Annals of Nuclear Energy 73 (2014) 189–199

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

# Stability analysis for single-phase liquid metal rectangular natural circulation loops

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ARTICLE INFO

*Article history:*
Received 22 October 2013
Received in revised form 6 June 2014
Accepted 8 June 2014

*Keywords:*
Natural circulation
Liquid metal
Nuclear reactor
Stability
Linear method

ABSTRACT

Natural circulation systems are preferred in some advanced nuclear power plants as they can simplify the designs and improve the inherent safety. The stability and steady-state characteristics of natural circulation are important for the applications of natural circulation loops (NCLs). A linear stability analysis method was used to study the stability behavior of liquid metal NCLs. The influences of the types of working fluids and loop geometry parameters on the stability of NCLs were evaluated. The liquid sodium (Na) loop and sodium–potassium alloy (NaK) loop would be more stable than lead bismuth eutectics (LBE) loop. The pressure drop could stabilize the loop behavior and also lead an increase of operating temperature for the loop. The NCL with a lower aspect ratio (ratio of vertical center distance between the heating and cooling section to the horizontal length of loop) is supposed to be more stable. It was found that the length of heating section would not have an obvious effect on the stability of NCL. However, the loop behavior could be stabilized by adding the length or heat transfer coefficient of the cooling section.

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## 1. Introduction

In order to increase the safety of nuclear power plants, some innovative nuclear power technologies have been applied in newer nuclear reactor designs, one of which is natural circulation systems. Natural circulation is a type of heat transport, in which the fluid motion is generated by density differences in the fluid due to the temperature gradients or the phase change. Natural circulation loops (NCLs) are preferred to transfer energy from a heat source to a heat sink as no pumping devices are needed. Because the heat transfer system could be simplified greatly, not only the system cost could be reduced but also the reliability may be enhanced.

Liquid metals such as lead (Pb), lead bismuth eutectics (LBE, 44.5% Pb and 55.5% Bi), sodium (Na) and sodium–potassium alloy (NaK, 78% potassium and 22% sodium) are currently being considered as optional coolants for the primary loops and passive heat removal systems (PHRSs) of a variety of Generation IV liquid metal reactors (LMRs) (Choi et al., 2011; IAEA, 2000, 2011; Smith et al., 2008; Wang and Cao, 2007). We also proposed a conceptual design of a small modular natural-circulation liquid metal fast reactor with alkali-metal thermal-to-electric conversion (AMTEC) units and provided a straightforward comparison of natural circulation characteristics for different liquid metals in previous studies (Xun and Daogang, 2013). In general, a high mass flow rate could be provided in liquid metals natural circulation loops, so it is possible that the liquid metals are used in natural circulation based primary coolant systems and natural circulation based residual heat removal systems to improve the systems' reliability and inherent safety. The NCLs with different working fluids would have different geometry parameters to generate necessary driving force, which also lead a variety of stability and steady-state characteristics of NCLs.

The NCLs can be simply classified according to the phase or type of working fluid. Two-phase NCLs generally provide higher circulation flow rates compared to single-phase NCLs. However, they may be more unstable. The operation of a single-phase NCL may not be easily controlled compared to forced circulation. The interaction between buoyancy and frictional forces could make the flow unstable, such as oscillations and reverse flow. As a result, the system instability becomes one of the most important factors that limit the applications of NCLs.

Most of the experimental investigations and theoretical analysis methods have been carried out for symmetrically heated and cooled loops (the heater at the bottom and the cooler at the top of the closed loops). Creveling et al. (1975) presented the stability characteristics of a single-phase toroidal NCL, and the experimental results agree well with the simulation predictions. Welander (1967) presented a theoretical discussion on the oscillatory instability of a differentially heated fluid loop which are composed of a point heat source and a point heat sink connected by parallel vertical branches. Zvirin and Greif (1979) also analytically investigated a point heat

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http://dx.doi.org/10.1016/j.anucene.2014.06.014
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source, point heat sink loop with two vertical branches and evaluated the transient behavior of the loops. Ramos et al. (1985) analyzed the steady state flow process in one- and two-phase variable area loops and found that multiple solutions for the flow are possible in both cases. Vijayan and Austregesilo (1994) experimentally proved that the power-to-volume scaling principles adequately describe the steady state behavior. Transient and stability behavior of the NCLs with different diameters was studied at the same time. Furthermore, Vijayan (2002) simulated the stability behavior of both uniform and non-uniform diameter single-phase NCLs consisting of two horizontal sections and two parallel vertical tubes. The experimental data and simulation results showed reasonable agreement. In the next few years, other mathematical models and analytical methods were proposed. Nayak et al. (1995) used linear stability theory and nonlinear finite difference method to investigate stability characteristics and the results are close to each other. Cammarata et al. (2003a,b), proposed a methodology based on the linear stability analysis around equilibrium points of a high order nonlinear mathematical model. Some soft codes, such as RELAP5 system code could also be applied to simulate stability behavior of the NCL, and similar results have been obtained (Maiani et al., 2003; Mousaviana et al., 2004; Pilkhwa et al., 2007). Furthermore, Vijayan and Date (1992) investigated the stability of natural circulation with throughflow in a figure-of-eight loop experimentally and theoretically. Stable and unstable regimes were presented in their research.

The researches mentioned above are about symmetrical water NCLs. Besides, the liquid metals and alloys could also be used in NCLs which operate at relatively higher temperature and provide higher heat flux. Thus, natural circulation is preferred in liquid metal reactors to simplify the primary circuit so that the costs for the construction, operation, and maintenance can be reduced. Other investigations are also carried out for the asymmetric liquid metal NCLs. Weimin et al. (2007) experimentally investigated the capability and stability of LBE NCL and used RELAP5 to estimate the natural circulation flow rate. Abánadesa and Penab (2009) used computational fluid dynamic codes to analyze the free convection cooling mode of the reference liquid metal-cooled accelerator driven system. Wu and Sienicki (2003) and Sabharwall et al. (2012) employed the Nyquist criterion and a root search method to study the stability of Argonne LBE NCL. Although there are many researches of natural circulation of liquid metals, the study of stability for liquid metal NCLs is still limited. In general, the liquid metal reactors have a high-power density core which would lead a great temperature change in the primary loop. Meantime, the instability behavior of NCLs may be observed at a greater temperature change across the heater or cooler according to the results of previous studies. Therefore, the stability behavior of liquid metal NCLs should be investigated to ensure its stable operation.

Using the nonlinear methods to generate a stability map would be extremely time consuming and costly, so a linear analysis method based on emulating the sign of eigenvalues of Jacobian matrix for the linearized model is employed in present work to study the stability behavior of liquid metal NCL (Fig. 1) with consideration of fluid axial conduction. The scope of this study is not only to analyze the stability of NCLs but also to investigate the factors that influence the stability and steady-state characteristics of liquid metal NCLs which would be useful for the development of stabilizing the natural circulation.

## 2. Calculation model and method

### 2.1. Mathematical model

A rectangular loop consisting of a vertical heater, a vertical cooler and two parallel horizontal tubes is shown in Fig. 1. The heater is placed at the left bottom of loop. The cooler is a coaxial cylindrical heat exchanger with low temperature fluid flowing through the annulus. The hot leg and cold leg are assumed to be perfectly insulated. In this design, the temperature difference between hot and cold leg can be changed by adjusting the input power of heater, the coolant temperature or the coolant flow rate in the heat exchanger. In the present simulation, the wall temperature of heat exchanger is supposed to be constant because of the atmospheric boiling heat transfer of water in the secondary loop. Other assumptions listed below have been used in the mathematical model to simplify the analysis.

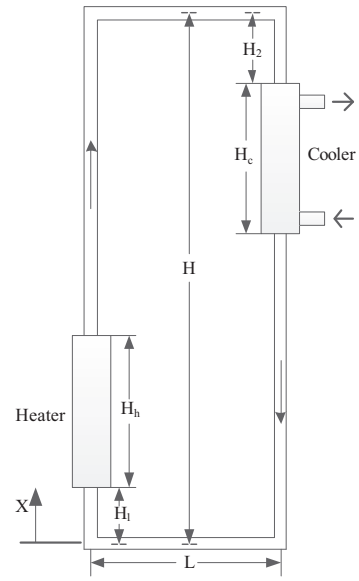


**Fig. 1.** Schematics of rectangular NCL.

(1) The model is one dimensional with the space coordinate being along the loop, which means that a radial temperature difference is neglected.
(2) Boussinesq approximation is employed, so the density is taken to be constant except in the body force term.
(3) The effect of viscous term in the model is not considered.

One-dimensional single-phase mass conservation, momentum and energy equations of the rectangular NCL in Fig. 1 could be given as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} = -\frac{\partial P}{\partial x} - \rho g - \frac{1}{2}\frac{f}{D}\rho u^2 \tag{2}$$

Heater:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho C_p}\frac{4q}{D} \tag{3}$$

Cooler

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho C_p}\frac{4h(T_{sec} - T)}{D} \tag{4}$$

Adiabatic sections

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial x^2} \tag{5}$$

From Eq. (1) we can see that flow velocity is only a function of time and independent of space coordinate when the fluid is incompressible, therefore the axial temperature distribution along the

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