This project has received funding from the
Euratom research and training programme 2014-2018
under grant agreement No 661891

Modelling and experimental investigation of natural circulation loop with internal heat generation

S. Lorenzi

Final meeting, 4 July 2019

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POLITECNICO MILANO 1863

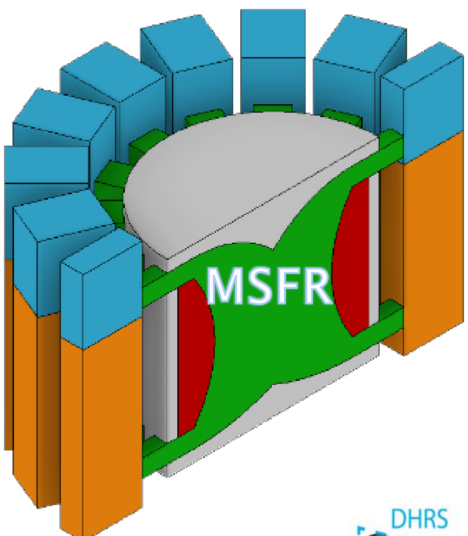
TU Delft

eDF

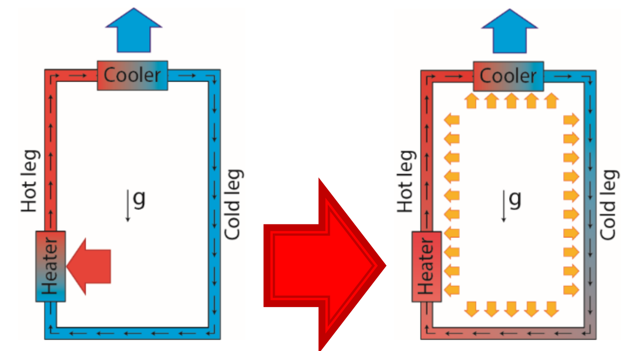
Natural circulation in MSFR

The interest is towards the study of the **phenomena** rather than the system

Non-representative simplified systems are considered as a first step.



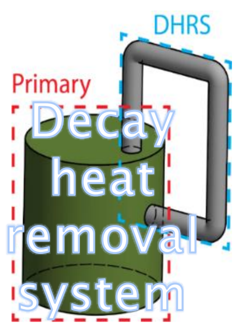
Natural circulation (NC) with DH

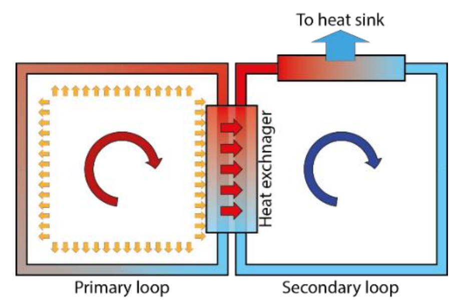


Conventional

Distributed

Coupled NC systems





Modelling and experiments

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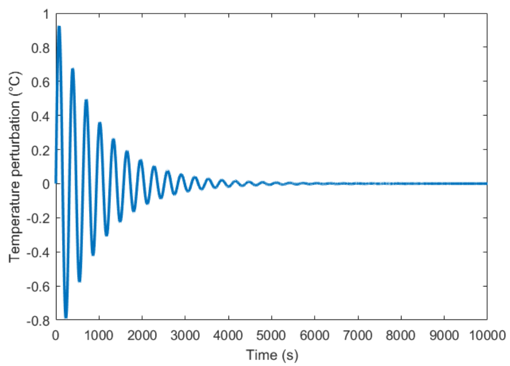
Natural circulation equilibrium stability

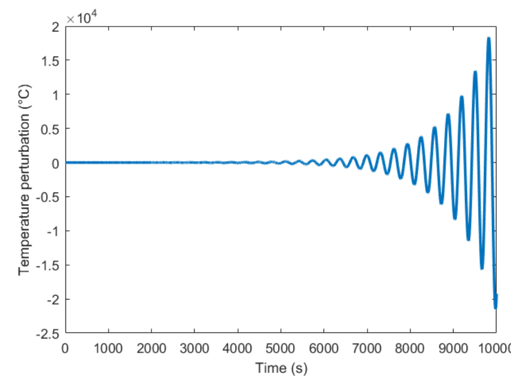
Natural circulation is the product of the balance between buoyancy forces due to temperature differences and friction forces

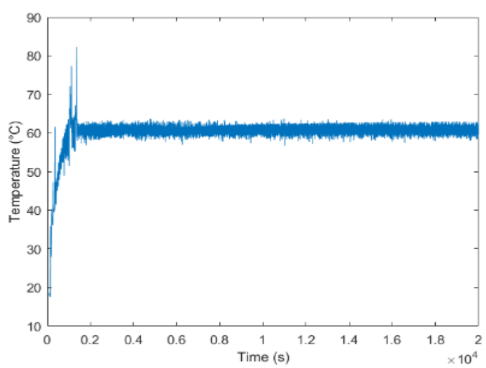
A stable equilibrium between the forces brings the system in a steady state

An unstable equilibrium between the forces can cause many types of flow types (pulsated, oscillating, etc.)

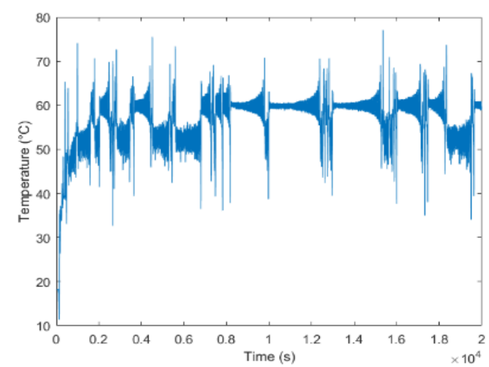


Lyapunov definition





"Engineering" definition



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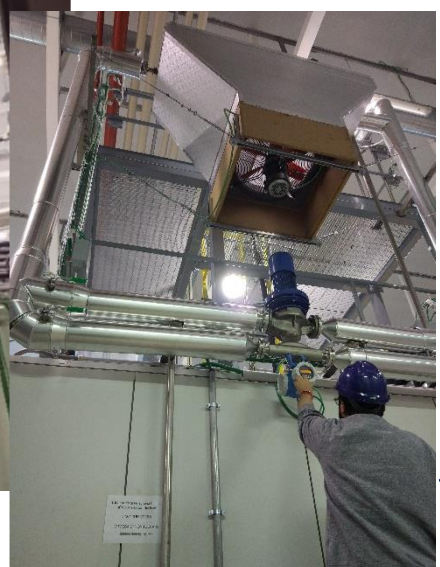
DYNASTY

Single loop, conventional/distributed

DYNASTY TESTING FACILITY

DYnamics of NAtural circulation for molten SalT internallY heated



	DYNASTY
SIZE	Height: 3.09 m Width: 3.10 m Piping: ϕ 42.16 mm x t 2 mm
THERMAL CARRIER	Molten salt (NaNO3-NaNO2-KNO3 7-40-53 wt%) Or Water
MATERIAL	AISI 304/316 L
HEATING SYSTEM	UP TO 6.8 kW (electrical strips – fibreglass knitted and braided)
HEAT EXCHANGER	Finned tube coupled to cooling fan
TEMPERATURE RANGE	26/ 80 °C (water) 180 / 350 °C (salt)
PRESSURE	1 atm at Filling tank top

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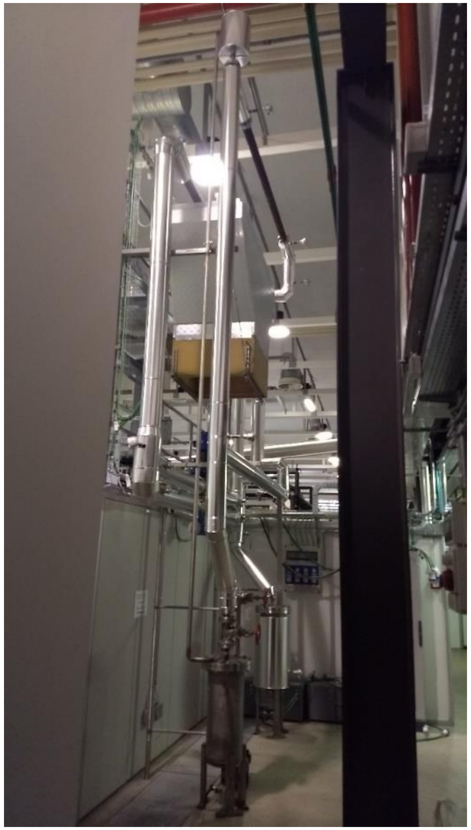
eDYNASTY

Coupled loops, conventional/distributed primary

Extended DYNASTY TESTING FACILITY



eDYNASTY DESIGN	
SIZE	Height: 3.20 m Width: 3.10 m Depth: 1.3 m Piping: ϕ 42.16 mm x t 2 mm
THERMAL CARRIER	Molten salt (primary loop) Diathermic oil (secondary loop)
MATERIAL	AISI 304/316 L
HEATING SYSTEM	Liquid-liquid heat-exchanger to DYNASTY
HEAT EXCHANGER	Coaxial cylindrical heat exchanger
TEMPERATURE RANGE	150 / 250 °C

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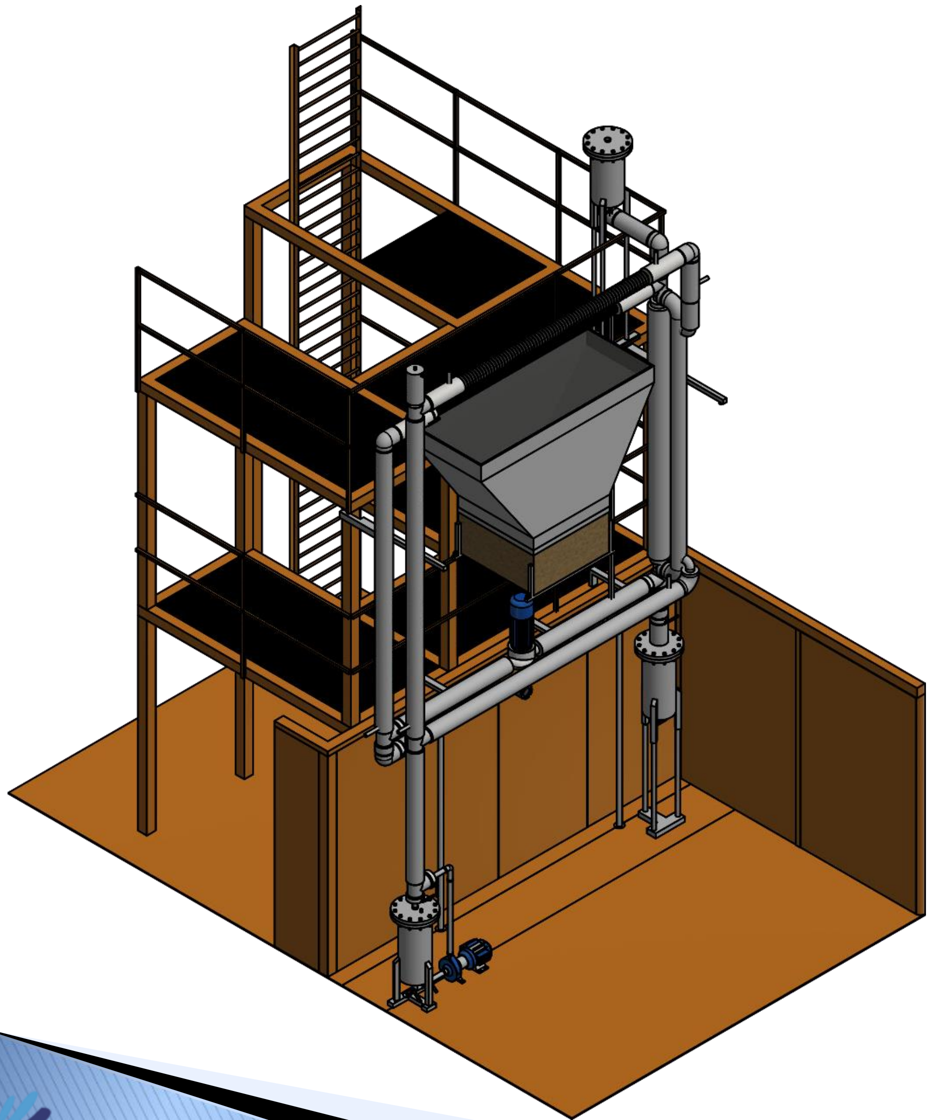
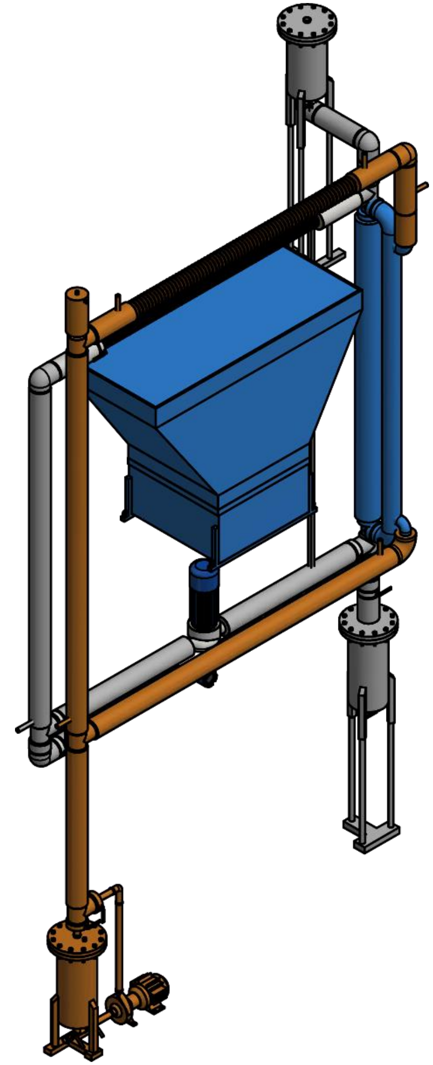
DYNASTY and eDYNASTY





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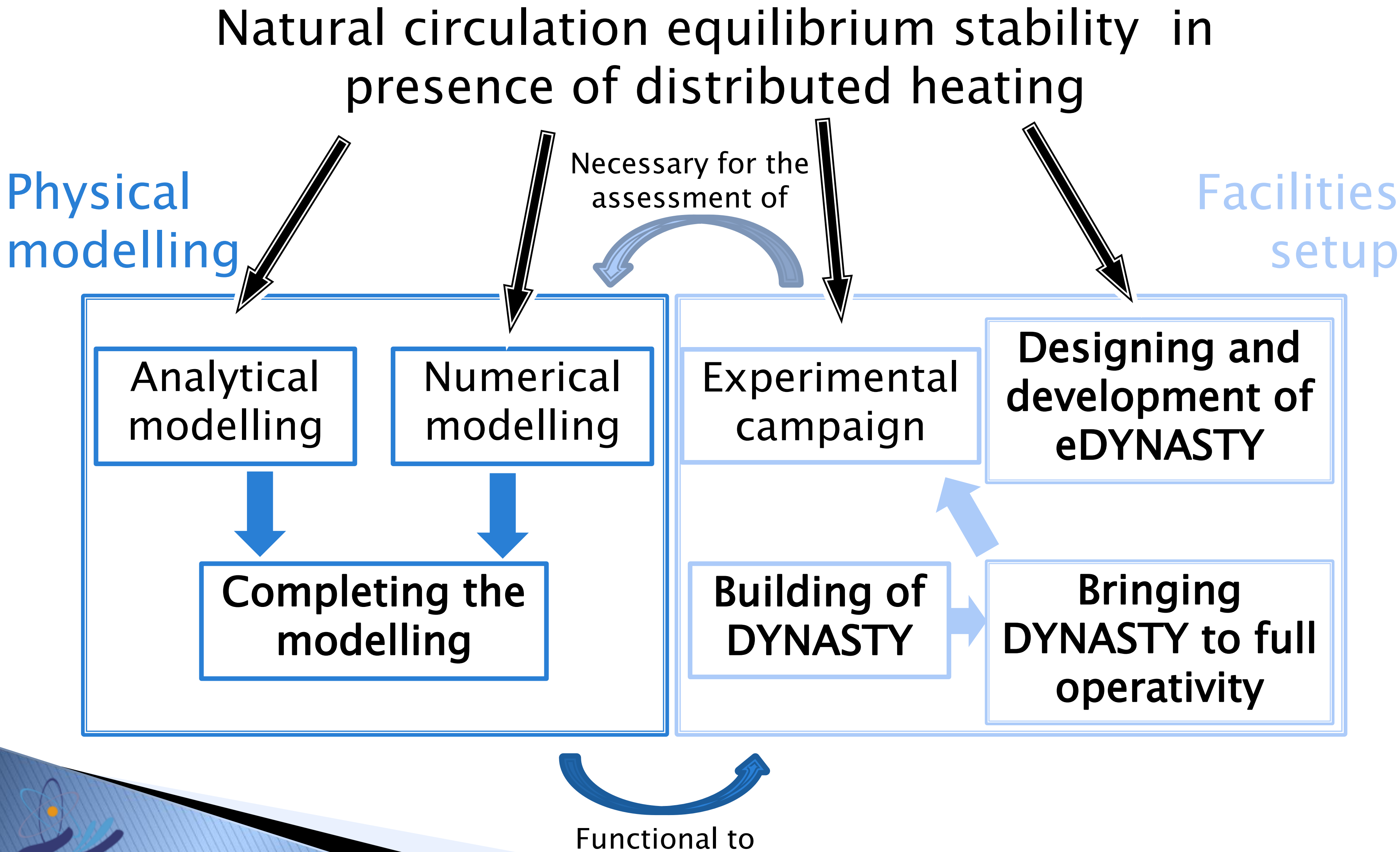
Research strategy



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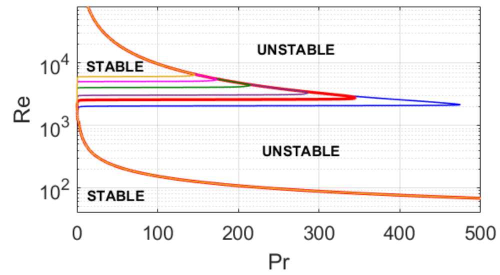
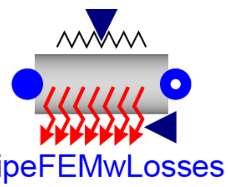
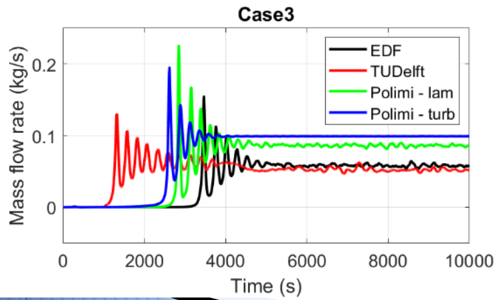
Summary

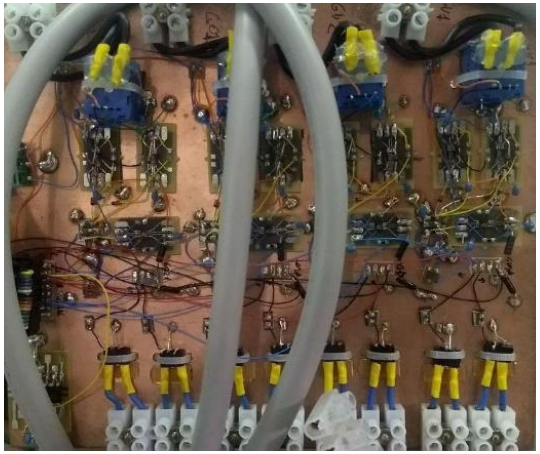
Physical modelling

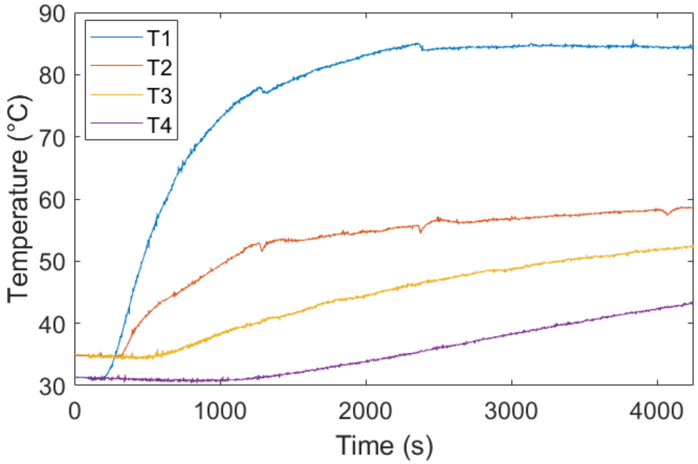






Facilities setup





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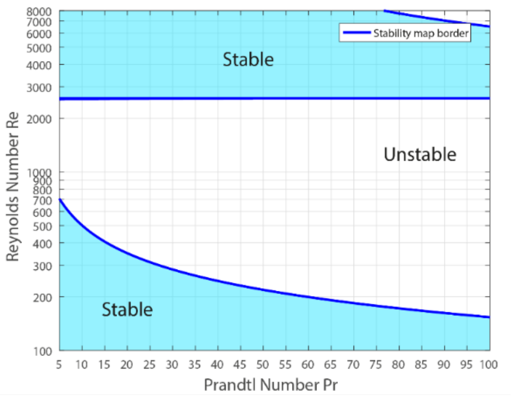
Physical modelling

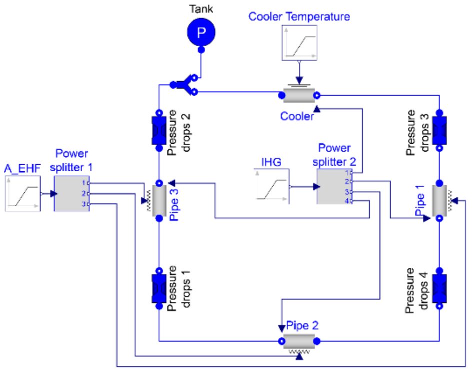
Developed models

Stability maps



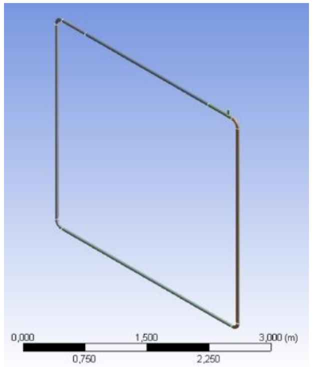
- Asymptotic behaviour
- Linear
- 1-D
- Correlations
- Preliminary design

1D dynamic model



- Transient behaviour
- Non-linear
- 1-D
- Correlations
- Design optimization

3D CFD dynamic model



- Transient behaviour
- Non-linear
- 3-D
- No correlations

Stability maps

$$\begin{cases} \dfrac{\partial G}{\partial s} = 0 \\ \dfrac{\partial G}{\partial t} + \dfrac{\partial}{\partial s}\dfrac{G^2}{\rho_f^*} = -\dfrac{\partial p}{\partial s} - \dfrac{1}{2}\lambda \dfrac{G^2}{\rho_f^* D_f} - g\,\rho_f^*\left[1 - \beta_f\left(T_f - T_f^*\right)\right]\,\hat{e}_z \cdot \hat{e}_s(s) \\ \rho_f^*\, c_f \dfrac{\partial T_f}{\partial t} + G\, c_f \dfrac{\partial T_f}{\partial s} = -h\left(T_f - T_{w,i}\right)\dfrac{\tilde{S}_f}{\tilde{V}_f} + q''' \end{cases}$$

Fluid element mass, momentum and energy balances

$$\rho_w\, c_w \frac{\partial T_{w,i}}{\partial t} = h\left(T_f - T_{w,i}\right)\frac{\tilde{S}_f}{\tilde{V}_{w,i}} - \frac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,i}\tilde{R}_w}$$

Inner pipe shell energy balance on

$$\begin{cases} T_{w,o} = T_C & \text{Cooler} \\ \rho_w\, c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \dfrac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q'' & \text{Heater} \\ \rho_w\, c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \dfrac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q''_{\#} & \text{Otherwise} \end{cases}$$

Outer pipe shell energy balance

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Stability maps

$$\begin{cases} \dfrac{\partial G}{\partial s} = 0 \\ \dfrac{\partial G}{\partial t} + \dfrac{\partial}{\partial s}\dfrac{G^2}{\rho_f^*} = \cdots \\ \rho_f^* \, c_f \dfrac{\partial T_f}{\partial t} + G \, c_f \dfrac{\partial T_f}{\partial s} = \cdots \end{cases}$$

$$\rho_w \, c_w \frac{\partial T_{w,i}}{\partial t} = \cdots$$

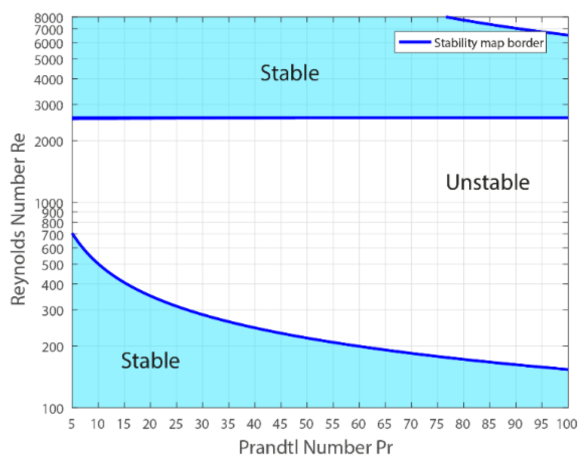
$$\rho_w \, c_w \frac{\partial T_{w,o}}{\partial t} = \cdots$$

Navier-Stokes equations
+
Energy conservation equations

$$G_0 = \cdots$$
$$T_{f,0}(s) = \cdots$$
$$T_{w,i,0}(s) = \cdots$$
$$T_{w,o,0}(s) = \cdots$$

$$Re_0 = \cdots$$
$$Gr_0 = \cdots$$
$$St_{m,0} = \cdots$$

Steady-state solution



$$\Theta(s,t) = \Theta_0(s) + \widehat{\Theta}(s)\, e^{\omega t}$$
$$\Theta = \{G, T_f, T_{w,i}, T_{w,o}\}$$

Perturbation form

$\Re(\omega) < 0$ stable

$\Re(\omega) > 0$ unstable

$\Re(\omega) = 0$ limit cycle

Equilibrium stability condition

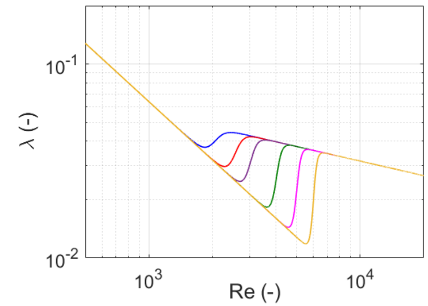
Stability map

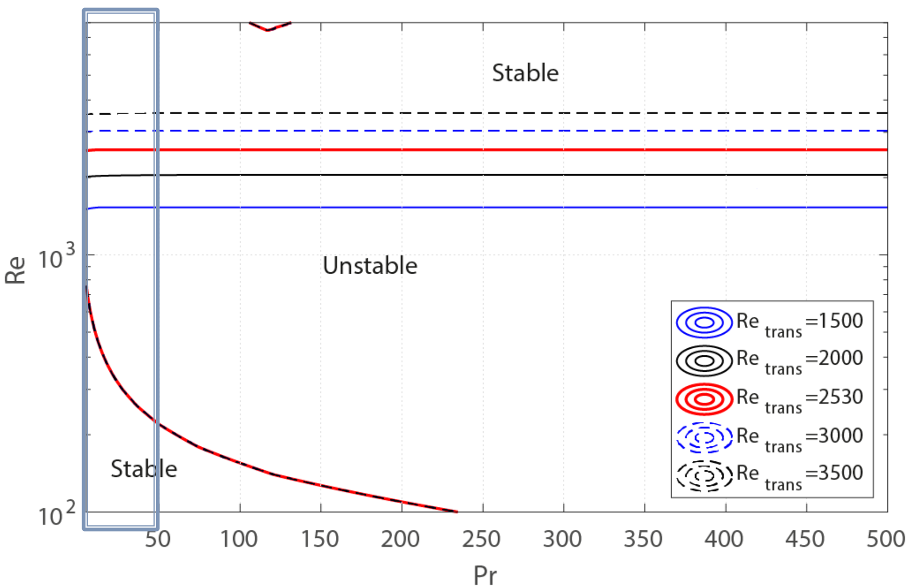
Influence of pressure drop definition on stability maps 1/2

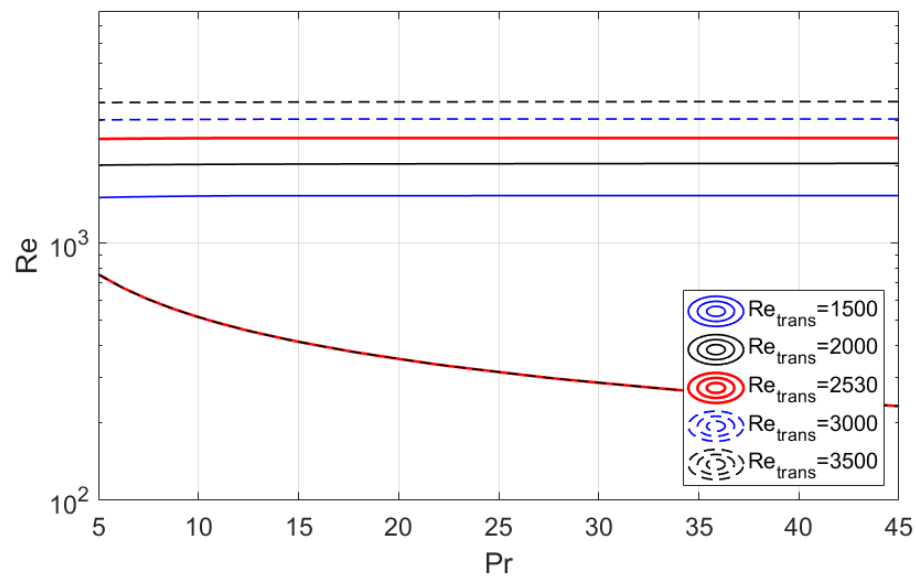
Changing the Reynolds threshold for laminar to turbulent regime transition

$$\lambda = \frac{64^{\psi_f} \cdot 0.316^{1-\psi_f}}{Re^{\psi_f + 0.25(1-\psi_f)}},$$

$$\psi_f = \frac{1}{1 + \exp\left(\sigma\left(Re - Re_{trans}\right)\right)}$$







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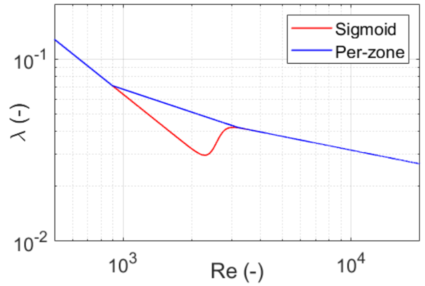
Stability map

Influence of pressure drop definition on stability maps 2/2

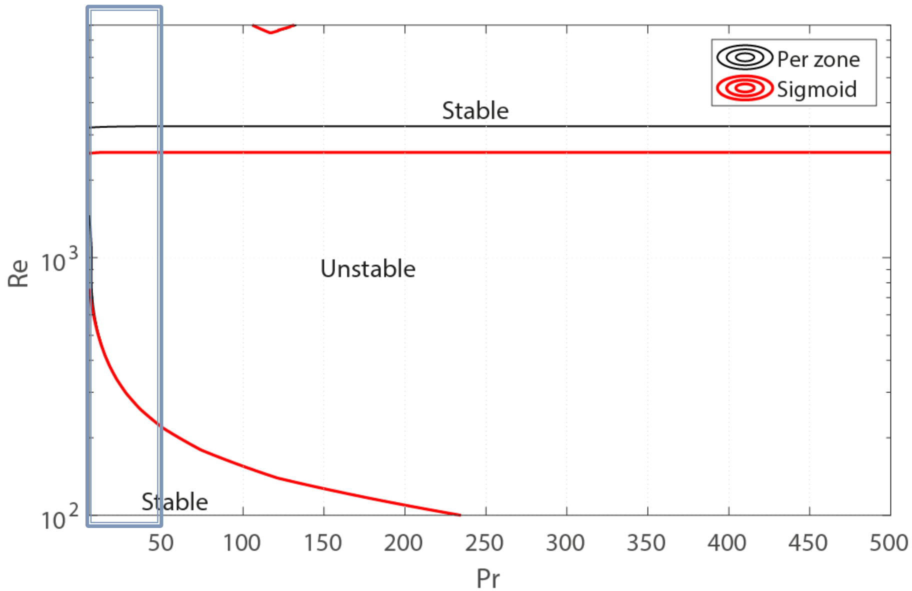
Changing slope of laminar to turbulent regime transition

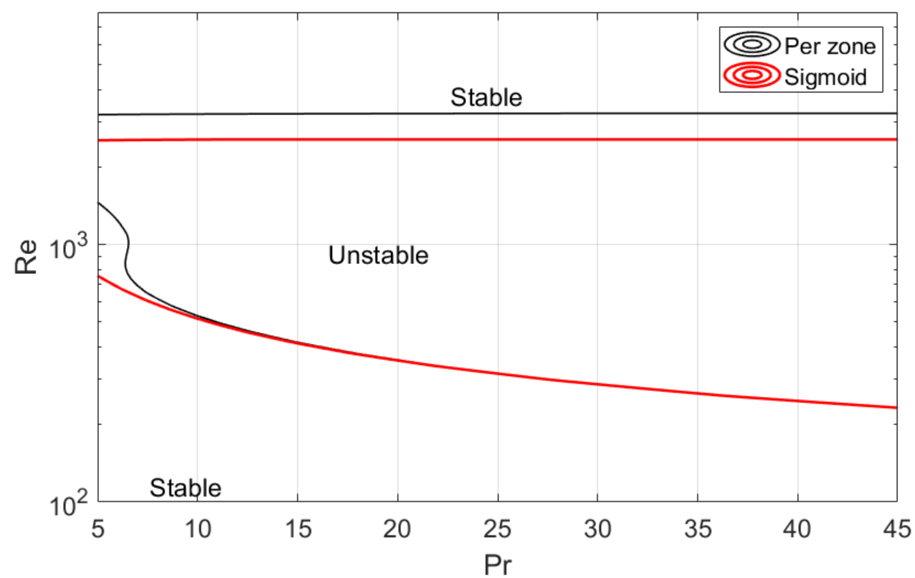
— $\lambda = \dfrac{64^{\psi_f} \cdot 0.316^{1-\psi_f}}{Re^{\psi_f + 0.25(1-\psi_f)}}$,

$$\psi_f = \frac{1}{1 + \exp\left(\sigma(Re - Re_{trans})\right)}$$



$$-\lambda = \begin{cases} \dfrac{64}{Re} & for\ Re \le 898 \\ \dfrac{1.2063}{Re^{0.416}} & for\ 898 < Re \le 3196 \\ \dfrac{0.316}{Re^{0.25}} & for\ Re > 3196 \end{cases}$$





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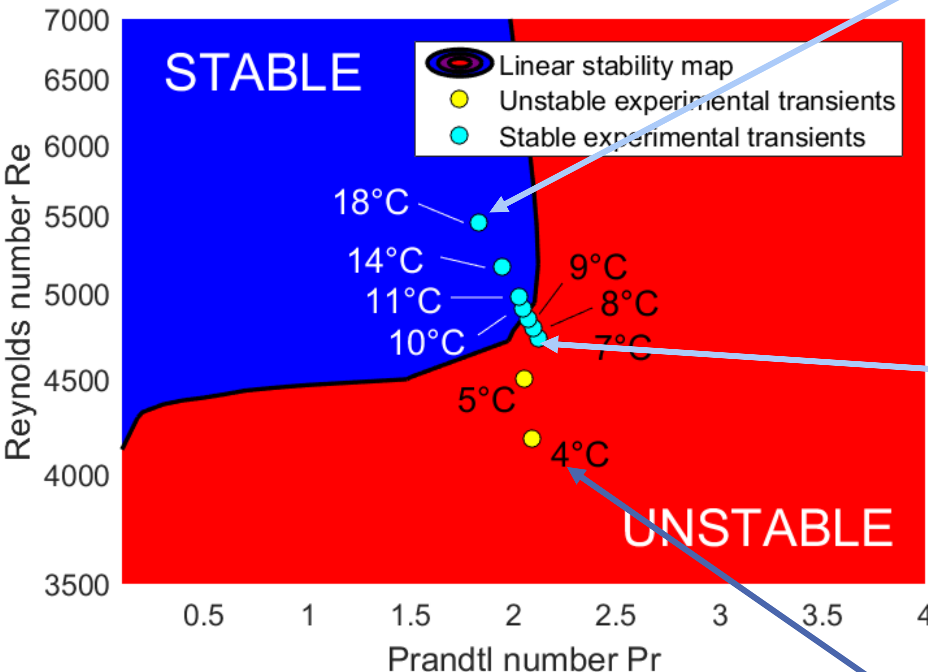
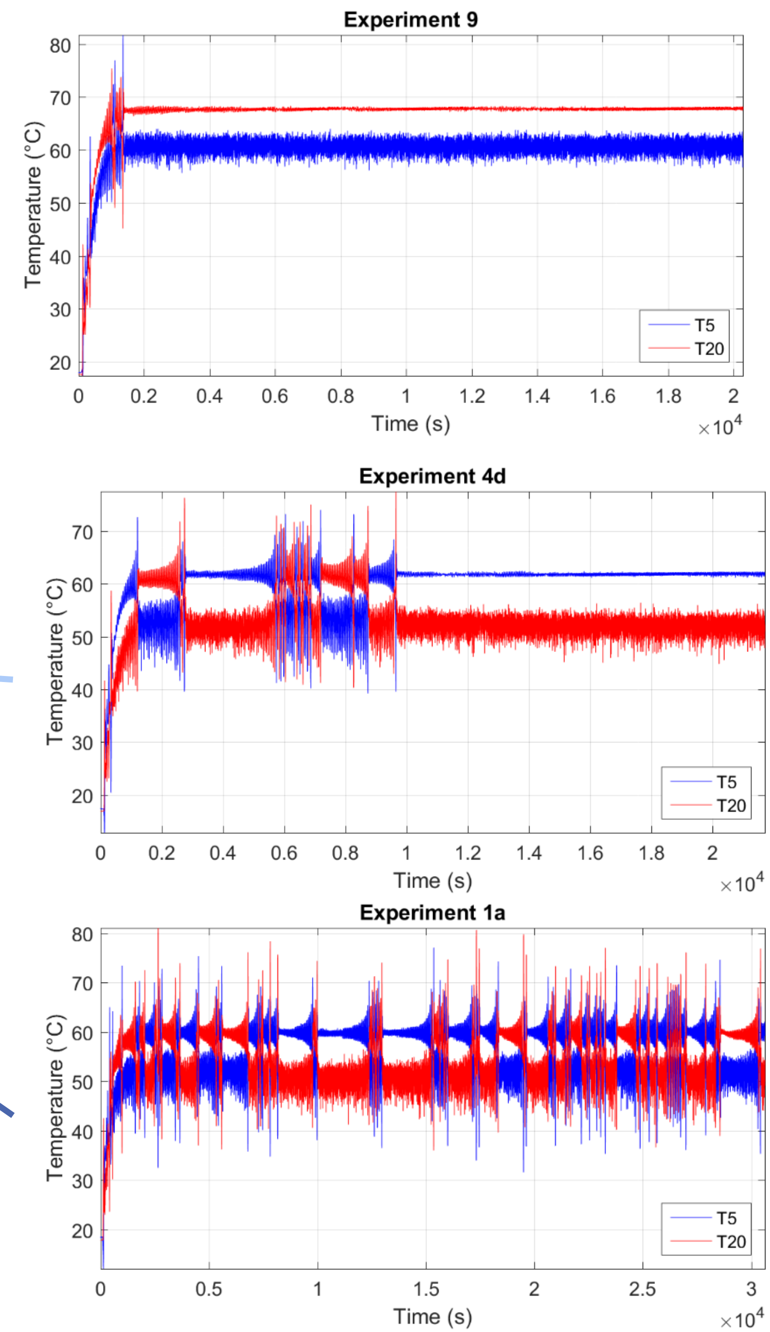
Stability maps

Assessment in conventional conditions





Luzzi L., Misale M., Devia F., Pini A., Cauzzi M. T., Fanale F., Cammi A., 2016. Assessment of analytical and numerical models on experimental data for the study of single-phase natural circulations dynamics in a vertical loop. *Chemical Engineering and Science*.

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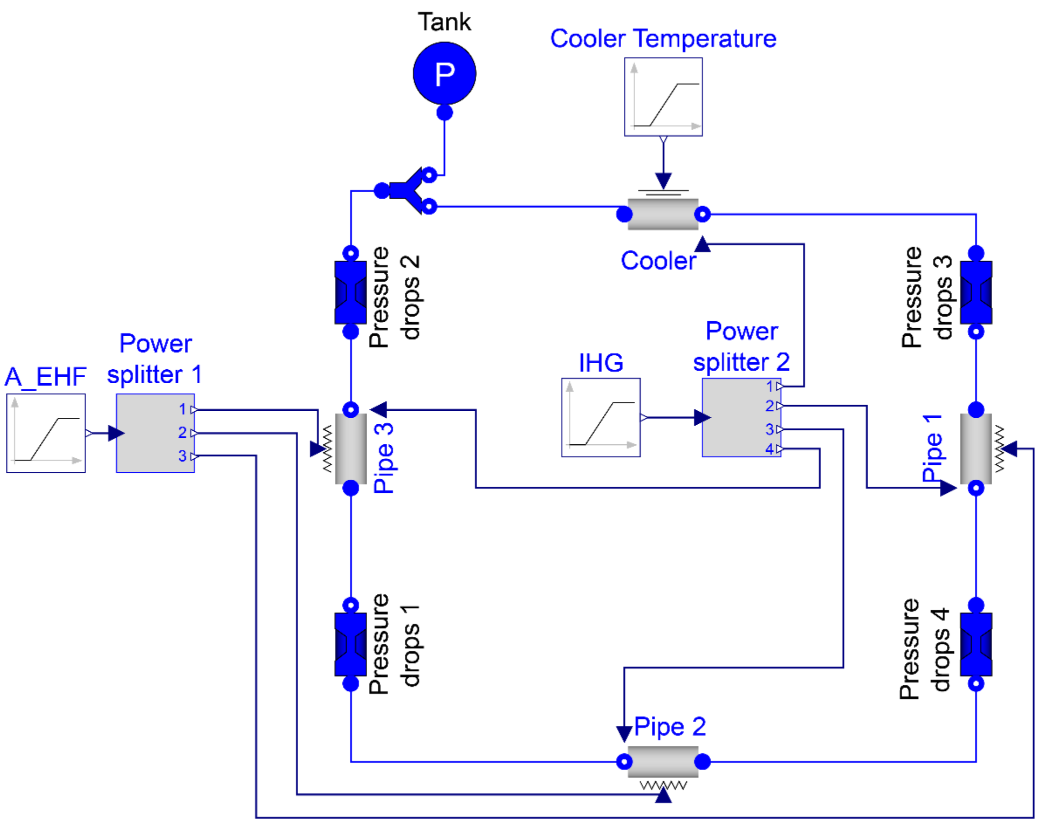
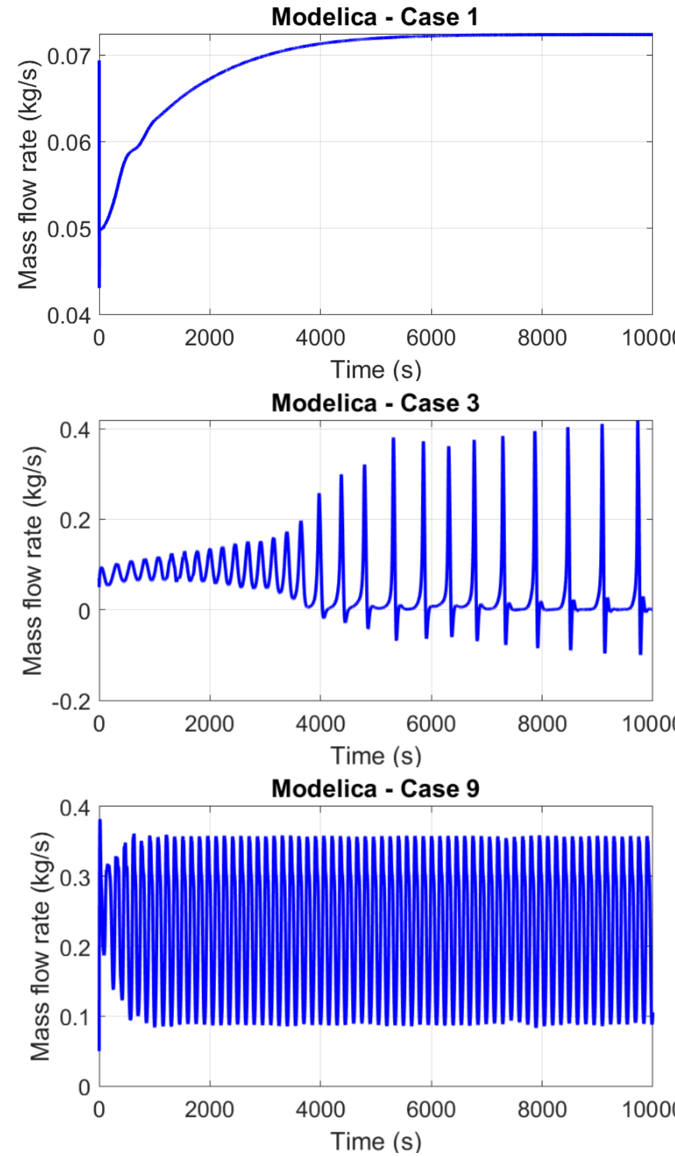
1D Modelica model



Loop model



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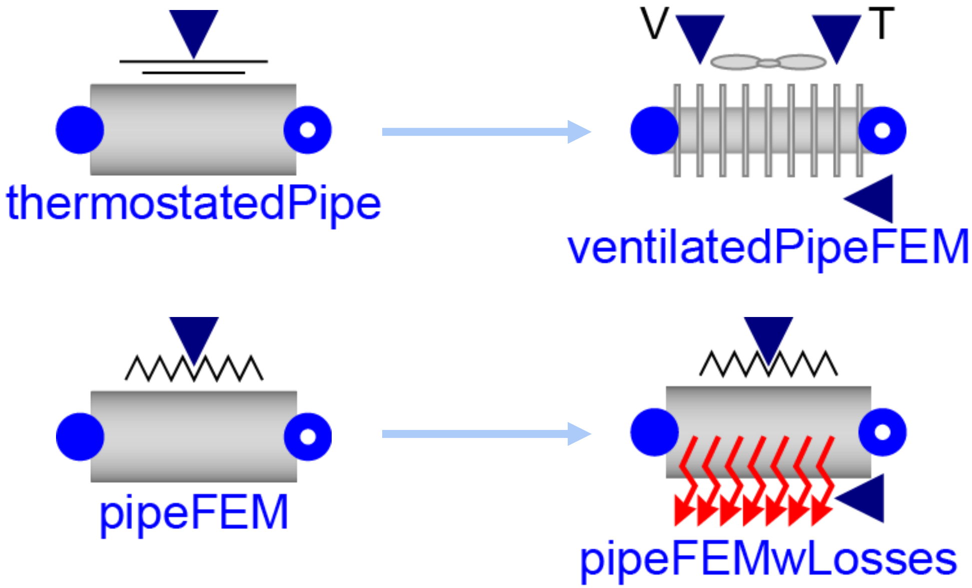
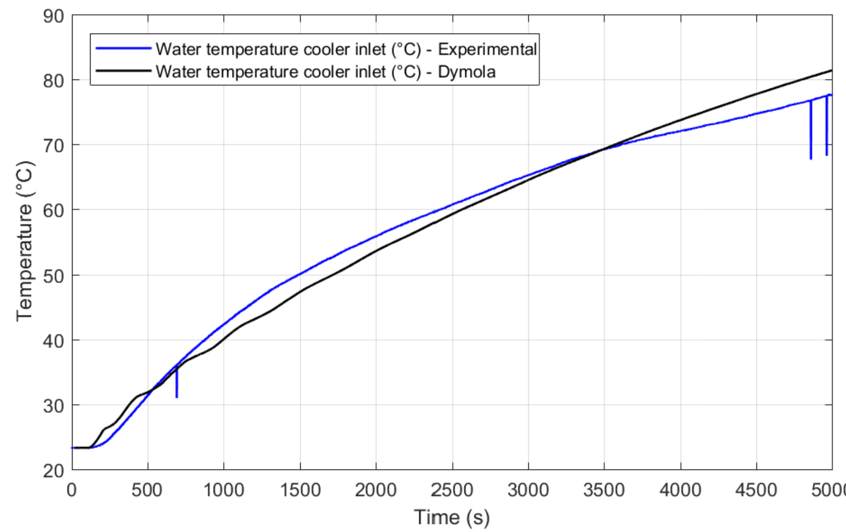
1D Modelica model

Improvement of 1D dynamic model



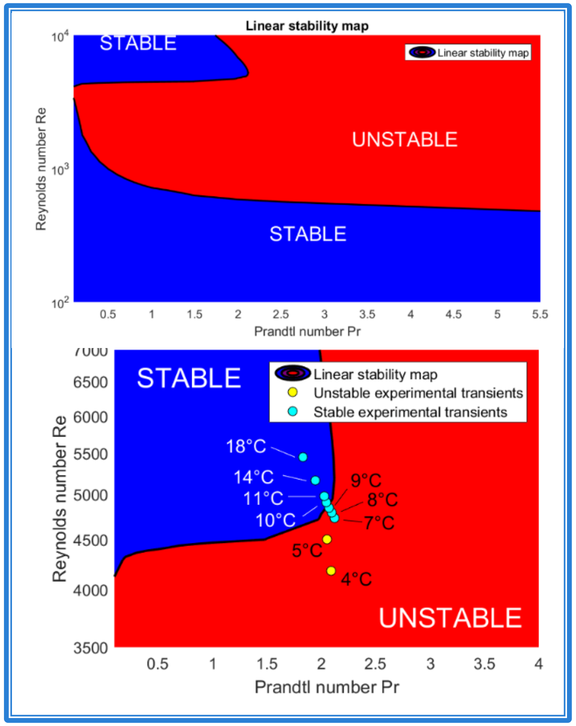


The new models give similar results to state of the art ones, if they are adapted to work in similar conditions; however they provide the possibility to operate in a greater range of conditions that be actually reproduced in DYNASTY.

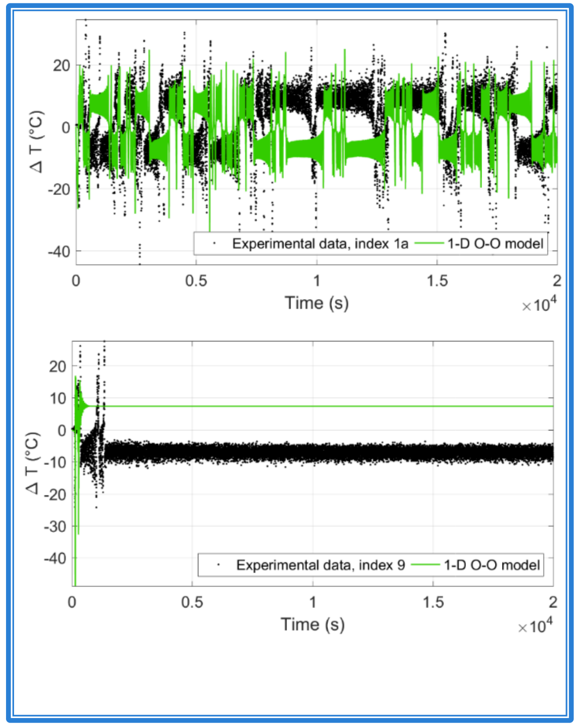
Physical modelling

Assessment of models in conventional natural circulation

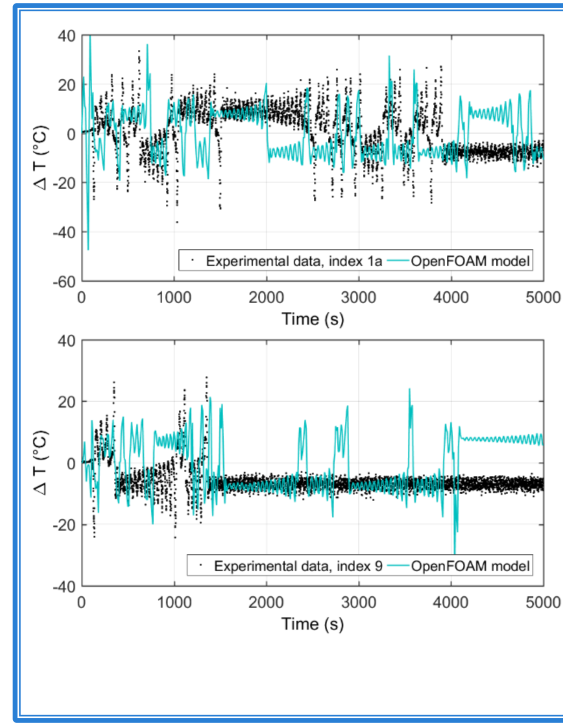
Stability maps



1D dynamic



3D CFD



Luzzi L., Misale M., Devia F., Pini, A., Cauzzi M.T., Fanale F., Cammi A., 2017. *Assessment of analytical and numerical models on experimental data for the study of single-phase natural circulation dynamics in a vertical loop,* Chemical Engineering Science 162, 262–283.

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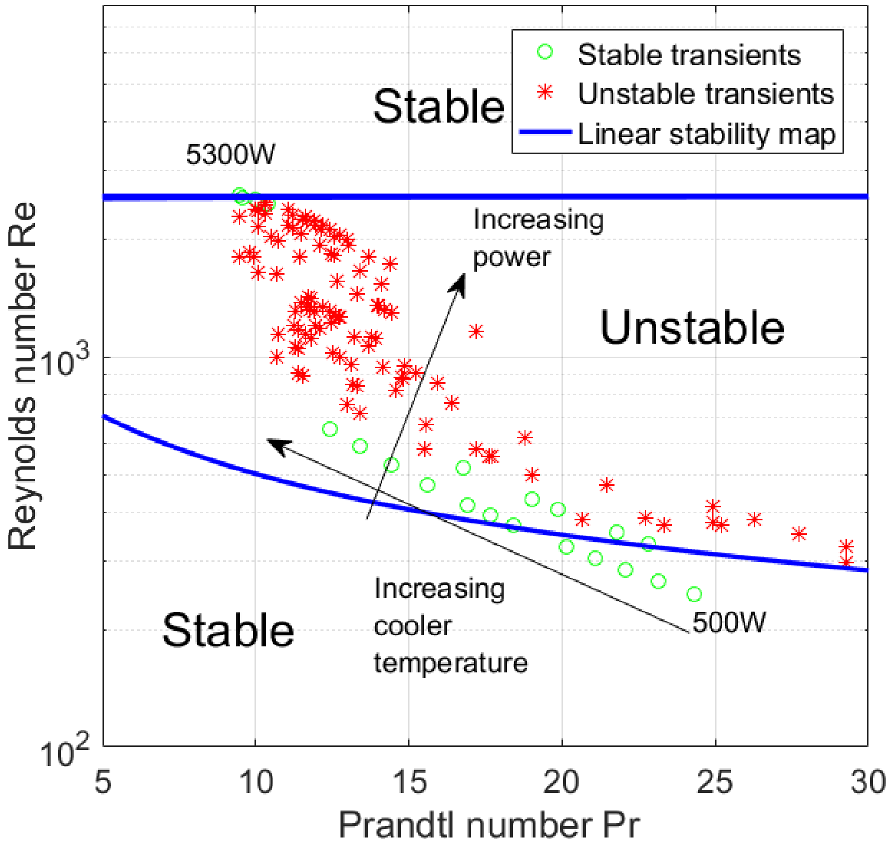
Comparison of stability behaviour

1-D Modelica model – Stability map



Equilibrium stability found with 1D simulations

		Cooler temperature (°C)							
		180	190	200	210	230	240	250	260
Power (kW)	0.5	S	S	S	S	S	S	S	S
	0.75	S	U	S	U	U	U	U	U
	1	U	U	U	U	U	U	U	U
	2	U	U	U	U	U	U	U	U
	4	U	U	U	U	U	U	U	U
	5	U	U	U	U	U	U	S	S
	5.3	U	U	U	U	S	S	S	S

S: Stable U: Unstable

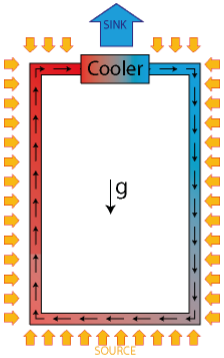
The transients collected in the table will be part of the DYNASTY experimental campaign.

Some of the cases will be used to benchmark the developed models with TUDelft and EDF models for the study of NC in presence of DH.

Physical modelling

Comparison of different modelling approaches

In the framework of the SAMOFAR project, 10 experimental cases were selected to perform a comparison between the application of numerical models and experimental data. The ten cases are studied by means of different models, using different hypothesis.



Experiments to be run

#	Power	T_{cooler}
1	0.5 kW	180 °C
2	0.75 kW	190 °C
3	0.75 kW	210 °C
4	0.75 kW	250 °C
5	1 kW	180 °C
6	1 kW	200 °C
7	1 kW	240 °C
8	5 kW	180 °C
9	5.3 kW	190 °C
10	5.3 kW	240 °C

Differences in the modelling approaches0

	PoliMi			EDF	TUDelft
	SM	1D	CFD	CFD	CFD
Spatial	1D	1D	3D	3D	3D
Turbulence	Full range	Full range	Laminar / k-ω SST	Laminar	Laminar
dp, heat transfer	Correlations	Correlations	Solve fields	Solve fields	Solve fields
Non-linearities	Neglected	Considered	Considered	Considered	Considered
Stability	Asymptotic	Dynamic	Dynamic	Dynamic	Dynamic
Heat losses	Neglected	Either	Neglected	Considered	Neglected
Cooler	T	T or x-flow	T	T	T

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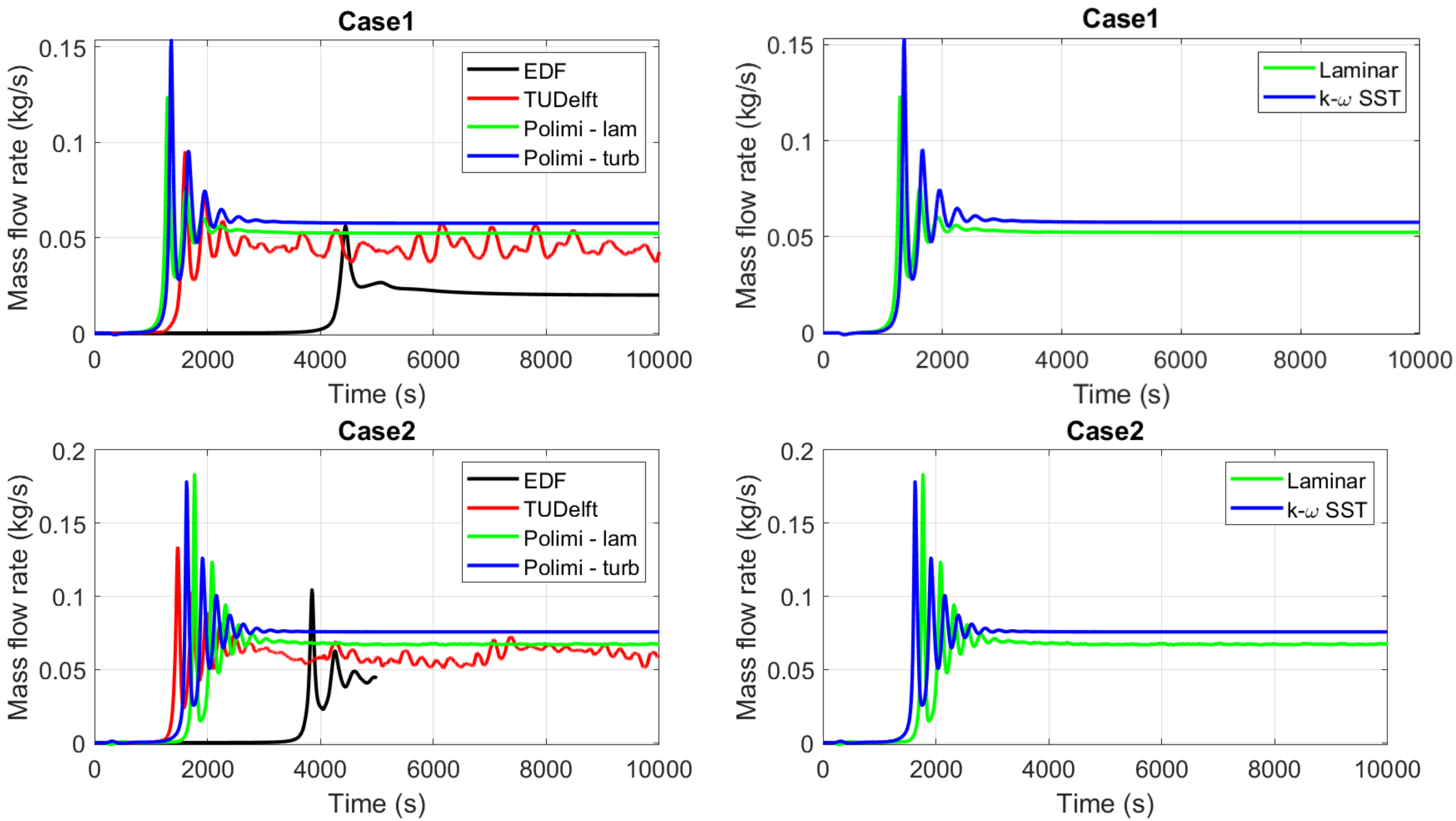
Physical modelling
3D CFD



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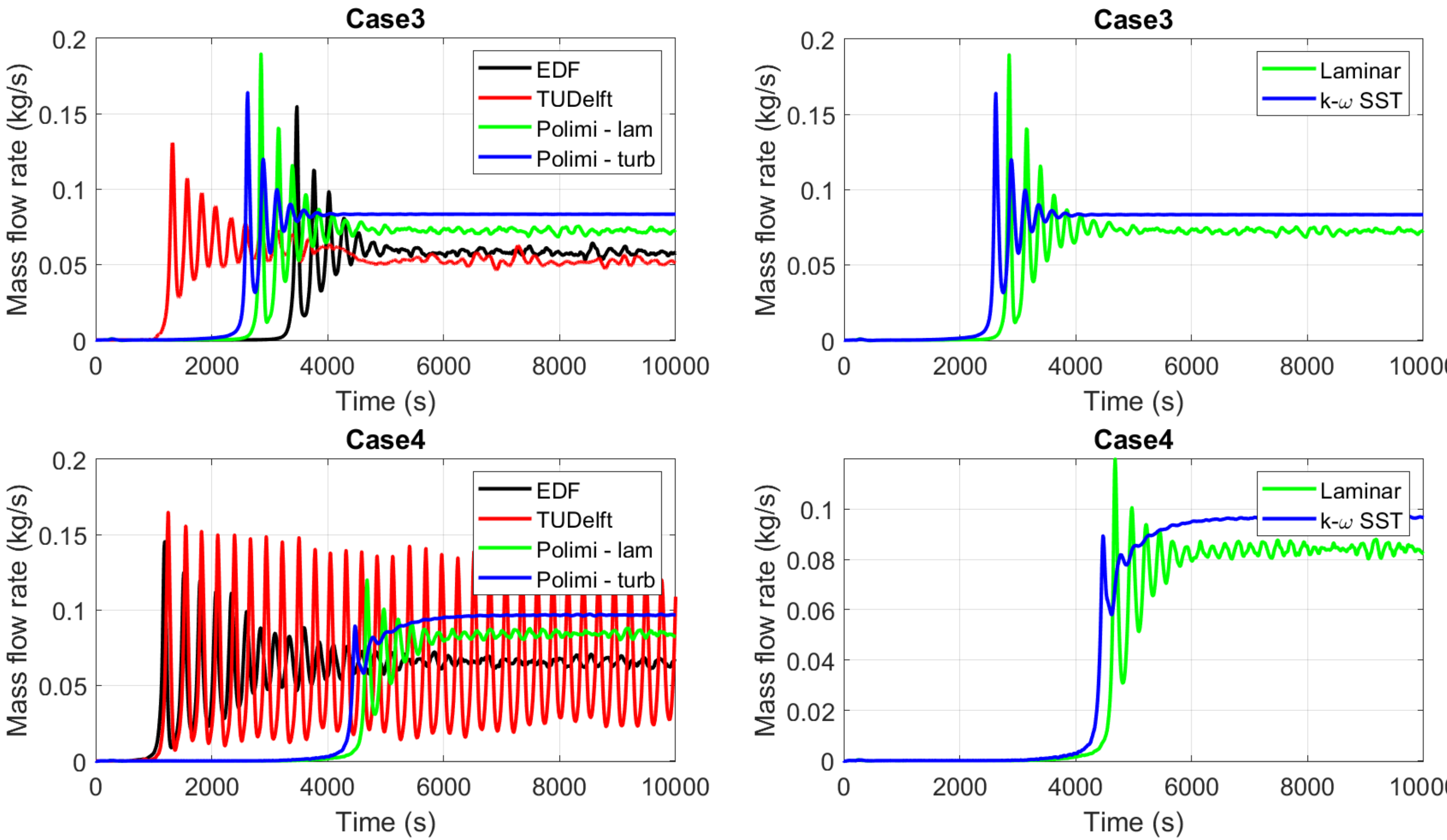
Physical modelling
3D CFD



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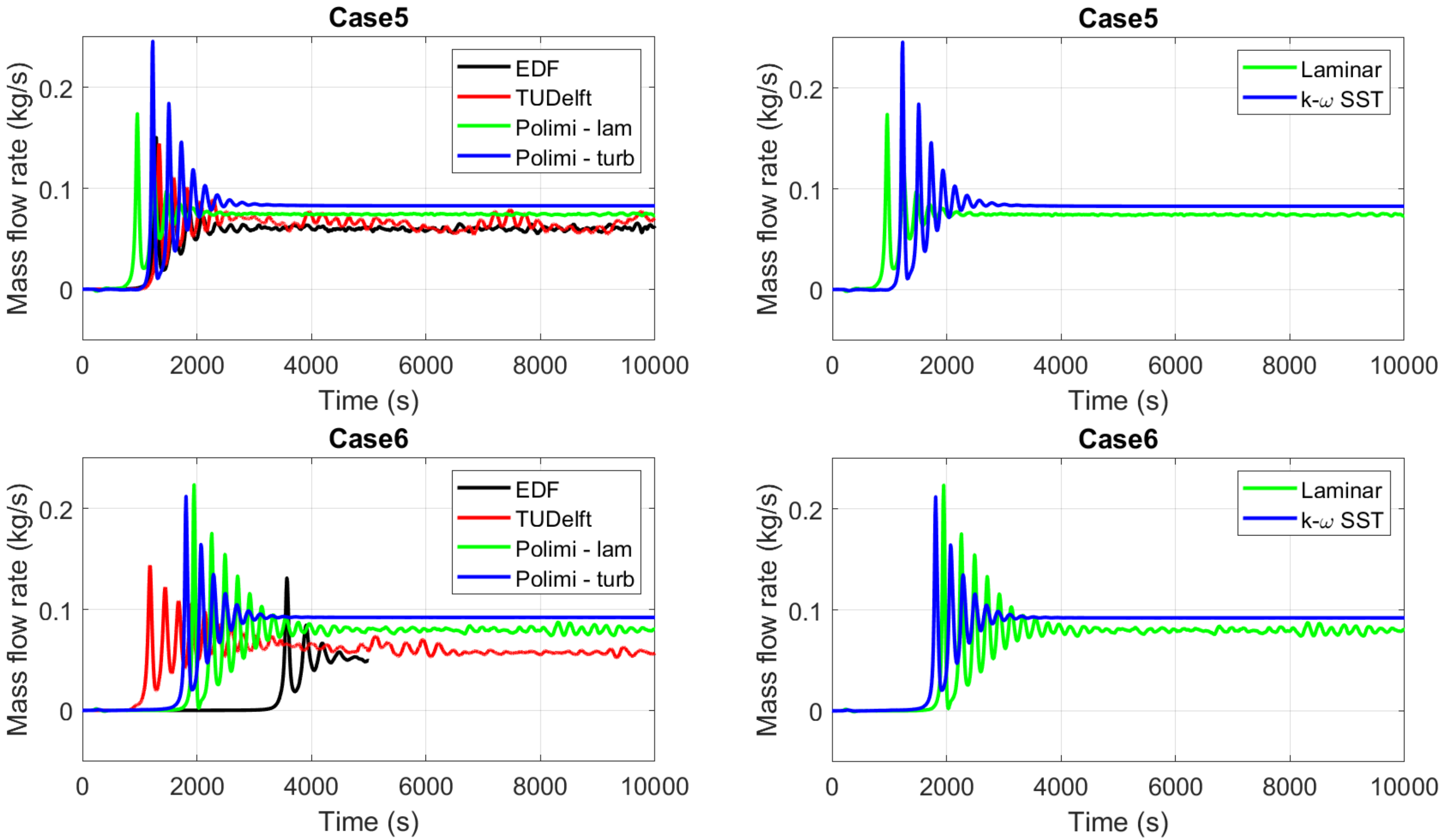
Physical modelling

3D CFD



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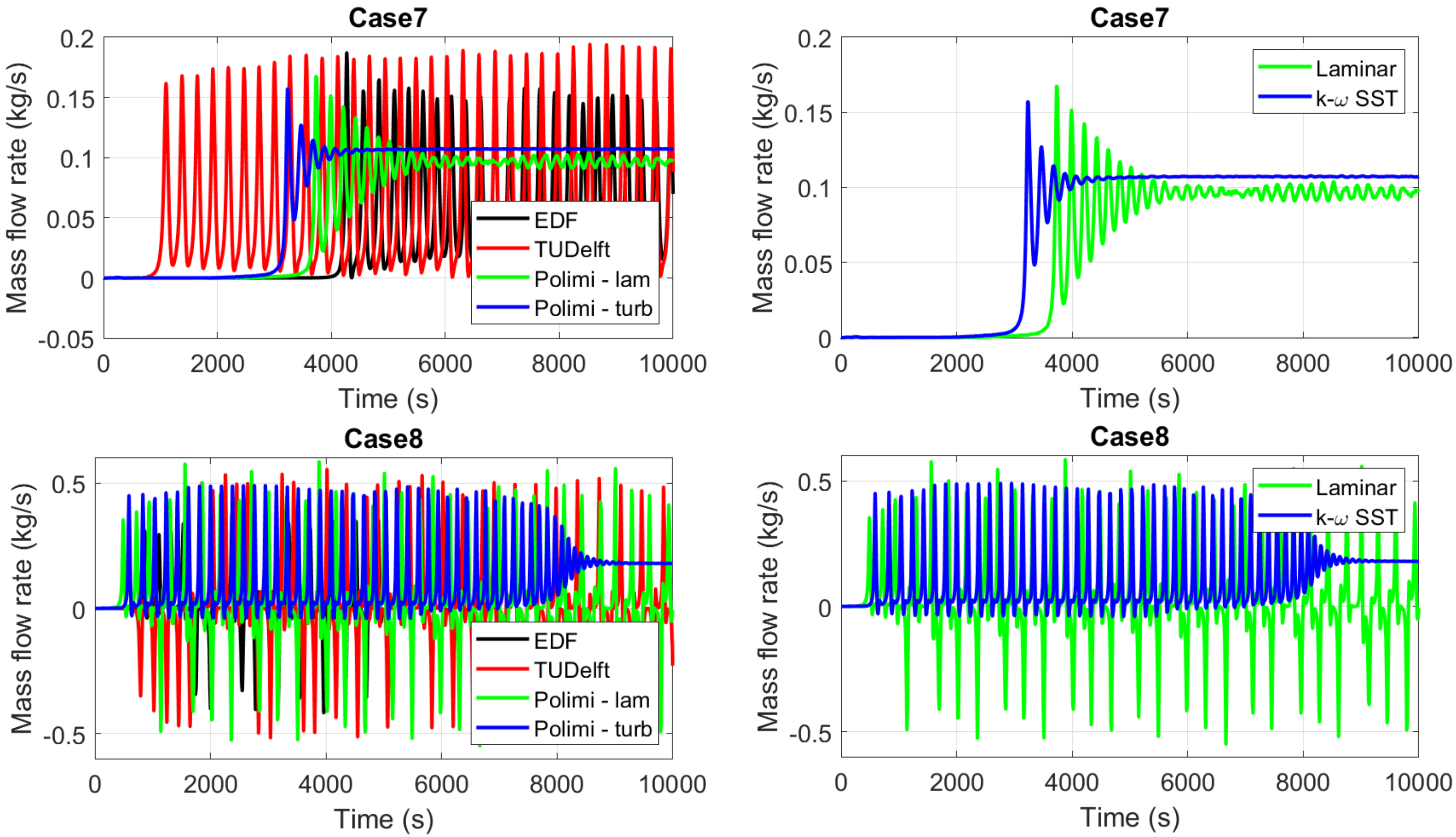
Physical modelling
3D CFD



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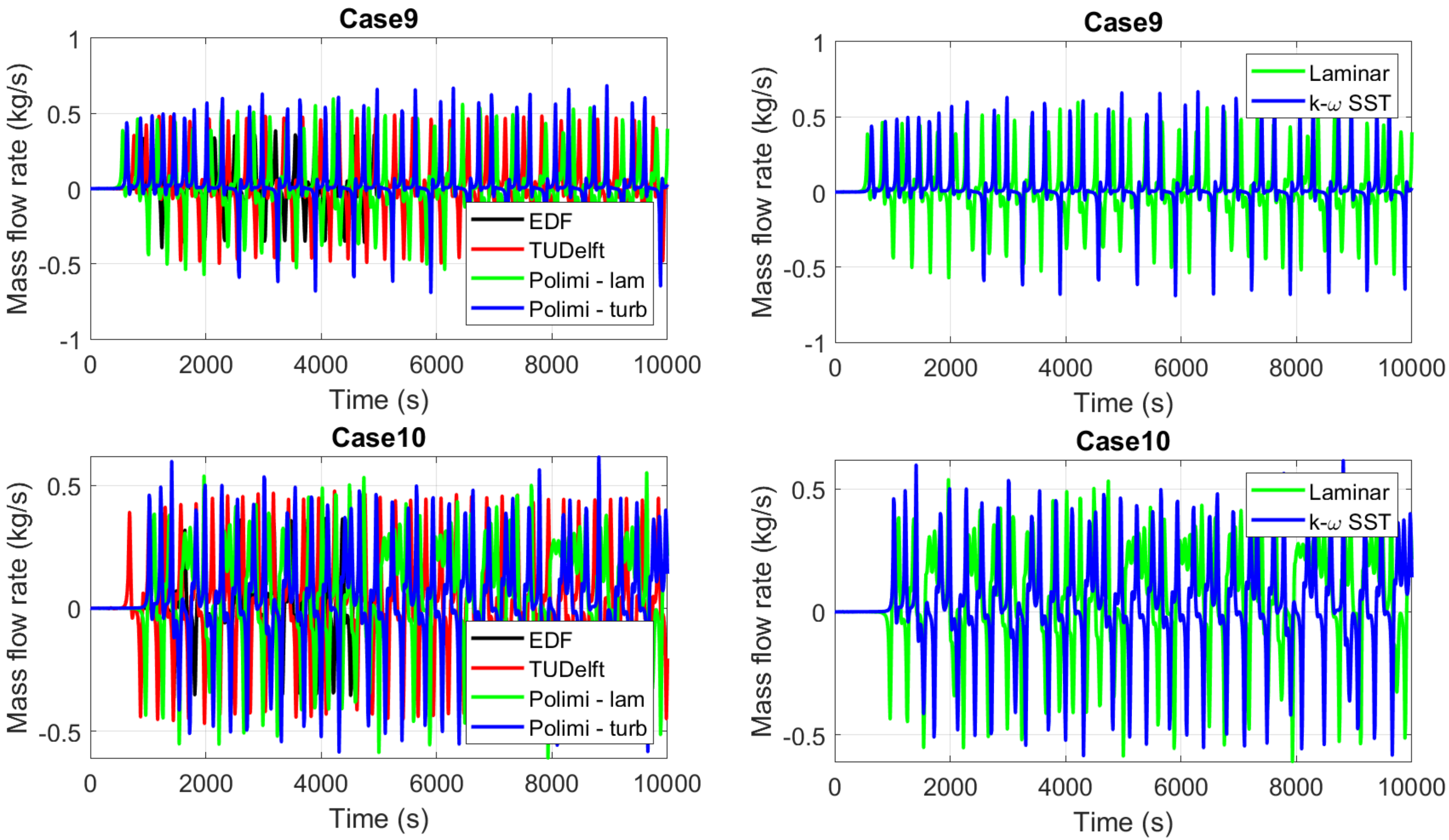
Physical modelling
3D CFD



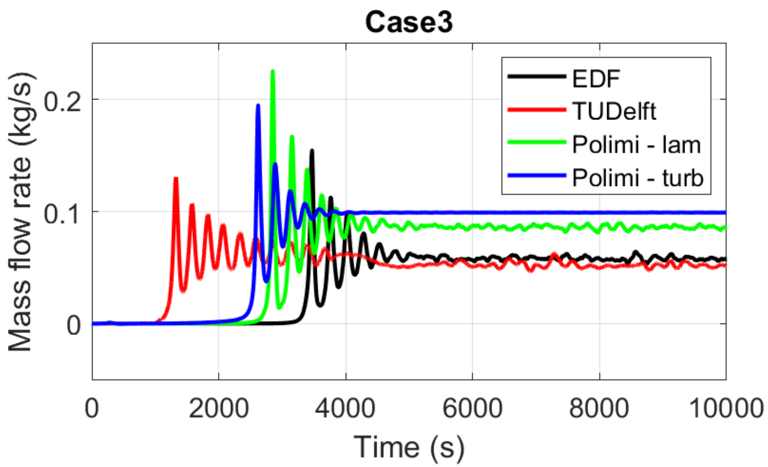
Physical modelling

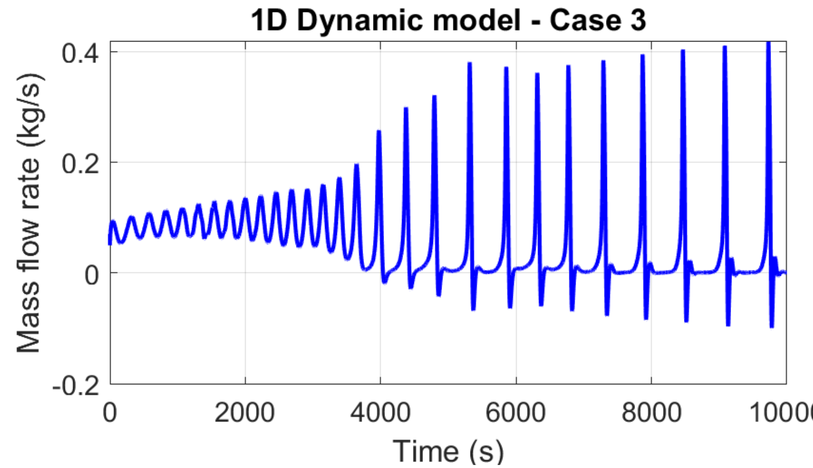
3D CFD

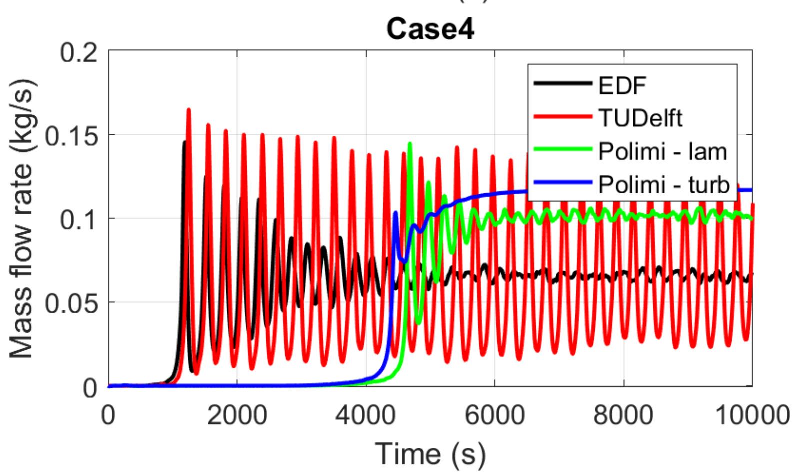
Overall comparison between behaviour found by different models					
Case	PoliMi			EDF	TUDelft
	Stability maps	1D Modelica	3D CFD (turb/lam)	3D CFD	3D CFD
1	Stable	Stable	Stable/Stable	Stable	Small oscill.
2	Unstable	Unstable	Stable/Stable	Stable (probably*)	Small oscill.
3	Unstable	Pulsed	Stable/Small oscill.	Small oscill.	Small oscill.
4	Unstable	Pulsed	Stable/Small oscill.	Small oscill.	Unstable
5	Unstable	Pulsed	Stable/Stable	Small oscill.	Small oscill.
6	Unstable	Pulsed	Stable/Small oscill.	Stable (probably*)	Small oscill.
7	Unstable	Pulsed	Stable/Small oscill.	Unstable	Unstable
8	Unstable	Unstable	Stable/Pulsed	Pulsed	Pulsed
9	Unstable	Unstable	Pulsed/Pulsed	Pulsed	Pulsed
10	Stable	Stable	Pulsed/Pulsed	Pulsed	Pulsed

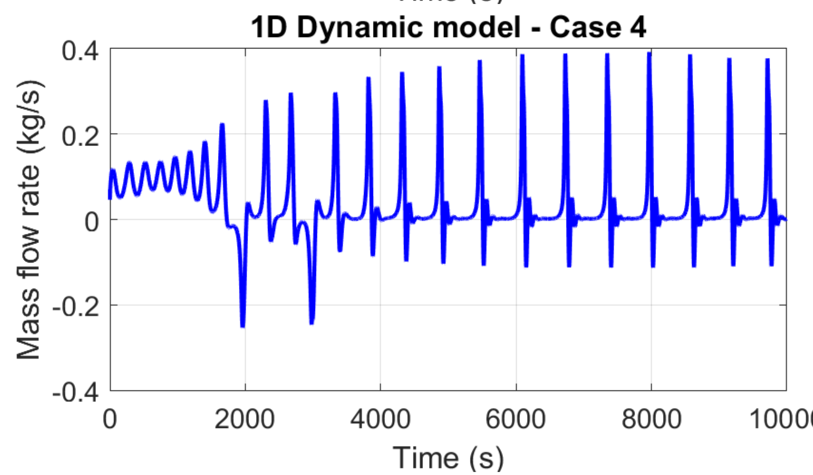
3D CFD analysis and turbulence model sensitivity

Turbulence modelling









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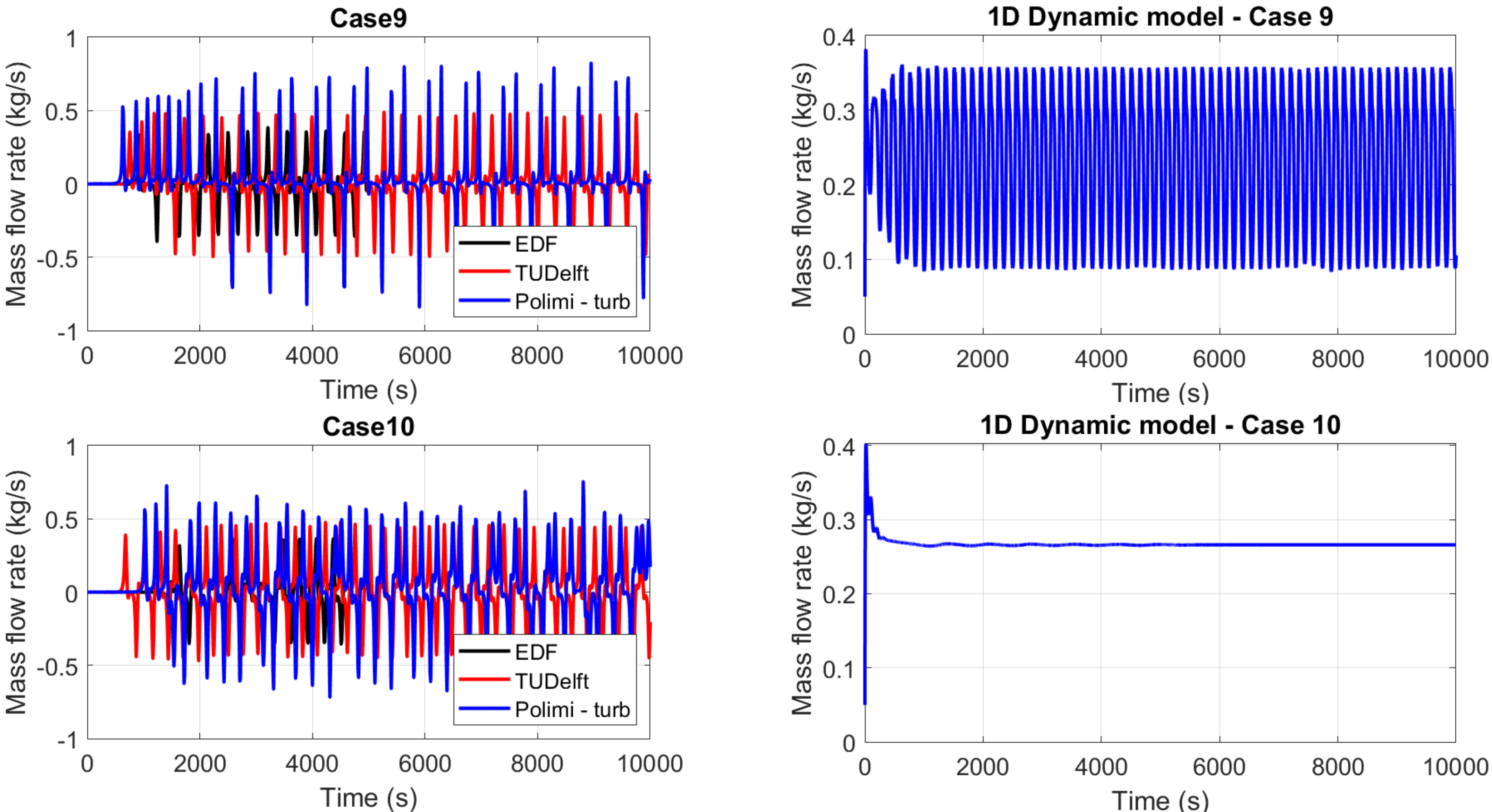
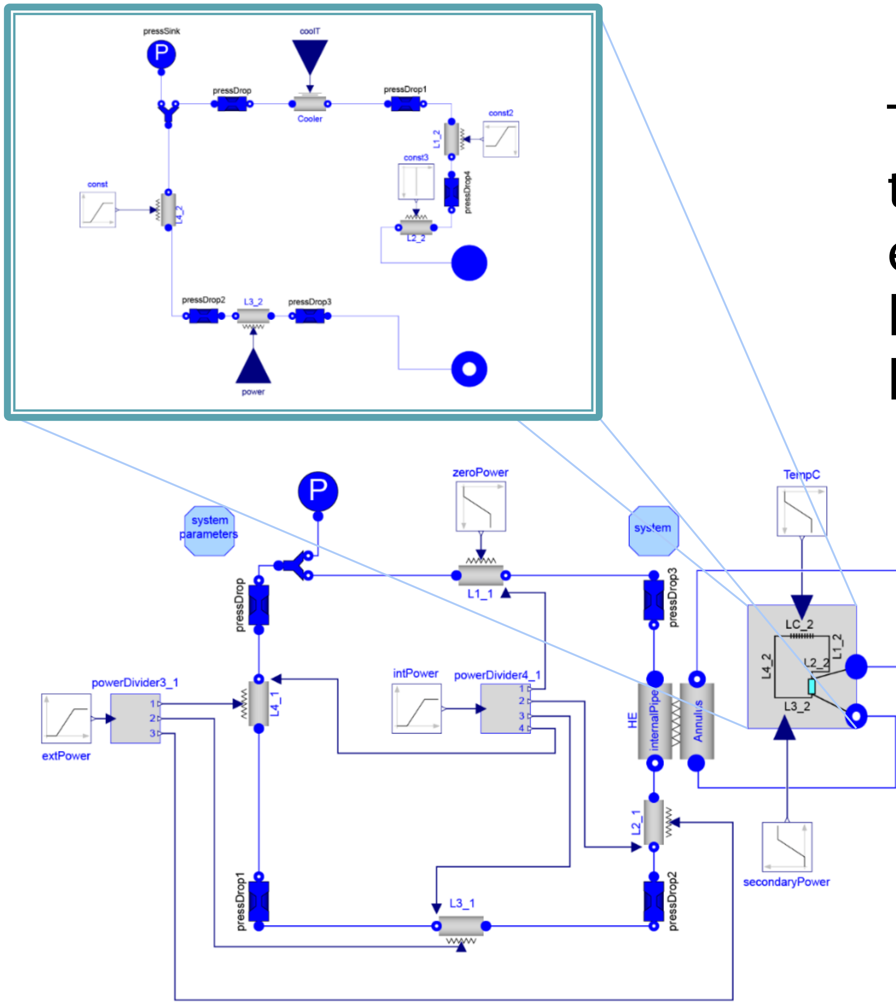
3D CFD analysis and turbulence model sensitivity

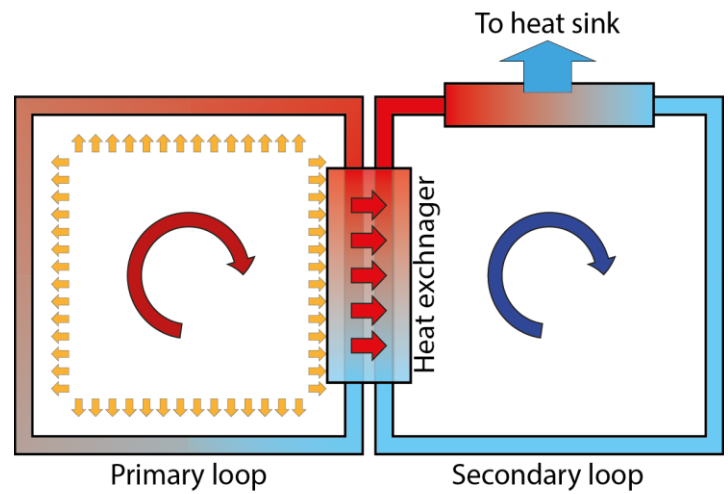
Turbulence modelling



Coupled natural circulation systems



The tools/models are built upon those for single loop study, extended to also include an heat exchanger and a secondary loop.

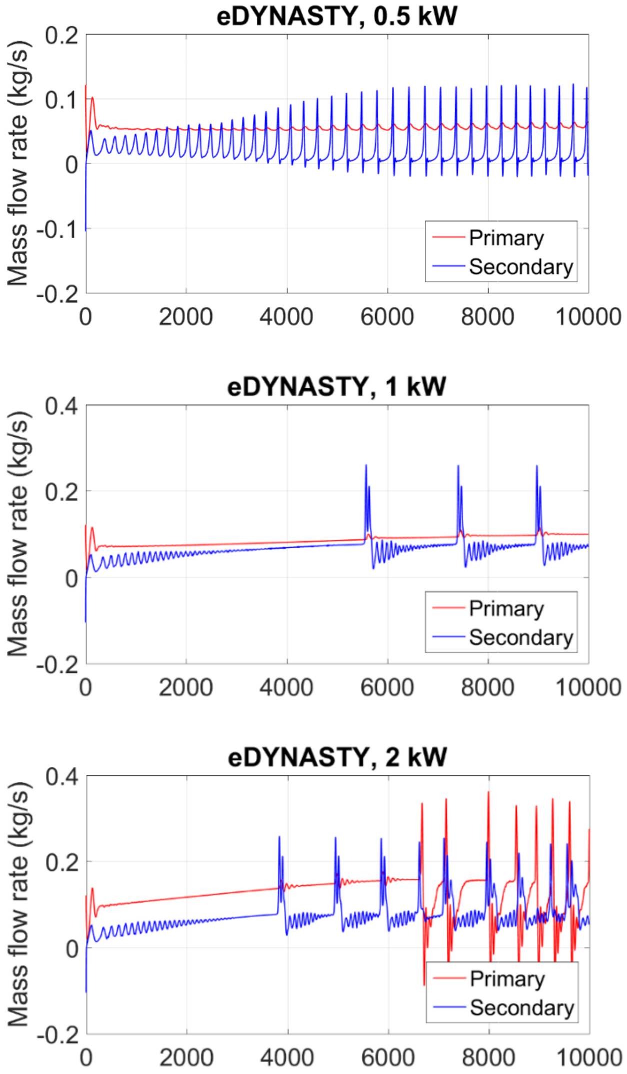


Coupled natural circulation systems

When considering coupled systems, complex behaviours can arise.

Coupled loops dynamics

Primary loop behaviour	Secondary loop behaviour
Unidirectional oscillations	Unidirectional oscillations
Unidirectional oscillations	Bidirectional oscillations
Bidirectional oscillations	Unidirectional oscillations
Bidirectional oscillations	Bidirectional oscillations
Stable	Stable



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DYNASTY & eDYNASTY setup

DYNASTY

eDYNASTY

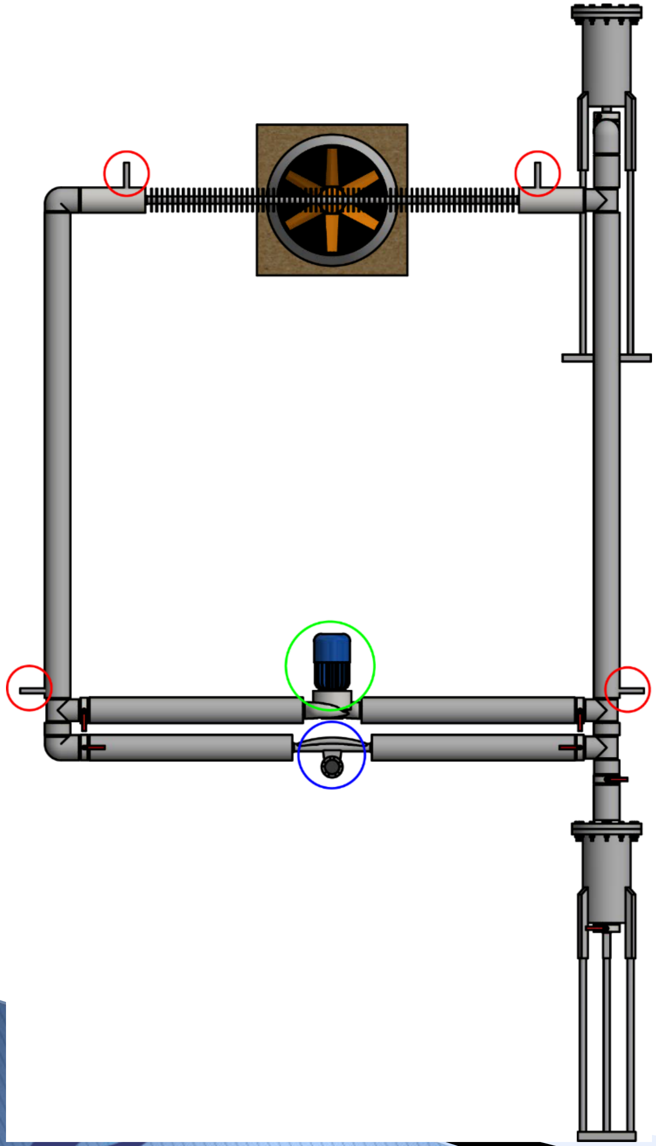








Facilities and instrumentation setup



DYNASTY data acquisition/control system has been developed in-house to have complete control over its functionality.

The system records the temperature of the fluid in four points, the temperature of each pipe and the mass flow rate.

The system controls:

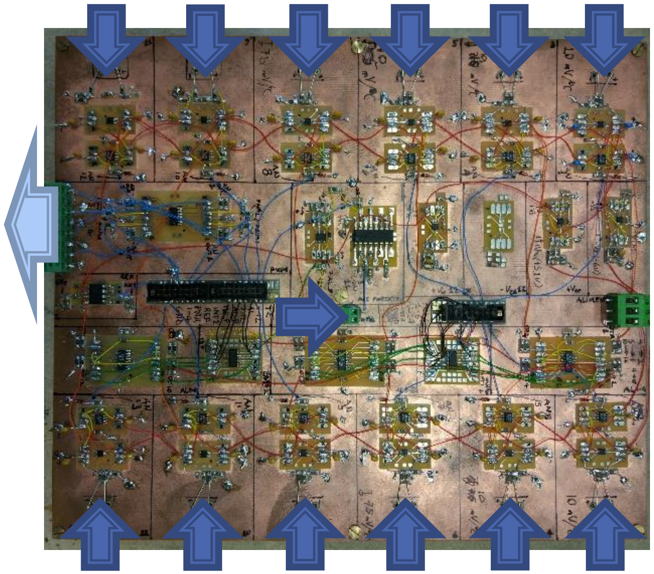
- Fan power;
- Pump power;
- Heaters power.

The fan power is regulated to keep the temperature of the cooler section around a desired value.

One of the main issues is **solidification** prevention.

Facilities and instrumentation setup

Data acquisition and control system (DACS)

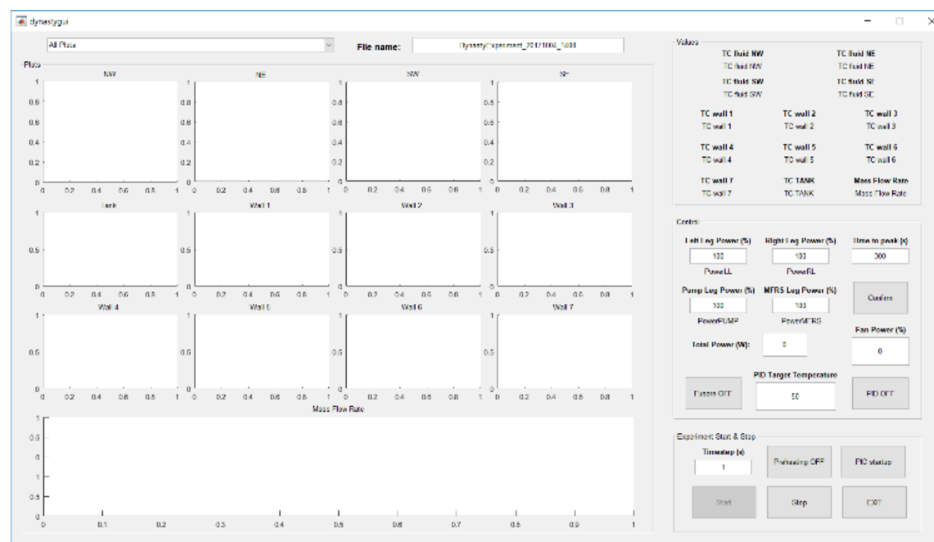


Prototype control system hardware:

- Micro-controller
- Thermocouple amplifiers and compensators
- Alarm system
- Output amplifiers
- Fan and pump control

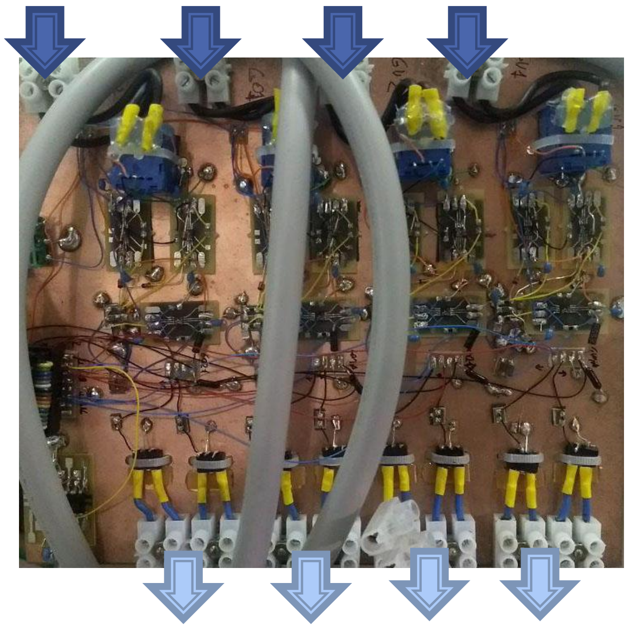
Control system software:

- Collected variable visualization
- Control variable (power provided and cooler temperature) selection



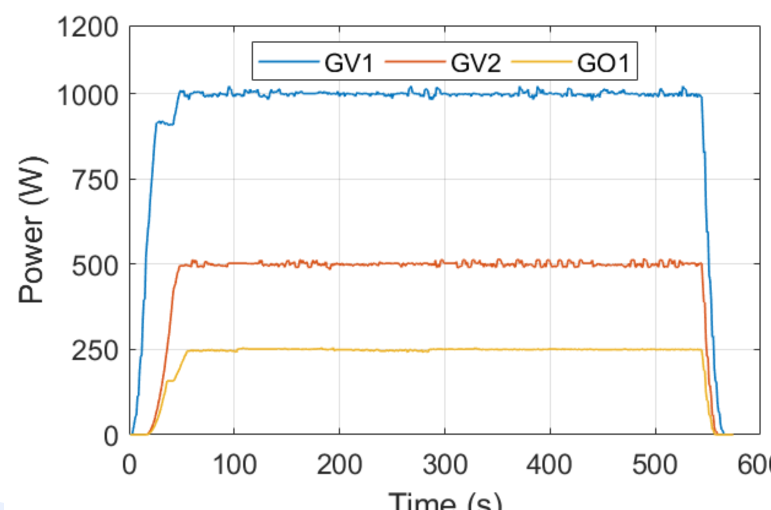
Facilities and instrumentation setup

Variacs control system (VARC)



The variac control system regulates the power provided to DYNASTY heating system. It measures the current circulating in the power lines and adjusts regulable transformers to change the power towards a desired value.

On the right is presented the power provided to three legs of DYNASTY over time, the target powers are 1000W for GV1, 500W for GV2 and 250W for GO1.



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Facilities and instrumentation setup

Salt preparation

DYNASTY working fluid is a molten salt named Hitec, a mixture of sodium and potassium nitrite and nitrate ($NaNO_3$–$NaNO_2$–KNO_3 7–40–53 wt%).

The salt has been chosen for its chemical safety and for the relatively low melting temperature (~138 °C).

Property	Value @573,15 K	Correlation as function of T (K)
Density (kg m^{-3})	1860	$2279.799 - 0.7324 \cdot T$
Viscosity (Pa s)	0.0032	$\exp(-4.343 - 2.0143 \cdot (\ln(T - 273) - 5.011))$
Specific heat capacity (J kg^{-1} K^{-1})	1560	Constant
Thermal conductivity (W m^{-1} K^{-1})	0.48	Constant
Pr (–)	10.4	$1560 \cdot \exp(-4.343 - 2.0143 \cdot (\ln(T - 273) - 5.011))/0.48$

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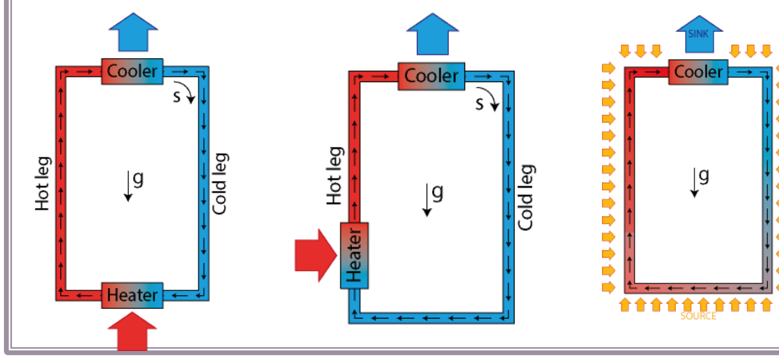
Preliminary experiments

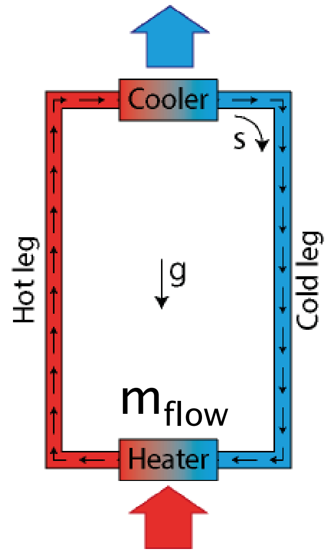
Testing the facility

Testing components

Testing working modes



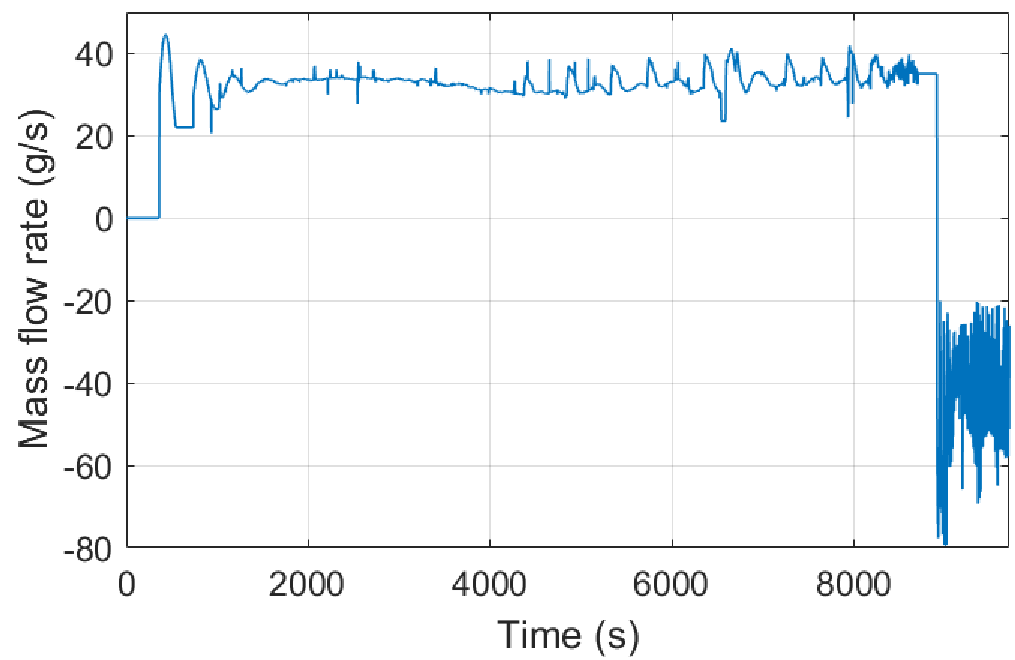
DYNASTY preliminary experiments



Verify if flow is inverted in HH configuration

Experiment conditions

- 1.6 kW provided to bottom horizontal leg;
- Cooler working in natural circulation (fan off);
- Mass-flow rate acquired.



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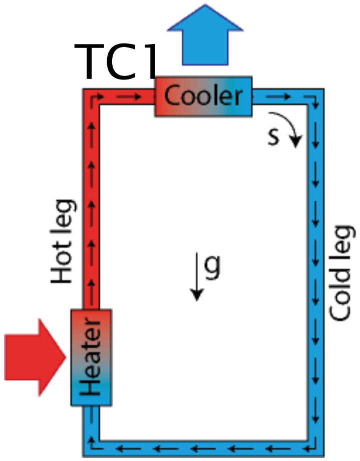
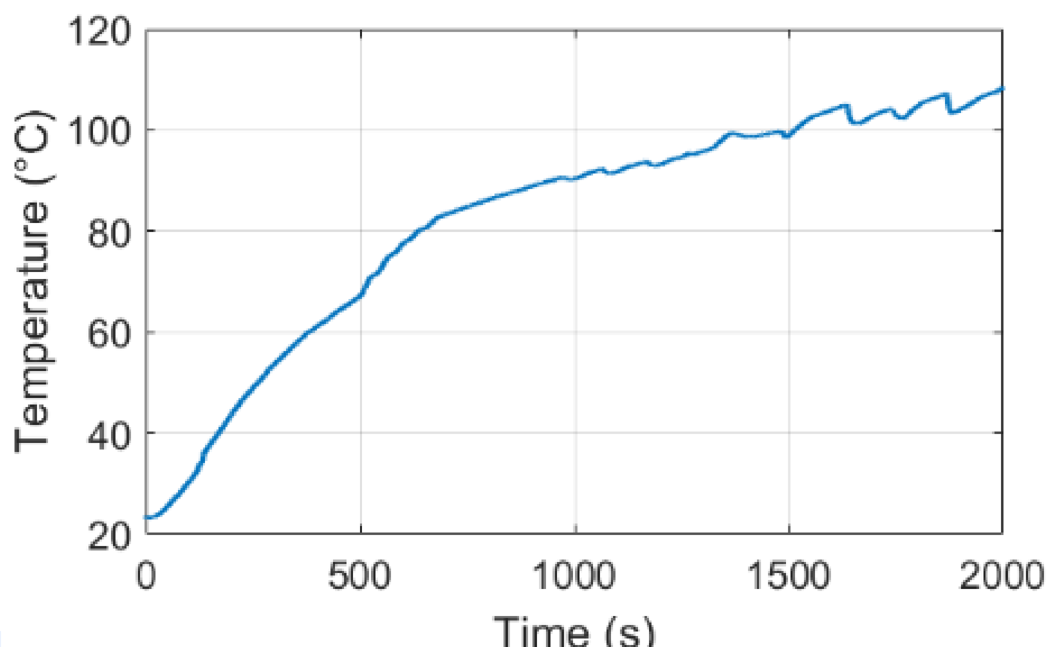
DYNASTY preliminary experiments



Verify if boiling is reached at full power and if thermocouples can register the temperature plateau.

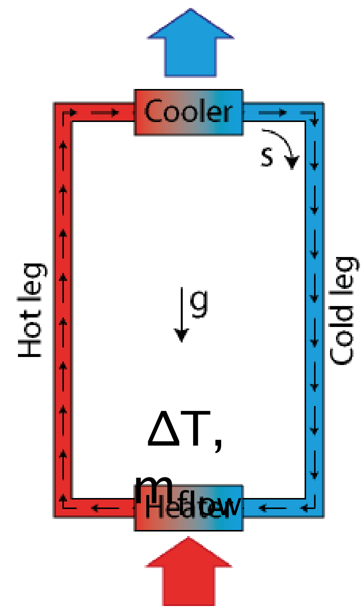
Experiment conditions

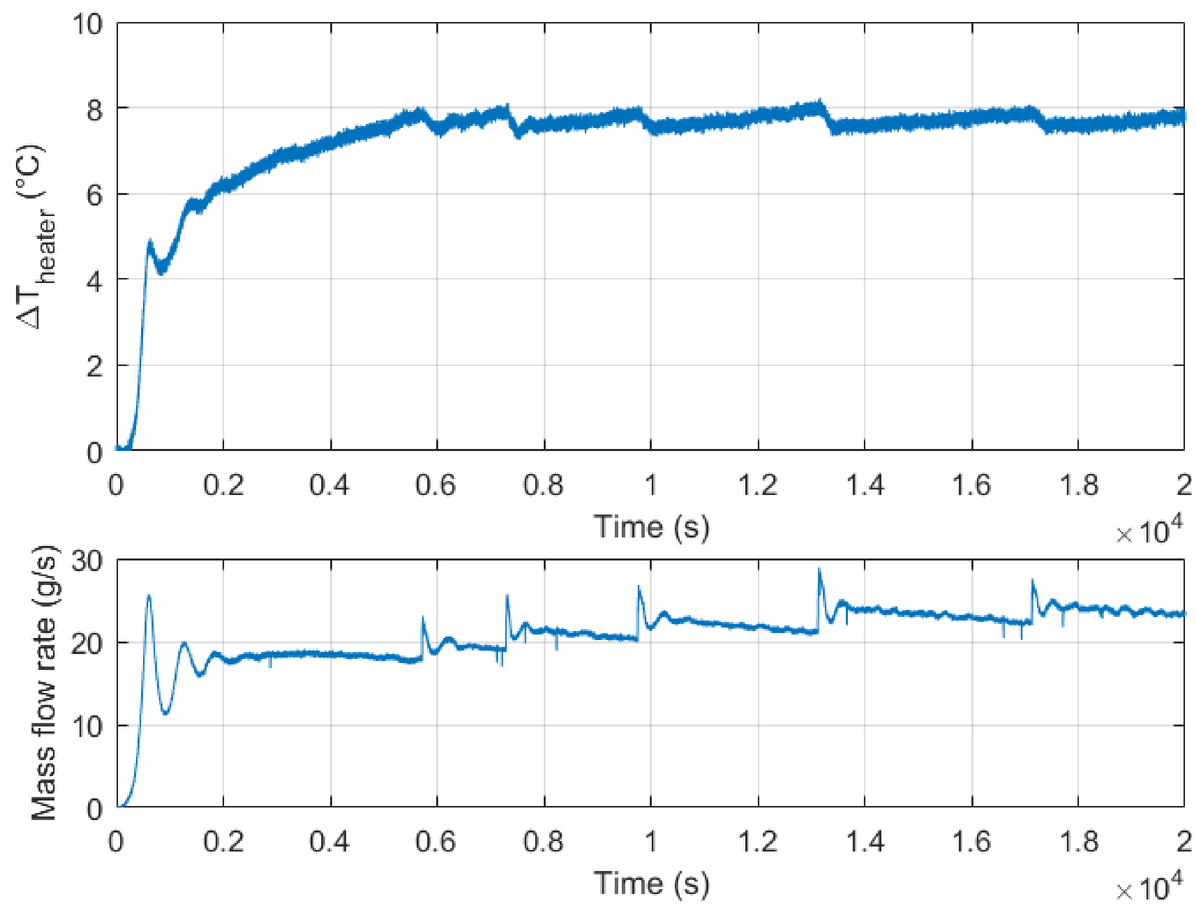
- 2.5 kW provided to left leg;
- Cooler working in natural circulation (fan off);
- Temperature TC1 acquired.



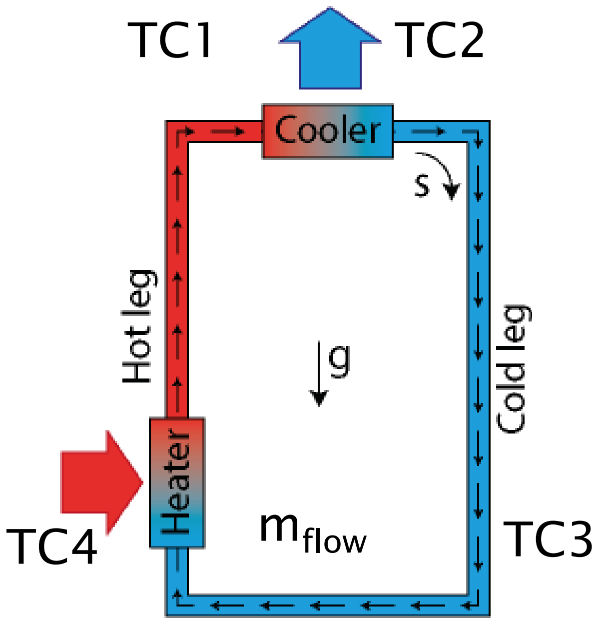
DYNASTY preliminary experiments

Test experiment using water, 836W to horizontal leg, cooler working in natural circulation.

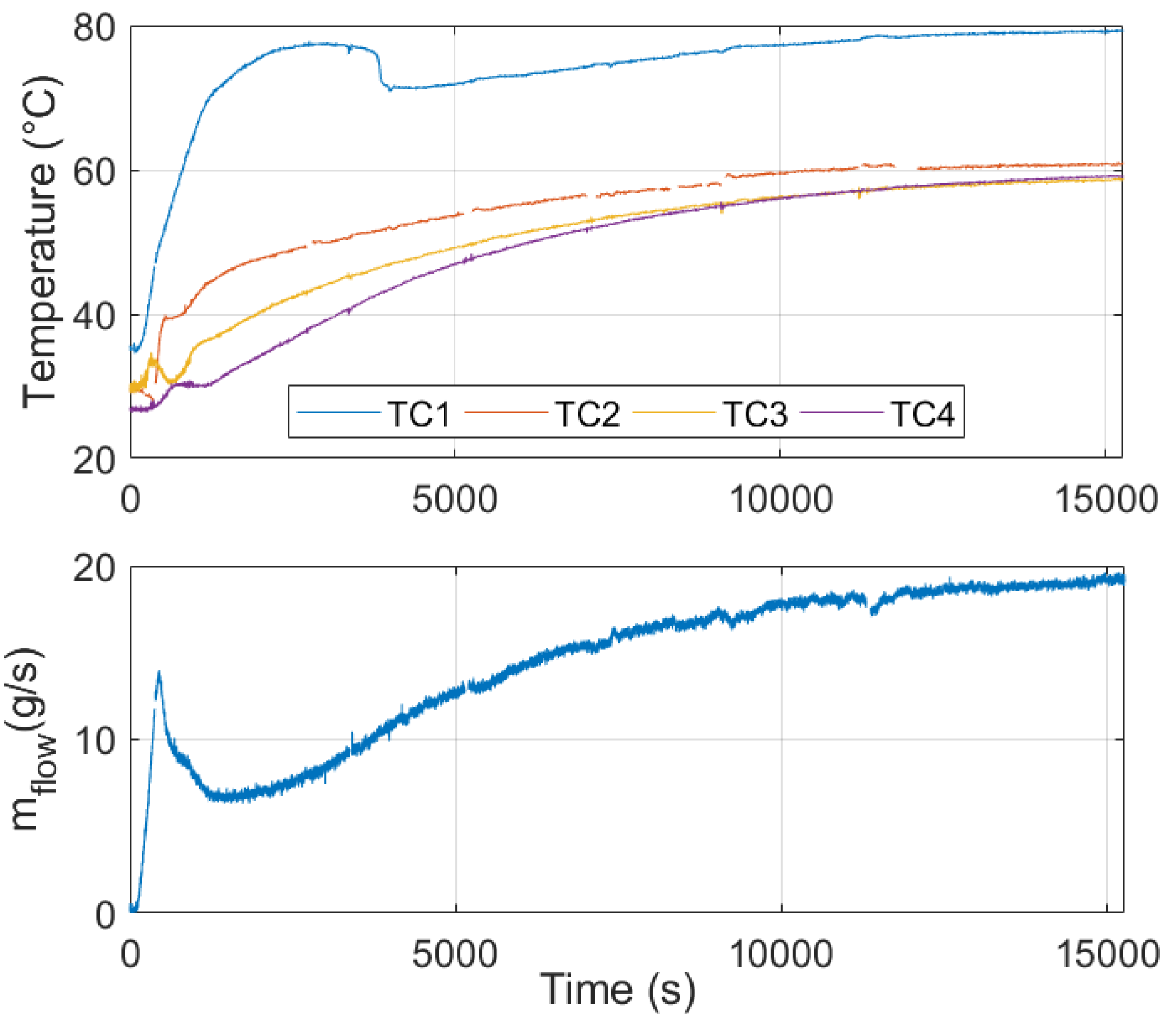




DYNASTY preliminary experiments



Test experiment using water, 1kW to vertical leg, cooler working at full speed



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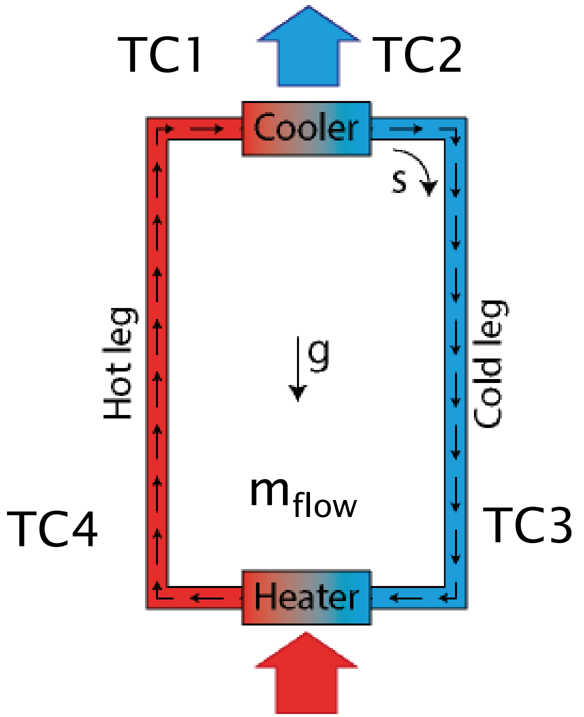
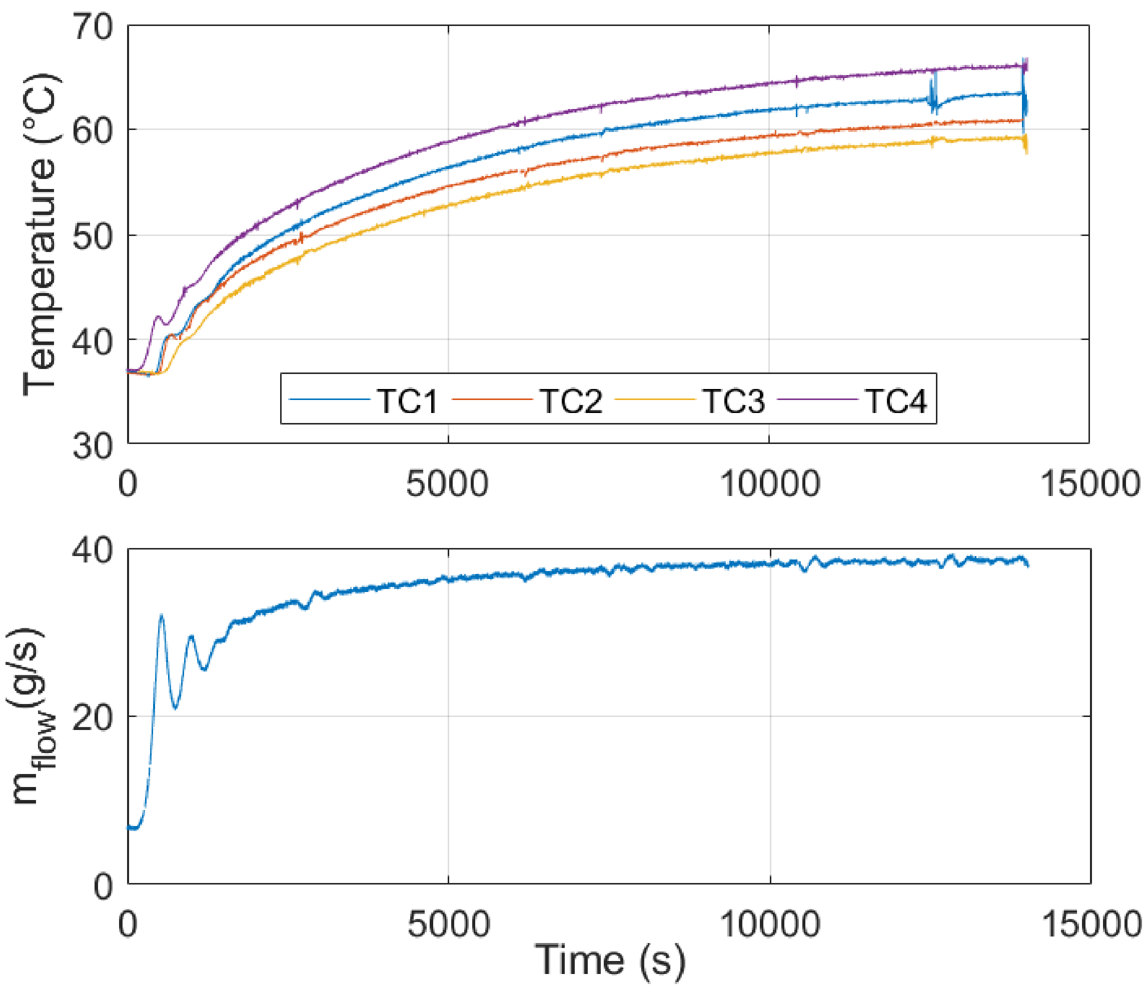
DYNASTY preliminary experiments





Test experiment using water, 1kW to horizontal leg, cooler working at full speed

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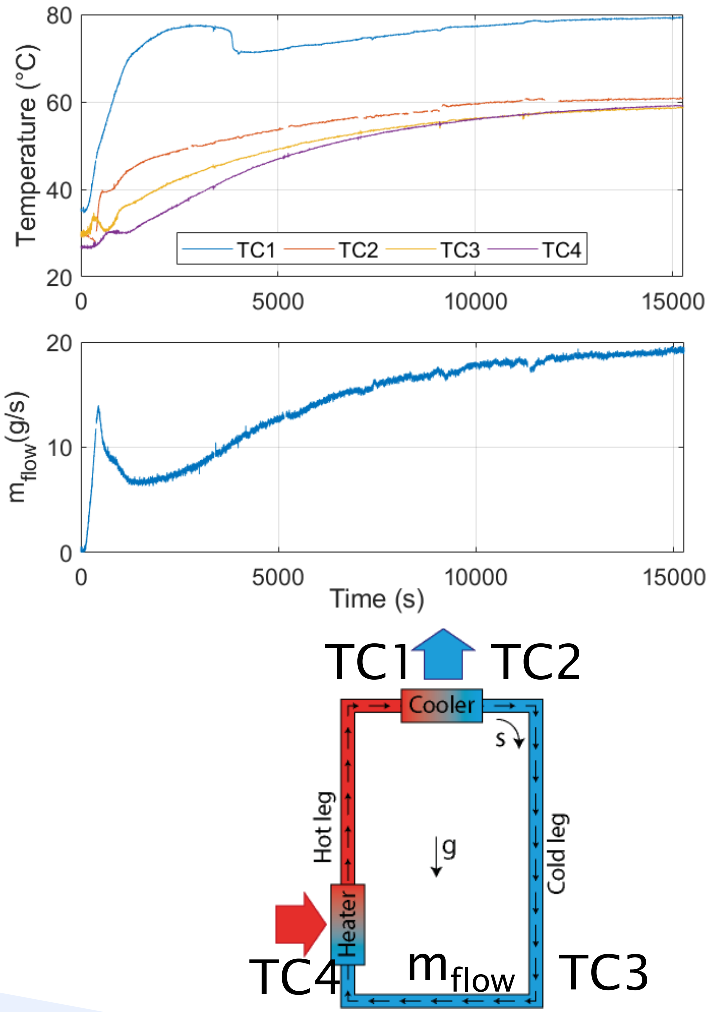
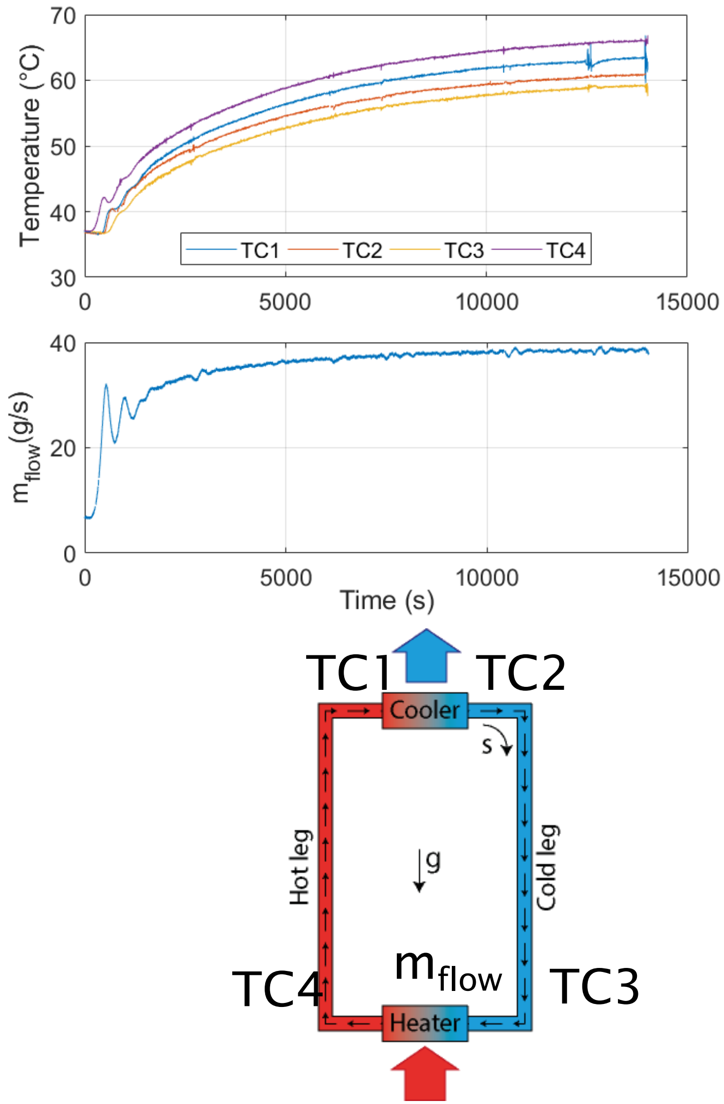
DYNASTY preliminary experiments

In both cases 1kW of power is provided and the fan is running at full speed





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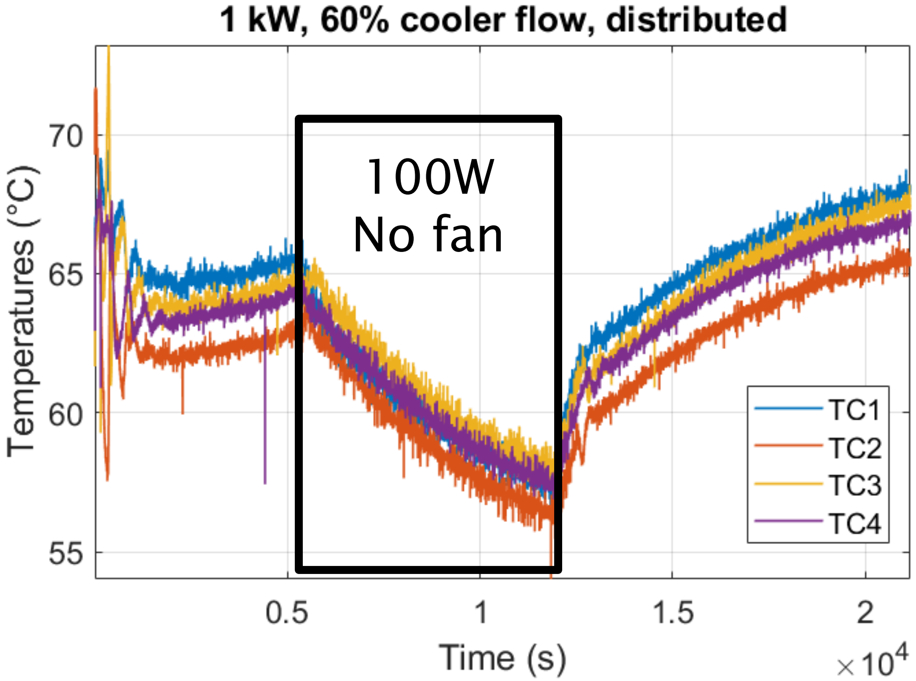
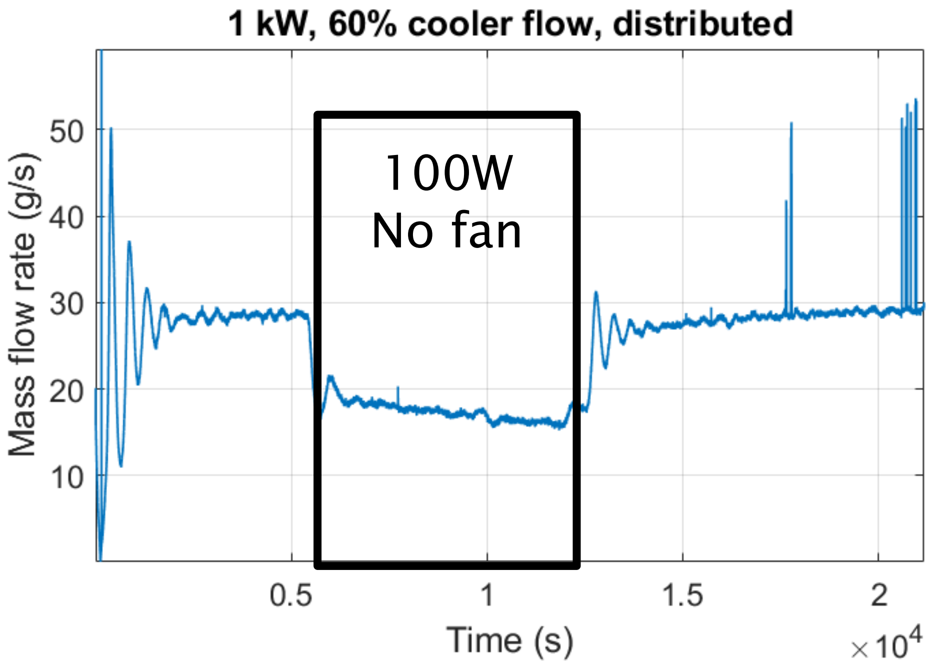
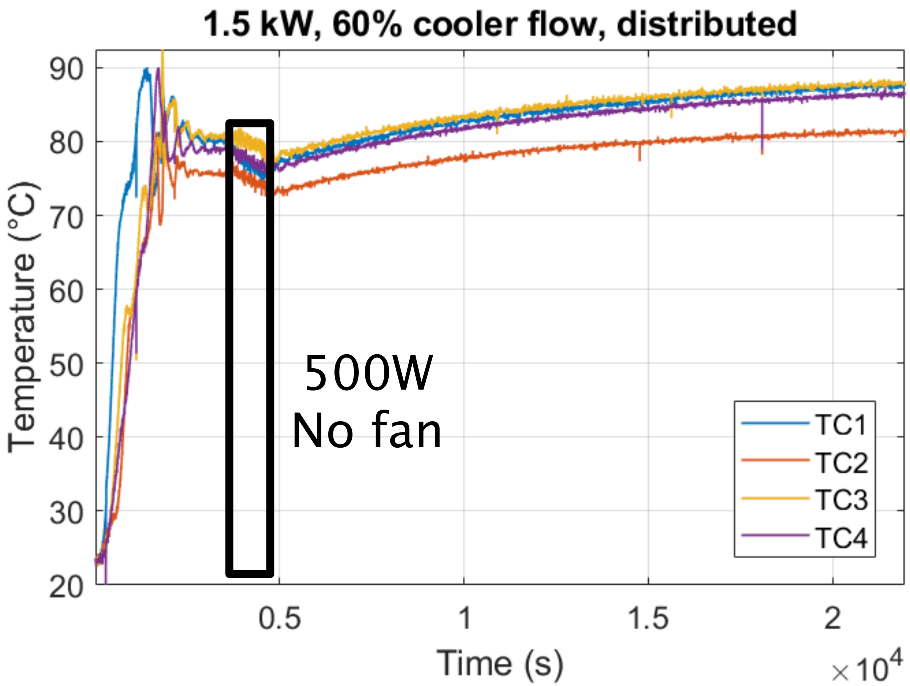
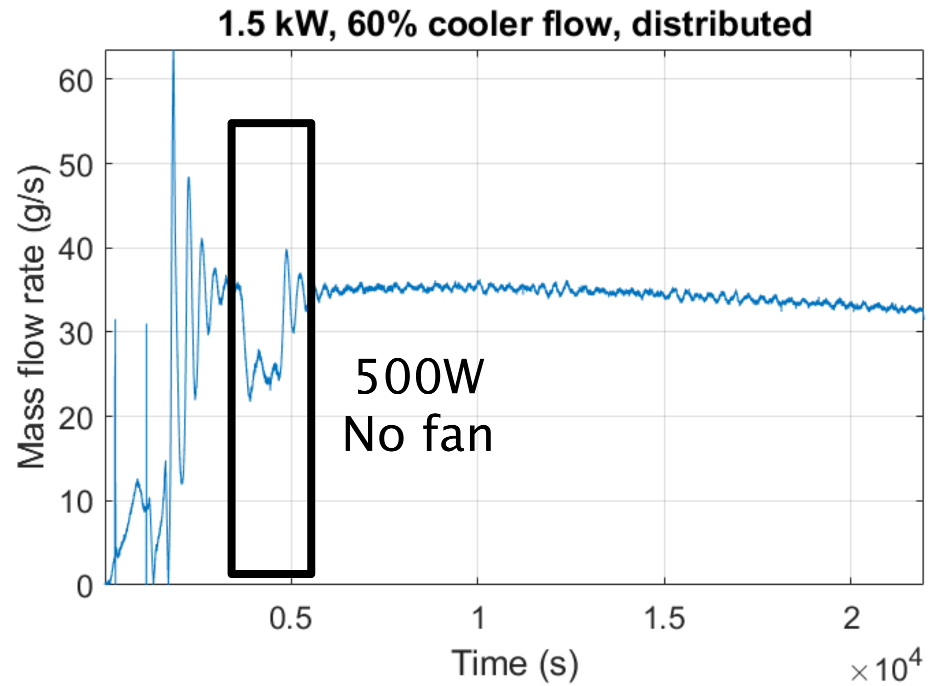
DYNASTY preliminary experiments





DYNASTY preliminary experiments





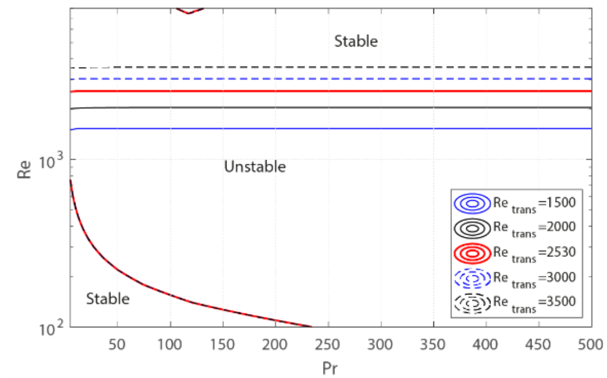
Conclusions

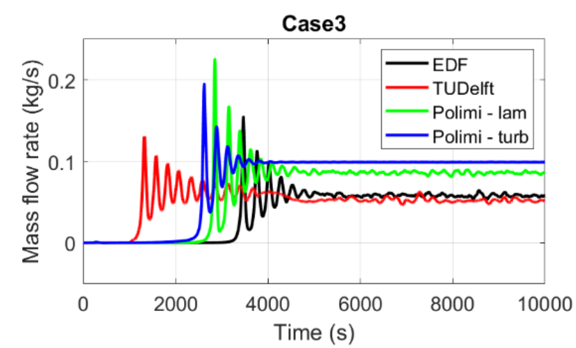
- The models to study natural circulation in presence of distributed heating have been developed, assessed in conventional natural circulation conditions and extended.

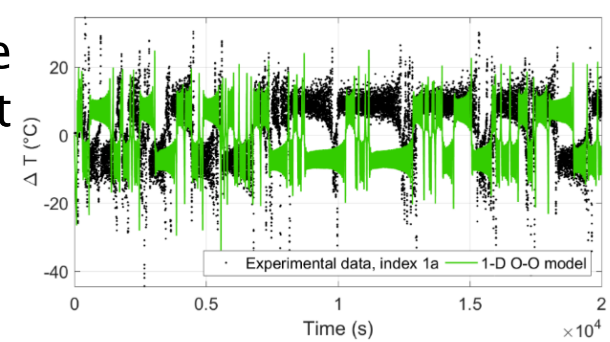
- The models were successfully employed to design the DYNASTY facility, showing that it should be able to operate in a variety of different working conditions.

- The models also showed to be able of good predictions of natural circulation equilibrium stability for conventional natural circulation systems.

- The qualitative sensitivity analysis showed the great influence of the laminar to turbulent transition on equilibrium stability.







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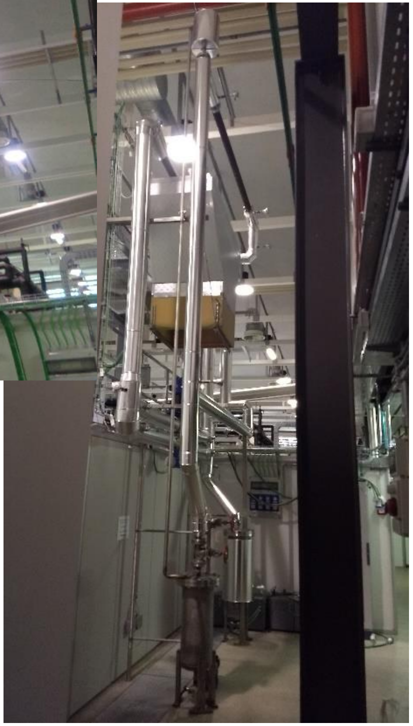
Conclusions

• The DYNASTY facility, which is a natural circulation loop, has been brought to full operativity, facing all the challenging issues that arose during building and testing, which required an update of the design on the go.

• The facility has been successfully operated with water, providing first sets of data.

• Also, the secondary eDYNASTY loop has been designed and constructed.



Thank you for your kind attention

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