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TEMPERATURE AND HUMIDITY ON EVAPORATIVE COOLING SYSTEMS ACTUATED BY CLASSICAL CONTROLLERS

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Abstract. *In recent years the planet has gone through major transformations, the reduction of water sources, global warming, floods and climate change has concerned the future of humanity. All these phenomena seem to be co-related and originated from a single factor, the environmental degradation. Within this context, the refrigeration and air conditioning vapor compression have high energy consumption and working with cryogenic fluids that influence the degradation of the environment. One alternative that was proposed and is being marketed is a system based on evaporative cooling of air whose main purpose is the reduction of dry bulb temperature of air, which can only be achieved by humidifying the stream air. Despite the reduction of the sensible heat of air through the humidification, there is no guarantee that the environment reach the thermal comfort zone, that because the entry conditions of humidity is critical, since the higher the local humidity less will decrease the dry bulb temperature, however, evaporative cooling systems can be used in warmer climates and dry. Another important parameter for thermal comfort is achieved is the amount of water to be released in the air stream, that because the saturation of the air flow can leave the very high humidity, so the amount of latent heat is great inserted, resulting in conditions which make it impossible to obtain the comfort zone. This paper presents the mathematical modeling of an evaporative cooling system. To ensure comfort conditions, ie, wet bulb temperature and wet bulb, through the mass of air entered, we are proposing a system of control. For the design and implementation of the control system is needed that the model has characteristics consistent with theories of classical control. The classic controllers used are the types of Proportional, Proportional Integral, Proportional Derivative and Proportional Integral Derivative which, to be deployed and unable to adequately control require an element of control. Each controller has its own characteristics, so their times of work did not only depend on the magnitude of the error, but also speeds and growth rates, ie the integral and derivative signal. After implementation of the controllers is expected that the thermal comfort conditions are achieved, that the system is stable to all types of disturbances in temperature and humidity of entry, the response time of the system is suitable both for changes in conditions operation and for disturbances. Another feature is that the maximum overshoot is about 40% of the desired value and the system has maximum error of 2% in steady state. The controller designed to ensure that the error due to disturbances is never greater than 10% of the desired value. The proposed system, meeting the performance specifications herein mentioned, is robust and stable and can be safely used to control the temperature and humidity of evaporative coolers in order thermal comfort in hot and dry regions.*

***Keywords**:* Evaporative cooler, air conditioning environments, classic controller

1. INTRODUCTION

For global sustainable development, it is necessary to reduce the primary energy consumption and to introduce renewable energy. The reduction of the primary energy can be performed with a reasonable utilization of waste thermal energy in a refrigeration process. Most of the refrigeration and the heat pump technologies are dominated by vapor compressor systems. The vapor compressor system, however, is highly concerned with the environmental regulations.

The energy demand for air conditioning to control temperature and humidity and for the provision of fresh air has increased continuously throughout the last decades especially in developed countries. This increase is caused amongst other reasons by increased thermal loads, occupant comfort demands, and architectural trends. This has been responsible for the escalation of electricity demand and especially for the high peak loads due to the use of electrically driven vapor compression machines. The provision of reliable supply to meet this demand requires huge electrical generation, transmission and distribution infrastructure. Additionally, the consumption of primary energy and the emissions of greenhouse gases associated with electricity generation from fossil fuels lead to considerable environmental consequences and monitory costs.

Air-conditioning consumes large amount of electrical energy, especially in hot and humid climatic areas. The cooling load of a building is the sum of the sensible and latent heat loads. While the former is due to the difference between indoor and outdoor temperatures, the latter is caused by the difference between indoor and outdoor humidity contents. Both these types of loads may be generated within the building.

Refrigeration and air conditioning system influences the environment in three aspects. Firstly, the CFCs and HCFCs used as working fluids are ozone-depleting substances. Secondly, refrigerant such as CFCs has the global warming potential. Recent natural disasters around the world have shown the negative effects of greenhouse gases including various refrigerants. Thirdly, refrigeration system consumes energy which in general is produced from fossil fuel and related to release of pollutions. These pollution materials, such as CO, SO_x and NO_x are harmful to the health of people, Wang and Liu, (2007). Particularly, air e water are clean, no combustibility and relatively low-pressure gas that is extremely safe natural refrigerants.

Conventional vapor-compression-based cooling systems are not able to cope with the current humidity standards required by the production and the storage of humidity sensitive products. Currently, the interior air quality (IAQ) rigid standards made problematical the use of conventional air conditioning system, especially in extreme humidity conditions. In order to reduce the electricity consumption, the substitution of vapor compression machines by thermally driven cooling systems using renewable energy or waste heat is a promising alternative.

As a result, researchers worldwide are working in the developing of air-conditioning systems that employ energy renewable resources and working fluids that cause no damage to the environment. In this context, evaporative cooling systems appear as a correct ecologically alternative to replace the traditional air-conditioning systems.

The evaporative cooling is due to the simultaneous process of heat and mass transfer which occurs when the air to be cooled enters in direct contact with a humid surface in such a way that water and air are the working fluid used in the system, Camargo *et al.*(2005). In some systems, the humid surface is replaced by jets of water droplets which are sprinkled on to the air draft (air washers). In some broader way, a warm and dry air stream is collocated into contact with a humid surface, where the air supplies the necessary latent heat that leads to the evaporation of a certain amount of water. The air is then cooled as a result of the sensible heat transferred to the water and humidified by liquid evaporation from the humid surface. The process of heat and mass transfer cease when the air reaches its saturation state in such way that the minimum temperature obtained for the air in evaporative coolers will be the inlet air humid bulb temperature. One of the main advantages of evaporative cooling is that the efficacy of the process increases, when the climate is very hot and dry; in other words, when the demand for thermal comfort increases. Another important advantage of the evaporative cooling is the total renewal of the air eliminating, in this way, the proliferation of fungi and bacteria in the conditioned space. Other benefits from this system may be named as follows: low energy consumption, easy maintenance, easy installation and operation, and it is free of the chlorofluorocarbons and hydrochlorofluorocarbons. Even in conditions where the air presents higher humidity content, evaporative coolers can be used together with adsorptive dehumidifiers, propitiating the appropriate thermal comfort conditions with low energy consumption, Camargo *et al.*(2003).

Works concerning the modeling of the heat and mass transfer process in evaporative coolers have been developed with the objective of exploring the potentialities of this technology. Maclaine-Cross and Banks (1983) have developed a study to model evaporative coolers. From the results obtained, a theory to correlate the transfer coefficients in humid and dry surface heater exchangers was proposed. Ismail and Mahmoud (1994) developed a mathematical model for the analysis of air washers. The model is used to determine the feasibility of the utilization of air washers and chemical dehumidifiers together liquid coolers in air-conditioning applications. Halasz (1998) developed a mathematical model to describe the physical behavior of different devices which uses evaporative cooling processes in its operation, such as: cooling towers, evaporative condensers, air washers and cooling and dehumidifying coils. Dai and Sumathy (2002) studied a direct evaporative cooler made up of an evaporative cell. A mathematical model made up of equations for the liquid film, the gaseous phase and the liquid-gas interface was proposed. The results indicate that parameters such as air channel lengths within the evaporative cell, flow rate of the feeding water, and the flow rate of the air process could be optimized in order to improve the performance of the cooler. Beshkani and Hosseini (2006) studied the effects of air velocity and the length of the evaporative panels on saturation efficiency and pressure drop in direct evaporative coolers. An analysis of the results showed that the cooler efficiency increases as a result of the reduction in the velocity of the process air stream, and the increase in the length of the panel.

Alternative systems to ensure reduction in power consumption compared to conventional systems, however, their income bands are, in general, low. To ensure high performance of thermal systems, in particular alternative refrigeration cycles, it is necessary to use automatic controllers. The refrigeration vapor compression always made use of these controllers. The first automatic controllers used in refrigeration vapor compression were on and off. This type of controller, applied to temperature control, operates according to the temperature of the air conditioner sucked (return air), which changes the resistance of the fluid contained in a bulb and this fluid acts on the relay that turns on or off the equipment. The simple construction and operation of this controller, besides the low cost, makes the majority of air conditioners for small and medium use it to maintain a constant average temperature, however, the need for better drivers, especially in systems large and the need to eliminate large variations in response, has caused other drivers to be developed on a commercial scale equipment. One example is the liquid coolers large (chiller), or systems developed for specific industries, which use classical control systems.

The need for better control of thermal systems has become so evident that some researchers in various parts of the world are currently working in this area. Because it is two distinct areas of engineering, control of thermal systems or process control is endowed with some extra degree of difficulty, since each system has its own thermal dynamics, where his mathematical model, experimental or theoretical, may be difficult to determine. Thus, the success of this type of work can be in creating a model that can be integrated with control systems, which requires knowledge of both areas.

Although some studies are already being developed, many commercial thermal systems have had their income reduced by the lack of a more adequate control. Perhaps the difficulties that exist in uniting researchers, disciplines and knowledge, besides the difference in approach in the treatment of problem analysis and display of results, are decisive factors for the lack of further development of these two areas (Braga, 2004).

Some relevant researches have been developed and attest to the efficiency of integration of thermal and control areas. Sfetsos and Coonick (2000) used artificial intelligence techniques, neural networks and neuro fuzzy, to predict the hourly solar radiation on a horizontal surface. Already Alkhamis et al (2000) used a Classic Controller, PID, to control the temperature of a bioreactor is powered by a solar collector. This work emphasized the importance of PID controller and compared the result to a league off. Kalogirou et. al (1999) studied the use of artificial neural networks for modeling a system of solar domestic water heating.

In the area of cooling, some studies were also presented. Braga (2000) studied a classical control system applied to a heat exchanger for evaporative cooling worked. The water leaving the heat exchanger should have controlled temperature to serve any process.

The objective of this work is to develop a system capable of producing a new round of climate environments that has a low power consumption also ensures the best operation within the income groups, as well as provide satisfactory response time, stability and rejection of disturbances.

2. MATHEMATICAL MODELLING

The development of the mathematical model was made in order to allow the use of the application of classical control models. One way of modeling that allows association with the theories of classical control is the overall analysis. Figure 1 shows the schema of an evaporative cooling system for cooling an environment.

For the energy balance to occur properly, the mathematical model can only be done after the definition of a control volume (Bejan, 1996). Thus, it was defined the box area of the spray as volume control. To perform the mathematical model considered insignificant variation of specific heat at constant pressure throughout the process and the variation of water vapor. It was also felt that the cooler temperatures are uniform. The heat transfer by conduction through the walls of the cooler was despised.

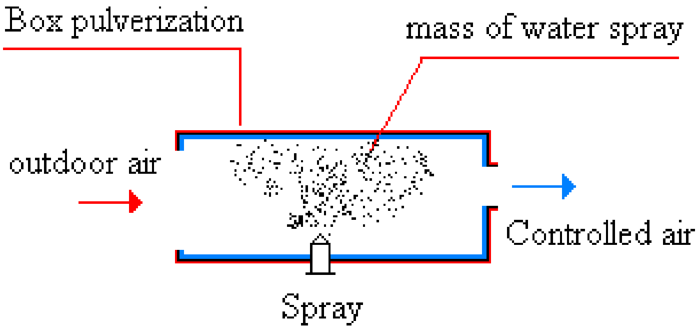

Figure 1. Evaporative cooler.

2.1. Mathematical equations

Equation 1 represents the energy balance between input and output of the evaporative cooler. Equation 2 represents the cooling system in transient state.

$$\dot{m}_{ar}.cp_{ar}.T_1+\dot{m}_{ag}.h=\dot{m}_{ar}.cp_{ar}.T_2 \qquad (1)$$

where: $\dot{m}_{ar}$ is the mass flow of circulating air

cp_{ar} is the specific heat at constant pressure

T_1 is the temperature at the entrance of the cooler

T_2 is the temperature at the outlet of the cooler

$\dot{m}_{ag}$ is the flow of water sprayed

M is the mass of air evaporative cooler
h is the energy of vaporization of water

The evaporative cooler, in transient state, results in equation (2).

$$M\ .cp_{ar}.\frac{dT_2}{dt} = -(\dot{m}_{ar1}+m_v).cp_{ar}.T_2+\dot{m}_{ar1}.cp_{ar}.T_1+\dot{m}_{ag}.h \qquad (2)$$

where: $\dot{m}_{ar2} = \dot{m}_v + \dot{m}_{ar1}$, air mass in the output is equal to mass of air at the entrance more water vapor added. The value of m_{ar2} is the quantity of water spray, which results in the appearance of a recurrent term in the equation. The value of the portion of water vapor is very small compared to the value of air mass and the total value of the denominator of the transfer function, thus the variation of water vapor due to spraying, the plot appears, may be neglected. The simulation with the portion in the maximum and minimum values does not differ in graphics response.

Applying the Laplace transform, we have:

$$(M.cp_{ar}.s+\dot{m}_{ar2}.cp_{ar}).T_2(s) = \dot{m}_{ar1}.cp_{ar}.T_1(s)+h.\dot{m}_{ag}(s) \qquad (3)$$

The transfer functions of the evaporative cooler will be conducted of the models developed. Equation 4 presents the model of the cooler.

$$.T_2(s) = \frac{\dot{m}_{ar1}.cp_{ar}.T_1(s)+h.\dot{m}_{ag}(s)}{(M\ .cp_{ar}.s+\dot{m}_{ar2}.cp_{ar})} \qquad (4)$$

Equation 4 give rise to two transfer functions. Equation 5 is the transfer function between output temperature of the cooler and the temperature of incoming air, which represents the disturbance of the plant. Equation 6 is the transfer function between the output of the cooler and the flow of water sprayed every moment, to be used as a control variable.

$$\frac{.T_2(s)}{T_1(s)} = \frac{\dot{m}_{ar1}.cp_{ar}}{(M\ .cp_{ar}.s+\dot{m}_{ar2}.cp_{ar})} \qquad (5)$$

$$\frac{.T_2(s)}{\dot{m}_{ag}(s)} = \frac{h}{(M\ .cp_{ar}.s+\dot{m}_{ar2}.cp_{ar})} \qquad (6)$$

3. PROJECT CONTROLLERS

The completion of the project for a suitable driver should consider the type of system that is being worked as well as the dynamic characteristics of the system. The following describes the actions of classical control, having features proportional, integral and derivative, as described by Ogata (2003). There are several techniques for controller design classics, such as the Routh stability criterion, the methods of Ziegler and Nichols or the method of pole placement. For the project is necessary to allocate the values to the terms of the equations. The values of the terms of the equations defining the dead time, time constant and the gain of the coupled system, which results in defining the dynamic behavior.

The values of the terms of the equations are defined as follows:

h = 539 kcal/kg; cp_{ar} = 0,24 kcal/kg.C; m_{ar1} = 0.28 kg/s; M = 0,25 kg; $\dot{m}_v$ = 0,005 kg/s;

3.1. Criterion Ziegler and Nichols.

The first step to realize the design of controllers is to establish performance specifications you want to achieve. The specifications for this project are: Response time less than 50 seconds on maximum signal less than 40% of the disorder for up to 10 seconds; response without many oscillations, which prevents premature wear of the final element of control.

To achieve the design of controllers were used to determine Ziegler and Nichols. From the application of this methodology was possible to measure the drivers and thus calculate the gains proportional, integral and derivative. After the calculation of earnings was necessary to carry out an adjustment to find the gains that the system would lead to responses that meet the performance specifications.

The designs of the controllers made by the method of Ziegler and Nichols, underwent final adjustments to fit the performance specifications. The controller gain obtained for each controller and containing the final adjustments will be presented in the results section.

4. RESULTS AND DISCUSSIONS

Following are the results obtained with the different classical controllers with gains proportional, integral and derivative adjusted from the values presented by the criterion of Ziegler and Nichols. To perform optimization, the gains have gone through fine-tuning.

The consideration is that the system is in equilibrium and a disturbance will tend to make the system stability, so there will be a step input. The applied step represents an increase of 5 ^{0}C in air temperature at the entrance of the cooler, which will cause an increase in air temperature in the output by modifying the air temperature.

Figure 2 shows the response of the system, initially at equilibrium, subjected to a disturbing entry, step type of temperature, equivalent to 5 ^{0}C, applied instantly. The disorder leads to the instability of the system response, however, the control system that was designed to reject external disturbances attempts to bring the system to the indicated value or minimize the effects of the disorder, with the required response time and lower signal on. The controller designed with proportional gain of 0.0001 produces a smooth, free of oscillations, however, the system presents a considerable error in steady state, up from the established performance specifications. Some adjustments in the controller gain result in an error about 75% lower, however, it is evident the appearance of small oscillations, as shown in Figure 3, whose proportional gain was 0,001. Insofar as the proportional gain increases, the oscillations become larger.

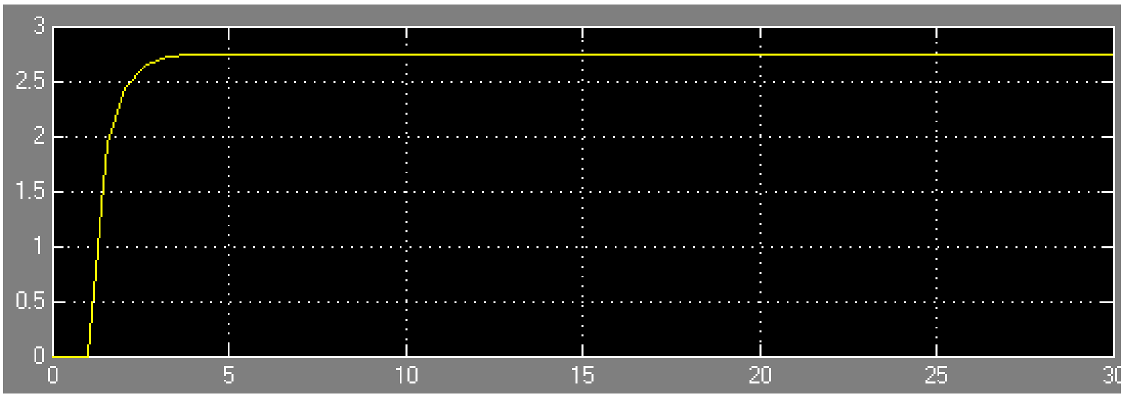

Figure 2. System response subjected to an entry into disorder and classic controller type Proportional (P)

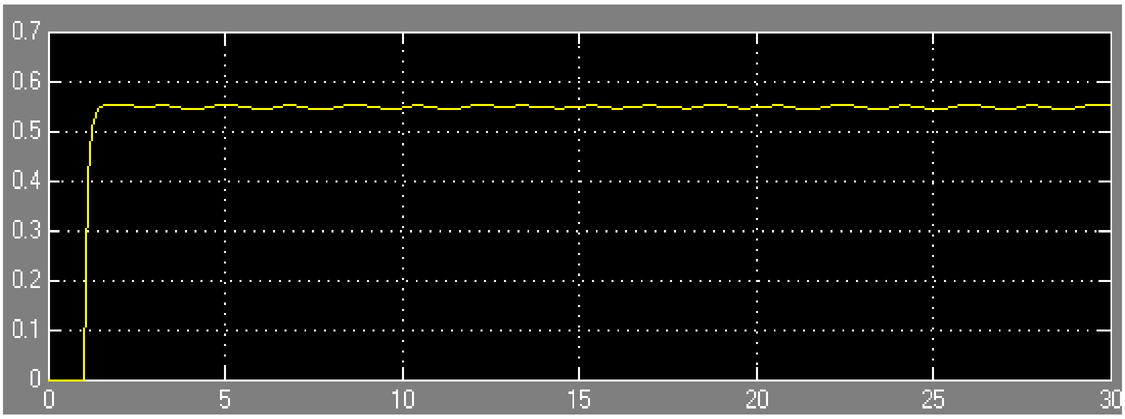

Figure 3. System response subjected to an entry into disorder and classic controller type Proportional (P), with gains modified.

Figure 4 shows the result of applying a controller proportional integral (PI) for evaporative cooling system. The controller produces a response without oscillations, with zero error in steady and signal about 1.8 ^{0}C, also has a small sign on reverse between 4 and 6 seconds. The response time of a PI-controlled system, with proportional gain of 0.0001 and integral gain of 2, is 6 seconds. The increase in earnings of PI controller results in less error in steady state and lower response time, but does not produce a smooth, with many oscillations, which reflects a behavior not appropriate pump, resulting in reducing the lifetime equipment.

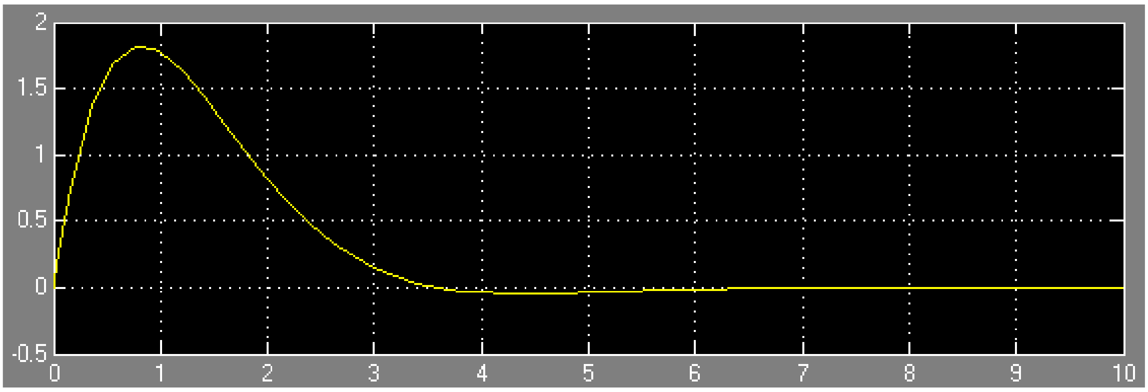

Figure 4. System response subjected to an entry into disorder and classic type controller Proportional-Integral (PI)

Figure 5 shows the response of the system, initially in equilibrium, which is undergoing a disturbing entry, type applied step input. To obtain the response we applied a PID controller proportional integral derivative, with proportional gain of 0.0001, integral gain and derivative gain of 2 and 0.5, respectively. The controller designed to produce a smooth, showing only one signal on the rise around 1.65 ^{0}C and a small sign on the descent, which in practice ensures proper behavior of the pump, resulting in a longer lifetime equipment. The application of PID results in response time less than 10 seconds, and zero error in steady state. An adjustment in earnings results in a smaller sign on, however, provokes a greater response time. Figure 6 represents the system response subjected to a PID controller with proportional gain of 0.0001, integral gain and derivative gain of 5 and 2.3, respectively. It is noted that the signal on the rise was 1.1 ^{0}C, the signal on the descent was 0.5. Implementation of the new controller resulted in a number of signals, which come in a short space of time, resulting in a continuous operation of the valve. The response time was also increased.

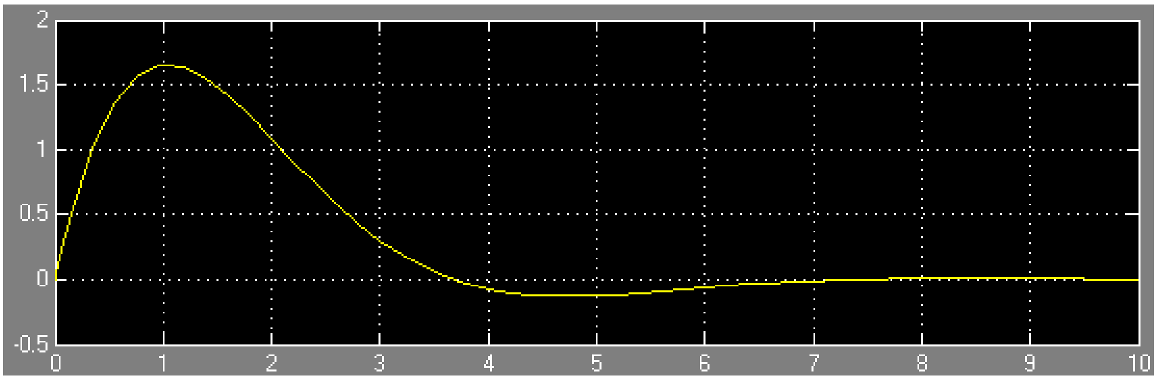

Figure 5. System response subjected to an entry into disorder and classic type controller Proportional-Integral-Derivative (PID)

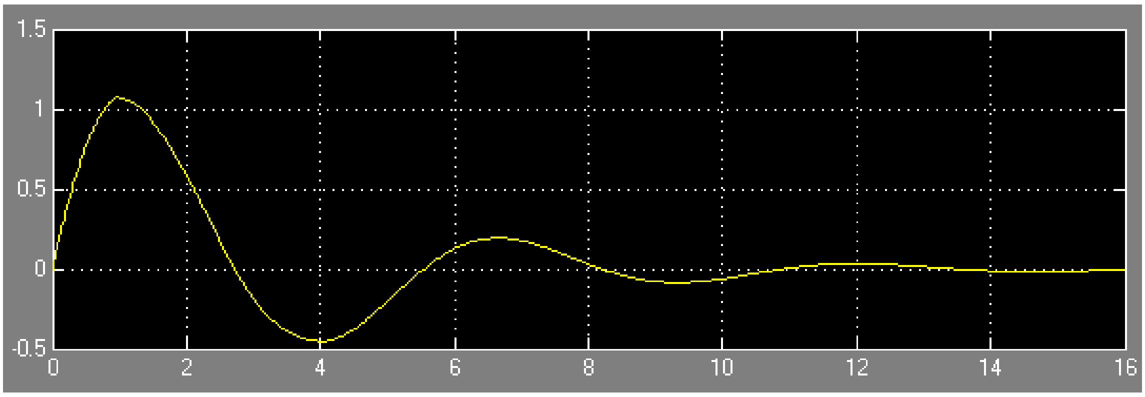

Figure 6. System response subjected to an entry into disorder and classic type controller Proportional-Integral-Derivative (PID), with gains modified.

5. CONCLUSIONS

In the present work, a theoretical study of the problem of heat and mass transfer in air washers operating as evaporative cooling devices has been discussed. The equations describing the processes of heat and mass transfer in air washers have been presented, and control procedure has been used as a solution for the proposed model.

The application of control systems to evaporative cooling resulted in improvement in the functioning of the system, especially when compared to those controlled by controllers on and off, which introduce large variations to the systems and do not allow effective control of temperature. The proportional controller was able to control the system, however, the error in steady not be used to enable this type of system. This controller, even with gains adjusted to reduce the error in the scheme, does not seem appropriate, because it appears undesirable oscillations. The proportional integral controller provides answers much better, the fit of the gains provided a smooth, about acceptable signal for the duration, good response time and stability, which enables features to be applied to coolers. PID controllers have good response times, on smaller signs that the PI, however, response time increased. The response times are higher, however, are within the established performance specifications. These controllers can be used for control of evaporative cooling systems, also provides flexibility for changes in specifications may submit responses on smaller signals, resulting in higher response time while maintaining stability.

The control of dry bulb temperature of air will be effectively achieved with the use of PI or PID controllers, however, the humidity is a property that depends directly on temperature and that will be controlled as the dry bulb temperature is also however, control of that property occurs within a range, so the moisture will oscillate around a certain value. A mathematical model can also be done for the proposed system in order to control humidity, making it possible to design controllers for the system. Similarly controllers will act to keep the conditions as the dry bulb temperature, which depend on the moisture, will also be oscillating within a band.

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