Latin American Applied Research 37:105-113 (2007)

THERMAL BEHAVIOUR OF FOREST BIOMASS DRYING IN A MECHANICALLY AGITATED FLUIDIZED BED

R. M. MORENO[1*], G. ANTOLÍN[2] and A. REYES[3]

[1]Instituto de Materiales y Procesos Termomecánicos Universidad Austral de Chile, Casilla 567, Valdivia, CHILE
[2]Departamento de Ingeniería Química. Universidad de Valladolid, 47011 Valladolid, ESPAÑA
[1]Departamento de Ingeniería Química. Universidad de Santiago de Chile, Casilla 10233, Santiago, CHILE
** Author to whom correspondence should be addressed.*

Abstract — **The results obtained in the analysis of the thermal behaviour of a forest biomass fluidized bed dryer with mechanical agitation, are reported. The study is carried out in a pilot size experimental equipment in batch operation. By means of Taguchi's techniques the specific consumption of energy and the rates of evaporation of water and production of dry biomass are analyzed based on the control factors (agitation speed, temperature of operation, superficial velocity and product load into the dryer). As noise factor the initial moisture content of the biomass was considered. The results of the study reveal that the drying process is obtained with a specific consumption of energy of 3040 kJ/kg and a thermal efficiency of 80%.**

Keywords— **Fluidized bed, Forestry Biomass, Particles Drying, Taguchi's method.**

I. INTRODUCTION

Nowadays the drying forest biomass particles has great importance due to the use given to this raw material in the manufacture of particle board, pellets, briquettes, as well as in the processes of combustion and gasification of biomass (Zabaniotou, 2000; Pang, 2000; Herguido *et al*., 1992; Olazar *et al*., 2000). Due to the high consumption of energy required during drying, an important variable to optimize is the thermal efficiency which is closely related to the specific consumption of caloric energy of the process (Snezhkin and Khavin, 1997).

At present the use of units of fluidized bed for particle drying has been increased due to the multiple advantages that this technology offers. Nevertheless, the forest biomass has the problem of high agglomeration of solids when they have a high moisture content (Moreno and Rios, 2002). For such a reason, diverse alternatives have been studied to improve the fluidization process showing that for particles between 1 and 4 mm the best system is a fluidized bed with mechanical agitation (Moreno *et al*., 2006). The objectives of this study are the analysis of the caloric energy consumption and the rate of water evaporation in the process of forest biomass drying in a mechanically shaken fluidized bed. Additionally, the behavior of the dryer in terms of the rate of production of dry biomass, is analyzed.

In this work the Design of Experiments of Taguchi's methodology is used as tool for the analysis of the behavior of the biomass dryer. In addition to the analysis of variance (ANOVA), the optimization incorporates a Signal/Noise analysis, using the Signal-to-Noise ratios (*S/N*), which allows to find the control factors levels of the process which guarantee that the variable to optimize is less sensible to the variations caused by the noise factor and therefore giving robustness to the process.

II. THEORETICAL BACKGROUND

A. Specific Background

The useful heat-flux in a drying process is the one used for warming up the wet product and for evaporating part of the contained water in the material and it is represented as:

$$\dot{Q}_{\acute{u}} = M_0 C_{p,0}\frac{dT_p}{dt} + M_0 w C_{H_2O}\frac{dT_{H_2O}}{dt} + M_0 h_{fg}\left(-\frac{dw}{dt}\right) \quad (1)$$

Bearing in mind that in the particulate material, the solid and liquid phases are in thermodynamic equilibrium then the temperatures of the water and the particle are equal so:

$$\dot{Q}_{\acute{u}} = M_0\left[C_{p,bs}\frac{dT_p}{dt} + h_{fg}\left(-\frac{dw}{dt}\right)\right] \quad (2)$$

Moreover, the energy flow used in the process corresponds to the sensible heat used in the heating unit to increase the air temperature from environmental temperature to operation temperature. Thus,

$$\dot{Q}_c = \dot{m}_g\, C_g\,(T_{g,i} - T_0) \quad (3)$$

and thermal efficiency of the process can be expressed as:

$$\eta(t) = \frac{M_0\left[C_{p,bs}\frac{dT_p}{dt} + h_{fg}\left(-\frac{dw}{dt}\right)\right]}{\dot{m}_g\, C_g\,(T_{g,i} - T_0)}100 \quad (4)$$

This efficiency varies with time as a consequence of the drying kinetics represented by the changing rates of moisture content and temperature of the particles in the dryer, d*w*/d*t* and dT_p/d*t*, respectively.

Another definition of efficiency is given by Vanecek *et al*. (1966), who say that the degree of heat utilization is given by $(T_{g,i}-T_p)/T_{g,i}$ and they show that the specific consumption of energy is decreased by the choice of high entrance temperatures of the gas fluidizing $T_{g,i}$.

The thermal efficiency can also be related to the specific energy consumption q which is defined as the rate between the total expended heat during the process and the mass of water evaporated in the same period of time, that is:

$$q=\frac{\int_{t=0}^{t_d}\dot{m}_g\,C_g\,(T_{g,i}-T_0)dt}{(w_i-w_f)M_0} \qquad (5)$$

For this investigation that looks for the conditions in which the drying process is made more efficient, this global procedure is more pertinent than the previous one, since it allows to analyze the entire process of drying including the stages of drying at constant rate and decreasing rate. The method of instantaneous efficiency can be used in the stage of modeling of kinetic drying, where the interest is placed on studying in details the mechanisms of heat and mass transfer that take place at different stages of the drying process, rather than on a global evaluation of the process.

Once the specific consumption of energy has been calculated, the global thermal efficiency of the drying process η_{gl}, can be defined as the ratio between the theoretical specific consumption given by the heat of water vaporization, h_{fg} plus the sensible heat to previously take water to the saturation point and the specific consumption of actual energy of the process q:

$$\eta_{gl}=\frac{C_{H2O}(T_{sat}-T_0)+h_{fg}}{q}100 \qquad (6)$$

If the analysis is done over a period where the particles have reached the temperature which the water evaporation takes place, Eq. (6) should be written as:

$$\eta_{gl}=\frac{h_{fg}}{q}100 \qquad (7)$$

Snezhkin and Khavin (1997) propose an indirect method for calculation based on energy balance in the dryer. The thermal efficiency is calculated as:

$$\eta=\frac{\dot{Q}_u}{\dot{Q}_u+\sum\dot{Q}_l}100\,, \qquad (8)$$

which has the disadvantage of requiring the calculation of the heat losses in the dryer, through the walls and the rest of the components of the equipment and the losses in the expelled air to the environment and in the dried product the leaves the dryer. The procedure here is independent from the losses calculation thus avoiding sources of uncertainty.

B. Water Evaporation and Production Rates

The water evaporation rate is defined as the evaporated water mass from a certain amount of initial moisture content w_i to a final content w_f in a unit of time and by the area unit of the dryer. It is calculated as:

$$\dot{m}_v=\frac{(w_i-w_f)M_0}{t_d A} \qquad (9)$$

On the other hand, the biomass production rate is defined as the anhydrous mass of the product the equipment is capable of drying from a certain amount of initial moisture content w_i to a final content w_f, in a unit of time and by the area unit of the dryer. It is calculated as:

$$\dot{m}_p=\frac{M_0}{t_d A} \qquad (10)$$

III. METHODS AND EXPERIMENTAL WORK

The variables to optimize in this investigation are the specific consumption of caloric energy in the heating unit of the fluidizing air and the drying capacity, expressed as rates of evaporation of water and production of dry biomass.

The factors that control a drying process and which have been considered in the energy optimization are:

- Factor A: agitation speed of the shaker.
- Factor B: temperature of operation.
- Factor C: mass flow of fluidizing.
- Factor D: load of product.

And the considered noise factor is :

- Factor R: initial moisture content of biomass

The initial moisture content of solids affects the energy consumption and probably it also affects the capacity of water evaporation. Therefore, since it is not being a controllable factor, it must be considered as a noise factor. In practice, it is impossible that a dryer operates with a constant initial moisture content and therefore it will be necessary to determine under what levels of the control factors, the efficiency and the capacity are more robust variables in comparison to the initial moisture content of solids.

The standard ANOVA will study the influence that control factors exert on the mean value of the variables to optimize (the thermal efficiency and the capacities of drying and production). The size of particle has not been considered as factor because when changing the size, it is necessary to modify the superficial velocity and therefore this variable can not be considered in the orthogonal array (OA). A representative size of the average of the biomass has been considered in the trials, that is, $d_{p\,m}$ = 1.85 mm according to ASTM E-11 specifications.

It is intended to evaluate the main effects as well as the effects of the interactions between control factors and noise factors. The used strategy is an inner OA for the control factors and an outer one OA for the noise factor.

The quality characteristics of Signal/Noise have been evaluated by means of the following expressions, valid for expected answers of the type higher is better and lower is better, respectively (Ross, 1996):

$$S/N=-10\log\left[\frac{1}{y_m^2}\left(1+3\frac{\sigma^2}{y_m^2}\right)\right] \qquad (11)$$

$$S/N=-10\log(y_m^2+\sigma^2) \qquad (12)$$

The selected levels for the experimentation are shown in Table 1. In the case of the agitation speed of the mechanical agitator N, they correspond to the values between which the optimizations of the process of fluidization of particles have been detected to take place (Moreno *et al.*, 2006).

Table 1. Factors and levels of the experimental design.

Factor	Level 1	Level 2
A Agitation speed (r.p.s.)	1	2
B Operation temperature (K)	333	413
C Mass flow (10^{-2} kg/s)	5.05	7.36
D Load of the product d.b. (kg)	1.0	1.5
R Biomass moisture d.b. (kg/kg)	0.8	1.5

Two levels of operation temperature have been chosen, one lower and the other higher to 373 K, hoping that at high levels a dryer can operate more efficiently, according to the report of Vanecek *et al.* (1966). The higher value is limited by the release of biomass volatiles. It has been decided on levels 333 and 413 K.

As it can be observed in the specific consumption of energy calculation equations, the air mass flow is an important factor and it was set at levels 5.0 x 10^{-2} and 7.36 x 10^{-2} kg/s levels. These levels correspond to values of 0.59 and 0.86 m/s superficial velocity of gas, respectively.

The product load levels have been set based on previous aerodynamic results (Moreno *et al*., 2006).

For the noise factor, levels of 1.5 and 0.8 kg/kg have been chosen that correspond to approximately the values of biomass moisture content the can be found in an industry.

To choose the OA with noise factors it is assumed that 4 degrees of freedom (d.f.) are necessary for the 4 control factors with two levels. The decision is for an AO L_8 with 7 d.f. (Table 2) to incorporate an interaction between temperature of operation and mass flow (BxC or BC), because it is estimated that it can be important in the consumption of energy and the capacity of moisture extraction. The columns *e** and *e*** in Table 2 are used for the estimation of the residual error in the experiment. This matrix, preserves the condition of orthogonality, indispensable requirement to independently evaluate the effect of all the factors and the residual error. The possibility of having two columns to evaluate the residual error makes it unnecessary to use a design with more replications.

The experimental equipment for the tests of specific consumption of energy and rates of evaporation and production is shown in Fig 1. The walls of the drying camera are isolated with Fibre Glass of 10 mm thick and 0.035 W/mK of thermal conductivity. For details of the equipment, see Moreno *et al.* (2006).

For the calculations of the energy consumption, the equation (5) has been made discreet in time because temperature recordings conducted by software ScanLink 2.0, during the drying tests are not continuous. Bearing in mind that the mass flow of the fluidizing remains constant during the drying of the biomass, equation (5) can be written as:

$$q = \frac{\dot{m}_g \, C_g \sum_{i=1}^{n} (T_{g,i} - T_0)_i \, \Delta t_i}{(w_i - w_f) M_0} \tag{13}$$

where each Δt_i corresponds to the time interval that separates two consecutive temperature data obtained with the software. Each interval was set at 4 seconds.

The drying time during which the analysis is carried out must be obtained from the drying curve of each test according to the initial and final moisture contents of the biomass, w_i and w_f, respectively. The value of M_0 corresponds to the mass of biomass loaded into the dryer, in anhydrous state.

The wet material used for drying is *Pinus Radiata D. Don*. Samples of solids were obtained from particles of 1.85 mm size and the biomass samples' initial humidity w_i are shown in Table 1. The final moisture content was set at 0.15 kg/kg d.b.

IV. RESULTS AND DISCUSSION

The results of this study are shown below. Firstly, the effect each control factor has on the mean of the different variables to optimize in the biomass drying using ANOVA, are shown. Next, the selection of the factor levels leading to optimal biomass drying conditions in fluidized bed, is carried out. Later the effect of the control factors on the variability of the drying process's variables are analyzed using *S/N* analysis to have a robust design of the dryer with low variability. Finally, an analysis of specific consumption of caloric energy during the drying process and the effects of the rotation speed of the agitator, are shown.

A. ANOVA of Results

The results obtained in each of the experiments of the orthogonal matrix L_8 are shown in Table 3. The orthogonality of the experiments has been verified in each case, by means of the comparison of the sum of squares of all the columns with the sum of total squares.

Table 2. Inner/Outer OA parameter design experiment.

	Control factors, interactions and residual							Noise factor	
Trial Nº	A	B	e*	C	D	BC	e**	R_1	R_2

1	1	1	1	1	1	1	1	y_1	y_1^*
2	1	1	1	2	2	2	2	y_2	y_2^*
3	1	2	2	1	1	2	2	y_3	y_3^*
4	1	2	2	2	2	1	1	y_4	y_4^*
5	2	1	2	1	2	1	2	y_5	y_5^*
6	2	1	2	2	1	2	1	y_6	y_6^*
7	2	2	1	1	2	2	1	y_7	y_7^*
8	2	2	1	2	1	1	2	y_8	y_8^*

Table 3. Experimental results from the orthogonal array L_8.

	Drying time (min)		Specific consumption of energy (kJ/kg)		*Thermal efficiency* (%)		*Evaporation rate* (kg/s m^2)		*Product output* (kg/s m^2)	
	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2
Trial Nº	y	y*	y	y*	y	y*	y	y*	y	y*
1	17	34	3827	3764	63.6	64.6	0.0090	0.0094	0.0139	0.0069
2	20	38.5	4204	3909	57.9	62.2	0.0115	0.0124	0.0177	0.0092
3	5.75	12.5	3167	3265	76.8	74.5	0.0267	0.0255	0.0410	0.0189
4	6.75	13.75	3845	3724	63.3	65.3	0.0341	0.0347	0.0524	0.0257
5	20	41	3182	3130	76.5	77.7	0.0115	0.0117	0.0177	0.0086
6	12	24.8	3981	3960	61.1	61.4	0.0128	0.0128	0.0196	0.0095
7	8.5	16.8	2913	2751	83.5	88.4	0.0271	0.0284	0.0416	0.0211
8	4.55	9.25	3683	3604	66.1	67.5	0.0337	0.0344	0.0518	0.0255

Table 4. ANOVA of the specific consumption of energy.

Factor	*SS*	d.f.	*V*	*F*	*P* (%)
A	195469	1	195469	20.5	14.6
B	282188	1	282188	29.5	21.1
e*	5025	1	5025		
C	753685	1	753685	78.9	56.3
D	79302	1	79302	8.3	5.9
BC	11590	1	11590		
e**	12051	1	12051		
e pooled	28666	3	9555		2.1
TOTAL	1339310				100.0

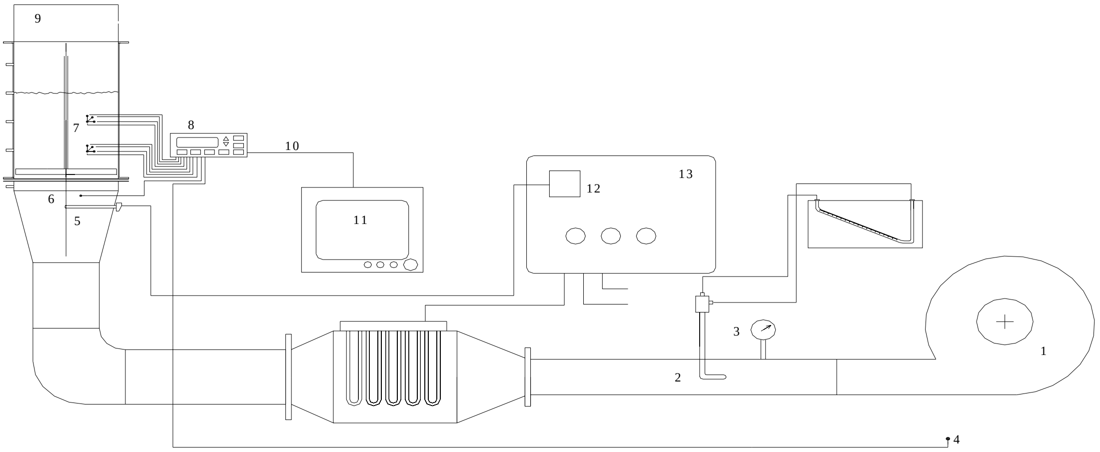

Fig. 1. Experimental equipment : (1) blower; (2) Pitot tube; (3) Bourdon manometer; (4) room temperature thermocouple; (5) PT100 sensor; (6) operation temperature thermocouple; (7) bed temperature thermocouple; (8) scanning thermometer; (9) drying chamber; (10) RS – 232 signal; (11) computer; (12) Fuzzy – Logic controller; (13) control board.

The statistical processing by means of standard ANOVA was carried out to look for the influence of the control factors in the average value of the defined variables of quality. The results for the specific consumption of energy are shown in Fig 2. It is possible to see that the most influential factor on the variable quality is, as expected, the air flow which confirms that although, when operating the dryer at low superficial velocity, the drying times increase, this is strongly and positively compensated by the decrease in the consumed energy in the whole period of drying due to the fact that warming up reduced air flows, is required.

It is also observed in Fig. 2 that when increasing the temperature of operation, the negative effect on the consumed heat flow is clearly compensated by the decrease in drying times. In relation to the effect of the agitation speed and load of the product both factors, at their high levels, favour the decrease of the energy consumption.

The effect each factor exerts on the specific consumption of energy appears in Table 4. The variance *V* is equal to the sum of squares *SS* divided by the degrees of freedom for each factor, interaction or error. The portion of the total variation observed in the experiment attributed to each factor, error or interaction, is reflected in the percent contribution *P*.

The factor air flow is the most relevant with 56.3 % of the total variation; temperature of operation with 21.1 % and the speed of agitation and load of the product with 14.6 and 5.9 %, respectively. The experimental error in the evaluation of the specific consumption of energy was less than 1 %. The interaction between factors B and C is buried within the residual one obtained in the ANOVA by means of the test of Fisher with pooling up strategy and 90 % of confidence.

According to these results, the thermal efficiency is strongly influenced by the gas speed or flow, as ob served in Fig. 3. In addition, according to an ANOVA conducted with 90 % of confidence, the results confirm that the most relevant factor in the optimization of the power variable is the gas flow (54.1 %), followed by the temperature of operation (19.4 %), speed of agitation (15.5 %) and load of the product (8.2 %). The residual in this case was less than 1 %.

In relation to the rate of water evaporation, according to the results shown in Fig 4, this variable is mainly favoured by the use of high temperatures, with a percentage influence of 92.2 %, followed by the fluidizing mass flow. The other factors and the interaction have a very small participation in the average value of the rate of evaporation.

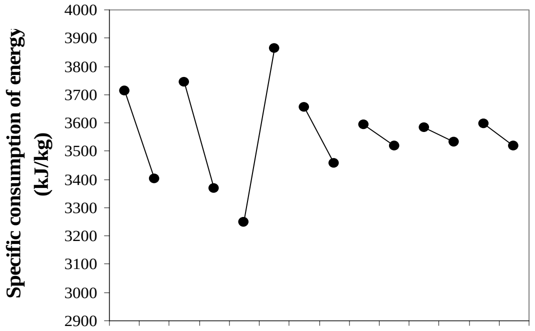

Fig. 2 Factorial graph for the specific energy consumption.

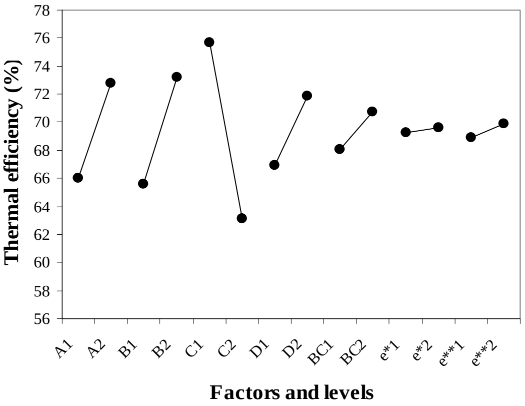

Fig. 3. Factorial graph for the thermal efficiency.

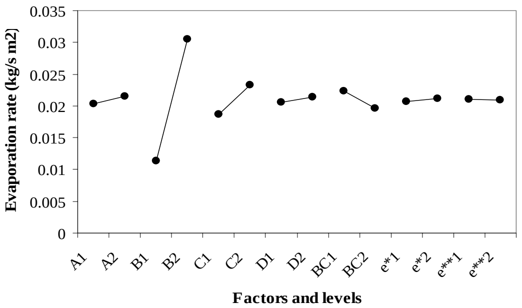

Fig. 4. Factorial graph of the water evaporation rate.

The above tendency is the same when analysing the exit variable production rate.

B. Optimal Conditions for Biomass Drying.

Based on the results obtained from the factorial graphs and ANOVA, the most influential factors in the forest biomass dryer performance in fluidized bed with mechanical shaker are the fluidizing gas flow and the operation temperature.

From the point of view of the temperature of operation, it can said that all the analyzed variables of quality are strongly favoured when high temperatures are used, that is when the temperature is set to its B_2 value. In relation to the superficial velocity or mass flow of the fluidizing, if the decrease in drying time it is to be privileged and consequently to favour high drying rates and dry biomass production, high levels of air mass flow ought to be chosen. Nevertheless, the influence percentage of the mass flow on these quality variables is very low, between 3.3 and 5.4%, in relation to the percentage of influence that the mass flow has on the specific consumption of energy and the thermal efficiency of the dryer, which is about 55 %. For such a reason, the variable mass flow must be chosen at its low level. The loss of performance, in terms of rates of evaporation of water and production of biomass, can be recovered if the dryer operates at temperatures higher than 140 ºC. This is feasible, since according to the results obtained in a previous study (Moreno *et al.*, 2004), based on a thermo-gravimetric analysis of the biomass (TG and DTG curves), it is possible to operate with temperatures still higher than those used in the OA L_8.

The interaction between the temperature of operation and the flow of the fluidizing is practically irrelevant in the performance of the drying process, which means that the positive effect of using high operation temperatures appears indistinctly if the dryer operates with low or high air flows, as shown in Fig. 5. Thus, it is possible to conclude quite clearly that an efficient operation is obtained with high temperatures and low air velocities.

The factors product load and agitation speed of the shaker play a less important role in the process. Particularly, the agitation speed should be set to its high level, since it is on the thermal efficiency where it has the most impact (15.5 % of influence). From the point of view of the rates of evaporation or production the effect of the agitation speed is negligible and it is covered by the residual one.

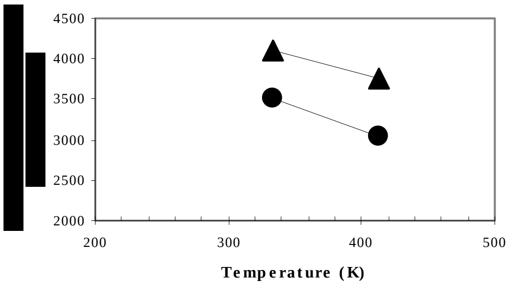

Fig. 5. Interaction between the temperature of operation and flow of gas, ●, 5.05 x 10^{-2} kg/s; ▲, 7.36 x 10^{-2} kg/s.

When decreasing the product load in the dryer, an effect of about 10.2 % is obtained in the total variation of the drying time. Nevertheless, when increasing the load a positive effect on the specific consumption of energy and thermal efficiency is obtained. The others variables are not affected by the product load. From the results, it is possible to infer that the load must be set to its highest level since it is more important to have an increase in thermal efficiency than to improve the drying time, which can strongly be improved by the factor temperature of operation.

C. Signal/Noise Analysis

The ANOVA allowed us to have a clear picture of the factors that affect the mean value of each of the defined variables of quality. In this section, it is investigated by means of *S/N* analysis, the influence of the control factors on the variability of the variables in relation to their mean value with the purpose of reaching a robust and highly reproducible process. The aim is to find the levels of the control factors at which the process is more insensible to the variations caused by the noise factor.

Figure 6 shows the result from the factorial analysis of *S/N* for the thermal efficiency of the drying process. Although the control factors, specially the gas temperature and flow, have an important effect on the mean value of the variables of energy consumption and thermal efficiency, as analyzed in the previous section, these factors do not significantly affect the variation of them. Nevertheless, the process will be more robust if the $A_2B_2C_1D_2$ combination is chosen and this will show that the same levels that favour the mean value of the variables in the standard ANOVA, also favour a greater *S/N*.

On the other hand, from the point of view of the rates of evaporation and production, the significant factor in the *S/N* is the temperature of operation and a B_1 level has to be chosen for a more robust process (Fig 7). The other factors are less significant.

The effect of the interactions between the factors of control and the noise factor on the thermal efficiency is shown in Fig. 8. From the parallelism between the tendency lines it can be concluded that no interaction is relevant to the performance of the dryer, which means that the negative or positive effects the control factors exert on the quality variable are independent of the noise factor level. This result is similar for all the analyzed variables of quality.

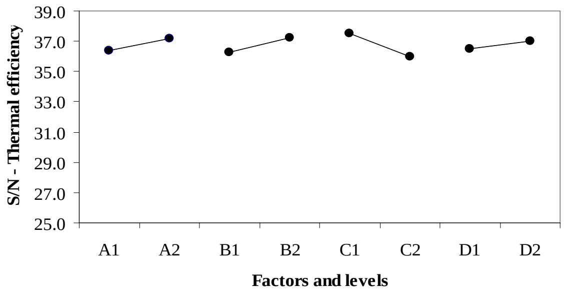

Fig. 6. *S/N* for the thermal efficiency of the dryer.

From the point of view of the thermal efficiency of the drying process, the air mass flow is a signal type factor, because it affects only the mean of the specific consumption of energy and thermal efficiency variables; it does not affect the variation of them around their mean values. Thus, the optimal level for the superficial velocity or mass flow is clearly the lowest (C_1) because with it the thermal efficiency is maximised without affecting its variability. Other control factors such as speed of agitation, temperature of operation and product load, are also signal type factors, for that reason they must be chosen at the levels they optimize the mean values of the thermal efficiency that is $A_2B_2D_2$.

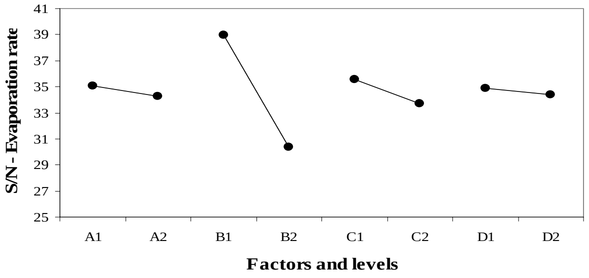

Fig. 7. *S/N* for the evaporation rate.

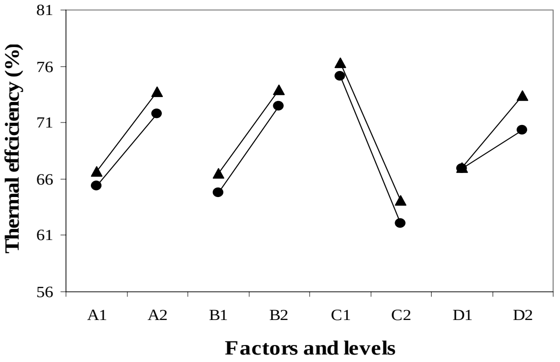

Fig. 8. Interaction between control factors and noise factor in thermal efficiency, ●, R_1; ▲, R_2.

On the other hand, from the point of view of the rate in which the drying process is carried out, the variables drying time, evaporation rates and biomass production, are clearly affected by the factor temperature of operation. Nevertheless, in this case the factor temperature also affects the variation of the variables in relation to the mean value. Thus, to fix the optimal level of the temperature of operation, one of the following criteria can be chosen: the criterion to optimize the rate of drying, and therefore the chosen level will be B_2. From the point of view of *S/N*, it would be wise to use the level of low temperature (B_1), to reduce the variability of the evaporation and production rates.

It is thought that the first criterion is more advisable using the B_2 level. With high temperatures of operation the drying rate is favoured, the thermal efficiency maximizes and the consumption of thermal energy is decreased and it has a cost only from the point of view of the variation of the variables that are related to rate of production. The reduction in the consumption of energy when increasing the temperature is concordant with the findings of Vanecek *et al.* (1966) for fluidized bed dryers.

On the other hand the factor air flow, from the point of view of the drying rate, should be chosen at its C_2 level. Nevertheless, the gained benefit is very small in relation to the loss of thermal efficiency that is obtained when operating at high superficial velocities. For this reason, it is better to operate the dryer at low superficial velocities (C_1), since the loss of drying rate can be recovered using greater temperatures of operation, as it was already discussed. The control factors agitation speed and product load must be chosen at the level that optimizes the mean values of the variables, since they do not affect the variability of them that is, A_2 and D_2.

D. Thermal Efficiency and Agitation Velocity

The drying process is obtained with a specific consumption of 2800 kJ/kg and a thermal efficiency of 85%. According to Hailer (1993), the best rotating dryers can have a consumption of energy of 2940 kJ per kilogram of evaporated water. In a later study, Snezhkin and Khavin (1997), postulate that the best dryers have a specific consumption of energy from 3350 to 4200 kJ/kg. In a spouted bed, Renstrom and Berghel (2002) demonstrated that the maximum power efficiency for sawdust drying with over heated steam is 70%, with product moisture content of 20% and operation temperature of 240 °C. In this work they also demonstrate that the power efficiency experiences a fall to 55% if the temperature of the steam is 160 °C.

It is worth emphasizing that, since the calculations of energy were carried out in periods where the temperature of the particle had already reached the value of wet bulb temperature. Thus, the power consumption corresponding to the initial period must be added to the consumption of energy of 2800 kJ/kg since the biomass is loaded in the dryer until the particles acquire the temperature of wet bulb corresponding to the period of constant rate drying. In this period, the particles and the water contained in them only increase their temperature, without undergoing evaporation, or it is at least a very low value, because it is a period of preparation of the material for drying. When carrying out the calculation of this additional consumption of energy, the thermal efficiency of the dryer decreases to 80 % which is equivalent to a specific consumption of energy of 3040 kJ per kg of evaporated water.

Improvements in the thermal efficiency can be obtained by taking advantage of the residual heat of solids when leaving the dryer. It is possible to see that if the biomass is dried to a moisture content of 0.15 kg/kg, the temperature of solids at the end of the process is 40ºC, according to the data provided by software ScanLink 2.0. This aspect can be very important in particleboard factories, since in those industrial processes the particle drying must approximately be run until reaching moisture values of 5 %. According to the drying curve, this final moisture content implies to prolong the drying time so the temperature of solids at the end of drying can be 53 ºC. This residual heat could be used to preheat the incoming air to the dryer, and that would imply a yield increase of 2.2 points.

In relation to the agitation speed of the mechanical shaker being used as promoter of a good fluidization quality, the best results are obtained with 2 r.p.s. At that level an acceleration of the moisture removal process of the product with a better thermal efficiency is obtained.

Higher values in the agitation speed are not recommendable. Even, with low moisture contents of solids it was possible to see that the agitation speed can be decreased to values of 0.5 r.p.s., a finding that agrees with the data reported by Reina *et al.* (2001) for particles of wood wastes. Although in this work, explicit reference to the content of moisture content of studied solids is not done, it is presumed that they did not study the fluidization behaviour of the biomass with moisture contents higher than 1.5 kg/kg.

It is clear that these results have been obtained on a pilot scale, thus it is possible to expect some loss of efficiency when carrying out the scale-up of the unit for demonstrative or industrial plant. In these scaling it is more difficult to have control on the factors that affect drying, with the same quality as in a pilot plant. Nevertheless, it is also certain that there is still a margin available in the temperature of operation, since the tests have been carried out at maximum temperatures of 140ºC, and it is possible to increase the temperature of operation up to 150 ºC.

V CONCLUSIONS

From the results, it is possible to conclude that the drying of biomass in fluidized bed with mechanical agitation is in conditions for competing with the alternatives available nowadays in the market to dry particulate products. The thermal efficiency of the dryer is 80 %, which is equivalent to a specific consumption of energy of 3040 kJ per kg of evaporated water.

In relation to noise factor, when operating the dryer with biomass loaded with different initial humidity contents, there are not important changes in the values of thermal efficiency nor in the rates of water evaporation. This behaviour is attributed to the fact that the drying process, according to what it has been observed in the drying curves, is carried out at such a rate that during a great portion of the total drying time, it remains constant. Indeed, it is seen that the variations in the rates of evaporation, in the specific consumption of energy and in the thermal efficiency, when varying the noise level from R_1 to R_2 (that is, when increasing the initial moisture, from 0.8 to 1.5 kg/kg) are 3.3, 3.2 and 3.0 %, respectively.

In relation to the agitation speed of the mechanical shaker, the best results are obtained with 2 r.p.s.; higher values in the spinning speed are not recommendable.

NOMENCLATURE

A	cross-sectional area of bed (m^2).
C_g	gas heat capacity (J/kg K).
C_{H2O}	water heat capacity (J/kg K).
$C_{p,bs}$	heat capacity of wet particle d.b. (J/kg K).
$C_{p,0}$	heat capacity of dry particle (J/kg K).
$d_{p,m}$	weight mean diameter of biomass particle (m).
$d.f.$	degrees of freedom.
e	residual error in the experiments.
F	parameter of Fisher test.
h_{fg}	heat of vaporization of the moisture (J/kg).
L_8	orthogonal array of 8 experiments.
$\dot{m}_g$	mass flow of fluidizing gas (kg/s).
$\dot{m}_p$	production rate or product output (kg/s m^2).
$\dot{m}_v$	evaporation rate (kg/s m^2).
M_0	mass of dry biomass in the bed (kg).
N	agitation speed (r.p.s.)
q	specific consumption of energy (J/kg).
P	percent contribution (%).
$\dot{Q}_c$	heat-flux consumed in the biomass drying (W).
$\dot{Q}_l$	heat loss in the dryer (W).
$\dot{Q}_u$	useful heat-flux in the drying (W).
S/N	Signal-to-Noise ratio.
SS	sum of squares.
t	time (s) or (min).
t_d	drying time (s) or (min).
T	temperature (K) or (ºC).
T_g	gas temperature (K) or (ºC).
$T_{g,i}$	inlet gas temperature in the dryer (K) or (ºC).
T_{H2O}	water temperature in the solids (K) or (ºC).
T_0	room temperature (K) or (ºC).
T_p	particle temperature (K) or (ºC).
T_{sat}	saturation temperature (K) or (ºC).
V	variance of factors.
w	moisture content in the biomass d.b. (kg/kg).
w_f	final moisture content of biomass d.b. (kg/kg).
w_i	initial moisture content of biomass d.b. (kg/kg).
y_m	mean value of variable y.
Δt	time interval (s) or (min).
$\eta(t)$	instantaneous thermal efficiency of dryer (%).
η_{gl}	global thermal efficiency of the dryer (%).
σ^2	variance of data.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of Dirección de Investigación of the Universidad Austral de Chile (Project: S200207), and to Universidad de Valladolid de España.

REFERENCES

Hailer, F., “El consumo de calor en el secado de pulpa y azúcar”, *Ingeniería Química*, **11**, 89-95 (1993).

Herguido, J., J. Corella and J. González-Saiz, “Steam gasification of lignocellulosic residues in a fluidized bed at a small pilot scale. Effect of the type of feedstock”, *Ind. Eng. Chem. Res*, **31**, 1274-1282 (1992).

Moreno, R. and R. Ríos, “Study on sawdust drying techniques in fluidized bed”, *Biosystems Engineering*, **82**, 321-329 (2002).

Moreno, R., G. Antolín, A. Reyes and P. Alvarez, “Drying characteristics of forest biomass particles of pinus radiata”, *Biosystems Engineering*, **88**, 105-115 (2004).

Moreno, R., G. Antolín, and A. Reyes, “Quality of fluidisation for the drying of forestry biomass particles in fluidised bed”, *Biosystems Engineering*, **94**, 47-56 (2006).

Olazar, M., R. Aguado, J. Bilbao and A. Barahona, “Pyrolysis of sawdust in a conical spouted-bed reactor with a HZSM-5 catalyst”, *AIChE Journal*, **46**, 1025-1033 (2000).

Pang, S., “Mathematical modelling of MDF fiber drying: drying optimization”, *Drying Technology*, **18**, 1433-1448 (2000).

Reina, J., E. Velo and L. Pigjaner, “Fluidization of waste-wood particles with mechanical agitation of the bed”, *In d. Eng. Chem. Res.*, **40**, 393-397 (2001).

Renström, R. and J. Berghel, “Drying of sawdust in an atmospheric pressure spouted bed steam dryer”, *Drying Technology*, **20**, 449-464 (2002).

Ross, P. J., *Taguchi Techniques for quality engineering*, 2nd ed., Ed. Mc Graw-Hill, New York (1996).

Snezhkin, Y.F. and A.A. Khavin, "Estimation of thermal efficiency of driers working with materials with various initial humidity", *Heat Transfer Research*, **28**, 349-351 (1997).

Vanecek, V., M. Markvart and R. Drbohlav, *Fluidized bed drying*, Ed. Leonard Hill, London, (1966).

Zabaniotou, A.A., "Simulation of forestry biomass drying in a rotary dryer", *Drying Technology*, **18**, 1415-1431 (2000).

Received: July 1, 2005.
Accepted for publication: January 11, 2006.
Recommended by Editor W. Ambrosini