Thermodynamic assessment of the phenomena of heat and mass transfer for energy-technological systems production of groats concentrates

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Abstract. To assess the thermodynamic excellence of food processing technologies of raw material, it is proposed to use the exergy method based on the second law of thermodynamics. A procedure has been developed for calculating thermal and exergy costs in the moisture-heat treatment of capillary-porous colloidal materials. Thermal and exergy calculations of the production of cooked-dried rice groats were performed. Thermal and exergy analysis of heat and mass transfer processes energy-technological systems (ETS) of various schemes for the production of groats concentrates was carried out. The thermal and exergy estimates of the processes of heat-mass exchange during the moisture-thermal treatment of capillary-porous colloidal materials are obtained using the example of cooked-dried groats. A thermodynamic assessment of the phenomena of heat and mass transfer of ETS for the production of groats concentrates based on the theoretical and experimental studies, which resulted in the development of recommendations on the scientific and practical support for heat and mass transfer processes of moisture-thermal treatment of raw materials. It has been proven that a change in product moisture has a greater effect on exergy than a change in temperature does. It is suggested to use, for an assessment of energy efficiency and a comparative exergy analysis of various ETS for processing raw materials, along with exergy efficiency, specific exergy values characterizing exergy costs per unit of dried finished product, per unit of moisture removal and moisture adsorption.

1. Introduction

In modern conditions of increasing energy consumption, there are questions of its rational use, utilization and recovery of heat in all technological processes of the food industry, including in the production of cooked-dried groats.

The most energy-intensive technological processes for the production of cooked-dried groats, requiring increased use of the energy potential of the coolant, are their cooking and drying. Moreover, thermal analysis does not always reflect the quality of the energy expended [1, 2].

The processing of edible vegetable raw materials based on moisture and heat exposure, is generally, is associated with a significant duration, low thermal efficiency of technological equipment, high specific consumption of energy and material primary product flows [2-4].
2. **Aim of the study**
Adaptation of thermodynamic assessment to determine the degree of efficiency of heat and mass transfer processes in the processing of various edible plant materials based on the second law of thermodynamics.

3. **Object of the study**
This work is related to the assessment of the phenomena of heat transfer and the mass of thermal processes associated with moisture adsorption and moisture removal for various energy-technological systems (ETS) of the production cooked-dried groats for groats concentrates.

The task is to determine the heat, exergy fluxes and their analysis for the processes of preliminary hydrothermal treatment (PHT), cooking and drying of groats, which are one of the main stages in the production of all types of groat concentrates.

The solution to this problem is based on studies of technological processes using oscillatory processing of groats under active hydrodynamic regimes of the product layer in continuous installations of the recirculation type [2-5].

4. **Materials and methods**
Thermal and exergy calculations for the production of cooked-dried rice groats were made on the basis of the compiled methodologies [2, 4, 5].

The comparative efficiency of various energy-technological systems for processing groats from the point of view of determining the degree of energy perfection of processes is considered, using three technological schemes for the production of cooked-dried rice groats as an example. According to the first scheme (I - basic, factory technology), groats are cooked after PHT using saturated steam under excessive pressure in a drum-type cooking boiler of periodic action, followed by cooling of the cooked product in evaporative bowls. According to the second scheme (II - prototype, factory technology), the cereals are cooked after hydration using a steam-air mixture of atmospheric pressure in strip-type apparatuses, followed by the direction of the cooked product for double drying with intermediate rolling. A distinctive feature of the third scheme under consideration (III - proposed) is the implementation of these processes at atmospheric pressure using superheated steam as a heat carrier, which, after drying, is humidified to a state of saturation and is sent to the processes of PHT and cooking of the product.

For all stages of the processing of groats, thermal and exergy balances of heat and mass transfer processes were compiled. Thermal and exergy analyses of both individual processes and various technological schemes of production, including control surfaces: PHT, cooking, drying, conditioning of raw materials, heating of the product, heating of water and air heater, have been performed [2].

The environment with a temperature of 293 K was taken as the reference point [1]. The calculation of the exergy of material flows was made taking into account their different temperature and humidity for each of the production schemes, as well as the design features of technological equipment with a capacity of 925 ... 1250 kg / h for the initial product.

In the calculation of heat and exergy flows at a productivity of 925 kg / h for the initial groat with a moisture content of 14%, the product has the following humidity: after preliminary hydrothermal treatment - 27%, cooking - 36.3%, drying - 9%.

The total thermal exergy of the initial groat before the PHT, which has an ambient temperature, is taken to be equal to zero.

The results of calculations of exergy of various production schemes for cooked-dried rice groats by technological indicators (table 1) are represented in table 2.

In the process of moisture and thermal treatment of products, heating, moistening and physico-chemical change of the colloidal capillary-porous material occurs. The physico-chemical change in groats, taking into account their chemical composition, is mainly due to the gelatinization of starch and protein denaturation [2].

Therefore, the change in the specific thermal exergy of the product is determined on the basis of the Gouy – Stodola equation [1]:

\[ e = e_0 - T \left( \frac{dH}{dS} \right)_0 \]

where \( e \) is the specific thermal exergy of the product, \( e_0 \) is the specific thermal exergy of the initial groat, \( T \) is the temperature of the environment, \( \left( \frac{dH}{dS} \right)_0 \) is the change in the specific enthalpy with the specific entropy of the initial groat.
where $e_{io}$ and $e_{ik}$ – specific thermal exergy of the product, respectively, before and after the thermal treatment, kJ / kg; $i_{io}$ and $i_{ik}$ – sensible heat of the product, respectively, before and after moisture-thermal treatment, kJ / kg; $\Delta s_f = (s_f - s_o)$ – the difference in the specific entropies of the product before and after moisture-thermal treatment, kJ / (kg·K).

**Table 1.** Technological indicators of production schemes of cooked-dried rice groats

| №  | Indicators                                                                 | Technological schemes |
|----|----------------------------------------------------------------------------|-----------------------|
| 1  | The amount of initial cereals before:                                        | I         | II        | III       |
|    | a) PHT, kg                                                                 | 730       | 925       | 925       |
|    | b) cooking, kg                                                             | 850       | 1124.15   | 1089.73   |
|    | c) drying, kg                                                              | 955       | 1251.8    | 1248.83   |
| 2  | The amount of product after drying with humidity W = 9%, kg                 | 682.14    | 872.13    | 874.18    |
| 3  | The moisture content of groats, %:                                          |           |           |           |
|    | a) initial                                                                 | 15.0      | 14.2      | 14.0      |
|    | b) after washing                                                            | 27.0      | -         | 27.0      |
|    | c) after hydration                                                          | -         | 29.4      | -         |
| 4  | The temperature of the water used in the stages:                           |           |           |           |
|    | a) sinks, K                                                                 | 313       | -         | 323       |
|    | b) hydration, K                                                             | -         | 323       | -         |
| 5  | The amount of steam at the stage of PHT, kg                                 | -         | 170       | 50        |
| 6  | Groat humidity:                                                             |           |           |           |
|    | a) after cooking, %                                                         | 35.0      | 36.6      | 36.3      |
|    | b) after drying, %                                                          | 9.0       | 9.0       | 9.0       |
| 7  | Steam pressure at the inlet to the control surface of the cooking, MPa      | 0.15      | 0.2       | 0.13      | 0.1       |
| 8  | Product temperature, K:                                                     |           |           |           |
|    | a) before drying                                                            | 293       | 363       | 372       |
|    | b) before conditioning                                                      | 353       | 363       | 393       |
|    | c) after conditioning                                                       | 333       | 333       | 353       |
|    | d) after drying                                                             | 318       | 318       | 393       |
| 9  | Fluid temperature before drying, K                                          | 353       | 363       | 413       |

The mass fraction of exergy spent on heat and mass transfer processes inside the control surface is determined by the equation:

$$\Delta F_o = \sum_{i=1}^{n} \Delta r_{i}$$  \hspace{1cm} (2)$$

where $\sum_{i=1}^{n} \Delta r_{i}$ – the total change in the entropy of all substances involved in the process of moisture-thermal treatment, determined by the equation:

$$\sum_{i=1}^{n} \Delta s_{f_i} = \Delta s_{f_i} + \Delta s_{o_i} = c_{1} \ln \left( \frac{T_{ik}}{T_{io}} \right)$$  \hspace{1cm} (3)$$
where \( \Delta S_{tm} \) and \( \Delta S_{tm}^{\prime} \) – changes in entropy, respectively, of dry matter and moisture of the product, kJ / kg; \( T_{in}, T_{hk} \) – changes in entropy, respectively, at the beginning and at the end of moisture-thermal treatment, K.

For the exergy of the energy flow, the basic equation of the exergy balance of technological processes can be represented in the general form by the relation:

\[
\sum_{i=1}^{n} E_{mi} = \sum_{i=1}^{n} E_{mi}^{\prime} + \sum_{i=1}^{n} \Delta E_{mi},
\]

where \( \sum_{i=1}^{n} A_{mi} \) – the sum of the exergy of the initial material flows in front of the control surface, kJ; \( \sum_{i=1}^{n} A_{mi}^{\prime} \) – the sum of exergy of the final material flows after the control surface, kJ; \( \sum_{i=1}^{n} \Delta E_{mi} \) – the sum of external and internal exergy losses due to the irreversible nature of technological processes, kJ.

To assess the energy efficiency and comparative exergy analysis of individual technological processes and various ETS of processing raw materials, thermal and exergy efficiency were used.

The thermal efficiency of the ETS was determined by the formula:

\[
\eta_{et} = \frac{Q_{mij} \left( \sum_{i=1}^{n} Q_{ij} \right)^{-1}}{100\%} = \left[ 1 - \sum_{i=1}^{n} Q_{ij} \left( \sum_{i=1}^{n} Q_{ij} \right)^{-1} \right] \cdot 100\%.
\]

where \( Q_{mij} \) - useful heat of the i-control surface j – schemes, kJ; where \( \sum_{i=1}^{n} Q_{ij} \) - total amount of heat entering the i-control surface of j – schemes, kJ; \( \sum_{i=1}^{n} Q_{ij} \) - total heat loss of the entire technological scheme.

Based on the exergy balance of the process, the exergy efficiency of the processes is equal to

\[
\eta_{e} = \sum_{i=1}^{n} E_{mi} \left( \sum_{i=1}^{n} E_{mi}^{\prime} \right)^{-1} \cdot 100\% = \left[ 1 - \sum_{i=1}^{n} E_{mi} \left( \sum_{i=1}^{n} E_{mi}^{\prime} \right)^{-1} \right] \cdot 100\%,
\]

where \( \sum_{i=1}^{n} E_{mi}^{\prime} \) – the sum of useful process exergy, kJ.

5. The discussion of the results

It was revealed that the main stages of the production of groats concentrates, which have a significant impact on the amount of energy and exergy, are associated with heat and mass transfer processes of moisture adsorption (PHT, hydration, cooking, etc.) and moisture removal (drying), which, due to their energy intensity, determines the cost of the finished products [2-5].

The exergy efficiency of Scheme III is 12.92% and, as a result, is 1.705 times higher compared to the same indicator for Scheme II and Scheme I – 2.094 times, which is due to more efficient use of the energy potential of the coolant in the processes of PHT, cooking and drying with recirculation, as well as heating the intermediate product after conditioning, water for PHT and cooking (Fig. 1, Table 2).

The exergy necessary for the production of groats concentrates is spent on the movement of moisture inside the processed groats (moisture gain and moisture removal) with the transformation of substances and product structures, as well as to cover losses arising from the irreversibility of heating processes and physico-chemical changes in the product’s substances relative to the environment.
Table 2. Exergy efficiency of various technological schemes for the production of cooked-dried rice groats

| Indicators | Designation | Technological schemes |
|------------|-------------|-----------------------|
|            |             | I         | II         | III        |
| The total cost of exergy for the entire technological scheme, kJ | \( \sum_{i=1}^{n} E_{i}^{mi} \) | 651453.735 | 792683.926 | 1236679.69 |
| Useful component of exergy according to the scheme with intermediate rolling based on useful work in control surfaces and use of waste coolant, kJ | \( \sum_{i=1}^{p} E_{i}^{w} \) | 40187.928 | 58980.56 | 159755.28 |

The total amount of useful exergy consists of exergy of the initial product, its increments during heating and physico-chemical change of substances, as well as exergy of the coolant used for recycling without loss to the environment.

**Figure 1.** Thermal (a) and exergy (b) efficiencies of various technological schemes for the production of cooked-dried rice groats

Confirmation of the proof of a better analysis of technological processes and the whole schemes based on exergy is the consideration, as an example, of a separate drying process with intermediate conditioning according to scheme III from the standpoint of thermal and exergy balances.

The useful component of exergy during drying, for example, of cooked-dried rice groats with intermediate conditioning and heating of the product is 17.791%, during thermal analysis, the useful component of heat is 78.943%, the total loss of exergy is 82.209%, and heat is 21.057%. Consequently, the exergy indicator more "rigidly" evaluates from a qualitative point of view the degree of effective use of the energy potential of the coolant and heat fluxes of the ETS.

The analysis of internal exergetic losses in the control surfaces of PHT, cooking and drying of cooked-dried rice groats show that they do not exceed 5% and are, respectively, 2.13%, 0.79% and 4.65%.

These losses are due to the irreversibility of establishing finite differences in temperature and equi-
librium moisture content of the product, i.e. deviation of the considered thermodynamic system from the equilibrium state. It was noted that the change in groats temperature in these processes is 303 K, 322 K, and 294 K, respectively, and the humidity change is 13.0%, 9.3%, and 27.3%. Similar results were obtained for boiled pearl-barley and buckwheat groats.

This circumstance allows us to conclude that internal exergy losses in control surfaces are more dependent on mass transfer processes and, to a lesser extent, on heat transfer.

To assess the energy efficiency and comparative exergy analysis of various ETS for processing raw materials, it is proposed to use, along with exergy efficiency, specific exergy values characterizing exergy costs per unit of dried finished product (kJ / t), per unit of moisture removal and moisture gain (kJ / (kg %)), taking into account the fact that a change in the moisture content of a product has a greater effect on exergy compared to a change in temperature.

A comparative thermodynamic assessment of the calculated heat and exergy fluxes of heat and mass transfer processes for the production of cooked-dried groats of the known and proposed technological schemes allowed us to offer directions for improving the processing technologies of raw materials and their apparatus design in terms of reducing energy consumption and ensuring resource conservation.

6. Conclusion
A thermodynamic assessment of the phenomena of heat and mass transfer of energy-technological systems for the production of groat concentrates based on the theoretical and experimental studies, which resulted in the development of recommendations on the scientific and practical support for heat and mass transfer processes of moisture-thermal treatment of primary product. It has been proven that a change in product moisture has a greater effect on exergy than a change in temperature does.

It is suggested to use, for an assessment of energy efficiency and a comparative exergy analysis of various ETS for processing raw materials, along with exergy efficiency, specific exergy values characterizing exergy costs per unit of dried finished product, per unit of moisture removal and moisture adsorption.

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