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SPECIFIC MECHANICAL ENERGY CONSUMPTION OF EXTRUSION--COOKING OF WHEAT FOAMED PACKAGING MATERIALS

Maciej Combrzyński*, Agnieszka Wójtowicz, Magdalena Klimek, Leszek Mościcki, Tomasz Oniszczuk, Stanisław Juśko

Department of Food Process Engineering, University of Life Sciences in Lublin
*Contact details: ul. Doświadczalna 44, 20-280 Lublin, e-mail: maciej.combrzynski@up.lublin.pl

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ABSTRACT

Extrusion-cooking technique, known from food processing, may be used in production of environmentally friendly foamed materials based on starch. The objective of the paper was to determine the specific mechanical energy consumption of the extrusion-cooking process of foamed materials made of wheat starch at a varied level of moisture of raw materials mixtures and varied participation of foaming components. Functional additives which support the foaming process were applied: PDE foaming agent and polyvinyl alcohol. Specific mechanical energy consumption (SME) was determined according to the moisture content of raw materials and additives used. Energy consumption of the extrusion-cooking process of foamed materials with addition of the foaming agent PDE was increasing along with the increase of moisture and decreased at higher participation of the additive. In case of mixtures with an addition of polyvinyl alcohol the values of SME were getting higher along with the increase of the additive content and moisture of raw materials mixture. The research proved possibility of obtaining starch foamed packaging materials, which may function as a filler in transport packages, at the high efficiency of the process and low energy consumption.

Introduction

Plastics based on petrochemical raw materials, used in the production of packagings are not biodegradable (Borowy and Kubiak, 2008; Żakowska, 2003; 2005). The process of decomposition of plastic may be initialized only as a result of its modification or introduction of additives. Presently, work on the possibility of production of packaging materials, which are environmentally friendly, focuses on searching for alternative raw materials, namely such which both on account of economy and utility will be able to considerably replace synthetic packaging plastics. Available produce, which constitute renewable natural materials, may be used for production of biopolymers (Mościcki, 2008; Roper and Koch, 1990). From among natural raw materials, starch is more frequently used in the research as a renewable organic material. Availability, prices and possibility of complete degradation weigh in its favour. The end of the 20th century is a period of fast increase of the research on new biodegradable plastics and new manufacturing technologies. The extrusion-cooking technique is one of them. It has been linked to the food production so far (Mościcki et al., 2007; Oniszczuk et al., 2012).

Extrusion-cooking of plant raw materials is a process of material processing under high pressure and at high temperature (Mościcki and Mitrus, 2004; Mościcki et al., 2006; Mościcki et al., 2007, Oniszczuk et al., 2006). Significant physical and chemical changes, and thus quality changes take place during thermal and mechanical treatment. Suitably selected parameters of the extrusion-cooking process allow shaping physical, chemical and functional properties of the processed materials.

Foamed materials constitute a group of packagings, which are used mainly in transport of products, susceptible to mechanical damages (Bhatnagar and Milford, 1996; Pushpadass et al., 2008). Most frequently produced from plastics constitute an ecological problem in utilization. However, research on the possibility of using starch in production of this type of materials has been carried out. Foamed starch may be obtained with the extrusion-cooking method when a foaming agent is introduced to the gelatinized starch, e.g. water (Sivertsen, 2007; Zhang and Xiuzhi, 2007). Foaming agents allow obtaining air bubbles in a structure. However, nowadays it is difficult to produce foamed materials based on starch with properties similar to synthetic materials (Janssen and Mościcki, 2009; Rejak and Mościcki, 2006).

Materials and methods

The use of various raw materials' mixtures and a varied level of moistening were used to evaluate how efficiency and specific mechanical energy consumption of the extrusion-cooking process of foamed starch packaging materials are changing. During the preliminary research, the impact of mixtures' moisture content on the extrusion-cooking process and the quality of the produced extrudates was reported (fig. 1). Based on the initial measurements, values of 17, 18 and 19% of moisture content were set.

Figure 1. Foamed starch materials produced in the Department of Food Process Engineering

In order to improve the foaming effect, additives in the form of foaming agents: Plastronfoam PDE agent and polyvinyl alcohol (AP) in the amount from 1% to 3%, were used. In the extrusion-cooking process a single-screw extruder-cooker TS-45 o L/D=12 was used (fig. 2). The following range of temperatures in particular sections of an extruder-cooker was applied: 80ºC the first section, 140ºC second section, 120ºC a head and the rotational speed of the extruder-cooker screw 2.16 s^{-1}, which was determined with the use of a tachometer DT-2234 B. The forming die diameter was 3 mm. During the extrusion-cooking the engine load and process efficiency were recorded. The recorded data allowed calculation of specific mechanical energy consumption of the extrusion-cooking process.

Figure 2. Single-screw extruder-cooker TS-45 with L/D=12

Efficiency was calculated according to the formula:

$$Q \equiv \frac{m}{t} (kg \cdot h^{-1}) \tag{1}$$

where:

Q – process efficiency, ($kg \cdot h^{-1}$)

m – mass of extrudate obtained in the measurement, (kg)

t – time of measurement, (h)

Energy consumption was determined with the use of specific mechanical energy consumption (SME) acc. to the formula provided by Ryu and Ng (2001):

$$SME = \frac{n}{n_m} \cdot \frac{O}{100} \cdot \frac{P}{Q} (kWh \cdot kg^{-1}) \tag{2}$$

where:

SME – specific mechanical energy consumption, ($kWh \cdot kg^{-1}$)

n – screw rotations, (s^{-1})

n_m – screw rating rotations, (s^{-1})

O – the engine load in comparison to the maximum, (%)
P – rated power, (kW)
Q – process efficiency, ($kg \cdot h^{-1}$)

The process efficiency was measured in 5 replications assuming an average value as a final result. The results which were obtained during tests were analyzed with the use of ~~a~~ Statistica 6.0 software. The analysis of the response surface methodology with the use of the distance weighted least squares, was applied. Moreover, polynomial regression and determination coefficients were determined.

Results and discussion

The extrusion-cooking process of wheat starch with additive of the foaming agent PDE was characterized with the process efficiency, that is, the amount of the obtained extrudate in the amount of 27.6 $kg \cdot h^{-1}$ to 34.8 $kg \cdot h^{-1}$ in relation to the applied parameters. Changes in efficiency depended on the raw materials' moisture and the content of the functional additive.

The results proved that the increase of the raw materials' moisture with an addition of the foaming agent PDE caused the decrease of the extrusion-cooking process efficiency (fig. 3). This effect was reported in the entire range of the additive use. In case of processing of the raw materials mixtures without PDE agent, a reverse relation was reported, the increase of moisture resulted in the increase of efficiency. Similar relation was presented by Mitrus and Combrzyński (2013) during extrusion-cooking of maize starch.

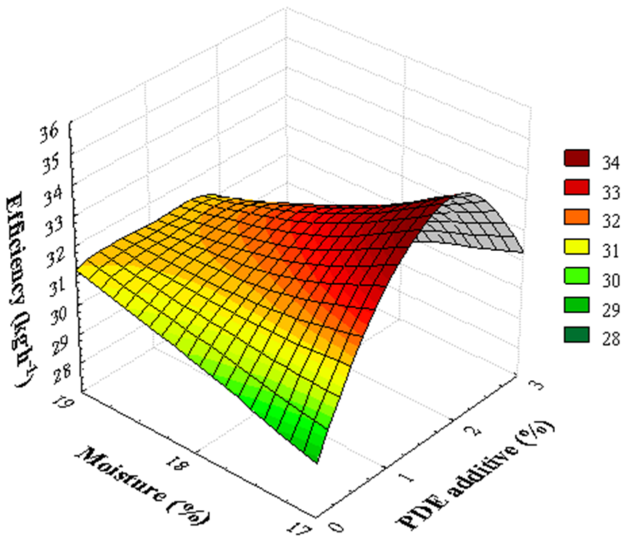

Figure 3. Process efficiency of wheat extrudates with varied addition of the PDE foaming agent

The lowest efficiency of 27.6 kg·h^{-1} was recorded for the raw materials' mixture with 19% of moisture and including 3% of PDE. The highest efficiency was observed during processing of a mixture with 17% of moisture content and 2% of the PDE agent. Increase of the amount of the foaming substance from 2% to 3% caused a considerable decrease of efficiency and disturbance of the wheat starch extrusion-cooking process, which may be proved by negative values of directional coefficients of regression equations (table 1).

The extrusion-cooking of wheat starch with addition of the PDE foaming agent characterized with a very low specific mechanical energy consumption (SME) within 0.073-0.088 kWh·kg^{-1}. The SME values depended equally on–the raw materials' moisture content and the amount of the foaming agent (fig. 4). Along with the increase of the foaming additive participation in the mixture, decrease of the SME value was reported, which may be also observed in the results presented by Mitrus' (2005), where the increase of glycerine additive decreased the SME value of potato starch extrusion-cooking. High values of determination coefficients (0.939-0.985) prove the impact of the PDE additive on the specific mechanical energy consumption (table 1). The opposite relation was observed – the increase of raw materials' moisture increased the SME. The lowest value, which was 0.073 kWh·kg^{-1}, was observed during processing of a mixture with 17% of moisture and at 3% of the foaming agent addition. The highest energy consumption (0.088 kWh·kg^{-1}) was calculated during extrusion-cooking of the mixture with 19% of moisture and 1% of the PDE content.

In case of extrusion-cooking of starch which does not include a functional additive, the SME value increased along with the increase of moisture. Values of the specific mechanical energy consumption were within 0.087-0.099 kWh·kg^{-1}.

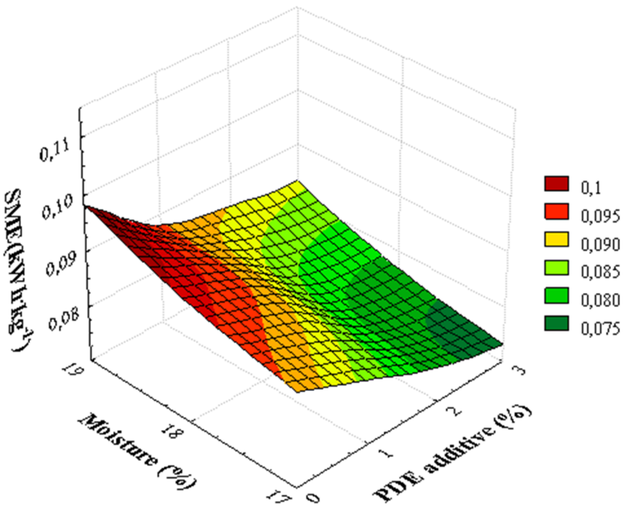

Figure 4. Specific mechanical energy consumption of wheat extrudates with varied addition of the PDE foaming agent

During the extrusion-cooking process of the wheat starch with an addition of the foaming agent in the form of polyvinyl alcohol also similar process efficiency within 28.4-32.2 kg·h^{-1} was reported. The values depended mainly on the raw materials' moisture.

The research showed that along with the increase of raw materials' moisture the efficiency of the extrusion-cooking process increased (fig. 5). This effect was reported in the entire range of the applied additive, as well as in the case of extrusion-cooking of starch without a foaming agent. The lowest efficiency of 28.4 kg·h^{-1} was recorded for the mixture with 17% of moisture and including 3% of the PDE agent. The highest efficiency, (32.4 kg·h^{-1}) was reported for the mixture with 19% of moisture and 2% of the functional additive content. During the analysis of the amount of polyvinyl alcohol, a tendency to decrease the process efficiency at the increasing participation of the additive in a recipe was observed. However, values of determination coefficients were not high (table 1).

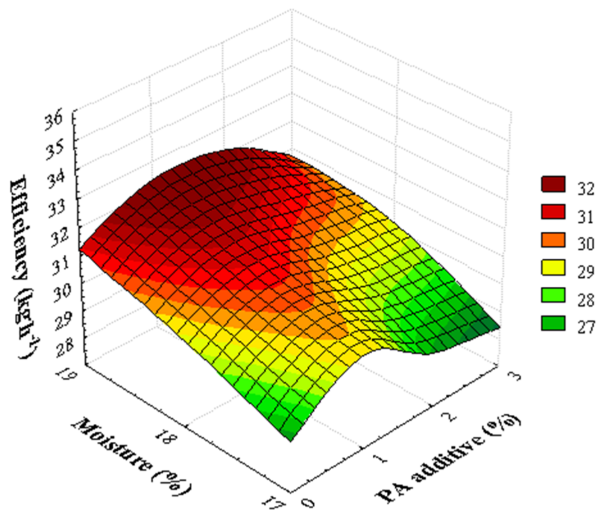

Figure 5. Process efficiency of wheat extrudates with a varied addition of polyvinyl alcohol

The extrusion-cooking process of wheat starch with addition of the foaming agent in the form of polyvinyl alcohol characterized with a higher energy consumption (SME) than in case of the PDE additive. Values within 0.090-0.109 kWh·kg^{-1} were reported. SME values depended on both, the raw material mixture moisture as well as the foaming agent content (fig.4). Along with the increase of polyvinyl alcohol participation in the mixture, the increase of the SME value was reported. A similar relation was noted for the increasing moisture level of raw materials' mixtures. Su (2007) observed a reversed relation, i.e. the SME value decreased during rice flour extrusion-cooking with addition of powdered eggs (the process was carried out with a twin-screw extruder).

The lowest value, which was 0.090 kWh·kg^{-1}, was observed for mixture with moisture of 17% and at 1% of the foaming agent addition. The highest specific mechanical energy consumption (0.109 kWh·kg^{-1}) was noted in case of processing of the mixture with 18% of moisture and 3% of the polyvinyl alcohol content. The increase of the SME and decrease of efficiency during extrusion-cooking of the foamed starch with addition of polyvinyl alcohol could be related to chemical characteristics of the additive, which is defined by the decomposition temperature exceeding 200ºC, whereas for PDE the decomposition temperature was determined as 140ºC (a product data sheet). Too low temperature than the one required for processing of polyvinyl alcohol could influence the change of mass properties in the cylinder of an extruder-cooker and cause impeded flow of material, which was reflected in lower values of the process efficiency and the increase of the specific mechanical energy consumption at the use of 2-3% of the PA additive. This phenomenon was not observed at the use of the PDE additive.

In case of extrusion-cooking of mixtures which do not include a functional additive, the SME values increased along with the increase of moisture. Values of specific mechanical energy consumption of the process were within 0.087-0.099 kWh·kg^{-1}. In the tests carried out by Ruis-Ruiz et al. (2008) a reverse relation was reported where along with the increase of the raw material moisture, the SME value decreased (mixture of corn flour and white beans was subjected to the extrusion-cooking process). For all tested foamed materials produced with addition of polyvinyl alcohol, high values of determination coefficients were obtained (0.793-0.916). They proved a significant impact of the amount of the additive used on the specific mechanical energy consumption during the extrusion-cooking (table 1).

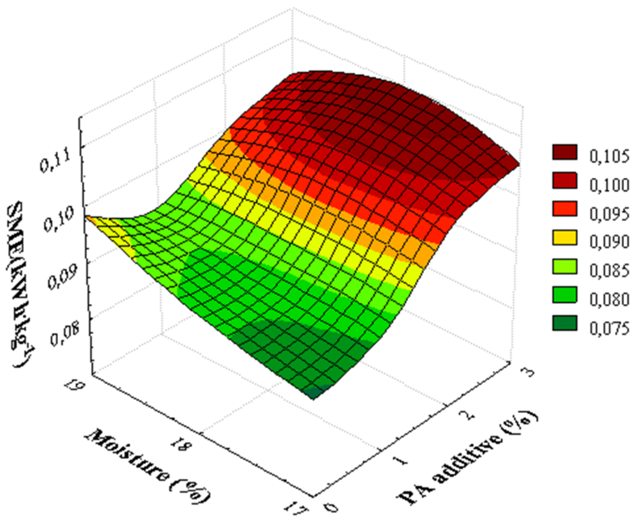

Figure 6. Specific mechanical energy consumption of wheat extrudates with a varied addition of polyvinyl alcohol

Table 1

Second degree equations of regression describinge the changes in the efficiency and specific mechanical energy consumption of the extrusion-cooking process in relation to moisture and the amount of the additive used

	Additive	Moisture (%)	Regression equation	R^2
Efficiency	PDE	17	$y = -2.04x^2 + 11.064x + 19.68$	0.991
		18	$y = -1.02x^2 + 5.028x + 26.1$	0.923
		19	$y = -0.84x^2 + 3.096x + 28.8$	0.955
	Polyvinyl alcohol	17	$y = -0.51x^2 + 2.274x + 27.27$	0.564
		18	$y = -0.3x^2 + 1.428x + 29.22$	0.623
		19	$y = -0.66x^2 + 3.132x + 28.74$	0.998
SME	PDE	17	$y = 0.0007x^2 - 0.0084x + 0.0954$	0.985
		18	$y = 0.0008x^2 - 0.0092x + 0.0998$	0.939
		19	$y = 0.0022x^2 - 0.0163x + 0.1127$	0.983
	Polyvinyl alcohol	17	$y = -0.0003x^2 + 0.0082x + 0.0784$	0.893
		18	$y = 0.0009x^2 + 0.0023x + 0.0865$	0.916
		19	$y = 0.003x^2 - 0.0125x + 0.1076$	0.793

Conclusions

1. As a result of increasing moisture of raw materials' mixtures, efficiency and specific mechanical energy consumption of the extrusion-cooking process of foamed materials with no foaming agents increased.
2. The increase of moisture content of raw materials with addition of the PDE foaming agent influenced the decrease of the process efficiency and caused the increase of specific mechanical energy consumption. Along with the increased amount of additive, efficiency and SME decreased.
3. Higher amount of polyvinyl alcohol, influenced higher SME whereas process efficiency dropped. Increase of moisture of raw materials' mixtures with addition of PA influenced the increase of specific mechanical energy consumption.
4. The research showed the possibility of obtaining environmentally friendly foamed packaging materials with high efficiency and low SME of the process. These extrudates, which include the foaming agent PDE and polyvinyl alcohol, may function as fillers in transport packagings.

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M. Combrzyński, A. Wójtowicz, M. Klimek, L. Mościcki, T. Oniszczuk, S. Juśko

ENERGOCHŁONNOŚĆ EKSTRUZJI PSZENNYCH SPIENIONYCH MATERIAŁÓW OPAKOWANIOWYCH

Streszczenie. Technika ekstruzji, znana z przetwórstwa spożywczego, może być stosowana w produkcji przyjaznych dla środowiska materiałów spienionych opartych na skrobi. Celem pracy było określenie energochłonności procesu ekstruzji materiałów spienionych, wytworzonych ze skrobi pszennej przy różnej wilgotności mieszanek surowcowych i różnym udziale komponentów spieniających. Stosowano dodatki funkcjonalne wspomagające proces spieniania: środek spieniający PDE oraz alkohol poliwinylowy. Energochłonność wyznaczano, wykorzystując wskaźnik jednostkowego zapotrzebowania energii mechanicznej (SME). Energochłonność procesu ekstruzji materiałów spienionych z dodatkiem środka spieniającego PDE zwiększała się wraz ze wzrostem wilgotności i obniżała przy większym udziale dodatku. W przypadku mieszanek z dodatkiem alkoholu poliwinylowego wartości SME były wyższe wraz ze wzrostem zawartości dodatku i wilgotności mieszanki surowcowej. Badania wykazały możliwość uzyskania skrobiowych spienionych materiałów opakowaniowych, które mogą pełnić rolę wypełniacza w opakowaniach transportowych, przy wysokiej wydajności procesu oraz niewielkiej energochłonności.

Słowa kluczowe: materiał spieniony, skrobia pszenna, ekstruzja, energochłonność, wydajność