DYNASTY: AN EXPERIMENTAL LOOP FOR THE STUDY OF NATURAL CIRCULATION WITH INTERNALLY HEATED FLUIDS

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ABSTRACT

This paper deals with the design and the features of the DYNASTY (DYnamics of NAtural circulation for molten SalT internallY heated) facility. DYNASTY is a natural circulation loop aimed at studying the dynamics of natural circulation with internally heated fluids. Although several works have been carried out on the analysis of free convection loops with localized hot and cold heat sinks ("conventional" natural circulation case), the instance of an internal and distributed power source inside the system has been little investigated. The effect of the internal heat generation on the dynamic behavior of natural circulation have been highlighted by semi-analytical and numerical models developed in our previous studies. Such analyses have been partially validated against conventional natural circulation experiments, and DYNASTY will provide the required data to complete their validation.

INTRODUCTION

In engineering applications where it is important to ensure heat removal in both operative and accidental conditions, the possibility of relying on natural circulation is generally sought to face the loss of active components. Natural circulation systems are usually vertical rectangular or toroidal loops provided with localized hot and cold sinks. However, in specific applications, the working fluid can be characterized by a volumetric heat source, like exothermic reagents or nuclear liquid fuels. In this regard, the main example is given by the Generation IV Molten Salt Reactor (MSR), in which the nuclear fuel is directly dissolved in a molten salt that also serves as coolant [1,2,3]. The presence of the Internal Heat Generation (IHG) alters the equilibrium stability of natural circulation systems with respect to the conventional case (i.e., without IHG), and can lead to the transition from a stable equilibrium state to an unstable one [4,5,6]. According to Ref. [7], natural circulation dynamics can be classified as either stable or unstable depending on its time development. If the fluid motion is stable, the velocity and the temperature distributions reach a steady-state value. In case of unstable conditions, the fluid flow is characterised by large oscillations of both the velocity and the temperature. This oscillating behaviour can be unidirectional (i.e., the main flow direction does not change) or can induce flow reversals.

NOMENCLATURE

c	[J/(kg K)]	Heat capacity
D	[m]	Diameter
$\hat{e}_s$	[-]	Unit vector following the fluid flow
$\hat{e}_z$	[-]	Unit vector pointing towards the positive vertical direction
g	[m/s^2]	Gravity acceleration
G	[kg/(m^{2}s)]	Mass flux
Gr_m	[-]	Modified Grashof number
h	[W/(m^2 K)]	Heat transfer coefficient
k	[W/(m K)]	Thermal conductivity
L	[m]	Pipe length
Nu	[-]	Nusselt number
p	[Pa]	Pressure
Pr	[-]	Prandtl number
q''	[W/m^2]	Localized external Heat Flux (LHF)
$q_{\#}''$	[W/m^2]	All-External Heat Flux (A-EHF)
q'''	[W/m^3]	Internal Heat Generation (IHG)
R	[m^{2}K/W]	Conductive thermal resistance of the pipe
Re	[-]	Reynolds number
s	[m]	Curvilinear axial coordinate
St_m	[-]	Modified Stanton number
t	[s]	Time
T	[K]	Temperature
u	[m/s]	Velocity

Special characters

δ	[-]	Perturbation
$\tilde{s}$	[m]	Length of an infinitesimal shell of the pipe
$\tilde{S}$	[m^2]	Lateral surface of an infinitesimal shell of the pipe
$\tilde{V}$	[m^3]	Volume of an infinitesimal shell of the pipe
β	[1/K]	Thermal expansion coefficient
ΔT_m	[K]	Weighted temperature difference inside natural circulation loops
Θ	[-]	Dummy variable
$\hat{\Theta}$	[-]	Space-dependent part of the dummy variable
λ	[-]	Darcy friction factor coefficient
μ	[Pa s]	Dynamic viscosity
ρ	[kg/m^3]	Density
τ	[m]	Pipe thickness
ω	[s^{-1}]	Perturbation pulsation

Subscripts-superscripts

c	Cooler
f	Fluid
i	Inner shell of the pipe
o	Outer shell of the pipe
T	Total length of the loop
w	Wall of the pipe
0	Steady-state value
*	Reference value

Acronyms

A-EHF	All-External Heat Flux
DYNASTY	DYnamics of NAtural circulation for molten SalT internallY heated
IHG	Internal Heat Generation
LHF	Localized external heat flux
MSR	Molten Salt Reactor
1-D	One Dimensional

As for the dynamic behaviour of natural circulation with and without IHG, semi-analytical and numerical models have been developed in previous works [4,5,6]. In order to validate them, a natural circulation loop, called DYNASTY (DYnamics of NAtural circulation for molten SalT internallY heated), is under construction at Energy Labs of Politecnico di Milano. In particular, the facility has been designed on the basis of the aforementioned analysis tools, which have been already validated in conventional natural circulation conditions [8]. As far as the paper structure is concerned, a general description of the DYNASTY facility is given in the first section. The subsequent section deals with a semi-analytical stability analysis. Then, a numerical approach is presented to simulate operative transients, and the facility design procedure is briefly outlined. In the last section, the main conclusions are drawn.

DYNASTY FACILITY

DYNASTY is designed to study, from an experimental point of view, the dynamics of natural circulation with internally heated fluids. Since the induction of a distributed internal heat generation entails not trivial technical issues (such as electrochemical phenomena and eddy currents) [6], in the facility the internal power source is substituted with an All-External Heat Flux (A-EHF) homogeneously distributed along the entire loop, except for the cooler section. For natural circulation loops characterised by a length-to-diameter ratio (L/D) very high, the A-EHF can be a good approximation of the IHG [6]. As for the detailed description of the facility, it is a vertical rectangular hydraulic loop (Figure 1), whose structural components and piping are made of stainless steel (AISI-304/AISI-316). In the top part of the system, the heat sink (cooler) is a finned pipe, which can operate either in passive mode or coupled with an axial fan able to provide a volumetric flow rate up to 5000 m^3/h. The bottom part of the loop is branched, with each branch devised for specific experiment types. In the top one (see Figure 1), a centrifugal pump (completely made of AISI-316 and featuring an in-line design) is present in order to initialize the mass flow at system start-up, and to conduct experiments in forced flow conditions.

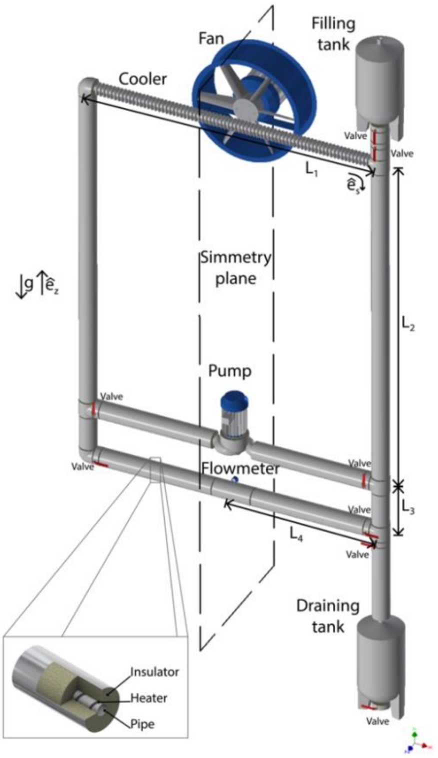


Figure 1 DYNASTY scheme (not in scale).

Table 1 DYNASTY dimensions.

Pipe outer *D* [mm]	Pipe wall τ [mm]	L_1 [m]	L_2 [m]	L_3 [m]	L_4 [m]
42.2	2.00	2.40	2.85	0.35	1.20

The bottom branch presents a flow-meter to be used in natural circulation experiments. The all-external heating system is implemented by fiberglass electrical resistances and can supply to the system a power from 0.5 to 10 kW. The power lines are divided into four groups, each with its own regulating system to allow several heating set-ups. In particular, the power distribution can be changed in order to obtain a localized heating in different power sections (as in conventional natural circulation experiments) or provide power to the whole loop (for distributed heating ones). It is also possible to combine localized and distributed heating modes. Several thermocouples are installed to measure the temperature in the loop, which is insulated with mineral wool material. Table 1 shows the dimensions of the loop referred to the scheme in Figure 1. The loop contains a molten salt as circulating fluid. In this regard, it should be mentioned that the study of the natural circulation of molten salts is an actual research field not only for the MSR, but also for other reactor concepts [9]. The DYNASTY salt is a mixture commercially known as Hitec® [10] composed of $NaNO_3$ (7wt%), $NaNO_2$ (40wt%), and KNO_3 (53wt%). A tank placed at the top of the loop, which serves also as expansion tank, is used to fill the loop. A second tank at the bottom is used as salt storage during the draining procedure. Figure 2 shows the values of physical properties [10] of the Hitec® molten salt as a function of temperature.

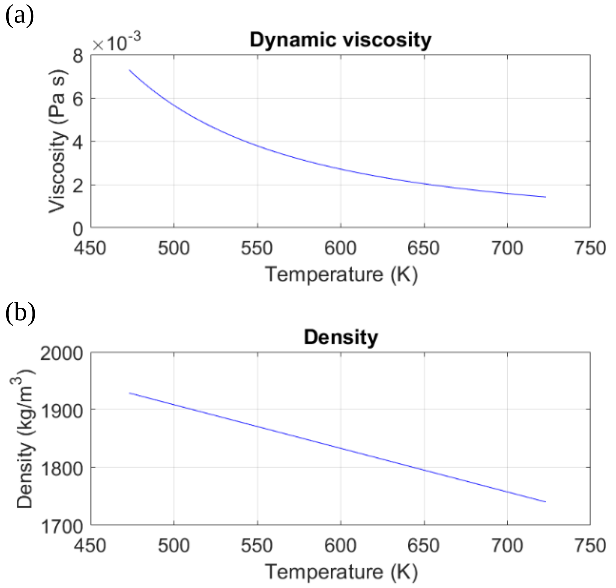


Figure 2 Hitec® dynamic viscosity (a) and density (b) as a function of temperature.

Thermal conductivity has been considered constant (0.48 W/mK). As far as the DYNASTY operative range is concerned, the maximum mass flow rate achievable in natural circulation mode is 0.35 kg/s (Re=4500), while in forced convection is 4 kg/s (Re=10000). The minimum and maximum operative temperatures are 523 K and 623 K, respectively.

STABILITY MAPS

In order to study the asymptotic dynamics of a natural circulation loop, the system governing equations (mass, momentum and energy balances) are linearized around a steady-state solution. Then, the investigation of the equilibrium stability is carried out by adopting the tools provided by linear analysis. The obtained results are collected in the so-called stability maps. To define a generic equilibrium state of the system, two dimensionless numbers can be used, such as St_m-Re, Pr-Re and St_m-Gr_m [4,5,6,11]. In the present work, the St_m and Gr_m numbers have been adopted. They are defined as [4,11]:

$$St_m = 4\frac{L_t}{D_f}\frac{Nu}{RePr}, \quad Gr_m = \frac{\rho_f^2 g D_f^3}{\mu_f^2}\beta_f \Delta T_m, \tag{1}$$

where ΔT_m is a weighted temperature difference inside the loop (for details, refer to [4,11]).

The procedure followed to compute the stability map is hereinafter briefly outlined. More details about this method can be found in [11] for conventional natural circulation problems, and in [4,5,6] when IHG is present. The first step is the definition of the system governing equations. Considering the peculiar case of a natural circulation loop characterised by two heat sources, the Localized external Heat Flux (LHF) and the distributed IHG, the following assumptions are applied:

- The flow is considered incompressible and one-dimensional in the axial direction of the pipes along the *s* coordinate.
- Boussinesq approximation is used.
- The external heat flux (q'') is localized in a section of the loop called heater. The IHG (q''') is homogeneous along the entire loop.
- The cooler is at fixed temperature (T_c).
- The same flow rate and regime are present in the whole loop.

With the above simplifications, governing equations are:

$$\frac{\partial G}{\partial s} = 0 \text{ where } G = \rho_f^* u, \tag{2}$$

$$\begin{gathered}\frac{\partial G}{\partial t} + \frac{\partial}{\partial s}\frac{G^2}{\rho_f^*} = -\frac{\partial p}{\partial s} - \frac{1}{2}\lambda\frac{G^2}{\rho_f^*}\frac{1}{D_f} - g\rho_f \hat{e}_z \cdot \hat{e}_s(s) \\ \text{with} \quad \rho_f = \rho_f^*\left[1 - \beta_f\left(T_f - T_f^*\right)\right],\end{gathered} \tag{3}$$

$$\rho_f^* c_f \frac{\partial T_f}{\partial t} + G c_f \frac{\partial T_f}{\partial s} = -h\left(T_f - T_{w,i}\right)\frac{\tilde{S}_f}{\tilde{V}_f} + q''', \tag{4}$$

$$\rho_w c_w \frac{\partial T_{w,i}}{\partial t} = h\left(T_f - T_{w,i}\right)\frac{\tilde{S}_f}{\tilde{V}_{w,i}} - \frac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,i}\tilde{R}_w}, \tag{5}$$

$$\begin{cases} T_{w,o} = T_c \quad cooler \\ \rho_w c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \dfrac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q'' \quad heater \\ \rho_w c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} \quad otherwise \end{cases} \tag{6}$$

where $\tilde{V}_f, \tilde{V}_{w,i}, \tilde{V}_{w,o}$ and $\tilde{R}_w$ are defined as:

$$\begin{gathered} \tilde{V}_f = \pi\left(\frac{D_f}{2}\right)^2 \tilde{s} \qquad \tilde{S}_f = \pi D_f \tilde{s} \\ \tilde{V}_{w,i} = \pi\left[\left(\frac{D_{w,i}}{2}\right)^2 - \left(\frac{D_f}{2}\right)^2\right]\tilde{s} \quad \tilde{S}_{w,i} = \pi D_{w,i}\tilde{s} \\ \tilde{V}_{w,o} = \pi\left[\left(\frac{D_{w,o}}{2}\right)^2 - \left(\frac{D_{w,i}}{2}\right)^2\right]\tilde{s} \quad \tilde{S}_{w,o} = \pi D_{w,o}\tilde{s} \\ \tilde{R}_w = \frac{\ln\left(\frac{D_{w,o}}{D_f}\right)}{2\pi k_w \tilde{s}}. \end{gathered} \tag{7}$$

The superscript * specifies the reference thermo-physical quantities for the fluid taken at the cooler entrance (ρ_f^* is the fluid reference density, while ρ_f is the fluid density along the loop). Equations (2-4) are the mass, momentum and energy balances for the fluid, respectively. Equations (5-6) represent the energy balance for the wall. Following Ref. [6], the pipe walls have been discretized along the radial coordinate into two coaxial shells (Figure 3a) by adopting a lumped parameter approach (Figure 3b). In this regard, a thermal capacitance (c_w) is assigned to each shell and a conductive thermal resistance (R_w) is placed between them. Axial conduction and thermal dissipations are neglected. On the basis of equations (2-6), the stability maps of a generic natural circulation loop with both the LHF and IHG can be derived. However, as mentioned above, DYNASTY is provided with an all-external heating system ($q_{\#}''$) to mimic the effect of the IHG. For this reason, in order to compute the stability maps specific for the DYNASTY loop, equations (4, 6) must be modified as follows:

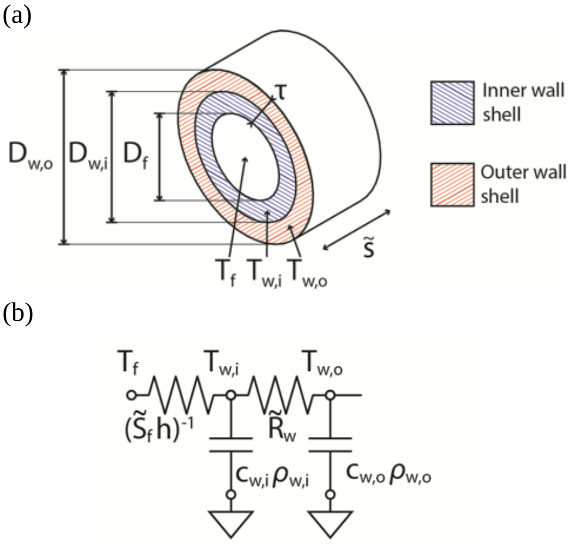


Figure 3 Discretization of the pipe walls (a) and electrical equivalent model (b).

$$\rho_f c_f \frac{\partial T_f}{\partial t} + G c_f \frac{\partial T_f}{\partial s} = -h\left(T_f - T_{w_i}\right)\frac{\tilde{S}_f}{\tilde{V}_f}, \qquad (8)$$

$$\begin{cases} T_{w,o} = T_c \;\; cooler \\ \rho_w c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \dfrac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q'' \;\; heater \\ \rho_w c_w \dfrac{\partial T_{w,o}}{\partial t} = \dfrac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \dfrac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q''_{\#} \;\; otherwise \end{cases} \qquad (9)$$

Equation (8) replaces the energy balance of equation (4), while equation (9) is the energy conservation equation for the outer pipe shell in case of all-external heating (the heat is not provided in the cooler section). Once the governing equations are defined, they are linearized around a generic steady-state solution. In particular, for the state variables $(G, T_f, T_{w,i}, T_{w,o})$ the following form is assumed:

$$\Theta(s,t) = \Theta_0(s) + \delta\Theta(s,t) = \Theta_0(s) + \hat{\Theta}(s)e^{\omega t}, \quad \omega \in \mathbb{C}. \qquad (10)$$

In equation (10), Θ represents a generic state variable for the system. In this way, the time derivatives are elided. Moreover, a simple linear stability condition for the system is provided, namely the real part of ω must be negative: $\Re(\omega) < 0$. Given a fixed value of Gr_m, a loop geometry and heating distribution, the governing equations can be solved with the constraint $\Re(\omega) = 0$. Hence, the limit value of St_m for which the equilibrium of the system is stable is found. The collection of the St_m-Gr_m points for which the real part of the perturbation pulsation is zero defines, on the stability map, the transition curve between asymptotically stable and unstable equilibria. Figure 4 shows the stability maps for DYNASTY in the St_m- Gr_m plane. It is possible to notice the influence of the different kinds of heating sources (IHG, LHF and A-EHF) on the equilibrium stability. In this analysis, the LHF case corresponds to a localized heater on the left vertical leg of the loop. From the achieved results, it can be noticed that the heating distribution deeply affects the shape of stability maps. As shown, the unstable zones increase when the power is provided by either the IHG or the A-EHF. As a matter of fact, for the LHF case the fluid flow has a preferable direction since the system is asymmetric with respect to the vertical axis (see Figure 1). When the power is provided either by the IHG or by the A-EHF, the loop presents a perfect axial symmetry (see Figure 1) and the fluid has not any preferable flowing direction. The lack of any preferable flow direction induces an increase of the instability, especially at low Re [4,5,6]. The achieved results confirm that the A-EHF and IHG induce comparable effects for natural circulation loops characterised by a L/D very high, from a stability point of view. Some differences arise in the high Reynolds number region and can be mainly connected to the fact that in the cooler section the heat flux is not applied with the A-EHF [6].

NUMERICAL SIMULATIONS

The described semi-analytical approach is characterised by some drawbacks. In particular, its derivation involves a linearization process, which is valid only when the perturbations applied to the system are small compared to the steady-state values. In order to take into account the effect of the non-linearity of the governing equations, a numerical approach has been adopted.

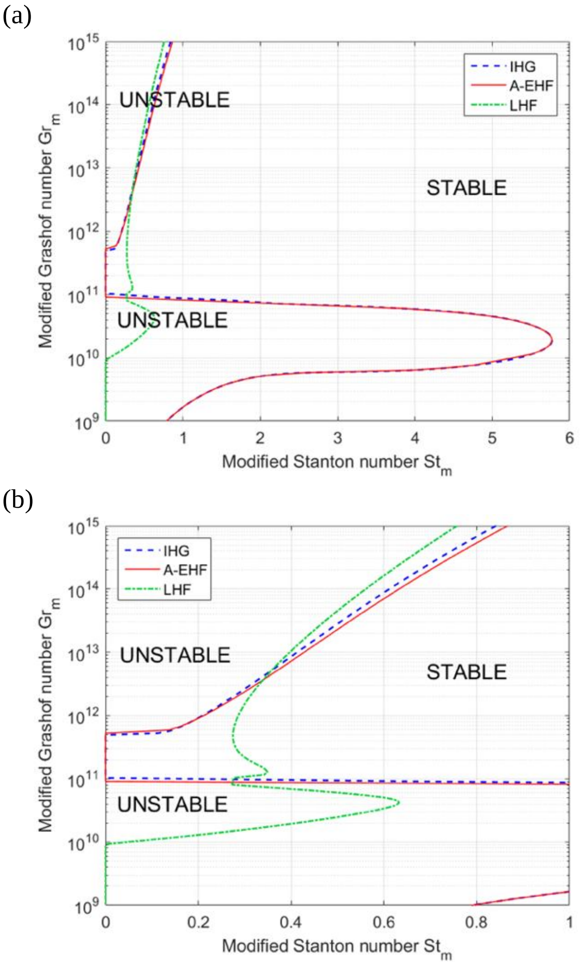
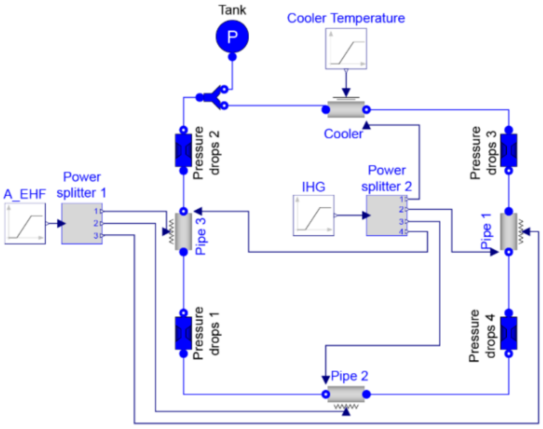


Figure 4 Complete DYNASTY stability map for the IHG, LHF and A-EHF cases in the Gr_m-St_m plane (a); zoomed for St_m values below 1(b).



Component	*Description*
Cooler	Heat sink with constant T
Pipe	Pipe with either A-EHF or IHG
Pressure drops	Localized pressure drops
Tank	Open expansion tank
Power splitter	Block for the IHG/A-EHF distribution

Figure 5 DYNASTY object-oriented model.

The aim of this method is the computation of the time evolution of the system. In this regard, a 1-D object-oriented model (Figure 5) based on the Modelica language [12] has been developed. The object-oriented model has been implemented in the Dymola [13] simulation environment using an extended version, hereinafter called ThermoPowerIHG, of the ThermoPower library [14]. In Refs. [5,6], the ThermoPowerIHG has been developed and assessed by comparing the object-oriented approach results with system codes and CFD simulations for both the IHG and LHF cases. Moreover, it has been validated against conventional natural circulation experimental data in Ref. [8]. On the basis of the DYNASTY object-oriented model, operative transients have been computed for different power levels provided to the facility (0.5 kW, 0.75 kW, 1 kW, 1.5 kW, 2 kW, 2.5 kW, 3 kW, 4 kW, 5 kW, 7 kW and 10 kW). Figures 6-8 show, for brevity, the time-dependent mass flow rate behaviour at 0.5 kW, 1 kW (Figure 6), 2 kW, 3 kW (Figure 7), 5 kW and 10 kW (Figure 8) for both the A-EHF and the IHG situations. As far as the fluid flow is concerned, the molten salt motion inside the loop is characterised by mass flow reversal up to 1 kW, unidirectional mass flow rate oscillations appears from 2 kW to 3 kW, while the fluid flow is stable at higher powers. According to the 1-D model, the time-dependent simulations show that the A-EHF adopted in the facility induces an effect similar to that of the IHG. The stability map prediction and the object-oriented simulations are compared in Figure 9. The blue squares represent the system equilibria starting from which unstable transients arise, while the green dots indicate the initial steady-states of stable transients. As it is possible to notice, the blue squares are confined in the unstable region computed by the linear analysis. It is worth noting that the two methods are complementary.

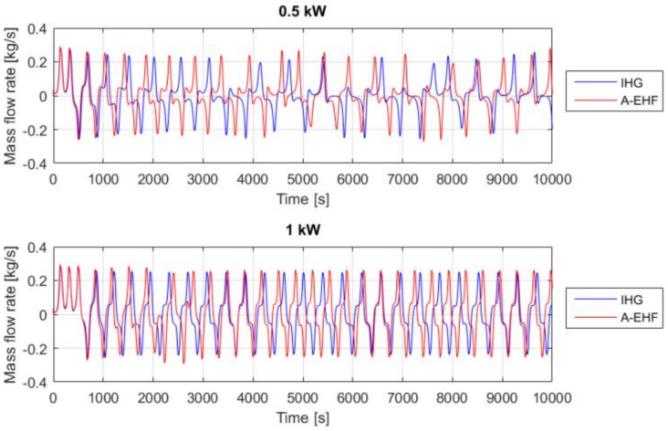


Figure 6 Mass flow reversal at 0.5 kW and 1 kW.

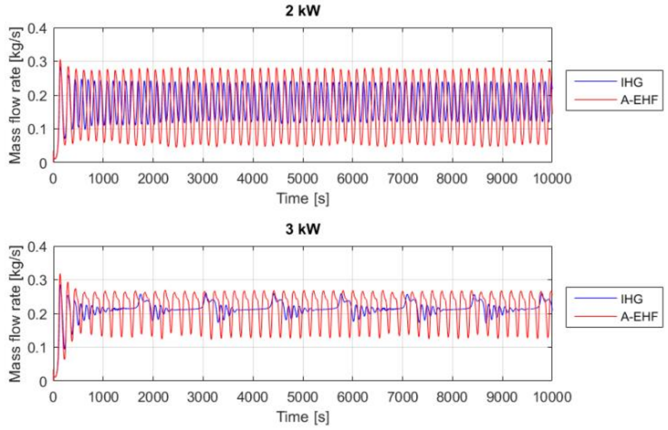


Figure 7 Unidirectional mass flow oscillations at 2 kW and 3 kW.

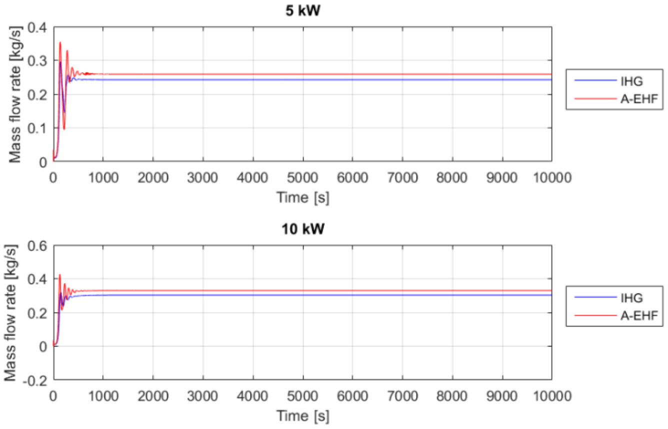


Figure 8 Stable mass flow rate at 5 kW and 10 kW.

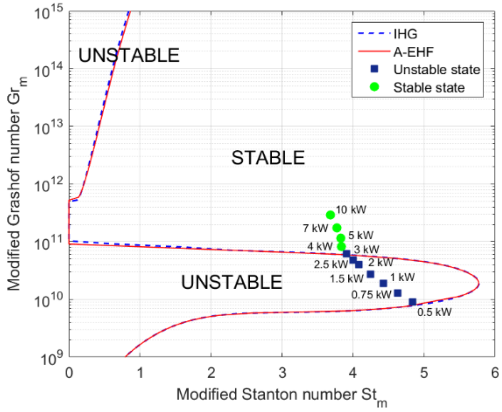


Figure 9 Comparison of stability map and object-oriented simulations.

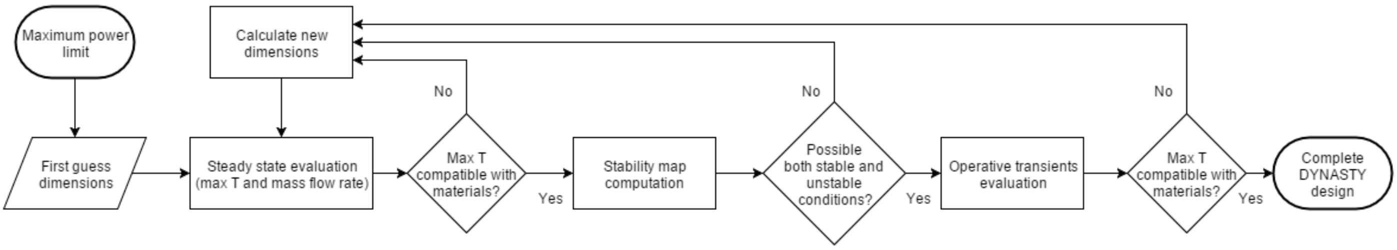


Figure 10 DYNASTY design procedure.

The stability maps give information on the asymptotic stability of the system and time-dependent simulations allow predicting the oscillations modes in case of an unstable equilibrium.

DYNASTY DESIGN PROCEDURE

It should be underlined that, thanks to the flexibility of the object-oriented approach, it is also possible to easily change several parameters among different simulations. In this way, the DYNASTY design (described above) was verified. Once the maximum operating temperature and power supply were fixed, the facility was designed adopting the following process (Figure 10):

- Definition of the facility guess configuration.
- Computation of the steady-state mass flow rate and temperature field at different power levels and distributions, by solving the governing equations with the time derivative terms equal to zero.
- Compatibility check of the obtained steady-state values with the prescribed limits.
- Computation of the stability map to study the dynamic behaviour of the steady-states.
- Evaluation of the facility capabilities to operate both in stable and unstable conditions.
- Verification and improvement of the design on the basis of the transient simulations results obtained with the object-oriented model.

Following this procedure, the design of the facility was defined, improved and checked. For example, the final length of the cooler was chosen on the basis of the outcomes of the object-oriented model simulations.

CONCLUSIONS

In this work, the DYNASTY loop aimed at studying the dynamics of natural circulation with internally heated fluids has been presented. Semi-analytical and numerical tools have been adopted to design the facility, which can be operated in both stable and unstable fluid motion conditions. Since from an experimental viewpoint the induction of a distributed IHG entails several issues, the distributed heat is provided by an all-external heat flux. The achieved results, both in terms of stability maps and time-dependent simulations, confirm that from a stability point of view the two situations are comparable for natural circulation loops characterised by a length-to-diameter ratio very high. As for the study of the dynamic behaviour of the DYNASTY loop, stability maps and transient simulation results are in agreement. The comparison between results from developed tools and experimental data deliverable from DYNASTY will be included in future works.

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