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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 sub cooling 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 there after decreases. The increase of loop diameter increases the mass flow rate at all heat inputs. 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 use 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, 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 are explore the influence of the following 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 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 [6] experimentally investigated the two phase thermo-syphon loop performance and validated with the theoretical analysis. N M Rao et al. [7] 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.

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 sub cooling, heat input, loop height and diameter on loop performance are analysed.

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. The loop fluid absorbs the heat from heat source and experiences phase change and rises in riser. At the sink, loop fluid rejects the heat and completely condensates, returns to source through downcomer. This situates riser is filled with two phase mixture and downcomer is filled with low density single phase liquid. 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.

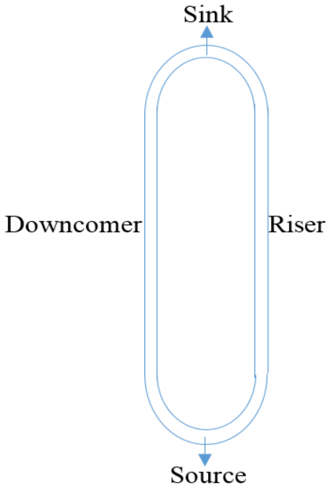


Fig.1 Schematic diagram of NCL

2.1 Governing equations

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

$$\frac{d\left(\rho_m uA\right)}{dz}=0 \quad 1$$

For uniform cross section of the loop above equation written as

$$\frac{dG}{dz}=0 \quad 2$$

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

0 Source/Sink

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

For two phase flow

0 Source/Sink

$$\frac{dp}{dz} = \begin{array}{ll} -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(s)\left(\frac{v_{fg}}{v_f}\right)\right) - G^2 v_{fg} \frac{dx}{dz} - \rho_m g & \text{Riser} \\ -\left(\frac{2}{D}\right) C_{fo} G^2 \left(\frac{1}{\rho_m}\right)\left(1 + x(s)\left(\frac{v_{fg}}{v_f}\right)\right) - G^2 v_{fg} \frac{dx}{dz} + \rho_m g & \text{Downcomer} \end{array} \qquad 4$$

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

$$C_{fo} = \frac{16}{\text{Re}} \text{ for laminar flow}$$
$$C_{fo} = \frac{0.072}{\text{Re}^{0.25}} \text{ for turbulent flow} \qquad 5$$

The energy conservation equation in the loop is given by

$$m\Delta h = Q$$

$$Where\ Q = \begin{array}{ll} Q_h & \text{(source)} \\ Q_c & \text{(sink)} \\ 0 & \text{(adiabatic sections)} \end{array} \qquad 6$$

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

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

For two phase flow

$$\frac{dh}{dz} = \frac{dx}{dz} h_{fg} \qquad 8$$

Where

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

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

$$f(G, x) = 0 \tag{10}$$

The steady state solution of two phase NCL is obtained by assuming the mass flux and solve the eq. (10) 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) ^oC
Heat interaction at source/sink ($Q_h = Q_c$)	0.5-10 kW

3. 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, 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 mass flow rate. 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.

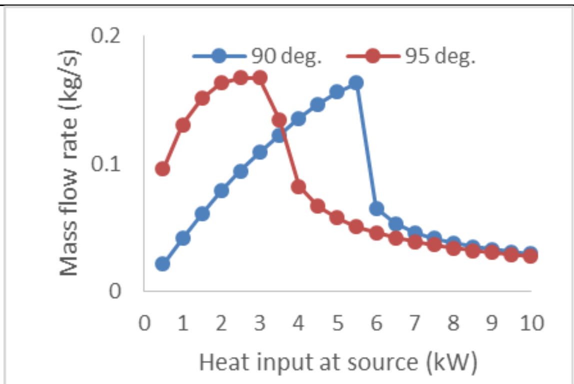


Fig.2 Variation of loop fluid circulation rate with heat input (loop length 1.5 m, diameter 0.01325 m)

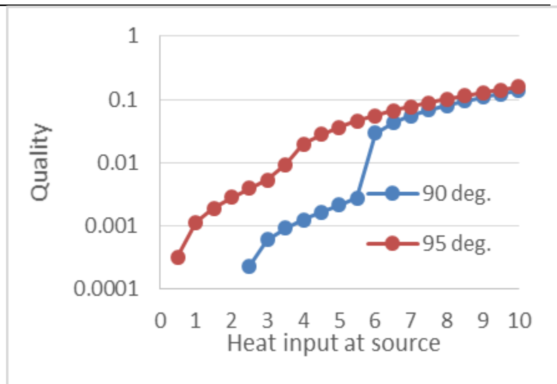
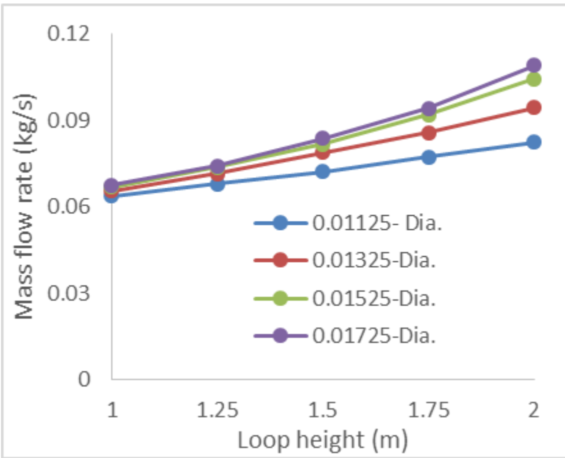


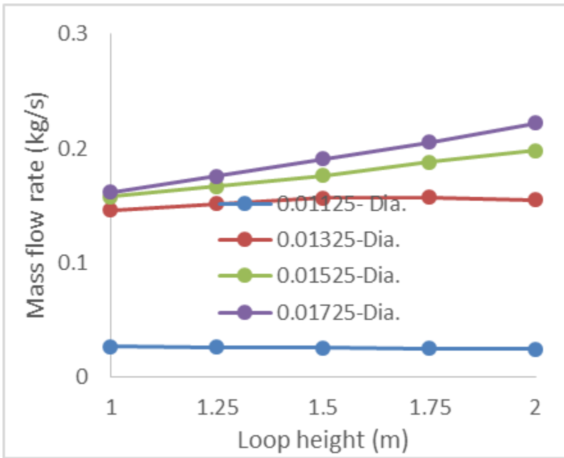
Fig.3 Variation of riser exit quality with heat input (loop length 1.5 m, diameter 0.01325 m)

3.1 Influence of degree of sub cooling

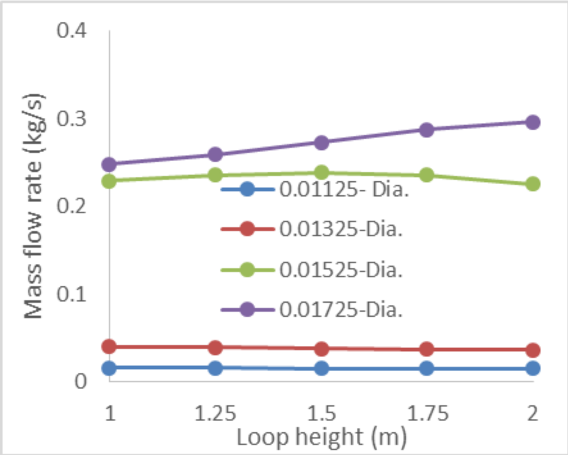
Mass flow rate is strongly influenced by loop fluid state condition at the heat source that can be observed in Fig. 2. Decreasing the sub cooling degree of the loop fluid at heat source, mass flow rate increases. Peak heat flux values are shifting towards the left as more vapour is available in the riser 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 influence of loop diameter and height on the mass flow rate

3.2 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 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

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 and operating parameter degree of sub cooling are varied to know the effect on NCL performance. The following important conclusions 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 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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