The 8th TSME International Conference on Mechanical Engineering
12-15 December 2017
Bangkok, Thailand

TSF0025

Numerical analysis of rectangular two phase natural circulation loop

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Abstract. This paper aims to present the steady state performance of a rectangular two phase natural circulation loop using a homogeneous equilibrium model. In the loop, uniform and equal heat flux are considered at the heater and cooling sections with water as the working fluid. The mass flow rate of the working fluid is influenced by various geometric parameters and operating conditions. The mass flow rate is progressively increasing with loop height. However, with the increase in heat flux, mass flow rate increases initially to an optimum level and then after falls. The optimum geometrical parameters and operating conditions are evaluated to get the maximum mass flow rate.

1. Introduction

In the natural circulation loop (NCL) energy is transported from the source to the sink in the absence of any mechanical devices such as pump, etc. In the loop, fluid may or may not undergo the phase change process, as the fluid in the loop doesn't go phase change, then we called as single phase NCL and if the fluid undergoes phase change then we called as two phase NCL. Earlier single phase NCL is used in different engineering applications [1], generally related to cooling applications [2], solar heaters [3]. Single phase NCLs are having its own constrained about loop fluid saturation point. If the heat capacity in source is increased or geometrical modifications in the loop leads to initiate the phase change or flashing in the system. As the circulating fluid undergoes phase change or flashing on one of the section and condensation or phase separation take place at some other section situating, the loop is filled up by high density single phase fluid and low density two phase mixture. This is causing high density differences in the loop and results stronger buoyancy forces generated, which promotes more circulation rate and performance of the system. Cohen et al. [4] investigated the best method for gas turbine cooling and they preferred thermosyphon is a lucrative option. Irrespective of quantity of the coolant, high amount energy could be transferred from the hot end to the cool end of the loop. Hence multi-phase NCLs have their application ranging from large scale nuclear field [5] to smaller scale like closed loop heat pipes, cooling applications [6] etc.

The present work aims to study the performance of two phase NCL system under steady state conditions. One dimensional approximations and Homogeneous Equilibrium Model are considered here. The effect of the geometrical parameters and operating conditions on mass flow rate of the loop is investigated.

2. Theoretical modeling

Figure 1. shows the schematic representation of two phase rectangular NCL. The heating and cooling sections are placed in the horizontal arms of the loop centrally. To get the favorable buoyancy force,

cooling section is placed at a higher elevation than the heater as shown in figure 1. By considering the state of the loop fluid, the total loop is subdivided into six zones, starting from the heater and details are given in table 1. In the loop, the loop fluid properties are varied by pressure and temperature only. The following assumptions are considered here to simplify the theoretical model.

- Uniform and equal heat flux are considered for heater and cooler
- Total loop is perfectly insulated i.e. no heat loss to the ambient.
- Pressure losses not considered at pipe bends and fittings.
- Fluid is flowing in a counter clockwise direction initiating from the heater.

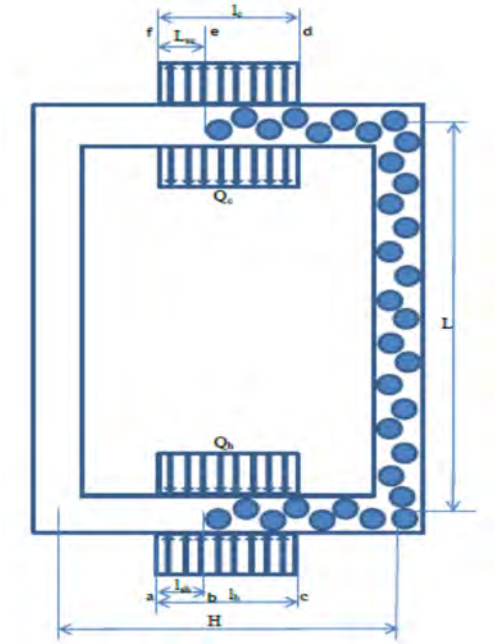

Figure 1. Schematic diagram of a two phase NCL

Table 1. Loop regions

S.No	Regions	Zone description
1	a - b	Sub cooled heating region
2	b - c	Vaporization region
3	c - d	Adiabatic two-phase region
4	d - e	Condensation region
5	e - f	sub-cooled cooling region
6	f - a	Adiabatic single phase region

2.1. *Governing equations*
The one dimensional conservation equations under steady state conditions for homogeneous equilibrium models are

2.1.1. Continuity equation.

$$\dot{m} = \bar{\rho} A \bar{u} \tag{1}$$

under steady state

$$\frac{dG}{ds} = 0 \tag{2}$$

Where G is the mass flux

2.1.2. Momentum equation.
The pressure drop for two phase flows is the sum of frictional, gravitational and acceleration, pressure drops and it is given by

$$-\left(\frac{dp}{ds}\right) = \left(\frac{dp}{ds}\right)_f + \bar{\rho} g sin\theta + G^2\left(\frac{d\bar{v}}{ds}\right) \tag{3}$$

Where θ is the inclination with the horizontal

Table 2. Pressure drop in the two phase NCL

Region	Pressure Drop expressions		
	Frictional	Gravitational	Acceleration
a-b	$-\frac{2C_{fo}G^2v_f l_{sh}}{D}$	0	0
b-c	$-\frac{2C_{fo}G^2v_f(l_h-l_{sh})}{D}\int_0^x \emptyset_{lo}^2\,dx$	0	$G^2(\bar{v}-v_f)$
c-d	$-\frac{2C_{fo}G^2v_f(H-l_h+L)}{D}\emptyset_{lo}^2$	$-gL(\rho_f(1-\alpha)+\rho_g)$	0
d-e	$-\frac{2C_{fo}G^2v_f(l_c-l_{sc})}{D}\int_0^x \emptyset_{lo}^2\,dx$	0	$G^2(\bar{v}-v_f)$
e-f	$-\frac{2C_{fo}G^2v_f l_{sc}}{D}$	0	0
f-a	$-\frac{2C_{fo}G^2v_f(H-l_c+L)}{D}$	$gL\rho$	0

Integrating the above equation gives total loop momentum equation.

$$\oint\left(\frac{dp}{ds}\right)_f ds+\oint\left(\frac{dp}{ds}\right)_g ds+\oint\left(\frac{dp}{ds}\right)_a ds=0 \tag{4}$$

By using the friction factor C_{fo} the above equation modified to

$$\oint\frac{2\beta f_{fo}G^2}{D\bar{\rho}}ds+\oint\bar{\rho}g\sin\theta ds+G^2\oint\frac{d\bar{v}}{ds}ds=0 \tag{5}$$

Where single phase friction factor $C_{fo}$is a function of Re and it is determined as

$f_{fo}=\frac{16}{Re}$ for laminar flow

$f_{fo}=\frac{0.079}{Re^{0.25}}$ for turbulent flow

Using the $\emptyset_{fo}^2$(two-phase friction multiplier), the two-phase pressure gradient is estimated as

$$\left(\frac{dp}{ds}\right)_{f2\emptyset}=\left(\frac{dp}{ds}\right)_{ffo}\emptyset_{fo}^2 \tag{6}$$

Where as$\left(\frac{dp}{ds}\right)_{f2\emptyset}$, $\left(\frac{dp}{ds}\right)_{ffo}$ are frictional pressure gradient of single phase and two phase. The two phase friction multiplier for HEM is given by (collinear) [7]

$$\emptyset_{fo}^2=\left[1+x\frac{v_{fg}}{v_f}\right]\left[1+x\frac{\mu_{fg}}{\mu_g}\right]^{-0.25} \tag{7}$$

The pressure drop for different zones is shown in table 2.

Energy interactions at the heater and cooling sections is estimated as

$$Q_h l_{21}=Q_c l_{65}=GA(h_2-h_1) \tag{8}$$

$$Q_h(l_{31}-l_{21})=Q_c(l_{64}-l_{65})=GAxh_{fg} \tag{9}$$

In the heater and cooler sections, the variation of the quality and temperature is assumed to be linear and uniform in nature.

Hence

$$\frac{dT}{ds} = \frac{\dot{q}}{mC_p} = \text{Constant} \quad \text{for single phase region} \tag{10}$$

$$\frac{dx}{ds} = \frac{\dot{q}}{mh_{fg}} = \text{Constant} \quad \text{for two phase region} \tag{11}$$

Table 3. Loop configuration and operating parameters

Parameter	Value
Diameter of the pipe	0.01325 m
Heating length	0.3 – 0.7 m
Cooling length	0.3 – 0.7 m
Height of the loop	1 – 2 m
Length of the horizontal portion	1 m
Pressure inside the loop inlet temperature	1 bar
Inlet temperature	90 C
Heat flux in/out heating and cooling sections	2 – 20 W/m

3. Solution procedure

The operating conditions and loop configuration parameters are presented in table 3. After simplifying the total loop momentum equation for HEM it gets into the form of

$$f(G, l_{21}, l_{65}, x) = 0 \tag{12}$$

The above equation (12) has four parameters and we have three equations only. To start up the solution we can fix the heater inlet condition and by using energy interaction equations above equation is modified to equation (13).

$$f(G) = 0 \tag{13}$$

The above equation (13) is solved iteratively by using bisection method.

4. Results and discussion

Figure 2 (a) and 2 (b) shows the variation of temperature and pressure profiles in the loop at pressure 1atm, loop height 2m, heating length 0.5m and heat flux 10kW/m. The temperature of the fluid remains constant in the zones cd & fa i.e. in riser and down comer, because it is assumed that loop is well insulated. However, it varies in the heater and cooler sections up to the saturation state of the loop fluid and the variation is in a linear manner because of the imposed uniform heat flux condition at heater and cooler sections.

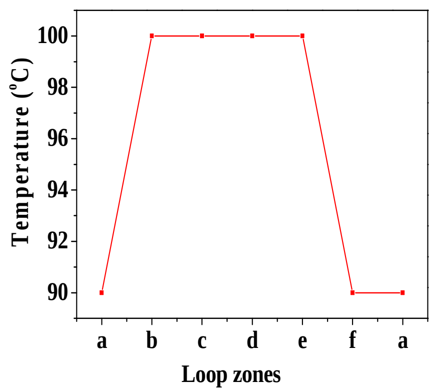

Figure 1(a). variation of pressure in the loop

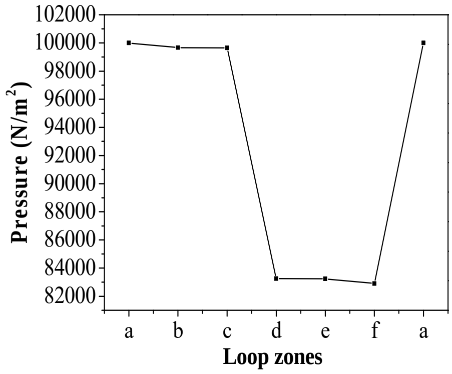

Figure 2(b). variation of temperature in the loop

The pressure variation in the loop is shown in figure 2(b). The total pressure drop is the sum of frictional and gravitational pressure. It is observed that there is no gravitational pressure in the heater and cooler sections because of the horizontal orientation. There is slight variation in pressure in heater and cooler because of the frictional resistance. From figure 2(b) it is observed that the pressure drop in riser section is compensated by the pressure gain in down comer and overall the total pressure drop in the loop must be zero.

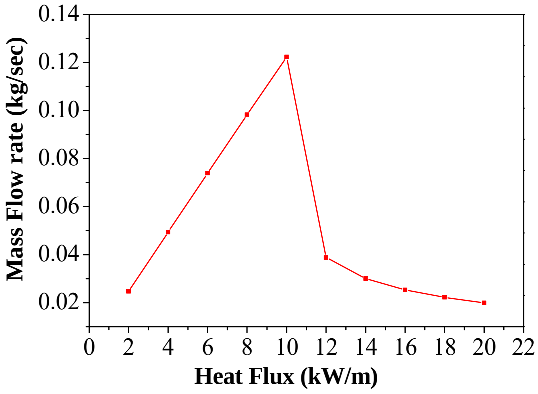

Figure 3(a). variation of mass flow rate

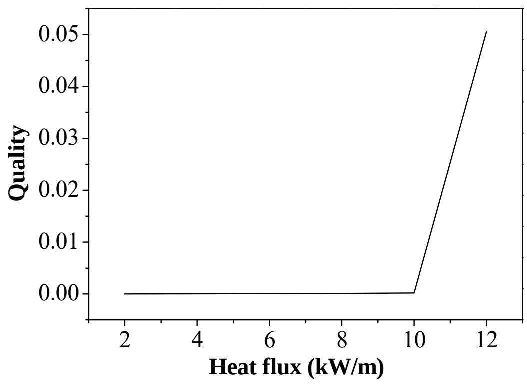

Figure 3(b). variation of heater exit quality

Figure 3(a) and 3(b) shows the variation of mass flow rate and heater exit quality at a pressure 1atm, loop height 2m & heating length 0.5m and at different heat fluxes. Increment of heat input in the loop enhances the mass flow rate as expected. Increase in heat flux increases the void fraction in the loop and causes high density differences between the riser and down comer, which creates more buoyancy forces in the loop hence flow rate increases. As a further increase in the loop quality, frictional forces in the loop also increase. Which opposes the circulation rate in the loop, hence the mass flow rate decreases at higher heat fluxes. So it is better to operate loop at optimum mass flow rate condition.

Figure 4 shows the effect of heater length on mass flow rate under low, medium and high heat flux conditions. The mass flow rate variation is not similar for all heat fluxes. For lower heat flux mass flow rate continuously increases, in moderate heat flux mass flow rate reaches an optimum value, then after decreases, and for high heat fluxes it continuously decreases. In general mass flow rate is depends on the two phase mixture in the riser. Up to certain limits the increase in quality in the loop enhances the mass flow rate. A further increase in the quality by giving high heat flux in the heater increases the frictional resistance in the loop.

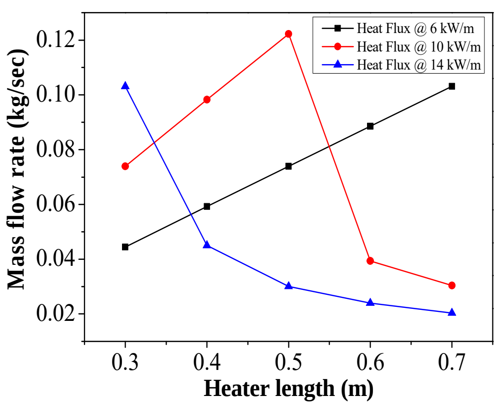

Figure 4. Effect of heating length on mass

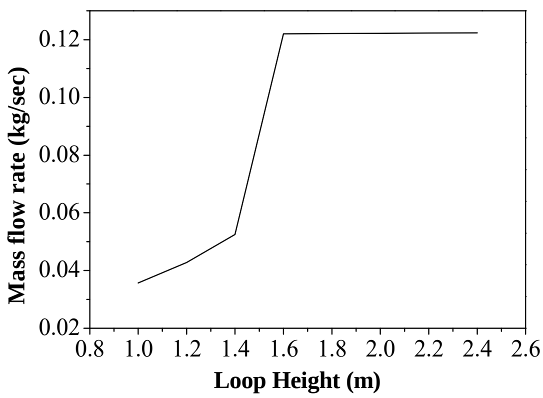

Figure 5. Effect of loop height on mass flow rate

flow rate at pressure 1atm, loop height 2m & degree of sub cooling 10 $^{\circ}$C.

at pressure 1atm, heater length 0.5 m, degree of sub cooling 10 $^{\circ}$C & heat flux 10kW/m.

Figure 5 shows the effect of loop height on mass flow rate. As loop height increase mass flow rate increases up to a certain length, then after no significant variation in the mass flow rate. As the loop height increases gravitational pressure variations in the riser and down comer increases, hence the mass flow rate increased. Further increment in loop frictional pressure increases, therefore for a given heater length and other parameters kept constant the variation in mass flow rate not significant.

5. Conclusions

A program is written to know the steady state performance of a two phase natural circulation loop. One dimensional approximation is considered here to simplify the problem. Loop parameters are varied to know the effect on NCL performance. Results are obtained by solving the equation (13). The major findings from this analysis are

- In two phase NCLs for a given particular configuration, always there is an optimum mass flow rate for a given heat flux range.
- Improvement of heater exit quality in the loop is not always favourable. There is a limiting quality, further increment affects the loop performance.
- In two phase flows, frictional pressure plays prominent role in the loop. It shows significant effect when loop performance is enhanced by using the above parameters.

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