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DEVELOPMENT OF POWER-EFFICIENT AND ENVIRONMENTALLY SAFE COFFEE PRODUCT TECHNOLOGIES

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На основі енергетичного й екологічного аудиту проведено аналіз матеріальних потоків, конверсії енергії, викидів в атмосферу й літосферу при виробництві розчинної кави.

Для підвищення енергоефективності, зниження екологічного навантаження розроблені інноваційні технологічні схеми й устаткування по переробці відходів і виробництву нових кавових продуктів.

Проведено експериментальне моделювання: кінетики мікрохвильового екстрагування водорозчинних речовин і масла з кавового шламу; гідравліки плину экстрагента через касети мікрохвильового екстрактора. Експериментальні дані узагальнені у вигляді критериального рівняння.

У результаті експериментального моделювання кінетики екстрагування встановлено, що тривалість процесу в мікрохвильовому полі приблизно в 20 разів менше, ніж у термостаті. Дія мікрохвильового поля впливає на швидкість екстрагування більшою мірою, чим температура процесу. Підвищення потужності мікрохвильової енергії підвищує вихід екстрактивних речовин з кавового шламу більш ніж у два рази.

Визначено технічні характеристики мікрохвильового екстрактора масла. Випробування зразка екстрактора проводилися при питомій потужності 180…240 Вт/кг у режимі кипіння екстрагенту. У якості екстрагенту використовувався етанол (концентрація 93…96 %). У результаті випробувань отримане якісне кавове масло, що характеризується вираженим ароматом і смаком кави й інтенсивним темно-коричневим фарбуванням.

Розроблено технологічну схему передекстрагування кави зі шламу. Додатковий витяг зі шламу кави водорозчинних екстрактивних речовин, підвищує вихід екстракту на 10…12 %. Істотно знижено температурний режим екстрагування, зменшені тривалість і енергоємність процесу.

Розроблено інноваційну технологічну схему виробництва рідкого концентрату кави – основи для напоїв на базі кави, готових до безпосереднього вживання. Концентрація сухих речовин становить 50…65 %

Ключові слова: харчові концентрати, масло кави, кавовий шлам, мікрохвильове екстрагування, енергетичний моніторинг

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1. Introduction

Food concentrates (FC) are characterized by speed of preparation, long shelf life and high quality. It is these qualities of FC that attract the interest of a wide range of consumers. Currently, most of the world's inhabitants are increasingly turning to products of the food concentrate industry [1]. Range of FCs and their markets expand rapidly. These are first and second courses, desserts, and drinks [2]. The instant coffee powder has become the most popular FC product in the world. The number of workers employed in the world coffee industry has reached 25 million.

In recent years, sales of instant coffee have been growing rapidly in the world [3]. Coffee is the second largest commodity after oil and the second most popular drink after water. Most manufacturers of coffee products face high prices for imported raw materials and energy. The key production operations, extraction and drying, are characterized by energy intensity and environmental problems [4, 5]. Since manufacturers of coffee products cannot exert influence upon the cost of raw materials, there are two competitive lines of action. The first implies innovative technologies aimed at the improvement of drying and extraction processes. The second means the use of innovative technologies of integrated processing of raw materials and switching production to green industry principles.

An urgent problem that the manufacturers of coffee products are facing currently is not just how to dispose of production waste but also the elaboration of new technological solutions that would cut down power consumption, reduce the burden on the environment and raise the product range.

Volumetric, gradient-free principles of power input to the elements of vegetable raw materials are considered to be new effective technologies of extraction and processing of raw materials. Transfer processes in such systems were intensified several times and sometimes by orders of magnitude.

It is the principles of targeted energy delivery in the processing of food raw materials that make it possible to develop innovative power-efficient equipment. The use of such equipment will enable the creation of fundamentally new manufacturing lines for processing waste and making coffee products.

2. Literature review and problem statement

The coffee industry produces a huge amount of waste in the form of spent coffee slurry which is one of the main by-products. Recycling such waste into fuel and value-added products is a promising way to solve problems of many countries that face daily difficulties and high waste disposal costs.

Various possibilities for using coffee slurry are discussed, namely, production of biofuel [6], biodiesel [7], biogas [8], bioethanol, fuel pellets [9, 10] and bio-oil [11]. It is proposed to produce value-added products from coffee slurry, such as bioactive compounds, adsorbents, polymers, nanocomposites [12] and compost [13].

However, issues related to system analysis of heat technologies for the production of instant coffee and food concentrates remained unresolved in [6–13]. It may be caused by the fact that researchers pay more attention to the problems of waste disposal though the technology of instant coffee production has immense reserves of improvement of energy efficiency and reduction of burden on the environment. It is advisable to conduct energy and environmental audit of heat technologies used in coffee production, identify reserves, develop and substantiate new flow diagrams.

Various equipment and technologies for extracting valuable substances from coffee and coffee slurry are offered. Mainly, equipment based on microwave (MW) extractors is being developed. It is proposed to use microwave extraction to extract polysaccharides from waste coffee slurry [14], green coffee oil [15], natural antioxidants from coffee slurry using ethanol as a solvent [16] or valuable polyphenol compounds from coffee slurry [17].

Results of studies of MW extraction of oil from green coffee beans are presented in [15]. It was shown that the use of MW extraction allowed the process to be carried out for 10 minutes at 45 °C compared with four-hour extraction in a Soxhlet apparatus. The obtained extracts show high antioxidant activity. However, issues related to the extraction of oil from coffee slurry remained unresolved. Perhaps this is because of the fact that oil content in ground coffee is greater than in waste. But studies show that slurry contains 7...12 % coffee oil. Residual substances in coffee slurry have a full chemical composition and are not inferior in quality to those contained in coffee. Slurry is a valuable additional source of coffee oil. Obtaining coffee oil from slurry and not from ground coffee will significantly reduce the cost of the product. It is advisable to conduct a study of the kinetics of extraction of water-soluble substances and oils from coffee slurry.

Results of studies of MW extraction of used filtered coffee which is waste in restaurants, cafes and households are presented in [16, 17]. Ethanol of 20 % concentration was used as an extractant. The result is an extract of polyphenols with high antioxidant activity. However, the issues related to the use of industrial line waste remain unresolved. The design of an industrial installation was not considered. It is advisable to conduct studies for conditions at the industrial scale.

Options of liquid extraction under pressure are considered [18] for obtaining oil from green coffee beans at low temperature (50 °C); and MW extraction of oil from waste coffee slurry using a solvent of CO_2 and ethanol [19]. It is shown that the use of these methods provides a high yield of extractive substances. The duration of the process is reduced and a less organic solvent is used. Results of studies of MW extraction of polysaccharides from waste coffee slurry are presented in [14]. Experiments were carried out in conditions of elevated temperature (140...200 °C) and pressure (4 MPa) but the use of high pressures, especially supercritical CO_2 extraction results in additional energy consumption. Complicated hardware implementation of the process is inherent in these technologies. It is advisable to design a universal power-efficient MW extractor that will provide operating modes at temperatures up to 100 °C and atmospheric pressure.

Recently, studies of drying food raw materials in infrared, MW field are intensively carried out [20–22]. It was shown that the application of these methods provides intensification of transfer processes several times and sometimes by orders of magnitude. However, the issues related to the use of such technologies in the production of instant coffee and food concentrates remained unresolved. Perhaps this is because of the fact that the abovementioned equipment is difficult to scale up for industrial facilities.

3. The aim and objectives of the study

The study objective is to develop power-efficient and environmentally friendly technologies for the manufacture of coffee products.

To achieve this objective, the following tasks were set:

– to conduct energy and environmental audit of material flows, energy conversion, emissions into atmosphere and lithosphere taking place in the production of instant coffee;

– to conduct experimental modeling of the process of microwave extraction of water-soluble substances and oil from coffee slurry, hydraulics of extractant flow through the MW extractor cassettes, summarize the obtained data in a form of a criterion equation;

– to elaborate a flow diagram of pre-extraction of coffee from slurry, determine characteristics of the semi-industrial installation, that is an MW extractor;

– to develop a flow diagram for processing coffee slurry, determine technical characteristics of a microwave oil extractor;

– to develop an innovative flow diagram for the production of liquid coffee concentrate.

4. Methods used in conducting energy and environmental audits and studies of the microwave extraction process

An energy audit of the instant coffee production line was performed according to the developed experiment-calculation procedure of determining heat losses [23] and using methods of heat balances. The environmental audit was based on the study of material flows of raw materials, semi-finished and finished products.

The bulk of experimental studies was devoted to extraction processes. The experiments were carried out at 4 experimental benches. A detailed description of the benches is given in [4, 5]. Bench 1 consisted of a dry-air thermostat and a container with ground coffee beans and extractant. Extraction modes of conventional technologies were simulated there. It is the results obtained at this bench that the data of benches 2–5 were compared with. An MW chamber was the main element of the bench 2. Radiation power was controlled and measured, temperature and concentration were determined. Experiments were carried out at benches 2 and 3 to extract water-soluble substances from coffee slurry.

The experimental program at bench 2 provided sequential operations of draining the extract and adding fresh extractant (water) to the slurry. Eleven fillings of coffee slurry with water at 80 °C and hydro modulus of 1:4 were made. Mass transfer of 0.5...2 mm particle fraction obtained after sieving from coffee slurry was studied under the action of electrophysical effect on the total amount of extractable substances. Extractability was determined by solution saturation [4, 5].

The influence of main parameters on the process of MW extraction from coffee slurry was studied at bench 3. Specific power was set equal to 270, 450, 630, 900 W/kg. The slurry layer height was 8, 14, 20 and 27 mm. The volumetric flow rate of the extractant was varied: $1\cdot10^{-6}$, $2\cdot10^{-6}$ and $3\cdot10^{-6}$ m^3/s. Hydro modulus was 1:3 and 1:10. The temperature was controlled by a radiation pyrometer and a DAN-1000 electronic thermometer.

Experiments on the kinetics of coffee oil extraction under conditions of MW field were conducted at bench 4. Experiments on the extraction of oils from coffee slurry were carried out in a wide range of temperatures, volumes and extractants differing in their chemical nature and interaction with the microwave field.

5. Results of energy and environmental audit and the studies of the microwave extraction process

5. 1. Results of energy and environmental audits in the production of instant coffee

Let us consider in more detail thermal engineering aspects of the instant coffee technology (Fig. 1). Heat *Qo* and *Qe* is lost from the roasting oven (RO) and extractors, respectively. The extract (E) is dehydrated with emission into the atmosphere of spent heat carrier (SHC) containing dust of instant coffee (IC). Loss of heat with a flow of finished product (IC) takes place. Slurry (S) in a volume of about 70 % of the charge stock is discharged from the extractor.

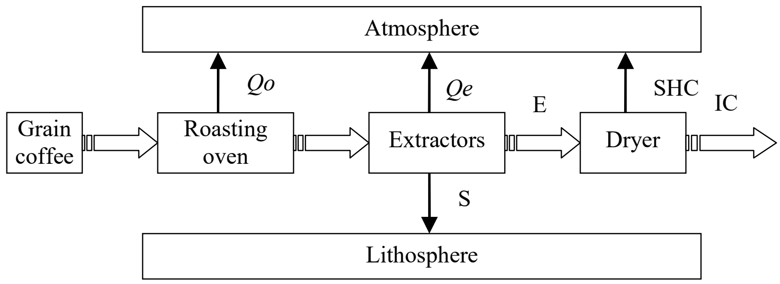

Fig. 1. Flows of raw materials, energy, and waste in the production of instant coffee where *Qo* is the heat loss from the roasting ovens; *Qe* is the heat loss from extractors; IC is the heat loss from the finished product flow; E is the extract; SHC is the spent heat carrier; S is the slurry

Analysis of material costs for resources in instant coffee technologies shows that the main costs are associated with payments for natural gas (66...70 %). The cost of electricity is 23...24 % and water cost is 7...10 %.

Main problems in the production of instant coffee: significant power intensity of the equipment, the process duration (7...8 hours) and the use of high pressure in extractors (0.3...1.5 MPa).

There are losses of valuable volatile flavoring and aromatic substances in the production process at the stages of grinding, storage, extraction and drying. These losses make up more than 80 % of their initial amount in roasted grains. With emissions of heat carriers, 8,200 GJ of thermal energy and 4,560 kg of the finished product (coffee powder) are lost per year from one dryer.

Ecological monitoring of the production of instant coffee has shown that the enterprise caused a serious environmental burden. Components of the flow of spent heat carrier such as moisture and coffee dust as well as heat are atmosphere pollutants. Coffee slurry is the source of lithosphere pollution. Despite the seriousness of environmental problems associated with specifics of coffee slurry loss of valuable substances with it (Table 1), there are no practical examples of its complete processing.

Table 1

Coffee slurry structure

No.	Component	Content, %	Ways of recycling
1	Water solvable substances	4	Complete extraction
2	Coffee oil	7...12	Extraction
3	Flavoring and aromatizing substances	3...5	Distillation
4	Proteins	5...7	Activation
5	Cellulose and lignin	60...75	Briquetting

Environment protection systems are proposed for collecting heat, moisture and dust of food products from aerosol emissions of dryers and deep processing of coffee slurry. When recycling slurry by extraction, coffee oil is obtained. Activation of defatted slurry makes it possible to get a binder component and produce building materials on its basis. Sequential processing of slurry in dryers and press granulators and briquetting will enable the production of agro pellets.

It is advisable to install systems of comprehensive recycling of heat and dust (HMU) of food products on coffee spraying dryers (SD). It is proposed to use electromagnetic generators of targeted energy delivery in extractors of liquid coffee concentrates (E2) and coffee oil (Eo). It is possible to solve the energy delivery problems at an enterprise of spent coffee grounds (SCG) conversion into agro pellets (Dp) which can completely replace natural gas in heating system and SD. Infrared generators (IRG) are of interest as they can be used in belt dryers (BD) as additional or independent heating elements. Microwave (MW) generators are effective. A system of such heat technologies of targeted delivery of energy to the elements of food raw materials will make it possible to switch production to the eco-industrial tracks (Fig. 2).

The characteristics of the process flows are given in Table 2.

The developed design of the heat and mass utilizer (TMU) was introduced into the line for drying instant coffee at a factory of food concentrates (Odesa, Ukraine) [23]. The recycling system reduces heat loss by up to 75 % and extracts up to 99 % of the food product dust, that is, coffee powder, from gas emissions during drying.

Serious reserves of reduction of energy consumption at the instant coffee production line consist of organizational measures. Only compliance with standard operating modes of equipment will reduce energy consumption from 18 % (in a boiler room) to 40 % (in the spraying dryer). Projects of recycling heat emissions of power-intensive equipment, the arrangement of thermal insulation are considered as the second stage of improvement of heat consuming technologies. Implementation of innovative projects of targeted energy delivery in drying and extraction technologies is the third stage of modernization.

Table 2

Structure of the process and energy flows

No.	Device	Process	Flow structure	
			entry	exit
1	Roasting oven (RO)	Dehydration and roasting	Raw grain coffee: Cs=20...33 %; Ws=10...15 %	Grain coffee: Cs=20...33 %; Ws=5...7 %
2	Mixer (M1)	Mixing	Grain coffee Cs=20...33 %; Extractant: water, *t*=20 °C	Grain coffee Cs=20...33 %; Extractant: water, *t*=160 °C
3	Extractor (E1)	Extraction	Grain coffee Cs=20...33 %; Extractant: water	Extract, Xe=19 %; SCG, Cscg=4...5 %
4	Evaporation unit (EU1)	Concentration	Extract, Xe=19 %	Extract, Xe=28 %
5	Dryer (SD)	Spraying drying	Extract, Xe=28 %; heat carrier, *t*=230 °C	Dust, Cd=95 %; heat carrier, *t*=140 °C
6	Heat and mass utilizer (HMU)	Air heating, condensation, dust solving	Gas, t=140 °C; 0.055 g per 1 m^3 of coffee dust	Solution, Xe=8 % air, *t*=60 °C
7	Extractor (E2)	Additional extraction	SCG, Cc=4...5 %; water	SCG, Cc=0,5 % extract, Xe=4...5 %
8	Belt dryer (BD)	SCG drying	SCG, Co=12 %; moisture, *w*=80...82 %	SCG, Co=12 %; moisture, w=9 %
9	Mixer (Ms)	Mixing	SCG, Co=12 %; extractant	SCG, Co=12 %; extractant
10	Oil extractor (OE)	Coffee oil extraction	SCG, Co=12 %	Oil extract
11	Evaporating unit (EU2)	Solvent distillation	Oil extract	Extractant, coffee oil
12	Press granulator (PG)	Briquetting	Defatted dry slurry	Pellets

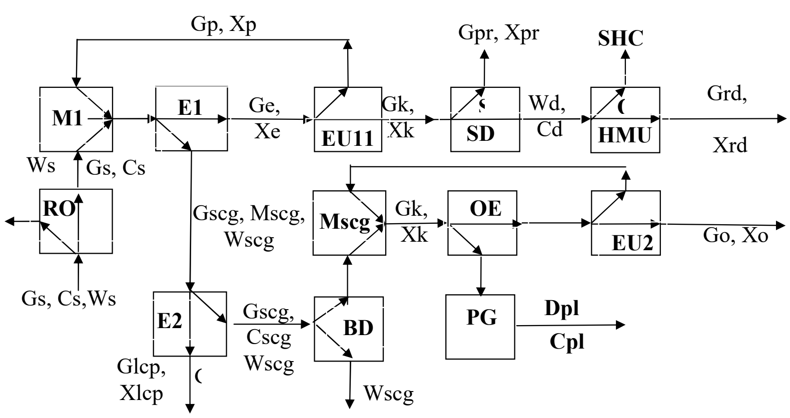

Fig. 2. Schematic diagram of a system of innovative heating technologies of coffee production: RO — roasting oven; M1, Ms — mixers; E1, E2 — extractors; EU1, EU2 — evaporation units; SD — spraying dryer, HMU — heat and mass utilizer; BD — belt dryer; OE — oil extractor; PG — press granulator; SHC — spent heat carrier; C, X — concentrations in a solid phase and in a solution, respectively; W — moisture content; t — temperature; indices: s — raw material; e — extract; o — oil; d — dust, scg — spent coffee grounds; p — solvent; pr — product (instant coffee); k — concentrate; lcp — liquid concentrated product; rd — recycled dust; pl — pellets

5. 2. Results of studies of the microwave extraction process

Values of ultimate concentration of extractive substances, the process hydraulics, effect of mode parameters and extractant flow rate on the intensity of mass transfer in extraction processes were studied successively.

The maximum concentration of extractives in the coffee slurry was found at bench 2. Fig. 3 shows the distribution of the amount of extracted soluble substances among fillings.

A total of 0.8 g of extractive substances were extracted from 100 g of coffee slurry under electromagnetic exposure. At the first filling, 0.16 % of the total amount of extractive substances were extracted from the samples exposed to electromagnetic effect, 0.12 % on the second filling, 0.08 % on the third filling. Values of 0.08 %, 0.08 %, 0.08 %, 0.06 %, 0.04 %, 0.04 %; 0.036 % and 0.028 % were obtained on subsequent fillings 4 through 11, respectively (Fig. 3).

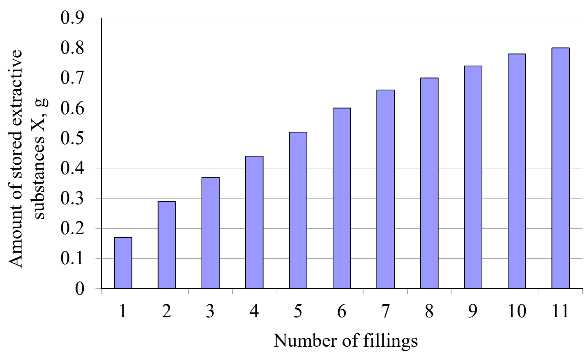

Fig. 3. Ultimate concentrations of extractive substances in coffee slurry

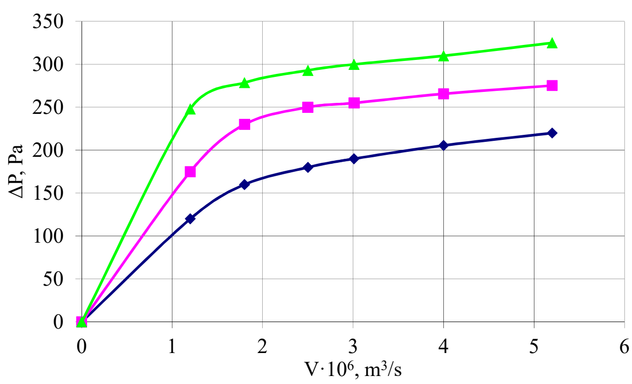

Fig. 4. Hydraulics of cassettes. Height of the product layer in the cassette: 1 – δ =2.7·10^{-2} m; 2 – δ =2·10^{-2} m; 3 – δ =1.4·10^{-2} m

Experiments were carried out on bench 3 to study hydraulics of extractant flow through cassettes (Fig. 4). It was established that in order to ensure thin-layer flows in the product and increase interphase surface, it is advisable to operate in flow ranges of 1.4·10^{-6}...4.2·10^{-6} m^3/s and with the values of the layer thickness of coffee raw materials of 1·10^{-2}...3·10^{-2} m.

The effect of applied microwave power, the height of slurry and the volumetric flow rate of extractant on the kinetics of extraction of substances from slurry were determined at bench 3 (Fig. 5).

Observations (Fig. 5, *a*) have shown that an increase in power of MW energy increased yield of extracts from coffee slurry by more than two times and significantly reduced the process duration and, therefore, reduced power intensity of the process of production of coffee extracts from coffee raw materials.

It was found that with an increase in the volumetric flow rate of extractant by a factor of 3, yield of extractives from slurry increased by 35 % and extraction time decreased by a factor of 2 (Fig. 5, *c*). This is a factor of a significant decrease in external diffusion resistance. With an increase in flow rate by 2.5...3.5 times, effective mass transfer coefficient increased by 2.7...5 times, respectively.

As a result of processing the array of experimental data, a relationship was obtained that takes into account the influence of the Reynolds and Schmidt numbers and the number of energy action (Bu). It was recommended to be used when calculating mass transfer intensity during the extraction of coffee products from coffee slurry under the effect of microwave field:

$$St_m=0{,}004\,(Re)^{-0{,}5}\,(Sc)^{0{,}43}(\Pi)^{0{,}6}(Bu)^{0{,}33}, \quad (1)$$

where St_m is the Stanton mass transfer number; Re is the Reynolds number; Sc is the Schmidt number; Π is the dimensionless parametric permeability; Bu is the Burdo number.

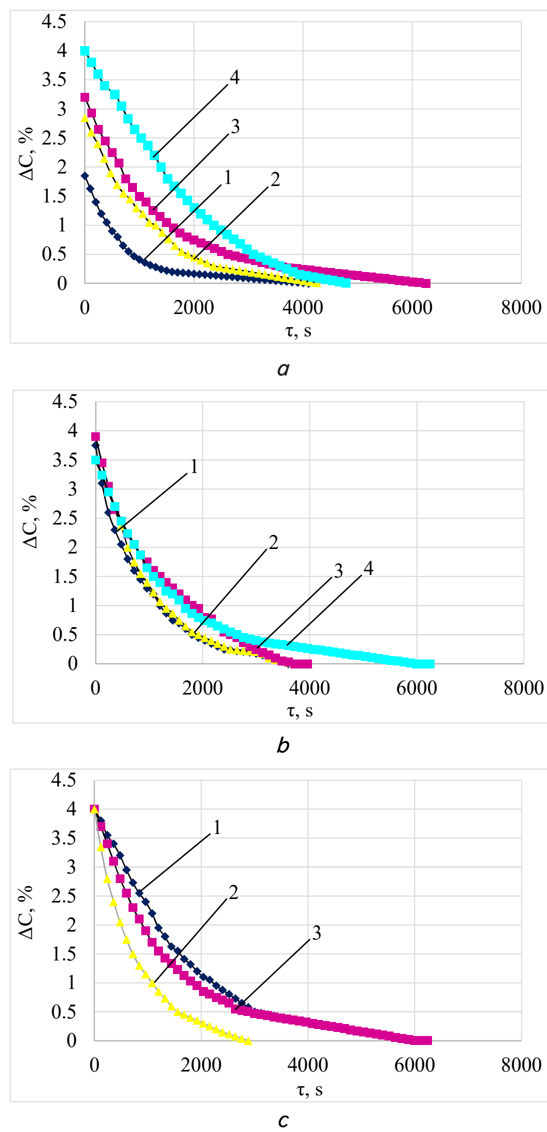

Fig. 5. Mass transfer kinetics of water-soluble substances in a MW field: *a* – applied microwave power: 1 – 270 W/kg; 2 – 630 W/kg; 3 – 450 W/kg; 4 – 900 W/kg; *b* – slurry layer height: 1 – δ=0.008 m; 2 – δ=0.014 m; 3 – δ=0.020 m; 4 – δ=0.027 m; *c* – volumetric flow rate of the extract: 1 – V=1·10^{-6} m^3/s; 2 – V=2·10^{-6} m^3/s; 3 – V=3·10^{-6} m^3/s

According to relation (1), the maximum relative calculation error was 17.6 % and it was observed at small values of the Stanton number.

In order to establish the effect of a microwave field on the intensity of the extraction process, experiments were performed both under conditions of conventional thermal supply of energy and in a microwave field.

A comparison of extraction intensity in a microwave extractor (bench 4) and in a thermostat (bench 1) without extractant boiling is shown in Fig. 6, 7.

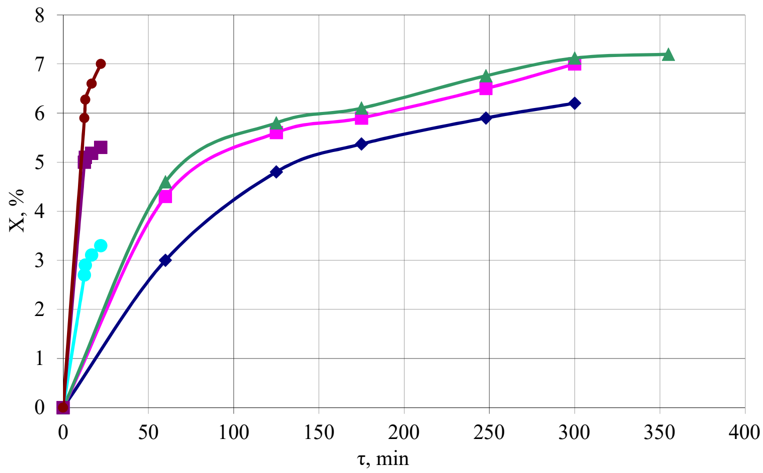

Fig. 6. Influence of the nature of energy supply on hexane extraction:
1 — thermostat, 40 °C; 2 — thermostat, 50 °C; 3 — thermostat, 60 °C;
4 — in a MW field, 40 °C; 5 — in a MW field, 50 °C; 6 — in a MW field, 60 °C

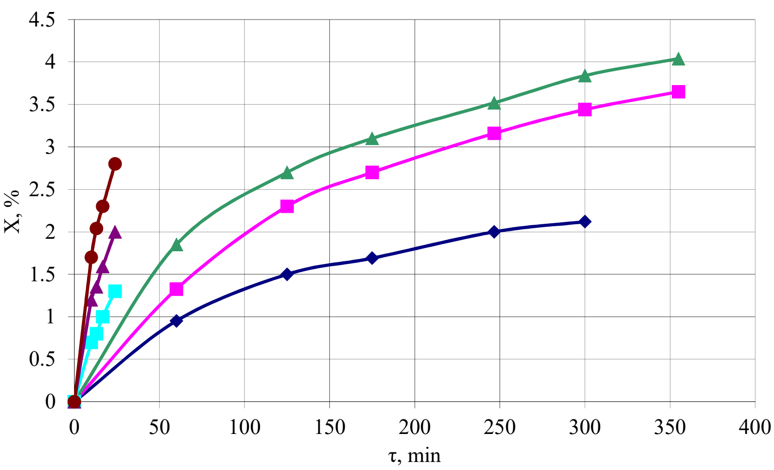

Fig. 7. Influence of energy supply nature on ethanol extraction:
1 — thermostat, 40 °C; 2 — thermostat, 50 °C; 3 — thermostat, 60 °C;
4 — in a MW field, 40 °C; 5 — in a MW field, 50 °C; 6 — in a MW field, 60 °C

With the growth of temperature, the rate of extraction from slurry increases in a microwave field (Fig. 6, 7) and in a case of solvent boiling, the processing speed and amount of extracted substances are much higher. This is explained by the turbulization of the near-boundary layer.

Processing of the array of experimental data has given equations of ethyl alcohol (2) and hexane (3) for calculating the process of mass transfer of oil from coffee slurry under influence of a microwave field.

$$Sh=0.0137(Sc)^{0.33}(\Gamma)^{0.15}(Bu)^{0.71}, \quad (2)$$

$$Sh=0.01(Sc)^{0.33}(\Gamma)^{0.05}(Bu)^{0.32}, \quad (3)$$

where Sh is the Sherwood number; Sc is the Schmidt number; Γ is hydro modulus; Bu is the Burdo number.

Unlike hexane, ethanol promotes the transition of additional aromatic components to the extract.

5. 3 Innovative technological line for pre-extraction of coffee from slurry

The problem consisted of an additional extraction of water-soluble substances from slurry in a continuous counterflow mode. The problem solution is based on the use of microwave extraction technologies. It seems appropriate to supply not pure water (as it is provided by the conventional technology) to the extraction batteries but an extract pre-saturated with coffee components extracted from the slurry. The process of such extractant preparation was called "pre-extraction" and the production complex for this problem was respectively called the line of "pre-extraction" from coffee slurry (LPES). According to the proposed scheme (Fig. 8), an extract with a concentration of up to 2…4 % is loaded to diffusion batteries. The depleted solid portion of the slurry is fed for further processing. The LPES processes proceed in the following sequence. Slurry from hopper 1 is fed by screw 2 to the point of slurry loading into cassettes 3. Next, the cassettes with raw material enter the MW extractor 4 where slurry is subjected to extraction with water at 80…95 °C. The separated solid portion is fed from the extractor to the dryer and the liquid portion is sent through the filter 6 to the intermediate tank 7 from where the extract having a concentration of up to 2…4 % is sent to the extraction batteries.

The microwave extractor is the key element in the LPES (Fig. 8). A prototype installation with parameters given in Table 3 was designed.

Table 3

Characteristics of a semi-industrial installation, the MW extractor

Parameters	MW extractor
Power consumed by MW radiators, kW	≤7.3 kW
Working volume, l	180
Overall dimensions of the installation (L/W/H), m	0.52/0.68/2.05
Output (by raw material), kg/h	≤24

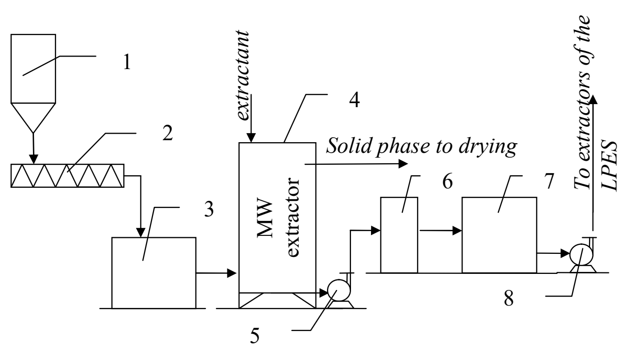

Fig. 8. Schematic diagram of the line of pre-extraction from coffee slurry: 1 — hopper; 2 — screw conveyer; 3 — station of loading slurry into cassettes; 4 — MW extractor; 5, 8 — pump; 6 — filter; 7 — intermediate tank

An experimental industrial sample of the MW extractor [4] is a continuous apparatus designed for the "solid-liquid" system. Its housing is built from a cascade of resonator chambers of stainless steel with magnetrons. The bottom of the upper chambers is connected with the surface of the lower chambers by lock channels. Cassette blocks with raw material loaded in them move through these channels. Cassettes have a hole in their lids into which a connecting pipe is inserted from the upper cassette. The connecting pipe is located at the bottom of the cassette in the area opposite to the hole. The inlet to the openings in the uppermost cassette is connected with the input container with extractant and the connecting pipe of the lowest cassette is located in the area of the extractant storage tank whose outlet is connected with the container of the finished product. Each of the chambers is equipped with a control panel with a digital display showing power level and a timer. A possibility is provided for controlling the extractant flow rate in a required range and speed of the solid phase movement.

Distribution of energy depending on loading of the chamber cassettes which varied from 0.15 to 0.75 kg was studied by the methods of thermal balances at an applied microwave power of N=900 W and water flow.

The study results have shown that with a five-fold increase in cassette loading, the net power of heat flux increased by 86 %. It was established that the net power of heat flux was ΣQ=1,186 W during the operation of two installation chambers (2 and 4). When three chambers (1, 3 and 5) were in operation, net power of heat flux was ΣQ=1,954 W. Observations have shown that distribution of heat flux power is affected by location of the cassette relative to the microwave radiator: the farther is the cassette from the radiator, the lower the net heat flux power.

5. 4. Flow diagram for processing coffee slurry

The line includes a dryer in which slurry with an initial moisture content of 80...82 % is dried to moisture content of 8...10 %, an extractor-concentrator in which oil is extracted and concentrated. The dry defatted slurry can be used as fuel, filler for mixed fodder, etc.

Microwave extractor is the key element in the scheme. A prototype microwave extractor was built. In fact, this is a multifunctional unit performing the main operation, which is the extraction of oil from slurry and additional operation of distilling the extractant from the spent solid fraction [4].

Specifications of the device are given in Table 4.

Table 4

Specifications of the microwave oil extractor

No.	Parameter	Value
1	Magnetron power	3 kW
2	Reaction volume	0.02 m^3
3	Slurry weight	1.6...6.0 kg
4	Oil yield	13...20 %
5	Extraction time	30...90 min

Oil yield is related to the dry slurry weight. The device with parameters given in Table 4 has passed bench tests. The extractor sample was tested at a specific power of 180...240 W/kg of the mixture in the mode of boiling extractant. Ethanol (concentration of 93...96 %) was used as an extractant.

As a result of the tests, coffee oil was obtained. It was characterized by a pronounced aroma and a coffee taste with an intense dark brown color.

The studies performed were used in the coffee slurry processing line. "Pre-extraction" is made at the first stage. Coffee oil and pellets are produced in the second stage (Fig. 9).

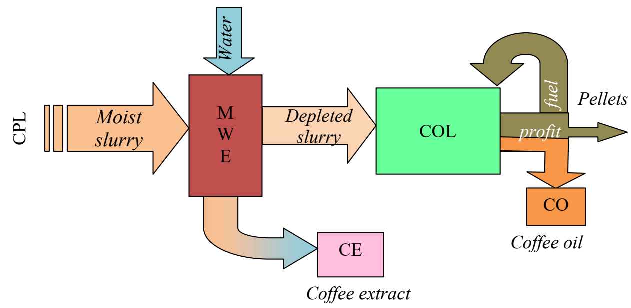

Fig. 9. The diagram of the distribution of raw material flows: CPL – coffee production line; COL – coffee oil production line; MWE – microwave extractor; CO – coffee oil; CE – coffee extract

From the coffee production line (CPL), wet coffee slurry goes to the MW extractor which also receives the water as an extractant. After extraction, two flows of substances are formed: a coffee extract and a solid phase (slurry depleted by water-soluble components). Next, slurry goes to the coffee oil production line (COL). The defatted slurry is fed to the pellet production line (PL). Pellets can be used as fuel at the enterprise, in particular, in the slurry dryer of the pellet production line. Excess pellets can be sold to make a profit [4].

5. 5. Flow diagram of production of liquid coffee concentrate

The basic flow diagram of such a line is fully consistent with that given in Fig. 8. The only difference is that the cassettes are loaded with ground coffee grains. The process temperature levels do not exceed 100 °C, pressure in the apparatus is ambient. The most attractive is the exclusion of the convective drying from the technology. It is in the dryer that the greatest loss of aromatic components occurs and namely, drying is associated with the main energy consumption. Therefore, according to the scheme (Fig. 8), two positive effects are expected: a significant increase in the quality of the finished product and a sharp decrease in specific energy consumption for the manufacture of the finished product. Naturally, a transition to the proposed technology is associated with certain difficulties but the expected effect justifies their overcoming.

In the present study, experimental samples of liquid coffee concentrate were obtained on an MW extractor and their tasting studies were carried out. The samples were distinguished by a high content of aromatic components and original shades of taste.

6. Discussion of the results obtained in energy and environmental audits and studies of the microwave extraction process

For all slurry layer heights, i. e. 27 mm, 20 mm and 14 mm (lines 1, 2, and 3, respectively, Fig. 4), dependences were obtained: they are convex curves while the classical dependence is concave. This "paradox" is explained by the fact that horizontal flows supply particles of the coffee raw material with energy. The thickness of the layer and its porosity increase. As a result, a decrease in hydraulic resistance of the layer is observed. This indicates a phenomenon favorable for the extraction processes, namely, a hydrodynamic situation with such fluidization of the bed will definitely contribute to the intensification of the transfer processes.

Nonpolar extractant, hexane, has quite close extraction rates at boiling point and at 60 °C (Fig. 6). This can be explained by the fact that MW energy is absorbed mainly by moisture contained in the slurry capillaries and hexane is then heated by the slurry. That is, the vapor phase in capillaries, and, accordingly, baro-diffusion flow are formed in the raw material even at low extractant temperatures. In addition, hexane isomers boil at temperatures of 49.7; 58 and 60.3 °C which can also cause partial turbulization of the near-boundary layer at temperatures below the boiling point.

In extraction using the MW field, the extractant type plays an important role. While hexane, nefras, etc. solvents are considered more effective in conventional technologies, ethanol is preferable in conditions of the MW field. Polar ethanol molecules strengthen the baro-diffusion effect and promote intense mass transfer.

Unlike hexane, ethanol contributes to additional transition of aromatic components to the extract which is more attractive in some technologies.

Thanks to a systems analysis of the heating technologies used in the production of instant coffee, the main disadvantages were identified:

– the significant energy content of the equipment and the process duration (7...8 hours);

– use of high pressure in extractors (0.3...1.5 MPa);

– loss of valuable volatile flavoring and aromatic substances (more than 80 % of the initial content in fried grains);

– low yield of the target component (20...33 % by weight of raw grains);

– production waste (coffee slurry) creates an environmentally dangerous situation polluting the environment.

Based on an analysis of "bottlenecks", methods for their elimination were proposed. Namely, a system of innovative heat technologies for coffee production, new technological lines including a line for pre-extraction of coffee slurry (Fig. 8), flow diagrams of processing coffee slurry and production of liquid coffee concentrate were developed (Fig. 2).

Studies of the kinetics of extraction of water-soluble substances and oil from coffee slurry have made it possible to develop a design of a universal energy-efficient MW extractor that provides operating modes at temperatures up to 100 °C and ambient air pressure. Tests of the design on an industrial scale have shown its high efficiency (Table 3).

The developed model (1) works only in the range of variation of the determining similarity numbers ($5 \le Re \le 50$; $3.82 \cdot 10^{-8} \le Bu \le 15.2 \cdot 10^{-8}$; $2.07 \cdot 10^{3} \le Sc \le 2.89 \cdot 10^{3}$; $93.3 \cdot 10^{-2} \le \Pi \le \le 346.9 \cdot 10^{-2}$) which imposes restriction on application of the obtained results.

Models (2), (3) work only in the range of variation of the determining similarity numbers ($0.07 \le \Gamma \le 0.42$; $0.06 \le Bu \le \le 2.94$; $183.6 \le Sc \le 303.9$).

A search for a common solution of the obtained models in similarity numbers (1)–(3) and models of the heat and mass transfer processes in capillary structures in targeted energy delivery can be recommended as a further study.

In the future, it is necessary to carry out structural and parametric optimization of technological systems for the most efficient consumption of energy and resources.

7. Conclusions

1. As a result of the energy and environmental audit, it has been shown that a company can have tangible profits from environmentally problematic waste. Commercial attractiveness of the projects is due to the following:

– additional extraction of water-soluble extractive substances from coffee slurry which increases the yield of the extract by 10...12 %;

– production of expensive and high-quality coffee oil (refined and common) having an ever-growing demand in the market;

– production of fuel material, namely, pellets. Characteristics of the pellets obtained from coffee slurry were experimentally established. Their burning temperature is 515 °C and calorific value is 17 MJ/kg.

2. As a result of experimental modeling of extraction kinetics, it was found that the duration of the process in a microwave field is approximately 20 times less than that of the processes carried out in a thermostat (Fig. 6, 7). The microwave field affects the extraction rate to a greater extent than the process temperature. The growth of microwave energy increases the yield of extractives from coffee slurry by more than two times (Fig. 5, *a*) and reduces the duration and energy intensity of the process of production of coffee extracts from coffee raw materials. It was found that with an increase in the volumetric flow rate of the extractant by a factor of 3, yield of extractives from coffee slurry increased by 35 % and extraction time decreased by a factor of 2 (Fig. 5, *c*).

Hexane and nefras are recognized as more effective extractants in conventional technologies. However, a significant intensification of the process of extraction with ethanol in the MW field is observed. Moreover, the yield of oil and other extractives in the microwave field with the use of alcohol is greater than with hexane and nephras.

When calculating extraction processes in MW extractors, it is recommended to use the criterion form of the equation of dependence of the mass transfer Stanton number on the Schmidt and Bourdo numbers and parametric complex, that is, hydro modulus, for ethyl alcohol (2) and hexane (3).

3. The developed technology of extraction in a microwave field is aimed at eliminating some of the drawbacks of conventional approaches while preserving all advantages of conventional extraction principles and acquiring a series of new advantages. Technological advantages include yield of target components from raw materials increased by 10...15 % with a significant decrease in temperature regime of extraction which helps to improve quality of the finished product; a significant (almost an order of magnitude) reduction of the process duration with virtually no product loss. Economic advantages include compact equipment, affordable cost of its manufacture and operation associated with simplicity and reliability of the design, moderate energy consumptions for the process (Table 3).

4. Attractive qualities of the microwave oil extractor are as follows: relatively low manufacturing and operating costs associated with the design simplicity; low power consumption; use of industrial waste as a raw material. The device with parameters given in Table 4 has passed bench tests. The extractor sample was tested at a specific power of 180...240 W/kg in the mode of boiling extractant. Ethanol (a concentration of 93...96 %) was used as an extractant.

As a result of the tests, coffee oil was obtained. It is characterized by a pronounced aroma, coffee taste, and an intense dark brown color.

5. The designed production line enables obtaining of concentrated coffee extract, the basis for preparing coffee drinks ready for immediate use. The concentration of solids is 50...65 %. An innovative assortment of coffee: with sugar, without sugar, with cognac, with milk, etc. It can be successfully used as a separate product or as an ingredient in confectionery and dairy products.

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