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Intensification of rapeseed drying process through the use of infrared emitters

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Abstract. The theoretical basis of the agricultural material drying techniques has been formed in the world for two and a half centuries. Nevertheless, despite the multitude of studies well presented in the literature, the industry still lacks universally recognized methods of design calculation for the majority of drying problems. Presumably, this is due to the fact that the dehydration of foodstuffs is one of the most energy-intensive and complicated work processes. In the process of thermal treatment during the drying, the physical state of the water in the treated item changes, the properties of the item itself are altered.

Recently, the drying of foodstuffs by means of infrared (IR) radiation has been gaining ever wider acceptance. At the same time, the technologies for dehydrating foodstuffs and materials are now far ahead of the theory of drying. Not only the classical literature on the drying problems, but even special studies on the subject cannot provide any specific recommendations for the design of installations with the electro-magnetic principle of energy input. Whereas that is exactly the type of installations that are now actively making headway, while offering serious challenges in their modelling. For that reason, experimenting has until now been the only reliable way of their studying. Despite the available extensive scientific literature on the drying, including works on IR units, the practical issues of engineering IR driers have not been tackled. All the existing studies consider solely particular cases. This study discusses the process of drying the fixed bed of rapeseeds with the use of the electromagnetic infrared emitter. The energy intensity of the process and the optimum thickness of the product bed are determined. The aim of the paper is to examine the effect that the operating condition parameters (energy input intensity, temperature, grain bed thickness) have on the drying kinetics and the energy characteristics of the process. The methods of research are based on the thermophysical analysis of the material’s structure. The experimental studies were carried out with the use of monitoring and measuring equipment, up-to-date methods and instruments, including solutions developed by the authors. The analytical treatment was performed with the use of the software packages: MathCAD, Excel. The sample testing and examination took place in the laboratory and the methods were in compliance with the applicable standards. A comprehensive experimental investigation of the effect that the operating parameters (specific load and power) have on the rape seed IR-drying kinetics had been accomplished

Key words: agricultural engineering, rape, infrared emitters, drying, load.

INTRODUCTION

The thermal treatment (heating) of grain is applied, as is known, in order to disinfect the grain prior to putting it to storage, predry it in order to improve the efficiency of the separation, micronisation of cereals, fodder grain crops, intensify the process of drying and oil extraction from oil crops. In this process, different equipment is employed in each case in terms of the method of heat input. In the equipment that is used most frequently for the preheating and drying of grain (cascade heaters, tower driers with air ducts), direct contact between the grain and the heat carrier gas or heat carrier-heated surface (gas duct, shelf etc.) is utilised. The main way of intensifying the heat and mass transfer between the surface and the heat carrier is increasing the latter's flow rate. But, the potential of the said process intensification method is limited by the removal of the material from the treatment zone and the inefficient excessive consumption of energy, which is lost with the exhaust heat carrier. It is possible to reduce the total amount of heat carrier and, accordingly, the heat consumption, if a no-contact method of thermal energy input is used. One of the efficient methods of transferring heat to grain without contacting it is the infrared irradiation of a layer of dispersed material.

Today's interpretation of the process of dehydration during drying is based on the scientific fundamentals of the heat and mass transfer during the change of state (Orsat et al., 2007; Wang et al., 2007; Wang et al., 2011) and the theory by Rebinder & Shchukin (1973) about the forms of bonding between moisture on the one hand and colloid and capillary-porous materials on the other hand. The theory of drying, the foundations of which were laid by A.V. Lykov (1968), had evolved in the works (Ginsburg, 1985). There are schools of: convection drying (Nikitenko et al., 2008; Aboltins & Upitis, 2012; Doymaz, 2014), filtration drying (Barna et al., 2013), dielectric drying (Jones & Rowley, 1996), dispersed material drying (Burdo, & Bezbah, 2008; Burdo et al., 2017), vibratory fluidized bed drying (Kats & Mazor, 2010).

Infrared radiation is the electromagnetic radiation within a wavelength range of 0.75 to 1000 μm. This range is divided into the three bands: near infrared (0.75–1.4 μm), intermediate infrared (1.4–3 μm) and far infrared radiation (3–1,000 μm).

The absorption of infrared radiation in the absorption spectra of foodstuffs of plant and animal origin results from the combined absorption by all components constituting the cells. Accordingly, superposition of individual lines is responsible for the appearance of the continuous spectrum with wavelengths of $\lambda > 3.0$ μm (Sandu, 1986).

It has been established (Wang et al., 2007) that the interaction between light and foodstuff manifests in the continuous reflection of heat and dispersion of light. The heat reflection is determined by the colour of the material. In case of near infrared radiation, around 50% of all rays reflect back, while far infrared radiation reflects at a rate of less than 10%. Experimental observations (Krishnamurthy et al., 2008) have shown that, as the thickness of the layer becomes greater, the radiation admittance declines and the reflection from the surface increases.

Overall, it has been noted (Sandu, 1986; Krishnamurthy et al., 2008; Das et al., 2009; Riadh et al., 2015) that solid materials absorb infrared radiation only in the thin surface layer. Another finding has been that with the temperature of the IR emitter getting lower the main radiation wavelength shifts towards the area of lesser absorption of infrared rays by the product. The development of continuous-operation dryers equipped with far and near infrared spectrum units can allow reducing the material costs, duration of drying and process temperatures. Anyway, the thickness of the product layer may not exceed 5 mm.

In order to ensure the reduced metal intensity of the equipment, the uniform distribution of the heat flows over the receiving surfaces and the improved quality of the semi-processed plant raw materials, reflectorless infrared film driers are used most frequently. Our experimental investigations on this issue have shown that infrared film driers have low metal consumption rates. Moreover, the emitter is easy to install, has low inertia, the low temperature of the working surface (45–85 °C) and the IR-wave length (3–15 μm) that is acceptable for drying plant raw materials, in particular, rape seeds (Kiptela et al., 2017)

The synergistic effect due to the combination of IR heating and convection drying has shown in the reduction of the process duration by 43% and the energy consumption by 63% as compared to the conventional convection drying. Also, it has been found that infrared radiation improves the effectiveness of inactivation of enzymes, pathogenic germs, thus contributing to the improvement of the product's quality and its shelf life.

When determining the optimum operating mode in the drying of rape seeds with a purpose of bringing them to the standard condition, several factors have to be taken into account, depending on the following use of the seeds – either for industrial processing or as seed grain (Table 1).

Table 1. Rapeseed shaft drying modes in relation to end use of seeds (Beregovaya & Stankevits, 2001)

Initial moisture content, ω (%)	Maximum temperature (°C)	
	drying medium	seeds
1. Seeds for foodstuffs and combined fodders		
ω ≤ 10	85	62
10 < ω ≤ 15	83	56
15 < ω ≤ 20	80	52
20 < ω ≤ 25	78	50
ω > 25	75	48
2. Seeds for sowing		
ω ≤ 17	65	40
17 < ω ≤ 19	60	37
ω > 19	55	35

It appears that the mentioned observations could be useful in the development of improved grain drying facilities.

The aim of the study is to examine the effect that the operating parameters (energy input intensity, temperature, grain bed thickness) have on the drying kinetics and the energy characteristics of the process.

MATERIALS AND METHODS

The investigation with the use of a fixed bed of rape seeds was carried out on the test bench (Figs 1 and 2) comprising IR-chamber, electronic scales, two IR-generators, trays with grain, system of measurement for registering the temperature of grain and air in the chamber as well as the energy consumption.

The movement of air in the chamber was created by a fan. The square tray measuring 200 mm x 200 mm with a 10-mm high flange was made of metal wire mesh. The tray hung from the scales on a system of wire cables with adjustable lengths, which enabled setting the required distance between the product and the emitters within a range of 7–15 cm.

The role of IR-radiation generators was played by quartz short-wave luminous elements with a wattage of 550 W, which ensured the attainment of the required temperature conditions virtually in 30 seconds. The supply voltage was controlled by the system comprising a laboratory transformer and a 2.5 accuracy class ammeter and a 1.5 accuracy class voltmeter. The readings of the ammeter and voltmeter were used to find the consumed power.

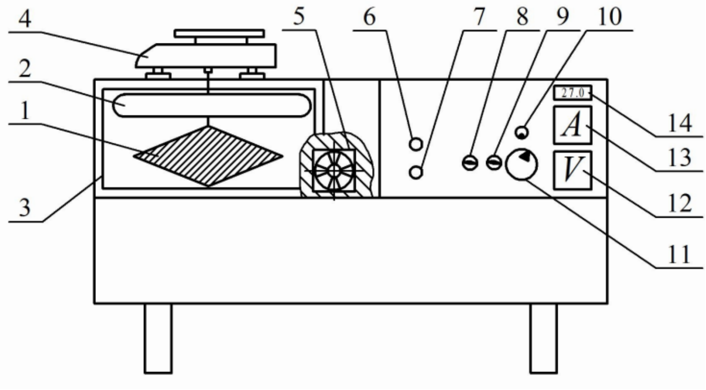

Figure 1. Schematic representation of experimental unit for drying with the use of infrared emitter: 1 – tray; 2 – infrared emitter; 3 – drying chamber; 4 – electronic scales; 5 – fan for drawing air out of chamber; 6 – unit start switch; 7 – unit stop switch; 8 – fan start switch; 9 – infrared emitter start switch; 10 – changeover switch for indication of temperature of product or air in chamber; 11 – infrared emitter power control; 12 – voltmeter; 13 – ammeter; 14 – indicator of temperature of product and air in chamber.

The velocity of the air leaving the chamber was measured with electronic anemometer-thermometer-hygrometer Testo 410-2. The air velocity was changed within a range of 0.5–2.5 m s^{-1} by adjusting the rpm of the fan motor with the use of the laboratory autotransformer. The system of measurement of the temperature of the product and the air in the chamber comprised two Chromel-Copel thermocouples shielded from the exposure to infrared radiation by asbestos rope and aluminium foil and a digital microvoltmeter PT-0193 with ambient temperature compensation.

Figure 2. General appearance of the laboratory experimental unit.

RESULTS AND DISCUSSION

The experimental part of the investigation included series of experiments with different loads (grain weights) and different inputs of electromagnetic radiation power into the chamber. The soft- and hardware system of the test unit registered the resulting changes of the bed's weight and temperature.

The electronic scales registered the product mass variations. The reduction of mass provided the basis for determining the amount of extracted moisture. In advance, the initial moisture content in grain, which was equal to 11.39 % in our experiment, and the mass of dried grain had been found using the conventional methods of drying to a constant weight.

The rapeseeds were placed on the hanger of the scales in the centre of the chamber. The computer continuously processed the information sent from the scales and thermocouples and output to the monitor display the trend lines for the mass of product, product dehydration amount and rate, product temperature, chamber air temperature, dry and wet bulb thermometer measurements of the air leaving the chamber.

Samples of rapeseeds with masses of 100; 200; 300; 400 g were placed on the tray, which created specific loads of 2.5; 5; 7.5; 10 kg m^{-2} respectively. After that, the tray was placed into the test unit with an IR emitter and immediately exposed to IR radiation with a specifically set power of 100, 200, 300, 400, 500 W, which had continued until the product temperature became equal to 70 °C. At the same time, the readings of product mass, product temperature and air temperature were continuously recorded.

The effect of the rapeseed load variation on the drying process is shown in Fig. 3. The results of the investigations represented by the following curves correspond to a distance of 10 cm between the emitter and the surface of the seed bed on the tray. That was the distance (maintained the same for different bed thicknesses), at which the most optimal results had been obtained.

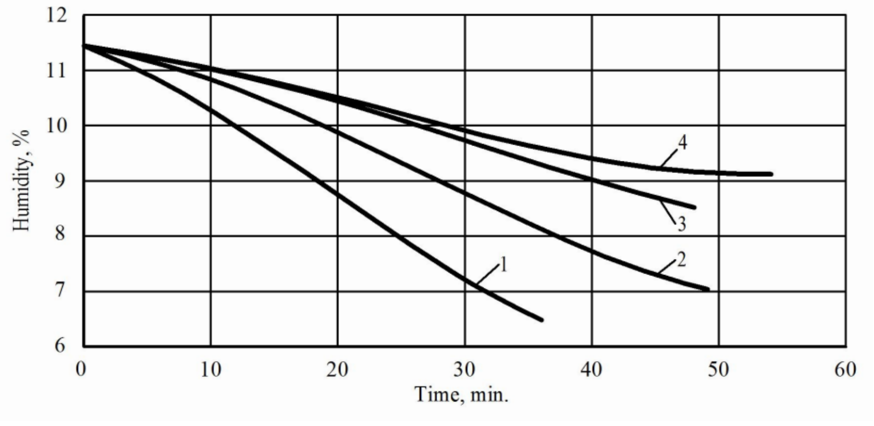

Figure 3. Dependence between reduction of humidity content and rape seed load at constant power of $N_в$ = 120 W: 1 – mass of 100 g, layer thickness of 4 mm; 2 – 200 g, 8 mm; 3 – 300 g, 12 mm; 4 – 400 g, 16 mm.

The comparison of the curves (Figs 3 and 4) reveals that the product temperature variation for all loads does not exceed 10 °C (Fig. 4), while an increase in the bed thickness results in the less intensive dehydration (Fig. 3).

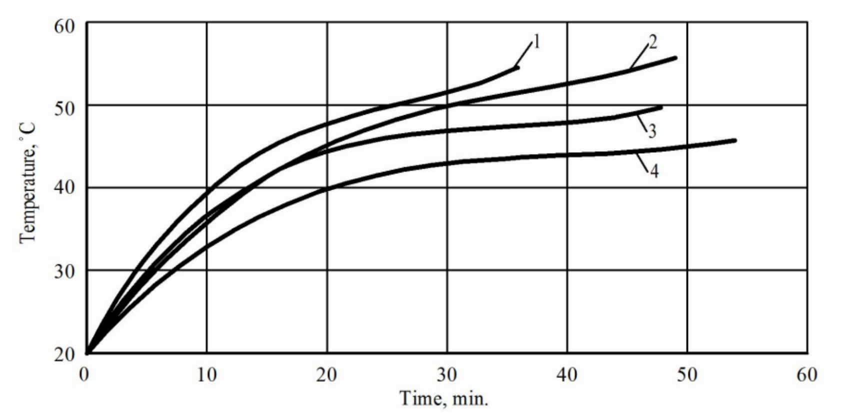

Figure 4. Rape seed thermograms at constant emitter power of $N_в$ = 120 W, different loads and layer thicknesses: 1 – 100 g, layer thickness of 4 mm; 2 – 200 g, layer thickness of 8 mm; 3 – 300 g, layer thickness of 12 mm; 4 – 400 g, layer thickness of 16 mm.

The results of the described investigation prove that drying with the use of an IR emitter with a power rating of 300 W provides the fullest moisture evaporation, but consumes more time. The other option with an increased power rating of 400…500 W allows increasing the dehydration rate, but in that case the heated product will reach faster the critical thermal point, which can significantly impair its properties.

It has been established that the drying of rapeseeds at a drying medium temperature of 100 °Chas no effect on the digestibility of their proteins, while the uniform thermal dehydration of rapeseeds at a temperature of 70 °Cimproves the nutritive properties of their proteins by increasing their digestibility from 61% to 64%. For that reason, the latter temperature was chosen for our experiments.

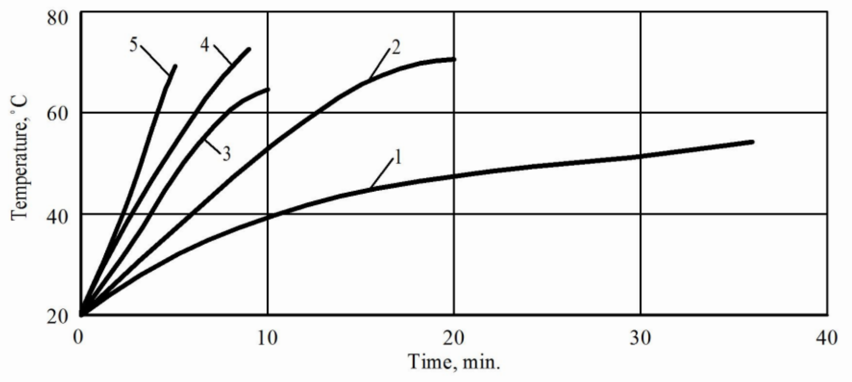

Figure 5. Rapeseed thermograms at varying emitter power: 1 – 100 W; 2 – 200 W; 3 – 300 W; 4 – 400 W; 5 – 500 W.

It can be seen from the above thermograms (Fig. 5) that a power rating of 100 W provides for the gradual heating of the product, but the duration of the process is rather long. When a power rating of 200 W is applied, adequate heating is facilitated, but with considerably reduced time consumption. Power ratings of 300 W and higher cause the product heating too fast.

CONCLUSIONS

1. A comprehensive experimental investigation of the effect that the operating parameters (specific load and power) have on the rape seed IR-drying kinetics has been carried out with the use of the laboratory experimental unit that was developed specially for the investigation.

2. The results of the experimental investigation prove that the reduction of the moisture content in the product improves substantially due to the use of IR emitters. Also, it has been established that raising the specific load of rapeseeds to 7.5 kg m^{-2} results in the increase of the moisture removal rate, while further increasing the specific load is inadvisable, as the moisture removal will not improve any more, the latter presumably explained by the insufficient penetration of the IR rays into all parts of the loaded product.

3. When the specific load of rapeseeds exceeds 7.5 kg m^{-2}, IR-heating works only in the surface layers of the grain bed, the deeper layers are heated only because of the thermal conductivity of the grain, which significantly reduces the efficiency of the drying process.

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