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Chemical and Process Engineering 2015, 36 (4), 437–447
DOI: 10.1515/cpe-2015-0031
PAN POLSKA AKADEMIA NAUK

Exergetic analysis for a complete node of fluidised-bed drying of poppy seeds

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The article presents an experimental-theoretical analysis of fluidised-bed drying of poppy seeds directed on minimisation of energy. The analysis was performed for a complete drying node incorporating a heat exchanger and a fan. Two complementary factors were used in the exergetic evaluation: exergy efficiency and unit consumption of exergy. An analysis of drying in stationary bed was carried out for comparison purposes. Results of the exergetic analysis can become a basis for innovative works focused on decreasing energy consumption of a technological node being analysed, e.g. by the use of recirculation of fluidising-drying medium.

Keywords: fluidised drying, efficiency, exergy, poppy seeds

1. INTRODUCTION

Drying commonly used to remove moisture is classified as the most energy-consuming operation of process engineering. It is estimated that energy consumption in the drying process is about 10 to 12% of total energy consumption in the industry (Strumiłło, 2006). Much of the drying energy consumption is due to the low thermal efficiency of industrial dryers currently operating, averages of which oscillate around 40–60% (Witrowa-Rajchert, 2012). Improving these devices may be the key to solving the problem of reconciling the increasing demand for energy with the need to reduce its consumption.

Modern trends in the intensification of the drying process of wet materials in many cases make use of the fluidisation technique. Fluidised bed granulation is a widely used method for drying particulate materials, as well as slurries, pastes, suspensions, which may be fluidised in beds with the inert carrier. This method is characterised by favorable technical and economic indicators (Strumiłło, 2006). The main advantages of the fluidised-bed drying arise from good mixing of solid particles and high heat and mass transfer coefficients (Nazghelichi et al., 2010). The competitiveness of this method compared to the traditional ones is associated mainly with low investment and operational costs.

Exergetic analysis can be used as a tool to improve the efficiency of the drying process. Exergy is defined as the maximum work that thermodynamically open system can perform in a given system by going to a state of equilibrium with the environment (Szargut and Petela, 1965). This definition, based on the first and second law of thermodynamics, by linking energy and entropy balances shows the exergy losses due to irreversibility of real processes, allows identification of stages where the energy is degraded during the process (Szargut and Petela, 1965). The main component of the operational costs is the energy used for drying (moisture removal). Information obtained on the basis of the exergetic analysis makes it possible to increase the efficiency of the process, and thus reduce process costs.

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In recent years, more and more attention has been paid to the exergetic analysis of drying processes and systems (Aghbashlo et al., 2013). The interest in this area of research is mainly motivated by rising energy prices, environmental issues, diminishing resources of fossil fuels and the demand for high quality dry products. Exergetic analysis is a tool to better illustrate the energy losses to the environment and internal irreversibility occurring in the drying process.

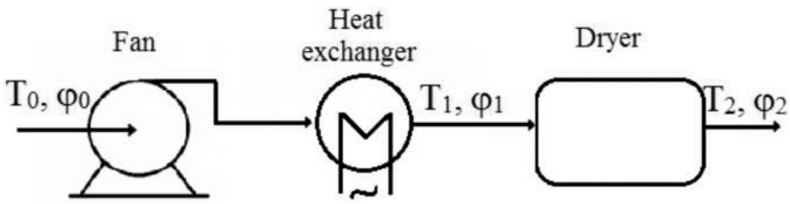

Fig. 1. Scheme of drying node

An analysis of the literature on the discussed issue shows that the authors focus on investigating the effects of selected operational parameters on the exergy efficiency of the process (Aghbashlo et al., 2013). In most publications exergetic analysis is limited to a drying column (Coskun et al., 2009; Erbay and Icier, 2009; Syahrul et al., 2002). For a better illustration of the drying process, not only the dryer, but the complete drying node (Fig. 1) should be balanced. A typical drying node, except the drying chamber, consists of a heat exchanger in which air is heated, and a fan which forces air into the system.

The work presents exergy assessment of the fluidised bed drying for a selected biomaterial (poppy seed). The analysis was made for the complete drying node. The effect of fluidisation number on drying exergy efficiency was investigated, and for evaluation two factors were used: exergy efficiency and unit consumption of exergy. Usability of the outlet air for potential recirculation was determined.

1.1. Exergetic analysis

Exergetic analysis was performed for the drying node, including the fan and heater. The general form of the exergy balance equation is as follows:

$$\dot{E}x_{a0} + \dot{E}x_{m1} + \dot{E}x_{ven} + \dot{E}x_{heat} = \dot{E}x_{a2} + \dot{E}x_{m2} + \dot{E}x_{vap} + \dot{E}x_{los} + \dot{E}x_{deg} \tag{1}$$

Based on the exergy balance it is possible to calculate the efficiency of the process considered, called exergy efficiency (Akpinar and Dincer, 2005; Colak et al., 2013; Ranjbaran and Zare, 2013). A useful result of the drying process is the evaporation exergy, while the input is the exergy supplied to the fan and heater. Thus, Equation (2):

$$\eta = \frac{\dot{E}x_{vap}}{\dot{E}x_{ven} + \dot{E}x_{heat}} \tag{2}$$

Heat of evaporation of water is supplied from air. Hence exergy of evaporation can be calculated using Eq. (3) (Fortes, 2004; Fortes and Ferreira, 2004).

$$\dot{E}x_{vap} = \left(1 - \frac{T_0}{T_a}\right)\dot{m}_w\, r \tag{3}$$

According to the proposal of Szargut (Szargut and Petela, 1965) exergy efficiency can be evaluated by use of unit exergy consumption coefficient, defined as the amount of exergy required to remove 1 kg of water, Eq. (4):

$$\mu = \frac{\dot{E}x_{ven} + \dot{E}x_{heat}}{\dot{m}_w} \tag{4}$$

1.2. Air recirculation

One possibility to increase the efficiency of drying is air recirculation (Strumiłło, 1983). Exergy of humid air is a function of six independent variables (Bes, 1962): temperature, humidity, and pressure of air under consideration and temperature, humidity and pressure of air in the environment.

For better evaluation of the suitability of air to be re-used, exergy of air (5) should be separated into the thermal, mechanical and chemical component, respectively. These components can be calculated from Eqs. (6–8) (Ren et al., 2011):

$$ex_a = ex_{th} + ex_{me} + ex_{ch} \tag{5}$$

$$ex_{th} = \left(c_a + Yc_v\right)\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) \tag{6}$$

$$ex_{me} = \left(1 + 1.6078\,Y\right) R_a T_0 \ln\frac{P}{P_0} \tag{7}$$

$$ex_{ch} = R_a T_0 \left[\left(1 + 1.6078\,Y\right)\ln\frac{1 + 1.6078\,Y_0}{1 + 1.6078\,Y} + 1.6078 Y \ln\frac{Y}{Y_0}\right] \tag{8}$$

2. EXPERIMENTAL

2.1. Test stand

Experiments were carried out at the Department of Chemical and Process Engineering, Cracow University of Technology using a test stand (Fig. 2). Air is forced by the fan (4) through the flowmeter (3) to the electric heater (2), and next to the fluidised bed column (1). The internal diameter of the column is 74 mm. Proper measurement and control equipment enable to acquire data for plotting the process characteristics and carrying out the exergy balance.

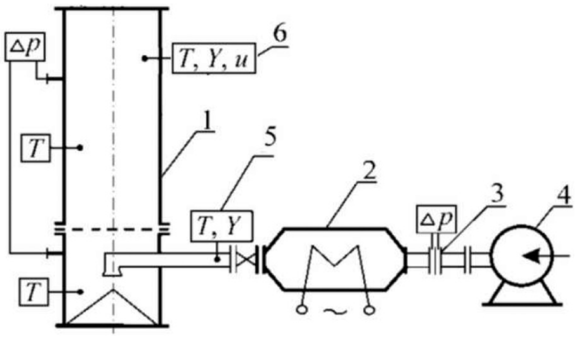

Fig. 2. Scheme of the test stand: 1 – fluidised bed dryer, 2 – heater, 3 – flowmeter (device TESTO 452 with suitable attachment), 4 – fan, 5, 6 – devices: TESTO 452 and TESTO 112

It should be emphasised that the test stand was equipped with a high quality measuring and control system. The majority of measuring devices were TESTO GmbH&Co products which ensured high accuracy of measurements of the process quantities. Device Testo 452 enables simultaneous (in place of installing) measurement of temperature, velocity and relative humidity.

Measuring accuracy was as follows:

- temperature +/– 0.1 °C,
- velocity +/–0.05 m/s,
- relative humidity +/– 2%

An additional probe enabled a measurement of pressure drop with accuracy ± 0.1 hPa. The device is equipped with a thermal printer which facilitates acquiring and archiving the measurement data. Following devices were also used in the study:

- Device TESTO 112 with an adequate probe for temperature measurement with accuracy ± 0.2 °C.
- Device Testo 416 (a compact vane anemometer with integrated flow probe) characterized by accuracy of ± 0.2 m/s.
- Thermobalance Radwag WPS 30S with accuracy of 0.01%.
- Measuring device of electric energy Pafal type A52 with accuracy of 0.01 kWh.

2.2. Experimental methods

For test runs poppy was used – a particulate material of natural origin belonging to Group B of Geldart classification (Geldart, 1973). The studied material was characterised by the following parameters:

- average diameter of grains $d_m = 0.7\times10^{-3}$ m,
- density of the material ρ_m = 1060 kg/m^3,
- bed porosity $\varepsilon_0 = 0.43$,
- critical moisture content X_{kr} = 0.15 kg/kg,
- equilibrium moisture content X_{eq} = 0.04 kg/kg,
- minimum fluidisation velocity u_{mf}=0.9 m/s.

Prior to the examinations the material was wetted to an initial moisture content of approximately 33%. The degree of wetting and the moisture content of the samples collected for determining the drying curve were evaluated with a thermobalance (Radwag WPS 30S, Poland). The results were verified in a classical chamber dryer by drying samples to a constant weight. Minimum fluidisation velocity (critical) was determined from fluidisation curves (Ciesielczyk, 2009).

During the tests at constant inlet air temperature the velocity of the flowing fluidising – drying medium was altered. This velocity referred to the critical fluidisation velocity gives the number of fluidisation *N*. The critical velocity was determined experimentally by the determination of fluidisation curves. Table 1 presents the basic parameters of the experiment.

Table. 1. Experimental parameters

Parameter	Value
Initial humidity of material dried	X_m = 33%
Mass of wet material	m_m = 0.225 kg
Relative humidity of air of the environment	φ_0 = 0.3–0.4
Temperature of air in the environment	T_0 = 21°C
Temperature of air after the heater	T_1 = 55°C

Table. 2. Fluidisation number *N* in subsequent runs

Run no.	Fluidisation number *N*
1	5
2	3.3
3	1.9
4	1
5	0.5
6	0.3

To compare the results, also tests of convective drying in a stationary bed were performed. Table 2 shows the fluidisation numbers at which the study was conducted. To examine the effect of the fluidisation number on exergetic efficiency of the drying process, two numbers from the range of convective drying (fixed bed) and four numbers from the range of fluidised-bed drying were selected.

3. RESULTS AND DISCUSSION

Based on the results collected during the experiment, exergetic assessment of the drying of poppy seeds was made at different fluidisation numbers: for the fluidised bed $N = 1$–5 and the stationary bed $N = 0.3$–0.5. Fig. 3 presents the drying curves for fluidisation numbers examined.

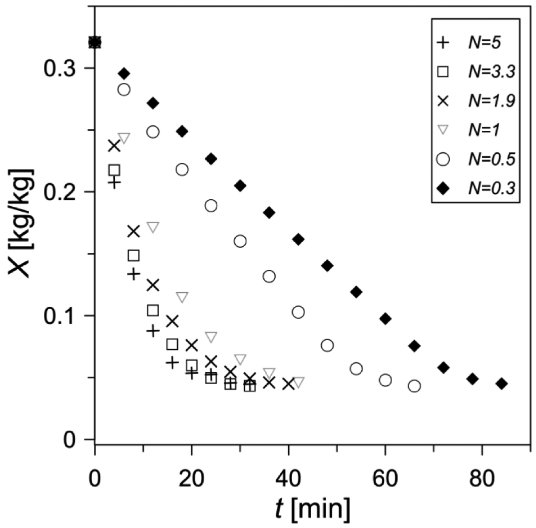

Fig. 3. Drying curve for poppy

An important indicator for the exergetic assessment of the drying process is exergetic efficiency, Eq. (2) and Figs. 4 to 6. Exergetic efficiency determines how far the actual process from the ideal reversible process actually is. An increase in the fluidisation number causes a decrease in the efficiency of the process.

Exergetic efficiency for all fluidisation numbers in the range of fluidised-bed drying significantly decreases with the loss of water in the material, i.e. with the duration of the drying process. Whereas for drying in a stationary bed, nearly constant efficiency values over the whole range of moisture content can be observed.

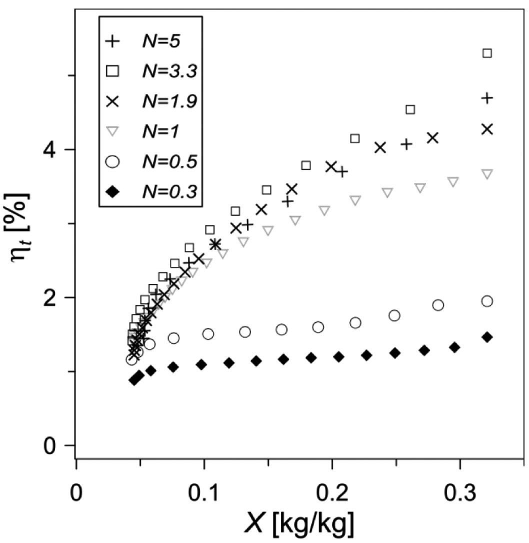

Fig. 4. Exergetic efficiency for different values of inlet air velocity

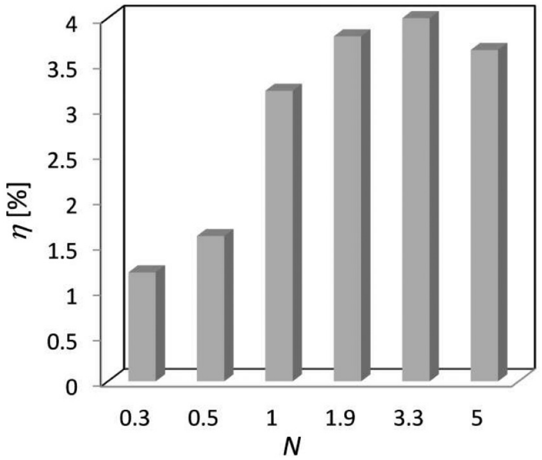

Fig. 5. Average exergetic efficiency for different fluidisation numbers when drying of poppy to moisture content ~ 20%

For better illustration the effect of the fluidisation number on the exergetic efficiency, Fig. 5 was drawn showing the value of exergetic efficiency of drying at a moisture content of 20%. In contrast, Fig. 6 demonstrates the instantaneous values of exergetic efficiency for each of the studied fluidisation numbers. Figs. 4 and 5 indicate that with an increasing fluidisation number from 0.3 to 0.5, the efficiency also slightly increases. Then, after exceeding a critical velocity, that is, when changing from drying in a stationary bed to fluidisation, we observe a significant increase of the exergetic efficiency, up to a maximum value for the fluidisation number of 3.3. Then, for the fluidisation number of 5 we observe a decrease.

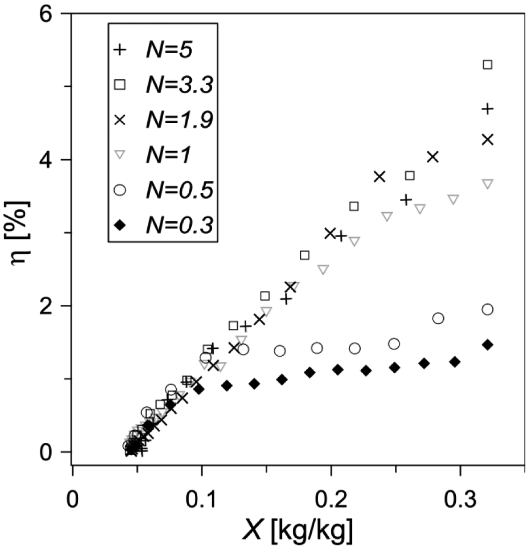

Fig. 6. Instantaneous exergetic efficiency

To illustrate changes in efficiency during the process, Fig. 6 was created showing the instantaneous values of exergetic efficiency. Based on the analysis of Fig. 6 the following observations can be formulated:

- For fluidisation numbers equal 5 and 3.3, an approximately linear decrease in efficiency with the water loss in the sample can be observed.
- For fluidization numbers equal 1.9 and 1, efficiencies in the initial drying period are similar, and then almost a linear decrease can be seen.
- For fluidisation numbers (stationary bed) 0.5 and 0.3, the range of moisture content for which efficiency is maintained at the same level is even higher, i.e. up to the value of approximately 0.1. After exceeding this value the relationship $\eta = f(X)$ linearly decreases. This may be due to changes in ratio of the rate of delivery of moisture to the material surface to the actual rates of the drying capabilities of the system.

In Figure 6 the same relationships for to the first drying period can also be observed as shown in Figs. 4 and 5. The maximum values of exergetic efficiency are achieved for a fluidisation number of 3.3. Similarly, there is significant increase in efficiency beyond the critical velocity of fluidization. In the final drying period, there is no such difference between the fluidised-bed drying and convective one, and even for the fluidisation number of 0.5 the highest efficiencies can be observed. This is due to slow internal transfer of moisture outside of the particles and fairly large, dependent on velocity, losses of exergy of flowing hot air. Therefore, it is necessary to analyze the change in a fluidised bed drying to that in a stationary bed in the case of drying to low moisture contents.

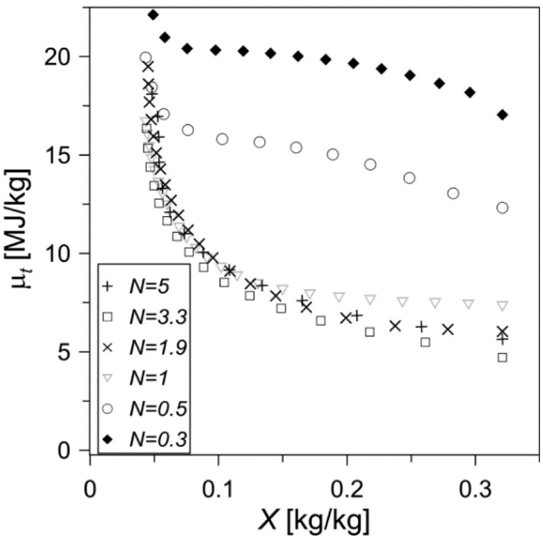

Fig. 7. Unit exergy consumption when drying of poppy versus moisture content

As an indicator for the exergetic assessment the unit exergy consumption coefficient, Eq. (4) can be used. The influence of the material moisture content on this coefficient is shown in Fig. 7. Fig. 8 shows the instantaneous values of unit exergy consumption coefficients for each of the studied fluidization numbers. The lowest exergy consumption per 1 kg of the evaporated water has been reached for fluidisation number of 3.3. As for the exergetic efficiency one can observe a sharp increase in the unit exergy consumption when changing character of the drying from fluidised bed to convective (in the stationary bed). Analysis of the results proves the correctness of proposed dependencies – unit exergy consumption coefficient and exergetic efficiency – and the interchangeability in using those indicators in an assessment of the exergy in the drying process.

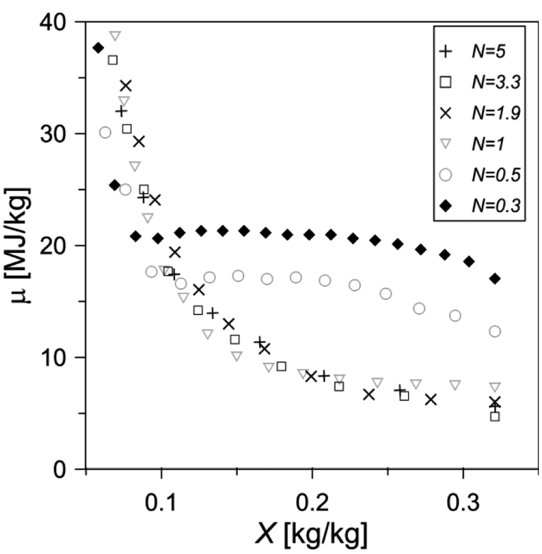

Fig. 8. The instantaneous unit exergy consumption when drying of poppy seed versus moisture content

Moreover, one can observe qualitative and quantitative similarity of the analysed relationships for fluidised-bed drying. Whereas for the stationary bed drying the course of relationships is similar, but significant differences in the unit exergy consumption above the value of approximately 0.1 can be seen.

When limiting the analysis to the drying chamber only, the expenditures in calculating the exergetic efficiency in Eq. (2) reduces to the exergy of drying air (Icier et al., 2010; Inaba et al., 2007; Syahrul et al., 2002). The literature (Assari et al., 2013; Fortes and Ferreira, 2004; Syahrul et al., 2003) and experimental data conducted by the authors (Skoneczna-Łuczków et al., 2013) indicates that during exergetic analysis which takes into account the drying column only, reducing air velocity results in an increase of efficiency. The exergetic analysis of the whole drying node shows the inverse relationships that may be caused by the fact that a decrease in the air flow rate increases drying time. This increases the energy required to power the fan and reduces intensification of the process.

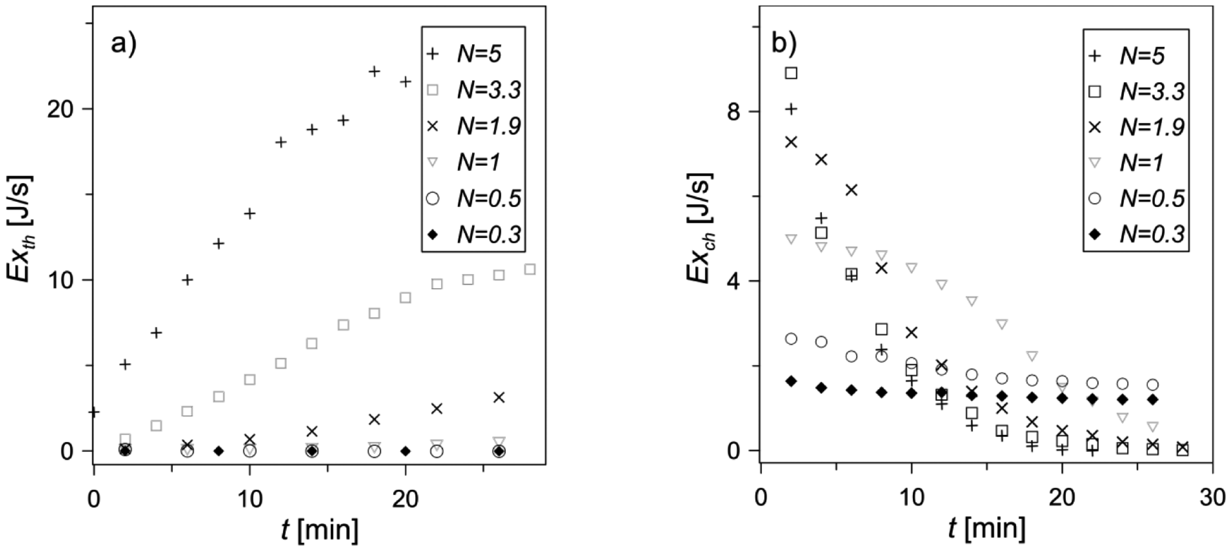

Fig. 9. Stream of: a) thermal exergy, b) chemical exergy of exhaust air versus time

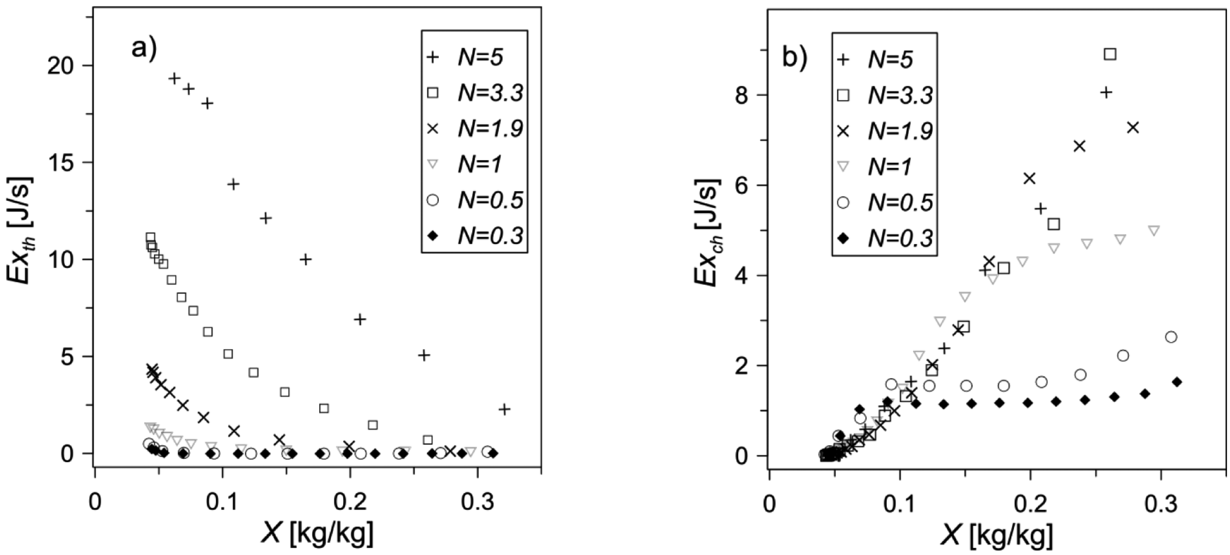

Fig. 10. Stream of: a) thermal exergy, b) chemical exergy of exhaust air versus moisture content

One of the disadvantages of drying is a significant energy loss (exergy) removed with the exhaust air. Exergy of air consists of thermal, mechanical and chemical components. The pressure of the air leaving the drying column is equal to the ambient pressure, therefore, the logarithm of the expression in the Eq. (7) is equal to 1, i.e. the mechanical component of the exergy of air is zero. Streams of thermal and chemical exergy are shown in Fig. 9 versus the duration of the process while in Fig. 10 versus the variation in moisture content of the material being dried. Chemical exergy depends on the amount of water evaporated from the material, hence thermal exergy is a component to be considered as the loss of exergy removed with the exhaust air.

Exergy consumption of the heating medium can be significantly reduced by the use of recirculation which, of course, is associated with lower operating costs. To clarify this issue, based on exergetic analysis it was decided to investigate the behaviour of the exergy flow in the outlet air during the drying process. When analysing the recirculated air it should be noted that in the initial stage of the drying, the exhaust air has low thermal exergy (Figs. 9a and 10a) and high chemical exergy (Figs. 9b and 10b).

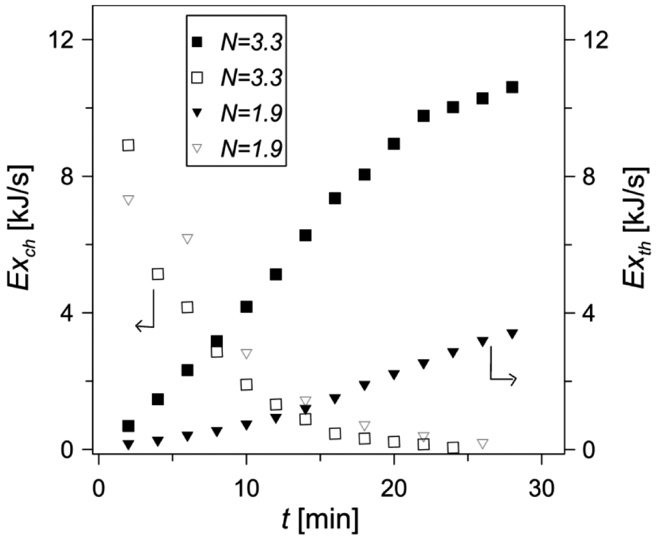

Fig. 11. Stream of thermal and chemical exergy of exhaust air
for fluidization number equal 1.9 and 3.3

The air in which major part of the exergy is the chemical exergy (of high moisture content) should not be recirculated to the process because, despite a considerable total exergy, it does not have sufficient potential for the drying process. After some time the share of thermal exergy exceeds the share of the chemical exergy, which is shown in Fig. 11 for fluidisation numbers analysed. The air whose thermal exergy is much higher than the chemical exergy can be reused for the drying process.

4. CONCULSIONS

The main task of the modern drying facilities is to minimise energy consumption in the removal of moisture to the expected value. Evaluation of the drying process based on the concept of exergy can be an effective tool for illustrating the energy consumption during the practical implementation of the fluidised bed drying. Exergy which is a measure of energy usability effectively allows to specify the source of energy losses and after their elimination to reduce operating costs.

- Two complementary indicators were used for exergetic evaluation, namely exergetic efficiency and coefficient of unit exergy consumption.
- Exergetic efficiency is higher at the beginning of the drying process than at the later stage, which results from the reduction of the rate of removal of moisture with the duration the process.
- The rate of fluidisation affects the exergetic efficiency and unit exergy consumption. This influence is different for fluidised-bed drying than for drying in a stationary bed.
- By using thermal exergy of exhaust air the losses related to unexploited exergy of air supplied to the process were determined.

- The separation of exergy of exhaust air into chemical and thermal exergy can specify the conditions of recirculation.
- The results agreed with expectations and views on the current achievements of the theory and techniques of fluidised bed drying.

SYMBOLS

c	specific heat, kJ/(kg·K)
d	diameter, m
ex	specific exergy, kJ/kg
$\dot{E}x$	stream of exergy, kJ/s
m	mass, kg
$\dot{m}$	mass stream, kg/s
N	fluidisation number, –
P	pressure, Pa
r	heat of vaporisation of water, kJ/kg
R	individual gas constant, kJ/(kg·K)
t	time, min
T	temperature, °C or K
u	superficial velocity, m/s
X	moisture content in a material, kg water/kg dry material
Y	absolute air humidity, kg water/kg dry air

Greek symbols

ε	bed porosity, –
η	efficiency, %
μ	coefficient of unit exergy consumption, kJ/kg water
ρ	density, kg/m^3
φ	relative humidity, %

Subscripts

a	air
ch	chemical
deg	degradation
eq	equilibrium
heat	heater
kr	critical
los	losses to the environment through the enclosure
m	material
me	mechanical
t	total
th	thermal
um	minimum fluidisation
v	vapor
vap	vaporisation
ven	fan
w	moisture
0	reference state (environment state)
1	quantity before chamber
2	quantity after chamber

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Received 06 April 2015
Received in revised form 28 September 2015
Accepted 21 October 2015