Chapter 9
Supercritical Natural Circulation Loop:
A Technology for Future Reactor

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ABSTRACT

Supercritical natural circulation loop is a compelling technology for cooling of modern nuclear reactors, which promises enhanced thermal-hydraulic performance in a simple design. Being a new concept, related knowledge base is relatively thin and involves several conflicting theories and controversies. The chapter summarizes the observation till date, starting from the very fundamentals. The phenomenon of natural circulation under steady state condition and suitability of supercritical medium as working fluid are discussed in detail. Different methods of analyses, including analytical, simple 1-d numerical, and multidimensional computational codes, as well as experimental, are elucidated. A comprehensive discussion is presented about the effect of various geometric and operating parameters on the system behavior, from both thermal-hydraulic and stability point of view. Finally, a few recommendations are included about the operation of such loops and future direction of research.

DOI: 10.4018/978-1-7998-5796-9.ch009

INTRODUCTION

The term *circulation*, in the engineering sense, refers to the transport of a fluid through a closed circuit. When such transmission takes place at the absence of any designated prime mover and solely because of a favorable density gradient across the loop under the influence of a body force, it is referred to as *natural circulation*. The term *internal natural convection* describes *flows arising in a body of fluid contained in a cavity or completely bounded by surfaces*. The most distinctive characteristics of natural circulation systems are their high sensitivity to the operative conditions and predisposition towards instability, predominantly due to the resilient pairing between flow and temperature fields. Considerably lower circulation rate, in contrast to the loops with prime movers, ensures identical orders of momentum and viscous dissipations, with negligible inertial effect, and the pivotal role of the prevailing body force field, commonly gravity. Accordingly, the flow field appears as an implicit function of numerous constituents encompassing geometry, boundary conditions and location, and hence is implausible to envisage without a comprehensive exploration.

Natural circulation loops (NCLs), despite the mathematical intricacy, proposes a convenient route of energy and species transport. The density differential can be accomplished either by introducing a lighter phase into the primary fluid or by modulating fluid temperature through complementary energy interactions with the surrounding in different segments of the flow path. The later contrives a proficient option of energy transport from a high-temperature source to a low-temperature sink, without them in direct contact. Warmer fluid from the source can rise to the sink owing to buoyancy, to dispense the accrued energy there, and return as a cooler medium, prepared to accumulate energy from the source again. Therefore, it is obligatory to place the sink at a higher elevation than the source to establish the favorable buoyancy field, and that generally remains the only constraint for an NCL configuration. Such simplicity in construction to suit any physical silhouette and enhanced reliability due to the omission of rotating machinery have stimulated innumerable engineering innovations, ranging from gigantic power cycles, nuclear plants, and automobiles, through domestic refrigeration (Kaga, Nomura, Seki, & Hirano, 2008), chemical processes (Joshi, 2001) and solar heaters (Close, 1962), to miniature chip cooling (Kim, Kim, Cha, & Kim, 2008), with undisputed success.

It is improbable to converge on any initiation period for commercial utilization of NCLs as heat transport systems. One of the pioneering applications can be identified in the early-1950s for turbine rotor cooling. Several arrangements have historically been proposed and developed with varying nature of the working medium, shape, and imposed body force. A complete list of classification is shown in figure 1. While the other factors are typical to a situation, the selection of operating fluid is generally governed by the operation convenience and range of parameters explored. Single-phase, mostly liquid-based, loops are favored in PWRs, solar heaters, and electronic cooling applications, whereas two-phase systems, comprising distinct boiling and condensing sections, are prevalent in power cycles, refrigerators, and heat pipes. Both are well-explored devices and under scrutiny since the very inception of the concept of NCL. The supercritical NCL, however, is a relatively new concept, with the pioneering research paper being publicized only in the late 1990s. A significant count of theoretical and experimental studies have followed over the next one and half-decades, only to propose several contradicting theories about the system performance on both thermal-hydraulic and stability aspects, leaving a reasonably thin knowledge base. Reported observations not being in consensus makes it very difficult for the beginners to grasp the initial concepts, which prepares the backdrop of the present chapter. The following segment will discuss the suitability of supercritical fluid as the working medium in NCL and also narrate the