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Development of a unified model for the steady-state operation of single-phase natural circulation loops

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ABSTRACT

Inherent reliability and enhanced passive safety has made natural circulation loop a very popular mode of heat transport, particularly in the fields of nuclear reactor heat removal and emergency core cooling. Despite a wide range of applications and a large volume of available research studies, the disparity in modeling approaches for single-phase NCLs is very much apparent. Varieties of standards have been adopted and diversified definitions of characterizing parameters are available, making the comparison of different loop geometries and various boundary conditions an impossible task. Hence a novel investigation has been undertaken which focuses on the unification of NCL modeling based on unified definition of characterizing parameters. A general set of governing equations has been developed and appropriate definition of all relevant dimensionless groups and reference parameters has been identified. A Proper choice of reference temperature drop has been suggested so that different heat input modes can be simulated without disturbing the basic structure of mathematical model. Applicable friction factor and heat transfer correlations have also been identified with proper definition of unified characterizing parameter. Analytical solution for a few representative loops under steady-state condition is developed and compared with a number of available experimental studies. Excellent degree of matching has been observed for all of them. Loops having identical geometry but different modes of heat input exhibit similar nature of steady-state solution, thereby signifying the success of such unification.

1. Introduction

Single-phase natural circulation loop (NCL) offers a very efficient option of removing heat from a high-temperature source and transport that to a low-temperature sink, without employing any prime mover. The fluid circulation is achieved by thermally-induced density difference between different sections of the loop. In order to have favourable buoyancy, it is required to place the heating section at a lower elevation than the cooling section. Such simplicity in configuration coupled with highly reliable performance has ensured widespread applications in a number of important technical fields [1], including early-day systems such as turbine blade cooling [2] or solar water heaters [3] to the modern areas of nuclear reactor core cooling [4], electronic chip cooling [5] or refrigeration [6]. Details of early applications can be found from Zvirin [7] and Greif [8]. Incorporation of NCLs for trans-critical or supercritical CO_2-based heat transport system has also gained significant popularity in the last decade [9–17]. The self-sustaining nature of natural circulation flows enhances passive safety of NCLs. But the intense interaction of buoyancy and frictional forces and lack of direct controlling measures also make them susceptible to flow oscillations and system instability. Improper handling of such fluctuating flows may lead to severe consequences, particularly in large-scale applications such as nuclear reactor. Hence it is absolutely essential to identify proper zone of action under all expected operating conditions at the design level itself. That poses a real challenge to the researchers and throughout the years, a large number of work has been done upon natural circulation and related effects.

Keller [18] was the first to theoretically predict periodic motion in a simplified loop, consisting of point heat source and heat sink, connected by parallel vertical branches. Under certain operating conditions, the system behaves like a self-excited oscillator. Welander [19] developed the concept on a similar configuration and presented a plausible explanation for the emergence of instability using the well-celebrated theory of warm and cold pockets of fluids. However, the first physical observation of instability under normal temperatures is credited to Creveling et al. [20] who carried out tests on a toroidal loop with distributed heating and cooling, each occurring over half of the loop length. Under specific operating conditions, unstable system response with repeated flow

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Nomenclature

A	area (m^2)
C	heat capacity ($W\,K^{-1}$)
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	diameter (m)
f	friction factor
g	acceleration due to gravity ($m\,s^{-2}$)
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
Gr_m	modified Grashof number $(= g\beta_{av}d_{hy}^3\rho_0^2 G_{ss}\Delta T_0 L_v/\mu_0^3)$
Gz	Graetz number $(= (d_{hy}/L_t)RePr)$
H	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
L	length (m)
p	pressure ($N\,m^{-2}$)
Pr	Prandtl number $(= \mu C_p/\lambda)$
$\dot{q}''_w$	wall heat flux ($W\,m^{-2}$)
Q	rate of heat transfer (W)
R_t	radius of the torus (m)
Re	Reynolds number $(=Gd_{hy}/\mu_0)$
Ri	Richardson number $(= g\beta_{av}\Delta T_0 L_v/u_{ss}^2)$
s	space coordinate
S	non-dimensional space coordinate
St_m	modified Stanton number $(= (4L_t/d_{hy})H/\rho_0 u_{ss}C_{p0})$
t	time (s)
T	absolute temperature (K)
u	local flow velocity ($m\,s^{-1}$)
$\dot{W}$	mass flow rate ($kg\,s^{-1}$)
z	coordinate along flow direction

Greek symbols

β	coefficient of thermal expansion (K^{-1})
ΔS	non-dimensional length of any section
ΔT	temperature difference/drop (K)
ϵ	heat exchanger effectiveness
θ	angular displacement with respect to a reference (rad)
Λ	friction number $(=f_{av}L_t/d_{hy})$
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
τ	non-dimensional time
φ	angle of inclination at reference location (rad)

Subscripts and superscripts

*	non-dimensional quantity
0,*ref*	reference
1	inlet to a flow section
2	outlet to a flow section
av	average
c	cooler/coolant
cl	cold leg
d	downcomer
f	working fluid
h	heater
hl	hot leg
hy	hydraulic
si	sink
so	source
ss	steady-state
t	total
v	vertical
w	wall material

reversal was observed. The accompanying theoretical analysis identified two different regimes of stable operation, with the region of instability matching the transition from laminar to turbulent flow. Following their pioneering works, a number of critical phenomena in natural circulation were explained considering a torus in vertical plane as the geometry, mainly due to the regular nature of the flow path resulting in mathematical simplicity. Hence, despite limited practical applicability, quite a few research works are available on toroidal NCL [21–26]. However, mainly to keep pace with the industrial requirements, rectangular geometry became the focus in the next phase, plenty of which introduced specialized computational techniques and well-defined correlations [27–33], thereby converging better towards reality.

However, a rigorous survey of the available literature shows incorporation of different standards and various methodologies adopted by different researchers, thereby making the standardization a gruelling job. Welander [19], in his simplified analysis, assumed frictional forces to be a linear function of instantaneous flow rate and stability characteristics were explained in terms of two dimensionless quantities a_{wel} and ε_{wel}, without showing any physical correspondence. Creveling et al. [20] employed two self-defined parameters D and E to plot the neutral stability curve and proposed indigenous correlations to estimate their values. But the follow-up work of Damerrel and Schoenhals [21] used a dimensionless flow velocity to explain the effects of loop inclination and different relations were used for both friction factor and heat transfer coefficient. Similar definition of characteristic velocity was also employed by Greif et al. [22] and Sen et al. [25] for non-dimensionalizing conservation equations. Mertol et al. [23] followed a similar approach for their two-dimensional model, but defined friction factor and heat transfer coefficient as functions of Graetz number (Gz). Use of a different velocity scales were suggested by Hart [24]. Even the recent work of Jiang and Shoji [26] defined characteristic velocity similar to Hart [24], but no information was provided about the nature of used correlations. Hence the disparity in modeling approach and scarcity of universally acceptable correlations are very much apparent for toroidal NCLs. More concentrated effort can be observed in case of rectangular NCLs, mainly due to the continual effort of a few research groups. The necessity of separate frictional and heat transfer correlations for natural circulation was stressed upon by Vijayan et al. [29,30,32], as they showed increase in frictional losses compared to assisted flows. Generalized correlations were also proposed by Vijayan [32], even for loops with non-uniform diameter. Use of finite-difference technique to capture transient behaviour was demonstrated by Nayak et al. [30] and Mousavian et al. [33]. Intricate details of computational modeling, particularly the effects of nodalization scheme, time period and truncation error on solution were explained by Ambrosini and Ferreri [31], thereby providing a sound base for development of computational codes for rectangular loops.

With the background elucidated above, the disparity in modeling of NCLs is very much apparent, particularly for toroidal loops. Also the methodology adopted for analyzing different geometries has been quite different. Similarly, the definitions of characterizing parameters employed by different researchers differ quite vastly, thereby making comparison between various geometries a gruelling and almost impossible task. Hence the present study focuses on standardizing the modeling approach for single-phase NCLs and on development of a generalized model applicable for all kinds of NCL geometries, utilizing the available concept for both rectangular and toroidal loops. The focus is more on the evaluation of steady-state performance. However, the developed model must also be capable of estimating transient behavior with minimal