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ASSESSMENT OF ADVANTAGES OF USING A DIFFUSION PULSATING APPARATUS FOR RECONSTRUCTION OF THE DIFFUSION SECTION OF A SUGAR FACTORY

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Abstract

The sugar industry in Russia plays a huge role in ensuring the country's food security and is a strategic industry. Of the 90 sugar factories in Russia today, a third of the factories are closed due to unprofitability associated with the high cost of sugar production due to low feed capacity. The raw material for sugar production is sugar beet, mainly domestically produced. The locations of most sugar factories are small municipalities, for which they are the town-forming enterprises. For the revival of closed sugar factories, it is necessary to increase their capacity, which is difficult to do due to the fact that in the diffusion section of each sugar factory there is one large-sized imported diffusion apparatus of a mechanical type, which does not allow increasing capacity in any other way than purchasing a new, more high-performance expensive imported diffusion apparatus of a mechanical type. In the current conditions of uncertainty and disruption of trade relations with other countries, new suppliers of high-performance diffusion apparatuses are needed in Russia itself, the apparatuses of which would at least not be inferior to the Western apparatuses. The Russian company Ingehim has developed a diffusion pulsating apparatus (DPA) without mechanical movable transporting devices, which reduces energy consumption, operating costs and lowers quality requirements for sugar beet chips. The test results obtained using an experimental unit showed the output to contain a higher quality of the diffusion juice. The lightness of the juice was found to be much higher compared to juices produced in conventional diffusion apparatuses, and the juice purity was found to be 5% higher at a comparable solids content, resulting in an additional amount of sugar produced per year and, thus, generating a faster return on investment.

Keywords: *sugar factory, diffusion section, diffusion, pulsating apparatus, sugar beet chips, juice purity, reconstruction, Ingehim*

INTRODUCTION

Sugar in Russia is produced primarily from sugar beets. Cultivation and processing of sugar beets are well-established processes. However, work is constantly being carried out to increase the yield and the sugar content of the crop and optimize the processing for the purpose of reducing the production cost and improving the resulting sugar quality. As a rule, sugar factories are located near sugar beet growing areas, often in small municipalities, for which they are the town-forming enterprises.

Processing of the entire harvested sugar beet is seasonal and carried out within 3-4 months a year. This requires high performance sugar factories. Processing of sugar beets into crystalline sugar is carried out via a technology presented in a simplified form as follows. Sugar beet roots arriving from the fields at a sugar factory are cleaned of dirt, stones and other inclusions, washed and cut into sugar beet chips (cossettes). The chips enter a diffusion apparatus containing hot water, in which a diffusion juice is formed. The diffusion juice is thickened by evaporation to the state of syrup. The syrup is boiled into a crystalline massecuite, and from the massecuite a wet crystalline sugar is obtained in centrifuges, which is dried, cooled and packaged. In total, there are several dozen apparatuses for various purposes on the line. These processing stages are carried out in structural production departments called sections.

The average processing capacity of sugar factories in Russia over the past ten years has not exceeded 5 thousand tons of beets per day [1], although some individual factories capacities reached almost 11 thousand t/day [2]. The latter factories are considered highly productive and cost-effective. Outside of Russia, however, there exist production facilities with a capacity of up to 25 thousand t/day [3].

According to official data, there are about 90 sugar factories in Russia today located in 22 regions [4]. A third of the factories are closed, which is very depressing and negatively affects the socio-economic development of sugar-producing regions in general and municipalities in particular [4]. Note that in some regions, up to 70% of sugar factories are now closed, while in some other regions, all factories are closed. In addition to the socio-economic decline of the regions, the problem of closed processing factories is also of national importance since the sugar industry is a strategic industry that ensures Russia's food security.

One of the primary reasons for the large amount of sugar factory closures in Russia is their low profitability caused by high operating costs, energy input, and other associated costs relative to low values of processing capacity (about 2-4 thousand t/day), which inevitably leads to an uncompetitive product on the commodity market. Another driving reason is often the lack of additional available acreage for growing beets in nearby regions, and transportation of sugar beets from remote locations is very costly.

If supplying the required amounts of sugar beets is stable, increasing sugar factory capacity is not technically difficult. In fact, it is possible to increase capacity of most sections of sugar factories (washing, cutting, filtering, evaporation, crystallization, etc.) by installing additional equipment that is standardly produced and can be used in-parallel to attain the required feed capacity of the section. The main problem lies in the diffusion section, which most often contains one large-sized imported diffusion apparatus for a given capacity. Most mechanical apparatuses in use are mechanical-type diffusion apparatuses from European manufacturers, and were acquired several decades ago. Such apparatus types include double-screw apparatus (DS) or rotary diffusion apparatus (RDA), which contain movable mechanical elements (for example, screw) requiring regular maintenance and repair. The necessary periodic replacement of parts or assemblies during maintenance is complicated either by parts obsolescence (low capacity apparatuses are no longer produced), or by their high cost. The apparatus design complexity and high energy consumption are the primary drivers of high operating costs. The possibility of a significant capacity increase of an existing DS or RDA is not technically feasible. The more modern type of diffusion apparatus, column diffusion apparatus (CDA), is also not free of the indicated disadvantages, since its design also has a movable mechanical transporting element – a tubular shaft with blades. The increased efficiency of CDA compared to DS and RDA is mostly due to a more complete use of working volume of the apparatus, a more compact vertical layout and lower energy consumption. However, a high dependence on quality of chips, their physical condition (the degree of frostbite, spoilage, putrefaction, etc.) and characteristics of cutting remains in CDA. Moreover, CDAs are produced for large capacities, starting from 6 thousand tons of beets per day and higher, and are available in Russia only from foreign manufacturers, which hinders the country's food security and import substitution on the used equipment. The latter circumstance is especially important in the current conditions of uncertainty and the disruption of Russia's established trade relations with its partners abroad.

For solving the problem of reconstructing non-operating or low-profit operating domestic sugar factories, the Russian company Ingehim developed a continuous diffusion pulsating apparatus (DPA), which does not have mechanical movable transporting devices and is based on a fundamentally new method of technological transportation of sugar beet chips described below. The method has not yet been used in sugar factories, but its effectiveness has been tested on other types of raw materials in the extraction of chicory [5], coffee, barley, peas, licorice, rosemary, as well as in the extraction of chaga birch mushroom and hops [6] in industrial conditions at the Russian enterprises "Tatkhimfarmpreparaty" and "Marposadsky Distillery", respectively. It should be noted that today there exists no operating industrial apparatus for the extraction of solid-phase raw materials, in which the method developed by the Ingehim Company is implemented. The proposed extraction method allows increasing the purity of diffusion juice, which gives an increase in sucrose yield and, therefore, provides an additional profitability increase.

The purpose of the present article is to study diffusion of sugar beet chips obtained from the beet cutting section of one of the sugar factories of Russia at an experimental unit that implements a pulsating method of transportation. In addition, the article aims to compare the indicators of diffusion juices obtained in a conventional diffusion apparatus and in DPA and the performance characteristics of CDA, RDA, DS and proposed DPA for the same processing capacity of 6 thousand tons of sugar beet chips per day. Finally, the article intends to assess the technical feasibility of DPA and develop a schematic diagram of the diffusion section of a sugar factory with the use of DPA.

OPERATING PRINCIPLE OF DPA

The pulsation technique is well known and widely used in various fields. There are especially many developments and implementations in the field of extraction in "liquid-liquid" systems to intensify the processes of interaction or separation of liquid-phase media [7]. There also exist solutions with the use of pulsations to intensify the processes of mixing [8], concentration of solutions [9], filtration in volume and heat and mass transfer enhancement.

In contrast to the above-mentioned pulsation technique, the DPA operation is based on the original pulsating method of continuous technological transportation of solid dispersion (raw materials in the form of beet chips). This is carried out by alternating the period of applying a pressure pulse and the period of discharging the pressure pulse using an external pulse creation system (Fig. 1). When a pulse is applied, the technological transportation of raw materials upwards occurs, and when the pulse is discharged, active filtration of the extractant (hot water) through the layer of raw materials takes place. Thus, the raw material moves upward from one pulse to another, actively and continuously interacting along the way with hot water in a constant non-stationary countercurrent mode. This determines the high efficiency of the process of diffusion (extraction) of sugar from sugar beet chips. The required feed capacity of DPA is attained by the DPA design parameters and the pulsating action.

Structurally, DPA can be implemented in the form of a U-shaped apparatus or a vertical column apparatus. Efficiencies of the apparatuses of both designs are approximately the same. The U-shaped design is more suitable for low-capacity apparatus, while the vertical column design is more suitable for use in large-capacity apparatuses, such as at sugar factories.

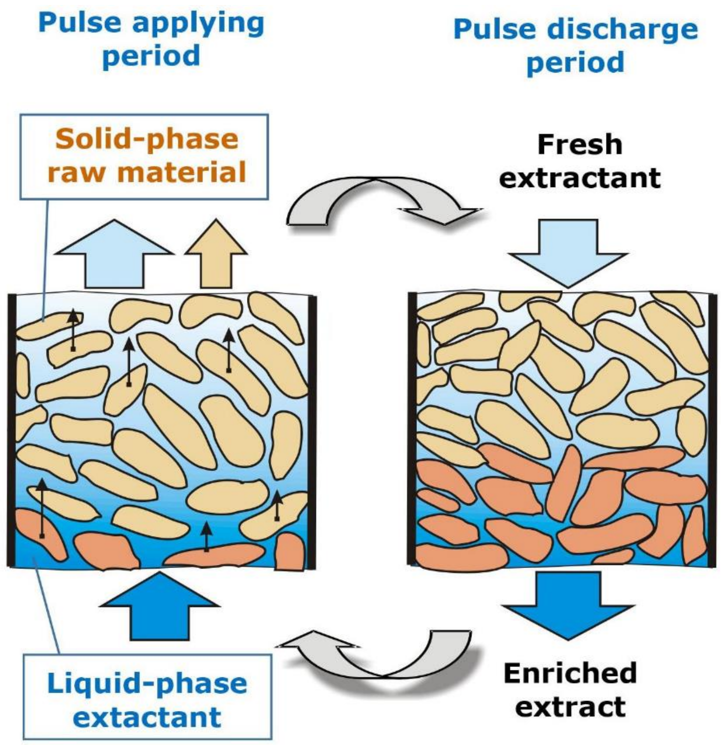


Fig. 1. Principle of the original pulsating method of continuous technological transportation of raw materials, which underlies the DPA operation

In the process of diffusion, diffusion juice is formed. In this work, it is planned to determine the indicators of diffusion juice obtained in DPA and compare them with the indicators of diffusion juice obtained under factory conditions in a conventional diffusion apparatus. The chips remaining after extraction of the juice represent beet pulp, which is usually pressed in sugar factories and used as livestock feed afterwards. The pulp water is returned to the diffusion apparatus, and the diffusion juice is transported to subsequent stages of processing to obtain crystalline sugar.

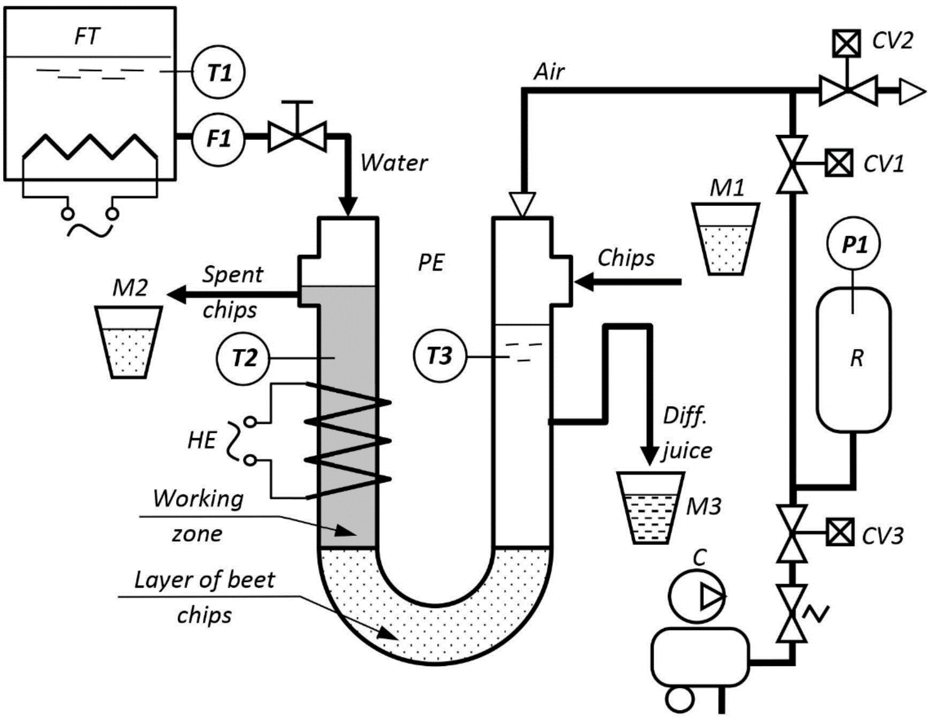
3. MATERIALS AND METHODS

3.1. Experimental unit

To study the diffusion of beet chips in a pulsating apparatus, an experimental unit was developed and assembled, and the schematic diagram is shown in Fig. 2. The primary element of the unit is a U-shaped apparatus – a pulsating extractor (*PE*) – with a working zone diameter of 100 mm and a working zone height of 1 m. The unit contains a node for loading beet chips, a node for unloading spent beet chips (pulp), a hot water (extractant) input node, a filtration node and a diffusion juice (extract) outlet node. In PE, a continuous countercurrent movement of the phases, which are sugar beet chips and hot water, is organized.

The pulsating effect is provided by a system for creating pulsations of the liquid phase (hot water). The system consists of compressor *C*, receiver *R*, control valves *CV1*, *CV2* and *CV3*, pressure gauge *P1*, automation system and piping system. To transmit the pressure pulse, a pulsation chamber is provided in the upper right part of the U-shaped apparatus.

The supply of beet chips is carried out in portions through the unit's loading node. After the chips pass through the apparatus, the spent sugar beet chips (pulp) are unloaded through the unit's unloading node. Fresh hot water is continuously supplied by gravity to the unit from the water feed tank *FT*. A flow meter *F1* is installed to control the flowrate. To maintain and control the set water temperature, the tank *FT* is equipped with a heater and temperature gauge *T1*.



<u>Main equipment:</u>
PE – pulsating extractor;
FT – water feed tank;
R – receiver;
C – compressor;
M1, *M2*, *M3* – measuring vessels;
CV1, *CV2*, *CV3* – control valves.

<u>Measured parameters:</u>
F1 – feed water flowrate;
T1 – feed water temperature;
T2, *T3* – temperature of the juice-chips mixture in apparatus;
P1 – pressure in receiver.

Fig. 2. Schematic diagram of an experimental unit for studying the diffusion of sugar beet chips carried out by the pulsating method

The diffusion juice obtained is discharged from the *PE* through the filtration node located below the loading node.

The unit has electric heating of the apparatus body using the heating element *HE* with continuously adjustable heating temperature, full thermal insulation of the body and is equipped with gauges for regulating the temperatures of the juice-chips mixture *T2* and *T3*, which allows the diffusion process to be carried out under specified thermophysical conditions.

The following additional equipment was used: measuring vessels (measurement accuracy ±1 ml), stopwatch (measurement accuracy ±0.1 s), scales (measurement accuracy ±1 g), ruler (measurement accuracy r ±1 mm), caliper (measurement accuracy ±0.1 mm), refractometer IRF 454 B2M (measurement accuracy in refractive index ±0.0001) (Kazan Optical-Mechanical Plant, Russia), and polarimeter SM3 (measurement accuracy ±0.04°) (Zagorsk Optical-Mechanical Plant, Russia).

3.2. Raw material

The raw material was sugar beet chips from the beet cutting section of the Buinsky Sugar LLC factory (Buinsk, Republic of Tatarstan, Russia) (Fig. 3).

Fig. 3. Studied sugar beet chips

Chips geometry (average):

- height × width × length: 3.5 × 3.5 × 60 mm;

- number of particles with a length of less than 30 mm: 35%;

- length of 100 g of chips: 9–10.5 m.

The state of beet tissue (determined visually) is partially frozen (up to 50%) with signs of putrefactive processes.

The sugar content in the original beet chips:

- sugar content: 14.5%;

- solids content in normal (i.e. cell) juice: 18.0%;

- sucrose content in normal juice: 14.7%;

- purity of normal juice: 81.6%.

3.3. Conditions for the diffusion process in the experimental unit

- Movement of solid dispersion and liquid phase: continuous and countercurrent.

- Solid dispersion: beet chips with a temperature of +75 to +85 °C, flowrate 1.7–2.5 kg/h.

- Liquid phase: hot water with a temperature of +65 to +75 °C, flowrate 2.0–3.0 kg/h.

- Diffusion process duration: 80–120 min.

- Draft: 110–135%.

- Sampling and preparation of samples, assessment of the quality of beets, diffusion juice and other indicators: carried out as per methods developed for Russian sugar factories using similar instruments (refractometer, polarimeter).

3.4. Desired characteristics

- Diffusion juice concentration with respect to solids, %.

- Diffusion juice concentration with respect to sucrose, %.

- Diffusion juice purity, %.

- Diffusion juice lightness.

3.5. Methodology for determining characteristics

An experimental-analytical approach was applied to determine the characteristics. The draft value was determined as the ratio of the liquid phase flowrate to the solid dispersion flowrate multiplied by 100%. Sugar content of beets, content of solids and sucrose in the diffusion and normal juices were determined experimentally by examining samples on refractometers and polarimeters. Diffusion juice purity was determined as the ratio of sucrose content to solids content in the diffusion juice multiplied by 100%. A qualitative indicator of diffusion juice – juice lightness – was determined visually by looking at the juice against the light.

4. RESULTS AND DISCUSSION

Results for diffusion juice lightness obtained in the conventional diffusion apparatus (RDA at Buinsky Sugar LLC) and in the experimental diffusion pulsating apparatus (DPA) for the same processing conditions are shown in Figure 4. Diffusion juice lightness is much higher after DPA than after the conventional diffusion apparatus due to significant reduction of oxidation processes during diffusion, higher pureness and low content of admixtures in the diffusion juice produced.

Fig. 4. Comparison of diffusion juice lightness. Left picture: diffusion juice obtained in a conventional diffusion apparatus (RDA at Buinsky Sugar LLC). Right picture: diffusion juice obtained in DPA

Values of diffusion juice purity obtained in the conventional RDA (at Buinsky Sugar LLC) and in the experimental DPA under the same processing conditions are shown in Table 1. A significant improvement of juice purity by approximately 5% for a comparable solids content is seen for a juice produced by DPA versus a juice produced by the conventional RDA. Thus, one would obtain more sugar after replacing the conventional diffusion apparatus with DPA and thereby accelerate the return on investment.

Table 1. Comparison of quality indicators of diffusion juices obtained in the conventional diffusion apparatus RDA (at Buinsky Sugar LLC) and DPA

Diffusion apparatus type	Sugar content, %	Draft, %	Residence (diffusion) time, min	Content in diffusion juice		Purity of diffusion juice, %
				Solids, %	Sucrose, %	
RDA	14.5	120	90	11.2	9.30	83.0
DPA	14.5	119	90	12.5	11.05	88.4

The results indicate that DPA outperforms the conventional diffusion apparatus in terms of quantity and quality of the obtained diffusion juice.

There are more advantages of DPA over conventional diffusion apparatuses than just an increase in diffusion juice purity. Table 2 compares the main performance characteristics of conventional column type (CDA), rotary type (RDA) and double-screw type (DS) diffusion apparatus versus DPA for the capacity of 6 thousand tons of sugar beets per day. Data on CDA are from the German company BMA (manufacturer), data on RDA and DS are from the open sugar-related literature of well-known authors (Sapronov A.R., Bugaenko I.F., Gorbatyuk V.I.), and data on DPA are calculations by the Ingehim experts.

The table shows the following distinctive advantages of DPA:

1. No mechanical transporting elements. Thus, no wear of the diffusion apparatus mechanisms; hence, expenditures on repair, operation and spare parts are reduced, service life is increased, etc.

2. No dependence of DPA efficiency on quality of beet chips, their physical condition (the degree of frostbite, spoilage, putrefaction, etc.) and characteristics of cutting, which allows, if necessary, to carry out processing of “broken” beets and beet tails, from which an additional amount of sugar can be produced.

3. No additional mechanical destruction of chips in DPA; hence, destructed chips amount in the diffusion juice is reduced, juice lightness is increased, and cost of the diffusion juice purification decreases. In conventional apparatuses, excessive destructed chips formation is due to mechanical movable transporting devices.

4. DPA has a much smaller working volume, which is 2.4 times smaller than CDA, 2.9 times smaller than RDA, and 4.7 times smaller than DS. Thus, DPA has the highest efficiency of all for the same conditions.

5. DPA requires up to 20% less footprint area compared to CDA and even more footprint savings compares to RDA and DS. This allows installing DPA compactly both inside and outside the building freeing up space for equipment of other sections.

6. Total power consumption of DPA is minimal compared to conventional diffusion apparatuses. It is 25% lower than that of CDA, over 50% lower than that of RDA, and 70% lower than that of DS. This directly reduces the operating and production costs.

7. DPA has a minimum weight that is, at least, 40% smaller compared to conventional diffusion apparatuses, which reduces the load on the foundation and cost of building the foundation, facilitates the apparatus transportation, etc.

8. As per customer requirements, a new DPA can be manufactured both for low capacity from 1 to 4 thousand tons of beets per day, and for high capacity from 6 thousand tons of beets per day and above, which expands opportunities for diffusion section modernizations both at existing and newly constructed sugar factories.

The above performance characteristics and advantages of DPA demonstrate both its functional applicability in sugar production, and high efficiency compared to conventional diffusion apparatuses of various types used in Russian sugar factories today.

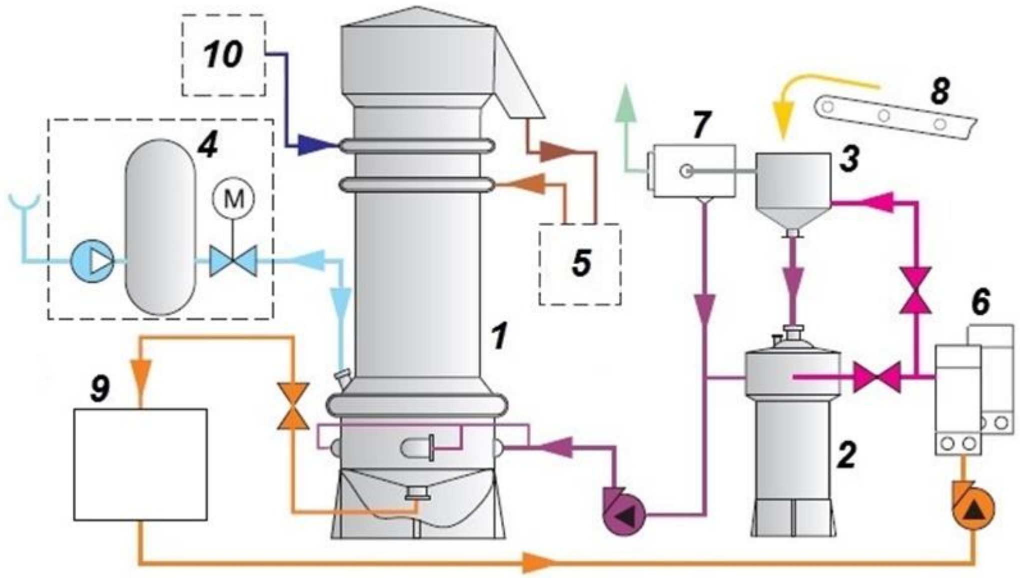
These distinctive advantages and high performance characteristics of DPA provide an opportunity for effective reconstruction of the diffusion section of sugar factories. Reconstruction can be carried out both by replacing a conventional diffusion apparatus of any type with DPA while maintaining the current capacity, and by creating an additional line based on DPA, which can be operated in parallel with the existing diffusion apparatus to increase the total capacity of beet processing. It should be noted that in the first case, all available sections, except for the diffusion section, remain unchanged and the technological inlet and outlet flows are preserved. A schematic diagram of the diffusion section of a sugar factory using DPA while maintaining the current capacity is shown in Figure 5. The DPA use does not alter the typical diffusion section scheme, but at the same time allows obtaining additional benefits in the form of reduced energy expenditures, increased yield of sugar from sugar beet chips, reduced apparatus dimensions, apparatus weight, capital costs, operating costs, complexity of repairs, etc. (see Table 2).

Table 2. Comparative characteristics of diffusion apparatuses processing 6 thousand tons of sugar beets per day

Diffusion apparatus type	CDA (column)	RDA (rotary)	DS (double-screw)	DPA (pulsating)
Transporting element	Tubular shaft with blades	Apparatus body	Screw	None
Characteristics of beet chips: length of chips weighing 100 g, m	8–12	14–16	13–15	6–16
Dependence of performance on quality and physical condition of beet chips (degree of frostbite, spoilage, putrefaction, etc.)*	High	High	High	Low
Additional chip breaking in apparatus**	High	Medium	High	None
Diffusion time, min	75–80	65–70	60–65	65–80
Working volume of apparatus, m^3	1005	1230	1986	424
Overall dimensions, m				
height	25	14	13.4	20
length	9	43.5	34.5	8
width	9	12	8.8	8
Total power consumption, kW	120	175	320	90
Apparatus weight, t	300	over 300	over 300	180

* Based on the design features of diffusion apparatus

** Due to mechanical movable transporting devices (screw, tubular shaft, etc.) that provide technological transportation of sugar beet chips



beet chips
pulp (spent beet chips)
heated juice
diffusion juice
juice-chips mixture
pulp water
circulation juice
feed water
compressed air

1 – DPA
2 – chips scalder
3 – chips heater
4 – pulse creation subsystem
5 – pulp-press section
6 – juice heater
7 – destructed chips catcher
8 – belt conveyor
9 – juice accumulator
10 – hot water preparation section

Fig. 5. Schematic diagram of the reconstructed diffusion section of a sugar factory using DPA

In addition to the diagram shown in Fig. 5, other variants for reconstruction of the diffusion section using DPA are also possible. For example, DPA can be installed in parallel with an existing diffusion apparatus of low capacity to somewhat increase the overall capacity of the diffusion section, if other sections have excess reserves of operating equipment. If DPA is used to significantly increase the overall capacity, it will be necessary to create all the required supporting sections in addition to the existing reserves of operating equipment. It makes sense to carry out reconstruction by gradually increasing the capacity of each individual section, which, unlike the diffusion section reconstruction, can be performed with the use of standard equipment. The sugar factory owners themselves will determine variants for reconstruction of the diffusion section and the sugar factory as a whole. The DPA use allows implementing any of the above variants due to possibility of manufacturing and supplying a new DPA for any given capacity, ranging from 1–4 to 6 thousand tons of beets per day and more.

It is worth noting that RDAs and DSs are already obsolete and no longer produced in the world, while CDAs are produced by foreign manufacturers for a capacity of 6 thousand tons of beets per day and more.

Since sugar factories operate only 3-4 months a year, a new diffusion section can be created with the use of DPA to process other types of plant raw materials in the off months, which would provide additional profit and jobs for year-round work.

Since DPA is entirely a domestic equipment developed and manufactured by the Russian company Ingehim, the use of DPA instead of an imported diffusion apparatus will help to solve the problem of import substitution on the used equipment and ensure Russia's food security.

CONCLUSION

Based on the study results, the following conclusions can be drawn. A new type of diffusion apparatus for Russian sugar factories called DPA, developed by the Ingehim Company, produces a diffusion juice no worse, and even better than that produced in conventional diffusion apparatuses from the same raw material under the same processing conditions: process temperature, diffusion time and sugar content of beet chips. In particular, diffusion juice lightness is much higher, and diffusion juice purity greater by 5% for a comparable solids content. The latter gives an additional amount of sugar produced allowing reducing the payback period from the implementation of DPA compared to that of a conventional diffusion apparatus of similar feed capacity. In addition, when comparing DPA to conventional diffusion apparatus, DPA provides a reduction in energy costs from 25 to 70%, footprint area by at least 20%, and an extended overhaul time. In addition, metal consumption and apparatus weight is much smaller, which reduces the apparatus cost, transportation expenditures during purchase, repair and operation, load on the foundation. The absence of mechanical movable parts increases the reliability and overall life of the apparatus. While being a completely domestic equipment developed in Russia itself, DPA can play an important role in ensuring Russia's food security. Since DPA is simpler and more reliable than its conventional counterparts, it can be used to reconstruct the diffusion sections of closed or low-profit operating sugar factories in Russia, increase the processing capacity of existing factories and construct diffusion sections of new sugar factories. Considering sugar factories process sugar beets only 3 to 4 months a year, it is possible to use DPA in the off months to process other types of plant raw materials.

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