Chemical Engineering Science 162 (2017) 262–283

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Assessment of analytical and numerical models on experimental data for the study of single-phase natural circulation dynamics in a vertical loop

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HIGHLIGHTS

- Analytical/numerical models for natural circulation loop dynamics are assessed against experiments.
- Thermal Inertia (TI) of piping materials influences Natural Circulation Loop (NCL) behaviour.
- The Heat-Exchanger (HE) section needs an accurate modelling.
- If TI and HE are properly modelled, 1D and CFD simulations are able to catch the L2 NCL dynamics.
- The SST k–ω model can be a good choice for the CFD turbulence treatment in the considered NCL.

ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 4 December 2016
Accepted 15 December 2016
Available online 29 December 2016

Keywords:
Natural circulation
Single-phase
Stability analysis
Thermal-hydraulics
Object-oriented modelling
CFD

ABSTRACT

In this paper, semi-analytical and numerical models developed in our previous works to study the dynamic behaviour of natural convection are assessed against the experimental data obtained by means of the L2 Natural Circulation Loop (NCL) of DIME-Tec Labs (University of Genoa). As for the experimental campaign, reference is made to a set of nine experiments performed using water as working fluid and providing a thermal power of 2 kW. This set of data is firstly adopted for the validation of a semi-analytical linear analysis tool aimed at studying the asymptotic behaviour of NCLs through the definition of dimensionless stability maps. Then, two different numerical models (adopted in our previous work to confirm the linear analysis) are assessed, namely an Object-Oriented (O-O) one-dimensional model and a three-dimensional Computational Fluid Dynamics (CFD) model. In this regard, the O-O model represents a fast tool for the evaluation of the most important quantities, such as the velocity and the temperature fields in the loop along the axial coordinate. On the other hand, the CFD tool, which is intended as a support to the 1D analysis, is characterised by a high computational burden, but allows highlighting interesting 3D spatial effects. The validation of these tools is not secondary with respect to that of the stability maps. Actually, the numerical approach is fundamental to study the time-dependent behaviour of both stable and unstable natural circulation regimes, for which the stability maps do not provide information. As for the achieved results, the developed models are able to catch the behaviour of the experimental data. In particular, this outcome is possible if an accurate modelling of both the heat-exchanger section and the piping thermal inertia is considered.

1. Introduction

Natural circulation systems are usually vertical rectangular or toroidal loops, in which the working fluid transfers heat between a hot source and a cold sink thanks to the action of the buoyancy force induced by temperature gradients. In Natural Circulation Loops (NCLs), the equilibrium state, which can be either dynamically stable or unstable, is achieved when the driving buoyancy force is in balance with the frictional one. In the unstable case, the fluid flow is characterised by oscillations in time of both velocity and temperature, whereas in the stable circumstance the velocity and the temperature distributions reach steady-state values.

In literature, NCLs are the subject of several works. Focusing on the analysis of natural circulation with single-phase fluids, the first theoretical studies were carried out by Keller (1966) and Welander (1967), while more recently Chen (1985), Nayak et al. (1995), Doster et al. (1998), Misale et al. (2000), Swapnalee and Vijayan (2011) and Saha et al. (2015) analysed the influence of the loop geometry on natural circulation instabilities. From the numerical

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http://dx.doi.org/10.1016/j.ces.2016.12.058
0009-2509/

Nomenclature

Latin symbols

$\widehat{B}$	parameter describing the effect of the heat exchange (–)
c	specific heat (J kg^{-1} K^{-1})
D	diameter (m)
$e_q(t)$	absolute error
$e_{q,\%}(t)$	percentage error (–)
e_q	mean/time-average of the absolute error
$e_{q,\%}$	mean/time-average of the percentage error (–)
$\hat{e}_s(s)$	unit vector following the fluid flow (–)
$\hat{e}_z$	unit vector pointing towards the positive vertical direction (–)
f	frequency (Hz)
g	gravity acceleration (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
Gr_m	modified Grashof number (–)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	height of the L2 facility (m)
k	thermal conductivity (W m^{-1} K^{-1})
l	autocorrelation delay (s)
L	length (m)
n, k	grade of the thermo-physical polynomial dependence on the temperature (–)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
q''	localized heat flux (W m^{-2})
q	generic variable of interest
R	conductive thermal resistance of the pipe (m^2 K W^{-1})
Re	Reynolds number (–)
s	curvilinear axial coordinate (m)
St_m	modified Stanton number (–)
t	time (s)
T	temperature (K)
u	velocity (m s^{-1})
W	width of the L2 facility (m)
X	X direction (–)
Y	Y direction (–)
Z	Z direction (–)

Special symbols

β	thermal expansion coefficient (K^{-1})
δ	perturbation (–)
$\delta_{q,\%}$	percentage difference (–)
ΔT	temperature difference across the cooling section (K)
ΔT_m	weighted temperature difference inside natural circulation loops (K)
λ	Darcy friction factor (–)
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
ϱ	coefficient of the thermo-physical polynomial dependence on the temperature (–)
θ	dummy variable (a.u.)
$\hat{\theta}$	spatial-dependent part of the dummy variable (a.u.)
ϕ	generic flow variable (a.u.)
ω	perturbation pulsation (s^{-1})
$\Re(\omega)$	real part of the perturbation pulsation (s^{-1})
RR_Y	autocorrelation function
$\tilde{s}$	length of the infinitesimal shell of the pipe (m)
$\widetilde{S}$	lateral surface of the infinitesimal shell of the pipe (m^2)
$\widetilde{V}$	volume of the infinitesimal shell of the pipe (m^3)
Y	generic signal

Subscripts-superscripts

0	steady-state value
$*$	reference value
c	cooler
f	fluid
h	heater
i	inner shell of the pipe
o	outer shell of the pipe
t	total length of the loop
w	wall of the pipe
x	X direction

Acronyms

1D	one dimensional
3D	three dimensional
amb	ambient
a.u.	arbitrary unit
BC	Boundary condition
CFD	Computational Fluid Dynamics
DYNASTY	DYnamics of NAtural circulation for molten SalT internallY heated
FEM	Finite Element Method
FFT	Fast Fourier Transform
MSR	Molten Salt Reactor
NCL	Natural Circulation Loop
PDS	Power Density Spectrum
O-O	Object-Oriented
RANS	Reynolds Average Navier-Stokes
RE	Relative Error
T1, … ,T30	Thermocouple No. 1, …, thermocouple No. 30
TI	Thermal Inertia

point of view, Ambrosini et al. (1998), Misale et al. (1999) and Mousavian et al. (2004) simulated natural circulation dynamics by means of both finite difference and system codes. As for the CFD approach, analyses were performed by Desrayaud et al. (2005), Ridouane et al. (2010) and Louisos et al. (2013) for toroidal loops, while for rectangular loops by Ambrosini et al. (2004),

Table 1
Summary of the main previous works on natural circulation dynamics dealing with experimental data.

Author	Year	Experimental facility	Analytical approach	Numerical approach	Direct comparison with experimental data
Mousavian et al.	2004	L1 loop[1]	No	Finite difference, RELAP5	Yes
Vijayan et al.	2007	BARC loop	Yes	Finite difference	No
Pilkhwal et al.	2007	BARC loop	No	GENLOOP, RELAP5 and CFD (Fluent)	No
Devia and Misale	2012	L2 loop	No	CFD (Fluent)	No
IAEA-TE-1752	2014	L2 loop	No	RELAP5	Yes
Kudariyawar et al.	2016	BARC loop	No	CFD (Fluent)	Yes
Present work	2016	L2 loop	Yes	O-O, CFD (OpenFOAM)	Yes

[1] The L1 loop was the facility installed at University of Genoa before the construction of the L2 loop.