TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2011, 11c, 273–282

THE ANALYSIS OF POSSIBILITY OF ENERGY RECOVERY DURING CONVECTIVE DRYING OF PAPRIKA

Stanisław Rudy, Andrzej Krzykowski, Dariusz Dziki, Paweł Kozak, Zbigniew Serwatka

Department of Thermal Technology, University of Life Sciences in Lublin,
Doświadczalna 44, 20-280 Lublin, Poland

Summary. In this paper, the enthalpy and the possible amount of energy recovery during paprika (cv. Kier) convective drying were determined. The drying was made for two velocities of the drying factor (0.3 and 0.5 ms^{-1}) and for four temperature levels (50, 55, 60, and 65ºC). The results showed that for all the independent variables the enthalpy of air leaving the dryer decreased during the drying time. At the respective air flow velocities, the air at the temperature of 65°C had the highest enthalpy and the air at the temperature of 50°C the lowest one. An increase of air flow velocity caused an increase in enthalpy, especially at the beginning of the process. The highest amount of energy (2,1 $kJ \cdot s^{-1}$), can be recovered during the drying of paprika at the temperature of 50°C, and at the air flow velocity of 0.5 $m \cdot s^{-1}$.

Key words: convective drying, heat flux, enthalpy, paprika.

Nomenclature:

φ- relative air humidity,
ρ_{1+x}- air density after leaving the dryer [m^3/kg],
c_{pg}- specific heat of dry air [kJ/(kg·K)],
c_{pw}- specific isobaric heat of water vapour [kJ/(kg·K)],
i_{1+x}- enthalpy of one kilogram of dry air and enclosed steam [kJ/kg],
p_0- ambient pressure [Pa],
p_w'' - saturation pressure of air [Pa],
Q- heat flux [kJ/s],
r_0- heat vaporization of water at the triple point temperature [kJ/kg],
R_w, R_g- individual gas constant of steam and dry air, respectively [J/kgK],
t- temperature [°C],
T- temperature [K],
V- volumetric flow rate of medium [m^3/s],
x- absolute humidity [kg H_2O/kg of dry air].

INTRODUCTION

The highest amount of energy needed for the support of the drying process is consumed for heating of drying air and for water evaporation from material [Mujumdar 2007, Ivanova et al.2001, Benali et al. 2006, Rudy 2009]. At the constant air flow velocity the intensity of water evaporation is the highest at the beginning of the process and decreases with the drying time [Flink 1977, Pabis 2007, Ratti 2001, Koyuncu et al. 2004, 2007].

The energy recovery from hot air during the convective drying can be made in a few ways. The simplest method is the recirculation of part of drying air leaving the drier. This method is used when at the beginning of the process the higher relative humidity of the air is required [Sokhansanj, Wood 1991, Savoie 2006, Didukh, Kirchuk 2007, Jech et al. 2006].

The air removed from the system can be used for pre-heating and preliminary drying the raw material before the process. Another method of heat recovery in the drying industry is the use of different kinds of diaphragm heat exchangers or air-air heat pumps. The process of heat recovery by using heat exchangers is more difficult to realize, however, it makes possible the recovery of low relative air humidity [Prvulovic et al. 2001, Atkins et al. 2010, Budin et al. 1996, Conde 1997, Ho et al. 2001, Tippayawong et al. 2009, Soylemez 2006].

MATERIALS AND METHODS

The aim of this study was to evaluate the influence of temperature and flow velocity of the drying air on the possible amount of thermal energy recovery form moist air after leaving the convective dryer.

The investigations of the convective drying process of sweet paprika (cv. Kier) were performed for two drying flow velocities, namely 0.3 and 0.5 ms^{-1}, at the temperature of 50, 55, 60, and 65ºC. The velocity and temperature of drying air were measured behind the drying material.

Before being dried, the material was cut into 0.5 mm thick cubes. Paprika was dried up to the 12% (w.b.) moisture level. The convection dryer's load was 25 kg/m^2. The enthalpy of moist air after leaving the dryer was calculated as follows:

$$i_{1+x} = c_{pg} \cdot t + x \cdot (c_{pw} \cdot t + r_0). \tag{1}$$

The absolute humidity of air was calculated according to the equation:

$$x = 0{,}622 \cdot \frac{\varphi \cdot p_w''}{p - \varphi \cdot p_w''}. \tag{2}$$

The constant value of absolute humidity of air (0.4) was assumed in the calculations. The absolute humidity of air after leaving the convective dryer was determined, taking into consideration the amount of evaporated water per unit of drying time.

With regard to the fact, that measurements of mass loss of the dried material were carried out at 20 min time intervals, it was assumed, that constant water content evaporated between the measurements. The amount of heat possible to recover from the drying air was calculated as follows:

$$\dot{Q} = \dot{V} \cdot \rho_{1+x} \cdot \left(i_{1_{(1+x)}} - i_{2_{(1+x)}} \right), \tag{3}$$

where:

$$\rho_{1+x} = \frac{1}{T} \cdot \left(\frac{\phi \cdot p_w^{''}}{R_w} + \frac{p_0 - \phi \cdot p_w^{''}}{R_g} \right). \quad (4)$$

The volumetric flow rate of drying air was calculated as product of air flow velocity and surface drying screen area. The air enthalpy after passing through heat exchanger was determined for constant value of air temperature equal to 20°C.

The convection drying was conducted using a vertical air-flow dryer. The heating assembly of the dryer consisted of three heating elements and, more specifically, of heaters in chamotte casings, with the total strength of 6.9 kW. The heating element of this dryer consists of three heaters in chamotte casings. One of these heaters is connected to the circulation system of the temperature regulator. The axial ventilator, powered by an electric engine with a multi-stage regulation of rotation, ensured the air flow. The convective dryer diagram was shown in Fig. 1.

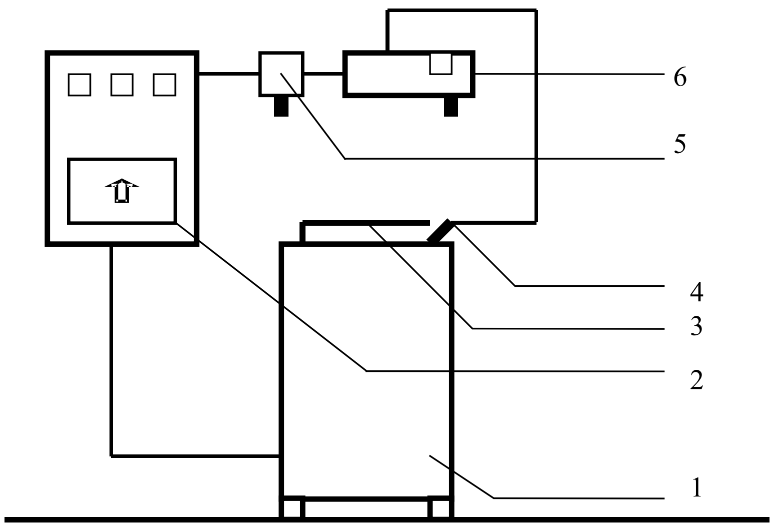

Fig. 1. The scheme of measuring stand for convective drying: 1 – *dryer*, 2 – *switchboard*, 3 – *screen*, 4 – *contact thermometer*, 5 – *contactor*, 6 – *stabilizer*

RESULTS AND DISCUSSION

The drying curves of paprika, obtained on the basis of experimental data in different drying conditions were shown in Figures 2 and 3. The regression equations described the changes in weight of the material during drying were presented in Tables 1 and 2.

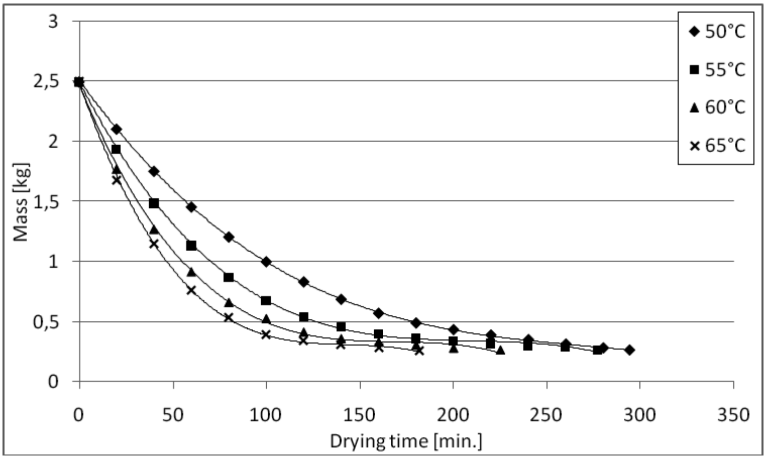

Fig. 2. Convective drying curves of paprika (air flow velocity 0,3 m/s)

Table 1. Regression equations described the relations between the changes in weight of the material and convective drying time (air flow velocity 0,3 m/s)

t [°C]	The regression equation	R^2
50	$m = -9\times10^{-8}\times x^3 + 7\times10^{-5}\times x^2 - 0{,}0216\times x + 2{,}5045$	1
55	$m = -2\times10^{-7}\times x^3 + 0{,}0001\times x^2 - 0{,}03\times x + 2{,}4871$	0,997
60	$m = -4\times10^{-7}\times x^3 + 0{,}0002\times x^2 - 0{,}0374\times x + 2{,}4681$	0,998
65	$m = -7\times10^{-7}\times x^3 + 0{,}0003\times x^2 - 0{,}0445\times x + 2{,}4839$	0,999

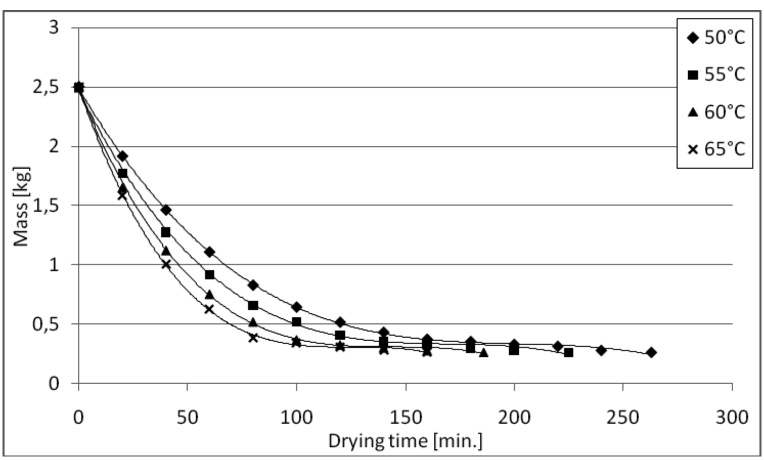

Fig. 3. Convective drying curves of paprika (air flow velocity 0,5 m/s)

Table 2. Regression equations described the relations between the changes in weight of the material and convective drying time (air flow velocity 0,5 m/s)

t [°C]	The regression equation	R^2
50	$m = -3\times10^{-7}\times x^3 + 0{,}0002\times x^2 - 0{,}0312\times x + 2{,}4889$	0,999
55	$m = -4\times10^{-7}\times x^3 + 0{,}0002\times x^2 - 0{,}0373\times x + 2{,}4697$	0,999
60	$m = -7\times10^{-7}\times x^3 + 0{,}0003\times x^2 - 0{,}0449\times x + 2{,}476$	0,998
65	$m = -10^{-6}\times x^3 + 0{,}0004\times x^2 - 0{,}0523\times x + 2{,}4927$	0,999

The highest weight loses were obtained at the beginning of the drying process. This tendency was found for two air flow velocities (at each temperature level). The amount of water evaporated from paprika suddenly decreased after exceeding half of drying time. At each air flow velocity the intensity of water removal increased with the air temperature.

An increase of air flow velocity from 0,3 $m\times s^{-1}$ to 0,5 $m\times s^{-1}$ caused intensification of the drying process.

The changes of enthalpy of moist air (determined on the basis of equation 1) after leaving the convective dryer in relation to the drying time were presented in Figures 4 and 5. The regression equations describing these changes during the drying process were presented in Tables 3 and 4.

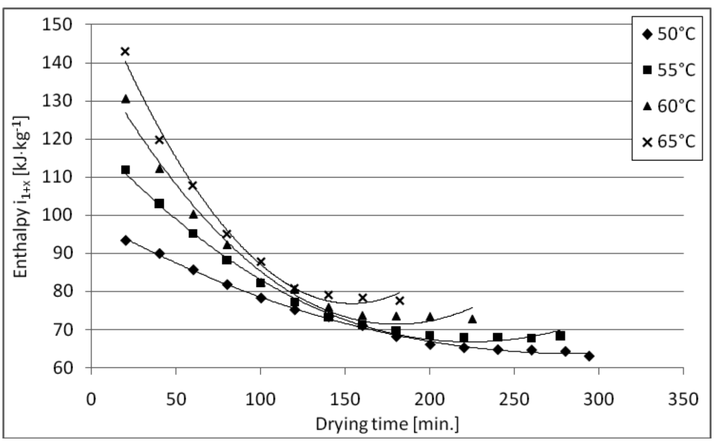

Fig. 4. Enthalpy of moist air in relation to drying time (air flow velocity 0,3 m/s)

Table 3. Regression equations describing the relations between the enthalpy of moist air and drying time (air flow velocity 0,3 m/s)

t [°C]	The regression equation	R^2
50	$i_{1+x} = 0{,}0004\times x^2 - 0{,}2433\times x + 98{,}578$	0,997
55	$i_{1+x} = 0{,}0011\times x^2 - 0{,}4781\times x + 120{,}2$	0,996
60	$i_{1+x} = 0{,}0022\times x^2 - 0{,}7808\times x + 141{,}69$	0,986
65	$i_{1+x} = 0{,}0036\times x^2 - 1{,}0934\times x + 160{,}86$	0,993

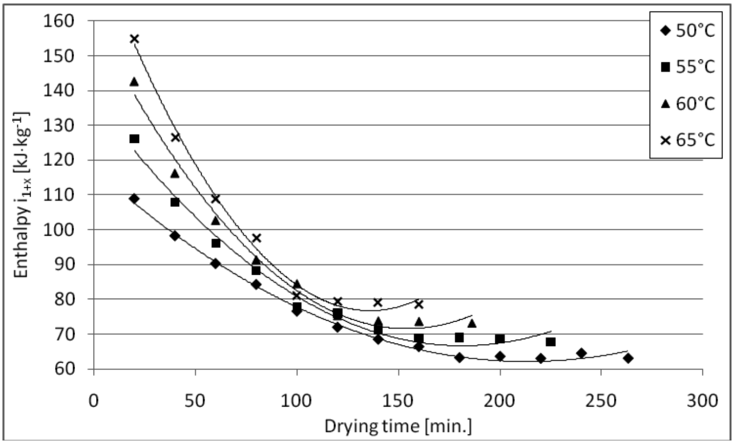

Fig. 5. Enthalpy of moist air in relation to drying time (air flow velocity 0,5 m/s)

Table 4. Regression equations describing the relations between the enthalpy of moist air and drying time (air flow velocity 0,5 m/s [1])

t [°C]	The regression equation	R^2
50	$i_{1+x} = 0{,}0012\times x^2 - 0{,}5184\times x + 117{,}46$	0,995
55	$i_{1+x} = 0{,}0022\times x^2 - 0{,}7805\times x + 137{,}37$	0,996
60	$i_{1+x} = 0{,}0037\times x^2 - 1{,}1516\times x + 160{,}28$	0,989
65	$i_{1+x} = 0{,}0057\times x^2 - 1{,}5467\times x + 181{,}91$	0,993

For all the considered independent variables the enthalpy of air decreased with the function of convective drying time. Such character of drying curves is conditioned by intensity of water evaporation from drying material.

The highest enthalpy was obtained for drying air removed from the dryer at the highest temperature from the measurement range (65^{o}C). This tendency was found for two air flow velocities. The lowest enthalpy was observed for air obtained after drying at 50^{o}C. An increase of air flow velocity caused an increase of air enthalpy at the beginning of the drying process. However, at the end of the drying the flow velocity had no influence on the enthalpy.

The changes of heat flux (determined on the basis of equation 3), possible to recover from moist air after leaving the convective dryer, in relation to the drying time were presented in Figures 6 and 7. The regression equations describing these changes during the drying process were presented in Tables 5 and 6.

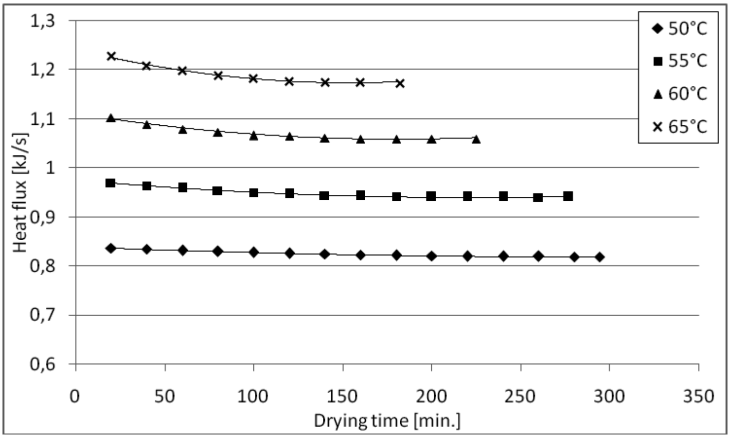

Fig. 6. Heat flux possible to recover for moist air in relation to drying (air flow velocity 0,3 m/s)

Table 5. Regression equations describing the relations between the heat flux and drying time (air flow velocity 0,3 m/s)

t [°C]	The regression equation	R^2
50	$Q = 2\times10^{-7}\times x^2 - 0{,}0001\times x + 0{,}8395$	0,997
55	$Q = 7\times10^{-7}\times x^2 - 0{,}0003\times x + 0{,}9754$	0,996
60	$Q = 2\times10^{-6}\times x^2 - 0{,}0006\times x + 1{,}1101$	0,986
65	$Q = 3\times10^{-6}\times x^2 - 0{,}0009\times x + 1{,}2418$	0,994

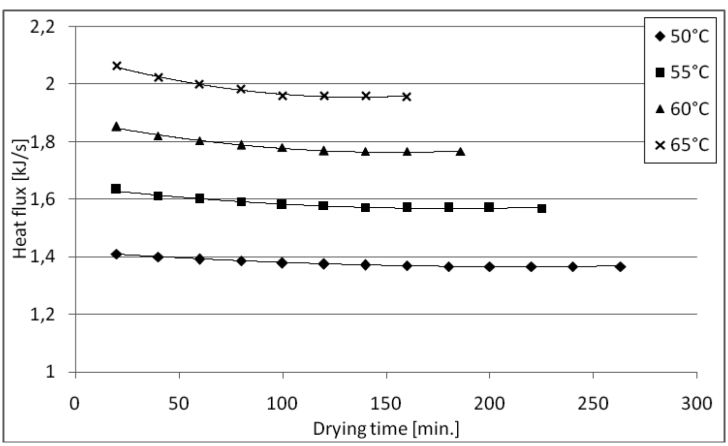

Fig. 7. Heat flux possible to recover for moist air in relation to drying (air flow velocity 0,3 m/s)

Table 6. Regression equations describing the relations between the heat flux and drying time (air flow velocity 0,3 m/s)

t [°C]	The regression equation	R^2
50	$Q = 10^{-6}\times x^2 - 0{,}0005\times x + 1{,}4185$	0,995
55	$Q = 2\times 10^{-6}\times x^2 - 0{,}0009\times x + 1{,}646$	0,986
60	$Q = 5\times 10^{-6}\times x^2 - 0{,}0014\times x + 1{,}8748$	0,989
65	$Q = 8\times 10^{-6}\times x^2 - 0{,}0021\times x + 2{,}1003$	0,993

The highest amount of energy in the unit of time, at about 2,06 $kJ\times s^{-1}$, can be recovered form the drying air after leaving the convective dryer at the beginning of the process, at the air flow velocity of 0,5 $m\times s^{-1}$, and at the highest used temperature.

For all the considered independent variables the heat flux possible to recover from the drying air decreased during the drying process

The increase of air flow velocity caused a significant increase of heat flux of moist air. At the temperature of 65°C and at the beginning of the process, the value of heat flux is higher by about 0,8 $kJ\times s^{-1}$. For both the air flow velocities, the highest heat flux possible to recover from the drying air is obtained for the highest temperature used, and the lowest for the lowest value of the drying air temperature.

Figure 8 presents the total quantity of heat possible to recover during the drying process (from the air leaving the convective dryer) in relation to temperature and air flow velocity.

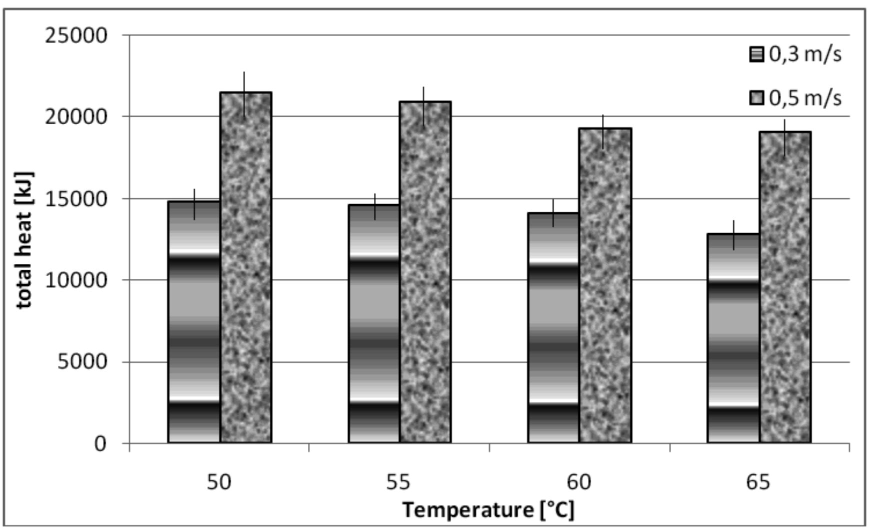

Fig. 8. The total quantity of heat which can be recovered during the convective drying process in relation to temperature and air flow velocity

For each temperature level, the higher amount of total heat can be recovered from the drying air for the higher flow velocity. It is caused by a higher amount of air passing through the dryer in the unit of time. At the respective air flow velocities, the possible amount of heat recovery decreased with the increase of drying temperature. It was caused by the shortening of the drying time with the increase of drying air temperature. The highest amount of heat can be recovered from the air at the temperature of 50^{o}C and at the air flow velocity of 0.5 m×s^{-1}.

CONCLUSIONS

On the basis of the carried out analysis concerning the possibility of heat recovery during the convective drying process of paprika, the following conclusions can be formulated:

1. For all the considered independent variables, the enthalpy of air leaving the dryer decreased during the drying time. At the respective air flow velocities, the highest enthalpy occurred at the air temperature of 65^{o}C, and the lowest one at the air temperature of 50^{o}C. The increase of air flow velocity caused the increase in enthalpy, especially at the beginning of the process.
2. The heat flux possible to recover from the drying air decreased as the drying time increased. The increase of air flow velocity caused the increase of heat flux in all the measured range. The increase of temperature caused the increase of the amount of heat carried off in the unit of time.
3. The total possible amount of heat energy recovery from the drying air is higher for the higher air flow velocity (at the respective temperature) and decreases with the increase of drying temperature (at the respective air flow velocity).
4. The highest amount of energy, reaching about 2,06 kJ×s^{-1}, can be recovered during the drying of paprika at the temperature of 50^{o}C, and at the air flow velocity of 0.5 m×s^{-1}.

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ANALIZA MOŻLIWOŚCI ODZYSKIWANIA ENERGII W PROCESIE KONWEKCYJNEGO SUSZENIA PAPRYKI

Streszczenie. W pracy określono entalpię oraz ilość energii cieplnej możliwej do odzyskania w procesie konwekcyjnego suszenia papryki. Suszenie konwekcyjne zostało przeprowadzone przy dwóch prędkościach przepływu czynnika suszącego oraz na czterech poziomach temperatury. Na podstawie przeprowadzonych badań można stwierdzić, że dla wszystkich zmiennych niezależnych entalpia powietrza opuszczającego suszarkę maleje w czasie trwania suszenia. Przy danej prędkości przepływu największą entalpię posiada powietrze o temperaturze 65°C, natomiast najniższą o temperaturze 50°C. Wzrost prędkości przepływu powietrza powoduje wzrost jego entalpii, zwłaszcza na początku trwania procesu. Największą ilość ciepła, wynoszącą około 21,5 MJ, można odzyskać prowadząc proces suszenia w temperaturze 50°C przy prędkości przepływu 0,5 m×s-1.

Słowa kluczowe: Suszenie konwekcyjne, strumień ciepła, entalpia, papryka.