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Influence of geometric parameters on thermalhydraulic characteristics of supercritical CO_2 in natural circulation loop

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ABSTRACT

Deterioration of mass flow rate in supercritical natural circulation loops, accompanied by rapid decline in the heat transfer coefficient, is a phenomenon reported both experimentally and theoretically in recent years. It is generally recognised as the consequence of fluid temperature crossing the pseudocritical limit throughout the loop and sets a practicable limit for loop operation. Present study investigates the dependence of such flow-induced deterioration on the associated geometric parameters, with an aim of identifying guidelines for a safer design. Accordingly a computational model of a rectangular loop, with source and sink in opposite horizontal arms, is developed and employed to explore the influence of geometric variables, including diameter, height, width, inclination, corner bends, and heating and cooling lengths and their orientations. Reduction in loop diameter and increase in adiabatic length in the horizontal arms are found to lead towards early initiation of deterioration, while the presence of an optimum loop height is envisaged. Length of heater is predicted to have minimal influence. However, a longer sink is found to be favorable, as that corresponds to a lower level of heat transfer coefficient for identical power supply. Positioning of the source and sink, and the specifications of the corner bends are also observed to impose trivial effect on the overall loop thermalhydraulics, apart from enforcing a pre-defined flow direction and minor centrifugal action respectively. Inclining the loop to vertical results in substantial reduction in the flow rate, owing to lower effective buoyancy, without significantly tampering the initiation of deterioration.

1. Introduction

Natural circulation loop (NCL) is a passive energy transport device, which can absorb thermal energy from a source and deliver it to a sink using buoyancy-driven flow. The general concept for such a system is to have distinct high- and low-temperature sections, connected by adiabatic segments, to form a closed circuit. Positioning the sink at a higher elevation than the source negative density gradient can be created in the direction of gravity, which initiates the motion of the heat-transport fluid through the loop. Absence of any rotating machinery for driving the flow makes it geometrically simpler and economic and also promises enhanced reliability and protection against power failures. Such advantageous features, aided by the flexibility of selecting from a wide range of fluids based on the desired conditions, often supersede the drawbacks of low driving head and stability-related apprehensions. Accordingly NCLs have encroached assorted application fields, encompassing solar heaters (Koffi et al., 2008; Zerrouki et al., 2002), geothermal power extraction (Atrens et al., 2010), high-temperature reactor cooling (Choi et al., 2011; IAEA, 2009), cryogenic refrigerators (Chang et al., 2003) and miniature electronic cooling (Haider et al., 2002), just to name a few. While the working zone for single-phase NCL is reasonably narrow owing to the constraint regarding the saturation temperature, two-phase loops suffer from the possibility of dryout and appearance of different flow regimes with contrasting heat transfer characteristics. Supercritical NCL (SCNCL) comes into the frame to alleviate the above-mentioned complications. While the superior heat transport capability and large volumetric expansion of supercritical fluid allows an excellent opportunity to couple the features of the two traditional versions, absence of exclusive phase-change eliminates bulky components like steam separator and dryer, leading to a more compact design. Therefore SCNCL is highly regarded as one of the technologies for near-future, particularly in the design of Gen-IV nuclear reactors.

Water, similar to the sub-critical devices, is generally considered as the common working fluid in supercritical systems. However, the non-toxic and non-explosive nature of supercritical CO_2 (sCO_2), coupled with its favorable transport properties, has propelled it in the forefront of supercritical research over last couple of decades and SCNCL is no

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Nomenclature

A	cross-sectional area (m^2)
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
g	gravitational acceleration ($m\,s^{-2}$)
Gr_m	modified Grashof number
H	height (m)
k	turbulent kinetic energy ($m^2\,s^{-2}$)
L	length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
p	pressure ($N\,m^{-2}$)
Pr	Prandtl number
$\dot{Q}$	input power (W)
Re	Reynolds number
T	temperature (K)
$\vec{V}_n$	normal velocity ($m\,s^{-1}$)
W	width (m)
x^*	dimensionless space coordinate

Greek symbols

β	volumetric expansion coefficient (K^{-1})
ε	turbulence dissipation rate ($m^2\,s^{-3}$)
ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^1$)

Subscripts and superscripts

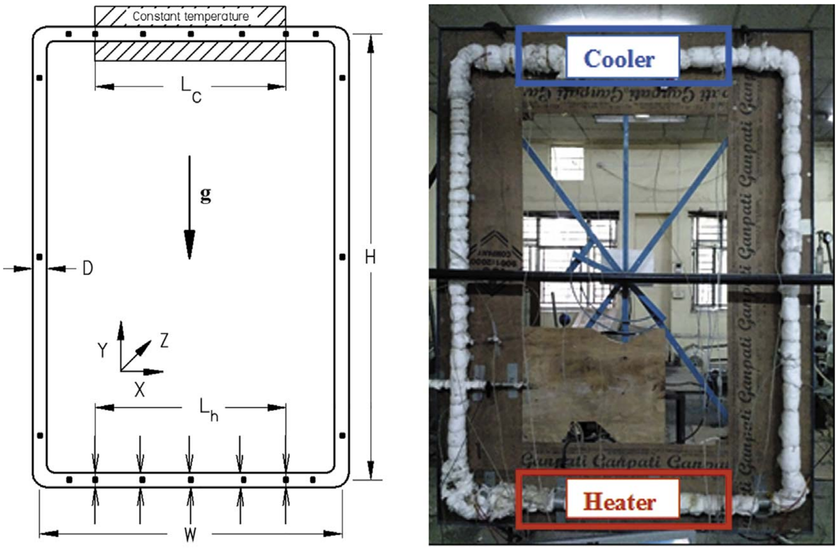
c	cooler
h	heater
pc	pseudocritical

Acronyms

FiHTD	flow-induced heat transfer deterioration
HTD	heat transfer deterioration
NCL	natural circulation loop
SCNCL	supercritical natural circulation loop

exception. The concept of SCNCL was introduced by Chatoorgoon (2001), who developed the first analytical as well as numerical model of single-channel SCNCL for stability analysis. His configuration encompassed both point- and distributed-type heat source and sink. Decent agreement was reported among the two approaches in terms of the bounding power in stable flow. Same methodology was extended by Chatoorgoon et al. (2005a,b) to incorporate CO_2 and H_2 as the loop fluid and facilitate a comparative appraisal. Based on the numerical results, both steady-state and stability characteristics of CO_2 were concluded to be analogous to water at supercritical level. Parameters like input power, height and heated length of the loop were found to affect the loop thermalhydraulics significantly. Subsequently several researchers have explored the role of geometric variables on both steady-state thermalhydraulics and stability characteristics. Chen et al. (2013a) numerically studied a 2-D SCNCL to inspect the influence of inner diameter, aspect ratio, inclination and orientation of heater and cooler. Loop operating temperature was found to greatly affect the heat transfer efficiency of the system, with higher efficiency corresponding to the larger diameter loop. A thorough investigation for various loop diameters was made by Chen and Zhang (2011), as they reported the stabilized flow to correspond to larger diameter loops. Flow in any NCL is initiated by buoyancy, which decreases with increased inclination to vertical plane, leading to reduced flow velocity and inferior heat transfer performance of the loop (Cao and Zhang, 2012; Chen et al., 2013b). At lower heat fluxes, inclination greatly affects the flow field and average value of Nusselt number, while the effects are not so significant for larger heat fluxes. The system was found to be more unstable, with occasional flow reversals, for lower heat fluxes. Orientation of the loop, in terms of the relative positioning of the heater and cooler in particular, has also been reported to have substantial influence (Chen et al., 2013c; Swapnalee et al., 2012). Due to higher effective vertical distance between the heater and cooler, maximum mass flow rate is found to correspond to the geometry with horizontal heater and cooler, whereas it is minimum with both being vertical (Sharma et al., 2012). Therefore it is clearly evident that the geometric parameters can have important role in determining the thermalhydraulic nature of SCNCL. More details on the relevant literature can be found in Sarkar et al., 2014.

An interesting observation was reported by Sarkar and Basu (2015) about the variation in loop flow rate with power under steady-state. Mass flow rate was found to increase with rise in heater power till a maxima, followed by a rapid deterioration in both flow rate and heat



(a)		(b)

Fig. 1. (a) Schematic representation and (b) photographic view of the rectangular loop under analysis.