Dynamics Modeling, Simulation and Control of Spray Dryer using Conventional PID and Hybrid Fuzzy P + ID Controllers

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Abstract

This article presents the modelling, simulation and control of an industrial drying operation. The main purpose of our model reflects the variation in product quality (moisture content) of the outgoing dry powder. A transient model is derived for a rotary atomizer spray dryer. Matlab program is used for the simulation of the transient model. In this article two control loops are studied using two variables, moisture content and the temperature of the dried product. The moisture content based on the relative humidity of the exhaust air is manipulated via the inlet air flow rate and the temperature is manipulated via the temperature of the inlet air. Two different control techniques are applied to control the drying process, conventional PID and hybrid Fuzzy P + ID controllers. The hybrid Fuzzy P + ID shows a significant improvement in the performance of the drying process rather than conventional PID controller.

Nomenclature & initial conditions

Ms	Weight of dry solids entering dryer/time (960kg/h (0.266 kg/sec))
M	Accumulated mass of solid
Ws1	Moisture entering in feed (1171 Kg/h (0.325 Kg/sec))
Ws2	Moisture leaving in product (40.3 kg/h (0.011 kg/sec))
Qs1	Enthalpy of the feed
Qs2	Enthalpy of the dry product
Qa1	Enthalpy of the inlet air
Qa2	Enthalpy of the exit air
Ql	Heat loss (27540 kcal/h (7.647j))
Ga	Air mass Flow rate (15272.9 kg/h (4.24 gm/sec))
ΔT	Temperature difference
Ts1	Feed temperature when atomized (15 °C)
Ts2	Temperature of dried product (80 °C)
Ta1	Temperature of inlet air (14 °C)
Ta2	Temperature of exit air (95 °C)
H_1	Humidity of inlet air (0.005 kg/kg dry air)
H_2	Humidity of exit air (0.0791 kg/kg dry air)
Cds	Heat capacity of dry solid (0.4 kcal/kg °C)
Cw1	Weight of moist/weight of dry solids (1.22 Kg/kg dry solid)
Cw2	Weight of moist/weight of dry solids (0.042 Kg/kg dry solid)
Cs	Heat capacity of water
λ	Latent Heat (597.3 kcal/kg at 0 °C)

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Introduction

Spray dryers are used to obtain a dry powder from a liquid feed. Although the process equipment is very bulky and operation is expensive, it is an ideal process for drying heat sensitive materials. Spray dryers have been used for nearly a century now, but it is very difficult to model the performance of this type of the process equipment, especially with respect to the quality of the dried product.

The interest in improving the performance of processes in industry is increased due to demands for higher product quality, lower production costs and environmental considerations. This article aims to develop a model which can be used to predict product quality. Product quality is directly related to the temperature of the product and the humidity of the exhaust air during the drying process. These factors can be derived from a combination of the temperature and humidity pattern in the drying chamber. It is obvious that the temperature and the humidity pattern depend directly on the air flow and its temperature.

It must be emphasized that the number of papers concerning "automatic control of dryers" is very low[1-11]. Moreover, only a few of them imply methods that can be easily generalized. Some of these methods have been tested only by simulation or on small scale pilot-plant. Moreover the drying range is often very narrow and disturbances are not as drastic as in industry.

Desplans et al. [12] tested two control strategies for a spray drying unit for milk: multiple PID controllers and internal model based predictive control. The problem was multivariable and thus the latter approach, while being less usual, led to increased performances.

The model purpose and the available information with its reliability determine the form and the detail of the model. In our case, we want a model for the purpose of testing control strategies on the simulated process. The model should primarily describe the evolution of product quality (moisture content in the product). Although model accuracy is an essential requirement, it should relate reasonably to the available measurements.

The rotary atomizer spray dryer being the subject of our study is part of an industrial process. The upward flowing hot air stream acts as transport and drying agent. In a series of cyclones the solids are separated from the air. We assume that the drying is mainly diffusion controlled and external drying takes only place at the entrance of the drying tower.

The aim of this work is to describe the modeling, simulation and control of the temperature of the final product and the humidity of the exit air.

Description of the system

For continuous operation with negligible holdup of the product in the drying chamber, the mass input of air and feed in unit time equals the mass output of air and product. Heat input of air and feed equals heat output of air and product plus the heat losses from the drying chamber. The difference in product input and output equals the accumulation. Heat and mass balance are drawn up below with reference to Figure 1.

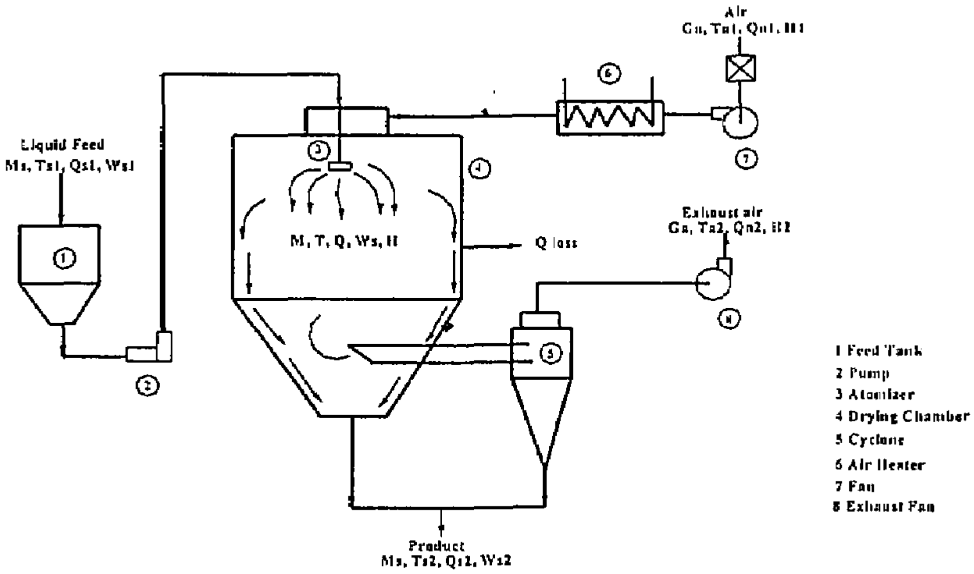

Figure 1. Spray Dryer Process flow sheet.

Suppose M_S weight units/sec of dry solid enter the spray dryer in a feed solution containing W_{S1} units of moisture per unit of dry solid by weight. The feed is dried to give solids leaving the dryer with moisture content of W_{S2} units of moisture per unit of dry solid by weight. The feed temperature when atomized is Ts1 and the product discharged at a temperature of T_{S2}. Drying air is supplied to the dryer at a rate of G_a weight units dry air per sec at temperature T_{a1}. The absolute air humidity at the inlet is H_1 that increases during the dryer operation to H_2. The air leaving the dryer is at temperature T_{a2}.

Transient state analysis

Moisture Mass balance:

Moist in feed = $M_S W_{S1}$ (1)

Moist in hot air = $G_a H_1$ (2)

Moist leaving dryer = $M_S W_{S2}$ (3)

Moist leaving exhaust air = $G_a H_2$ (4)

Accumulation of Moisture = Input - out put

Accumulation of Moisture = $M_S W_{S1} + G_a H_1 - M_S W_{S2} - G_a H_2$ (5)

Accumulation rate = input – out put

$$\frac{d(\mathrm{MWs}+\mathrm{GH})}{dt} = M\frac{dWs}{dt} + Ws\frac{dM}{dt} + G\frac{dH}{dt} + H\frac{dG}{dt} = M\frac{dWs}{dt} + G\frac{dH}{dt} \tag{6}$$

Where, $\frac{dG}{dt} = 0$ & $\frac{dM}{dt} = 0$

Assume that $\frac{dWs}{dt} = \frac{dH}{dt}$ & $\frac{dH}{dt} = \frac{dH_2}{dt}$

Then, $(M+G)\frac{dH_2}{dt} = MsWs1 + GaH_1 - MsWs2 - GaH_2$ (7)

$$\frac{dH_2}{dt} = \frac{MsWs1 + GaH_1 - MsWs2 - GaH_2}{(M+G)} \tag{8}$$

The purpose of this equation of moisture mass balance to show the relation between H_2 and Ws2.

Heat balance:

Enthalpy of inlet air = $G_a Q_{a1}$

Enthalpy of feed = $MsQs1$

Enthalpy of exhaust air = $G_a Q_{a2}$

Enthalpy of dry solid = $Ms\,Qs_2$

Accumulation of heat = Heat in - Heat out - Heat loss

$$= G_a Q_{a1} + M_s Q_{s1} - G_a Q_{a2} - Ms\,Qs_2 - Q_l \tag{9}$$

Accumulation rate = heat input – heat output – heat loss

$$\frac{d}{dt}(MQs + GQ_a) = M\frac{dQs}{dt} + Qs\frac{dM}{dt} + G\frac{dQa}{dt} + Qa\frac{dG}{dt} \qquad (10)$$

Assume $\frac{dG}{dt} = 0$ & $\frac{dM}{dt} = 0$

Then, $$\frac{d}{dt}(MQs + Gq_a) = M\frac{dQs}{dt} + G\frac{dQa}{dt} \qquad (11)$$

Where $Qs = Cds\,(\Delta T) + Ws1Cw\,(\Delta T)$ (12)

$Qa = Cs\,(\Delta T) + H\,\lambda$ (13)

$C_S = 0.24 + 0.46\,H$ (14)

By substitution of equations 12&13 in equation 11

Then, $$(MCds + MCwWsav. + GCs)\frac{dT}{dt} + (G\lambda + MCwT)\frac{dH2}{dt}$$

$$= GaQa1 + MsQs1 - GaQa2 - MsQs2 - Q1$$

Where $$\frac{dH2}{dt\cdot} = \frac{(MsWs1 + GaH1 - MsWs2 - GaH2)}{(M+G)}$$

Then

$$(MCds + MCwWsav. + GCs)\frac{dT}{dt} + \frac{(G\lambda + MCw\Delta T) * (MsWs1 + GaH1 - MsWs2 - GaH2)}{(M+G)}$$
$$= GaQa1 + MsQs1 - GaQa2 - MsQs2 -- Ql$$

Assume

$$A = \frac{GaQa1 + MsQs1 - GaQa2 - MsQs2 - Ql)}{(MCds + MCwWsav. + GCs)}$$

$$B = \frac{(G\lambda + MCw\Delta T) * (MsWs1 + GaH1 - MsWs2 - GaH2)/(M+G)}{(MCds + MCwWsav. + GCs)}$$

Then, $$\frac{dT}{dt} = A + B \qquad (15)$$

The control strategy

The aim of a spray dryer control system is to maintain of the dried product quality, irrespective of disturbances, which occurs within the drying operation and variation in feed supply. The most effective product parameter is the moisture content which is the more expensive solution due to the cost of on line moisture content sensors. The humidity of the air is well correlated to the product moisture content, which is a cheap solution. Also the product temperature is linked with the moisture of the final product.

Therefore, there are two control loops in spray dryer as shown in Fig 2, firstly the humidity of the air control loop which is manipulated via the inlet air flow rate and secondly, final product temperature control loop which is manipulated via the inlet temperature of the air. The main disturbances of the spray dryer system are the inlet moisture content and inlet flow rate of the feed. Two control techniques are adopted and compared, in case I, conventional PID controllers are used in these two control loops, while, in case II conventional PID controller is used in the second control loop and Fuzzy P +ID controller is used the first control loop.

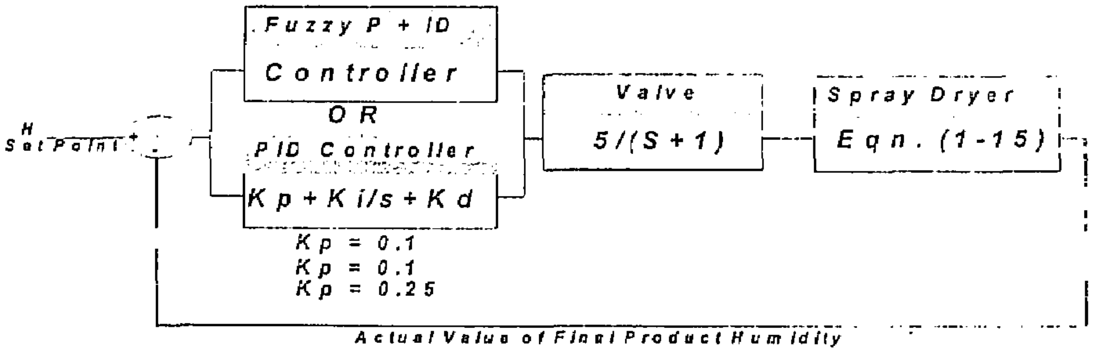

Fig. 2.a Block diagram of Humidity control loop

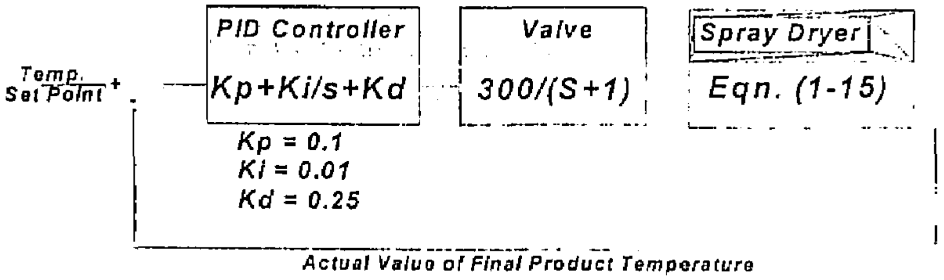

Fig. 2.b Block diagram of Temperature control loop

Hybrid fuzzy P + ID controller [13-15]

The PID controller is widely adopted in industrial application due to its simple structure. Its control signal for a manipulated variables Ga (t) or Ta (t) is easily computed by combining proportional, integral and derivative terms:

$$T_i(t) = Kp\, e_i(t) + ki \int e_i(t)dt + kd\, \dot{e}_i(t)$$

Where K_p, and K_i and K_d are the controller parameters. The reason for wide use the PID is that it can be easily designed by adjusting only the three controller parameters K_p, K_i and K_d. In addition, its control performance can be accepted in many applications. In order to maintain this simple structure, we propose a hybrid FUZZY P + ID controller, it uses an incremental fuzzy logic controller in place of the proportional term; while the integral and derivative terms are kept unchanged. In the FUZZY P + ID controller, the incremental fuzzy logic controller is a standard one which has two inputs *e (k)* and $\dot{e}(k)$ and the output Δ *u (k)*. In this paper, the membership functions for both inputs are defined to identical as shown in Table 1. membership functions (*N, Z, P*), assigned with linguistic variables, are used to fuzzify physical quantities. For the output Δ *u (k)*, the fuzzified inputs are inferred to a fuzzy rule base, which is used to characacterize the relationship between fuzzy inputs and fuzzy outputs. The rule base of a fuzzy logic controller directly can be defined human-knowledge. Thus, the fuzzy rule base of the incremental fuzzy logic controller is fixed, as shown as in Table1.

Table 1. Rule set of Fuzzy controller

e=ERROR	Δe= Δ ERROR		
	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Simulation Study

The mathematical model of a spray dryer with the previous data is simulated using MATLAB program. The two control loops, the temperature of the product and the humidity of the exit air are applied to the simulator. The simulation results will be regarded to step control and disturbance rejection control in our simulation, the sample time is chosen to be 1 sec. Firstly the tuning of the PID is achieved by trial and error. The evaluation of the control performance in all cases is based on the value of the overshoot, settling time and steady state errors.

RESULTS AND DISCUSSION

Set Point Tracking Control for Temperature and Humidity Loops

The nominal set point of the temperature control loop is 80 °C while the nominal set point of the humidity control loop is 0.08 kg/kg. The step control action is simulated and tested in four cases, first case by increasing the set points of the temperature and the humidity, which is called "increase-increase case". The second case, which is called "decrease-decrease case", where, the set points of the temperature and the humidity are decreased. The third case, by increasing the set points of the temperature and decreasing the set point of the humidity, which is called "increase-decrease case". The fourth case, by decreasing the set point of the temperature and increasing the set point of the humidity, which is called "decrease-increase case".

Fig. 3 shows the increase-increase case, where the set points of the temperature and humidity are 90 °C and 0.09 kg/kg, respectively. In case I, conventional PID controller applied in the two loops, the positive overshoot are (13°C and 0.13 kg/kg), negative overshoot is (15 °C and 0.0 kg/kg), settling times is (100 sec and 140 sec), and no steady state error. In case II, Fuzzy P + ID controller applied in humidity loop while the same PID controller applied in temperature loop, the positive overshoot is (1°C and 0.01 kg/kg), negative overshoot is (10 °C and 0.0 kg/kg), settling time is (50 sec and 50 sec), and no steady state error. In case II, Fuzzy P + ID controller in humidity loop shows a better performance than PID controller in case I and it is reflected on temperature loop.

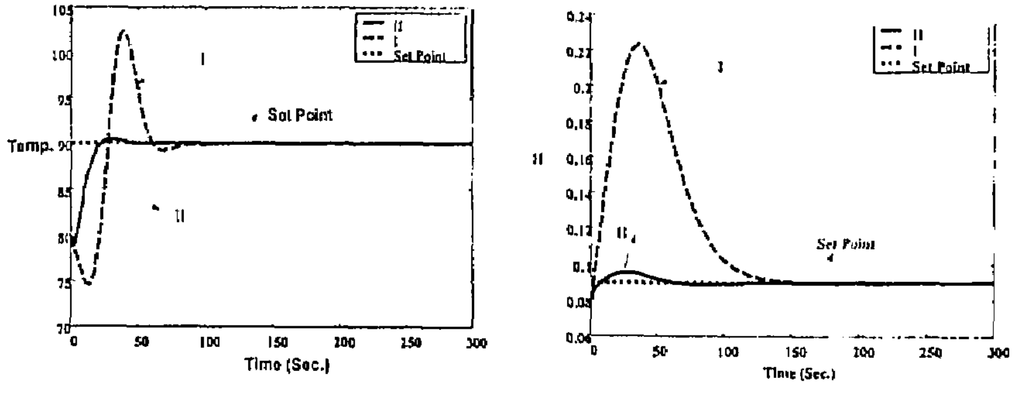

Fig. 3 step control of the temperature and humidity changes "increase-increase" case

Fig. 4 shows the decrease-decrease case, where the set points of the temperature and humidity loops is 70 °C and 0.07 kg/kg, respectively. In case I, the positive overshoot are (10 °C and 0.14 kg/kg), negative overshoot is (12 °C and 0.0 kg/kg), settling time is (70 sec and 300 sec), and no steady state error. In case II, the positive overshoot is (10 °C and 0.02 kg/kg), negative overshoot is (7 °C and 0.0 kg/kg), settling times is (40 sec and 60 sec), and no steady state error. In case II, Fuzzy P + ID controller in humidity loop shows a better performance than PID controller in case I.

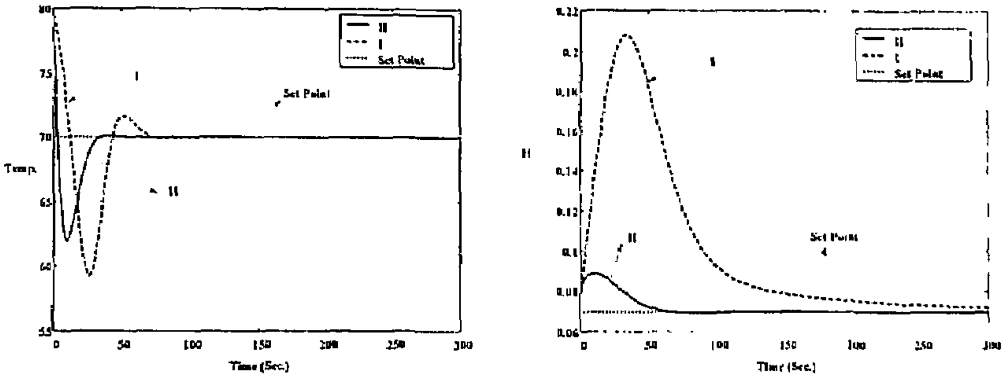

Fig. 4 Step control of the temperature and humidity changes "decrease-decrease" case

Fig. 5 shows the increase-decrease case, where the set points of the temperature and humidity are 90 °C and 0.07 kg/kg, respectively. In case I, the positive overshoot are (10 °C and 0.14 kg/kg), negative overshoot is (14 °C and 0.0 kg/kg), settling time is (90 sec and 300 sec), and no steady state error. In case II, the positive overshoot is (1 °C and 0.02 kg/kg), negative overshoot is (11 °C and 0.0 kg/kg), settling times is (40 sec and 60 sec), and no steady state error. In case II Fuzzy P + ID controller in humidity loop shows a better performance than PID controller in case I.

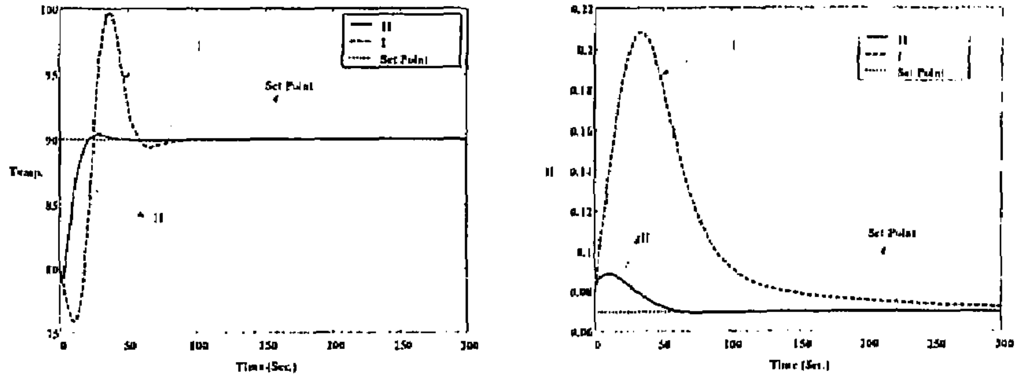

Fig. 5 Step control of the temperature and humidity changes "increase-decrease" case

Fig. 6 shows the decrease-increase case, where the set points of the temperature and humidity are 70 °C and 0.09 kg/kg, respectively. In the case I, the positive overshoot are (10 °C and 0.14 kg/kg), negative overshoot is (12 °C and 0.0 kg/kg), settling time is (70 sec and 150 sec), and no steady state error. In case II, the positive overshoot is (10 °C and 0.005 kg/kg), negative overshoot is (8 °C and 0.0 kg/kg), settling times is (50 sec and 70 sec), and no steady state error. In case II Fuzzy P + ID controller in humidity loop shows a better performance than PID controller in case I.

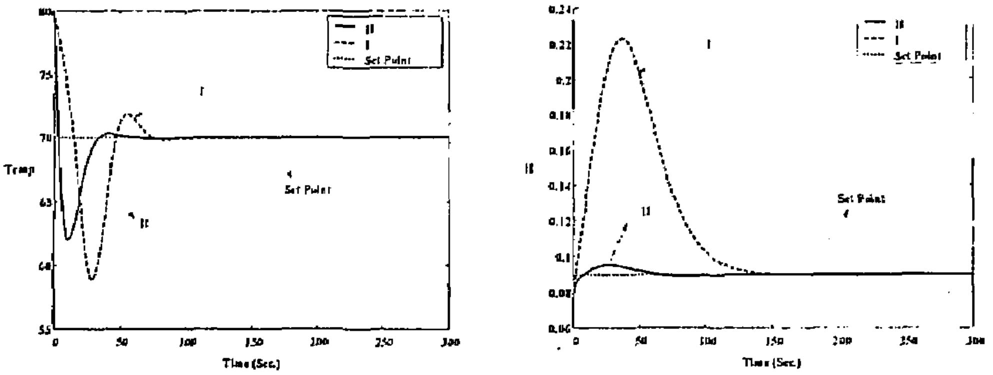

Fig. 6 Step control of the temperature and humidity changes "decrease-increase" case

Disturbance Rejection Control

The two main disturbances which applied and simulated in this study are the inlet mass flow rate and moisture content of the inlet mass flow rate which are varied by ± 20 %, The set points of the temperature and humidity are constant at 80 °C and 0.08 kg/kg, respectively. Fig. 7 shows the characteristic response by varying the feed mass flow rate by (-20%). In case I, conventional PID control action is used in the two loops while, in case II, the same PID control action is used in the temperature loop and Fuzzy P+ID action is used in humidity loop. As shown in Fig. (7), in case I, the positive overshoot is (4.0 °C and 0.11 kg/kg), negative overshoot is (8 °C and 0.0 kg/kg), settling time is (100 sec and 150 sec), and no steady state error. In case II, the positive overshoot is (0.2 °C and 0.01 kg/kg), negative overshoot is (7 °C and 0.005 kg/kg), settling time is (50 sec and 60 sec), and no steady state error which proves that the using of the Fuzzy P+ID controller makes the performance better in this case.

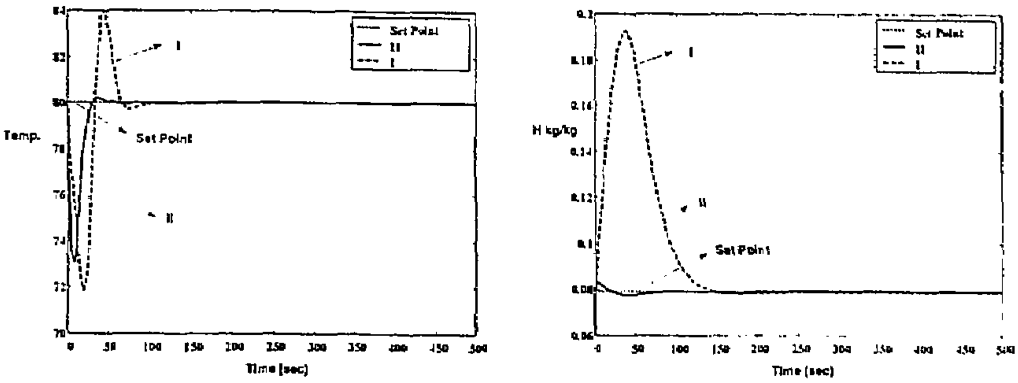

Fig. 7 Control performance "-20 % inlet mass flow rate Disturbance"

Fig (8) shows the characteristic response by varying the inlet mass flow rate by (+ 20 %), in the case I, the positive overshoot is (3.8 °C and 0.15 kg/kg), negative overshoot is (8.5 °C and 0.0 kg/kg), settling time is (100 sec and 300 sec), and no steady state error. In case II, the positive overshoot is (0.2 °C and 0.02 kg/kg), negative overshoot is (7.0 °C and 0.0 kg/kg), settling time is (50 sec and 60 sec), and no steady state error, which proves that the using of the Fuzzy P+ID controller makes the performance better in this case.

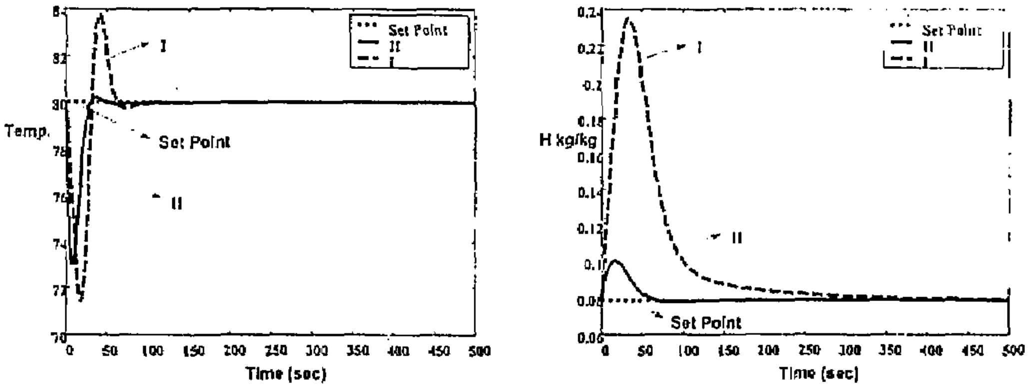

Fig. 8 Control performance "+20 % inlet mass flow rate Disturbance"

Fig (9) shows the characteristic response by varying moisture content of the inlet feed (- 20%), in case I, the positive overshoot is (4.0 °C and 0.11 kg/kg), negative overshoot is (8.0 °C and 0.0 kg/kg), settling time is (125 sec and 150 sec), and no steady state error. In case II, the positive overshoot is (0.20 °C and 0.005 kg/kg), negative overshoot is (6.5 °C and 0.005 kg/kg), settling time is (50 sec and 50 sec), and no steady state error which proves that the using of the Fuzzy P + ID controller makes the performance better in this case.

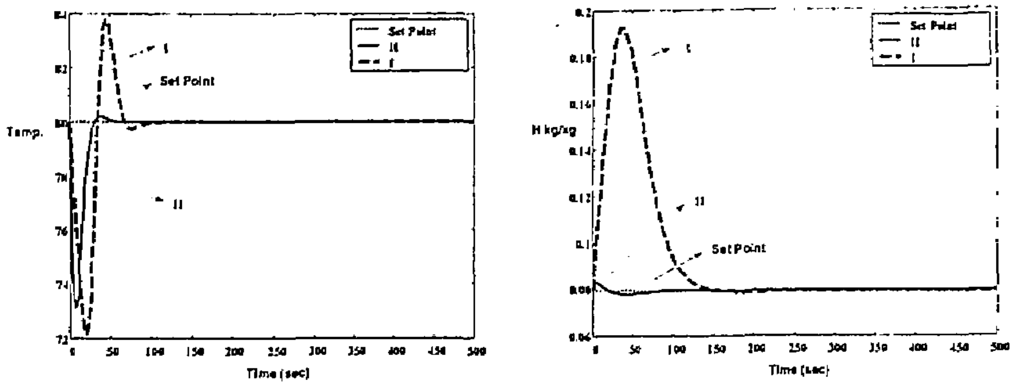

Fig. 9 Control performance "-20 % inlet moisture content"

Fig (10) shows the characteristic response by varying moisture content of the inlet feed (+ 20%). In case I, the positive overshoot is (4.0 °C and 0.15 kg/kg), negative overshoot is (9.0 °C and 0.0 kg/kg), settling times is (100 sec and 300 sec), and no steady state error. In case II, the positive overshoot is (0.20 °C and 0.02 kg/kg), negative overshoot is (7.0 °C and 0.0 kg/kg), settling time is (70 sec and 60 sec), and no steady state error, which proves that the using of the Fuzzy P + ID controller makes the performance better in this case.

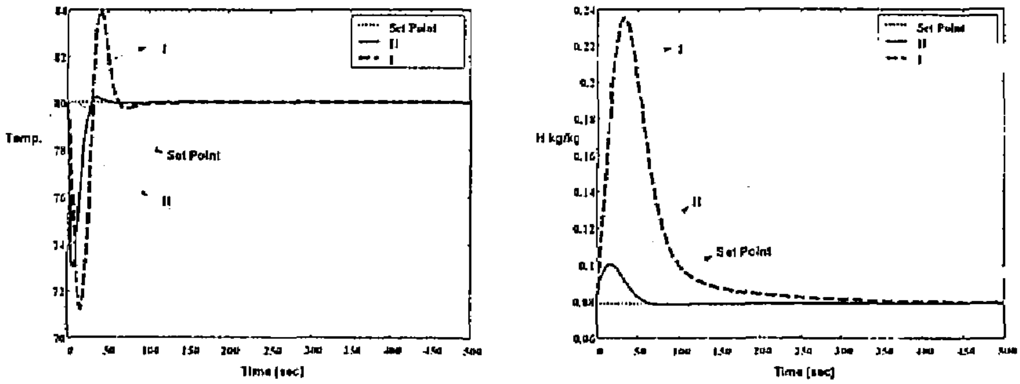

Fig. 10 Control performance "+20 % inlet moisture content"

Conclusion

The structure of the fuzzy P + ID controller is very simple, since it is constructed by replacing the proportional term in the conventional PID controller with an incremental fuzzy logic controller. In fact, it takes much longer time to tune the PID controller parameters than to tune the Fuzzy P + ID controller parameters during implementation. The Fuzzy P + ID is shown to result in more accurate tracking of the temperature and the humidity set points of a simulated spray dryer and rejection the effect of the disturbances.

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