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

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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.

*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”

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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.