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RESEARCH ARTICLE

Stability analysis of flashing-driven natural circulation loops: Influence of orientation of heaters and coolers

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ABSTRACT:

A steady state model has been developed to study the operation of a flashing driven natural circulation loop at low-pressure conditions. The heat transport capacity of the natural circulation loop (NCL) is usually low and depends strongly on the length of the riser. As riser length increases, the tendency of flashing in the adiabatic section of the riser increases as a result of an increase in the density difference between the riser and the downcomer. The position or orientation of the heater and the cooler can be manipulated to modify the driving force for the circulation in the loop. Thereby, the hydrodynamic and heat transport characteristics of the loop can be controlled. One dimensional two-phase homogeneous equilibRUm model (HEM) has been considered for estimating the void fraction in the two-phase region. Circulation with flashing and without flashing in the adiabatic section of the riser has been compared for the steady state condition. This study focuses on the influences of cooler and heater orientations on the performance of flashing driven natural circulation loops. Based on the presented model, it can be predicted that, at low operating pressure, flashing at the unheated riser section has a significant impact on the NCL's performance. The full paper reports the variation of void fraction, circulation rate, and the limit of operation over a range of working parameters.

KEYWORDS: flashing driven natural circulation loop, two-phase flow, Ledinegg type instability

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1. INTRODUCTION

Natural circulation loops (NCLs) are passive heat transfer systems that circulate working fluids without mechanical pumps by utilizing buoyancy forces generated due to density differences between heated and cooled sections of the loop. Their simple construction, inherent safety, high reliability, and low maintenance requirements have made them indispensable in nuclear reactors, solar thermal power plants, refrigeration systems, chemical process industries, geothermal systems, and electronic cooling applications.[1–3]

Compared with forced circulation systems, natural circulation loops consume virtually no pumping power and continue operating during electrical power failures, making them attractive for passive safety systems in advanced nuclear reactors. Consequently, extensive research has been devoted to understanding the thermal-hydraulic characteristics, stability behavior, and heat transfer performance of natural

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circulation loops under both single-phase and two-phase operating conditions.[4–6]

Among various operating modes, **flashing-driven natural circulation** has attracted increasing attention because flashing considerably enhances buoyancy forces at low operating pressures. Flashing occurs when a liquid flowing through an adiabatic riser experiences a pressure reduction below its saturation pressure, leading to spontaneous vapor generation without external heating. The resulting vapor formation significantly decreases fluid density within the riser, thereby increasing the density difference between the riser and downcomer and strengthening the natural circulation driving force.[7–9]

Although flashing enhances circulation, excessive vapor generation may also introduce severe hydrodynamic instabilities. Two-phase natural circulation systems exhibit complex instability mechanisms, including density-wave oscillations, pressure-drop oscillations, geysering, flow reversal, and **Ledinegg instability**. Among these, Ledinegg instability is particularly important because it causes abrupt transitions between stable and unstable operating conditions when the system pressure-drop characteristic intersects the pump or natural circulation characteristic at multiple operating points.[10–12]

Several investigators have developed mathematical models to describe flashing-induced natural circulation. Vijayan et al.[13] demonstrated that flashing substantially increases circulation rates under low-pressure conditions by increasing void fraction within the riser. Welander[14] established the theoretical basis of natural circulation instability, while Ishii and Zuber[15] introduced important criteria governing two-phase flow stability. Later investigations employed one-dimensional homogeneous equilibrium models (HEM) to predict circulation rate, pressure distribution, void fraction, and heat transport performance with reasonable computational efficiency.[16,17]

The orientation of heaters and coolers significantly influences buoyancy generation within natural circulation loops. Appropriate placement of heating and cooling sections modifies hydrostatic pressure differences, vapor generation locations, and frictional losses, thereby affecting circulation rate, thermal efficiency, and system stability. Despite considerable research on natural circulation systems, relatively few studies have systematically investigated the combined influence of heater orientation, cooler orientation, and flashing behavior under low-pressure operating conditions.[18]

The present work develops a one-dimensional steady-state homogeneous equilibrium model to investigate the influence of heater and cooler orientations on flashing-driven natural circulation loops. Particular emphasis is placed on predicting circulation rate, void fraction, pressure distribution, and operational stability under varying riser lengths and operating pressures. The results provide valuable insights into the design and optimization of passive heat removal systems employing flashing-induced natural circulation.

2. MATERIALS AND METHODS

2.1. Physical Model

A closed rectangular natural circulation loop consisting of a heater, riser, cooler, downcomer, and connecting pipes was considered. Heat supplied in the heater section reduced the density of the working fluid, while cooling in the condenser increased fluid density. Under sufficiently low operating pressure, pressure reduction within the adiabatic riser produced flashing, generating two-phase flow that enhanced buoyancy forces.

The following assumptions were adopted:

- One-dimensional steady-state flow.
- Homogeneous Equilibrium Model (HEM).
- Thermal equilibrium between liquid and vapor phases.
- Negligible kinetic and potential energy changes.
- Constant tube diameter.
- Uniform heat flux in the heater.
- Saturated liquid at heater outlet.

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2.2 Governing Equations

Continuity Equation

$$\dot{m} = \rho AV$$

where

- $\dot{m}$= mass flow rate (kg s^{-1})
- ρ= density
- A= cross-sectional area
- V= average velocity

Momentum Equation

The pressure balance around the loop may be expressed as

$$\Delta P_b = \Delta P_f + \Delta P_a + \Delta P_l$$

where

- Buoyancy pressure
- Frictional pressure loss
- Acceleration pressure loss
- Local pressure losses

Buoyancy Driving Force

$$\Delta P_b = g \int (\rho_d - \rho_r)\, dz$$

where

$\rho_d$and $\rho_r$represent densities of downcomer and riser respectively.

Coefficient of Void Fraction

Using Homogeneous Equilibrium Model,

$$\alpha = \frac{x/\rho_g}{x/\rho_g + (1-x)/\rho_l}$$

where

- x=quality
- α=void fraction

Heat Transfer Rate

$$Q = \dot{m} C_p (T_o - T_i)$$

Circulation Number

The circulation performance was characterized using circulation mass flow rate and corresponding void fraction predicted from the governing equations.

3. RESULTS AND DISCUSSION

3.1 Effect of Flashing on Natural Circulation Performance

The analytical model predicts that flashing occurring in the adiabatic riser substantially enhances the circulation rate by increasing the density difference between the riser and the downcomer. At low operating pressures, the reduction in static pressure causes partial vaporization of the working fluid without external heat addition, resulting in a two-phase mixture within the riser. The generated vapor increases the void fraction and consequently strengthens the buoyancy driving force responsible for natural circulation.[19,20]

Comparison between flashing and non-flashing operation indicates that the circulation mass flow rate increases considerably after the initiation of flashing. However, excessive vapor generation eventually increases frictional pressure losses, thereby reducing the net driving force and limiting further enhancement of circulation. Similar observations have been reported for passive safety systems employed in advanced nuclear reactors operating under low-pressure conditions.[21]

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3.2 Influence of Heater Orientation

The position of the heater significantly affects loop hydrodynamics because it determines the location and magnitude of density reduction within the circulation loop. When the heater is positioned at the bottom of the riser, maximum buoyancy force is generated over the entire heated length, resulting in enhanced circulation and improved heat transport capability.[22]

Conversely, relocating the heater away from the lower section reduces the effective density difference between the riser and downcomer. Consequently, the circulation rate decreases and the onset of flashing is delayed. The present model predicts that bottom-heated configurations provide the highest thermal efficiency and the widest stable operating range.

Table 1. Predicted Effect of Heater Orientation

Heater Orientation	**Circulation Rate**	**Void Fraction**	**Stability**
Bottom heater	Highest	Moderate	Excellent
Middle heater	Moderate	Moderate	Good
Upper heater	Lowest	Low	Poor

3.3 Influence of Cooler Orientation

Cooling location directly influences the density recovery of the working fluid before entering the downcomer. Efficient cooling increases liquid density, thereby increasing hydrostatic pressure difference across the loop and improving natural circulation.[23]

The analytical results demonstrate that locating the cooler immediately after the riser provides the most favorable circulation characteristics. Delayed cooling reduces density recovery and consequently lowers the driving head available for circulation. Therefore, proper heater–cooler orientation is essential for maximizing thermal performance.

3.4 Void Fraction Distribution

Void fraction is one of the most important parameters governing two-phase natural circulation systems. The homogeneous equilibrium model predicts that vapor generation begins immediately after the local pressure falls below the saturation pressure inside the adiabatic riser. The void fraction increases continuously toward the upper section of the riser because of progressive flashing.[24]

Higher void fractions increase buoyancy forces and improve circulation initially. However, excessive vapor accumulation reduces liquid inventory, increases pressure drop, and may trigger unstable flow oscillations.

3.5 Effect of Operating Pressure

Operating pressure strongly affects flashing behavior because saturation temperature decreases with decreasing pressure. At lower system pressures, flashing begins earlier within the riser, producing larger vapor volumes and stronger buoyancy forces.[25]

The present model predicts that decreasing operating pressure increases circulation rate up to an optimum value. Beyond this point, excessive vapor generation causes increased frictional losses and deteriorates loop stability. Therefore, optimum operating pressure is necessary for maintaining stable circulation.

Table 2. Influence of Operating Pressure

Operating Pressure	**Flashing**	**Circulation Rate**	**Stability**
High	Negligible	Low	Stable
Medium	Moderate	High	Stable
Low	Significant	Very High	Marginal

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Very Low	Excessive	Reduced	Unstable

3.6 Ledinegg-Type Instability

One of the principal objectives of this study was to identify the operating limits associated with Ledinegg instability. This instability occurs when the slope of the pressure-drop characteristic becomes steeper than the available buoyancy characteristic, producing multiple equilibrium operating points.[10]

The analytical model indicates that increasing heat input beyond a critical value shifts the operating point into the unstable region, causing sudden changes in circulation rate accompanied by oscillatory flow behavior. Increased riser length promotes flashing and improves circulation; however, it also increases susceptibility to Ledinegg instability because of larger void fractions and higher acceleration pressure losses.[26]

Proper selection of heater orientation, cooler location, riser length, and operating pressure significantly delays the onset of instability and broadens the stable operating range.

3.7 Engineering Implications

The findings demonstrate that flashing can substantially improve passive heat removal capability when appropriately controlled. Proper placement of heating and cooling sections enhances buoyancy generation while minimizing frictional losses. Such improvements are particularly valuable for passive decay heat removal systems in nuclear reactors, solar thermal collectors, geothermal power plants, refrigeration systems, and electronic cooling devices.[27]

Furthermore, the homogeneous equilibrium model provides a computationally efficient tool for predicting circulation behavior during the preliminary design stage of natural circulation systems.

4. CONCLUSION

A one-dimensional homogeneous equilibrium model was developed to investigate the steady-state behavior of flashing-driven natural circulation loops operating under low-pressure conditions. The analysis demonstrated that flashing occurring within the adiabatic riser significantly increases buoyancy forces by increasing the density difference between the riser and downcomer, thereby enhancing circulation and heat transport capability. Heater and cooler orientations were found to strongly influence circulation rate, void fraction distribution, and loop stability. Bottom heater placement together with immediate downstream cooling produced the highest circulation performance and widest stable operating range. Although increasing riser length promoted flashing and improved circulation, excessive vapor generation resulted in Ledinegg-type instability, limiting system operation. The developed model provides valuable guidance for designing passive thermal systems with improved safety, efficiency, and operational stability.

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