Annals of Nuclear Energy 73 (2014) 250–263

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Review

A state-of-the-art review of recent advances in supercritical natural circulation loops for nuclear applications

Milan K.S. Sarkar, Abhilash K. Tilak, Dipankar N. Basu *

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form 16 June 2014
Accepted 18 June 2014
Available online xxxx

Keywords:
Natural circulation loop
Supercritical
Stability analysis
Thermal–hydraulic

ABSTRACT

The concept of supercritical natural circulation loop (SCNCL) is an important inclusion in Generation-IV nuclear reactors. Use of supercritical fluids promises a simplified design, along with higher thermal efficiency for heat transport systems. Characteristics of such loops are markedly different from its single-phase and two-phase counterparts, while carrying quite a few similarities with both as well. Therefore significant number of research studies is carried out on SCNCL in the present millennium and current work presents a state-of-the-art summary of all associated observations. Most of the reported studies are theoretical in nature, with only a limited number of experimental works being reported. A number of indigenous computation codes were developed, while use of commercial software can also be found. Thermal–hydraulic and heat transfer aspects are discussed in details, showing the gradual growth of knowledge and comprehending the influence of various geometric and operating variables on steady-state profile. Water and carbon dioxide are identified as the only fluids considered for analysis both numerically and experimentally. Both time-domain and frequency-domain approach of stability analysis are discussed meticulously. Available experimental works are described, with exhaustive discussion on the novelty of the concerned facility and major observations. Finally a few topics are ear-marked as the possible guidelines for future research.

Contents

* Corresponding author. Tel.: +91 361 2583431; fax: +91 361 2582699.
E-mail address: dipankar.n.basu@gmail.com (D.N. Basu).

http://dx.doi.org/10.1016/j.anucene.2014.06.035
0306-4549/

Nomenclature

A	Area (m^2)
d	Diameter (m)
g	Gravitational acceleration ($m\ s^{-2}$)
Gr_m	Modified Grashof number
L	Length (m)
N_{SPC}	Pseudo-phase-change number
N_{TPC}	Pseudo-subcooling number
q_0	Heat flux ($W\ m^{-2}$)
Re	Reynolds number
Greek symbols	
β	Volume expansion coefficient (K^{-1})
θ	Inclination angle (rad)
ρ	Density ($kg\ m^{-3}$)
Subscripts and superscripts	
b	Bounding
m	Maximum
t	Total
C_p	Specific heat ($J\ kg^{-1}\ K^{-1}$)
f	Friction factor
G	Mass flux ($kg\ m^{-2}\ s^{-1}$)
h	Enthalpy ($J\ kg^{-1}$)
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
NU	Nusselt number
Q	Power (W)
T	Temperature (K)
Π_h	Heated perimeter (m)
in	Inlet
pc	Pseudo-critical
$*$	Non-dimensional

1. Introduction

Natural circulation loops (NCLs) offer a very convenient option of transporting thermal energy from a high-temperature source to a low-temperature sink, without bringing them in direct contact. Elimination of pump and associated accessories considerably simplifies the construction, operation and maintenance of power systems, thereby reducing the fabrication and operating cost quite significantly. NCLs are also characterized by enhanced reliability, increased passive safety and longer thermal response time. Low driving head and possibility of thermal–hydraulic instabilities, however, are major concerns and hence lots of research studies have been reported on such systems, particularly in relation with the working medium. The loop fluid continues to be in the same phase, commonly liquid, throughout the flow path for single-phase NCLs, which are used for heat removal in solar heaters (Close, 1962; Shitzer et al., 1979), PWRs (Delmastro, 2000) and electronic chip cooling (Kim et al., 2008), to name just a few of many possible applications. Higher rate of heat removal and larger circulation rates are associated with two-phase NCLs due to the presence of boiling and/or condensing sections, and hence found application mostly in power industries. Two recent examples can be Economic Simplified Boiling Water Reactor (Rohde et al., 2010) and Advanced Heavy Water Reactor (Sinha and Kakodkar, 2006).

Supercritical Water Reactor (SCWR) is one of most important concepts of Generation-IV initiative of nuclear reactors. Supercritical fluid exhibits very good heat transport capabilities, comparable to single-phase liquid, and high volumetric expansion, of the order to boiling mixture. It also provides the added advantage of higher projected efficiency, elimination of bulky accessories like separator and dryer and compact size in power producing systems. Hence supercritical fluid has been identified as another promising working fluid for NCLs and supercritical natural circulation loop (SCNCL) has attracted significant attention from researchers over the last decade. The notable examples of SCNCLs are S5G and S8G US naval reactors (http://en.wikipedia.org.wiki/S5G_reactor). It is a relatively new concept, with lots of potential for application to nuclear industry in near future. Hence it is essential to summarize the research outcome till date to present a comprehensive picture of the state-of-the-art of SCNCL and current work focuses precisely on the same, providing a systematic development of SCNCL and ascertain the key topics for future investigations.

2. Steady-state flow characteristics

Steady-state implies a condition where the system parameters are invariant with time. Assessment of steady-state characteristics is important both for system design and performance comparison point of view and hence various theoretical models have been proposed. Chatoorgoon (2001) was probably the first one to develop an analytical model of single-channel SCNCL (Fig. 1), as he presented numerical results using SPORTS (Special Predictions Of Reactor Transients and Stability) code (Chatoorgoon, 1986). He studied both distributed and point heat source and sink, with the point source being a simplified representation to eliminate nonlinear effects. Solving conservation equations for mass, momentum and energy, steady-state flow rate was found to increase with power supply till a maxima and decrease afterwards (Fig. 2). He postulated that the stability threshold for such system can be determined through steady-state analysis using the following criterion.

$$\frac{\partial G}{\partial Q} = 0 \quad (1)$$

Therefore the location of maximum flow rate was identified as the threshold. The value of power corresponding to that maxima was termed as the bounding power. Integration of steady-state momentum equation around the loop also provided a closed-form expression of mass flux having the following form,

$$G^2 = \frac{2dgL_t(\rho_1 - \rho_1)}{\frac{f_1L_1+f_3L_3}{\rho_1} + \frac{f_2L_2}{\rho_2}} \quad (2)$$

Here 1 refers to the section between entrance and heat source, 2 is the hot leg between heat source and sink and 3 is the cold leg of the loop. f_i and ρ_i indicates the friction factor (inclusive of obstruction coefficient) and fluid density in the ith section. A simple equation of state was considered with density being a sole function of enthalpy and no pressure dependence. Couple of non-dimensional parameters were introduced as,

$$Q_b^* = \frac{Q_b}{AG_mh_1}, \qquad G_m^* = \frac{G_m}{\xi\rho_1} \quad (3)$$

Here G_m is the maximum steady-state mass flow rate, Q_b is the bounding power corresponding to maxima of mass flow rate and