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DRYING REFINED SUGAR ON THE CONTINUOUS PULSED FLUIDIZED BED DRYER: EXPERIMENTAL STUDY ON THE MAIN TECHNOLOGICAL PARAMETERS DETERMINATION

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Abstract:-

A continuous pulsed fluidized bed (CPFB) dryer with relocated gas stream was employed to conduct the drying of refined sugar. The experiments were carried out according to the 2-level orthogonal experimental plan, combined with multiple response optimization according to Response Surface Method (RSM) to determine the appropriate parameters (hot air temperature, hot air velocity, pulse frequency, particle mean diameter) in the refined sugar drying process. The appropriate conditions of drying process were identified at 71.5□C of hot air temperature, 2.1 m/s of hot air velocity, 0.55 Hz of pulse frequency and 467□m of particle mean diameter. At these conditions the dried refined sugar reached final moisture content of 0.035% (wet basis), the specific electrical energy and the specific heat value consumption reached 187 Wh/kg product and 1024 kJ/kg product, respectively.

Keywords:- *Refined sugar drying, continuous pulsed fluidized bed, relocated gas stream, fluidized bed drying, multiple factor experiment, Multiple Response Optimization*

1. INTRODUCTION

Refined standard sugar (RS) is the material formed by crystallization, the moisture content after centrifugation is usually from 1% – 2% (Baikow, 2013). Unless this moisture is removed, the wet sugar will rapidly deteriorate and be attacked by bacteria. Actual adhesive properties will cause difficulties in drying in the continuous layer of granules, while the quality requirements of the product should be high.

Sugar is an important ingredient in the food industry, which is a precursor to daily diet and a source of energy to the body. Normally, the moisture content of raw sugar required for preservation must not be greater than 0.2% (TCVN 6961: 2001) and not more than 0.05% (TCVN 6958: 2001) for refined sugar. It is necessary to dry sugar before storage. In addition, the sensory criteria and the physical properties of sugar must be in accordance with national standard.

Therefore, the post-centrifugal drying is necessary for long-term preservation and standard humidity. In the past, rotary drier dryers have been used extensively in sugar drying technology but after fluidized bed technology has developed in the field of drying, fluidized bed dryers have been increasingly used. The advantages of fluidized bed technique have been analyzed and verified (Kudra & Mujumdar, 2009).

The biggest disadvantage of fluidized bed drying is the high energy costs because of operating at high air velocity and high hot air temperature. To solve the energy cost problem in the fluidized bed drying process, some authors have studied a new fluidized bed drying method that is a pulsed fluidized bed (PFB) dryer (Gawrzynski et al, 1999). The publications analyzed in the content section show that the experimental model yields good results in terms of energy savings.

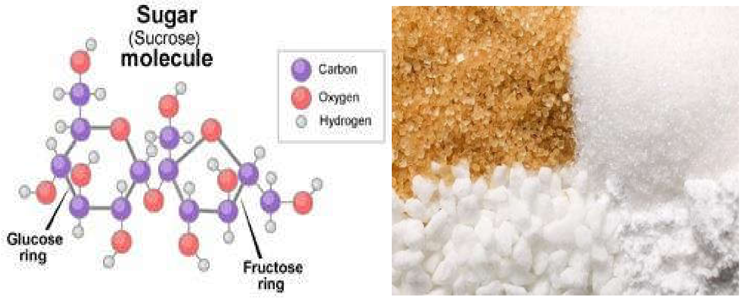


Fig 1. Molecular structure and types of sugar

Study on the hydrodynamic and kinematic properties of pulsed fluidized bed drying focuses on building the relationship between air velocity and pressure loss at variable pulse frequencies and have demonstrated the influence of the pulse frequency on the pressure loss through the particle layer (Kudra T. et al., 2002; Gawrzynski Z. and Bartosz Pieczaba, 2006; Sobrino et al., 2007; Grzegorz Rogula, 2009). According to Kudra T. et al. (2002), Gawrzynski Z. et al. (1999), Ambrosio-Ugri M. C. B. et al. (2007), Godoi F.C. et al. (2011), the frequency range of the pulses suitable for batch drying is 5-15 Hz. But according to Li et al. (2004) and Ali and Asif (2012), the pulse frequency should be lower than 1 Hz. Thus, for each type of material the determination of the pulse frequency is necessary.

Experimental studies to determine the effect of technological parameters on PFB drying were conducted on a PFB experimental scale dryer published by Gawrzynski Z. et al. (2003). The effect of hot air temperature, air velocity and pulse frequency on pressure losses, drying time were investigated (Gawrzynski Z. et al., 1999; Marcello and Taranto, 2004; Reyes et al., 2007, 2010). From these studies, some experimental equations for the heat transfer coefficient and mass diffusion coefficient during PFB drying were determined (Gawrzynski Z. et al., 1999; Reyes et al., 2007, 2010).

Regarding the comparison of the specific heat value consumption between the PFB dryer and the conventional fluidized bed dryer, Luciane FG de Souza et al., (2010) and Somkiat Prachayawarakorn et al., (2004) reported that with PFB drying process, the energy consumption could be saving from a 40- 50% compared with conventional fluidized bed drying process.

The purpose of this study was to determine the suitable PFB drying mode for refined sugar as well as reducing energy consumption. Factors that need to be optimized include the final moisture content (Y_1, %), the final collectable product efficiency (Y_2, %), the specific electrical energy consumption (Y_3, Wh/kg product) and the specific heat value consumption (Y_4, kJ/kg product) at the lowest value. These factors are highly dependent on the hot air temperature (Z_1, °C), the hot air velocity (Z_2, m/s), the pulse frequency (Z_3, Hz) and the mean diameter of particle (Z_4, μm).

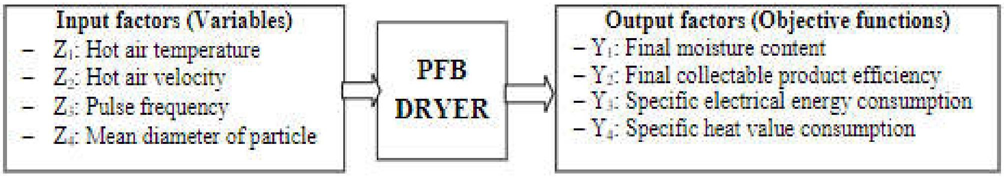


Fig 2. The black box model

2. DESIGN OF EXPERIMENTAL (DOE)

The 2nd empirical regression function of objective functions is defined by the following expression (Box & Hunter, 2005):

$$Y = b_0 + \sum_{j=1}^{k} b_j X_j + \sum_{\substack{j,l=1 \\ j=l}}^{k} b_{jl} X_j X_l + \sum_{j=1}^{k} b_{jj} X_j \qquad (1)$$

The number of coefficients in (1) is

$$\begin{aligned} m &= k + 1 + k + C_k^2 \\ &= 2k + 1 + \frac{k!}{2!(k-2)!} = \frac{(k+1)(k+2)}{2} \end{aligned} \qquad (2)$$

Consider the experimental element Zj, have:

$$Z_j^0 = \frac{Z_j^{\max} + Z_j^{\min}}{2}; \qquad j = 1:k \qquad (3)$$

where: $Z_j^{\max}$ is high level (Upper level)

$Z_j^{\min}$ is low level (Lower level)

Z_j^0 is basic level

Variable range of element Zj from its center

$$\Delta Z_j = \frac{Z_j^{\max} - Z_j^{\min}}{2}; \qquad j = 1:k \qquad (4)$$

If elements of matrix Xbelong to [-1,1] then the matrix which are contructed have orgothonal property. However, the value of the variables we study are not in [-1,1], we need to transform these variables from real value Zjinto new dimension less variables (coded variables) Xj. Let

$$X_j = \frac{Z_j - Z_j^0}{\Delta Z_j}; \qquad j = 1:k \qquad (5)$$

Where $-1 \le X_j \le 1$ and $X_j^0 = 0$

The experimental no. is determined as:

$$N = n_k + n_* + n_0 = 2^k + 2k + n_0 \qquad (6)$$

The value of the star point:

$$\alpha = \sqrt{\sqrt{N.2^{(k-2)}} - 2^{(k-1)}} \qquad (7)$$

For the plan to be orthogonal, the variable X2jis replaced by X’j calculated by the formula:

$$X_j' = X_j^2 - \overline{X}_j^2 = X_j^2 - \frac{\sum_{j=1}^{N} X_j^2}{N} = X_j^2 - \frac{(2^k + 2\alpha^2)}{N} \qquad (8)$$

And conditions of the orthogonal matrix:

$$\lambda = \frac{(2^k + 2\alpha^2)}{N} \qquad (9)$$

Regression coefficients are determined by the formula:

$$b_j = \frac{\sum_{i=1}^{N} X_{ji} Y_i}{\sum_{i=1}^{N} X_{ji}^2}; \quad b_{jl} = \frac{\sum_{i=1}^{N} (X_j X_l) Y_i}{\sum_{i=1}^{N} (X_j X_l)_i^2}; \quad b_{jj} = \frac{\sum_{i=1}^{N} X_{ji}' Y_i}{\sum_{i=1}^{N} (X_{ji}')^2} \qquad (10)$$

Variance of these regression coefficients:

$$s_{b_j}^2 = \frac{s_{bk}^2}{\sum_{i=1}^{N} X_{ji}^2}; \quad s_{b_{jl}}^2 = \frac{s_{bk}^2}{\sum_{i=1}^{N} (X_j X_l)_i^2}; \quad s_{b_{jj}}^2 = \frac{s_{bk}^2}{\sum_{i=1}^{N} (X_{ji}')^2} \qquad (11)$$

After applying the change variables, we have:

$$\begin{aligned} Y = {} & b_0' + b_1.X_1 + \ldots + b_k.X_k + b_{12}.X_1.X_2 + \ldots + b_{k-1}.X_{k-1}.X_k \\ & + b_{11}\left(X_1^2 - \overline{X}_1^2\right) + \ldots + b_{kk}\left(X_k^2 - \overline{X}_k^2\right) \end{aligned} \qquad (12)$$

To convert (11) into (1), b_0 are determined by the formula:

$$b_0 = b_0' - b_{11}.\overline{X}_1^2 - \ldots - b_{kk}.\overline{X}_k^2 \qquad (13)$$

And variance of b_0:

$$s_{b_0}^2 = s_{b_0'}^2 + \left(\overline{X}_1^2\right)^2 s_{b_{11}}^2 + \ldots + \left(\overline{X}_k^2\right)^2 s_{b_{kk}}^2 \qquad (14)$$

Testing the significance of the coefficients: Using the reappearance variance [3]
To calculate the reappearance variance, n_0 experiments of center are carried out. Then, the reappearance variance is determined by the formula:

$$s_{rv}^2 = \frac{\sum_{u=1}^{n_0} (Y_u^0 - \overline{Y}^0)^2}{n_0 - 1} \qquad (15)$$

The significance of the coefficients in the regression function are tested according to the Student standard:

$$t_j = \frac{|b_j|}{s_{b_j}} \qquad (16)$$

Test the significance of regression function:
For hypothesis testing "the compatibility of the regression equation with the real data", the Fisher test is used:

$$F_{1-p}(f_1, f_2) = \frac{s_{re}^2}{s_{rv}^2} \qquad (17)$$

Where: p: significance levels
f_1: the first degree of freedom, $f_1 = N - L$
f_2: the second degree of freedom, $f_2 = n_0 - 1$
L: number of coefficients which are statistically significant
The residual variance:

$$s_{re}^2 = \frac{\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2}{N - L} \qquad (18)$$

If $F < F_{1-p}(f_1, f_2)$ Then regression function is statistically significant.

3. MATERIALS AND METHODS

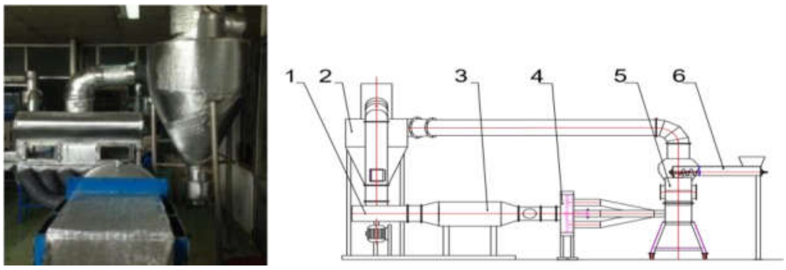
3.1. Materials

Refined sugar materials used in the experiment were selected in Cantho sugar joint stock company (CASUCO), classified by sieves, the moisture content of wet sugar was determined by the moisture analyzer Axis AGS100 and result was 1.5%.

Fig 3. The refined sugar before and after drying

3.2. Apparatus

The experiments were carried out on PFB dryer of Industrial University of Ho Chi Minh city (Fig 4). The air drying was heated by resistor with the regulator. Fan and pulse motor was installed with inverters so the velocity of hot air and the pulse frequency could be adjusted and these parameters were displayed and monitored in the drying process.
The moisture content of sugar was measured by the moisture analyzer Axis AGS100 with the range of 0 to 100% and the error of 0.01% for the sample >5g. Temperature controller Autonics TZN4M and the PNTECH DDC-C46 were used to control and monitor the temperature of hot air the temperature with the range of $0 \div 400$°C and the error of 0.5°C. Determining velocity of air drying by Extech SDL350 hotwire anemometer datalogger with the error of 0.01m/s. Hioki HiTester 3286-20 Power Clamp-Meter was used to definite the energy consumption. The fan speed and pulse frequency were adjusted by Hitachi X200 inverter and Schneider electric inverter ATV312HU15M2.



1- Fan; 2- Cyclone; 3-Heater; 4- Pulsator; 5- Drying chamber; 6- Feeder Fig 4. The PFB dryer and its diagram

3.3. The method for evaluating the output factors of drying process

Determining the final moisture content (Y_1, %): Six final product samples were collected every 10 minutes until the end of the drying process (60 minutes). The final moisture content is mean of six moisture content samples determined by the moisture analyzer Axis AGS100.

$$Y_1 = \frac{G_i - G_f}{G_i}100\% \qquad (19)$$

Where: G_i – mass of initial sample, g
G_f – mass of final sample, g

Determining the final collectable product efficiency (Y_2, %):

$$Y_2 = \frac{G_2}{G_{2th}}100\% \qquad (20)$$

Where: G_2 – mass of final products, kg/h
G_{2th} – theoritical mass of final products, kg/h

While doing experiments, the moisture content of drying refined sugar material (M_1) was kept 1.5%, the input capacity (G_1) was 20kg per 1 hour. The requirement of moisture content of the final product (M_2) is 0.05%, so that the theoritical mass of final product (G_2) is:

$$G_{2th} = G_1\frac{100 - M_1}{100 - M_2} = 20\frac{100 - 1.5}{100 - 0.05} = 19.7\,\text{kg per hour} \qquad (21)$$

Determining the specific electrical energy consumption (Y_2, Wh/kg product) by Power meter,

$$Y_3 = \frac{N}{G_2} = \frac{U \times I \times \cos\varphi \times \tau}{G_2} \qquad (22)$$

Where: N – total electrical energy consumption, Wh
U – Voltage, V; I – current, A $\cos\varphi$ – power factor; τ – drying time, h

Determining the specific heat value consumption (Y_3, kJ/kg product) by Power meter,

$$Y_4 = \frac{Q}{G_2} = 3.6\frac{U \times I \times \tau}{G_2} \qquad (23)$$

Where, U (V) and I (A) are the voltage and current of heating resistor in drying process, respectively.

4. RESULTS AND DISCUSSION

4.1. Establishing the constituent objective functions of the multi-objective problem

The experimental number is determined as:

$$N = 2^k + 2k + n_0 = 29$$

With: $k = 4$; $n_k = 2^k = 16$; $n_* = 2.k = 2.4 = 8$; choose the number of experiment in center $n_0 = 5$.

The value of the star point:

$$\alpha = \sqrt{\sqrt{N.2^{(k-2)}} - 2^{(k-1)}} = \sqrt{\sqrt{19.2^{(3-2)}} - 2^{(3-1)}} = 1.664$$

Experimental domains are established through 2nd orthogonal planning as follows (Canh N, 2004):

$$X_j' = X_j^2 - \frac{(2^4 + 2.1,664^2)}{29} = X_j^2 - 0,7427$$

Experimental planning under 2nd orthogonal planning shown in Table 2 is completely equivalent to the result obtained using the software Statgraphics Centurion XVII version 17.2.00. After carrying out 29 experiments, the results of the output factors are shown in Table

Table 1 Multi-objective experiment domains

factor	-α (-1.664)	lower (-1)	central (0)	upper (+1)	+α (+1.664)	Deviation ΔZ_i
Z_1 (□C)	53.36	60	70	80	86.64	10
Z_2 (m/s)	1.168	1.5	2	2.5	2.832	0.5
Z_3 (Hz)	0.084	0.25	0.5	0.75	0.916	0.25
Z_4 (□m)	467	600	800	1000	1133	200

Table 2 the 2nd orthogonal experimental matrix

N	Coded variables				Objective value			
	X_1	X_2	X_3	X_4	Y_1	Y_2	Y_3	Y_4
1	-1.664	0	0	0	0.087	87.82	214	596
2	-1	-1	1	1	0.123	60.41	252	853
3	-1	-1	-1	1	0.119	65.48	234	729
4	-1	-1	-1	-1	0.102	70.56	201	662
5	-1	-1	1	-1	0.107	67.01	211	769
6	-1	1	-1	1	0.051	91.37	269	909
7	-1	1	1	-1	0.039	98.48	237	764
8	-1	1	1	1	0.056	100	246	788
9	-1	1	-1	-1	0.061	96.95	242	808
10	0	-1.664	0	0	0.112	52.79	219	810
11	0	0	0	0	0.06	87.82	214	1004
12	0	0	1.664	0	0.082	85.79	234	1103
13	0	0	0	0	0.06	87.31	215	1067
14	0	0	0	1.664	0.05	73.1	272	1333
15	0	0	0	0	0.058	92.39	203	1011
16	0	0	0	-1.664	0.025	100	178	940
17	0	0	0	0	0.06	87.31	215	1057
18	0	0	-1.664	0	0.09	81.22	229	1105
19	0	0	0	0	0.062	87.31	215	1067
20	0	1.664	0	0	0.04	100	270	1168
21	1	-1	-1	1	0.078	58.88	260	1467
22	1	-1	-1	-1	0.09	71.07	186	1148
23	1	-1	1	1	0.066	51.78	294	1737
24	1	-1	1	-1	0.07	63.45	222	1371
25	1	1	-1	1	0.072	71.07	346	1685
26	1	1	1	1	0.049	86.29	296	1465
27	1	1	1	-1	0.058	100	234	1214
28	1	1	-1	-1	0.07	91.37	256	1310
29	1.664	0	0	0	0.063	73.6	255	1556

4.2. Establishing the mathematical model of the output factors The regression equations (24), (25), (26) and (27) were obtained after processing the experimental data, calculating by the Student test, and testing the regression equations for the fitness of the experimental results by Fisher test (Box and Hunter, 2005):

The final moisture content:

$$\begin{aligned} Y_1 = {} & 0.0592 - 0.0067X_1 - 0.0194X_2 - 0.0041X_3 \\ & + 0.0118X_1X_2 - 0.0037X_1X_3 - 0.0039X_1X_4 \\ & + 0.0063X_1^2 + 0.0066X_2^2 + 0.0103X_3^2 - 0.0073X_4^2 \end{aligned} \qquad (24)$$

With $R^2 = 95.004\%$, Standard Error of Est. = 0.0068 and Mean absolute error = 0.0038.

Final collectable product efficiency:

$$\begin{aligned} Y_2 = {} & 87.974 - 3.715X_1 + 14.181X_2 - 5.496X_4 \\ & + 3.584X_2X_3 - 2.633X_1X_4 \\ & - 3.076X_1^2 - 4.634X_2^2 - 2.067X_3^2 \end{aligned} \qquad (25)$$

With $R^2 = 96.783\%$, Standard Error of Est. = 3.1934 and Mean absolute error = 2.1277.

Specific electrical energy consumption:

$$\begin{aligned} Y_3 = {} & 211.0 + 12.546X_1 + 16.289X_2 + 26.204X_4 \\ & + 11.750X_1X_4 - 12.375X_2X_3 \\ & + 9.510X_1^2 + 13.120X_2^2 + 8.428X_3^2 + 6.081X_4^2 \end{aligned} \qquad (26)$$

With $R^2 = 95.707\%$, Standard Error of Est. = 8.9916 and Mean absolute error = 6.0920.

Specific heat value consumption:

$$\begin{aligned} Y_4 = {} & 1057.94 + 311.636X_1 + 37.272X_2 + 104.041X_4 \\ & + 64.687X_1X_4 - 75.313X_2X_3 + 37.872X_4^2 \end{aligned} \qquad (27)$$

With $R^2 = 96.492\%$, Standard Error of Est. = 64.7167 and Mean absolute error = 39.8765.

The Pareto charts for each objective function presented in Fig 5, Fig 6, Fig 7 and Fig 8 show that the effect of four technological factors to four objective functions.

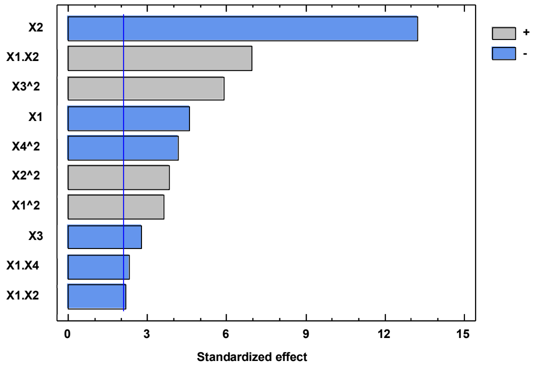


Fig 5. Standardized Pareto chart for Y_1

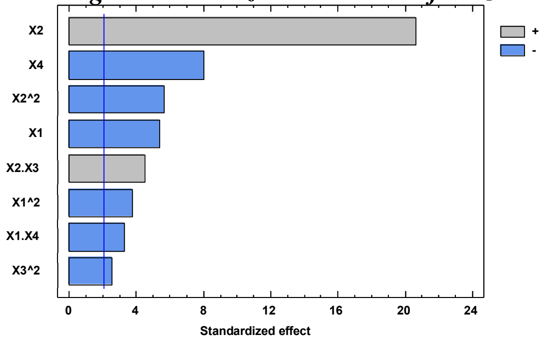


Fig 6. Standardized Pareto chart for Y_2

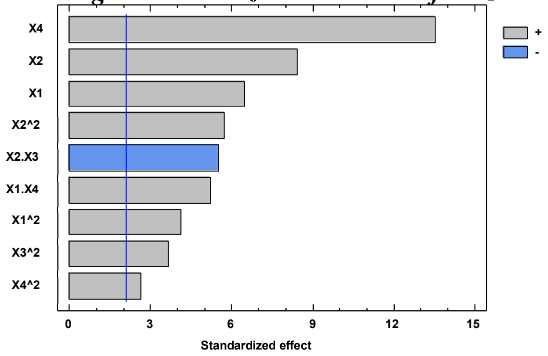


Fig 7. Standardized Pareto chart for Y_3

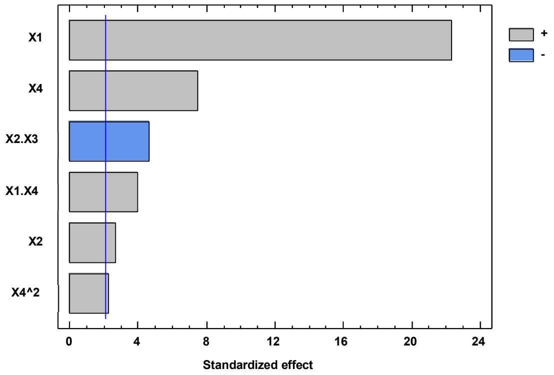


Fig 8. Standardized Pareto chart for Y_4

As can be seen in Fig 5, the velocity and temperature of the hot air (X_1 and X_2) affect the final moisture content ($p<0.05$), while the effect of the particle mean diameter (X_4) is not significant ($p>0.05$). Conversely, for the Y_2, Y_3 and Y_4 functions, the effect of the particle mean diameter (X_4) is significant ($p>0.05$).

The Pareto charts for Y_3 and Y_4 (Fig 7 and Fig 8) show that the influence of X_1, X_2, X_4 factors to Y_3 and Y_4 is positive, meaning that increasing the value of the technological parameters will reduce the output capacity, thus increasing the specific electrical energy and heat value consumption. However, simultaneously increasing the hot air velocity and pulse frequency values will increase the output capacity so the specific energy consumption for 1kg of the product is reduced.

4.3. Optimizing the technological parameters

The purpose of the optimization problem is to determine the value of the technological parameters so that the objective functions have the lowest value. For the multi-objective optimization problem during refined sugar drying, the optimal values of variables X_1, X_2, X_3 and X_4 are calculated so that the values of the objective functions Y_1, Y_3, Y_4 are the smallest and Y_2 is the largest in the range $-1.664 \le X_1, X_2, X_3, X_4 \le 1.664$. Response Surface Method (RSM) is used in this case to determine the optimal technological parameters for the drying process.

The technological parameters (X_1, X_2, X_3, X_4) of the PFB drying process of refined sugar had the simultaneous impact on these objective functions (Y_1, Y_2, Y_3, Y_4) with the identified domain D(X) = $-1.664 \le X_1, X_2, X_3, X_4 \le 1.664\}$. Thus, the four-objective optimization problem determining the technological drying mode of refined sugar was restated as: Finding in

$X = \left(X_1^{opt}, X_2^{opt}, X_3^{opt}, X_4^{opt}\right) \in D(X)$ in order that:

$$\begin{cases} Y_1 = f_{1\min}\left(X_1^{opt}, X_2^{opt}, X_3^{opt}, X_4^{opt}\right) = \min f_1(X_1, X_2, X_3, X_4) \\ Y_2 = f_{2\max}\left(X_1^{opt}, X_2^{opt}, X_3^{opt}, X_4^{opt}\right) = \max f_2(X_1, X_2, X_3, X_4) \\ Y_3 = f_{3\min}\left(X_1^{opt}, X_2^{opt}, X_3^{opt}, X_4^{opt}\right) = \min f_3(X_1, X_2, X_3, X_4) \\ Y_4 = f_{4\min}\left(X_1^{opt}, X_2^{opt}, X_3^{opt}, X_4^{opt}\right) = \min f_4(X_1, X_2, X_3, X_4) \\ \forall X = (X_1, X_2, X_3, X_4) \in \{-1.664 \le X_1, X_2, X_3, X_4 \le 1.664\} \end{cases} \quad (28)$$

Using Multiple Response Optimization in Statgraphics Centurion XVII software version 17.2.00 to perform optimization calculations for technological parameters during refined sugar drying. The results have identified the values of the optimal variables as follows:

$X_1^{opt} = 0.147$; $X_2^{opt} = 0.210$; $X_3^{opt} = 0.205$; $X_4^{opt} = -1.664$, corresponding to the values of the objective function: $Y_1^{\min} = 0.035\%$; $Y_2^{\max} = 100\%$; $Y_3^{\min} = 187$ Wh/kg product; $Y_4^{\min} = 1024$ kJ/kg product;

Transforming into real variables:

$Z_1^{opt} = 71.5^\circ\text{C}$; $Z_2^{opt} = 2.1\,\text{m/s}$; $Z_3^{opt} = 0.55\,\text{Hz}$; $Z_4^{opt} = 467\,\mu\text{m}$

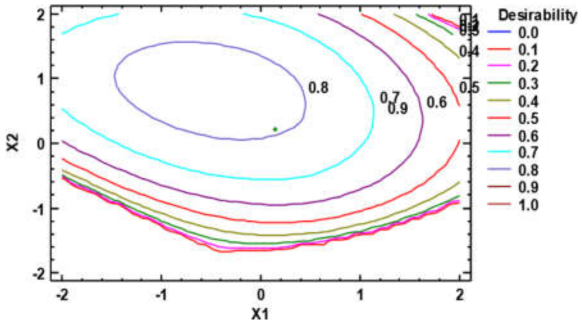


Fig 9. Contours of Estimated Response Surface, X_3=0, X_4=0

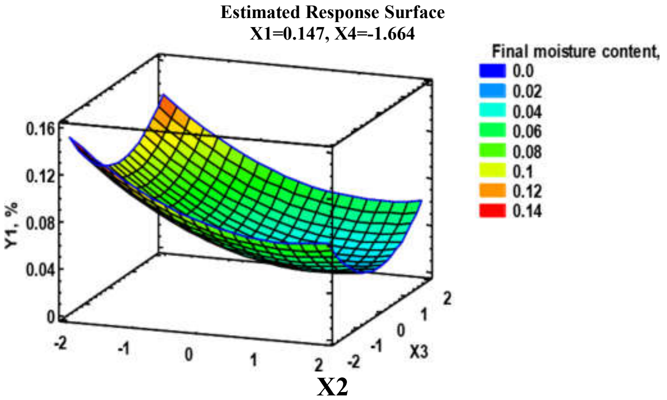


Fig 10. The final moisture content,
X1 =0.147, X$_4$ =-1.664

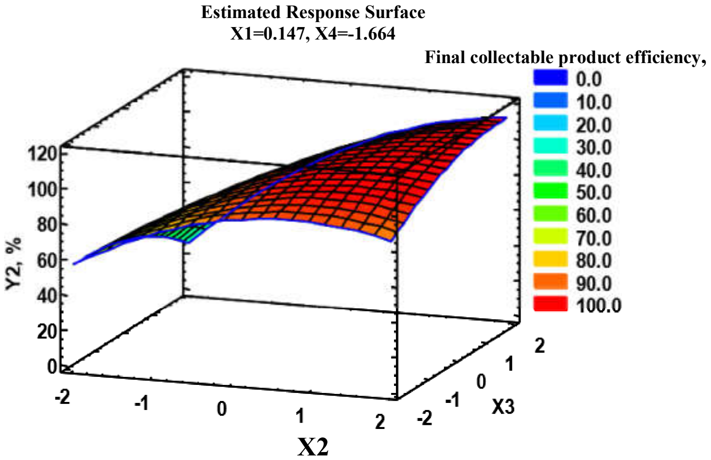


Fig 11. The final collectable product efficiency,
X$_1$ =0.147, X$_4$ =-1.664

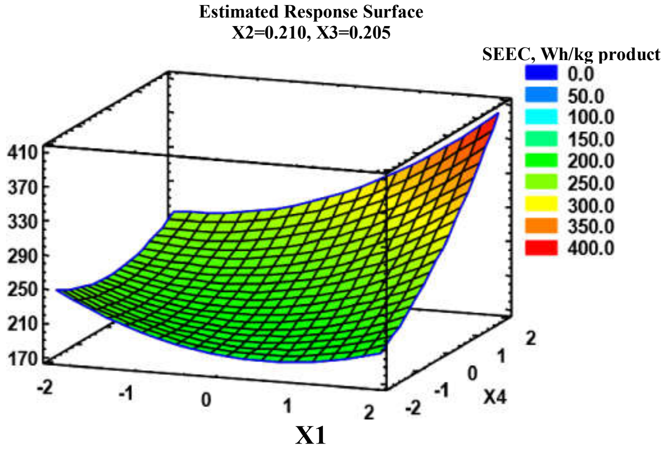


Fig 12. The specific electrical energy consumption,
X$_2$=0.210, X$_3$=0.205

Estimated Response Surface
X2=0.210; X3=0.205

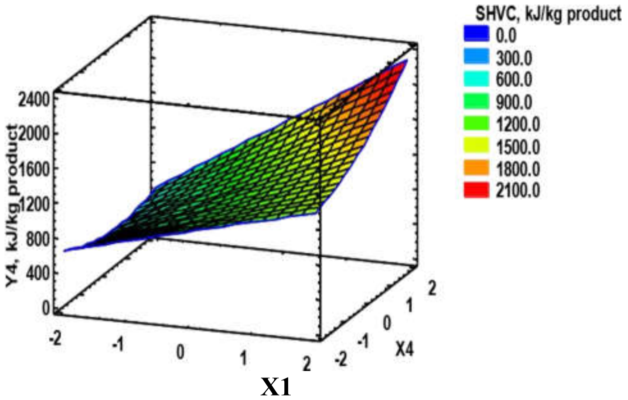


Fig 13. The specific heat value consumption,
$X_2=0.210$, $X_3=0.205$

5. CONCLUSION

Application of CPFB method in refined sugar drying process is not yet widely found in the literature. The results of the paper show that the CPFB is suitable for drying of refined sugar because of the good fluidizing behaviour for the adhesive material and the high heat and mass transfer coefficient. However, the appropriately technological parameters of the drying process should be predicted and empirically demonstrated.

The effect of the technological parameters (hot air temperature and velocity, pulse frequency and particle mean diameter) on product quality and drying cost (final moisture content, final collectable product efficiency, specific electrical energy consumption and heat value consumption) though multi-factorial experiments is very clear. The multi-objective optimization results of the pulsed fluidized bed drying method for refined sugar with the temperature of hot air is 71.5°C, the hot air velocity of 2.1 m/s, the pulse frequency of 0.55 Hz and the particle mean diameter of 467μm were empirically verified.

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