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ScienceDirect

Energy Procedia 101 (2016) 10 – 17

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

An Experimental Facility to Investigate the Natural Circulation Dynamics in Presence of Distributed Heat Sources

A. Pini[a], A. Cammi[a], M. Cauzzi[a], F. Fanale[a], L. Luzzi[a,]*

[a]*Politecnico di Milano, Department of Energy, CeSNEF (Enrico Fermi Center for Nuclear Studies), via La Masa 34, 20156 Milano, Italy*

Abstract

This paper deals with the dynamic behaviour of the DYNASTY facility.DYNASTY is a natural circulation loop aimed at studying the natural circulation dynamics in presence of volumetric distributed heat sources,and is provided with an All-External Heat Flux (A-EHF) to reproduce the effect of the Internal Heat Generation (IHG). To comparethe A-EHF and the IHG cases, semi-analytical and numerical approaches are considered. As for the semi-analyticalinvestigation, a linear analysis is performed to study the asymptotic equilibrium stability.Regarding the numerical viewpoint, an Object-Oriented 1D model and a 3D Computational-Fluid-Dynamicsmodel are adopted to study the time-dependent behaviour.

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*Keywords:*Natural circulation; Internal heat generation; Stability analysis; Thermal-hydraulics; Object-oriented modelling;CFD.

1. Introduction

Natural circulation systems are generally vertical rectangular or toroidal loops, where the working fluid transfers heat between a hot source and a cold sink thanks to the action of the buoyancy force. However, in specific applications, a distributed volumetric heat source can be present in the working fluid (e.g., exothermic reagents or nuclear liquid fuels). The main example is the Generation IV Molten Salt Reactor (MSR), in which the nuclear fuel is dissolved in a molten salt that also serves as thermal carrier [1,2].

The Internal Heat Generation (IHG) modifies the stability of natural circulation with respect to the "conventional"

* Corresponding author. Tel.:+39 02 2399 6326.
E-mail address: lelio.luzzi@polimi.it

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doi:10.1016/j.egypro.2016.11.002

Nomenclature

Latin symbols

c	Heat capacity $(J\ kg^{-1}K^{-1})$
D	Diameter (mm)
$\hat{e}_s$	Unit vector following the fluid flow$(-)$
$\hat{e}_z$	Unit vectorpointing towards the positive vertical direction $(-)$
g	Gravitational acceleration $(m\ s^{-2})$
G	Mass flux$(kg\ m^{-2}s^{-1})$
Gr_m	Modified Grashof number$(-)$
h	Heat transfer coefficient$(W\ m^{-2}K^{-1})$
H	Height (m)
k	Thermal conductivity$(W\ m^{-1}K^{-1})$
L	Length (m)
Nu	Nusselt number$(-)$
p	Pressure(Pa)
Pr	Prandtl number$(-)$
q''	Localized external heat flux $(W\ m^{-2})$
$q''_{\#}$	Distributed external heat flux $(W\ m^{-2})$
q'''	Internal heat generation $(W\ m^{-3})$
$\tilde{R}_w$	Conductive thermal-resistance of the wall $(K\ W^{-1})$
Re	Reynolds number$(-)$
s	Curvilinear axial coordinate(m)
$\tilde{s}$	Length of an infinitesimal shell of the pipe (m)
$\tilde{S}$	Lateral surface of an infinitesimal shell of the pipe (m^2)
St_m	Modified Stanton number$(-)$
t	Time (s)
T	Temperature (K)
u	Velocity $(m\ s^{-1})$
$\tilde{V}$	Volume of an infinitesimal shell of the pipe (m^3)
W	Width (m)

Greek symbols

β	Thermal expansion coefficient (K^{-1})
δ	Perturbation$(-)$
$\Theta, \hat{\Theta}$	Dummy variable, Space-dependent part of the dummy variable$(-)$
λ	Darcy friction factor coefficient$(-)$
μ	Dynamic viscosity $(Pa\ s)$
ρ	Density $(kg\ m^{-3})$
ω	Perturbation pulsation (s^{-1})

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

case (i.e., without IHG), and can lead to the transition from a stable equilibrium state to an unstable one. As a matter of fact, an equilibrium state can be either dynamically stable or unstable. In the unstable case, the fluid flow is characterised by oscillations of both the velocity and the temperature fields, while in the stable circumstance the velocity and the temperature distributions reach a steady-state value.

To study the dynamic behaviour of natural circulation with internally heated fluids from an experimental point of view, the DYNASTY (DYnamics of NAtural circulation for molten SalTinternallY heated) facility has been built at the Energy Labs of Politecnico di Milano. Since the system adopts an All-External Heat Flux (A-EHF) to reproduce the effect of the IHG, the present work exploits different approaches to compare the two heating modes in order to highlight similarities and differences. Firstly, a semi-analytical model is introduced in order to predict the asymptotic stability of system equilibria by means of the so-called stability maps. Then, two different numerical strategies are adopted to simulate operative transients, namely an Object-Oriented (O-O) 1D model and a 3D Computational FluidDynamics (CFD)model.Both the semi-analytical and the numerical methods have been validated against experiments concerning the conventional natural circulation in Ref. [3].

As far as the state of the art on Natural Circulation Loop (NCL) modelling is concerned, details about the stability maps can be found in Ref. [4] for conventional NCLs, while the first applications of such analysis to IHG systems are proposed in [5,6]. A detailed description of the O-O model is givenin Ref. [6]. Regarding the CFD approach, several works are present in literature for the conventional case (e.g., Refs. [7,8]), while for NCLs with internally heated fluid reference is made to [6].

As for the paper structure, a general description of the DYNASTY facility is given in Section 2. Section 3 deals with the semi-analytical stability analysis. In Section 4, the numerical approaches are described.Section 5 addresses the comparison between the results of the different approaches. In the last section, the main conclusions are drawn.

2. DYNASTY facility

The induction of a distributed IHG entails not trivial technical issues (such as electrochemical phenomena and eddy currents).Hence, in the DYNASTY facility the internal (volumetric) power source is substituted with an A-EHF homogeneously distributed along the entire loop, except for the heat sink section. As discussed in the present paper on the basis of CFD and O-O simulations, for NCLs characterised by a length-to-diameter ratio (L_t/D) very high, the A-EHF can be a good approximation of the IHG, at least from the stability point of view.

Here below, DYNASTY is briefly described (a more detailed description of the facility can be found in Ref. [9]). The facility is a vertical rectangular hydraulic loop (Fig. 1a) made of stainless steel(AISI-304/AISI-316) components. In the top part of the system, the heat sink is a finned pipe that can operateeither in passive mode or coupled with an axial fan. The bottom part of the loop is branched, with each branch devised for specific experiment types. In the top one, a centrifugal pump is present in order to initialize the mass flow at system start-up, and to conduct experiments also in forced flow conditions.The bottom branch presents a flow-meter to be used in natural circulation experiments. Fiberglass electrical resistances are employed to provide the all-external heating 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 have a Localized Heat Flux (LHF) in different power sections (as in conventional natural circulation experiments) or provide power to the whole loop (for distributed heating ones). Several thermocouples are present to measure the temperature in the loop, which is insulated with mineral wool material. 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 acurrent research field not only for the MSR, but also for other reactor concepts [10]. The DYNASTY salt is a mixture commercially known as Hitec®[11] 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 volume, is used to fill the system. A second tank at the bottom is used as salt storage during the draining procedure. As for the dimensions of the system, the height and the width of the loop are 3.2 m and 2.4 m, respectively. The inner diameter of the pipe is 38.2 mm (with a thickness of 2 mm). 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≈10^4). The minimum and maximum operative temperatures are 523 K and 623 K, respectively.

3. Stability maps

In this Section, a semi-analytical model is adopted in order to predict the asymptotic stability of the system equilibria.Referring to DYNASTY, threedifferent heat sources are considered, namely: the LHF (q'') in a portion of the loop (hereinafter called heater), theIHG in the entire fluid volume (q'''),and the A-EHF along the entire loop ($q_{\#}''$). The IHG and the A-EHF are mutually exclusive. In this regard, to highlight the differences between the two heating modes, the electrical equivalent representing an infinitesimal portion of the system is reported in Fig. 1c for the IHG case and in Fig. 1d for the A-EHF one.

To study the DYNASTY asymptotic stability, the governing equations (i.e., mass, momentum and energy balances) are linearized around a steady-state solution and simplified on the basis of the following hypotheses: the flow is incompressible and 1D in the axial direction of the pipes; the Boussinesq approximation is used; the heat sink (hereinafter called cooler) is at fixed temperature (T_c); the same flow rate and regime are present in the whole loop.

With the above simplifications, the governing equations can be written as follows ($\tilde{V}_f, \tilde{V}_{w,i}, \tilde{V}_{w,o}, \tilde{S}_f, \tilde{S}_{w,i}, \tilde{S}_{w,o}$ being geometrical parameters, and $\tilde{R}_w$ the conductive thermal-resistance of the wall):

$$\frac{\partial G}{\partial s} = 0 \text{ where } G = \rho_f^* u, \tag{1}$$

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

$$\rho_f^* c_f\frac{\partial T_f}{\partial t} + Gc_f\frac{\partial T_f}{\partial s} = -h\left(T_f - T_{w,i}\right)\frac{\tilde{S}_f}{\tilde{V}_f}, \tag{3}$$

$$\rho_w c_w \frac{\partial T_{w,i}}{\partial t} = h(T_f - T_{w,i})\frac{\tilde{S}_f}{\tilde{V}_{w,i}} - \frac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,i}\tilde{R}_w} + q''', \tag{4}$$

$$\begin{cases} T_{w,o} = T_c \; cooler \\ \rho_w c_w \frac{\partial T_{w,o}}{\partial t} = \frac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \frac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q'' + \frac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q_{\#}'' \; heater \\ \rho_w c_w \frac{\partial T_{w,o}}{\partial t} = \frac{T_{w,i} - T_{w,o}}{\tilde{V}_{w,o}\tilde{R}_w} + \frac{\tilde{S}_{w,o}}{\tilde{V}_{w,o}} q_{\#}'' \; otherwise \end{cases} \tag{5}$$

$$\begin{aligned} &\tilde{V}_f = \pi\left(\frac{D_f}{2}\right)^2 \tilde{s}, \qquad \tilde{S}_f = \pi D_f \tilde{s}, \\ &\tilde{V}_{w,i} = \pi\left[\left(\frac{D_{w,i}}{2}\right)^2 - \left(\frac{D_f}{2}\right)^2\right]\tilde{s}, \qquad \tilde{S}_{w,i} = \pi D_{w,i}\tilde{s}, \\ &\tilde{V}_{w,o} = \pi\left[\left(\frac{D_{w,o}}{2}\right)^2 - \left(\frac{D_{w,i}}{2}\right)^2\right]\tilde{s}, \quad \tilde{S}_{w,o} = \pi D_{w,o}\tilde{s}, \\ &\tilde{R}_w = \frac{\ln\left(\frac{D_{w,o}}{D_f}\right)}{2\pi k_w \tilde{s}}. \end{aligned} \tag{6}$$

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). As can be noted, both the fluid and the solid regions of the system are taken into account. Eqs. (1-3) are the mass, momentum and energy balances for the fluid, whileEqs. (4-5) represent the energy balance for the wall. The pipe walls are discretized along the radial coordinate into two coaxial shells (Fig. 1b) by adopting a lumped parameter approach. As shown in the Electrical Equivalent (EE) of the system (Figs. 1c and 1d), aheat capacity (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.

Under the assumption that the perturbations are small with respect to the steady-state values, thestate variables

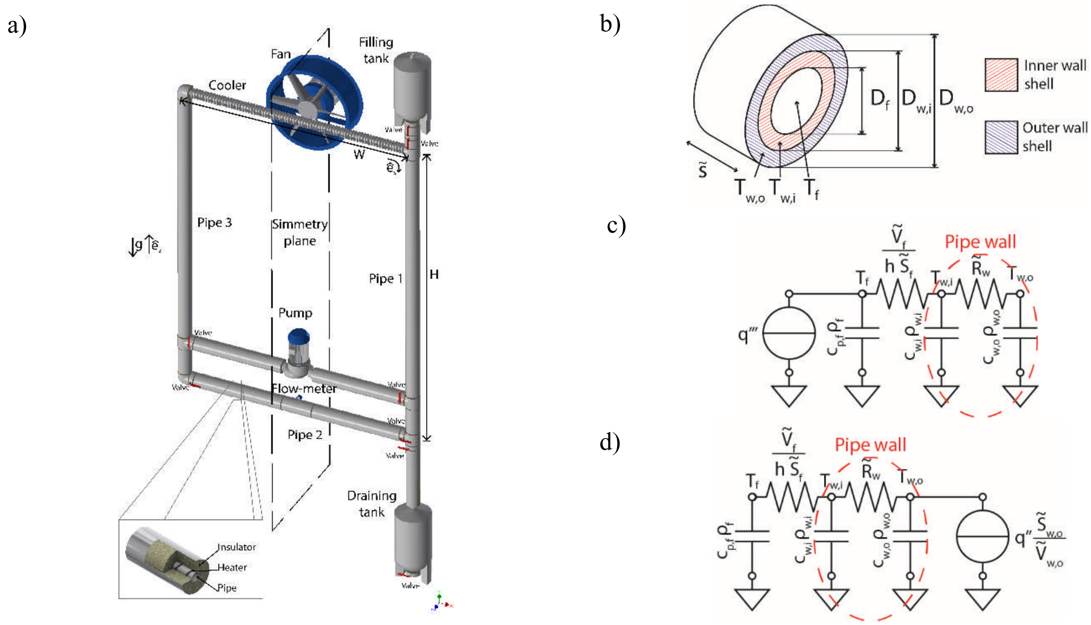

Fig. 1. (a) DYNASTY scheme (not to scale); (b) discretization of the pipe walls; (c) electrical equivalent model for the IHG case; (d) electrical equivalent model for the A-EHF case.

$(G, T_f, T_{w,i}, T_{w,o})$ are expressed as $\Theta(s,t) = \Theta_0(s) + \delta\Theta(s,t)$, where Θ represents a generic state variable for the system.In this regard, eachequilibrium of the system can be identified by two dimensionless numbers, such as $St_m = (4L_t Nu)/(D_f Re Pr)$ and $Gr_m = (\rho_f^2 g D_f^3 \beta_f \Delta T_m)/\mu_f^2$ (ΔT_m is a weighted temperature difference inside the loop [4]).By assuming a perturbation form like $\hat{\Theta}(s)e^{\omega t}$ (with $\omega \in \mathbb{C}$) the time derivatives are elided and 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 (ω) is zero defines, on the stability map, the transition curve between asymptotically stable and unstable equilibria. The derivation of the stability maps has been briefly outlined.

4. Numerical models

The described semi-analytical approach relies on the linearization process and gives information only on the asymptotic stability of the system equilibria. In order to take into account the effect of the nonlinearity of Eqs. (1-5) and to observe the time-dependent behaviour of the velocity and temperature oscillations in case of unstable equilibria, numerical approaches must be adopted. In particular, two different strategies are followed here below. The first one adopts a 1D O-O model, while the second one is based on the CFD approach.

The O-O model is a very fast tool for computing fundamental quantities, such as the velocity and the temperature fields in the loop (along the axial coordinate of the pipes), but it relies onsemi-empirical treatments for the pressure drop and heat transfer evaluation. As for the CFD tool, is based on a 3D formulation of the mass, momentum and energy equations and solves the temperature and the pressure fields without relying on correlations. The drawback is a high computational burden. Both the models of the DYNASTY loop take into account the IHG and the A-EHF, and consider the fluid and the solid region (piping material) of the system as well. The cooler section is a heat exchanger with constant wall-temperature.The thermo-physical properties of the Hitec® salt have been used [11].

The 1D O-O model (see Fig, 2a) is based on the Modelica® language [12] and is implemented in the Dymola® [13] simulation environment using an extended version, hereinafter called *ThermoPowerIHG*, of the *ThermoPower* library [14]. As for the modelling of the heat transfer, the correlation presented in [6] is adopted, while for the pressure drop evaluation reference is made to [5].

The CFD study has been performed by means of the open source finite volume software OpenFOAM® [15]. In orderto analyse both the fluid and the solid regions and the conjugate heat transfer between them, the adopted solver is a modified version of the *chtMultiRegionFoam* (hereinafter called *chtSourceMultiRegionFoam*), in which an internal heat source term is added. Regarding the flow inside the loop, both the laminar and the turbulent regimes are

a) b)

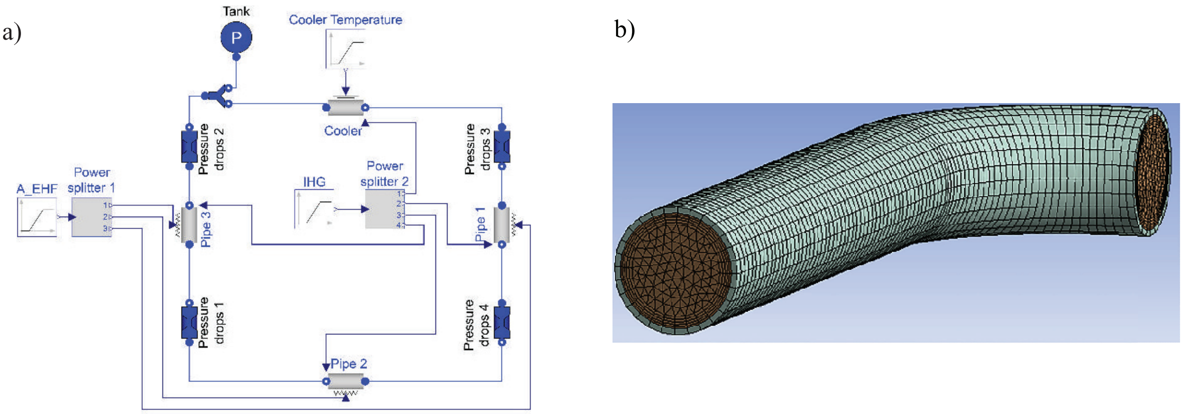

Fig. 2. (a) Main components of O-O model: cooler (heat sink with constant T), pipes (pipe with either A-EHF or IHG), pressure drops (localized pressure drops), tank (open expansion tank), power splitter (block for the IHG/A-EHF distribution); (b) details of the computational grid used in CFD simulations.

considered. As far as the turbulence is concerned, the SST k-ω model with scalable wall functions is adopted. Regarding the computational grid (composed by 885959 elements), a sensitivity study has been carried out so as to reach the independence of the solution with respect to the discretization.

5. Results and discussion

Figs. 3a and 3b depict the stability maps of DYNASTY. The orange squares represent the system equilibria from which unstable transients arise, while the green dots indicate the initial steady-states of stable transients. Such points refer to operative transients computed for different power levels(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)and mainly simulated by means of the O-O model. Only the transients at 2 kW and at 10 kW have been repeatedadoptingthe CFD approach, due to the high computationalburden (3000 CPU-hours vs. 0.1 CPU-hours).It is worth noting that all the O-O simulations, but also the CFD-based ones, are in agreement with the stability maps (for sake of brevity, Fig. 4 presents just the transients at 2 kW and 10 kW).

As for the influence of the different kinds of heating sources (IHG, LHF and A-EHF) on the equilibrium stability, the stable zones are smaller when the power comes from the IHG or the A-EHF (in this analysis, the LHF case corresponds to a localized heater on the left vertical leg of the loop). The reason is related to the geometry of the loop. On one hand,for the LHF case, the fluid flow has a preferred direction since the system is asymmetric with respect to the vertical axis (see Fig. 1a).On the other hand, when the power is provided either by the IHG or by the A-EHF, the loop presents a perfect axial symmetry and the fluid has no preferred flowing direction. Moreover, it is already possible to noticefrom the stability maps that the A-EHF and IHG induce similar effects,at least for NCLs characterized by a very high L_t/D ratio.Some differences arise in the region of high Reynolds numbers(see Fig. 3b) and are related to the fact that in the cooler section the heat flux is not applied with the A-EHF and to the influence of the thermal inertia of piping materials. In this regard, the following analysis focuses on the comparison between the IHG and the A-EHF cases adopting the O-O and the CFD models.

Figs. 4a and 4b show the time dependent behaviour, in terms of mass flow rate, computed by the O-O model at 2 kW and 10 kW considering the IHG and A-EHF. As can be noticed, a similar behaviour is predicted for both the heating systems. In particular, the transient at 2 kW is characterised by unidirectional oscillations (after an initial time interval in which the system experiences bidirectional pulsations), while stable conditions are reached for the transient at 10 kW.

The same comparison is presented in Figs. 4c and 4d for the CFD results. As can be observed, the transient at 2 kW (laminar) presents an unstable behaviour (with bidirectional oscillations) for both the IHG and A-EHF cases, while at 10 kW (turbulent) the same mass flow rate of the O-O model is reached (around 0.3 kg/s for all the numerical approaches and heating modes).

If Figs. 4a and 4c are analysed together, an interesting aspect can be noted, i.e., the different oscillation mode (unidirectional vs. bidirectional) for the transient at 2 kW predicted by the O-O and the CFD models (independent of

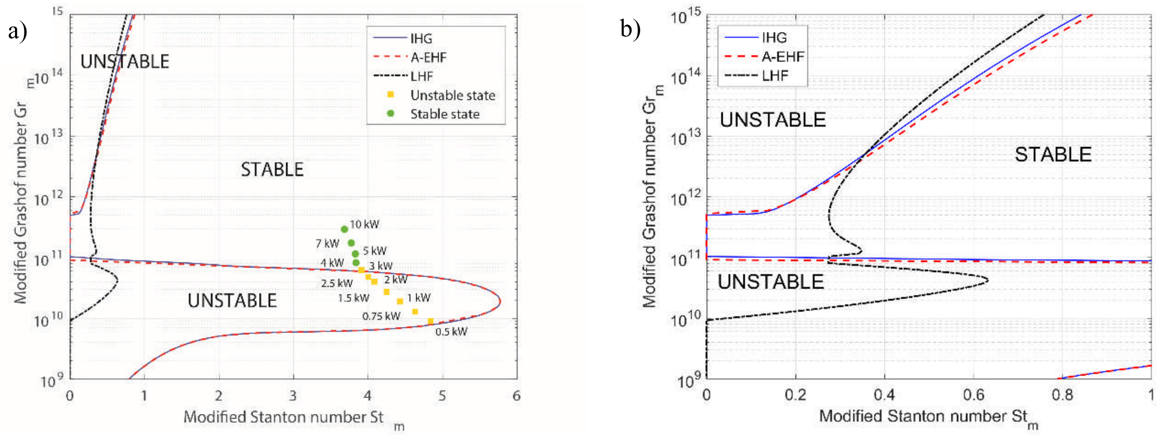

Fig. 3. (a) DYNASTY stability map for IHG, LHF and A-EHF with operative points; (b) Zoomed stability map for St_m values below 1.

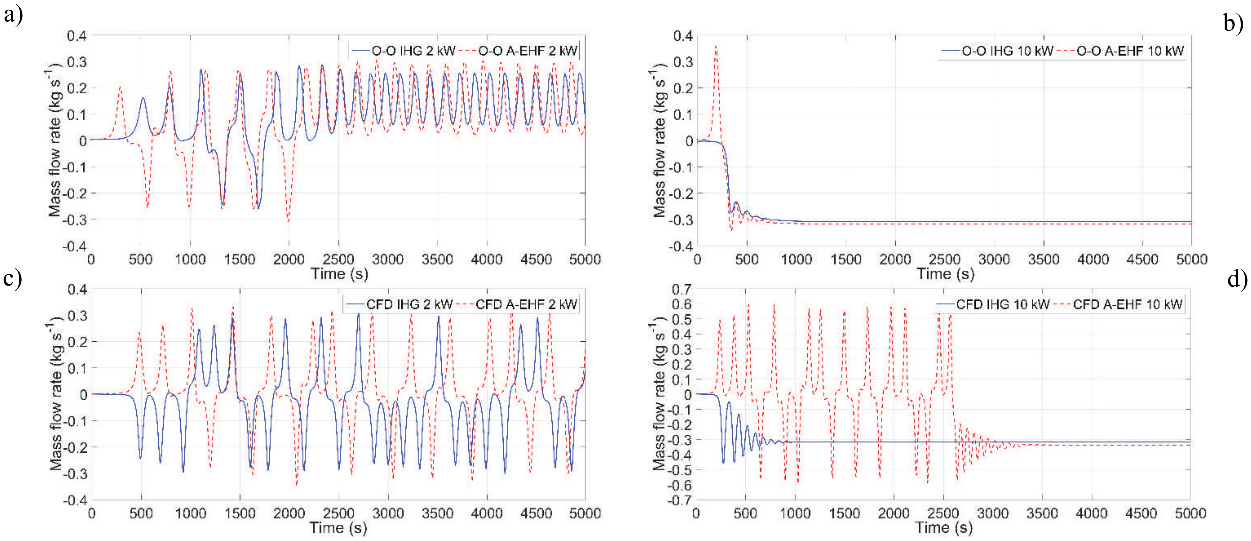

Fig. 4. (a) IHG vs. A-EHF at 2 kW (O-O); (b) IHG vs. A-EHF at 10 kW (O-O); (c) IHG vs. A-EHF at 2 kW (CFD); (d) IHG vs. A-EHF at 10 kW (CFD).

the heating mode). This occurrence is connected to the heat exchange and the pressure drop evaluation. As mentioned before, the O-O model uses semi-empirical correlations, which are not adopted by the CFD approach.

Focusing on Fig. 4d (CFD - 10 kW) and comparing the IHG case with the A-EHF, it is possible to observe that the system does not reach the stable steady-states at the same time instance. As a matter of fact, the temporal interval spent before the achievement of the stable equilibrium point is influenced by the chaotic nature of symmetric natural circulation systems [6] and by the turbulence model whose adoption is not rigorous (but widely used in literature, see e.g. [7, 8]) during the mass flow reversal when the fluid motion reaches the stagnation condition (zero flow).

In addition, another effect, connected to the different heating mode, influences the dynamics of the system. When the heat is provided by means of an imposed external heat flux, the energy is firstly absorbed by the piping materials (loading the capacitor representing, in the EE of Fig. 1d, the thermal inertia of the pipes) and successively is yielded to the fluid. On the contrary, with the IHG, the internal energy source directly loads the capacitor of the fluid (referring to the EE of Fig. 1c). Hence, the overall dynamics of the system depends on the different time-constants (related to heat capacity, mass and thermal conductivity) of the piping material and of the fluid.

Fig. 5 compares the velocity and temperature radial profiles computed by the CFD for the transient at 10 kW, at the half of the cooler section.In this regard, Figs. 5a and 5b show the velocity referring to the IHG and A-EHF cases, respectively. Itis possible to notice thatvery little differences are present in terms of distribution and values.Figs. 5cand 5d depict the temperature (for the same transient and position), showing again the agreement between the two heating modes. A temperature distribution is present in the pipe cross-section with the hot layer of the fluid occupying the top region of the pipe. Such effect influences the velocity field, which slightly differs from the classical distribution predicted for circular pipes because of buoyancy effects.

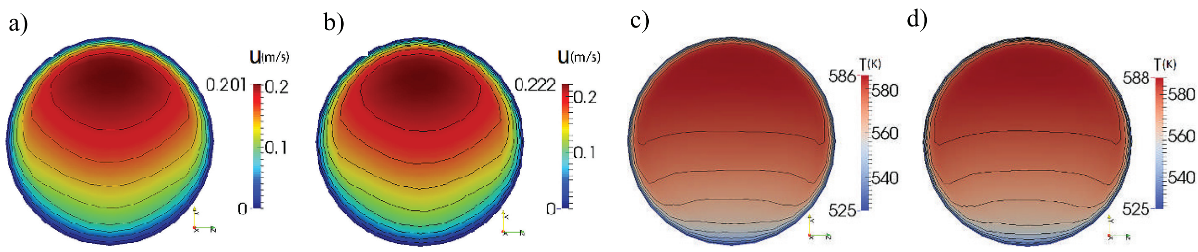

Fig. 5.CFD radial velocity magnitude distribution for IHG (a) and A-EHF (b); CFD radial temperature distribution for IHG (c) and A-EHF (d). The distributions are evaluated at 5000 s, and the section is taken at the half of the cooler.

6. Conclusions

In this work, the dynamics of the DYNASTY facility loop has been investigated by means of semi-analytical and numerical tools. In the facility,the IHG is substituted by the A-EHF. The achieved results, both in terms of stability maps and time-dependent simulations (1D and 3D), confirm that from a stability point of view the two situations are comparable for NCLs characterised by a very high L_t/D ratio. Moreover, stability maps and transient simulation results are in agreement. The treatment of the turbulence during mass flow reversals and the comparison between the results from the developed simulation tools and the experimental data achievable from DYNASTY will be the subject of future works.

Acknowledgements

The authors gratefully acknowledge the FARB Project (Grant no. DDM2RIST06) for funding the DYNASTY facility and AscoPompes.r.l. (http://www.ascopompe.com) for the pump design and supply. DYNASTY will be adopted for extensive experimental activities in the framework of the Euratom SAMOFAR (http://samofar.eu) Project (Grant no. 661891).

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