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Steady State Performance of Two Phase Natural Circulation Loop: Two Vertical Branches with Point Heat Source and Sink

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Abstract: *A simple one dimensional numerical method is presented for the evaluation of the steady state behaviour of a two phase natural circulation loop. This method is applicable for loop consisting of two vertical limbs connected by point heat source and sink. In this work, Thermo-physical properties are considered as per the loop fluid state. The influence of following parameters such as heat input, inlet subcooling at heat source, loop diameter and height on the loop performance is analysed. Results show that mass flow rate increases with heat input. However, with the increase in heat input, mass flow rate increases initially up to a peak value and thereafter decreases. Also, the increase of loop diameter increases the mass flow rate for all heat inputs. However, increase of loop height has peculiar effect.*

Keywords: Point heat source, Two phase mixture, Quality, Flashing.

I. INTRODUCTION

Natural circulation loop (NCL) is a lucrative choice to transport energy from source to sink without use of any mechanical devices like pump etc. Due to its simplicity in design and reliable in operation, NCL is used in wide range of engineering applications such as solar heaters (Close, 1962; Shitzer, Kalmanoviz, Zvirin, & Grossman, 1979), cooling of turbine blades(Heisler, 1982), nuclear reactors (Hagen, T.H.J.J. van der; Bragt, D.D.B. van; Kaa, F.J. van der; Killian, D.; Wouters, J.A.A.; Karuza, J.; Nissen, W.H.M.; Stekelenburg, 1997) etc. In NCL, fluid circulation is attained due to density difference. This density difference is achieved by either varying the loop fluid temperature (Single-phase NCL) or phase change process (Two-phase NCL).

From the past decades onwards, theoretical and experimentally studies have explore the influence of the parameters such as heater and condenser orientations, geometrical and operating conditions and use of different working fluids on NCL performance. For example, Chen and Chang (K. S. Chen & Chang, 1988) analytically examined the two phase NCL under steady state conditions using homogeneous equilibrium model (HEM) with saturated water–vapour as working fluid. Square and toroidal configurations are considered for their analysis with the assumption of a linear variation in quality of working fluid. The mass flow rate strongly depends on the flow cross sectional area and the two phase zone length. Lee and Mittal (Lee, Sang Yong, 1990) experimentally investigated the two phase thermo-syphon loop performance and validated with the theoretical analysis. N M Rao et al. (Rao, Sekhar, Maiti, & Das, 2006) presented the steady state performance of a two phase NCL with vertical heater and condenser using HEM and thermally equilibrium drift flux model (TEDFM). They reported that loop mass flow rate is depending on geometrical parameters and operating conditions such as heater length, loop height, inlet temperature, pressure & heat flux. Chen (K. S. Chen, 1991) experimentally analysed the steady-state behaviour of two-phase square loop at different heat fluxes and quantity of liquid. At lower liquid inputs, the liquid attains higher temperature and increases the possibility of evaporation in the loop. Chen (L. Chen, Zhang, & Jiang, 2014), Archana et.al.(Archana, Vaidya, & Vijayan, 2015), numerically investigated the steady state characteristics of NCL by using different combination of heaters and coolers. Sudheer et.al.(Sudheer & Kumar, 2018) and Dewangan et.al.(Dewangan & Das, 2018) numerically studied the flashing phenomena in two phase NCLs. Similar works were available in the open literature using different computational techniques.

In the present work, the steady state performance of two phase NCL is numerically estimated. Loop consists of point heat source, sink, riser and downcomer. For this one dimensional approximation is considered. HEM used in two phase regions. The influence of inlet subcooling, heat input, loop height and diameter on loop performance are analysed.

II. THEORETICAL MODELLING

The schematic diagram of NCL with a point heat source and heat sink as shown in Fig.1. These types of loops are idealizations of the actual loops. The loop fluid absorbs the heat from heat source and experiences phase change which rises in the riser. At the sink, loop fluid rejects the heat and condenses completely and returns to source through downcomer. This situates riser is filled with two phase mixture while the downcomer is filled with low density single phase liquid. This thermally induced density difference is the cause for loop fluid circulation. In order to investigate this simple NCL behaviour, the following assumptions are considered.

1. Heater and condenser sections are treated as a point heat source and heat sink respectively. Hence the pressure drop across the source/sink is zero.
2. The thermo-physical properties are considered at system pressure.
3. Viscous dissipation effect and axial conduction are neglected.
4. The riser and downcomer are completely insulated.
5. The minor losses in the loop are neglected.

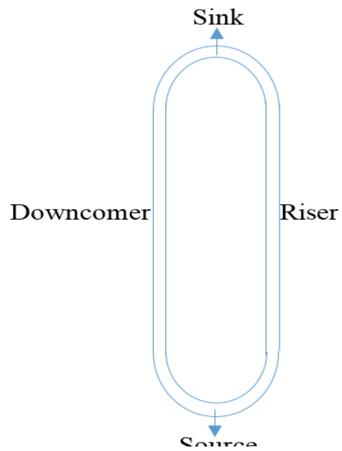


Figure 1: Schematic diagram of NCL

1.2 Governing equations

Steady state 1-D governing equation for conservation of mass is given by

$$\frac{d(\rho u A)}{dz} = 0 \qquad (1)$$

For uniform cross section of the loop above equation is written as

$$\frac{dG}{dz} = 0 \qquad (2)$$

Where G is mass flux (kg/m^2-sec) and z is running coordinate

The 1D momentum equation is derived in terms of pressure gradient. The resulting pressure gradient at every section in the loop as per the loop fluid state is given by

For single phase flow

$$\frac{dp}{dz} = \begin{cases} 0 & \text{Source/Sink} \\ -\left(\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_f}\right) + g\rho_f\right) & \text{Riser} \\ -\left(\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_f}\right) - g\rho_f\right) & \text{Downcomer} \end{cases} \qquad (3)$$

For two phase flow

$$\frac{dp}{dz} = \begin{cases} 0 & \text{Source/Sink} \\ -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(z)\left(\frac{\vartheta_{fg}}{\vartheta_f}\right)\right) - G^2\vartheta_{fg} - \rho_m g & \text{Riser} \\ -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(z)\left(\frac{\vartheta_{fg}}{\vartheta_f}\right)\right) - G^2\vartheta_{fg} + \rho_m g & \text{Downcomer} \end{cases} \qquad (4)$$

Where the single phase friction factor (C_{fo}) is given by

$$C_{fo} = \begin{cases} \dfrac{16}{Re} & \text{for laminar flow} \\ \dfrac{0.079}{Re^{0.25}} & \text{for turbulent flow} \end{cases} \quad (5)$$

The energy conservation equation in the loop is given by

$$m\Delta h = Q$$

$$where\ Q = \begin{cases} Q_h & \text{Source} \\ Q_c & \text{Sink} \\ 0 & \text{Adiabatic sections} \end{cases} \quad (6)$$

The 1D energy equations is derived in terms of enthalpy gradient. The resulting enthalpy gradient in the riser and downcomer sections of the loop as per the loop fluid state is given by

For single phase flow

$$\frac{dh}{dz} = \begin{cases} -\left(G^2\left(\frac{1}{\rho}\right)\right)\left(\frac{d\vartheta}{dp}\right)\left(\frac{dp}{dz}\right) - g & \text{Riser} \\ -\left(G^2\left(\frac{1}{\rho}\right)\right)\left(\frac{d\vartheta}{dp}\right)\left(\frac{dp}{dz}\right) + g & \text{Downcomer} \end{cases} \quad (7)$$

For two phase flow

$$\frac{dh}{dz} = \frac{dx}{dz} h_{fg} \quad (8)$$

Where

$$\frac{dx}{dz} = \begin{cases} \dfrac{-g}{h_{fg} + \left(\frac{G}{\rho_f - \rho_g}\right)^2 \left(x(z) + (1 - x(z)\rho_g)\right)} & \text{Riser} \\ \dfrac{g}{h_{fg} + \left(\frac{G}{\rho_f - \rho_g}\right)^2 \left(x(z) + (1 - x(z)\rho_g)\right)} & \text{Downcomer} \end{cases} \quad (9)$$

III. SOLUTION PROCEDURE

The analysis has been performed by considering the following loop configuration and operating conditions are mentioned in Table 1. In NCL the pressure drop in the loop is used to estimate the mass flow rate. So the loop is discretised into number of section and summing up the pressure drop by using the above set of equations.

Under steady state condition, the total pressure drop in the loop is zero. By fixing the initial condition of the loop at heater inlet (pressure and temperature) and adding the pressure gradient in every section across the loop by using equations 5 and 6 as per the loop fluid state condition, gives equation in the form of

$$f(G, x) = 0 \quad (12)$$

Solve the eq. (12) by using Regual-falsi iterative method.

Table 1: loop configuration and operating parameters

Parameter	Value/Range
Diameter of the pipe (D)	0.01325 m
Height of the loop (L)	1-2 m
Pressure inside the loop (p)	1 bar
Inlet temperature (T_i)	(90 – 95) ^oC
Heat interaction at source/sink ($Q_h = Q_c$)	0.5-10 kW

IV. RESULTS AND DISCUSSION

Fig. 2 depicts the variation of loop mass flow rate at a given heat input range (0.5-10 kW). The developed buoyancy force in the riser and gravitational force in the downcomer are responsible for fluid circulation in the loop. As the heat input increases, loop fluid mass flow rate increases linearly. For a fixed configuration, as the heat input increases, the quality of loop fluid increases (Fig. 3). This is due to the fact that the density difference between riser and downcomer increases with increasing heat. However, it can be observed from Fig. 2 that further increase of heat input results in a decrease in mass flow rate. This is because of the higher frictional drag at higher dryness fractions. So, it can be concluded that there is a limiting heat input value (peak heat input) for each configuration of the loop.

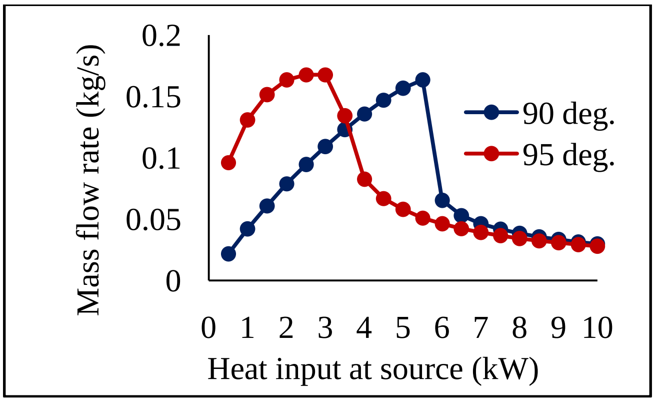


Figure 2: Variation of mass flow rate with respect to heat flux (loop length 1.5 m, diameter 0.01325 m)

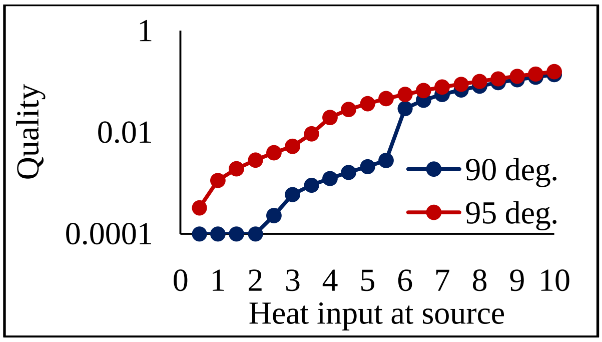
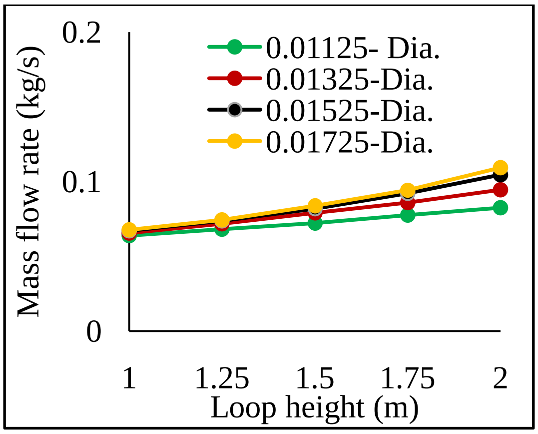


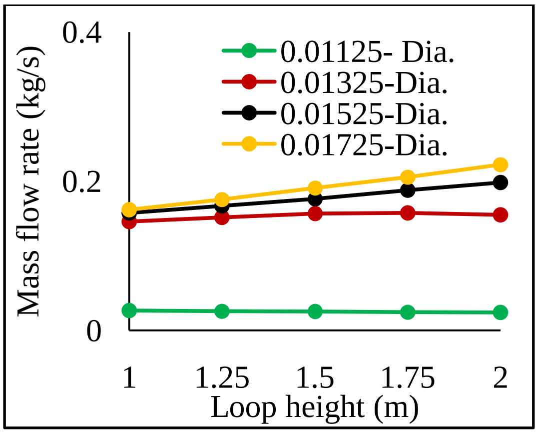
Figure 3: Variation of riser exit quality with respect to heat flux (loop length 1.5 m, diameter 0.01325 m)

The mass flow rate is strongly influenced by loop fluid state condition at the heat source that can be observed in Fig. 2. By decreasing the subcooling degree of the loop fluid at heat source, mass flow rate increases. Peak heat flux values are shifting towards the left as more vapour is available in the riser section. This happens because loop fluid requires less sensible heat to reach saturation state hence the quality increases at heat source. Furthermore, the loop fluid undergoes flashing in the riser section results improvement in the vapour quality that can be observed in Fig.3. This can situates more buoyancy forces in the riser and results higher mass flow rates in NCL.

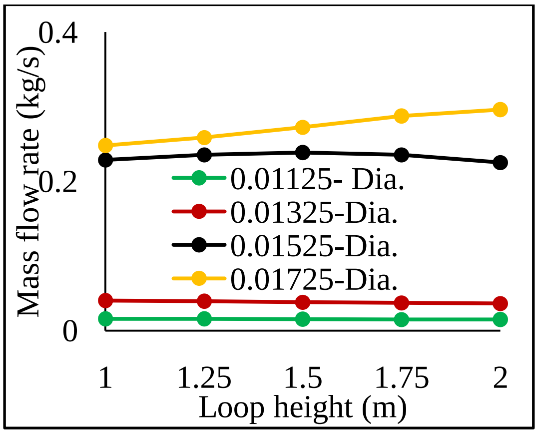
4.1 Influence of degree of subcooling



(a). Inlet temp. 90 ^{O}C, heat input 2 kW



(b). Inlet temp. 90 ^{O}C, heat input 5 kW



(c). Inlet temp. 90 ^{O}C, heat input 8 kW

Figure 4: Effect of loop diameter and height on the mass flow rate

4.2 Influence of loop height and diameter

The loop fluid mass flow rate is expressed as function of loop height and diameter and it is shown in Fig.4 (a), (b) and (c) at the heat inputs of 2, 5 and 8 kW, respectively. The mass flow rate increases with increase in loop diameter at all the heat inputs. As the diameter increases, the frictional force in the loop decreases, hence mass flow rate also increases. The influence of loop height on mass flow rate is strongly depends on the heat input and loop diameter. At the heat input of 2kW, the mass flow rate increases linearly with loop height for all the loops. However, at 5kW heat input, the 0.01125 m dia. loop's mass flow rate has an insignificant variation with loop height. The 0.01325 m dia. loop's mass flow rate increases up to the height 1.75 m, then after mass flow rate decreased. The other two loops (0.01525 m dia. and 0.017525 m dia.) increases the mass flow rate with loop height. Similarly at 8kW heat input the 0.01125 and 0.01325 m dia. loops mass flow rates have an insignificant variation with loop height. The 0.01525 m dia. loop's mass flow rate increases up to the 1.5 m height, and there after decreases. The 0.01725 m dia. loop's mass flow rate linearly increases with loop height. The increase of loop height is not always preferable and is dependent on loop diameter and heat input. The credible reason for the peculiar mass flow rates with increase of loop height is as follows. In riser section the loop fluid undergoes flashing and increases the quality. As the loop height increases more vapour is formed due to flashing. This vapour quality in the riser solely cause for either increases or decreases the mass flow rate.

V. CONCLUSIONS

In the present work, a simple numerical model for steady state performance of a two phase natural circulation loop (NCL) is presented. Loop consists of point heat source, sink, riser and downcomer. One dimensional approximation is considered to simplify the problem. The mass flow rate in the loop is obtained by balancing the buoyancy and opposed frictional forces. Loop parameters such as diameter and height (geometric) and degree of subcooling (operating parameter) are varied to know the effect on NCL performance.

The following important conclusions are drawn from this study:

- Two phase NCLs performance is influenced by different parameters such as inlet temperature of loop fluid, loop height, diameter and heat input.
- In two phase NCL, for a given configuration and operating conditions, loop exhibits maximum mass flow rate as heat input varies. It is advantageous to operate NCL at these conditions.
- The increase of quality in the loop is not always favourable. There is a limiting quality beyond which further increment drags the loop performance.
- The increases of loop diameter always increase the mass flow rate. Whereas the increase of loop height is not always favourable.
- The flashing phenomena in the loop fluid increases in the riser section with loop height and also increases vapour quality. This situation helps to increase the mass flow rate up to only a certain limit. Thereafter the vapour quality in the riser offers more drag results into decrease in the mass flow rate.

Acknowledgement

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Conflict of Interest

We have no conflict of interest and we are not at published same work elsewhere.

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