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

**S V Sai Sudheer[a], K. Kiran Kumar[a], Karthik Balasubramanian[a], Ramesh Babu B[b]**
[a]*Department of Mechanical Engineering, National Institute of Technology, Warangal-506004,Telangana,India*
[b]*Department of Mechanical Engineering, Sasi Institute of Technology & Engineering,, Tadepalligudem-534101, Andhra Pradesh, India*

*Corresponding author Email: svsaisudheernitw@gmail.com

## 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 branches with a 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 sub cooling at heat source, loop diameter and height on the loop performance is analysed. Results show that the mass flow rate increases with heat input. However, with the increase in heat input, the mass flow rate increases initially up to a certain value and there after decreases. It is also observed that increase of loop diameter increases the mass flow rate. However increase of loop height has peculiar effect.

**Keywords** Point heat source, two phase mixture, Quality, Flashing

## 1. Introduction

Natural circulation loop (NCL) is lucrative choice to transport energy from source to sink without aid of any mechanical devices like pump etc. Due to simple in design and reliable in operation NCL is used in wide range of engineering applications such as solar heaters [1], [2], cooling of turbine blades[3], nuclear reactors [4] etc. In NCL the circulation of the fluid is attained due to density difference in the loop. This density difference is achieved by either varying the temperature of the loop fluid (Single-phase NCL) or phase change process (Two-phase NCL).

From the past decades onwards, theoretical and experimentally studies are explore the effect of 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 [5] analytically examined the two phase NCL under steady state conditions using 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 depends on the two phase zone length and flow cross sectional area. N M Rao et al. [6] presented the steady state performance of a two phase NCL with vertical evaporator and vertical 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. Lee and Mittal [7] experimentally investigated the performance of a two phase thermo-syphon loop filled with Freon-11 and water and are validated with the theoretical analysis.

The present work aims to numerically investigate the fluid flow behaviour of the two-phase NCL using water as the loop fluid. In this study, the point heat source and heat sink are considered. The effect of loop height, diameter, inlet sub cooling and heat input on loop performance are analysed. For this study, an in-house MATLAB code developed to solve the loop governing equations.

**NOMENCLATURE**

| | | | |
|---|---|---|---|
| A | Flow cross sectional area, $m^2$ | $C_{fo}$ | Single phase friction factor |
| m | mass flow rate, kg/s | G | Mass flux, $kg/m^2$ s |
| g | Acceleration due to gravity, $m^2/s$ | $x$ | Dryness fraction, dimension less |
| D | Diameter, m | $L$ | Loop height, m |
| $Q_h$ | Heat input at the source, kW/m | $Q_c$ | Heat output at sink, kW/m |
| h | Enthalpy, kJ/kg | T | Temperature, $^oC$ |
| p | Pressure, $N/m^2$ | $dp/ds$ | Pressure gradient, $N/m^2$ |
| s | Space coordinate, m | | |
| ρ | Density, $kg/m^3$ | $v$ | Specific volume, $m^3/kg$ |
| $\mu$ | Viscosity, kg/ms | | |

*Subscripts*

| | | | |
|---|---|---|---|
| f | Saturated liquid/frictional | g | Saturated gas(vapour)/gravitational |
| a | Acceleration | | |
| fg | Difference between gas(vapour) and liquid properties at saturated state | | |

## 2. Theoretical modelling

The schematic diagram of NCL with point heat source and heat sink as shown in Fig.1. These types of loops are idealizations of the actual loops. In this, source and sink are connected by two vertical adiabatic limbs called as riser and downcomer. The loop fluid absorbs the heat from heat source and undergoes phase change and rises in riser. At the sink, loop fluid rejects the heat and completely condensates, returns to source through downcomer. Hence, riser and downcomer is filled with low density two phase mixture and high density single phase liquid respectively. This thermally induced density difference is cause for the loop fluid circulation. In order to investigate this simple NCL behaviour the following assumptions are considered.

1. Heater and condenser sections are treated as point heat source and heat sink respectively. Hence the pressure drop across the source/sink is/was 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.

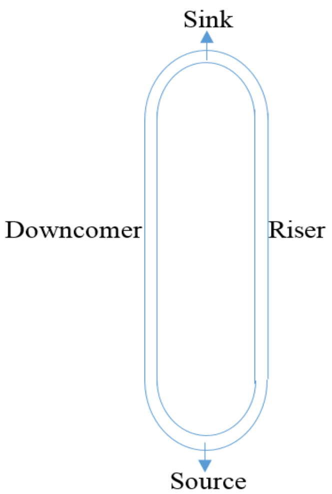


Fig.1 Schematic diagram of NCL

Using the homogeneous flow model the mean density of the two phase mixture is written as:

$$\frac{1}{\rho_m} = \frac{x}{\rho_g} + \frac{1-x}{\rho_f} \qquad 1$$

The friction factor for two phase flow has been evaluated using mean two phase viscosity $\mu_m$ in the standard single phase friction factor equations and is given by [8]

$$\frac{1}{\mu_m} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f} \qquad 2$$

### 2.1 Governing equations

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

$$\frac{d\left(\rho_m u A\right)}{ds} = 0 \qquad 3$$

For uniform cross section of the loop above equation written as

$$\frac{dG}{ds} = 0 \qquad 4$$

Where G is mass flux (kg/m$^2$-sec) and s is running co – ordinate

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

$$\frac{dp}{ds} = \begin{cases} 0 & \text{Source/Sink} \\ -\left(\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_f}\right) + g\rho_f\right) & \text{Riser} \\ -\left(\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_f}\right) - g\rho_f\right) & \text{Downcomer} \end{cases} \qquad 5$$

For two phase flow

$$\frac{dp}{ds} = \begin{cases} 0 & \text{Source/Sink} \\ -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(s)\left(\frac{v_{fg}}{v_f}\right)\right) - G^2 v_{fg}\frac{dx}{ds} - \rho_m g & \text{Riser} \\ -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(s)\left(\frac{v_{fg}}{v_f}\right)\right) - G^2 v_{fg}\frac{dx}{ds} + \rho_m g & \text{Downcomer} \end{cases} \qquad 6$$

Where $C_{fo}$ is the single phase friction factor and it is estimated as

$$C_{fo} = \frac{16}{\text{Re}} \text{ for laminar flow}$$
$$C_{fo} = \frac{0.072}{\text{Re}^{0.25}} \text{ for turbulent flow} \qquad 7$$

The energy conservation equation in the loop is given by

$$m\Delta h = Q$$

$$Where\ Q = \begin{cases} Q_h \text{ (source)} \\ Q_c \text{ (sink)} \\ 0 \text{ (adiabatic sections)} \end{cases} \quad 8$$

The 1D energy equation 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

$$\frac{dh}{ds} = \begin{cases} -\left(G^2\left(\frac{1}{\rho}\right)\right)\left(\frac{d\upsilon}{dp}\right)\left(\frac{dp}{ds}\right)\text{-g} \quad \text{Riser} \\ -\left(G^2\left(\frac{1}{\rho}\right)\right)\left(\frac{d\upsilon}{dp}\right)\left(\frac{dp}{ds}\right)\text{+g} \quad \text{Downcomer} \end{cases} \quad 9$$

For two phase flow

$$\frac{dh}{ds} = \frac{dx}{ds} h_{fg} \quad 10$$

Where

$$\frac{dx}{ds} = \begin{cases} \dfrac{\text{-g}}{\left(\mathrm{h_{fg}} + \left(\dfrac{G}{\rho_f \rho_g}\right)^2 \left(\rho_f - \rho_g\right)\left(x(s) + (1 - x(s)\rho_g\right)\right)} \quad \text{Riser} \\ \dfrac{\text{g}}{\left(\mathrm{h_{fg}} + \left(\dfrac{G}{\rho_f \rho_g}\right)^2 \left(\rho_f - \rho_g\right)\left(x(s) + (1 - x(s)\rho_g\right)\right)} \quad \text{Downcomer} \end{cases} \quad 11$$

## 2.2 Solution procedure

The analysis has been performed by considering the following loop configuration and operating conditions and is given in Table 1.

Fixing the initial condition of the loop and adding the pressure gradient in every section, gives equation in the form of

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

The steady state solution of two phase NCL is obtained by assuming the mass flux and solve the eq. (12) using a suitable iterative procedure.

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 ($T_i$) | (88 – 90) °C |
| Heat interaction at source/sink ($Q_h = Q_c$) | 0.5-10 kW |

## 3. Results and discussion

Steady state performance of a two phase rectangular NCL, having point heat source and heat sink at atmospheric pressure, is numerically estimated by solving the governing equations. Loop performance is analysed by varying the inlet sub cooling degree, diameter and height of the loop under different heat inputs. Fig. 2 shows the variation of loop mass flow rate at different heat inputs. The developed gravitational force in the downcomer and buoyancy force in the riser are responsible for circulation of fluid in the NCL. As the heat input increases, the mass flow rate of the system 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, density difference between riser and downcomer increases with increasing heat. However, it can be observed from the Fig. 2 that further increase of heat input results in decrease in flow rates. This is due to 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.

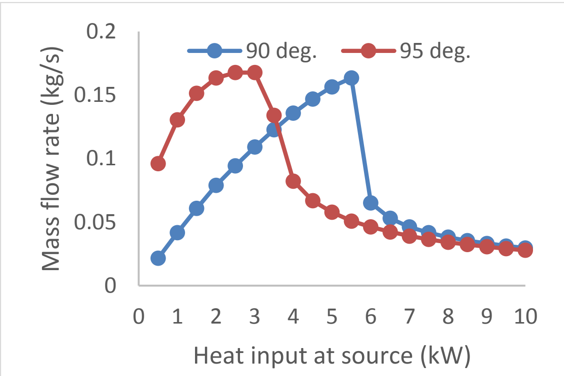



Fig.2 Variation of mass flow rate with respect to heat flux (loop length 1.5 m, diameter 0.01325 m)

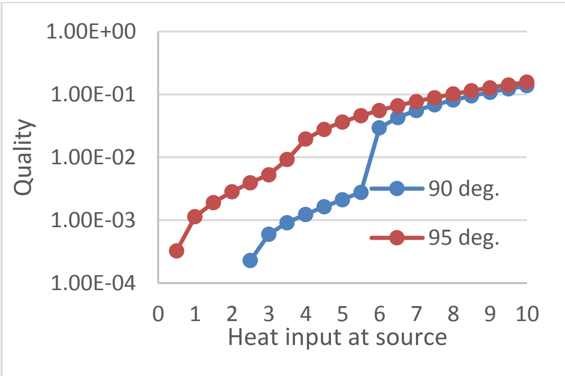
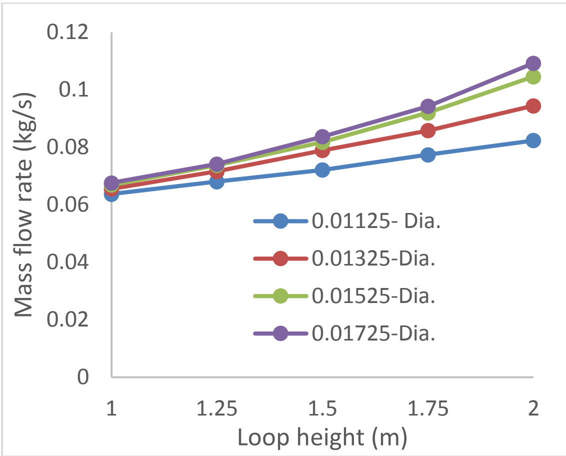


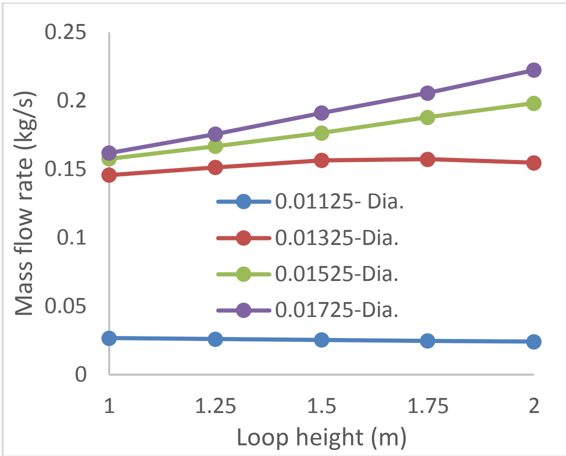

Fig.3 Variation of riser exit quality with respect to heat flux (loop length 1.5 m, diameter 0.01325 m)

### 3.1 Influence of degree of sub cooling

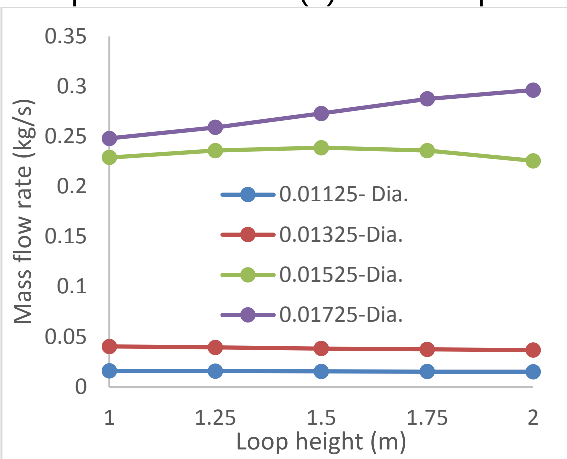
Fig. 2 depicts that, mass flow rate is strongly influenced by loop fluid state condition at the heat source. Decreasing the sub cooling degree of the loop fluid at heat source, mass flow rate increases. Peak heat flux values are shifting towards the left as more vapour is available in the riser section. 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 into increase in 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.




(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

Fig.4 Effect of loop diameter and height on the mass flow rate

### 3.2 Influence of loop diameter and height

The mass flow rate is expressed as function of loop diameter and height and shown in Fig.4 (a), (b) and (c) at the heat inputs of 2, 5 and 8 kW, respectively. The mass flow rate is 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, mass flow rate linearly increases with loop height for all the loops. However, at 5kW heat input, the 0.01125 m dia. loop's mass flow rate has insignificant variation with loop height. The 0.01325 m dia. loop's mass flow rate increases up to the 1.75 m height, 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 has insignificant variation with loop height. The 0.01525 m dia. loop's mass flow rate increases up to the 1.5 m height, then 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 formed due to flashing. This vapour quality in the riser solely cause for either increases or decreases the mass flow rate.

## 4. Conclusions

The steady state performance of a two phase natural circulation loop (NCL) having point heat source and sink is analysed. One dimensional approximation is considered to simplify the problem. The mass flow rate in the loop is obtained by balancing the buoyancy and opposing frictional forces. Loop parameters such as diameter and height and operating parameter degree of sub cooling are varied to know the effect on NCL performance.

The following important findings are noted during the analysis

- Two phase NCLs performance is affected 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 increases the mass flow rate. Whereas the increase of loop height has not always favourable.
- The flashing phenomena in the loop fluid is increases in the riser section with loop height and increases vapour quality. This situation helps to increase the mass flow rate up to certain limit only. Then after the vapour quality in the riser offers more drag results into decrease in the mass flow rate.

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