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Hydrodynamics of a natural circulation loop in a scaled-down steam drum-riser-downcomer assembly

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HIGHLIGHTS

- Experimental investigation of loop hydrodynamics in a scaled-down simulated AHWR.
- Identification of flow regimes and transition analyzing conductance probe signal.
- Downcomer flow maximizes with fully developed churn flow and lowest for bubbly flow.
- Highest downcomer flow rate is achieved with identical air supply to both risers.
- Interaction of varying flow patterns reduces downcomer flow for unequal operation.

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ABSTRACT

Complex interactions of different phases, widely varying frictional characteristics of different flow regimes and the involvement of multiple scales of transport make the modelling of a two-phase natural circulation loop (NCL) exceedingly difficult. The knowledge base about the dependency of downcomer flow rate on riser-side flow patterns, particularly for systems with multiple parallel channels is barely developed, necessitating the need for detailed experimentation. The present study focuses on developing a scaled-down test facility relevant to the Advanced Heavy Water Reactor conceived in the atomic energy programme of India to study the hydrodynamics of the NCL using air and water as test fluids. An experimental facility with two risers, one downcomer and a phase-separating drum was fabricated. Conductivity probes and photographic techniques are used to characterize the two phase flow. Normalized voltage signals obtained from the amplified output of conductivity probes and their subsequent analysis through probability distribution function reveal the presence of different two-phase flow patterns in the riser tubes. With the increase in air supply per riser void fraction in the two-phase mixture increases and gradually flow patterns transform from bubbly to fully developed annular through slug, churn and dispersed annular flow regimes. Downcomer flow rate increases rapidly with air supply till a maximum and then starts decreasing due to enhanced frictional forces. However, the maximum value of downcomer water flow for any magnitude of total air flow can be obtained only for identical air supply through both risers. Any disparity in air flow through the risers has been found to cause as much as 2% reduction in downcomer flow rate owing to the interaction of varying flow patterns through the two riser tubes.

1. Introduction

Flow in a natural circulation loop (NCL) is driven by buoyancy force developed due to density difference between the fluid streams flowing through two parallel vertical branches. Two-phase loops generally have a single-phase liquid in one arm and a two-phase mixture in the other, resulting in high circulation rates owing to the large difference between the density of liquid and vapour phases. Potential of two-phase thermosyphons for fields such as gas turbine blade cooling (Schmidt, 1951) and frozen permafrost (Long, 1963) was demonstrated long back. Hence such loops have established themselves as the principal mode of circulation in nuclear core cooling over last couple of decades, particularly since the Three-Mile-Island incident. The enhanced passive safety of NCLs over their assisted circulation counterparts has been the most attractive feature and so a wide area of dynamic research and development has been opened up. The emergency core cooling mechanism of Dodewaard nuclear reactor of Netherlands (van der Hagen et al., 1997), Economic Simplified Boiling Water Reactor (ESBWR) designed by General Electric (Hinds and Maslak, 2006) and Advanced Heavy Water Reactor (AHWR), next-generation Indian nuclear reactor proposed by BARC (Sinha and Kakodkar, 2006) are fine examples

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of NCL in nuclear power applications. Names of early generation BWRs such as Gentilly-1 and Fugen reactors can also be cited in the present context. Two-phase situation can be achieved in the loop either by phase transition on heating or by introducing the lighter phase in specially designed section. While the former is more relevant to nuclear applications, the latter finds significant use in chemical industries (Joshi, 2001). Despite their external disparity, both systems are comparable in terms of the complicated phasic entrainment, interfacial mass, momentum and energy exchange and inherent hydrodynamics.

Such intricate interactions of associated parameters and involvement of multiple scales of transport variables make it extremely difficult to model two-phase NCLs. Appearance of unstable oscillations in a two-phase NCL for intermediate power ranges and around the boiling point of the water was reported by Wissler et al. (1956) in the very early days of the technology. Two markedly different forms of instabilities were identified by Fukuda and Kobori (1979) during their experiment on a 14 MW heat transfer loop. Despite escalating improvement in computational techniques (Staedtke et al., 2005), presence of large number of case-dependent coefficients, treatment of interfacial transport and choice of closure relations still remain grey areas. Development of a framework to couple the two-group interfacial area transport equations (IATEs) with a modified two-fluid model is only a recent initiative (Ishii et al., 2009). In an effort to eliminate the flow regime dependency, one group IATEs have been incorporated into commercial codes like FLUENT for modelling simple forced flow situations with encouraging results. However, similar endeavour on natural circulation situation is rare in the open literature. That makes the adoption of experimental techniques inevitable for investigating two-phase NCLs. That is particularly relevant for industrial processes having complex geometrical construction and unknown physical interpretation. Methodical study of different hydrodynamic behaviour with such an experimental facility can contribute a great deal towards future development of theoretical models.

Identification of flow regime is an important aspect of any two-phase system and even more so for two-phase NCLs, as the frictional characteristics strongly depend on the prevailing flow pattern. Accordingly, the circulation rate is adjusted which again may lead to a change in flow pattern thereby forming a self-correcting system. Drastic change in flow pattern due to small modification in the flow rate may also lead to system instability, as has been illustrated by Boure et al. (1973), Kakac (1985), Prasad et al. (2007) and Bhattacharyya et al. (2012). Nayak et al. (2003) showed that it is a static instability having characteristics similar to flow excursion, but is generally of more importance than typical Ledinegg instability in two-phase NCLs. Jeng and Pan (1999) have earlier proved that flow pattern transition can significantly affect even the steady-state. Hence large number of researchers has worked on flow pattern identification in multiphase systems. Early day efforts of Hewitt and Roberts (1969) for vertical up flow and Baker (1954) and Taitel and Dukler (1976) for adiabatic horizontal tubes are well-cited studies in forced flow. The diabatic flow pattern maps of Kattan et al. (1998) and Wojtan et al. (2005) and the map proposed by Tabatabai and Faghri (2001) for miniature channels are also worth mentioning. A comprehensive review of proposed gas-liquid flow-pattern maps has been presented by Cheng et al. (2008), which covered maps for macro- and micro-scale channels, tube bundles, diabatic and adiabatic conditions and even microgravity and highly viscous Newtonian fluids. Paranjape et al. (2012) developed an electrical impedance void metre for flow regime identification in an adiabatic channel of 780 μm diameter. Image processing algorithm was employed for calibrating their device, whereas probability density functions of void fraction fluctuations, coupled with neural network based self-organizing map algorithm for pattern recognition, were used for data processing.But similar attempts for NCLs are quite rare in open literature. Flow regimes were reported by Hsu et al. (1998) for a hot leg U-bend loop simulating LWR. Hsieh et al. (1997) employed dynamic image processing techniques on the riser of an NCL to identify four different modes of flow. Time percentage of each flow pattern during chaotic mode was observed to be quite sensitive to the experimental conditions. The influence of channel geometries on flow regime and heat transfer was investigated by Khodabandeh and Furberg (2010). Three different flow regimes were identified, namely, bubbly flow with nucleate boiling, confined bubbly/slug flow with backflow for small channel height and slug/churn flow at high heat fluxes. Different techniques have also been employed to identify the flow pattern, ranging from differential pressure fluctuations (Matsui, 1984) to photographic techniques (Yang and Shieh, 2001). However, most of such efforts were limited to forced flows.

Another important aspect of two-phase NCL hydrodynamics is the dependence of downcomer flow on the riser-side flow pattern and the situation becomes particularly complicated with the presence of multiple parallel channels. But that is the most common occurrence for power boilers and nuclear reactor cores. Chato (1963) was probably the first to develop a generalized model of several vertical parallel channels connected between two isothermal headers and perform experiments on a three-channel system identifying multiple metastable flow patterns. Sen and Fernandez (1985) mathematically analyzed a system of multiple tubes, having varying lengths and orientations, connected between two common points. Zvirin et al. (1981) experimentally studied a loop with electrical heating on one arm and convective cooling on two other parallel arms. About 30% discrepancy was noted between two sets of results and that was attributed to the 3-D nature of the real flow field. However practical systems generally have larger number of risers compared to downcomers. For example, AHWR has 113 riser and 4 downcomers connected to each steam drum (Sinha and Kakodkar, 2006). Number of experimental investigations were performed over the last decade to explore the stability aspects of multiple-channel NCLs (Chen et al., 2001; Linzer and Walter, 2003; Marcel et al., 2010; Jain et al., 2010). However, the difference in flow rates through parallel risers and resultant disparity in flow patterns can also adversely affect the flow through downcomers and hence the whole working of loops. Hardly any indication about possible consequences is found from literature and any proposition can be obtained only through a comprehensive experimental study. Therefore present work focuses on developing an experimental facility in the form of a two-phase NCL with multiple parallel channels. As the application area concerns principally nuclear core cooling, any of the two-phase NCL-based reactor designs cited earlier can be considered as the prototype. The Indian AHWR has been taken as the prototype for the present study, mainly due to the availability of relevant information. Suitable scaling methodology will be followed to develop a facility for lab-scale investigations. The developed facility has been decided to have multiple parallel channels connected with a separator drum, thereby giving a feel of real-life systems. It has also been decided to introduce pressurized air into liquid stream, in order to achieve two-phase condition. The facility will be made of transparent acrylic materials, in order to have visual access and also to employ photography. Major objective of the study is to understand NCL hydrodynamics in terms of flow regimes and dependence of downcomer flow on riser flow rates.

2. Experimental facility

2.1. Development of scaled-down facility

Performing phenomenological experiments on real industrial-scale system is not only expensive and time-consuming, but may