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Dynamic stability of natural circulation loops for single phase fluids with internal heat generation

D. E. Ruiz [a], A. Cammi [b], L. Luzzi [b,*]

[a] Princeton University, Department of Astrophysical Sciences, Princeton, NJ 08544, USA
[b] Politecnico di Milano, Department of Energy, CeSNEF (Enrico Fermi Center for Nuclear Studies), via La Masa 34, 20156 Milano, Italy

HIGHLIGHTS

- Internal heat generation (IHG) can alter the stability of natural circulation loops.
- The unstable regions of the stability maps increase when IHG becomes larger.
- For the VHHC loop, the unstable regime increases largely if IHG increases.
- The VHVC loop shows a better stability behavior when IHG is present.

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ABSTRACT

Previous studies have investigated the dynamic stability of natural circulating flows inside closed loops. The systems considered have an external heat source, and the circulating fluids do not generate heat internally. In this work, the effects of internal heat generation on the stability of natural circulating flows are investigated for the first time. A semianalytical linear method and a numerical nonlinear method are applied in order to characterize the effects of internal heat generation on the stability maps of different closed loop configurations. Results show that when internal heat generation dominates the external heat source, it can modify the shape and area of the stability regions. Among the different loop configurations studied, the Vertical Heater-Vertical Cooler (VHVC) configuration shows a better stability behavior.

1. Introduction

In a natural circulation loop, the circulating fluid removes heat from a source and transports it to a heat sink. The driving force is the fluid buoyancy force. In a closed loop, steady state natural circulation is achieved when the driving buoyancy forces are in balance with the frictional forces. However, under certain circumstances, the achieved steady state can be dynamically unstable. The possible instabilities can lead to large oscillations in the fluid flow and on the temperature field and cause an inconvenient operation of the closed loop system. Since natural circulation has gained importance in many engineering applications, such as in the chemical and nuclear engineering communities, it is important to determine the dependence of the stability maps on the external parameters (IAEA, 2005).

Natural circulation loop instabilities have been studied both theoretically and experimentally. The first theoretical studies on the subject were presented by Keller (1966) and Welander (1967). Further theoretical studies have focused on the stability analysis for different loop geometries (Chen, 1985; Swapnalee and Vijayan, 2011; Vijayan et al., 2007, 2008). Using another approach, stability analysis of thermosyphon loops was studied via finite difference methods (Ambrosini and Ferreri, 1998, 2000; Misale et al., 2000). On the other hand, the first experimental studies on the subject were done by Creveling et al. (1975) and Gorman et al. (1986). Subsequent experimental studies have been performed by Vijayan et al. (2007), Swapnalee and Vijayan (2011), and others. These works have studied in detail natural circulation in a variety of closed loop configurations in which there is an external heat source and an external heat sink. However, no attention has been given to single-phase natural circulating flows with internally heated fluids (Pini et al., 2014).

This work studies oscillating instabilities in closed single-phase thermosyphon loops when internal heat generation is present. Until now, it is unknown how the stability of closed natural circulation loops is affected when internal heat generation effects are considered. A fluid with internal heat generation might be, for

* Corresponding author. Tel.: +39 02 2399 6326.
E-mail address: lelio.luzzi@polimi.it (L. Luzzi).

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example, a fluid with internal exothermic chemical reactions or a molten salt fuel in a nuclear Molten Salt Reactor (MSR) (GIF, 2013; Serp et al., 2014). In MSRs, fission products decay inside the molten salt and release energy (Di Marcello et al., 2010; Fiorina et al., 2014; Luzzi et al., 2012, 2010). Other examples of fluids with internal heat generation might include fluids heated via electrical currents (ohmic heating). It is believed that the study of natural circulation of internally heated fluids may concern a number of engineering domains.

In the present paper, two methods were used in order to calculate the stability maps of the investigated natural circulation loops: a semianalytical linear method and a numerical nonlinear method. These methods were applied to investigate the stability of two closed loop configurations: the Vertical Heater - Horizontal Cooler (VHHC) and the Vertical Heater - Vertical Cooler (VHVC) configurations. In these circuits, the heat sink position and orientation are varied.

The present work is organized as follows. Section 2 presents the general procedures and mathematical tools used for the stability analysis. In Section 3, the obtained stability analysis methods are applied to study the dynamical stability of the VHHC and VHVC circuit loops. In Section 4, the main results are presented and discussed. Concluding remarks are given in Section 5.

2. General stability analysis methods

In the present section, the methods for performing the stability analysis are presented. The developed model allows for both external heating and internal heat generation. The section is organized as follows: first, a general description of the system with the governing equations is presented. Then, the procedure for determining the steady state is given. Finally, the linear stability analysis and the numerical nonlinear stability analysis methods are presented.

2.1. System description and governing equations

In this work, the closed loop configurations studied are composed of a single "heater" and a single "cooler" in a closed rectangular loop with a circular tube cross-section of constant diameter (see Fig. 1). In this configuration, the cooler length is denoted as L_c. The tube section connecting the "cooler" with the "heater" is called the "cold leg" of length L_{cl}. The length of the "heater" is denoted L_h. Finally, the tube section transporting the hot fluid from the "heater" to the "cooler" is called the "hot leg" of length L_{hl}. The total length of the circuit is $L_t \doteq L_c + L_{cl} + L_h + L_{hl}$.[1] This general notation to designate the sections of the closed-loop circuit will be used throughout the work.

The system governing equations refer to an incompressible fluid, with the following additional assumptions:

- The fluid flow is considered one-dimensional. The curvilinear coordinate "s" denotes the position inside the closed loop, and it follows the direction of the fluid flow. The origin is taken at the entrance of the system heat sink or "cooler".
- The Boussinesq approximation is considered. A linear variation of the fluid density due to temperature change is considered in the gravitational term of the conservation of momentum equation.
- Two heat sources are included. The first heat source is that of the system external heater (this could be an electrical heater in a test-loop facility or a nuclear reactor). The second heat source is the fluid internal heat generation, which is considered uniform inside the circuit.[2]
- The system heat sink is modeled as a constant wall temperature cooler.
- Dissipative terms of the energy conservation equation are neglected.
- Heat conduction inside the fluid is neglected.
- It is supposed that the circuit has constant diameter D.
- Regarding the pressure losses due to friction inside the circuit, it is supposed that the same flow regime (laminar or turbulent) exists for the whole circuit. Also, the fluid dynamic viscosity, μ, is supposed to be constant along the circuit. The previous two assumptions were relaxed in the work of Vijayan et al. (2008).

[1] Throughout this paper, we denote $a \doteq b$ meaning that "a" is defined as "b".

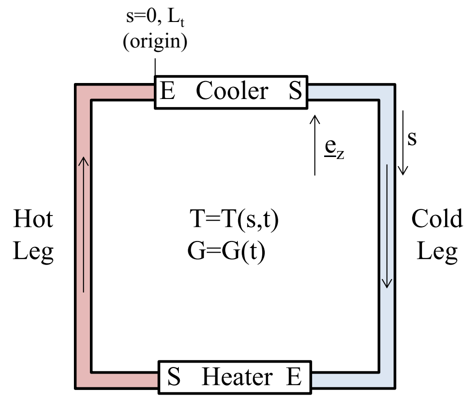

Fig. 1. General schema of a natural circulation closed loop. The symbols "E" and "S" denote the entrance and exit cross-sections, respectively.

Throughout the present work, the velocity of the fluid is defined as $\underline{v} \doteq v\underline{e}_s(s)$, where $\underline{e}_s(s)$ is the unit vector of the flow and $v \geq 0$. The governing equations with the above assumptions are

$$\frac{\partial G}{\partial s} = 0, \tag{1}$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial s}\left(\frac{G^2}{\rho^*}\right) = -\frac{\partial p}{\partial s} - \rho g \underline{e}_z \cdot \underline{e}_s - \frac{1}{2} f \frac{G^2}{\rho^*}\frac{1}{D}, \tag{2}$$

$$\rho^* c_p \frac{\partial T}{\partial t} + G c_p \frac{\partial T}{\partial s} = \begin{cases} -\overline{h}(T - T_w)\dfrac{P}{A} + q''' & \text{cooler} \\ q''\dfrac{P}{A} + q''' & \text{heater} \\ q''' & \text{otherwise} \end{cases}, \tag{3}$$

$$\rho(T) = \rho^*\left[1 - \beta(T - T^*)\right], \tag{4}$$

where $\rho^* \doteq \rho_0(s=0)$ is the reference density (taken at the cooler entrance) at steady state, $G(t) \doteq \rho^* v$ is the mass flux, $T(s,t)$ is the fluid temperature field, β is the thermal expansion coefficient, $f \doteq a/Re^b$ is the Darcy friction factor, T_w is the cooler wall temperature, c_p is the fluid specific heat, D is the diameter of the circuit, P is the perimeter of the tube, A is the area of the tube cross-section, and $\overline{h}$ is the heat transfer coefficient.

It is important to notice that in Eq. (3) there are two heat source terms. The first source term denoted by q'' represents the

[2] For nuclear applications with circulating-fuel MSRs, it is well known that for nominal operating conditions the decay heat varies by a small percentage inside the circuit. The strongest decay heat release takes place inside or immediately outside the core and is caused by the fastest decaying fission products. During emergency or accidental conditions, in which the nuclear core is shut down, the decay heat may be considered uniform.