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Computational stability appraisal of rectangular natural circulation loop: Effect of loop inclination

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ABSTRACT

Controlling stability behavior of single-phase natural circulation loops, without significantly affecting its steady-state characteristics, is a topic of wide research interest. Present study explores the role of loop inclination on a particular loop geometry. Accordingly a 3D computational model of a rectangular loop is developed and transient conservation equations are solved to obtain the temporal variation in flow parameters. Starting from the quiescent state, simulations are performed for selected sets of operating conditions and also with a few selected inclination angles. System experiences instability at higher heater powers and also with higher sink temperatures. Inclination is found to have a strong stabilizing influence owing to the reduction in the effective gravitational acceleration and subsequent decline in local buoyancy effects. The settling time and highest amplitude of oscillations substantially reduces for a stable system with a small inclination. Typically-unstable systems can also suppress the oscillations, when subjected to tilting, within a reasonable period of time. It is possible to stabilize the loop within shorter time span by increasing the tilt angle, but at the expense of reduction in steady-state flow rate. Overall a tilt angle of 15° is suggested for the selected geometry. Results from the 3D model is compared with the predictions from an indigenous 1D code. While similar qualitative influence of inclination is observed, the 1D model predicts early appearance of the stability threshold and hence hints towards larger instability. Accordingly the limitations of 1D approach in terms of the dependence on correlations is highlighted.

1. Introduction

Adoption of natural circulation loops (NCLs) for reactor core cooling is of wide interest to nuclear scientists, particularly in post-Three-Mile-Island era. Fluid motion through a closed circuit is achieved solely by creating favorable density gradient, either through a temperature differential or through phase change, thereby making the circulation system inherently more reliable. Absence of any rotary prime mover provides enhanced passive safety, in comparison to the loops with assisted circulation. While the single-phase NCLs are limited by the saturation temperature constraints and stability boundaries, appearance of several types of static and dynamic instabilities are of major concern in two-phase versions (Fukuda and Kobori, 1979). Lesser restrictions on the system orientations and simplified construction requirement have allowed single-phase loop application in several engineering fields along with the nuclear industry (Borgohain et al., 2011; Linzer and Walter, 2003; Vijayan and Date, 1992), such as the solar heaters (Nahar, 2003), electronic chip cooling (Tuma and Mortazavi, 2006), refrigeration (Kumar and Gopal, 2009) and ship propulsion (Yan and Yu, 2012). Low flow rate in such loops, however, ensures identical orders of momentum and viscous dissipations and strong dependence on prevailing gravitational field, thereby making them susceptible to unstable fluctuations. Accordingly the general focus of NCL research is mostly directed towards stability appraisal and control, to enhance the regime of stable operation.

Creveling et al. (1975) were the first to demonstrate instability and repeated flow reversals with water by experimenting on a toroidal loop. Their observations established the postulate proposed by Welander (1967), considering a hypothetical loop with point source and point sink, connected by parallel vertical branches. Possible laminar-to-turbulent transition at noticeably low Reynolds number was reported by Hallinan and Viskanta (1985), using flow visualization experiments on a rectangular loop with tube bundles as source and sink. Vijayan and Date (1992) predicted the limits of conditional stability for a figure-of-eight configuration using both linear stability analysis and finite-difference method. Their study encouraged a substantial volume of subsequent research following similar approaches (Basu et al., 2013a; Mousavian et al., 2004; Nayak et al., 1995; Vijayan et al., 2007), thereby developing a

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Nomenclature

A	cross-section area, m^2
C_p	specific heat, J kg^{-1} K^{-1}
d	loop diameter, m
f	friction factor
g	acceleration due to gravity, m s^{-2}
H	loop height, m
Gr_m	modified Grashof number, $g\beta d^3\rho^2\dot{Q}H/A\mu^3C_p$
k	turbulent kinetic energy, m^2 s^{-2}
L	total length, m
$\dot{m}$	mass flow rate, kg s^{-1}
p	pressure, N m^{-2}
$\dot{Q}$	input power, W
Re	Reynolds number, $\dot{m}d/\mu A$
S_E	rate of energy addition, W m^{-3}
t	time, s
T	temperature, K
T_c	sink temperature, K
u	velocity, m s^{-1}
x	spatial coordinate, m

Greek letters

α	inclination angle
β	volumetric expansion coefficient, K^{-1}
ε	turbulent dissipation rate, m^2 s^{-3}
ρ	density, kg m^{-3}
μ	viscosity, kg m^{-1} s^{-1}
μ_t	turbulent viscosity, kg m^{-1} s^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
τ	shear stress, N m^{-2}

decent database about the role of pertinent geometric and operating parameters on system stability. A few recent attempts of employing multi-dimensional system codes can also be found in relevant literature (Angelo et al., 2012; Pilkhwal et al., 2007; Wang et al., 2013), most of which were restricted to steady-state simulation. More discussion on the same can be found from (Basu et al., 2014).

As the understanding on the stability behavior of single-phase NCLs started consolidating, efforts were initiated to control the nature of stability response and expand the stability threshold using both active and passive means. Misale and Frogheri (1999, 2001) experimented with sharp-edged orifices of different sizes within a rectangular loop. All orifices showed stabilizing effect, manifested by the reduced amplitude of oscillation and damping period, but at the expense of larger pressure drop inside the loop, and hence lower flow rate. Similar role of properly-designed mechanical gadgets was demonstrated by Bodkha et al. (2010). Garibaldi and Misale (2008) suggested the use of higher-viscosity working fluid to obtain qualitatively similar effect on initial transients. None of them, however, can be the most practicable option, as the magnitude of such added resistances required to stabilize a specific system strongly depends on the imposed power level (Basu et al., 2013a). Misale et al. (2011) was able to control the nature of oscillations in a rectangular loop by altering the sink temperature. Circulation frequency was found to increase with the sink temperature, as the same was varied within the range of -10 to 30 °C. But the sink-side condition is customarily bound by the prevailing ambient temperature and it is not economically feasible to reduce the coolant temperature below that level. A few researchers explored the role played by the modality of supplying power to NCLs (Basu et al., 2013b; Misale, 2016; Rao et al., 2005). Another possible option originated from the experiments of Cammarata et al. (2004). They substantiated that a reduction in the effective gravitational force can stabilize the loop. Basu et al. (2013a) utilized the same in a simple 1D model by tilting a rectangular loop to vertical. A tilt angle of 30° was found to be sufficient in suppressing oscillations at higher power levels, without significantly affecting the steady-state flow rate. This particular route of stabilizing an NCL can be incorporated at the design level quite conveniently and hence merits further exploration. It is also a well-established fact that 1D models generally provide a highly-conservative estimate to the stability threshold and hence should merely be restricted for obtaining the preliminary approximation towards the same, which can further be utilized to initiate higher-order analysis.

The present study, therefore, focuses on developing a 3D computational model for a rectangular NCL and performs transient simulation to ascertain the stability behavior, with particular emphasis on the role of loop inclination. As was explained by Vijayan et al. (2007), rectangular loops with heater and cooler in opposite horizontal arms are inherently more unstable, and hence

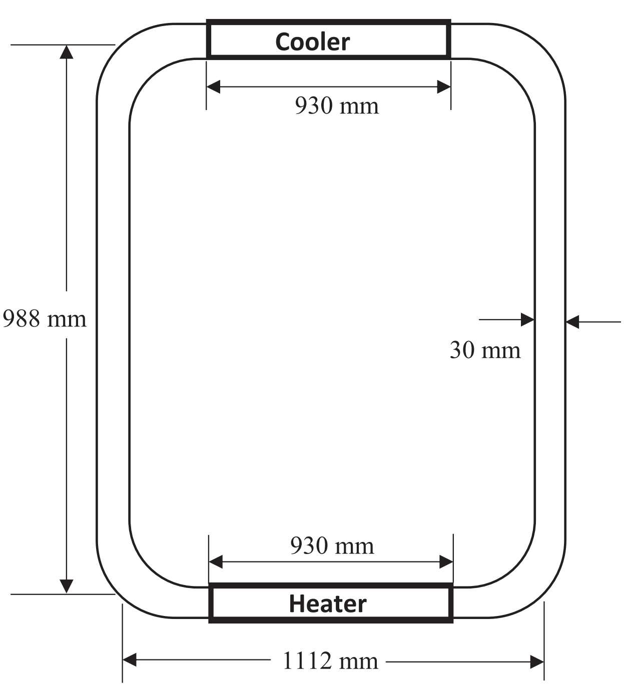

Fig. 1. Schematic view of the rectangular NCL.

Table 1
Details of the mesh systems adopted for numerical simulation.

	Model 1	Model 2	Model 3
No. of nodes	143488	255460	474496
No. of elements	135900	240768	449280
Orthogonal quality	0.977	0.979	0.982
Skewness	0.13	0.12	0.11
Element quality	0.24	0.50	0.58