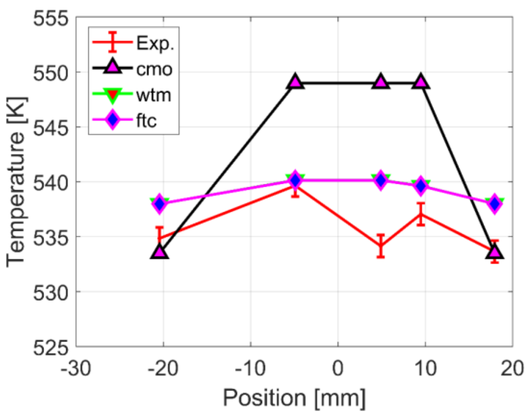
Simulation Results

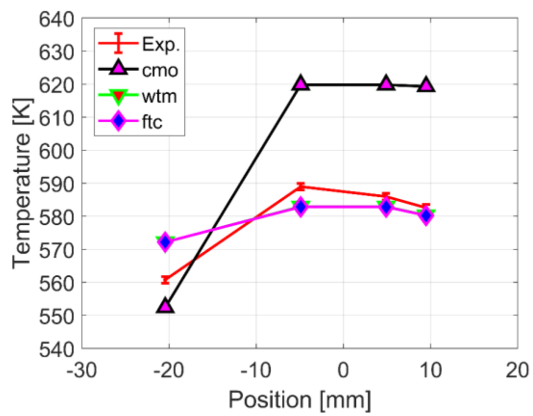
Section A

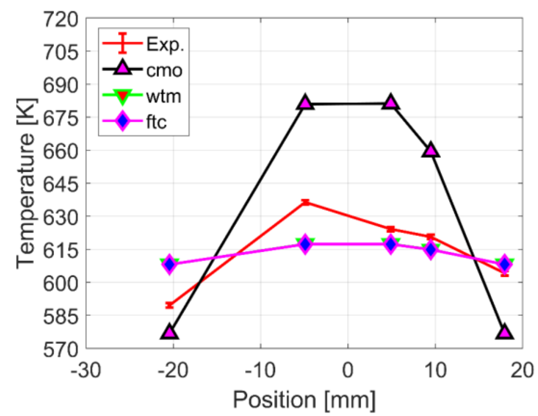
Section B

Section C

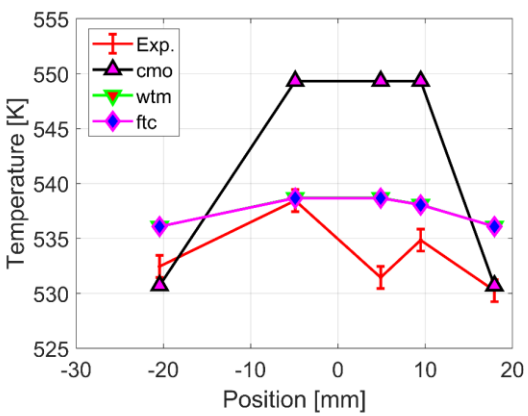
t1

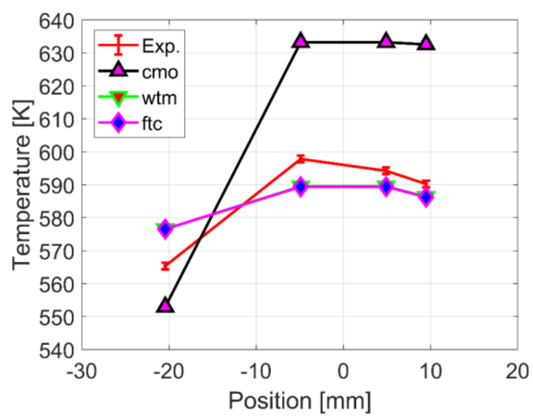


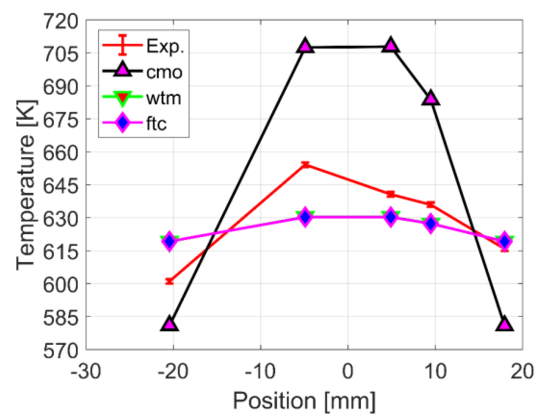




t2







Simulation Results

- When only cross-flow is considered ('**cmo**') a partial mixing occurs in the bundle but it is not enough to flatten the temperature distribution as much as in the empirical observations.
- The introduction of the wire turbulent mixing has a deep impact on this aspect. The temperature profiles obtained as outcomes of '**wtm**' input deck are always able to qualitatively reproduce the empirical acquisitions.
- Instead, the introduction of the fluid thermal conduction, '**ftc**', has a negligible effect on the simulation results. This is in accordance with what suggested by [Yoo et al., 2003], about the relevance of radial conduction only when it comes to low flow transients. Thus, an ultimate judgement on the importance of such phenomenon on the LFR transient behavior can be formulated only after the analysis of FT3, where the complete transition from gas-lift to natural circulation is foreseen.
- Along with code reliability enhancement, also increment of computational time must be considered, rising with input deck complexity. It goes from **67 h** for '**cmo**' to **70 h** for '**wtm**' and **76 h** for '**ftc**'. Only the first increase is justified by the improvement in the calculation outcomes.

Simulation Results

- Referring to ‘**wtm**’ and ‘**ftc**’ input decks and **section A**, it is visible that numerical outcomes are above the experimental data for all the temperature radial profile (i.e., the LBE average temperature at the correspondent axial location is higher). This could be due to an excessive fraction of the overall pin power associated to the ‘theoretically unheated entry region, according to indications in [Di Piazza et al., 2019]. This parameter will be object of a sensitivity study in the future.
- Instead, in **sections B and C**, what can be detected is that system code tends to enhance the flattening of the temperature radial profile, overestimating the edge channel temperatures (29, 26) and underestimating the inner channel ones (2, 5, 22). This could be due to the parameters computed for $\boldsymbol{\varepsilon}^*$ and $\boldsymbol{C_{1L}}$. In the future developments of the activity a sensitivity study will be performed to study the impact of such elements on the simulation results.
- Finally, the code have similar performances in predicting both the **pre and post-transient conditions**.

Conclusions

- The technical activity presented was focused on the preliminary evaluation of the RELAP5-3D© STH code w.r.t. subchannel analysis related to LFR applications.

- To verify the RELAP5-3D© capabilities, FT1 experiment results coming from NACIE-UP facility hosted at ENEA Brasimone R.C. were selected.

- 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.

- 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.

- <u>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.</u>

Future Perspectives

This technical activity will be developed in the upcoming years by:

- Performing the transient simulations related to FT2 and FT3 experiments;
- Performing sensitivity studies to address the issues arisen from the quantitative differences (**slight**) between numerical outcomes and experimental results. Parameters preliminary selected are: pin power in the 'unheated' entry region, $\boldsymbol{\varepsilon}^*$ and $\boldsymbol{C_{1L}}$.
- Updating the Cheng and Todreas model by considering its upgrade, [9].
- Participating to the IAEA CRP related to the other experiments performed at NACIE-UP facility, namely ''Thermal-Hydraulic Analysis of Lead Cooled Experimental Subassembly''. In this way, STH results can be compared not only with new test data but also with numerical outcomes coming from SCTH and CFD codes.

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Thanks for your attention

Any questions?