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ANALYSIS OF SINGLE PHASE NATURAL CIRCULATION AT SMALL INCLINATION ANGLES AND UNDER ROLLING MOTION

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Abstract. *A naval reactor operates on a ship with six degrees of freedom: heave, sway, surge, roll, pitch, and yaw. This work investigates the behavior of the reactor coolant in a single-phase natural circulation of a rectangular circuit under small inclination angles and under rolling motion. Firstly, the steady state natural circulation is analyzed, with the loop under small inclination angles. The mass flow rate is determined as a function of heating power and the inclination angle by solving a transcendental equation. The transient behavior of the natural circulation is then analyzed for different amplitudes and periods of rolling motion. In this case, the temperature of the fluid varies with space and time. The energy conservation equation is discretized in the spatial variable along the loop by finite difference method, resulting in a system of ordinary differential equations for fluid temperature at discretization nodes, which is solved together with the integrated momentum conservation equation for the transient mass flow rate. All implementations are performed in Wolfram Mathematica 11.3 software. It is found that the mass flow rate decreases with increasing inclination angle at steady-state and that the mass flow rate oscillates with the same period of rolling motion.*

Keywords: *Natural circulation, rolling, naval reactor, single phase, method of lines, inclined loop*

1. INTRODUCTION

Natural circulation occurs when a fluid circulates continuously in a closed circuit without pump, due to temperature difference between the lower and higher sections. When the fluid is heated in the lower part of the circuit, it expands thermally, becomes lighter, and thus moves upwards. Whereas the fluid is cooled in the upper part, it contracts, becomes denser, and moves downwards due to the gravity. Due to its passive nature and reliability, natural circulation is an important safety mechanism in advanced nuclear reactors. For marine reactors, additional factors due to the vessel motion must be considered in the analysis of natural circulation. The vessel motion is influenced by wind and sea currents. A ship at sea has six degrees of freedom: surge, sway, heave, pitch, roll and yaw. This work investigates how the mass flow rate of single phase natural circulation is affected under small inclination angles in steady state and under rolling motion in transient state.

Zhu *et al.* (2013) and Yang *et al.* (2014) studied experimentally steady-state single phase natural circulation, in a symmetrical two-circuit test loop under inclined conditions with 0 to 45 degrees inclination. It is concluded that the increase of inclination angle reduced the mass flow rate of natural circulation, and that a loop with a large average distance difference between the cooler and the heater and a small width is more advantageous for natural circulation. This loop design restricts the influence of the inclination angles. However, if the loop width were too small, it will affect the circulation capability for inclination angles. He *et al.* (2017) analyzed the natural circulation in an Integral Pressurized Water Reactor under inclination angles using a modified RELAP5 code and concluded that inclined conditions decrease the mass flow rate. In the case of rolling motion, the most studies are experimental, due to the complexity of thermal-hydraulic analysis of natural circulation under rolling motion. Murata *et al.* (1990) performed an experimental study of single phase natural circulation under rolling motion, using a model reactor at an oscillatory platform. They concluded that the rolling motion introduce inertial forces at the coolant: tangential force, centrifugal force and Coriolis force. Moreover, when experimental apparatus starts oscillating, the mass flow also oscillates. When the period of oscillatory platform decreases, the amplitude of oscillation of the mass flow increases. A one-dimensional analytical model was proposed to estimate the effects of rolling motion at coolant in the central part of the reactor. Murata *et al.* (2002) used same apparatus experimental of Murata *et al.* (1990) and concluded that the heat transfer at core reactor improves with rolling motion. When the period of oscillatory platform decreases, the amplitude of mass flow rate in the riser and the downcomer increases. Tan *et al.* (2009) performed a model experiment about single-phase natural circulation in rolling motion, and also concluded that the heat transfer improves with the oscillatory motion. The heat transfer coefficient increases with the amplitude and the frequency of rolling motion, while the friction fator also increases in this case of rolling motion. The natural circulation efficiency of the system decreases.

In this paper, the mass flow rate is analyzed for different inclination angles and different horizontal and vertical sizes of the loop. Moreover, the mass flow rate is analyzed for oscillatory case with rolling motion. The rectangular natural circulation loop has the same internal diameter in all components. The heat flux at the inner surface of the heater is uniform and constant. The coolant temperature at the secondary side of the cooler and the heat transfer coefficient between the first and the second coolants are constant.

2. METHODOLOGY

The behavior of the coolant in a single-phase natural circulation of a rectangular circuit under small inclination angles and under rolling motion is analyzed by analytical model. The natural circulation circuit is formed by four components: (1) downcomer, (2) heater, (3) riser, and (4) cooler, in clockwise order as shown in Figure 1. The internal diameter D_i is the same for all components. The heat flux at the inner surface of the heater q''_w is uniform and constant. The fluid temperature at the secondary side of the cooler T_a is constant, with a constant heat transfer coefficient h between the first and the secondary fluids.

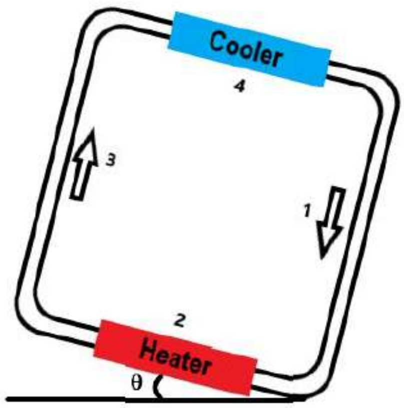

Figure 1. Single-phase natural circulation of a rectangular circuit.

For study of the inclined case, the mass flow rate is analyzed for different inclination angles and different horizontal and vertical sizes of the loop. The inclination angle is measured clockwise between the heater and the horizontal. The mass flow rate is theoretically determined by solving the momentum conservation equation for the steady-state. One-dimensional model with Boussinesq approximation is adopted. The temperature distribution along the loop is determined from the energy conservation equation. The momentum conservation equation is integrated along the loop, resulting in a transcendental equation for the mass flow rate.

For case of the rolling motion, the mass flow rate of the natural circulation is analyzed for different amplitudes of rolling motion and different periods of rolling motion. In this case, the temperature of the fluid varies with space and time. Therefore, the finite difference method is used to perform the semi-discretization of the energy conservation equation in the spatial variable, in order to obtain the temperature distribution along the loop and, together with the time-varying mass flow rate.

2.1 Mathematical equations

The rolling motion of the natural circulation circuit is described by a sine wave and can be written as:

$$\theta = \theta_m \sin \frac{2\pi t}{P}, \tag{1}$$

where θ is the rolling angle, θ_m is the rolling amplitude , t is the time and P is the rolling period.

Due to rolling motion, two coordinate systems are established: an inertial and a non-inertial reference systems, as shown in Figure 2. The non-inertial reference system has an angular velocity ω equal to angular velocity of the natural circulation circuit.

The rolling motion of the loop introduces additional accelerations to the fluid motion: the Coriolis, centripetal, and the tangential accelerations. The Coriolis acceleration is perpendicular to flow direction. Hence, the Coriolis force of the main stream will be null and it is not affected the mass flow of the natural circulation loop. Therefore, the fluid particle will be affected only by the gravitational acceleration, the centripetal acceleration and the tangential acceleration. This

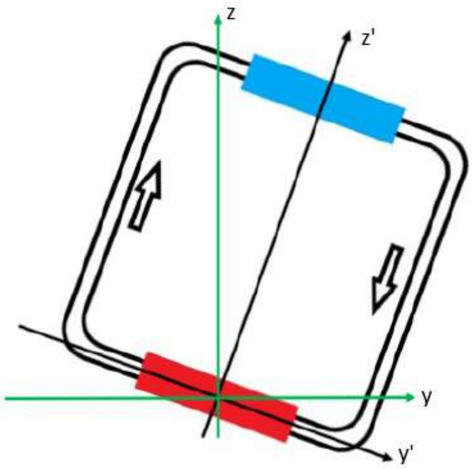

Figure 2. Inertial reference system $0XYZ$ and noninertial reference system $0X'Y'Z'$

way, the momentum conservation equation is integrated around the loop as follows:

$$\sum_k \frac{L_k}{A_k}\frac{\partial \dot{m}_k}{\partial t} = \Delta p_b + \Delta p_a - \Delta p_f, \quad k = 1, 2, 3, 4, \tag{2}$$

where L_k is the length of the k^{th} flow section of constant area A_k, $k = 1$ for downcomer, $k = 2$ for heater, $k = 3$ for riser, and $k = 4$ for cooler; $\dot{m}$ is the mass flow rate, Δp_b is the buoyancy pressure head, Δp_a is the additional pressure drop, and Δp_f is the frictional pressure drop around the loop. The buoyancy pressure head is as follows:

$$\Delta p_b = \oint \rho \vec{g}\, d\vec{s}, \tag{3}$$

where ρ is the fluid density, g is the gravitational acceleration, and s is the spatial coordinate along the loop. The additional pressure drop is as follows:

$$\Delta p_a = \oint \rho \vec{a}\, d\vec{s}, \tag{4}$$

where $\vec{a}$ is given by the vectorial sum of the tangential and centripetal accelerations. The Boussinesq aproximation is considered for all segments of the loop. The density ρ_0, the thermal expansion coefficent β and the specific heat c_p are all taken at a reference temperature T_0. In this way, the density for each segment is given as follows:

$$\rho_k = \rho_0[1 - \beta(T_k - T_0)], \quad k = 1, 2, 3, 4. \tag{5}$$

The frictional pressure drop around the loop is given by:

$$\Delta p_f = \frac{f(Re)}{D_i}\frac{L_1 + L_2}{\rho_0}\left(\frac{\dot{m}}{A}\right)^2, \tag{6}$$

where f is the friction factor determined by the Petukhov-Gnielinski's correlation (Gnielinski, 1976), Re is the Reynolds Number, L_1 is the vertical length of the circuit and L_2 is the horizontal length of the circuit.

The energy conservation equation for the heater is as follows:

$$A\rho c_p \frac{\partial T}{\partial t} + \dot{m} c_p \frac{\partial T}{\partial s} = q''_w P_h, \tag{7}$$

where T is the fluid temperature and P_h is the heated perimeter.

The energy conservation equation for the cooler is as follows:

$$A\rho c_p \frac{\partial T}{\partial t} + \dot{m} c_p \frac{\partial T}{\partial s} = -h\pi D_i(T - T_a), \tag{8}$$

where D_i is the hydraulic diameter.

Finally, the energy conservation equation for the riser and the downcomer is as follows:

$$A\rho c_p \frac{\partial T}{\partial t} + \dot{m} c_p \frac{\partial T}{\partial s} = 0. \tag{9}$$

2.2 Mathematical model of inclined case

In this case, natural circulation circuit is at small inclination angles. The temporal term of the momentum conservation equation will be absent, as follows:

$$\Delta p_b = \Delta p_f. \tag{10}$$

Moreover, the temporal term of the energy conservation equation will also be absent and the additional pressure drop will be equals to zero. In this way, the equation for the mass flow rate will be a transcendental equation, and can be written as:

$$\frac{(L_1+L_2)\dot{m}^2}{A^2 D_i \rho_0 [0,79 \ln Re - 1,64]^2} = \frac{D_h g L_h q''_w \beta \rho_0}{2c_p \dot{m}} \left[2L_1 \pi \cos\theta - \frac{2c_p \dot{m}}{D_c h} \sin\theta + L_c \pi \coth\left(\frac{D_c h L_c \pi}{2c_p \dot{m}}\right) \sin\theta \right], \tag{11}$$

where L_h is the heater length, L_c is the cooler length, D_h is the heater diameter and D_c is the cooler diameter. This equation will be solved using Wolfram Mathematica 11.2 Student Edition software.

2.3 Mathematical model of oscillating case

In this case, the temporal term of the moment conservation equation and the energy conservation equations will be considered. For to solve these equations, the method of lines is adopted. Firstly, it is applied the finite difference method to discretize the spatial variable of the energy equations conservation, as follows:

$$T(s,t) = T(s_j,t), \tag{12}$$

where j is a nodal point that will be calculated.

The partial derivative of temperature is discretized by using the backward difference, as follows:

$$\frac{\partial T(s,t)}{\partial s} \approx \frac{T(s_j,t) - T(s_{j-1},t)}{\Delta s_j} = \frac{T_j(t) - T_{j-1}(t)}{\Delta s_j}, \tag{13}$$

where $\Delta s_j = s_j - s_{j-1}$.

Equations 7, 8 and 9 are discretized in space respectively as follows :

$$\frac{dT_j(t)}{dt} = -\frac{u(t)}{\Delta s}(T_j(t) - T_{j-1}(t)) + \Omega, \tag{14}$$

$$\frac{dT_j(t)}{dt} = -\frac{u(t)}{\Delta s}(T_j(t) - T_{j-1}(t)) - \varepsilon(T_j(t) - T_a), \tag{15}$$

$$\frac{dT_j(t)}{dt} = -\frac{u(t)}{\Delta s}(T_j(t) - T_{j-1}(t)). \tag{16}$$

where:

$$u(t) = \frac{\dot{m}(t)}{A\rho_0}, \quad \Omega = \frac{q''_w P_h}{A\rho_0 c_{p0}}, \quad \text{and} \quad \varepsilon = -\frac{h\pi D_i}{A\rho_0 c_{p0}}. \tag{17}$$

Figure 3 shows the discretization of the spatial variable along the circuit. The mesh size of each node Δs is constant, as follow:

$$\Delta s = \frac{L}{n}, \tag{18}$$

where:

$$L = L_h + L_c + L_1 + L_2, \tag{19}$$

and

$$n = N_d + N_h + N_r + N_c, \tag{20}$$

where N_d are nodal points of first branch, N_h are nodal points of second branch, N_r are nodal points of third branch and N_c are nodal points of last branch.

The ordinary differential equation of the mass flow as function of time is obtained after numerical integration of the buoyancy pressure head equation and the additional pressure drop equation. Thus, it is resulted a systems of $n+1$ ordinary differential equations, for $T_j(t)$, where $j = 1, 2, ...n$, and for $\dot{m}(t)$. The system of ordinary differential equations is solved by using **NDSolve** function of Wolfram Mathematica Software.

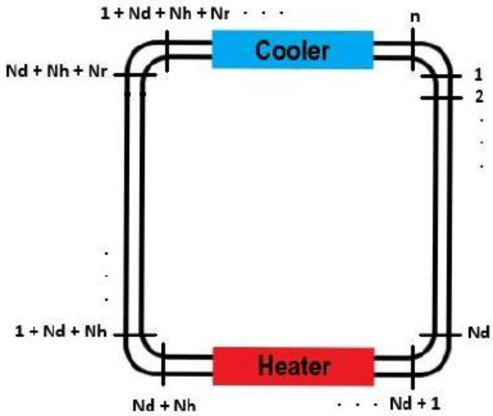

Figure 3. Schematic of the nodes used in the discretization the spatial variable along the circuit

3. RESULTS

Firstly, the natural circulation is analyzed for the steady state, where the circuit is under certain angles of inclination. The range of angles is between - 25 degrees to 25 degrees. Moreover, the heater has three different powers: 40 kW, 60 kW and 80 kW. Figure 4 shows that the mass flow decreases as the tilt angle increases for clockwise or anticlokwise. The mass flow is maximum when the loop is at horizontal, due to the symmetry of the loop. The mass flow rate increases with heater power input. Figures 5 shows the mass flow rate analyzed for different inclination angles in different diameters of

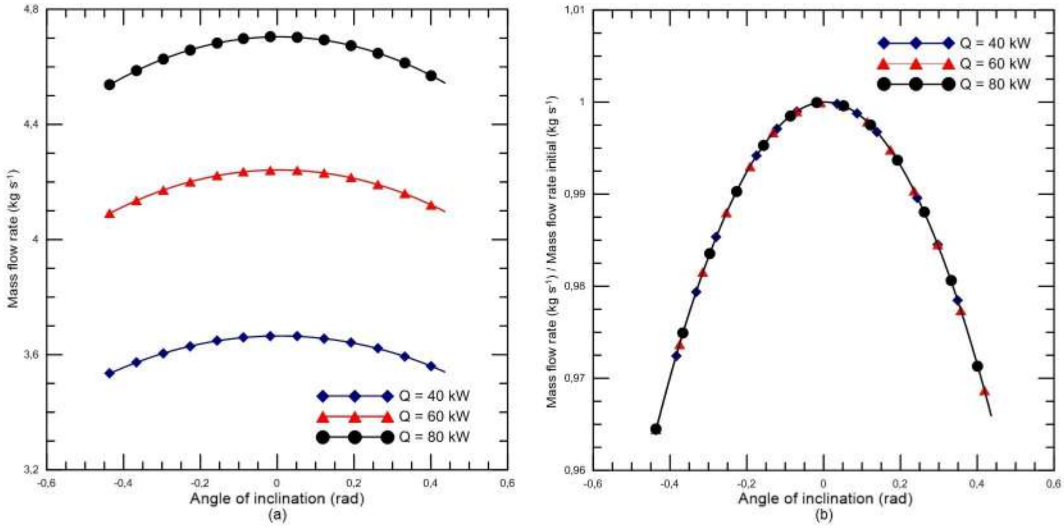

Figure 4. (a) Mass flow rate as a function of the inclination angle with heater power input at 40 kW, 60 kW, and 80 kW; (b) Relative mass flow rate as a function of the inclination angle with heater power input at 40 kW, 60 kW, and 80 kW.

the loop. When the tubes diameter increase, the mass flow rate increases. The mass flow rate also is analyzed for different length of the tubes, but the size of heater and cooler do not vary. The mass flow rate increases when the horizontal length of the loop decreases. On the other hand, the mass flow rate decreases when the vertical length of the loop decreases.

For case of the rolling motion, the mass flow rate is analyzed for four cases:

- Rolling amplitude is equal to 5 degrees and three rolling periods (5 seconds, 10 seconds and 15 seconds);
- Rolling amplitude is equal to 10 degrees and three rolling periods (10 seconds, 15 seconds and 30 seconds);
- Rolling amplitude is equal to 15 degrees and three rolling periods (15 seconds, 20 seconds and 25 seconds);
- Rolling period is equal to 12 seconds and three different rolling amplitudes (5 degrees, 10 degrees and 15 degrees).

As showed in Fig. 6, the amplitude of the mass flow decreases when the period of rolling motion increases. The mass flow presents an overlap of sinusoidal oscillations too. When the period of oscillation decreases, this overlap of oscillations increases. When we consider the oscilation with more frequency, the period of this oscillation has the same period of the rolling motion.

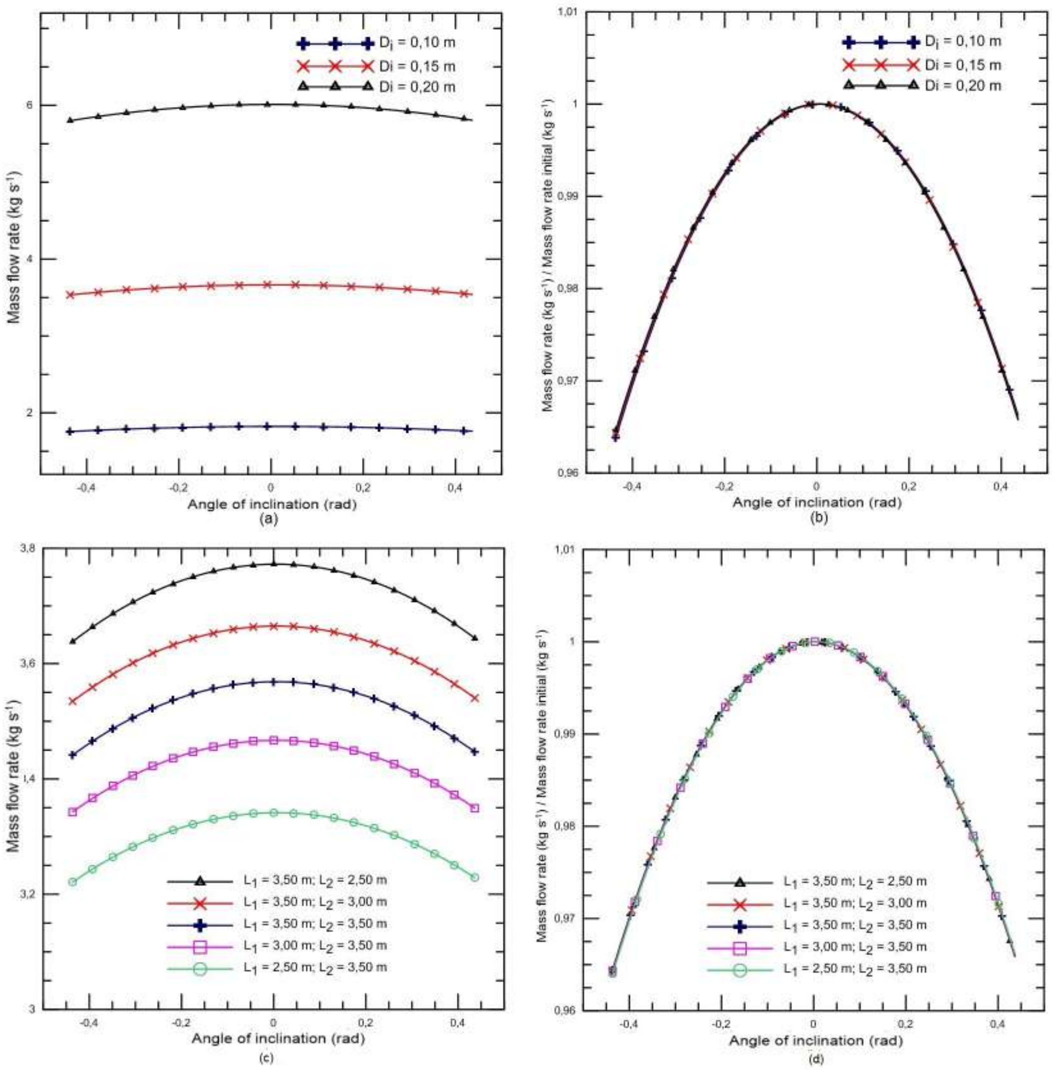

Figure 5. (a) Mass flow rate as a funtion of the inclination angle with the loop diameter at 0.20 m, 0.15 m and 0.10 m; (b) Relative mass flow as funtionc of the inclination angle with the loop diameter at 0.20 m, 0.15 m and 0.10 m; (c) Mass flow rate as a function of the inclination angle for different sizes of the loop; (d) Relative mass flow rate as a function of the inclination angle for different sizes of the loop.

Figure 7 shows that for the rolling period equals to 12 seconds, the amplitude of the mass flow increases, when the amplitude of the rolling motion increases. The period of the mass flow is equal to the rolling period.

4. CONCLUSIONS

When the natural circulation circuit at steady state is under small angles of inclination, the mass flow decreases both for clockwise and counter-clockwise inclination angles, with the mass flow rate achieves the maximum when the circuit is at horizontal. The mass flow rate increases when the heater power increases, or when the diameter of the circuit tubes is increased. Moreover, the mass flow rate increases when the horizontal length of the circuit decreases, with the distance between the cooler and the heater kept constant. However, when this distance decreases with the horizontal length kept constant, the mass flow rate also decreases.

When the natural circulation circuit is under rolling motion, the mass flow rate oscillates with the same period of the rolling motion, presenting an overlapped harmonic oscillations. Moreover, for the same rolling period, the amplitude of the mass flow rate oscillation increases as the rolling amplitude increases. On the other hand, for same rolling amplitude, the amplitude of the mass flow rate oscillation decreases when the rolling period increases. The numerical results of the present work are in agreement with the experimental studies of Murata *et al.* (2002) and Tan *et al.* (2009).

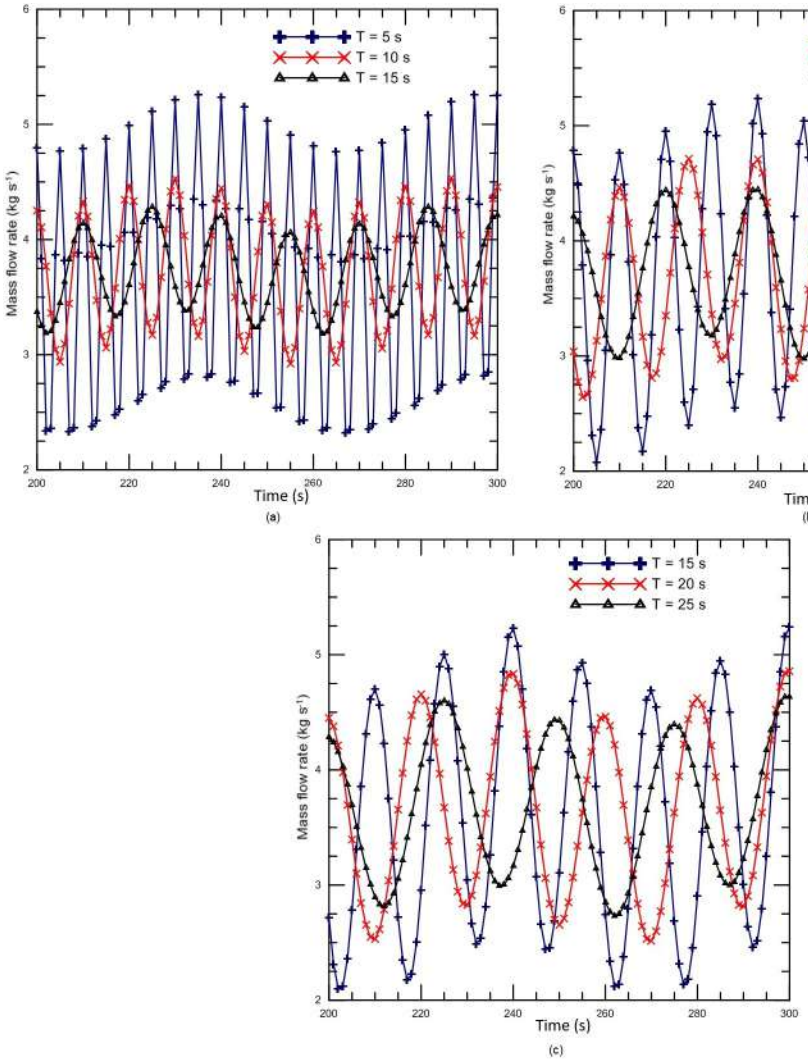

Figure 6. (a) Mass flow rate as a function of time for the rolling amplitudes: (a) 5 degrees, (b) 10 degrees; and (c) 15 degrees.

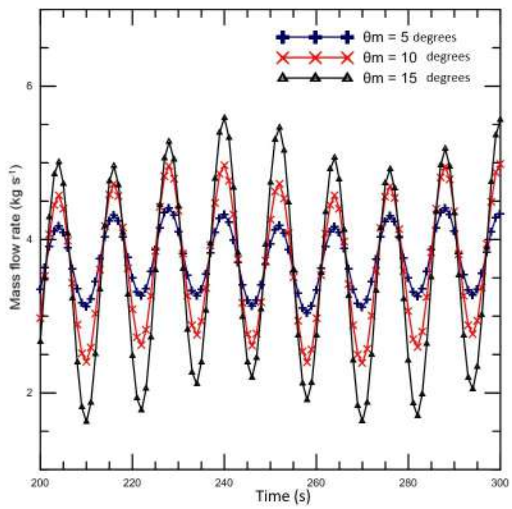

Figure 7. Mass flow as function of time with the rolling period of 12 seconds.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE