ENCIT 2018

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0160
SLIGHTLY ENHANCED SINGLE PHASE NATURAL CIRCULATION AT SMALL INCLINATION ANGLES

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Abstract. *A marine reactor is affected by the ship motion. In certain situations, the ships are inclined under small angles. This paper will investigate the fluid in a steady-state single-phase natural circulation of a rectangular circuit under small inclination angles. The rectangular natural circulation circuit is composed of a downcomer, a heater, a riser and a cooler. All of them have the same inner diameter. The inclination angle is measured between the heater and the horizontal and an one-dimensional model with Boussinesq approximation is adopted. The temperature distribution along the loop is determined by the energy conservation equation. The momentum conservation equation is integrated along the loop. The mass flow rate is analyzed for different inclination angles and different horizontal and vertical sizes of the loop. These implementations are performed in Wolfram Mathematica 11.2 Student Edition software. As the main result, the mass flow rate does not decrease immediately after varying the angle of inclination. There is an angle range that the mass flow rate increases to a maximum value, and then decreases. For a ship, this inclination angle range occurs frequently, and so, it is important to optimize the natural circulation to that the circulation ability is not so affected by the inclination.*

Keywords: *Natural Circulation, Inclination, Marine Reactor*

1. INTRODUCTION

A natural circulation occurs in a closed circuit when the fluid is heated in its lower part, becoming less dense, and, in this way, the fluid flows upstream. Whereas in the upper part, the fluid is cooled, becoming denser, and, thus, the fluid moves downwards by the action of gravity. Natural circulation is a safety element in nuclear reactors and it is widely used in the marine reactors. It removes heat from the core without needing electrical power supply for the use of a pump. Hence, the analysis of the thermo-hydraulics of a natural circulation loop is important. A natural circulation of a marine reactor is directly affected by the marine motions. A ship could be influenced by the waves, by the currents and the wind. Therefore, it is essential to investigate the changes that these motions can introduce into the reactor.

Zhu *et al.* (2013) and Yang *et al.* (2014) performed an experimental study of the steady-state single-phase natural circulation under inclined conditions. Both papers have investigated experiments on natural circulation in a symetrical two-circuit test loop under inclined conditions from 0 to 45 degrees. According to both authors, the inclination affects total circulation flow rate. The increase of slope angle weaks the overall circulation. Moreover, both authors have concluded that a loop with a large average distance difference between the cooler and the heater and a small width is more advantageous. This loop design restricts the influence of the inclination angles. However, if the loop width were too small, it will affect the circulation ability for large angle inclinations.

Zhu *et al.* (2013) also performed a theoretical study of natural circulation under inclined conditions and they concluded that an inclination angle of $45°$ has a total flow rate about 10% less than the angle of $0°$. These results indicate that the circulation capacity is inhibited when the inclination angle increases, as the experiments showed. The inclined conditions cause a reduction in the thermal conduction, in addition to breaking the thermo-hydraulic symmetry of the reactor. Meanwhile, Yang *et al.* (2014) also set up a CFD model that could predict the behaviors of the loop beyond the experimental scope.

He *et al.* (2017) studied the natural circulation of integrated pressurized water reactor under inclination angles and rolling motions. These authors modified the RELAP5 Code and they developed an ocean-based thermal-hydraulic system analysis. They also concluded that the inclination angles reduces the mass flow rate. Iyori *et al.* (1987) performed a steady-state single-phase natural circulation test and they analyzed the effect of inclination circuit with a configuration similar to an integrated type of marine reactor. They concluded that stable natural circulation flow rate hold up approximately 90 degrees and several types of flow pattern occur in the loop for different range of inclination angles.

In this paper, the mass flow rate of a single-phase natural circulation under inclined conditions will be theoretically determined by solving the momentum conservation equation for the steady-state. Before it, we will calculate the temperature distribution and the buoyancy pressure head both around the loop. For this analysis, one-dimensional model with Boussinesq approximation will be used. The equations will be solved by using Wolfram Mathematica 11.2 Student Edition software.

2. METHODOLOGY

Let us consider a single-phase natural circulation in a rectangular loop formed by four components: (1) downcomer, (2) heater, (3) riser and (4) cooler. The internal diameter D_i is the same for all components. The length of the downcomer and the riser are equal to L_1, while the length of the heater L_h and cooler L_c are same, $L_h = L_c = L_2$. 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 considered constant as well as the heat transfer coefficient h between the first and the second fluids. Figure 1 shows this circuit.

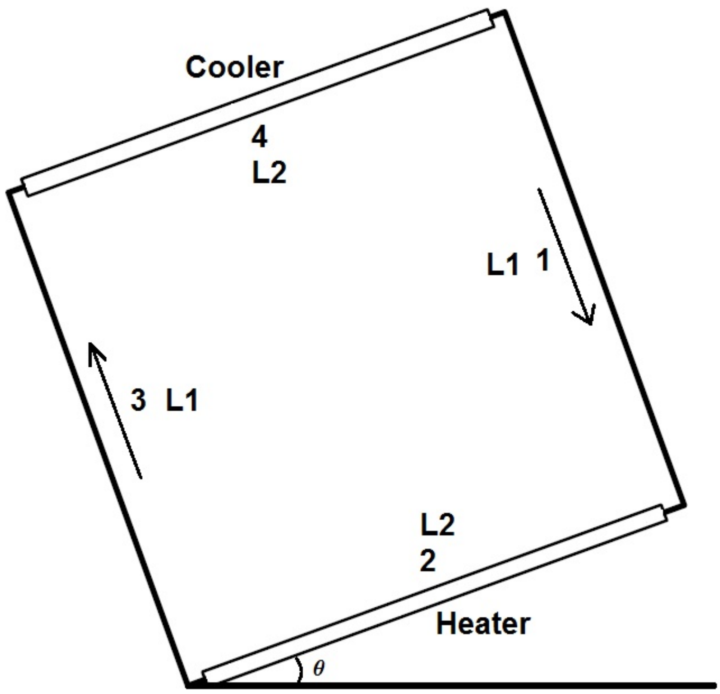

Figure 1. Natural circulation loop

We define Γ as the ratio between the horizontal length of the circuit (L_2) and the vertical distance between the cooler and the heater (L_1):

$$\Gamma = \frac{L_2}{L_1}. \tag{1}$$

2.1 Mathematical equations

The momentum conservation equation is integrated around the loop and can be written as:

$$\sum_k \frac{L_k}{A}\frac{\partial \dot{m}}{\partial t} = \Delta p_b - \Delta p_f, \tag{2}$$

where L_k is the length of the k^{th} flow section of constant area A, $\dot{m}$ is the mass flow rate, Δp_b is the buoyancy pressure head 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.

We will apply the Boussinesq approximation for all segments of the loop. The density ρ_0, the thermal expansion coefficient 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:

$$\rho_j = \rho_0[1 - \beta(T_j - T_0)], \tag{4}$$

where j is the loop's segment part: downcomer (1), heater (2), riser (3) or cooler(4).

Whereas, the frictional pressure drop around the loop is given by:

$$\Delta p_f = \frac{f(Re)}{D_i}\frac{L_1 + L_2}{\rho_o}\left(\frac{\dot{m}}{A}\right)^2, \tag{5}$$

where f is the Darcy frictional resistance coefficient for turbulent flow:

$$f(Re) = aRe^{-n}, \tag{6}$$

where $a = 0,184$, $n = 0,2$ and Re is Reynolds Number:

$$Re = \frac{\dot{m}D_i}{A\mu_0}, \tag{7}$$

where the viscosity of the fluid μ_0 is taken at a reference temperature T_0.

The energy conservation equation for the heater is as follows:

$$A\frac{\partial}{\partial t}(\rho c_p T) + \dot{m}\frac{\partial c_p T}{\partial s} = q''_w P_h, \tag{8}$$

where ρ is the fluid density, c_p is the specific heat, T is the fluid temperature, P_h is the heated perimeter and s is the spatial coordinate along the heater.

The energy conservation equation for the cooler is as follows:

$$A\frac{\partial}{\partial t}(\rho c_p T) + \dot{m}\frac{\partial c_p T}{\partial s} = -h\pi D_c(T - T_a), \tag{9}$$

where D_c is the hydraulic diameter.

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

$$A\frac{\partial}{\partial t}(\rho c_p T) + \dot{m}\frac{\partial c_p T}{\partial s} = 0. \tag{10}$$

2.2 Temperature distribution

In the steady-state, the energy conservation equation for the heater is simplified to:

$$\dot{m}c_p\frac{dT_2}{ds} = q"_w\pi D_h, \quad \text{for} \quad -\frac{L_h}{2} < s < \frac{L_h}{2}, \tag{11}$$

where D_h is the heater diameter, with the initial condition at the inlet of the heater:

$$T_2(-L_h/2) = T_c, \tag{12}$$

where T_2 is the temperature along the heater and T_c is the temperature in the downcomer.

Equations (11) and (12) have the following solution:

$$T_2(s) = \frac{\dot{Q}}{2c_p\dot{m}}\frac{(L_h + 2s)}{L_h} + T_c, \tag{13}$$

where $\dot{Q}$ is the heating power of the heater:

$$\dot{Q} = q''_w\pi L_h D_h. \tag{14}$$

We have for the cooloer:

$$\dot{m}c_p\frac{\mathrm{d}T_4(s)}{\mathrm{d}s} = -h\pi D_c(T_4(s) - T_a), \quad \text{for} \quad -\frac{L_c}{2} < s < \frac{L_c}{2}, \tag{15}$$

$$T_4(-L_c/2) = T_h, \tag{16}$$

where T_h is the temperature in the riser.

Equations (15) and (16) have the following solution:

$$T_4(s) = T_a + (T_h - T_a)e^{\frac{-D_c h\pi}{2c_p\dot{m}}(L_c+2s)}. \tag{17}$$

The temperatures T_c and T_h are determined by requiring $T_2(L_h/2) = T_h$ and $T_4(L_c/2) = T_c$, so finally we have:

$$T_h = Ta + \frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{-\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1}, \tag{18}$$

$$T_c = \frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1} + T_a. \tag{19}$$

It can be readily verified that:

$$T_h - T_c = \frac{\dot{Q}}{\dot{m}c_p}. \tag{20}$$

2.3 Density distribution

The density distribution in each branch will be given by substituting Eq. 13, 17, 18 and 19 at Eq. 4, so we will have:

Downcomer:

$$\rho_1 = \rho_0\left[1 - \beta\left(\frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1} + T_a - T_0\right)\right]. \tag{21}$$

Heater:

$$\rho_2(s) = \rho_0\left[1 - \beta\left(\frac{\dot{Q}}{2c_p\dot{m}}\frac{(L_h + 2s)}{L_h} + T_c - T_0\right)\right]. \tag{22}$$

Riser:

$$\rho_3 = \rho_o\left[1 - \beta\left(Ta + \frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{-\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1} - T_0\right)\right]. \tag{23}$$

Cooler:

$$\rho_4(s) = \rho_0\left[1 - \beta\left(T_a + (T_h - T_a)e^{\frac{-D_c h\pi}{2c_p\dot{m}}(L_c+2s)} - T_0\right)\right]. \tag{24}$$

2.4 Buoyancy pressure head

The buoyancy pressure head for the different segments of the loop is given by:

Downcomer:

$$\Delta p_{b1} = gL_1\rho_0\left[1 - \beta\left(\frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1} + T_a - T_0\right)\right]\cos\theta; \tag{25}$$

Heater:

$$\Delta p_{b2} = gL_h\rho_0\left[-1 + \beta\left(\frac{\dot{Q}}{2c_p\dot{m}} - T_0 + T_c\right)\right]\sin\theta; \tag{26}$$

Riser:

$$\Delta p_{b3} = -gL_1\rho_o\left[1 - \beta\left(Ta + \frac{\dot{Q}}{c_p\dot{m}}\left(-1 + e^{-\frac{D_c h L_c \pi}{c_p\dot{m}}}\right)^{-1} - T_0\right)\right]\cos\theta; \tag{27}$$

Cooler:

$$\Delta p_{b4} = g\rho_0\beta\left[\frac{\left(c_p - c_p e^{\frac{-D_c h L_c \pi}{c_p\dot{m}}}\right)\dot{m}(T_a - T_h)}{D_c h\pi} + L_c(1 + T_0 - T_a)\right]\sin\theta; \tag{28}$$

where the buoyancy pressure head around the entire loop is:

$$\Delta p_b = \Delta p_{b1} + \Delta p_{b2} + \Delta p_{b3} + \Delta p_{b4}. \quad (29)$$

When $\theta = 0°$, the buoyancy pressure head total is:

$$\Delta p_b = gL_1\rho_0\beta(T_h - T_c). \quad (30)$$

2.5 Mass flow rate

In the steady-state, we have for Eq. (2):

$$\Delta p_b = \Delta p_f. \quad (31)$$

Replacing Eq. (5) and Eq. (29) on Eq. (31):

$$\frac{a\dot{m}^2 2^{3-2n}\pi^{n-2}(2L_1 + L_c + L_h)\left(\frac{\dot{m}}{D_i\mu}\right)^{-n}}{D_i^5\rho_0} = \frac{g\rho_0}{2c_pD_i\dot{m}}\left\{\left[2c_p\dot{m}\left(D_i(L_c - L_h)(\beta T_0 - \beta T_a + 1) - \frac{\beta D_h\dot{Q}}{\pi D_c h}\right)\right.\right. \quad (32)$$

$$\left.\left.+\frac{\beta D_h L_h\dot{Q}\left(e^{\frac{D_c h L_c\pi}{c_p\dot{m}}} + 1\right)}{e^{\frac{D_c h L_c\pi}{c_p\dot{m}}} - 1}\right]\sin\theta + 2\beta D_h L_1\dot{Q}\cos\theta\right\}. \quad (33)$$

Equation (32) is a transcendental equation for the mass flow rate $\dot{m}$. This equation was solved using Wolfram Mathematica 11.2 Student Edition software.

2.6 Heat-transfer coefficient

Using Nusselt number Nu and Prandtl number Pr, we have:

$$h = \frac{Nuk_0}{D_h}, \quad (34)$$

where thermal conductivity k_0 is taken at a reference temperature T_0 and Nusselt number and Prandtl number are given by:

$$Nu = 0.023Re^{0.8}Pr^{0.3}, \quad (35)$$

$$Pr = \frac{\mu_0 c_{p0}}{k_0}. \quad (36)$$

3. RESULTS

For the inclined steady-state, the variation of the total flow rate as function of the inclination angle is analyzed. The behavior of the overall flow rate for Γ less than 1, equals 1 or large than 1 as function of the inclination angle is studied. From this analysis, we can note that the flow rate reaches a maximum value and then decreases. So, the value of the angle corresponding to the maximum flow rate is calculated. This analysis aims to find the value of the angle, where the total flow rate is equivalent to its initial value. In this way, the range angle in which the flow will not be less than its initial value will be found. The parameters used are given in Tab. 1.

Table 1. Numerical data

Pressure	15,17 MPa	T_0	310 °C
$\dot{Q}$	1,8 MW	ρ_0	$699,9\,kJ\,m^{-3}$
$D_i = D_h = D_c$	0,15 m	c_{p0}	$5,78 \times 10^3\,J\,Kg^{-1}\,K^{-1}$
T_a	278,5 °C	μ_0	$8,97 \times 10^{-5} Kg\,m^{-1}s^{-1}$
g	9,8 ms^{-2}	k_0	$0,542\,Wm^{-1}K^{-1}$
L_1	2 m	β	$3,27 \times 10^{-3}$ °C^{-1}

Firstly, we analyze the overall flow rate according to the variation of the width of the natural circulation loop.

In Fig. 2 (a), the graph for three cases of Γ is presented. When the horizontal width of the circuit is less than the vertical distance between the cooler and the heater (Γ < 1), the flow curve lies below the curve of the square circuit

($\Gamma = 1$). On the other hand, when the horizontal width of the circuit is larger than the vertical distance between the cooler and the heater ($\Gamma > 1$), the curve is located above.

Also in Fig. 2 (a), we can note the occurrence of a maximum point in the three curves. The mass flow rate of a natural circulation under inclination angle does not immediately decrease as Zhu *et al.* (2013) states.

The mass flow rate only decreases after reaching this maximum value. It is important to know from which angle the flow rate decreases in relation to its initial value, because this type of inclination motion is very common in a ship or offshore platform. We analyze what is the corresponding angle to the maximum total flow rate. Then, the angle from which the flow decreases is found and this angle is defined as θ_0. Whereas, the corresponding angle to the maximum flow is defined as θ_{max}. A curve of the maximum flow rate as function of the Γ with ten points is presented in Fig. 2 (b) and the Tab. 2 presents these values.

As it can be seen in the Fig. 2 (a), the curve of the flow rate as a function of the inclination angle has a similar behavior to a parabola. Based on this, the angle θ_0 is twice the angle θ_{max}. The Tab. 2 shows the values of the angle at which the flow rate equals the initial flow rate θ_0. Figure 2 (c) presents the curve of the angle at which the flow rate equals the initial flow rate θ_0 as a function of the Γ.

In addition, we analyze how much the flow rate under inclination of 45° decreases relative to the initial flow rate at 0°. The Tab. 2 presents these results. At an inclination angle of 45° the flow rate is approximately 10% to 12% less than the flow rate at angle 0°.

Table 2. The maximum flow rate; the corresponding angle to the maximum flow rate; the angle at which the flow rate equals the initial flow rate and the decrease of the flow rate under inclination of 45° relative to the initial flow rate at 0°

Γ	$\frac{\dot{m_{max}}}{m(0)}$	θ_{max}	θ_0	$1 - \frac{\dot{m}(45^\circ)}{\dot{m}(0)}$
0,125	1,00000	$0,00491225^\circ$	$0,00982442^\circ$	0,116395
0,375	1,00000	$0,0448486^\circ$	$0,8966965^\circ$	0,116169
0,5	1,00000	$0,0802273^\circ$	$0,160453^\circ$	0,115970
0,75	1,00000	$0,0182502^\circ$	$0,365007^\circ$	0,115393
1	1,00001	$0,327547^\circ$	$0,655092^\circ$	0,114578
1,5	1,00003	$0,748701^\circ$	$1,49741^\circ$	0,112217
1,75	1,00006	$1,0259^\circ$	$2,05182^\circ$	0,110671
2,0	1,00010	$1,34808^\circ$	$2,69621^\circ$	0,108881
2,25	1,00016	$1,71557^\circ$	$3,43125^\circ$	0,106848
2,5	1,00025	$2,12862^\circ$	$4,25746^\circ$	0,104575

4. CONCLUSIONS

The results obtained for the decrease of the flow rate under inclination of 45° relative to the initial flow rate at 0° are in agreement with the work of Zhu *et al.* (2013), which states that at an inclination angle of 45°, the flow rate is approximately 10% less than the flow rate at angle 0°. We can also conclude that the geometry of the circuit interferes on the flow rate of the fluid, and, consequently, with the heat exchange, as has been concluded by Zhu *et al.* (2013) and Yang *et al.* (2014). Moreover, when the loop width is smaller, the overall flow rate increases.

The corresponding angle to the maximum flow rate θ_{max} grows with the increase of Γ. Consequently, the value of the angle θ_0 at which the flow rate is equal to its initial rate also grows. This means that the geometric arrangement of the circuit is able to interfere directly at the beginning of the decrease of the mass flow according to the inclination angle of the system. For $\Gamma = 2.5$, we have $\theta_0 = 4.25746^\circ$ and up to this angle of inclination the overall flow rate does not decrease. For a nuclear reactor located in a ship or offshore platform, this analysis becomes essential, since it is necessary to know from which angle of inclination the natural circulation system will have its efficiency affected.

Therefore, for the inclination angles up to this angle range that there is no decrease in the flow rate, the heat removal efficiency of the natural circulation will not be affected. In this way, it is an important result to be considered in nuclear reactors in ships or floating platforms, since the measurements of the horizontal and vertical branches of a natural circulation loop are capable of directly influence the efficiency of the flow of the fluid, consequently in the removal of heat from the core.

5. ACKNOWLEDGEMENTS

The authors are grateful to CNPq and FAPERJ for the financial support.

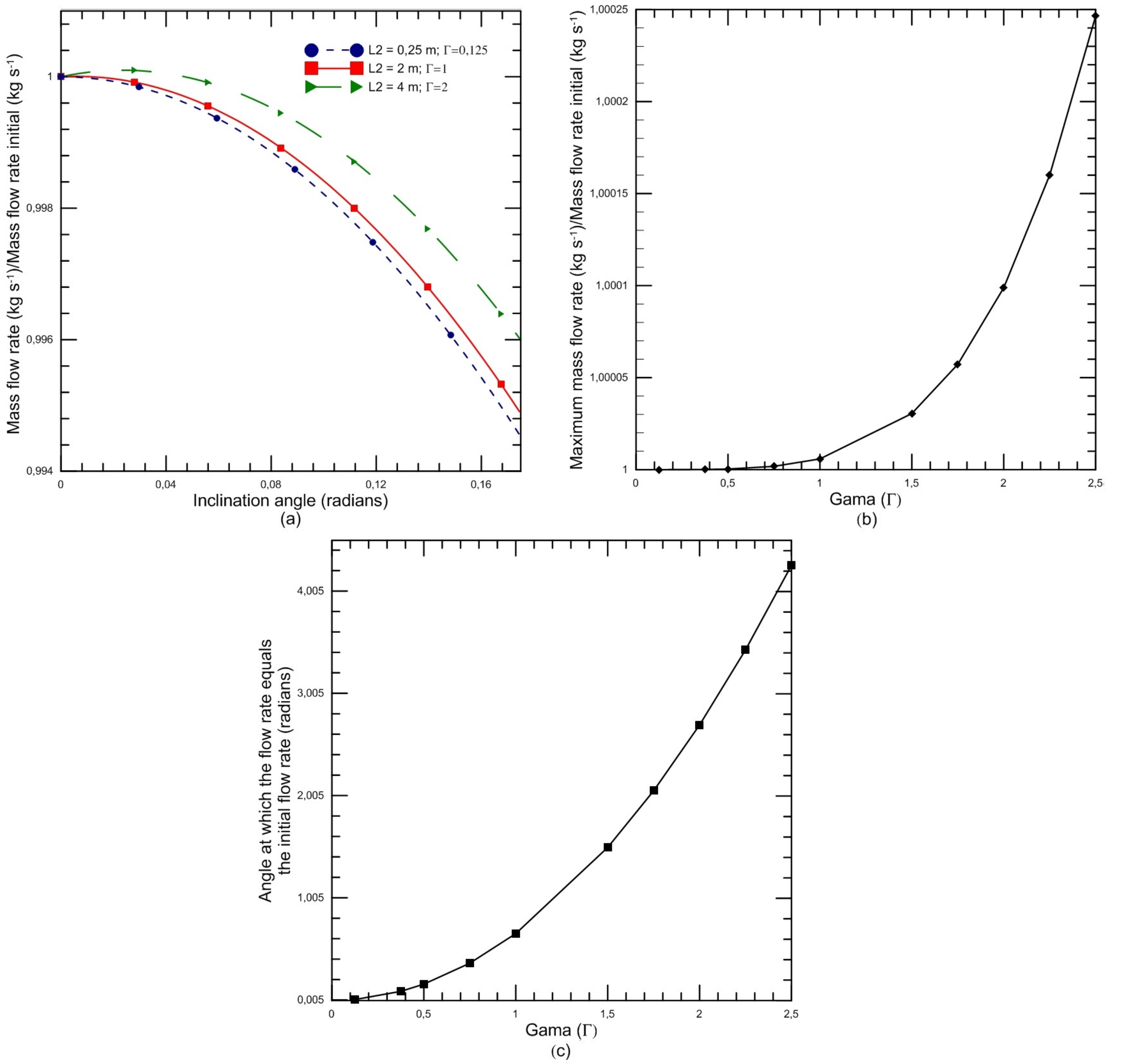

Figure 2. (a) Relative mass flow rate as function of the inclination angle ranges from 0° to 10°, (b) Relative mass flow rate maximum as function of Γ and (c) Angle at which the flow rate equals the initial flow rate as function of Γ.

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