Energy and Exergy Studies for Different Intensifying Processes of Malt Drying

GABRIELA ISOPENCU[1], ALINA MONICA MARES[1]*, GHEORGHITA JINESCU[1,2]

[1] Politehnica University, Chemical and Biochemical Engineering Department, 1-7 Polizu Str., 011061, Bucharest, Romania

[2] Romanian Academy of Technical Sciences, 26 Dacia Blvd., 010413, Bucharest, Romanian

In this research, a comprehensive thermodynamic investigation through energy and exergy analyses is conducted to assess the performance of malt and mixtures of malt - inert add drying process. In this regard, energy and exergy efficiencies are evaluated with the experimental thermodynamic data for different techniques of malt drying (fixed, fluidized and modified fluidized bed with inert add). For all drying techniques analyzed, the study evidenced that energy utilization increases with drying agent velocity, drying time and temperature, meanwhile the energy utilization ratio decreases with this parameters. On the other hand, exergy loss and exergy efficiency increases with air velocity and drying temperature, but they have an antagonist behavior regarding with drying time: exergy loss decreasing in time, meanwhile the exergetic efficiency increases in time. The energetic values of the parameters for the fluidized bed are considerable smaller than those of fixed bed, which recommends the fluidization as intensification technique for malt drying. Also, the study evidenced the good influence on the energetic behavior of the fluidized bed, if the malt particle are mixed with a porous, hygroscopic inert add.

Keywords: malt, inert add, drying, fluidization, energy, exergy

Drying is generally used to remove moisture or liquid from a wet solid by converting this moisture into gaseous state. In most drying operations, water is the liquid evaporated and air is normally employed as drying gas [1].

In many practical applications, drying is a process which requires high energy input because of the high latent heat of water evaporation and relatively low energy efficiency of industrial dryers. It is reported that industrial dryers consume on average about 12% of the total energy used in industrial processes. In those processes where drying is required, the cost of drying can approach to 60-70% of the total cost [2-3]. Thus, one of the most important challenges of the drying industry is to reduce the cost of energy sources for good quality dried products. Drying equipment may be classified in several ways. The most common classification is based on the mode of heat input. The heat needed for drying is supplied to the material by one of the following methods [2-4]: radiation drying; convective drying (using a drying medium, i.e., air); contact drying (by conduction from a surface that is in direct contact with the material to be dried).

Intensifying drying of the biomaterials need to realize a uniform contact between phases to reach homogeneous structures of the layers. This fact is imposed by the degradation tendency of the biomaterials, which lead to a final product pour in active substances (vitamins, amino acids, etc). The basic target of biomaterials drying is to remove water to a final concentration, which assures microbial spoilage of the product and minimizes chemical and physical changes of the food during storage.

Although a large number of experimental and theoretical studies are about drying process, few papers have studies on energy and exergy analyses of drying systems [1, 5–13].

Syahrul et al. [1] studied the exergy analysis of fluidized bed drying of moist particles for optimizing the operating conditions and the quality of the products. Dincer and Sahin [5] carried out a new model for thermodynamic analysis, in terms of exergy, of a drying process. Exergy efficiencies are derived as functions of heat and mass transfer parameters. As a result, this work is intended not only to demonstrate the usefulness of exergy analysis in thermodynamic assessments of drying processes, but also to provide insights into their performances and efficiencies. The energy and exergy analyses of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer, were made by Celma and Cuadros [6]. Using the first law of thermodynamics, energy analysis was carried out to estimate the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Midilli and Kucuk [7] analysed the energy and exergy parameters of the drying process of shelled and unshelled pistachios using a solar drying cabinet. Using the first law of thermodynamics, energy analysis was carried to estimate the amounts of energy gained from solar air collectors and the ratios of energy utilization. Liu et al. [8] studied the exergy analysis for a freeze-drying process. They have used a mathematical model for exergy loss analysis of a freeze-drying process to evaluate the exergy losses in the individual operations and the distribution of exergy losses in a freeze-dryer. Zvolinschi et al. [9] studied about the second-law optimal operation of a paper drying machine. Colak and Hepbasli [10] investigated the performance evaluation of a single layer drying process of green olives in a tray dryer using exergy analysis method. Aghbashlo et al. [11] presented the energy and exergy analyses of drying process in a semi-industrial continuous band dryer. Experiments were performed on thin layer drying of carrot slices. Liapis and Bruttini [12] realized the exergy analysis of freeze drying of pharmaceuticals in vials on trays. Karamarkovic and Karamarkovic [13] assessed the energy and exergy analysis of biomass gasification at different temperatures. The study is focused on air gasification of biomass with different moisture at different gasification temperatures.

In this study, a malt drying process is investigated with a perspective of energy and exergy analysis. The energy and exergy analyses of malt drying process are investigated by using the thermodynamic data based on the experiments made into the previous work [14] which consist in establishing the advantageous dynamic conditions for

* *email: monalina.mares@gmail; Phone: +40 021 402 3969*

drying process and drying kinetics and all phenomena associated within. The energy and exergy analyses made in this study are related to heat and mass transfer parameter of malt drying in different contacting techniques (fixed, fluidized and modified fluidized bed with inert add).

Experimental part

Materials

Malt is a product made from grains (mostly barley) sprouted, dried and ground, used to make beer and spirits or roasted, for the preparation of a coffee substitute.

The purpose of malt drying is to ensure long time preservation, in normal storage conditions, through water removal. Function of the malt type (obtain by processing - white or brown), the drying process has as purpose: - the reducing to the minimum of the enzymatic processes (biochemical); - some chemical changes which, together with the biochemical processes give a particular color and flavor to the final product; - the removing of the fresh malt flavor and of the rootlets, whose presence intensify the water adsorption in the dried malt stored in improper conditions. The drying of the grains in fixed bed present some disadvantages such as: - the moisture removal take place in long time (hours) with low percents (3-5%); - need supplementary devices such as vibratory sieve, rotating perforated platforms, with purpose to disperse the layers with high moisture and agglomerating tendency [15].

Fluidization is often used in granular grain drying as intensification technique. The developments of the regime of fluidization and subsequent design modifications have made fluidization a desirable drying technique among others. To improve fluidization regime, one method is to change bed structure by adding another material with different shape/size (called inert), fact evidenced in an early ours work [16]. In our study, this material was chosen considering the chemical and physical nature: sand (an inorganic material, mineral nature, with low hydroscopic tendency); smashed malt (organic material, easy moisturizing, useful because require any separation process after drying), as presented in table 1.

The presence of the inert material determines the support for the malt particle fluidization improvement and the moisture distribution in the bed. Thus, it is transformed a convective drying process, in convective one with contact surface, which increases the heat and mass transfer.

Description of experimental plant

A schematic of fluidized bed dryer system used to obtain the experimental data of drying is shown in figure 1.

The experimental installation consists of a fluidized bed column (7), an electric heater (4) and a blower (1). The cylinder column is made of borosilicate glass with an internal diameter of 60 mm with overall length of 400 mm. Air is supplied by blower and it is passed through a silica gel column (5) and a heater. Also the experimental

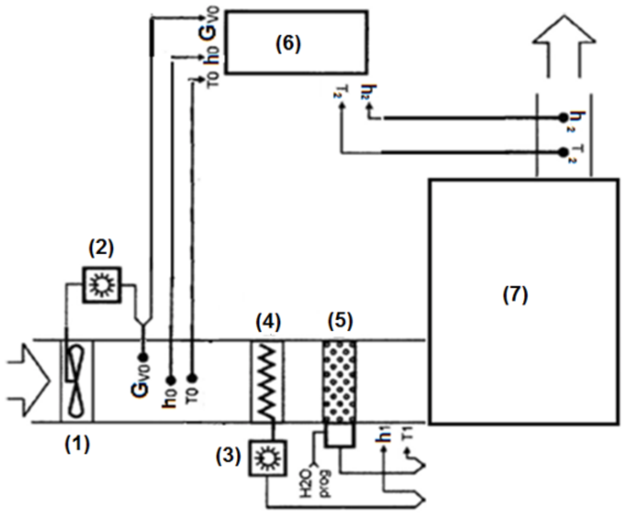

Fig. 1. Scheme of experimental plant

installation is provided with measurement devices (2, 3, 6):-temperature (Temperature Measuring RTD Thermometer TESTO); - flow rate (glass tube rotameter); - pressure drop in the bed (is measured with a Dwyer transducer connected to a computer controlled by data acquisition system). Pressure readings have an estimated error of ±1%. For the modified fluidization, it was used a basket to sustain the malt particles in the fluidized environment of inert particles.

Mathematical assumptions

The general assumptions for energetically analysis of the drying process:

- the capillary porous material is rigid and no chemical reactions occur in the sample;
- local thermodynamics equilibrium is reached among each phase and the gas phase is ideal in the thermodynamics sense;
- the process can be modeled as steady-flow;
- in a macroscopic sense, the bed is assumed to be homogeneous and isotropic, and liquid water is not bound to the solid matrix;
- a dry layer (evaporation front) is formed immediately after water saturation approaches the irreducible value and the distributions of water saturation in the bed differ greatly depending on his structure (geometrical and dynamical) even if the total volume of water that exists among the voids in the beds is identical;

The need to understand the linkages between exergy and energy, and environmental impact has become increasingly significant. Lower exergy efficiency leads to higher environmental impact. Considering the importance of the cost of energy, the availability of fuel and their consequences on the environment, the exergy efficiency model in the drying process becomes a very useful tool of analysis [17, 18].

Table 1
PHYSICAL PROPERTIES OF THE MATERIALS USED

Material	Specific surface diameter	Density	Shape factor	Initial moisture
	d_p $[10^{-3}]m$	ρ_p $[kg/m^3]$	Ψ	u_0 $[kg_w/kg_{db}]$
Malt - grain (M)	3	1146	0.70	0.08
Inert – dried sand (S)	0.150	2400	0.70	0.00
Inert – dried smashed malt (SM)	0.375	900	0.84	0.08

Energy analysis

The traditional methods of thermal system analysis are based on the first law of thermodynamics. These methods use an energy balance on the control volume to determine heat transfer between the system and its environment. The first law of thermodynamics introduces the concept of energy conservation, which states that energy entering a thermal system with fuel, electricity, flowing streams of matter, and so on is conserved and cannot be destroyed. In general, energy balances provide no information on the quality or grades of energy crossing the thermal system boundary and no information about internal losses.

The drying process includes the process of heating, cooling through humidification of the drying agent (air). The process can be modeled as steady-flow processes by applying the steady-flow conservation of mass (for both dry air and moisture) and conservation of energy principles, General equation of mass conservation of drying air, in the rate form, as:

$$\sum \dot{m}_{air,1} = \sum \dot{m}_{air,2} \tag{1}$$

where *m* was the mass flow rate.

General equation of mass conservation of moisture:

$$\sum(\dot{m}_1 \cdot y_1 + \dot{m}_p \cdot u_1) = \sum(\dot{m}_2 \cdot y_2 + \dot{m}_p \cdot u_2) \tag{2}$$

General equation of energy conservation:

$$\dot{Q} - \dot{E} = \sum \dot{m}_2 \cdot \left(h_2 + \frac{w_2^2}{2}\right) - \sum \dot{m}_1 \cdot \left(h_1 + \frac{w_1^2}{2}\right) \tag{3}$$

It was taken into consideration the kinetic energy of the fan, while the potential and kinetic energy in other parts of the process were neglected.

During the energy and exergy analyses of drying process, the following equations were used to compute the enthalpy of drying air:

$$h = c_{p,da} \cdot T + y \cdot h_{sat@T} \tag{4}$$

The enthalpy equation of the fan outlet is given by the Bejan equation [19]:

$$h_{fan,2} = h_{fan,1} + \left(\dot{E}_{fan} - \frac{w_{fan,2}^2}{2 \cdot 1000}\right) \cdot \frac{1}{\dot{m}_{da}} \tag{5}$$

The specific and relative humidity of drying air at the outlet of the fan were determined according to Akpinar [20, 21], considering the values of *dry bulb* temperature and enthalpy from eq. (5). The inlet conditions of the heater were assumed to be equal to the outlet conditions of the fan. The useful energy gained from the heater which enters in the drying chamber as the convection heat source, was defined as:

$$\dot{Q}_u = \dot{m}_{da} \cdot c_{p,da} \cdot \left(T_{h,2} - T_{h,1}\right) \tag{6}$$

The inlet conditions of the dryer were determined depending on the inlet temperatures and specific humidity of drying air. It was considered that the mass flow rate of dried air which passed throughout the dryer was constant. The specific moisture of the solid particles at the outlet of the dryer can be defined as:

$$u_2 = u_1 - \frac{\dot{m}_w}{\dot{m}_{da}} \tag{7}$$

The heat utilized during the humidification process at the chamber, can be estimated by

$$\dot{Q}_p = \dot{m}_{da} \cdot (h_1 - h_2) \tag{8}$$

The enthalpy of air humidity at outlet of dryer can be defined as

$$h_2 = h_1 - \frac{\dot{m}_w}{\dot{m}_{da}} \cdot h_{sat@T} \tag{9}$$

The energy utilization ratio (EUR) is obtain considering the theories of Akpinar [21]

$$EUR = \dot{E}_u = \frac{\dot{m}_{da} \cdot (h_1 - h_2)}{\dot{m}_{da} \cdot c_{p,da} \cdot (T_{m,2} - T_{m,1})} \tag{10}$$

The thermal efficiency of the drying process can be defined as [22]:

$$\eta_e = \frac{\text{Energy transmited to solid}}{\text{Energy incorporated in dring air}} \tag{11}$$

The thermal efficiency can be expressed in terms of energy efficiency using the energy rate balance equation, as:

$$\eta_e = \frac{\dot{m}_p \cdot [r \cdot (u_{p,1} - u_{p,2}) + c_{p,p} \cdot (T_{m,2} - T_{m,1})]}{\dot{m}_{da} \cdot (h_1 - h_2)} \tag{12}$$

The specific heat of malt were calculated considering the experimental results of Jirickova [23]

$$c_{p,p} = 866.4 \cdot u_p^3 - 2524 \cdot u_p^2 + 3486 \cdot u_p + 509{,}6 \tag{13}$$

All physical properties of the mixtures were calculated as weighted average of the parameters function of water content and mass fraction.

Exergy analysis

Any discussion of the basic principles of convective heat transfer must include the second law of thermodynamics [19, 24].

The second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal systems. As known, exergy analysis evaluates the available energy at different points in a system. Exergy is a measurement of the quality or grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering in a thermal system with fuel, electricity, flowing streams of matter, or other sources is destroyed within the system due to irreversibility.

The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems. In the scope of the second law analysis of thermodynamics, total exergy of inflow, outflow and losses of the dryer are estimated.

The basic procedure for exergy analysis of the dryer is determined by the exergy values at steady-state points and the reason of exergy variation for the process. The exergy values are calculated by using the characteristics of the working medium from a first law energy balance. For this purpose, the mathematical formulations used to carry out the exergy balance are as show below according with Ahern [25]:

$$\begin{aligned} Ex = {} & (U - U_\infty) - T_\infty \cdot (S - S_\infty) + \frac{p_\infty}{J}\left(V_0 - V_{0,\infty}\right) + \\ & + \frac{w^2}{2 \cdot g \cdot J} + \frac{g}{g_c \cdot J} \cdot (z - z_\infty) + \\ & + \sum_k (\mu_k - \mu_\infty) \cdot N_k + E_i \cdot A_i \cdot F_i \cdot \\ & .(3 \cdot T^4 - T_\infty^4 - 4 \cdot T_\infty \cdot T^3) + \cdots \end{aligned} \tag{14}$$

In the exergy analyses of many systems, only some of the terms shown in eq. (14) are used but not all. Since exergy is energy available from any source, it can be developed using electrical current flow, magnetic fields, and diffusion flow of materials. One common simplification is to substitute enthalpy for the internal energy and *PV* terms that are applicable for steady-flow systems. eq. (14) is often used under conditions where the gravitational and momentum terms are neglected. In addition to these, the pressure changes in the system are also neglected because of $V_0 \cong V_\infty$, hence eq. (14) is reduced to:

$$Ex = \overline{c}_p \cdot \left[(T - T_\infty) - T_\infty \cdot ln \frac{T}{T_\infty} \right] \quad (15)$$

The inflow and outflow of exergy can be found using the above expression depending on the inlet and outlet temperatures of the drying column. Hence, the exergy loss is determined as:

Exergy loss = Exergy inflow - Exergy outflow

$$\sum Ex_L = \sum Ex_1 - \sum Ex_2 \quad (16)$$

The exergy inflow for the dryer is stated as below:

$$Ex_1 = Ex_{p,1} = \overline{c}_{p,da} \cdot \left[\left(T_{m,1} - T_\infty\right) - T_\infty \cdot ln \frac{T_{m,1}}{T_\infty} \right] \quad (17)$$

The exergy outflow for the drying chamber is:

$$Ex_2 = Ex_{p,2} = \overline{c}_{p,da} \cdot \left[\left(T_{m,2} - T_\infty\right) - T_\infty \cdot ln \frac{T_{m,2}}{T_\infty} \right] \quad (18)$$

The exergetic efficiency can be defined as the ratio of the product exergy to exergy inflow for the dryer, as outlined below:

$$Exergy\ \ efficiency = \frac{Exergy\ \ inflow\ \ - Exergy\ \ loss}{Exergy\ \ inflow} \quad (19)$$

The exergy efficiency provides a true measure of the performance of the drying system from the thermodynamic viewpoint. In defining the exergy efficiency it is necessary to identify both the product and the fuel. The exergy efficiency of the dryer is the ratio between product and fuel. Where the product is only the rate of exergy evaporation process and the fuel is the rate of exergy drying air enters the dryer column, the exergy efficiency on the basis of the exergy rate balance is given as Topic [26]:

$$\eta_{ex} = \frac{\dot{E}_{evap}}{\dot{E}_{da,1}} = \frac{\dot{m}_w \cdot (y_1 - y_2) \cdot r}{\dot{m}_{da} \cdot h_1 \cdot \left(1 - \frac{T_\infty}{T_m}\right)} \quad (20)$$

where $\dot{E}_{evap}$ is the rate of exergy evaporation (kJ/s); $\dot{E}_{d,i}$- rate of exergy drying air entering the drying column (kJ/s).

Results and discussions

Thermodynamic conditions of the experiments used in this study were achieved in our previous studies [14, 16, 27]. The dynamic parameters of granular fluidized bed were established to be suitable for the bed structure. Drying kinetics was performed in the most suitable dynamic conditions chosen and the temperature values (35, 45 and 60° C) were established by degradation studies.

In table 2 are presented the main parameters used to do the energetic analysis.

Fixed bed

The results of the energetically analysis for malt grains in fixed bed are presented in following figures. It was represented the variation of energy utilization and energy utilization ratio (EUR), versus drying time for malt and mixture of malt with sand, in the experimental conditions presented in table 2.

The amount of energy needs of the malt drying in fixed bed varies between 16.45 -9.5 kJ/s, while EUR varies in 33-56 [%] domain, as input values.

The exergetic analysis represents the variation of exergy loss and exergetic efficiency versus drying time. Those parameters show that the values of the exergy inflow and outflow vary between 1.14-6.75 kJ/s and 0.4-5.4 kJ/s respectively.

Because as it can be seen, the amount of energy is very high, the experiments of drying were performed in the presence of an inert material, such as sand. The energy efficiency is better for drying in fixed bed of the mixture malt – sand (fig. 3), which evidences the distribution of the moisture in the bed. Because the sand is a pour hygroscopic material, the moisture which this material take, is only surface moisture, which determine an easy water removing.

The values for the energy utilization, as input values, are lower, ranging between 6.47 – 13,53 kJ/s, with a EUR of 29-52%. Also the exergy inflow and outflow decreases,

Table 2
THE WORKING PARAMETERS OF THE EXPERIMENTAL SERIES

Material	Solid fraction weight [grams]	Bed structure	Index of fluidization ratio, $Z = \frac{W}{W_{mf}}$
Malt (M)	10	Fixed bed	0.275
			0.5
			0.9
Mixture malt – sand (MS)	10 150	Mix-fixed bed	0.275
			0.5
			0.9
Mixture malt – sand (MS)	10 150	Flotation fluidized bed	1
			1.1
			1.2
Mixture malt – smashed malt (MSM)	35 25	Flotation fluidized bed	1
			1.1
			1.2

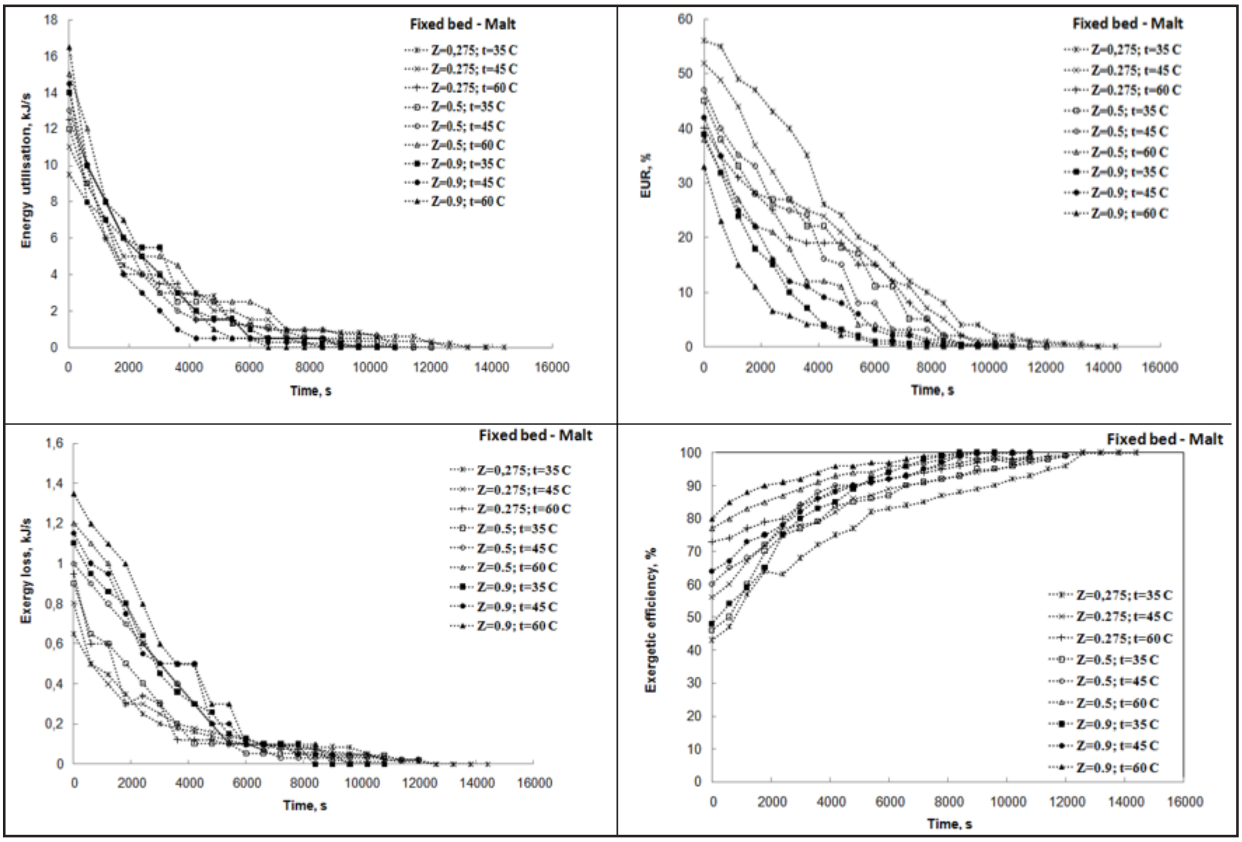

Fig. 2. Energetic analysis of fixed bed malt drying.

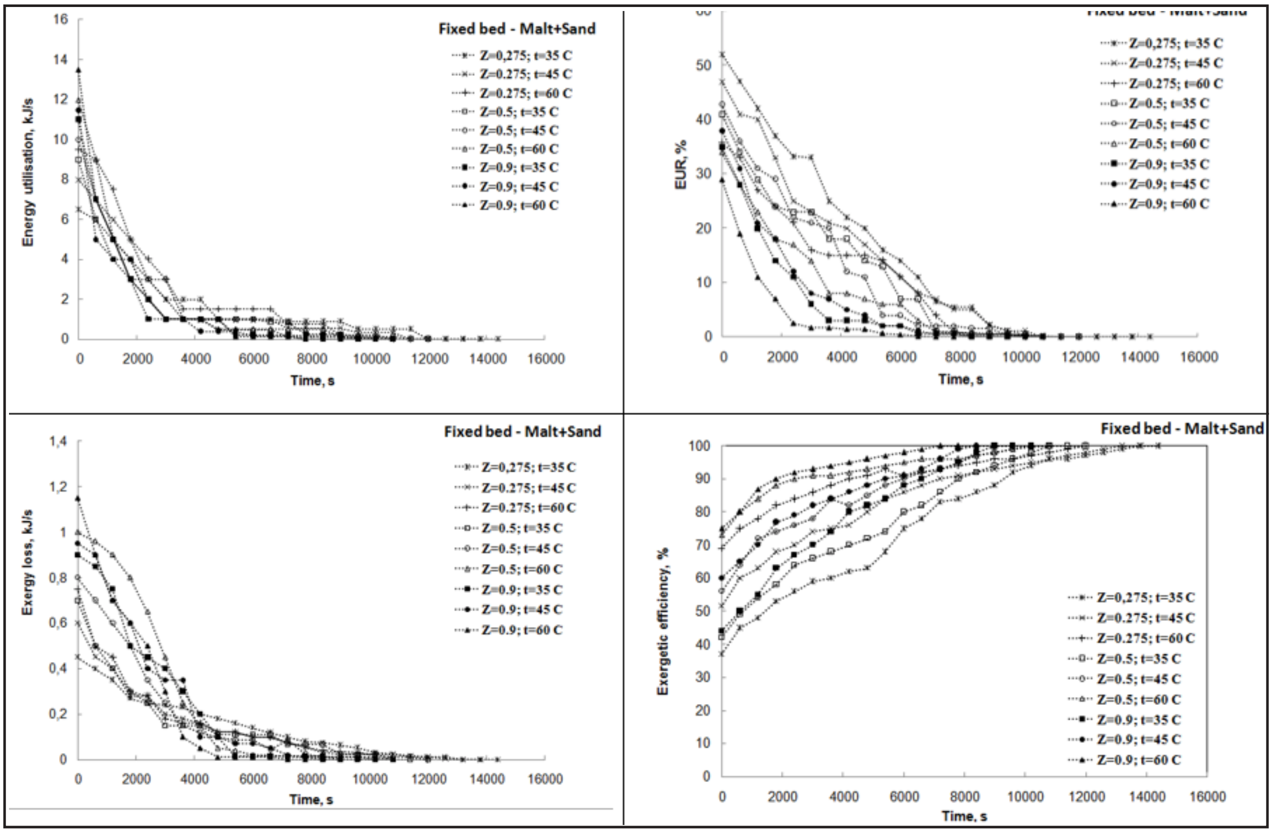

Fig.3. Energetic analysis of fixed bed of mixture malt-sand drying

such as: 0.71-4.6 kJ/s for inflow exergy and 0.26-3.45 kJ/s for outflow exergy.

Fluidised bed

The fluidized bed drying was operated at different fluidization degrees for the mixture malt –sand (fig. 4), which appears to be most efficient, from the previous studies, and malt-smashed malt (fig. 5), introduced in order to avoid the need of materials separation, but to obtain appropriate energetic values.

In fluidized bed drying of mixture malt-sand (fig. 4), the values of the energy utilization and EUR decreases comparatively with others studied drying techniques (2.5-9.4 kJ/s and 24-47% respectively). Same, the values for the exergy inflow and outflow decreases, with the remark that

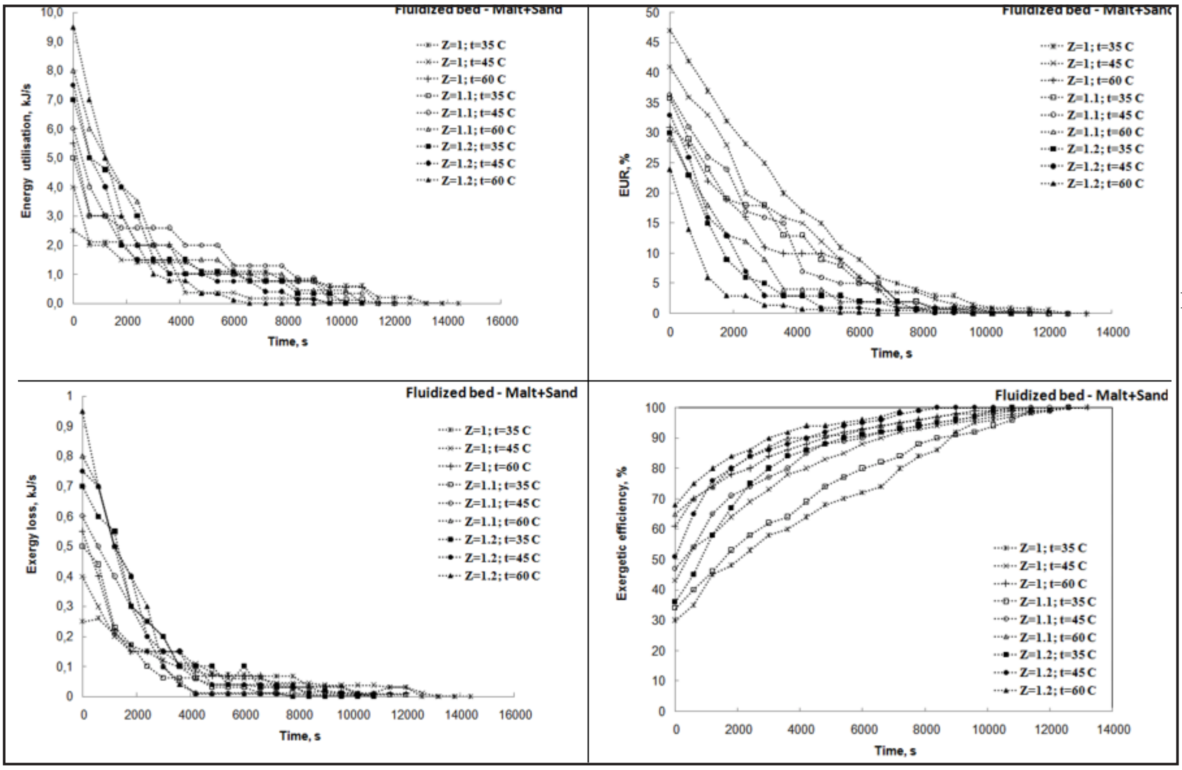

Fig.4. Energetic analysis of fluized bed of mixture matl-sand drying

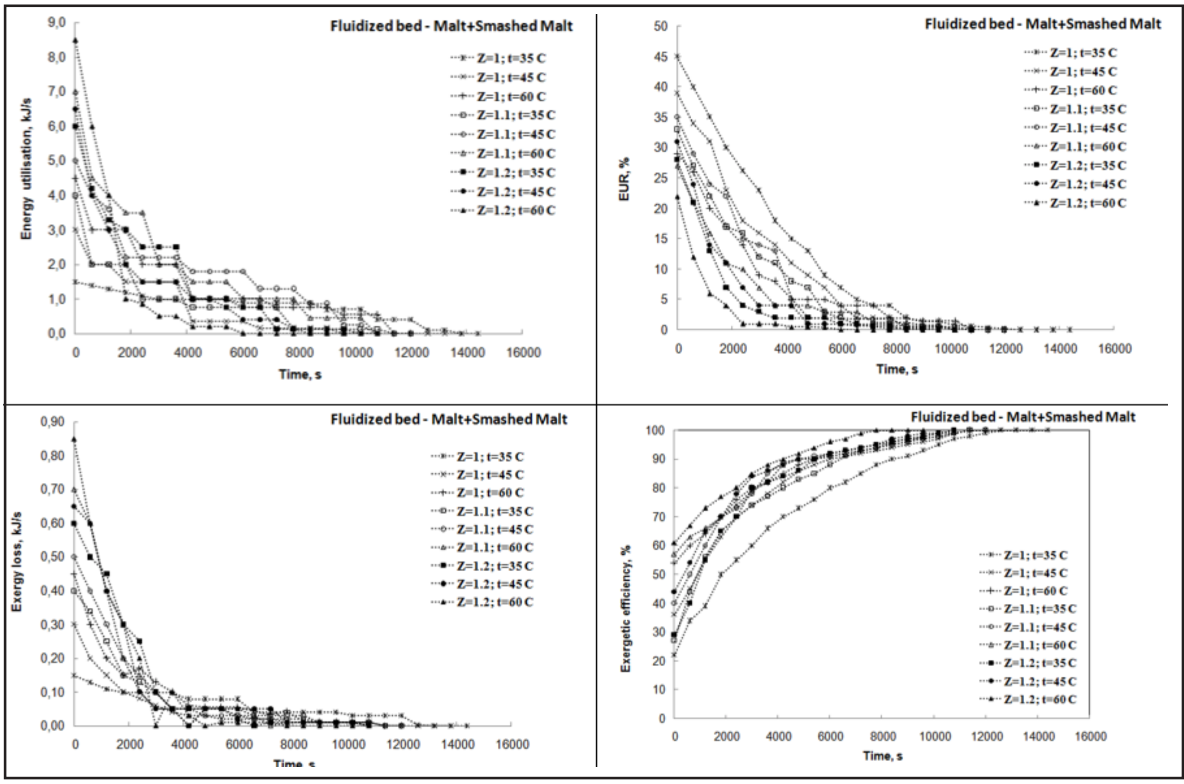

Fig.5. Energetic analysis of fluized bed of mixture malt-smashed malt drying

the variation interval was shrink (0.36-2.97 kJ/s for inflow and 0.11-2.02 kJ/s for outflow).

When the inert is smashed malt, the hygroscopic character of this material is increased by smashing. In the mixture malt – smashed malt, the moisture of both materials (inert and malt particles) is distributed in the bed and became internal. In these conditions, the energetically efficiency is higher than in conditions of the single malt drying, if we try to remove a large amount of moisture, also, it is maintain at low values: energy utilization of 1.5-8.5 kJ/s and EUR of 22 - 44.6 %.

The exergy of the process indicate a better utilization of the air thermal energy with water evaporation from the malt particle only. The inflow exergy varies between 0.19-2.18 kJ/s and outflow 0.04 - 1.32 kJ/s.

Conclusions

The energetic analysis follow the determination of a better contacting method between the particulate grains and drying agent in purpose to obtain a final product with standards qualities required of the storage and minimum energy consuming. It was evidenced the advantages of the modified fluidized bed with inert add, used like support for malt particle fluidization. It is important to choose the optimal inert material, considering:- the dynamic point of view; -structure of inert material;- fouling degree for the main material submitted to drying.

For all drying techniques analyzed, the study evidenced that energy utilization increases with drying agent velocity and temperature (45-60% for fixed bed and 20-30% for fluidized bed), and decreases with drying time (tending to zero at the end of drying), meanwhile the EUR decreases (around 50-60%) with all this parameters. On the other hand, exergy loss and exergy efficiency increases with air velocity and drying temperature (exergy loss in range 40-45% for fixed bed and 19-25% for fluidized bed; exergy efficiency in range 40-60% for fixed bed and 40-45% for fluidized bed), but they have an antagonist behavior regarding with drying time: exergy loss decreasing in time, meanwhile the exergetic efficiency increases in time.

In these conditions, it would be advantageous to use an air velocity higher than the minimum fluidization velocity at the first draying stage (up to 1.1 fluidization index) and to reduced it later, to the lowest value (corresponding to minimum fluidization for dried particles) to increase the system performance.

Nomenclature

c_p - specific heat, kJ(kg K)$^{-1}$
E – energy, kJ s^{-1}
EUR - energy utilization ratio, %
g - gravitational acceleration, m s^{-1}
g_c - constant in Newton's law
h - specific enthalpy, kJ kg^{-1}
J - Joule constant
m – mass, kg
$\dot{m}$ - mass flow rate, kg s^{-1}
N - number of species
P – pressure, kPa
Q- net heat, kJ/s
r - latent heat of vaporization, kJ kg^{-1}
S – entropy, kJ kg^{-1} K^{-1}
T – temperature, K
u – moisture, $kg_{water}/kg_{dry\ base}$
V_0 - specific volume, m^3 s^{-1}
w - fictive velocity, ms^{-1}
y - molar fraction, $kg_{water}/kg_{dry\ air}$
z - spatial coordination, m

Greek letters

η - efficiency, %
μ - chemical potential, kJ kg^{-1}
τ - time, s

Subscripts

a - air
d - dry
d.b - dry base
e - energy
eq - equilibrium
ex - exergy
f - fixed bed
h - heat
m - medium
mf - minimum fluidized bed
p - particle
sat - saturated
u - utile
w - wet/water
1 - input
2. - output
∞ - ambient

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