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EFFECT OF INCLINATION ANGLE ON THERMALHYDRAULIC BEHAVIOR OF A SUPERCRITICAL CARBON DIOXIDE NATURAL CIRCULATION LOOP

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Abstract. *In view of the importance of passive cooling systems, specially in the nuclear sector, combined to the current improvements in supercritical fluids technology, supercritical natural circulation loops (SCNCLs) have been in focus over the past decade. In this work, a 3D CFD model was implemented in ANSYS Fluent to investigate the effect of inclination on the steady state behavior of a supercritical* CO_2 *natural circulation loop with cooler and heater on the vertical position. The heat transfer deterioration regime (HTD) was observed in all cases studied and was characterized by the steep mass flow rate reduction immediately after a peak. Compared to the upright case, loops with positive tilt angles presented a decrease in natural circulation flow rate, whereas loops with negative tilt angles presented a flow rate increase.*

Keywords: *CFD, natural circulation, supercritical fluids, heat transfer deterioration*

1. INTRODUCTION

In line with the implementation of sustainability goals within the nuclear sector, the development of new design concepts embracing efficiency and safety has been a key factor. The use of supercritical thermodynamic cycles, for example, presents several advantages over traditional cycles, such as higher efficiency and simplified design. Supercritical fluids thermalhydraulics has been in focus, specially ever since the Supercritical Water Reactor (SCWR) was chosen as one of the Generation IV advanced reactor models (Jain and Rizwan-uddin, 2008).

A natural circulation loop (NCL) is a physical model where heat is removed from a source and delivered to a sink exclusively by means of buoyancy, that is, without the need for any external machinery. One of the most studied loop layouts is the rectangular NCL and it presents four basic configurations: (i) horizontal heater horizontal cooler (HHHC), (ii) horizontal heater vertical cooler (HHVC), (iii) vertical heater horizontal cooler and (iv) vertical heater vertical cooler (Archana *et al.*, 2015).

Nuclear passive safety systems have become a requirement for new reactors licensing and employing natural circulation is among the most common and reliable ways of providing it. Supercritical natural circulation loops (SCNCLs) are still a concept, although it is known that they can be a good alternative to traditional subcritical NCLs, in some cases, delivering higher flow rates at a lower temperature level. SNCLs have reported applications in other technological fields, such as solar thermosyphons, refrigeration systems and cooling of rotating machinery (Sarkar and Basu, 2017a).

The variation of thermal physical properties in the vicinity of the pseudocritical point is sharp for all fluids. Figure 1 shows the properties of CO_2 as a function of the temperature, at a pressure of 9.0 MPa as stated by Zhang *et al.* (2010).

Although there is a significant number of papers regarding supercritical rectangular natural circulation loops in the literature, most of the works focus on the HHHC configuration due to its higher flow rate and heat transfer coefficient. On the other hand, there are evidences that the VHVC configuration may present the advantage of having a higher stability zone compared to the other configurations (Archana *et al.*, 2015). That, associated to the fact that most nuclear reactors present vertical cores and steam generators, reinforces the importance of studying the VHVC configuration as much as the others.

It has been reported by most authors that one of the main limitations of SCNCLs is the so called heat transfer deterioration phenomenon (HTD), which is characterized by a sudden fall in natural circulation flow rate and, consequently, a steep increase in the temperature. It happens due to the departure of the pseudocitical point within the heater. Once the lowest energy point over the entire loop is above the pseudocritical temperature, the density difference becomes much smaller and, thus, buoyancy forces decrease rapidly (Sarkar and Basu, 2017a).

An important remark is that, in the literature, there are very few empirical correlations for supercritical natural circulation and none of them apply specifically to the VHVC loop configuration. There is, however, a flow correlation proposed

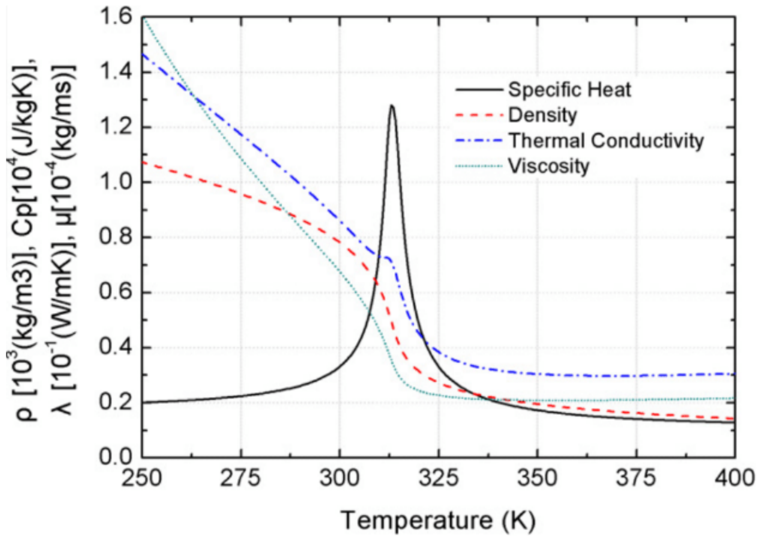

Figure 1. Variation of CO_2 properties at 9.0 MPa

by (Yadav *et al.*, 2012), which is based on an experiment. As it regards to heat transfer, the correlation of (Yadav *et al.*, 2012) was the only one observed in the literature and was obtained through simulation data adjustment. Both mentioned correlations considered only the HHHC loop configuration.

As it regards to the effect of inclination on a HHHC loop, (Sarkar and Basu, 2017b) have observed that, for the rotation on the loop's plan (x-y plan), higher tilt angles cause the natural circulation flow rate to decrease, as it can be seen in Fig. 2. This happens because the height difference between heater and cooler decreases by a factor $cos\theta$, being θ the tilt angle. As a consequence, buoyancy also decreases and so does the natural circulation flow rate. It is evident that, due to symmetry, the effect of the tilt angle in the HHHC case is the same for clockwise and anticlockwise rotations, however, when it comes to the VHVC configuration, the effect is not the same and needs further consideration.

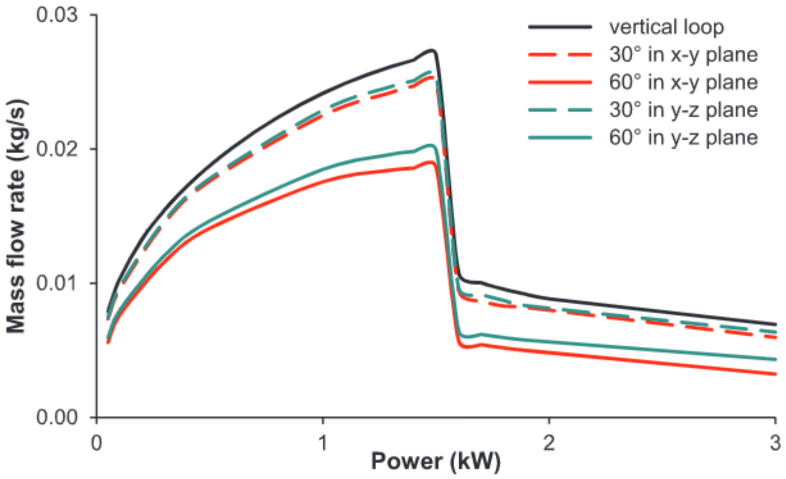

Figure 2. Mass Flow Rate as a Function of Power for Different Tilt Angles in a HHHC loop (Sarkar and Basu, 2017b).

2. METHODOLOGY

The studied geometry is shown in Fig. 3 and consists of a rectangular natural circulation loop of height H, width W and tube diameter D. The cooler and the heater are both vertical and have lengths L_C and L_H, respectively. H_1 and H_2 are geometric parameters, as it can be seen in Fig. 3.

In a first approach, the loop was considered perpendicular to the ground. Then, for the assessment of inclination effect, a tilt angle θ was considered, on the $x - y$ plan, according to the following convention: negative for clockwise rotation and positive for anticlockwise rotation. This convention and the reference axis are represented in Fig. 3.

For the simulation, a 3D steady state model was adopted. The boundary conditions are: (i) constant temperature T_C at the cooler, (ii) constant input power Q at the heater, (iii) adiabatic tubes.

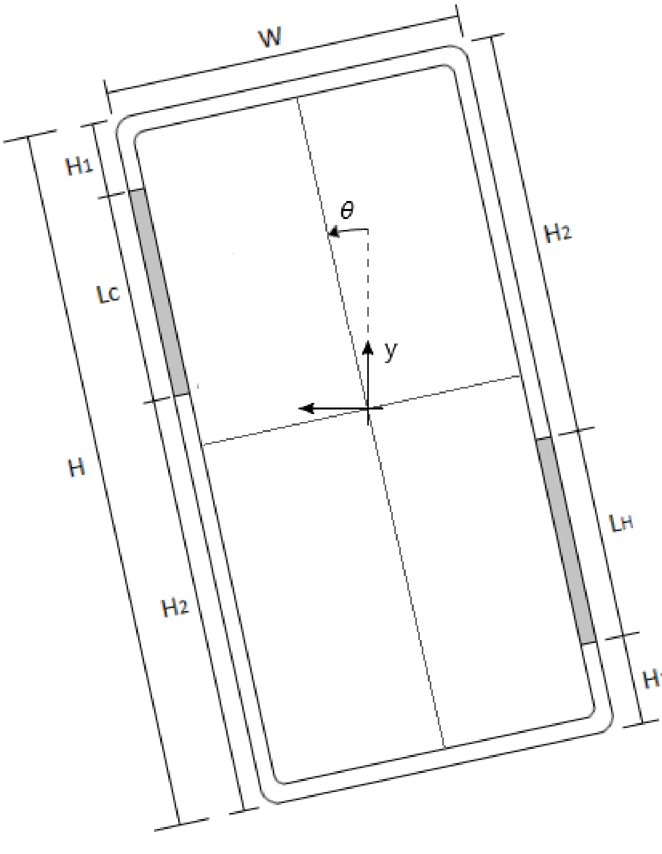

Figure 3. Geometry of the VHVC loop

The turbulence model utilized was RNG κ - ε and the thermophysical properties of CO_2 were obtained from NIST REFPROP v 7.0.

The governing equations used for solution are presented hereinafter, for the steady state.

Conservation of mass equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \tag{1}$$

Conservation of momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ji}}{\partial x_j} + \rho g_i \tag{2}$$

The shear stress (τ_{ji}) is determined as follows:

$$\tau_{ji} = \mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_j}{\partial x_j}\right) \tag{3}$$

The term μ_{eff} is the effective viscosity, or molecular viscosity, and is defined by:

$$\mu_{eff} = \mu + C_\mu \rho \frac{\kappa^2}{\varepsilon} \tag{4}$$

Here, C_μ is derived using RNG theory and equals to 0.0845, κ is the turbulent kinetic energy and ε is the turbulent dissipation rate.

The conservation of energy equation is:

$$\frac{\partial}{\partial x_j}\left(\rho u_j h_{tot}\right) = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_j} + u_j \tau_{ji}\right) \tag{5}$$

In the equation above, k_{eff} is the effective thermal conductivity and h_{tot}, the total enthalpy, determined by the following equation:

$$h_{tot} = h + \frac{1}{2}u_i^2 \tag{6}$$

The governing equations were solved numerically by using ANSYS Fluent v. 18.2, through the finite volume method. The discretization of the momentum equation was carried out with PRESTO and the other terms were discretized using a second-order scheme. The pressure-velocity coupling was executed with the PISO algorithm.

In order to investigate the effect of buoyancy, turbulence and heat transfer, the following dimensionless numbers have been used.

Reynolds number:

$$Re = \frac{D\dot{m}}{A\mu} \tag{7}$$

where $\dot{m}$ is the mas flow rate, A is the cross sectional area of the tube and μ is the fluid's viscosity.

Modified Grashof number:

$$Gr_m = \frac{gQ\beta D^3\rho^2 H}{A\mu^3 C_p} \tag{8}$$

where g stands for the gravitational acceleration, Q is the thermal input of the heater, β is the volumetric expansion coefficient of the fluid, while ρ is its viscosity and C_p its heat capacity.

Nusselt number:

$$Nu = \frac{\bar{h}D}{k} \tag{9}$$

where $\bar{h}$ is the average heat transfer coefficient and k is the thermal conductivity of the fluid.

3. RESULTS AND DISCUSSION

The problem described in former section was simulated considering the geometric parameters presented in Table 1. The tubes are 1 mm thick and made of stainless steel. The cooler temperature T_C = 298 K and the operating pressure is 9.0 MPa. A set of steady state simulations was conducted with Q ranging from 0 to 1000 W.

Table 1. Geometric parameters

Parameter	H	H_1	H_2	W	L_C	L_H	L_1	L_2	D_i
Dimension (m)	1.1	0.1	0.6	0.6	0.4	0.4	0.1	0.1	0.008

Prior to the simulation, a mesh independence study was carried out where four generated meshes were compared. The meshes are presented in Table 2. In this study, the cross sectional averaged temperature was evaluated as a function of the heater position for the power Q= 700 W and the result is presented in Fig. 4, where it can be seen that the Mesh 3 is the smallest one with nearly the same precision of the most refined mesh, thus it was chosen for the upcoming simulations. The y^+ value obtained for this mesh was 46.9, which is compatible with the turbulence model used.

Table 2. Mesh indicators

Name	Number of elements	Number of nodes	Minimum orthogonal quality
Mesh 1	111,780	123,120	0.7160
Mesh 2	198,464	214,412	0.6568
Mesh 3	408,480	432,768	0.7847
Mesh 4	802,368	843,760	0.7681

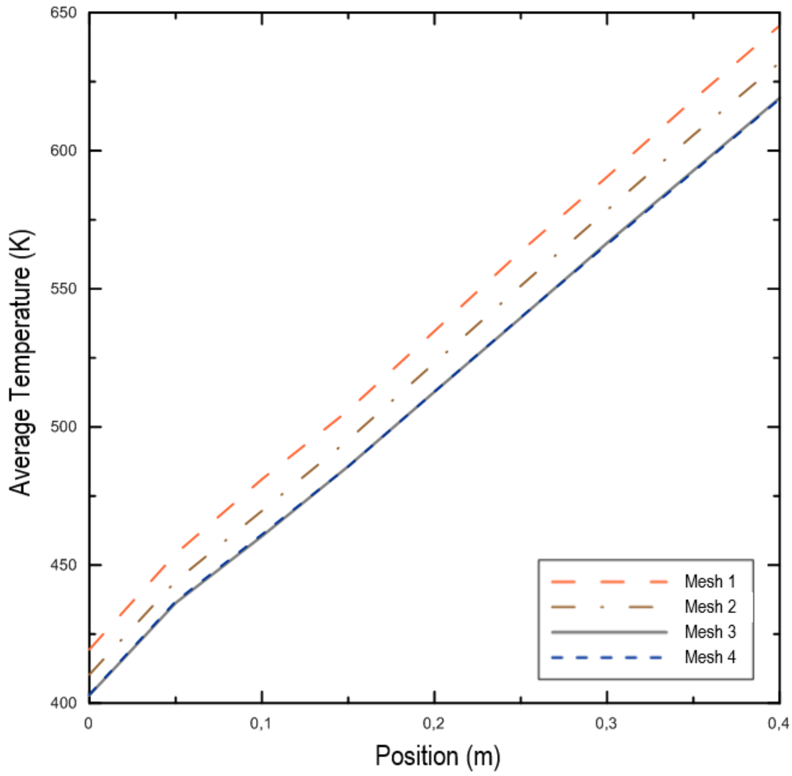

Figure 4. Mesh independence study of the temperature distribution along the heater.

Considering the absence of experimental studies on the VHVC loop configuration with supercritical fluids, the only possible verification of the simulations was through the correlation of (Swapnalee *et al.*, 2012). This comparison is presented in Fig. 5. It can be seen that the correlation overestimates Reynolds number (up to 10%) and it is expected because these correlations were based on experimental data from a HHHC loop, where the Reynolds numbers are intrinsically higher when compared to loops with vertical heaters, as it has been reported by a few authors in the literature.

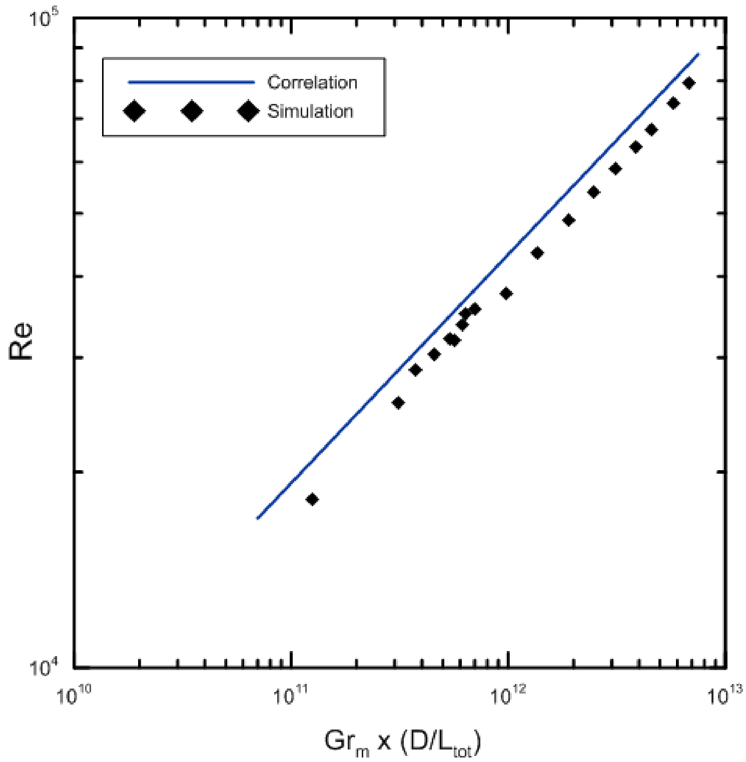

Figure 5. Reynolds number as a function of the modified Grashof number for the VHVC loop.

As it regards to the heat transfer, the simulation results were compared to the ones predicted by the correlation of (Yadav *et al.*, 2012), as it can be seen in Fig. 6. The results presented a good agreement with the correlation, for the normal heat transfer regime, that is, before HTD takes place.

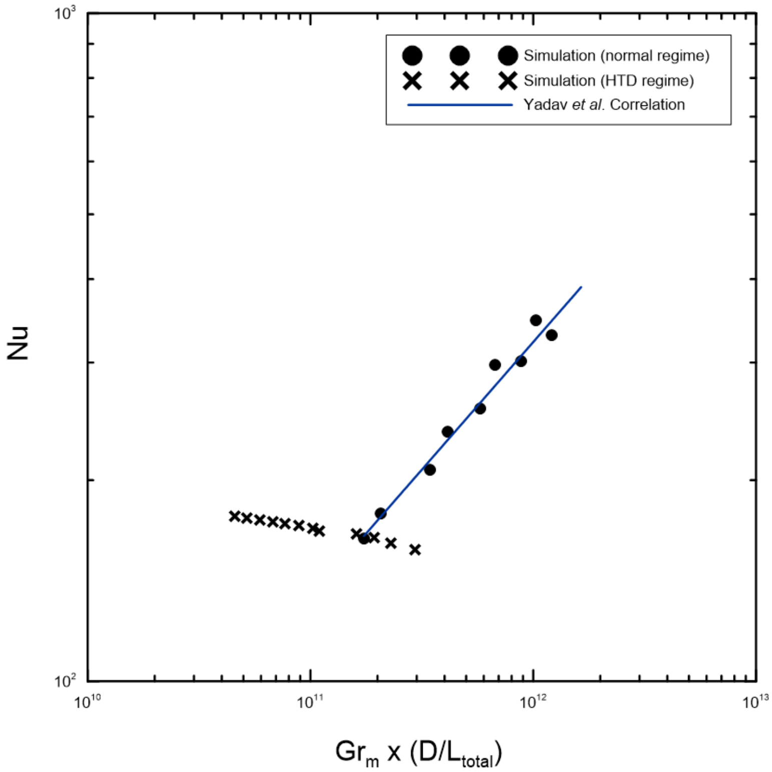

Figure 6. Relation between Nu and Ra for heat transfer before the advent of HTD for the VHVC loop.

For each tilt angle, the steady state flow rate was analyzed as a function of the heater power and represented in Fig. 7. It was observed for all cases, that the mass flow rate increases until it reaches a maximum, then declines very rapidly beyond that point and, after that, continues to decrease at a lower rate. This behavior has been observed by many authors and the steep flow rate decrease is a consequence of the heat transfer deterioration regime and is caused by the pseudocritical zone departure within the heater. Once the entrance of the heater has reached the supercritical zone, density does not experience the same sharp variation as before, causing buoyancy to drop rapidly.

The effect of the inclination is such that, for positive angles, the flow rate decreases compared to the upright case and, for negative angles, it increases. Also, the bigger the absolute value of the angle, the bigger, the variation is, compared to the upright position. That can be explained by observing the vertical distance Z between cooler and heater mass centers. For small angles, positive θ rotations cause Z to increase, whereas negative angles cause Z to decrease. Once the buoyancy term is proportional to Z, if Z increases, buoyancy increases and when Z decreases, buoyancy decreases. The relationship between the flow rate and Z, however, not linear because friction forces also increase when buoyancy increases and this is why, the more Z increases, the smaller are the mass flow rate increments.

In addition, it was observed that, for bigger tilt angles ($|\theta| > 20^o$), for some values of power, there has not been observed a steady state convergence. That points out to the fact that inclination may shrink the stability zone of the system.

4. CONCLUSIONS

The given geometry is able to operate in steady state for tilt angles $|\theta| \leq 20^o$ for Grashof numbers up to $8\text{x}10^{12}$. The appearance of the HTD regime was observed in all the cases studied. It was characterized by the sudden drop in the natural circulation flow rate within the SCNCL followed by a mild and approximately linear decrease in flow rate as power increases. For bigger tilt angles, that is, $|\theta| > 20^o$, steady state convergence was not observed for some values of power and, thus, not presented in this work. This observation indicates that the stability zone may shrink upon loop inclination. The empirical correlation of (Swapnalee *et al.*, 2012) overestimates Reynolds numbers when compared to the simulations. It was, however, somewhat expected once this correlation is not intended for a different loop configuration (HHHC, instead of VHVC). On the other hand, the heat transfer correlation of (Yadav *et al.*, 2012) presents a good agreement with the simulation results for the upright case. The effect of inclination on the very loop's plan was studied and it was observed that for the VHVC configuration, the tilt angle orientation matters, that is, while positive tilt angles

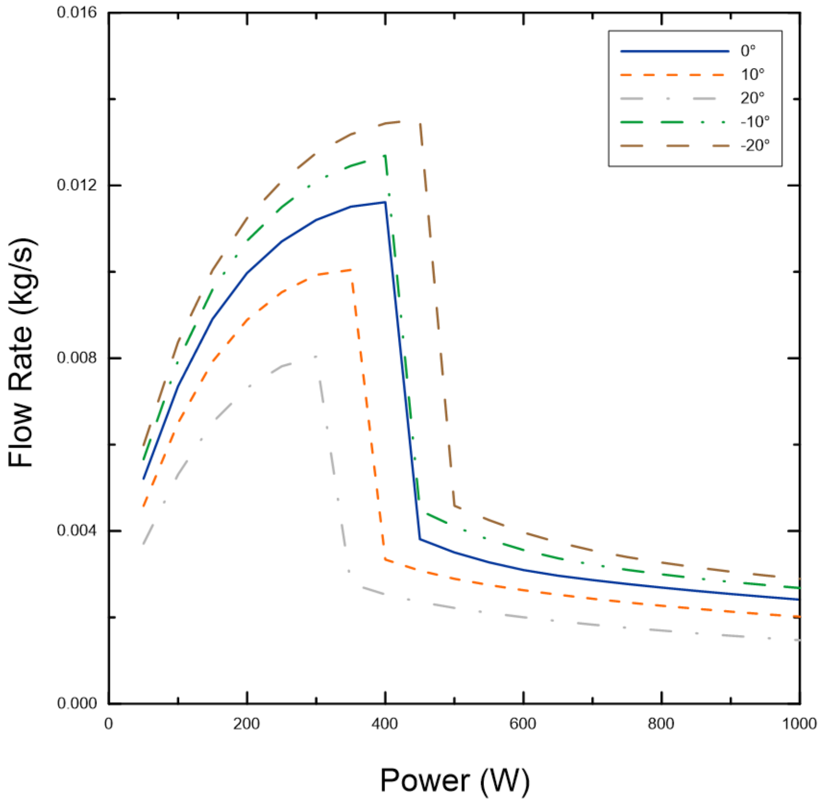

Figure 7. Mass flow rate as a function of power for different angles for the VHVC loop.

cause flow rate to decrease, negative angles, on the other hand, cause flow rate to increase.

As a suggestion for the next studies, the transient behavior of the system needs to be investigated in order to understand the effect of inclination on the oscillations and the stability threshold of the system.

5. ACKNOWLEDGEMENTS

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