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One-dimensional thermo-hydraulic analysis of single-phase coupled natural circulation loops

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Abstract. *Natural circulation has been actively studied due to the use of passive safety systems in nuclear power plants, such as the Passive Residual Heat Removal System (PRHRS) which removes the decay heat from the reactor core by natural circulation without an external power supply. This paper reports a one-dimensional steady-state thermo-hydraulic analysis of a natural circulation system composed of two coupled loops subjected to an inclination angle. Each natural circulation circuit consists of an arbitrary number of straight components of constant hydraulic diameter. As an example, a natural circulation system of two rectangular loops coupled through an intermediate heat exchanger (IHX) is analyzed. The energy equation in each component is solved analytically to determine the temperature distribution, depending on whether the component is a heater, cooler, tube with adiabatic wall, or IHX. All analytical and computational development was implemented using the software* Mathematica*. Parametric studies of the mass flow rates in the coupled loops were carried out as a function of the angle of inclination, the heating power, and the height of the circuit.*

Keywords: *Natural circulation, Coupled circuits, Thermo-hydraulic analysis*

1. INTRODUCTION

Natural circulation is the circulation of fluid due to the density changes caused by temperature differences. Natural circulation loops have been actively studied due to their applications in passive safety systems in nuclear power plants, which do not need external power supply and thus brings inherent safety in emergency situations.

A pioneering study on inclined single-phase natural circulation circuits was carried out by Iyori *et al.* (1987) using an experimental apparatus based on a marine reactor where the mass flow pattern for different inclination angles was calculated. Zhu *et al.* (2013) and Yang *et al.* (2014), using a double loop experimental circuit, concluded that the circuit inclination causes a decrease in the mass flow due to the decrease in the effective height between the heater and the cooler. Vijayan *et al.* (2007) and Krishnani and Basu (2017) reported that the introduction of small angles of inclination in natural circulation circuits leads to greater stability of the system.

Complex systems like the PRHRS are made up of multiple loops, which can be modeled by a system of two circuits of natural circulation coupled through an intermediate heat exchanger. A detailed study of single-phase coupled natural circulation systems, and the influence of inclination angles on them, has been carried out recently by Dass and Gedupudi (2019) and Dass and Gedupudi (2021).

This work analyzes steady-state single-phase natural circulation in a natural circulation system consisting of two rectangular loops coupled by an intermediate heat exchanger. A general formulation for one-dimensional thermal-hydraulic analysis of two coupled loops with each loop consisting of an arbitrary number of components is presented. The energy equation in each component is solved analytically to determine the temperature distribution, depending on whether the component is a heater, cooler, tube with adiabatic wall, or intermediate heat exchanger (IHX). All analytical and computational development was implemented using the software *Mathematica*. Parametric studies of the mass flow rates in the coupled loops were carried out as a function of the angle of inclination, the heating power, and the height of the circuit.

2. ANALYSIS

We consider a system of natural circulation composed of two coupled loops, as illustrated in Figure 1. The loop with the heater is denoted as the "lower loop" and identified by subscript 1, and the loop with the cooler is denoted as the "upper loop" and identified by subscript 2. The gravitational center of the lower loop is always below that of the upper loop. There is an intermediate heat exchanger (IHX) that couples the two natural circulation loops. The IHX functions as a cooler in the lower loop and as a heater in the upper loop. The lower loop ($k = 1$) is composed of N_1 components, and the upper loop ($k = 2$) is composed of N_2 components. The analysis can be generalized to systems of more than two coupled loops.

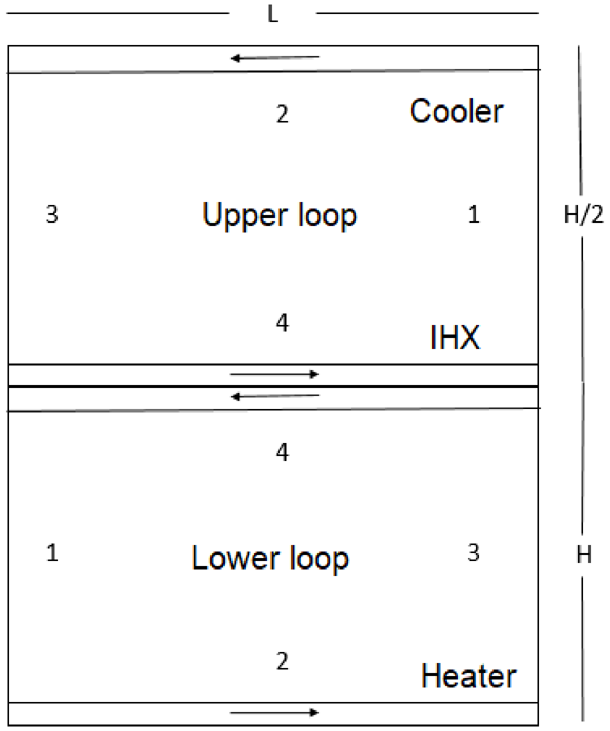

Figure 1: A coupled natural circulation system consisting of two rectangular loops coupled by an intermediate heat exchanger (IHX), each one with four components.

2.1 One-dimensional equations of conservation

For component i in loop k with a constant transversal area $A_{k,i}$, the one-dimensional equations of conservation of mass, momentum, and energy can be written as (Todreas and Kazimi, 2010):

$$\frac{\partial \rho_k}{\partial t} + \frac{\partial G_{k,i}}{\partial s} = 0, \tag{1}$$

$$\frac{\partial G_{k,i}}{\partial t} + \frac{1}{\rho_k}\frac{\partial G_{k,i}^2}{\partial s} = -\frac{\partial p_k}{\partial s} - \frac{f G_{k,i}|G_{k,i}|}{2D_{k,i}\rho_k} - \rho_k\, g\, \cos\theta_{k,i}, \tag{2}$$

$$\rho_k \frac{\partial h_{k,i}}{\partial t} + G_i \frac{\partial h_{k,i}}{\partial s} - \frac{\partial p_k}{\partial t} = \frac{q''_{k,i} P_{h_{k,i}}}{A_{k,i}} + \frac{G_{k,i}}{\rho}\left[\frac{\partial p_k}{\partial s} + \frac{f_{k,i} G_{k,i}|G_{k,i}|}{2D_{k,i}\rho}\right], \tag{3}$$

where s is the spatial coordinate along the axis of the flow channel, $G_{k,i}$ is the mass flux, ρ_k is the fluid density in loop k, g is gravitational acceleration, p_k is the pressure in loop k, $P_{h_{k,i}}$ is the heated perimeter, and $D_{k,i}$ is the equivalent hydraulic diameter of the flow channel.

The Boussinesq approximation is adopted for the analysis of natural circulation. The fluids are considered incompressible with constant density ρ_{k0} in all terms except the gravitational term in Eq. (2), in which the density is approximated by a linear relation with the temperature

$$\rho_k = \rho_{k0}(1 - \beta_k(T_k - T_{k0})), \tag{4}$$

where T_{k0} is the reference temperature and β_k is the thermal expansion coefficient of the fluid in loop k.

Equation (2) is integrated along the loop,

$$\sum_i^{N_k} \frac{L_{k,i}}{A_{k,i}} \frac{\mathrm{d}\dot{m}_k(t)}{\mathrm{d}t} = \sum_i^{N_k} \left(\frac{f_{k,i} G_{k,i} |G_{k,i}|}{2 D_{k,i} \rho_0} L_{k,i} \right) + \Delta p_{k,ex} + \sum_i^{N_k} \int_i \rho\, g\, \cos\theta_{k,i} \mathrm{d}s, \tag{5}$$

where $\Delta p_{k,ex}$ represents the sum of localized pressure drop in loop k, which will be neglected in the following analysis.

For steady-state natural circulation in the coupled loops, we have

$$0 = \sum_i^{N_k} \left(\frac{f_{k,i} G_{k,i} |G_{k,i}|}{2 D_{k,i} \rho_0} L_{k,i} \right) + \sum_i^{N_k} \int_i \rho\, g\, \cos\theta_{k,i} \mathrm{d}s, \tag{6}$$

or

$$\Delta p_{k,f} = \Delta p_{k,b}, \tag{7}$$

where the total frictional pressure drop $\Delta p_{k,f}$ is given by

$$\Delta p_{k,f} = \sum_i^{N_k} \left(\frac{f_{k,i} G_{k,i} |G_{k,i}|}{2 D_{k,i} \rho_0} L_{k,i} \right), \tag{8}$$

and the total pressure drop by buoyancy Δp_b is given by

$$\Delta p_{k,b} = \sum_i^{N_k} \int_i \rho_k\, g\, \cos\theta_{k,i} \mathrm{d}s. \tag{9}$$

Considering turbulent flow in a smooth circular pipe, the Darcy friction factor is given by :

$$f_{k,i} = \frac{a}{Re_{k,i}^b}, \tag{10}$$

where Reynolds number $Re_{k,i}$ in component i of loop k is defined by

$$Re_{k,i} = \frac{\dot{m}_k\, D_{k,i}}{A_{k,i}\, \mu_k}, \tag{11}$$

where μ_k is the fluid viscosity of loop k. Substituting the Reynolds number (11), we have the friction factor in terms of the mass flow rate $\dot{m}_k$:

$$f_{k,i} = \frac{a\, A_{k,i}^b\, \mu_k^b}{\dot{m}_k^b\, D_{k,i}^b}. \tag{12}$$

Introducing temperature integrals

$$I_{k,i} = \int_0^{L_{k,i}} T_{k,i}(s) \mathrm{d}s, \tag{13}$$

in the buoyancy pressure drop Δp_b and using the friction factor (12) in the frictional Δp_f, we have the following loop-integrated momentum conservation equations in the two coupled natural circulation loops

$$\left(\sum_i^{N_k} \frac{a A_{k,i}^{b-2} \mu^b L_{k,i}}{2 D_{k,i} \rho_{0,k}} \right) \dot{m}_k^{2-b} = \rho_{0,k} \beta_k g \sum_i^{N_k} I_{k,i} \cos\theta_{k,i}, \quad k = 1, 2. \tag{14}$$

Equations (14) form a system of two transcendental equations for the determination of two mass flow rates $\dot{m}_1$ and $\dot{m}_2$. For the two coupled natural circulation loops with geometric parameters $L_{k,i}$, $D_{k,i}$, $P_{h_{k,i}}$, $A_{k,i}$ and $\theta_{k,i}$, thermophysical properties $\rho_{0,k}$, $c_{p,k}$, μ_k and β_k, and operational parameters q''_{wi}, h_i, T_{ai}, the mass flow rates $\dot{m}_1$ and $\dot{m}_2$ can be obtained by solving numerically Eqs. (14) using the subroutine **FindRoot** of software *Mathematica*.

2.2 Temperature distributions

For the heater, cooler, adiabatic wall tube, and intermediate heat exchanger (IHX), the temperature distribution in each component is determined analytically by solving the energy equation depending on the type of component, and then integrated along the component to obtain its share of contribution $I_{k,i}$ to the pressure drop Δp_b in Eqs. (14).

2.2.1 Temperature distribution in the heater

The energy equation of the fluid in the heater is as follows:

$$\dot{m}_k\, c_{p,k} \frac{\mathrm{d}T_{k,i}(s)}{\mathrm{d}s} = q''_{w_{k,i}} P_{h_{k,i}}, \tag{15}$$

with the boundary condition

$$T_{k,i}(0) = T^{(k,i)}, \tag{16}$$

where $T_{k,i}(s)$ is the fluid temperature in component i of loop k, as a function of the spatial coordinate s, with $s = 0$ at the inlet of the component, $\dot{m}_k$ is the mass flow rate of the fluid in loop k, $c_{p,k}$ is the specific heat of the fluid loop k, $q''_{w_{k,i}}$ is the uniform heat flux at the wall of the heater i in loop k, and $P_{h_{k,i}}$ is the heated perimeter of component i in loop k, $T^{(k,i)}$ is the fluid temperature at the inlet of component i in loop k.

The analytical solution of Eq. (15) with the boundary condition (16) is:

$$T_{k,i}(s) = T^{(k,i)} + \frac{q''_{w_{k,i}} P_{h_{k,i}}}{\dot{m}_k\, c_{p,k}} s. \tag{17}$$

2.2.2 Temperature distribution in a cooler

The energy equation of the fluid in the cooler is as follows:

$$\dot{m}_k\, c_{p,k} \frac{\mathrm{d}\,T_{k,i}(s)}{\mathrm{d}\,s} = -h_{k,i} P_{h_{k,i}} (T_{k,i}(s) - T_{a_{k,i}}), \tag{18}$$

with the boundary condition

$$T_{k,i}(0) = T^{(k,i)}, \tag{19}$$

where $h_{k,i}$ is the global heat transfer coefficient between the fluid in the cooler i in loop k, and $T_{a_{k,i}}$ is the temperature of the external cooling fluid in cooler i at loop k.

The analytical solution of Eq. (18) with the boundary condition (19) is:

$$T_{k,i}(s) = T_{a_{k,i}} + (T^{(k,i)} - T_{a_{k,i}}) \exp\left(-\frac{P_{h_{k,i}} h_{k,i}}{\dot{m}_k\, c_{p,k}}\right) s. \tag{20}$$

2.2.3 Temperature distribution in a pipe with adiabatic wall

The energy equation of the fluid in the tube with adiabatic wall is as follows:

$$\frac{\mathrm{d}\,T_{k,i}(s)}{\mathrm{d}\,s} = 0, \tag{21}$$

with the boundary condition

$$T_{k,i}(0) = T^{(k,i)}. \tag{22}$$

The analytical solution of Eq. (21) with the boundary condition (22) is:

$$T_{k,i}(s) = T^{(k,i)}. \tag{23}$$

2.2.4 Temperature distribution in the intermediate heat exchanger (IHX)

For the convenience of programming, the intermediate heat exchanger (IHX) is identified as the last component in both loops, i.e., component N_1 in lower loop and component N_2 in upper loop.

The energy equation of the fluid at the side of the lower loop (primary fluid) of IHX is:

$$\dot{m}_1\, c_{p,1} \frac{\mathrm{d}\,T_{1,N_1}(s)}{\mathrm{d}\,s} = -U_1 P_{h_{1,N_1}} (T_{1,N_1}(s) - T_{2,N_1}(s)). \tag{24}$$

with the boundary condion

$$T_{1,N_1}(0) = T^{(1,N_1)}, \tag{25}$$

where U_1 is the global heat transfer coefficient of the primary side of IHX i.

The energy equation of the fluid at the side of the upper loop (secondary fluid) of IHX is:

$$\dot{m}_2\, c_{p,2} \frac{\mathrm{d}\, T_{2,N_2}(s_2)}{\mathrm{d}\, s_2} = -U_2 P_{h_{2,N_2}} (T_{1,N_1}(s) - T_{2,N_1}(s)). \tag{26}$$

with the boundary condition

$$T_{2,N_2}(0) = T^{(2,N_2)}, \tag{27}$$

where U_2 is the global heat transfer coefficient of the primary side of IHX i. Note that Eq. (26) is written in spatial coordinate s_2 with the origin at the inlet of the secondary side.

To solve the coupled ordinary differential equations (24) and (26), a transformation of coordinate is carried out in Eq. (26):

$$s_2 = L_{2,N_2} - s,$$
$$\frac{\mathrm{d}\, T_{2,N_2}(s_2)}{\mathrm{d}\, s_2} = -\frac{\mathrm{d}\, T_{2,N_2}(s)}{\mathrm{d}\, s}.$$

Eq. (26) and boundary condition (27) are rewritten as

$$\dot{m}_2\, c_{p,2} \frac{\mathrm{d}\, T_{2,N_2}(s)}{\mathrm{d}\, s} = -U_2 P_{h_{2,N_2}} (T_{1,N_1}(s) - (T_{2,N_2}(s)). \tag{28}$$

$$T_{2,N_2}(L_{N_1}) = T^{(2,N_2)}. \tag{29}$$

For the conciseness of analytical solution, Eqs. (24) and (28) are rewritten in the following form:

$$\frac{\mathrm{d}\, T_{1,N_1}(s)}{\mathrm{d}\, s} = -\psi_1 (T_{1,N_1}(s) - T_{2,N_1}(s)), \tag{30}$$

$$\frac{\mathrm{d}\, T_{2,N_2}(s)}{\mathrm{d}\, s} = -\psi_2 (T_{1,N_1}(s) - T_{2,N_2}(s)), \tag{31}$$

where

$$\psi_1 = \frac{U_1 P_{h_{1,N_1}}}{\dot{m}_1\, c_{p,1}}, \quad \psi_2 = \frac{U_2 P_{h_{2,N_2}}}{\dot{m}_2\, c_{p,2}}. \tag{32}$$

The analytical solution of Eqs.(30) and (31) with boundary conditions (25) and (29) is as follows:

$$T_{1,N_1}(s) = T^{(1,N_1)} + \psi_1 (T^{(2,N_2)} - T^{(1,N_1)}) \frac{1 - \exp\left[-(\psi_1 - \psi 2) s\right]}{\psi_1 - \psi_2 \exp\left[-(\psi_1 - \psi 2) L\right]}, \tag{33}$$

$$T_{2,N_2}(s) = T^{(1,N_1)} + (T^{(2,N_2)} - T^{(1,N_1)}) \frac{\psi_1 - \psi_2 \exp\left[-(\psi_1 - \psi 2) s\right]}{\psi_1 - \psi_2 \exp\left[-(\psi_1 - \psi 2) L\right]}. \tag{34}$$

2.2.5 Nodal temperatures in the loops

For each component i of loop k, the fluid temperature at the exit $T^{(k,i+1)}$, for $i = 1, 2, .., N - 1$, is given by:

$$T^{(k,i+1)} = T_{k,i}(L_i), \quad \text{para} \quad i = 1, 2, ..., N_1 - 1, \quad k = 1, 2. \tag{35}$$

For component N_1 of Loop 1 and component N_2 of loop 2, the temperatures at the exits are given by:

$$T^{(1,1)} = T_{1,N_1}(L_{N_1}). \tag{36}$$

$$T^{(2,1)} = T_{2,N_2}(L_{N_2}). \tag{37}$$

The $N_1 + N_2 - 2$ equations given the connectivity conditions (35) and the two equations given by conditions (36) and (37) form a linear sistem of $N_1 + N_2$ equations, which is solved to $N_1 + N_2$ nodal temperatures $T^{(1,i)}$, $i = 1, 2, ..., N_1$ and $T^{(2,i)}$, $i = 1, 2, ..., N_2$ at the inlets of the components of the coupled loops. Thus the temperature distributions along the two coupled natural circulation loops are completely determined.

2.3 Temperature Integrals along the components

The temperature distribution $T_{k,i}(s)$ in each component is integrated along the component:
For the heater:

$$I_{k,i} = L_{k,i} T^{(k,i)} + \frac{q''_{w_{k,i}} P_{h_{k,i}} L_{k,i}^2}{2\dot{m}_k \, c_{p,k}}. \tag{38}$$

For the cooler:

$$I_{k,i} = L_{k,i} T_{a_{k,i}} + (T^{(i)} - T_{a_{k,i}}) \frac{\dot{m}_k \, c_{p_k}}{P_{h_{k,i}} h_{k,i}} \left(\exp\left[-\frac{P_{h_{k,i}} h_{k,i}}{\dot{m}_k \, c_{p_k}} L_{k,i} \right] - 1 \right). \tag{39}$$

For the pipe with adiabatic wall:

$$I_{k,i} = L_{k,i} T^{(k,i)}. \tag{40}$$

For the primary side of IHX:

$$I_{1,N_1} = L_{1,N_1} T^{(1,N_1)} + \psi_1 (T^{(2,N_2)} - T^{(1,N_1)}) \frac{L_{1,N_1} - (1 - \exp\left[-(\psi_1 - \psi 2) L_{1,N_1}\right])/(\psi_1 - \psi 2)}{\psi_1 - \psi_2 \exp\left[-(\psi_1 - \psi 2) L\right]}. \tag{41}$$

For the secondary side of IHX:

$$I_{2,N_2} = L_{2,N_2} T^{(1,N_1)} + (T^{(1,N_1)} - T^{(2,N_2)}) \left(\frac{1}{\psi_1 - \psi 2} - \frac{1 + \psi_1 L_{2,N_2}}{\psi_1 - \psi_2 \exp\left[-(\psi_1 - \psi 2) L\right]} \right). \tag{42}$$

3. RESULTS AND DISCUSSION

For simplicity, we consider that all components of each loop have the same inner diameter D_k and perimeter P_k. We present here an example of a natural circulation system of two coupled rectangular loops, each one with four components. The relative angles $\theta^0_{k,i}$ between the components are specified with the heater, cooler and IHX in relation to the horizontal. The whole double-loop system will be inclined with an angle ϕ relative to the horizontal. The actual angles of the components of the inclined system are given by $\theta_{k,i} = \theta^0_{k,i} + \phi$. The numerations of the components of the Lower and Upper loops are listed in Table 1.

Table 1: Numeration of the components of the double-loop system at initial horizontal position

Component (k,i)	Inclination angle	Type
(1,1)	270°	Downcomer
(1,2)	0°	Heater
(1,3)	90°	Riser
(1,4)	180°	IHX (primary side)
(2,1)	270°	Downcomer
(2,2)	180°	Cooler
(2,3)	90°	Riser
(2,4)	0°	IHX (secundary side)

Table 2 shows the data used for the analysis of the coupled natural circulation system defined in Table 1. The height of the upper loop ($k = 2$) is taken as a half of the lower loop ($k = 1$). There are four free parameters in the analysis of the natural circulation system: the heating power $\dot{Q}$, the inclination angle ϕ, the width L, and the height H.

Table 2: Fixed parameter for the analysis of natural circulation system

Parameter	Value	Unit	Parameter	Value	Unit
D_1	0.15	m	D_2	0.15	m
$T0_1$	310	°C	$T0_2$	310	°C
ρ_1	699.8	kg/m^3	ρ_2	699.8	kg/m^3
c_{p1}	5.78	kJ/kg.K	c_{p2}	5.78	kJ/kg.K
μ_1	8.97 $\times10^{-5}$	kg/m.s	μ_2	8.97 $\times10^{-5}$	kg/m.s
β_1	3.27 $\times10^{-3}$	1/K	β_2	3.27 $\times10^{-3}$	1/K
$L_{1,1}$	H	m	$L_{2,1}$	$H/2$	m
$L_{1,2}$	L	m	$L_{2,2}$	L	m
$L_{1,3}$	H	m	$L_{2,3}$	$H/2$	m
$L_{1,4}$	L	m	$L_{2,4}$	L	m
P	15.17	MPa	$Ta_{2,2}$	278.5	°C

3.1 Influence of the inclination angle ϕ

Figure 2 shows the variation of the mass flow rates $\dot{m}_1$ and $\dot{m}_2$ in the coupled loops as a function of the inclination angle ϕ for different heating powers, $\dot{Q} = 1.7$ MW, $\dot{Q} = 1.8$ MW, $\dot{Q} = 1.9$ MW, and $\dot{Q} = 2.0$ MW. Perceptibly, the flow rate is higher in the low circuit for the same angle of inclination and power. It can also be seen that as the angle of inclination increases both to the left and to the right, the mass flow decreases.

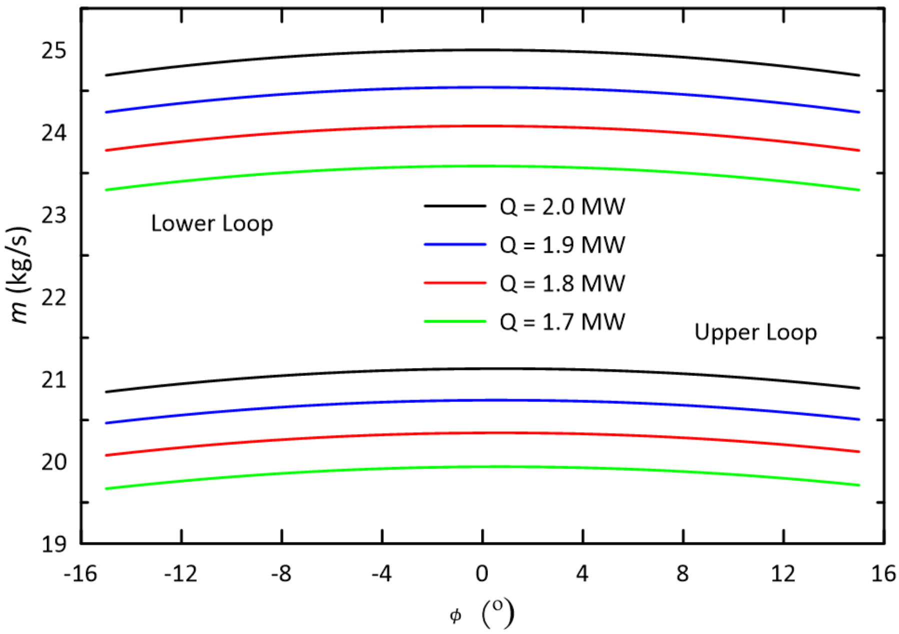

Figure 2: Mass flow rates $\dot{m}_1$ and $\dot{m}_2$ of natural circulation as a function of inclination angle ϕ for different heating powers.

3.2 Influence of the heating power $\dot{Q}$

Figure 3 shows the influence of heating power on the mass flow rates for four angles of inclination, ϕ=0°, ϕ=5°, ϕ=10° and ϕ=15°, with H=3 m and L_1=2 m and the heating power ranging from 1.0 MW to 2.0 MW. We can see that as the heating power increases, mass flow rates also increase in both natural circulation loops, regardless of the angle of inclination of the double circuit system. We also observe that the mass flow rate is always higher in the low circuit for the same values of ϕ and Q.

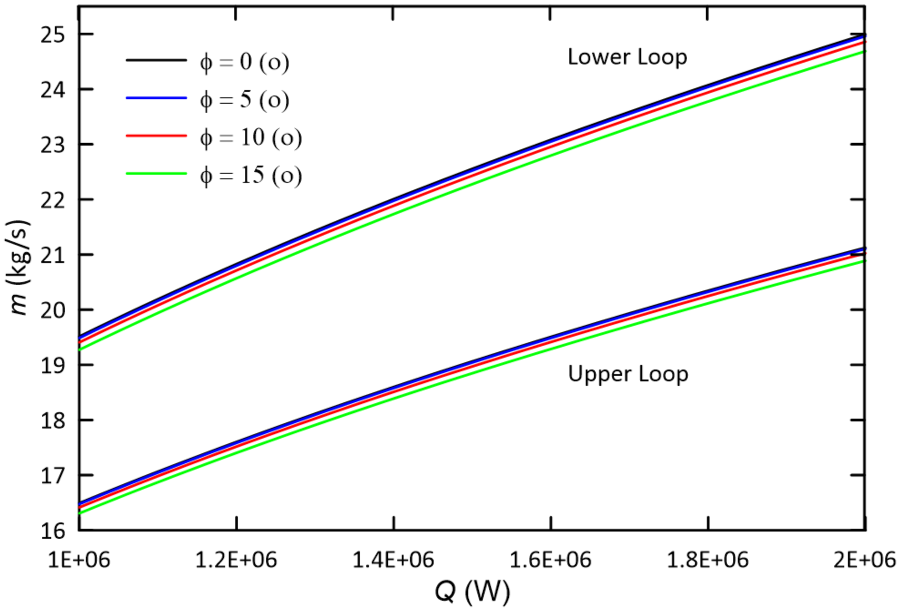

Figure 3: Mass flow rates $\dot{m}_1$ and $\dot{m}_2$ of natural circulation as a function of heating power $\dot{Q}$ for different inclination angles.

3.3 Influence of the loop height H

Figure 4 shows the influence of the circuit height variation on the fluid mass flow rates for four inclination angles, ϕ=0°, ϕ=5°, ϕ=15° and ϕ=15°, with $L = 2$ m and the height H of the circuit varying from 2 m to 4 m. It can be seen that as the height of the circuit increases, the mass flow increases regardless of the angle of inclination. the initial mass flow rate is slightly higher the greater the angle of inclination to which the circuit is subjected. It is also noticeable that, for the low circuit case, the mass flow rate is always higher than for the high circuit for the same values of ϕ and H, as the height of the lower loop is double that of the upper loop.

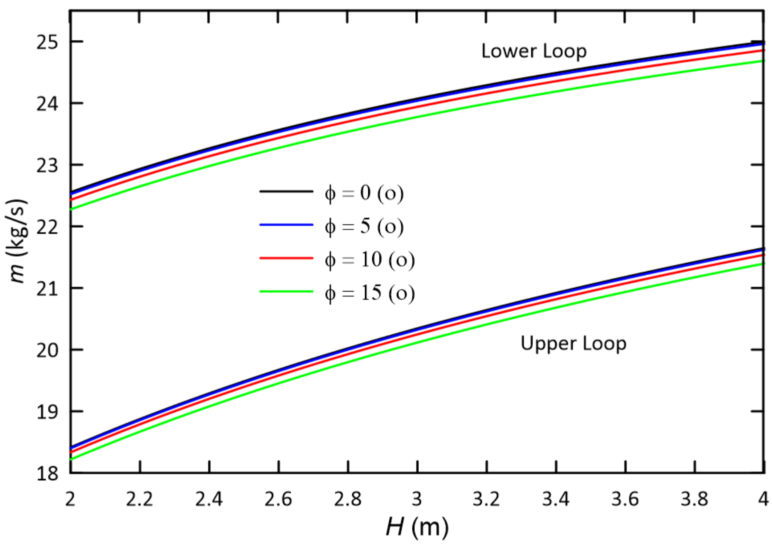

Figure 4: Mass flow rates $\dot{m}_1$ and $\dot{m}_2$ of natural circulation as a function of loop height H for different inclination angles.

4. CONCLUSIONS

Steady-state natural circulation in coupled loops was analyzed. Temperature distributions in the components of the loops are determined analytically as functions of the mass flow rates, which are determined numerically by solving a system of transcendental equations based on the integrated momentum balance around the loops. As an example, an analysis of a specific case of a natural circulation system consisting of two rectangular loops coupled through an intermediate heat exchanger (IHX) is presented. The mass flow rates $\dot{m}_1$ and $\dot{m}_2$ of natural circulation in the loops are determined in functions of the inclination angles ϕ, heating power $\dot{Q}$, and loop height H. It is shown that the mass flow rates increase with both increasing heating power and loop height, while decrease with increasing inclination angle, either clockwise or counterclockwise. The mass flow rate in the upper loop is lower than in the lower loop as the height of the upper loop is taken as half of the lower loop. The proposed method can be used in the thermal-hydraulic analysis of coupled natural circulation circuits for passive removal of residual heat in advanced nuclear reactors.

5. ACKNOWLEDGEMENTS

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