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MATHEMATICAL MODELING AND SIMULATION OF A MECHANICAL VENTILATOR WITH HEATING AND AIR HUMIDIFICATION FOR INTENSIVE CARE UNITS

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Abstract. *Mechanical ventilators are machines built to help patients that are clinically unstable or in bad general condition, not able to spontaneously breathe. That is the case of patients who are infected with the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). The temperature and the absolute humidity of the trachea of a healthy person varies between 32 and 34ºC and 25 and 35 mgH_2O L^{-1} respectively, with relative humidity of approximately 95%. The temperature and relative humidity of the air supplied to patients connected to a ventilator varies between 32 and 34ºC and between 95 and 100%, respectively. International recommendations standardize that the supplied air must have 100% relative humidity, absolute humidity between 36 and 40mgH_2O $L^{-1}$and temperature between 31 and 35ºC. We herein present a mathematical model of a mechanical ventilator that supplies air with properties recommended by international guidelines, which will impose less discomfort to the patients during intubation and a fast recovery, leading to quicker discharge making equipment and beds more promptly available to others. The model will be used for real time control of temperature and humidity of the air in the interface machine/patient (mouth) to keep the insufflated air in conditions recommended by the protocols. The model will be a design tool for ventilators, since it controls in real time parameters as temperature and humidity avoiding to inflict other medical conditions to the patients as for example hypothermia, hyperthermia, mucus, lesions in the bronchial tree, mucosal ulceration, inflammation, reduction in pulmonary complacency and ciliostasis.*

1. INTRODUCTION

The increased rates of disease dissemination and number of critically ill patients who require the use of mechanical ventilation due to COVID-19 have raised scientific questions about the specific methods and equipment management for COVID-19 treatment. It is true that the correct handling of the parameters of the mechanical ventilators reduces mortality and reduces the health costs for patients, however, with the constant development and the search for more efficient procedures that allows a speedy return to spontaneous breathing, it is concluded that early intubation is essential for successful treatment.

As delayed intubation may worsen the outcome of coronavirus disease 2019 (N. De Vita, 2021), the demand for mechanical ventilation has been exponentially increased during the COVID-19 pandemic. Before the pandemic, endotracheal intubation was mostly reserved to patients with high energy trauma or risk of impaired consciousness. However, for COVID-19, the recommendations are for early intubation of COVID-19 positive patients with oxygen demands higher than 5 Liters per minute to keep oxygen saturation at a minimum of 93%, even for patients without impaired consciousness (Associação de Medicina Intensiva Brasileira, 2020).

With the complexity and high cost of production of mechanical ventilators, the uncertainty of the parameters applied in artificial respiration and the growing concern about the availability of devices in ICU beds, the study of optimization of existing mechanical ventilation equipment is necessary, so that they meet the new demand for low cost and fast manufacturing process. In order to recognize the ventilation mode, adequacy of the inspiratory and expiratory time, ability to detect changes in the patient condition, monitoring through the volume, pressure and flow curves over time is essential. For professionals who are not trained in the health field, the main challenge is the lack of knowledge about respiratory mechanics, lung injuries caused by mechanical ventilation and the influence on other systems than the respiratory system. Knowledge of ventilation modes and cycling is of paramount importance for safe and efficient artificial respiration, to ensure the integrity of the airways and correct function of the respiratory system, avoiding fatigue and helping to restore muscle strength.

Mechanical ventilators are devices used to help clinically unstable patients or patients that are not capable of breathing spontaneously to recover their health. This is the case of critical patients that are under acute respiratory distress syndrome due to COVID-19. It was experimentally verified that the temperature at the trachea level of a normal person varies between 32 and 34ºC, the absolute humidity (AH) varies between 25 and 35mgH_2O L^{-1} and the relative humidity (RH) is approximately 95% (Shelly, 1998; Branson, 1999). Based on the experimental data, the Compêndio de Medicina Intensiva (2004) published by the Brazilian Association of Intensive Care (Associação Brasileira de Medicina Intensiva) recommends that the temperature of the air provided to intubated patients (under mechanical ventilation) must be between 32 and 34ºC and the relative humidity between 95 and 100%. Internationally, similar conditions were standardized to provide air with relative humidity (RH) of 100%, absolute humidity (AH) of 36 to 40 mg L^{-1} and temperature between 31 a 35 °C (Cairo, 2013).

As can be seen by those guidelines, the air humidity plays an important role in the mechanical ventilation. The control of humidity must be accurate enough so any response of the patients while intubated can be associated with their physiological interaction with medication and not to the excess of lack of humidification of the inhaled air. Studies have shown that data regarded humidity presented by manufacturers are questionable (Lellouche *et al.,* 2009).

Additional measurement instruments have been used in practice to monitor the humidity during the use of the mechanical ventilator, as for example, hygrometer-thermometer, which unfortunately are not always available (Ashry and Modrykamien, 2014). Therefore, other ways of monitoring the humidification are employed, as for example the secretion characteristics. There is a direct relation between the volume of the secretion and the level of humidification. High levels of humidification lead to the volume increase of secretion and low humidification lead to crusting and decrease in its volume (Sottiaux, 2006).

Overheating is also an issue in mechanical ventilation. High air temperature may cause localized hyperthermia, increase of the patient metabolic activity to keep its normothermia. Such increase of temperature also may cause protein, enzyme, cardiac and respiratory dysfunctions and even delay on the extubation. Conventional mechanical ventilators do not have temperature sensors measuring local temperature of the insufflated air, only the oscillation of the temperature is measured. Under this circumstance, the temperature of the air at the interface, tube-patient is not controlled.

The objective of this study is to introduce a mathematical model that predicts the response of a ventilator that is connected to an oil-free compressor at one end and the patient to the other end. The model will be used for real time control of temperature and humidity of the air in the interface machine/patient (trachea) to keep the insufflated air in conditions recommended by the protocols. The model will be used to design a ventilator that controls in real time parameters as temperature and humidity avoiding inflicting additional medical conditions to the patients caused by poor control of temperature and humidity.

2. MATHEMATICAL MODEL

In Figure 1 we show a schematic of the mechanical ventilator represented by the control volume 1 (CV1). The mathematical model is conceived applying the mass and energy conservation principles considering the known parameters: input mass flow rate of humid air, $\dot{m}_{in}$; input relative humidity, ϕ_{in}; input humid air temperature, T_{in} and input humid air pressure, P_{in}. The output parameters, temperature (T_{out}) and relative humidity (ϕ_{out}), are chosen according to medical protocols for patients diagnosed with COVID-19 or other diseases, in need of mechanical ventilation.

The input mass flow rate of humid air is modeled by the following expression:

$$\dot{m}_{in} = \dot{m}_{a,in} + \dot{m}_{v,in} \tag{1}$$

where $\dot{m}_{in}$ is the input mass flow rate of humid air (kg/s), $\dot{m}_{a,in}$ is the input mass flow rate of dry air (kg/s), $\dot{m}_{v,in}$ is the input mass flow rate of water vapor (kg/s).

The input vapor pressure, molar fraction of vapor and absolute humidity are defined respectively as follows:

$$P_{v,in} = \phi_{in} P_{v,sat}(T_{in}) \tag{2}$$

$$x_{v,in} = \frac{P_{v,in}}{P_{in}} \tag{3}$$

$$\omega_{in} = 0.622 \frac{P_{v,in}}{P_{in} - P_{v,in}} = \frac{\dot{m}_{v,in}}{\dot{m}_{a,in}} \tag{4}$$

where $P_{v,in}$ is the inlet vapor pressure (Pa), ϕ_{in} is the input relative humidity of inlet air flow, T_{in} is the temperature of the inlet air (K), $P_{v,sat}$ (T_{in}) is the vapor saturation pressure at the temperature T_{in} (Pa), $x_{v,in}$ is the input molar fraction of the vapor, P_{in} is the input pressure of humid air (Pa) and ω_{in} is the absolute humidity of the input air.

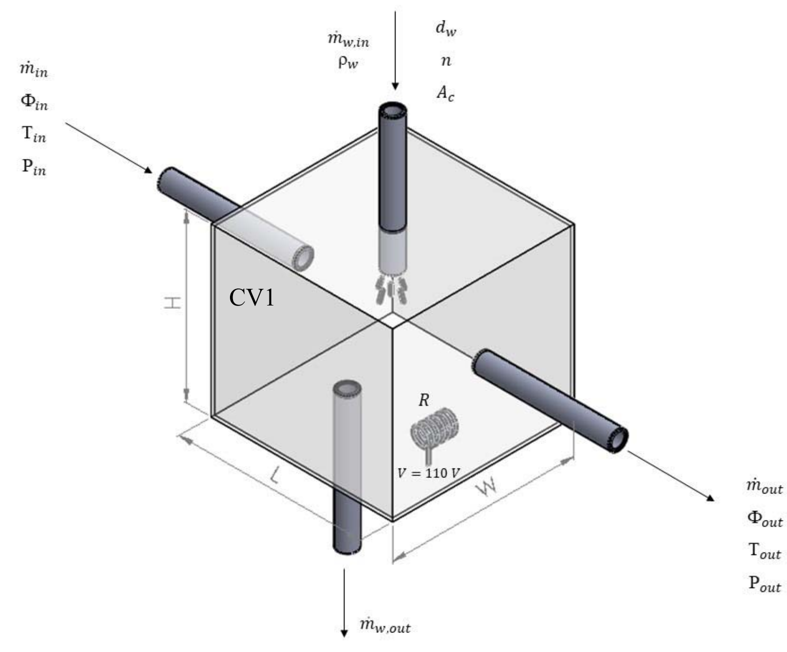

Figure 1. Schematic of the mechanical ventilator considering the analysis of the CV1, where $L = H = W = 10^{-1}$ m.

Considering the Eq. (1) and Eq. (4), we are able to express the input mass flow rate of dry air ($\dot{m}_{a,in}$) and the input mass flow rate of water vapor ($\dot{m}_{v,in}$), respectively as follows:

$$\dot{m}_{a,in} = \frac{m_{in}}{1 + \omega_{in}} \tag{5}$$

$$\dot{m}_{v,in} = \omega_{in} \dot{m}_{a,in} \tag{6}$$

The input mass flow rate of water vapor is then determined as $\dot{m}_{v,in} = \dot{m}_{in} - \dot{m}_{a,in}$ or by the Eq. (6) directly. The mass conservation principle applied to the CV1 states that:

$$\frac{dm_{v1}}{dt} = \dot{m}_{v1} + \dot{m}_{v,out} \tag{7}$$

where m_{v1} is the mass of water vapor in the CV1 (kg), $\dot{m}_{v,1}$ is the total input mass flow rate of water vapor that enters the CV1 (kg/s) and $\dot{m}_{v,out}$ is the output mass flow rate of water vapor (kg/s).

The total input mass flow rate of water vapor can be expressed as:

$$\dot{m}_{v1} = \dot{m}_{v,in} + \overline{h}_m A_{mt} \left(\rho_w - \rho\right) \tag{8}$$

where $\overline{h}_m$ is the average mass transfer coefficient (m/s) and A_{mt} is the total mass transfer area between the water stream from the nozzle and the air inside of the CV1 (m^2). The density of the liquid water ρ_w, (kg/m^3) and the density of the water vapor in the CV1 ρ, (kg/m^3) are computed as follows:

$$\rho_w = \frac{1}{v_g(T_1)} \tag{9}$$

$$\rho = \frac{m_{v1}}{\forall_1} \tag{10}$$

The properties in the Eq. (9) and Eq. (10) are the following $v_g(T_1)$: the specific volume of the saturated water vapor, (m^3/kg) where T_1 is the temperature of the CV1, (K) and $\forall_1$ is the volume of the CV1 (m^3).

With the intent of finding the $\dot{\mathrm{m}}_{v1}$ from Eq. (8), $\overline{h}_m$ is calculated based on the wet length, L_w (m) which is taken as the height of CV1 and considering that there is an air velocity in CV1 due to natural convection (Bejan, 2004), as follows:

$$\overline{h}_m = \frac{D}{L_w}\overline{Sh} \tag{11}$$

$$\overline{Sh} = 0.644 Sc^{1/3}\,\mathrm{Re}^{1/2} \tag{12}$$

$$\mathrm{Re} = \frac{U_a d_w}{\upsilon_a} \tag{13}$$

$$U_a = \frac{\dot{m}_{w,in}}{n\rho_w A_c} \tag{14}$$

where, D is the air-water mass diffusivity taken as 2.6×10^{-5} m^2/s at 298 K and 2.88×10^{-5} m^2/s at 313 K (Bejan, 2004), $\overline{Sh}$ is Sherwood number, S_c is the Schmidt number and Re is the Reynolds number. U_a is velocity of each stream (m/s), υ_a is the kinematic viscosity of water (m^2/s), n is number of water jets in the CV1, d_w is diameter of each stream (m) and A_c is the cross sectional area of each stream (m^2).

The total mass of dry air in the CV1, m_{a1} (kg); the vapor molar fraction in the CV1, x_{v1}; the vapor partial pressure in the CV1, P_{v1} (Pa); and the relative humidity of the air in the CV1, ϕ_1 ; respectively, are given by:

$$m_{a1} = \rho_a(T_1)\forall_1 \tag{15}$$

$$x_{v1} = \frac{m_{v1}/M_{H_2O}}{m_{v1}/M_{H_2O} + m_{a1}/M_a} \tag{16}$$

$$P_{v,1} = x_{v,1}P_{in} \tag{17}$$

$$\phi_1 = \frac{P_{v1}}{P_{v,sat}(T_1)} \tag{18}$$

where $\rho_a(T_1)$ is the density of the dry air at the temperature T_1 (kg/m^3), M_{H_2O} is the molar mass of water (kg/kmol), M_a is the molar mass of dry air (kg/kmol), $P_{v,1}$ is the partial vapor pressure in the CV1 (Pa) and $P_{v,sat}(T_1)$ is the vapor saturation pressure at the temperature T_1 (Pa).

When $\phi_1 = 1$, condensation starts on the inner surfaces of chamber (CV1) and $\dot{m}_{v,in} = \dot{m}_{v,out}$ and $\frac{dm_{v1}}{dt} = 0$, i.e., the liquid water production starts. Following what was exposed above and considering incompressible flow, the mass transfer for the dry air states that:

$$\dot{m}_{a,out} = \dot{m}_{a,in} \tag{19}$$

where $\dot{m}_{a,out}$ is the output mass flow rate dry air (kg/s).

Taking that the air/water mixture leaves CV1 with a relative humidity ϕ_1, then it is possible to evaluate the output mass flow rate composition as follow:

$$\omega_1 = 0.622\frac{P_{v,1}}{P_{in} - P_{v,1}} = \frac{\dot{m}_{v,out}}{\dot{m}_{a,out}} \tag{20}$$

where ω_1 is the absolute humidity in the CV1.

According to the Eq. (20) we can calculate the output of mass flow rate of water vapor $\dot{m}_{v,out}$ (kg/s) and the output mass flow rate of humid air $\dot{m}_{out}$ (kg/s) as:

$$\dot{m}_{v,out} = \omega_1 \dot{m}_{a,out} \tag{21}$$

$$\dot{m}_{out} = \dot{m}_{a,out} + \dot{m}_{v,out} \tag{22}$$

The initial partial vapor pressure in CV1, $P_{v,0}$ (Pa); initial mass fraction of the water vapor in CV1 and the initial water vapor mass in CV1, $m_{v,0}$ (kg) are given by the following expressions:

$$P_{v,0} = \phi_{v,0} P_{v,sat}(T_{1,0}) \tag{23}$$

$$x_{v,0} = \frac{P_{v,0}}{P_{in}} \tag{24}$$

and

$$m_{v,0} = \frac{x_{v,1} M_a M_{H_2O}}{(1 - x_{v,0}) M_a} \tag{25}$$

where $\phi_{v,0}$ is the initial relative humidity in CV1 and $P_{v,sat}(T_{1,0})$ is the vapor saturation pressure at the initial temperature T_1 in CV1 (Pa).

Assuming air as a non-participating medium and radiation heat transfer negligible, the energy conservation principle applied to the mechanical ventilator (CV1) states that:

$$-U_\infty A_\infty (T_1 - T_\infty) + \dot{Q}_R + \dot{m}_{a,in} c_{p,a} (T_{in} - T_1) + \dot{m}_{v,in} h_g (T_{in}) - \dot{m}_{v,out} h_g (T_1) = (m_a c_{v,a} + m_v c_{v,v}) \frac{dT_1}{dt} \tag{26}$$

where U_∞ is the global heat transfer coefficient between CV1 and the environment (W/kgK), A_∞ is the heat transfer area between CV1 and the environment (m^2), T_∞ is the ambient temperature (K), $\dot{Q}_R$ is the heat generated by electric resistance in the CV1 (W), $c_{p,a}$ is the specific heat at constant pressure of air (W/kgK), $c_{v,a}$ is the specific heat at constant volume of air (W/kgK), $c_{v,v}$ is the specific heat at constant volume of water vapor (W/kgK), $h_g\left(T_{in}\right)$ is the enthalpy of the input water vapor at the temperature T_{in} (J/kg) and $h_g\left(T_1\right)$ is the enthalpy of the input water vapor at the temperature T_1 (J/kg).

The heat generated by the electric resistance in CV1 is computed as $\dot{Q}_R = V^2 / R$, where V is the electric potential (V) and R is the electric resistance (Ω).

3. RESULTS

In this section we present the results of the mathematical model and analyze their physical meaning. Adequate environmental and operating conditions for the cases herein studied are presented in Table 1. The control parameters were defined with two set points for temperature (*$tempset_1$ and $tempset_2$*), thus resulting in 3 zones of voltage and its subsequent power applied to the resistance (V_1, V_2 and V_3), and with two set points for humidity (*$humset_1$ and $humset_2$*), thus resulting in 3 zones of water mass transfer rate from the water inlet ($\dot{m}_{w,in,1}$, $\dot{m}_{w,in,2}$ and $\dot{m}_{w,in,3}$). Furthermore, control robustness refers to the ability of a control system to withstand parameter variations while it maintains stability. In order to increase the system robustness, deadbands were introduced in both temperature and humidity controls. For the temperature control a deadband of 1K was introduced before the variation of the resistance voltage control. For the humidity control, a deadband of 5% was introduced before the variation of the water mass flow rate control.

The converged model was simulated for 20 seconds, as it already reached periodic steady state with satisfactory control volume output temperature (309 K) and humidity (95%) after 10 seconds.

Table 1. Initial values and simulation parameters.

$\dot{m}_{in} = 10^{-4}\ kg/s$	$V_1 = 20\ V$
$T_{in} = T_\infty = 298.15\ K$	$V_2 = 12\ V$
$P_{in} = 10^5\ N/m^2$	$V_3 = 7.5\ V$
$\phi_{in} = 30\%$	$\dot{m}_{w,in,1} = 10^{-1}\ kg/s$
$d_w = 10^{-3}\ m$	$\dot{m}_{w,in,2} = 5\times10^{-2}\ kg/s$
$n = 30$	$\dot{m}_{w,in,3} = 1.7\times10^{-1}\ kg/s$
$\forall_1 = 10^{-3}\ m^3$	$tempset_1 = 303.15K$
$U_\infty = 5\ W/kgK$	$tempset_2 = 309.65K$
$S_c = 0.6$	$humset_1 = 80\%$
$R = 11.5\ \Omega$	$humset_2 = 99\%$

Figure 2 shows the resulting vapor mass at the CV1. After the 9 seconds, the system reaches periodic steady state with stabilization of the water vapor mass in the CV1 at an average of 2.1x10^{-5} kg.

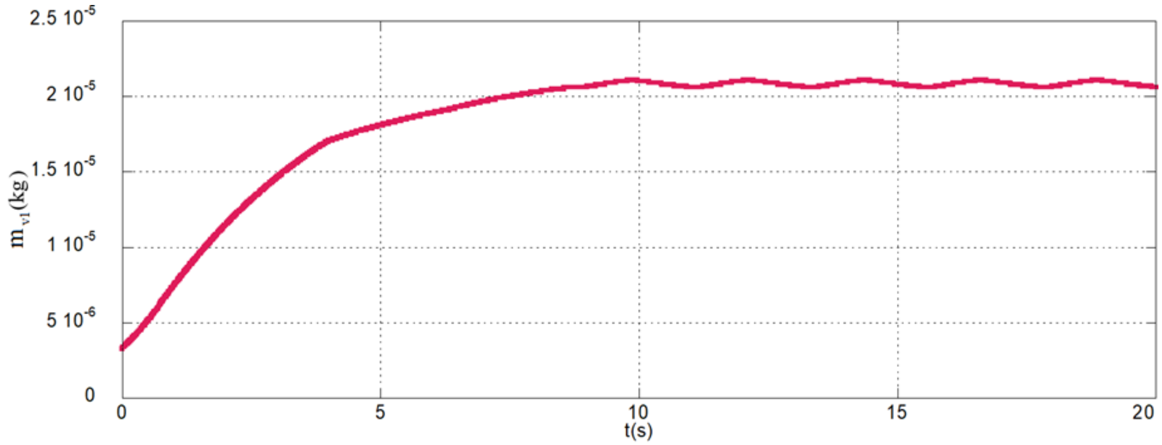

Figure 2. Mass of vapor in the CV1

Figure 3 shows the resulting temperature at the control volume. After 2 seconds, the system reached periodic steady state with stabilization of the control volume temperature at an average of 309.65 K. Both temperature setpoints were used for refined temperature control with the electrical resistance, thus creating 3 resistance voltage zones: When the temperature is below tempset1 (303.15K) a higher power is used with the resistance (V_1=20V and P_{V1}=35W). When the temperature reaches the interval between $tempset_1$ and $tempset_2$ (309.65 K), an intermediate voltage is used with the resistance (V_2=20V and P_{V2}=13W). Finally, when the temperature rises above $tempset_2$, a lower voltage is used with the resistance (V_3=35V and P_{V3}=5W).

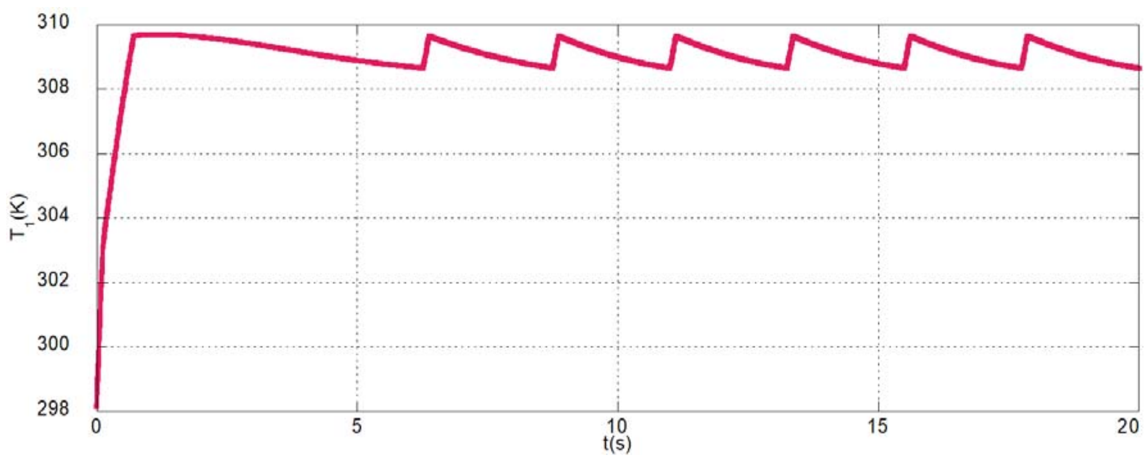

Figure 3. Air and vapor temperature of the CV1

Figure 4 shows the resulting humidity at the control volume. After 9 seconds, the system reaches periodic steady state with stabilization of the control volume humidity at an average of 98%. Both humidity setpoints were used for refined humidity control with the total water mass flow rate at the water inlet, thus creating 3 injected water mass flow rate zones: When the humidity is below $humset_1$ (80%) a higher water mass flow rate is controlled to water inlet (0.1 kg/s). When the humidity reaches the interval between $humset_1$ and $humset_2$ (99%), an intermediate water mass flow rate is controlled to the water inlet (0.05 kg/s). Finally, when the humidity rises above *humset2*, a lower water mass flow rate is controlled to the water inlet (0.017 kg/s).

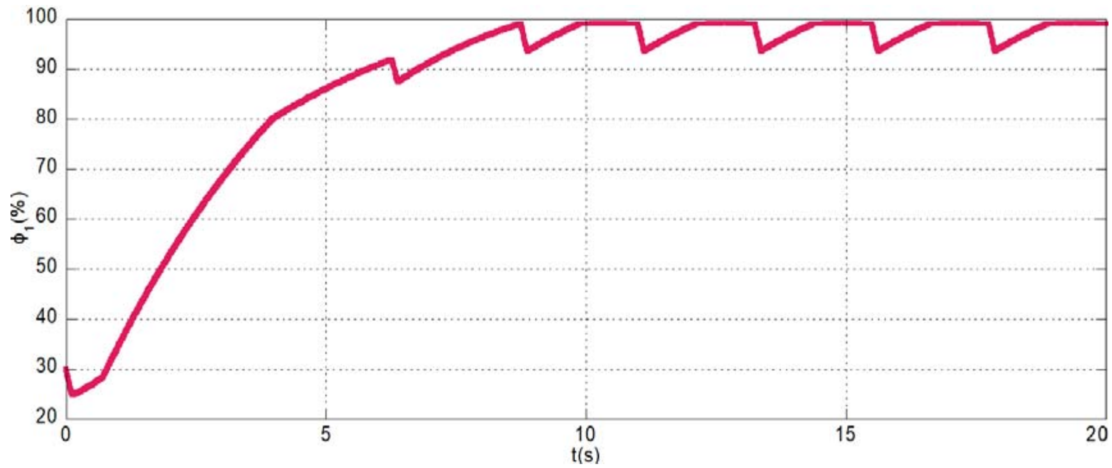

Figure 4. Air humidity of the CV1

4. CONCLUSION

The main conclusions of this study are that the mathematical model was efficient in capturing the expected physical trends of (i) the mass transfer and mass conservation principles between the input humid air, water nozzle and the chamber (CV1); (ii) the energy conservation between the air inlet, water nozzle, electric resistance and the control volume, requiring only 10 seconds to simulate 20 seconds of water vapor mass transfer, temperature and humidity at the CV1. With this, the model is ready for experimental validation with low cost temperature and humidity controlled ventilator.

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