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ENERGY-CONSUMPTION AND ENVIRONMENTAL ASPECTS OF DRYING PROCESSES

Introduction. *Energy saving and environment protection are global problems. The energy capacity of world production is growing faster than the industry's output. Currently, the world has been experiencing a shortage of energy, while environmental pollution has been increasing, as the industrial load on the environment has grown several times in recent years. Therefore, energy resource saving and environment protection have been becoming more and more important.*

Problem Statement. *Drying belongs to complex energy-intensive processes. Industries that use drying processes consume significant energy resources. The use of outdated drying equipment and imperfect technological processes contributes to the energy resources consumption and environment pollution with vapor that is part of greenhouse gases. Therefore, it is urgent to find ways to reduce these adverse consequences.*

Purpose. *The purpose of this research is to identify and to analyze the trends in reducing energy consumption and hazardous vapor emissions in the drying processes.*

Material and Methods. *Analytical and practical methods, comparative analytical and systemic approaches have been employed. Scholarly research works and developments of Ukrainian researchers in the field of study have been used as materials.*

Results. *The main methods of saving energy and reducing vapor emissions in drying processes have been summarized. The developments of Ukrainian researchers of the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine have made it possible to obtain a significant energy saving that is estimated at 2.0—2.1 million tons of conventional fuel, and to reduce environmentally hazardous vapor emissions by at least 4 million tons per year.*

Conclusions. *The creation and implementation of new energy-efficient and environmentally safe equipment and technologies allows not only reducing energy consumption and emissions of dangerous vapor into the environment, but also optimizing the use of raw materials and obtaining high-quality products in drying processes.*

Keywords: energy saving, drying, and ecology.

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In advanced economies that have high-tech production, a large share of added value in the gross domestic product (GDP) and a high energy efficiency, GDP grows with a practically steady and, in some countries, even downward trend in the consumption of fuel and energy resources (FER) (Fig. 1, curves *2*, *3*). In Germany, in addition, there has been reported a significant reduction in greenhouse gas emissions (Fig. 1, curve *4*) [1, 2].

In general, the global consumption of primary FER has been showing a steady growth by approximately 1.3% annually [3]. According to the global statistics, the ascending dynamics of demand for energy resources and almost absent decarbonization of production lead to a fatal pollution of the environment with 34.17 Gt greenhouse gases worldwide (Table 1). As can be seen from Table 1, the "leaders" in CO_2 emissions are the PRC (28.76%) and the USA (14.53%), although they have the largest RES consumption (22.9% in PRC, and 20.1%, USA) [4].

The greenhouse gas emissions by sector of the EU economy in 1990 and 2018 are structured as follows: fuel combustion and uncontrolled fuel emissions 62% (53%); transport (including air transport) 15% (25%); agriculture 10% (10%); industrial processes and use of fuel products 9% (9%); incineration of industrial and household waste 4% (3%) [5]. The experts have estimated that the economic losses from climate change in the world reach approximately USD 544 trillion. The EU has set a goal of reducing greenhouse gas emissions by 55% till 2030, as compared with the 1990 level. According to the experts, this will make it possible to achieve climate neutrality in the EU by 2050. Ukraine has also developed the concept of the transition to green energy, which provides for achieving a climate neutral country by 2060.

The final consumption of FER in the economic sectors of different world countries is presented in Table 2. In Ukraine, as can be seen from the

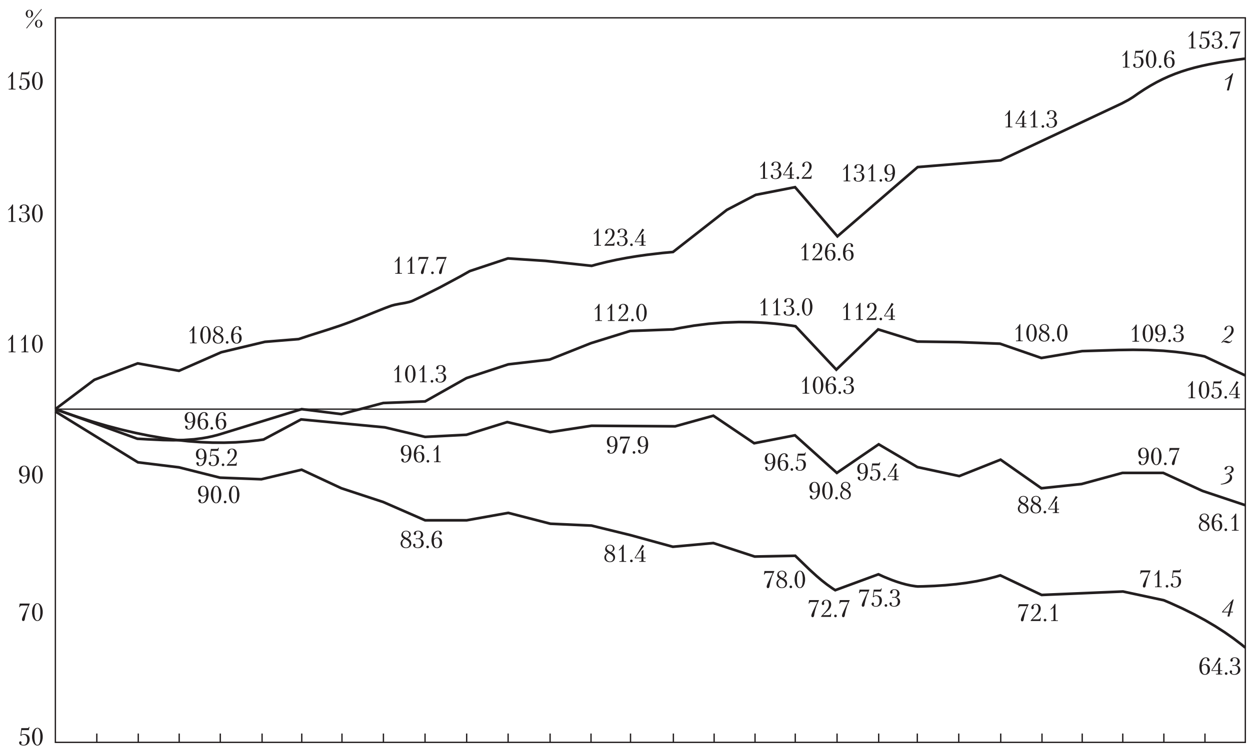


Fig. 1. Dynamics of GDP (*1*), gross energy consumption (*2*), primary energy consumption (*3*), and greenhouse gas emissions (*4*)

given data, the industry, households, and agriculture have the largest share in the FER consumption, which exceeds 83%. This is the highest value among the leading world countries. It shows the inefficiency of energy use. The following industries have the greatest specific energy saving potential in Ukraine [6].

Drying processes are complex energy-intensive technological processes. In each specific case, it is necessary to preserve biological activity and nutritional properties of raw materials, as well as to meet bacterial requirements for the product, etc. The industries that use drying processes are characterized by a high energy

Table 1. **World Structure of RES and CO_2 Emission in 2019**

	Country, group of countries	Consumption of RES in the structure of energy resources		CO_2 emission	
		World	Geographical group	CO_2 Gt	%
1	Europe	28.2%		4.11	12.03
2	EU	26.0%	Total for countries 2—4 (EU + PRC + USA) = 69.0 %	3.33	9.75
3	PRC	22.9%		9.83	28.76
4	USA	20.1%		4.965	14.53
5	Germany	7.3%	Total for the first 10 countries 3—12: (PRC + USA + Germany + + Brazil + India + Japan + + Great Britain + Spain + + Italy + France) = 75.90%	0.684	2.00
6	Brazil	7.0%		0.441	1.29
7	India	4.2%		2.480	7.26
8	Japan	3.8%		1.123	3.29
9	Great Britain	3.7%		0.387	1.13
10	Spain	2.6%		—	—
11	Italy	2.2%		0.325	0.95
12	France	2.1%		0.299	0.88
13	OECD	57.9		12.01	35.15
14	Ukraine*	0.2		—	—
15	Total worldwide**	100		34.17	100
16	Total CO_2 emission in EU + PRC + USA + Brazil + India + Japan + Great Britain			23.24	68.0

Table 2. **The Share of Final Consumption of FER by the Industries**

Country	Industry, %	Transport, %	Households and agriculture, %	Non-energy consumption %
Ukraine	51	13	32	4
Japan	44	27	26	3
Germany	32	26	40	2
UK	25	32	40	3
France	29	30	38	3
Italy	33	31	32	4
Canada	35	28	33	4
USA	29	36	30	5

consumption and a low energy efficiency ratio (≈ 40—50%).

Using imperfect technological processes and outdated drying equipment annually leads to the ineffective consumption of a large amount of energy resources and a significant pollution of the environment with water vapors that belong to greenhouse gases. The share of energy costs in the total cost of production already reaches, in some cases, 70%, and as fuel prices rise, it grows. For a large number of products, the prices are expected to increase above the world ones, which reduces the product competitiveness on the domestic and world markets.

In Ukraine, the main industries that use drying equipment are the agro-industrial complex, chemical, pharmaceutical, construction, fuel, and wood processing industries. It would be interesting to evaluate their energy efficiency and environmental safety.

The agro-industrial complex (AIC) traditionally plays an important role in Ukraine. It includes agriculture and food industry.

In agriculture, many drying plants are used for drying grain. The relevance of the problem of energy saving during grain dehydration is conditioned by large harvests of 60—70 million tons annually. From 50 to 80% and even 100%, in the case of unfavorable weather conditions, of the annual grain harvest is subject to drying. The specific consumption for drying 1 ton with a decrease in grain moisture from 20 to 14% is 14—18 kg conventional fuel and 2.5—3.2 kW electricity, i.e. the total costs exceed 18 kg conventional fuel or more than 5000 kJ per 1 kg evaporated moisture, which indicates a low energy efficiency of the processes. In Ukraine, according to our calculations, the energy costs of drying amount to about 0.5 million tons of conventional fuel, with about 3 million tons of water vapor emitted into the environment.

For grain drying, the Institute has developed a condensation method of dehydration with the use of a heat pump (HP). The energy consumption for moisture evaporation in heat pump dryers is 1.5—2 times lower than in the existing dry-

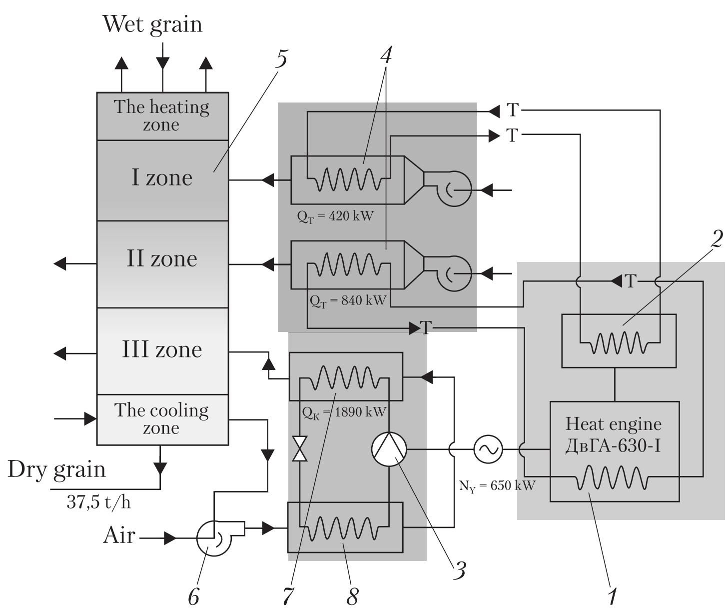


Fig. 2. Diagram of heat pump plant based on the DvGA-630 engine for DSP-32 grain dryer: *1* — gas engine generator; *2* — waste heat exchanger; *3* — heat pump compressor; *4* — air heaters; *5* — convective 3-zone grain dryer; *6* — circulation fan; *7* — heat pump condenser; *8* — heat pump evaporator

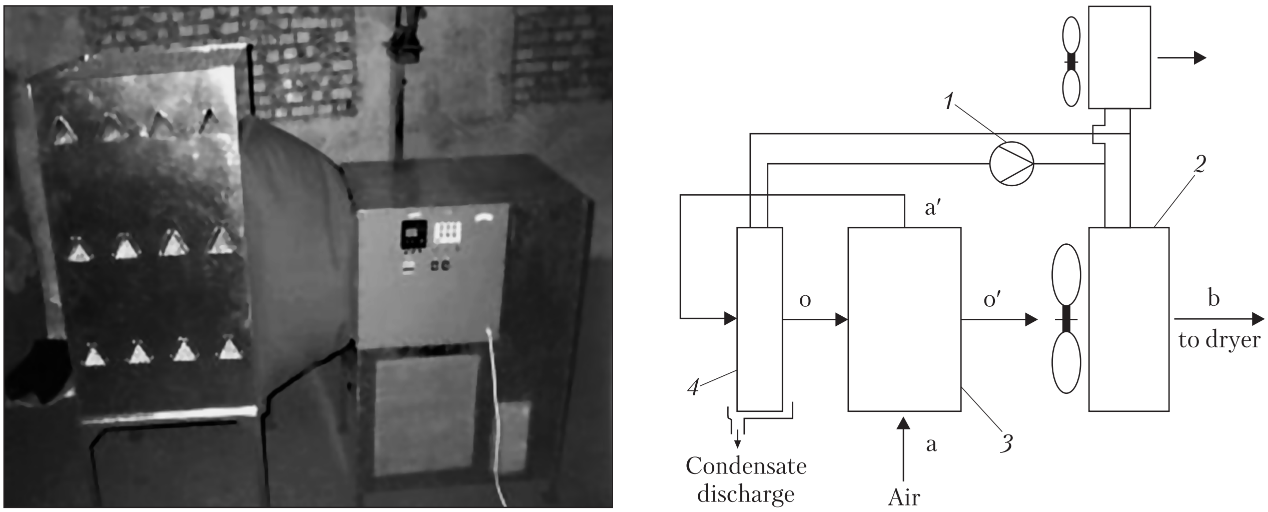


Fig. 3. Condensation grain dryer: *1* — compressor; *2* — air condenser; *3* — recuperator; *4* — evaporator

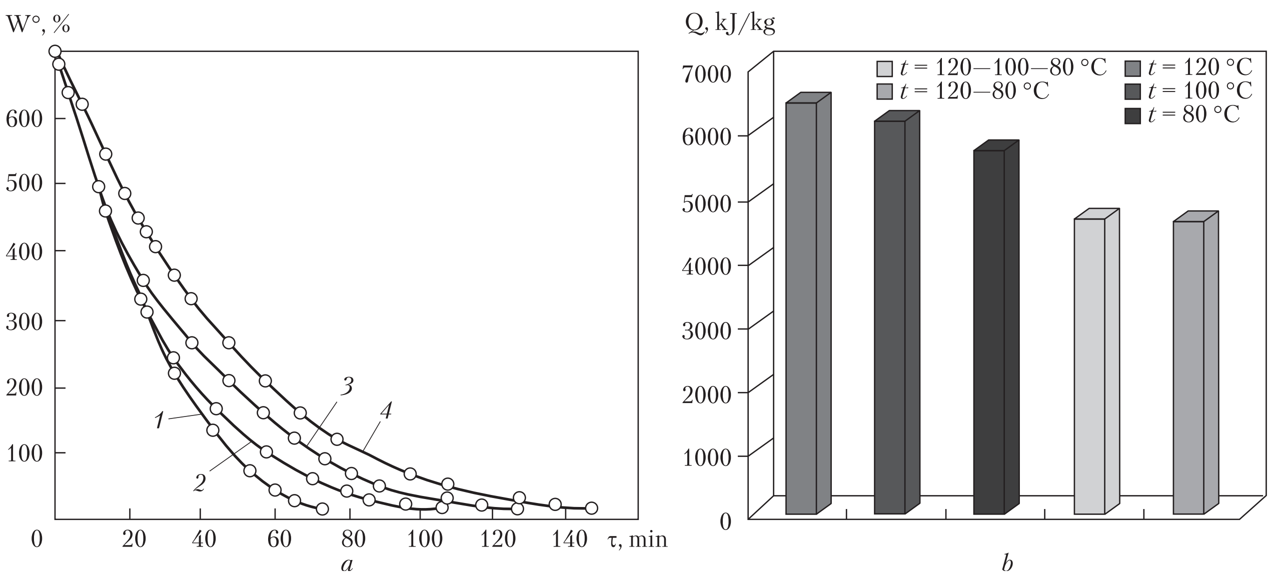


Fig. 4. Multi-stage drying: *a* — staged drying modes: beet root *V* = 1 m/s; *d* = 10 g/kg dry air; *g* = 6.3 kg/m^2; *1* — 120 °C; *2* — 120...100...80 °C; *3* — 120...80 °C ; *4* — 80 °C; *b* — specific heat consumption for evaporating 1 kg moisture

ers. All the evaporated moisture condenses to a liquid and is stored in separate units. In this way, the surrounding environment is not polluted by water vapor.

For the first time in Ukraine, we have developed a drying and power-generating complex for the production of electrical and thermal energy based on engine generator DvGA-630. The proposed complex covers whole-year electrical and thermal energy needs of agricultural firm, as well as seasonal energy needs for heat-moisture processing of plant raw materials, primarily grain. The coolant preparation system based on a heat pump with a heat engine has the highest fuel utilization ratio, due to the use of a heat engine for driving the HP, with the waste coolant from the dryer be-

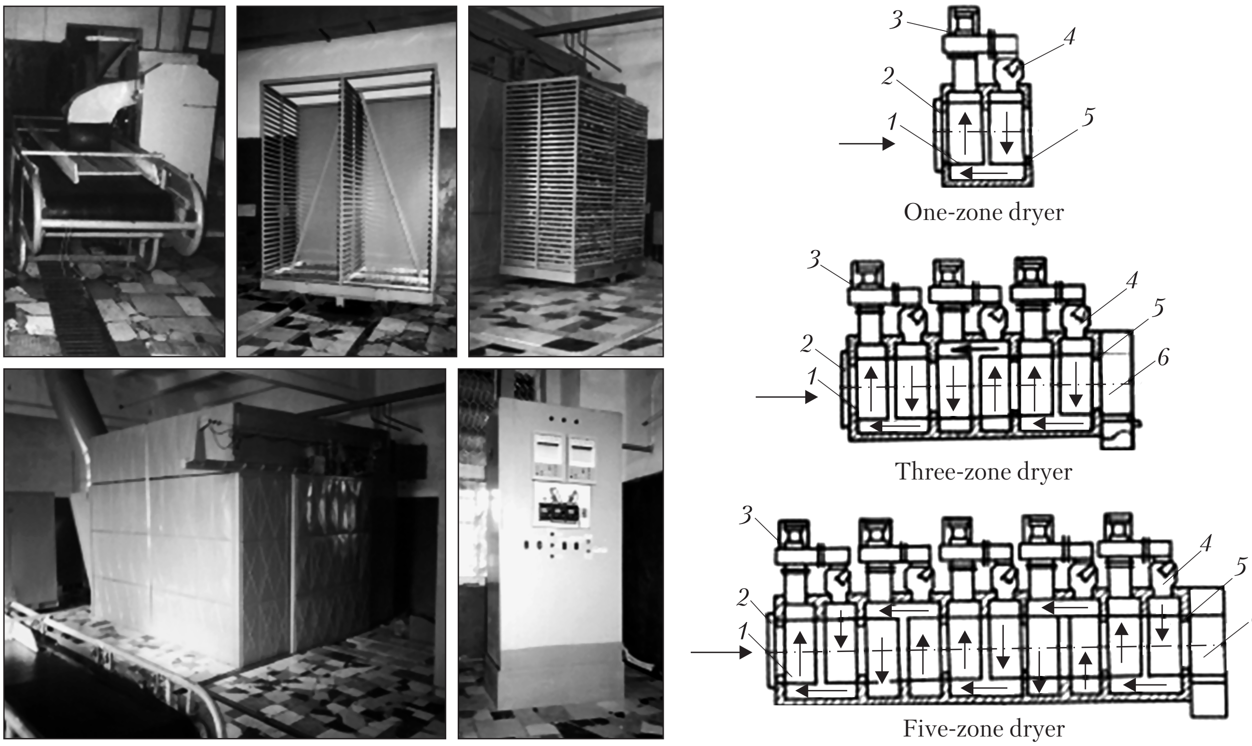


Fig. 5. Appearance of multi-zone dryers

ing a low potential source of energy for the HP. The complex provides a fuel utilization ratio of 0.94—0.96 and a 1.6-time reduction in the energy consumption for removing 1 kg moisture. The costs of 1 kW capacity range within USD 300—400, with a payback period of 2—4 years [6].

The diagram of the heat pump based on DvGA-630 engine for the DSP-32 grain dryer is presented in Fig. 2 [7].

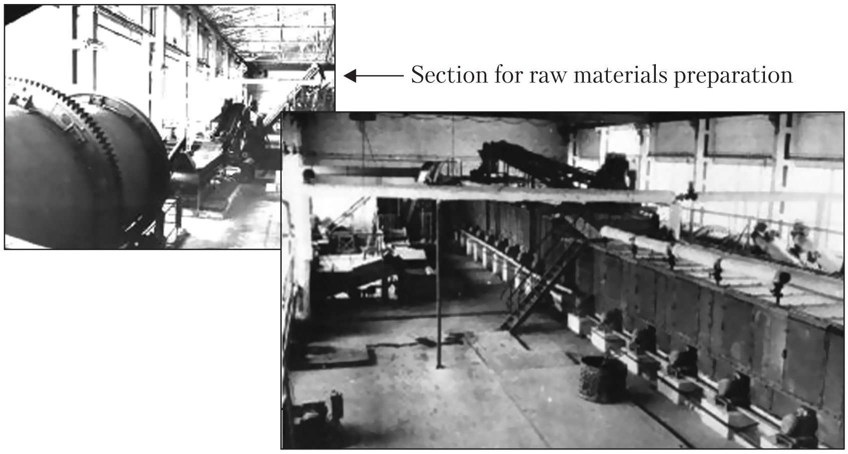
The condensation seed dryer that is designed at the Institute, uses HP (Fig. 3) allows reducing the cost of heat energy for the evaporation of 1 kg moisture by 30% of the standard costs for seeds, ensures 100% seed germination and is environmentally safe, as the evaporated moisture is condensed in the HP evaporator [8].

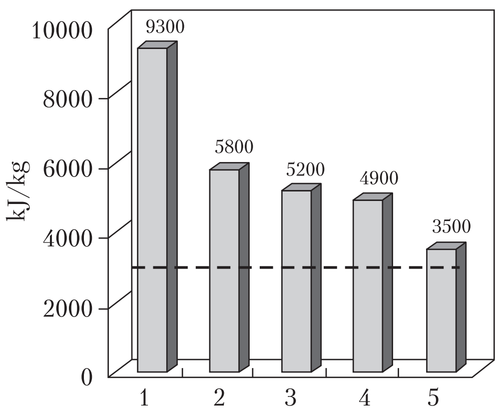
The total energy saving potential for the drying of grain and leguminous crops is about 0.2 million tons of conventional fuel, with water vapor emission into the environment decreasing by 0.9 million tons.

The second most important drying industry in the agricultural sector is the production of dried vegetables, fruits, their juices, beet pulp, pasta and other food products.

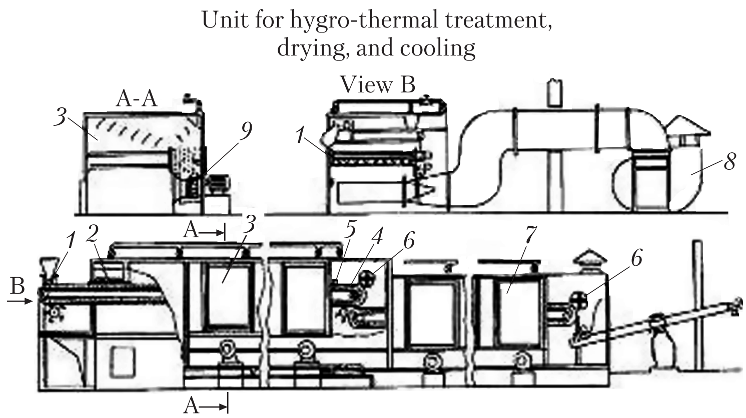
The production of fresh vegetables, their extracts and beet pulp reaches 22—26 million tons per year. According to our estimates, at least 10% of agricultural raw materials are subject to drying. The energy costs for their dehydration exceed 0.7 million tons of conventional fuel, with more than 1.7 million tons of water vapor released into the environment.

The Institute has developed a multi-stage drying method (Fig. 4). The method is based on keeping the maximum temperature of heat carrier in the drying processes throughout the dehydration process; it depends on the maximum allowable temperature of the material. The multi-stage drying modes enable reducing specific heat consumption for evaporation of 1 kg moisture by 15—25% [9].





Belt dryers:
1 — VT-6, Czech Republic
2 — 4G KSK NIIKhimMash, Russia
3 — Sandvik, Sweden
4 — KS 2 IETP, Ukraine
5 — AGSO, IETP, Ukraine



1 — spreader screw; *2* — hygro-thermal treatment zone;
3 — drying zone; *4* — drying belt;
5 — loosener; *6* — discharger; *7* — cooling zone;
8 — exhaust fan; *9* — drying zone fan

Fig. 6. Multi-zone belt drying unit

For this drying method, multi-zone tunnel dryers with a capacity ranging from 0.1 to 1.1 t/h have been designed (Fig. 5). Special temperature and humidity dehydration conditions are kept in each zone of such a dryer. The energy consumption per 1 kg evaporated moisture is 1.5—2 times lower as compared with the existing analogs [10].

For the dehydration of vegetable raw materials in the conditions of a high-humidity climate, a four-zone dryer based on heat generators has been created with the use of a heat pump in the 4th zone of the dryer. This has made it possible to obtain natural food powders from pineapples and bananas for the first time in the world, in the highly humid climatic conditions of Vietnam, and to reduce the energy consumption of dryers of this type by 10—15%.

To implement the multi-stage drying method, a multi-zone belt dryer has been designed (Fig. 6). It has a zone for high-temperature wet processing of the material, eight temperature zones and a cooling zone. The dryer capacity is 1.2 tons of raw material per hour. The heat consumption per 1 kg evaporated moisture is 1.4—2.7 times lower as compared with the existing analogs [11].

The total energy saving potential for the drying of fruit and vegetable raw materials and beet pulp is about 0.2 million tons of conventional fuel, with 0.5 million tons of water vapor emitted to the environment.

In Ukraine, there is a large fleet of evaporating and spray dryers used in the food and chemical and pharmaceutical industries. They produce thousands tons of sugar, dry skimmed and whole milk, whey, instant coffee, penicillin, streptomycin, etc. In most cases, the drying processes consume 2.5 to 3.0 times more energy than is needed to convert moisture into vapor. The energy consumption for these processes is 0.2—0.3 million tons of conventional fuel, with about 0.6 million tons of water vapor emitted into the environment.

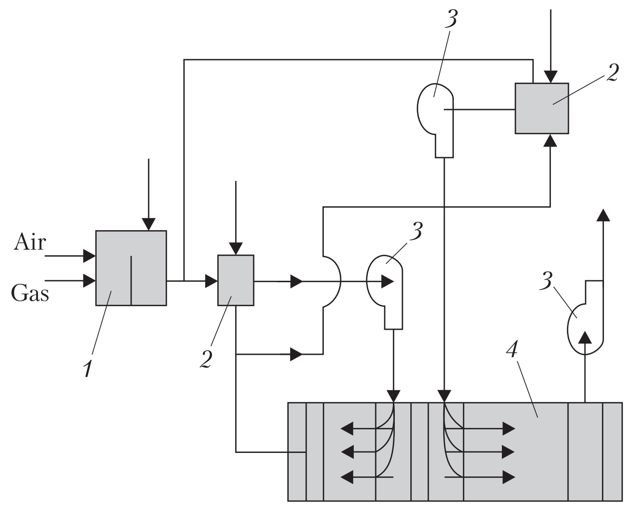


Fig. 7. Two-zone plant for drying lamellar bricks: *1* — heat generator; *2* — air distributors; *3* — blower fans; *4* — dryer

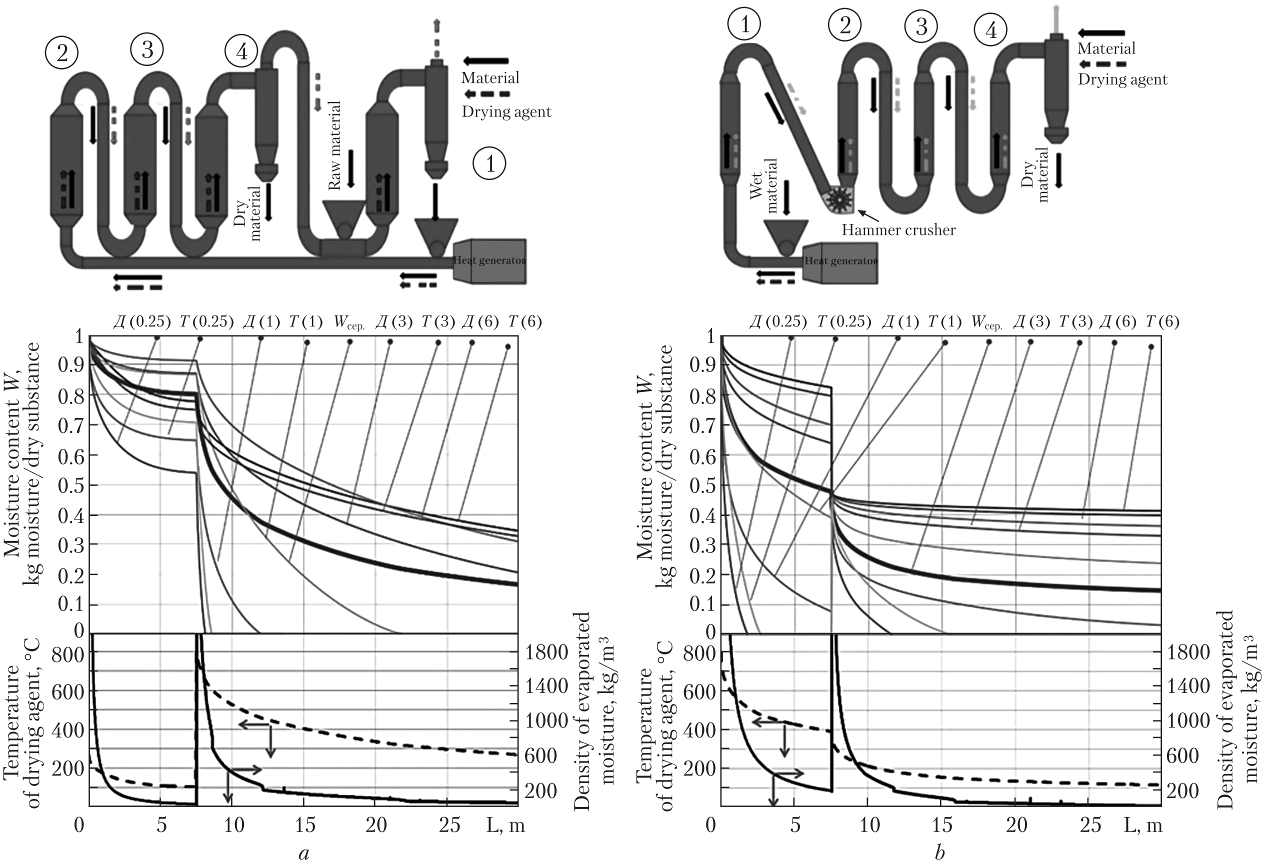


Fig. 8. Pneumatic dryer for fuel dehydration: *a* — scheme with the expansion of the ascending channels and the combined motion of the drying agent; *b* — diagram of a dryer with an intermediate grinding stage

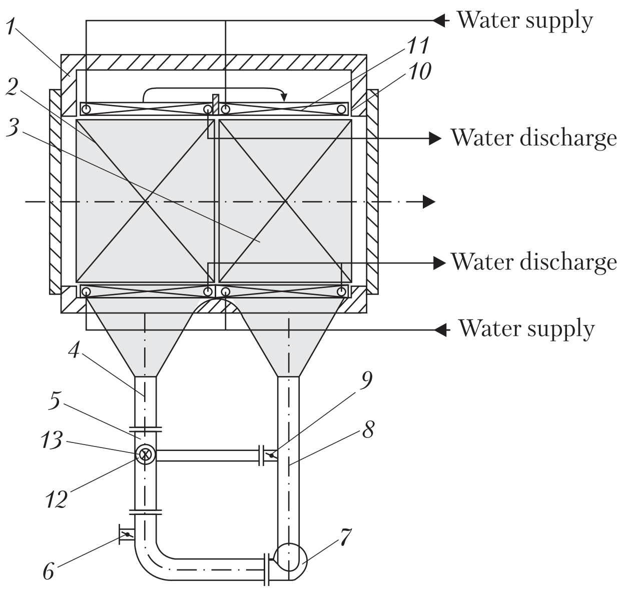


Fig. 9. Geothermal dryer: *1* — drying chamber; *2, 3* — carts; *4, 5* — air ducts; *5* — heat generator; *6, 9* — pipe with a valve; *10, 11, 14, 15* — radiators; *12* — heat exchanger; *13* — smoke pipe

At the Institute, a staged spray drier has been designed. The use of this equipment makes it possible to preserve biologically active substances during dehydration of heat-labile materials; to concentrate solutions; to increase the product yield due to wet trapping; to solve problems of environment protection, and to reduce heat consumption by 18—25%.

The energy saving potential for the drying of food and chemical and pharmaceutical products and materials on the spray dryers is about 0.05 million tons of conventional fuel, with about 0.2 million tons of water vapor emitted into the environment.

In the construction materials industry, dryers are used in the production of bricks and ceramic tiles. Their production in Ukraine reaches 6 billion conditional bricks annually. For drying bricks, as a rule, there are traditionally used tunnel dryers with an average capacity of 300 conventional bricks per hour or up to 1 t/h dry material. The specific energy consumption per 1 kg evaporated moisture is about 6000 kJ that exceeds the standard value by 50—60%. The energy consumption in the production of construction materials in Ukraine exceeds 2 million tons of conventional fuel, with about 0.6 million tons of water vapor emitted into the environment.

The Institute has designed a 2-zone tunnel dryer for the dehydration of lamellar bricks (Fig. 7). The soft conditions in the shrinkage zone and the maximum intensification in the post-drying zone make it possible to reduce the duration of drying by 20—40% and the specific fuel consumption by 15—20%, with a significant decrease in dried waste.

The energy saving potential for the drying of construction materials is about 0.7 million tons of conventional fuel, with water vapor emissions into the environment reduced by 0.2 million tons.

Fuels (coal, peat) needs to dry because of a rather high moisture content in them after extraction. The initial moisture content is 28—43 % for coal; 40—50% for peat. According to the requirements for railways transportation, the moisture content should not exceed 7.5%. About 50 million tons of such fuel is used in Ukraine. The drying equipment is represented by drum dryers, fluidized bed and suspended bed dryers, as well as by pneumatic nozzle and pipe dryers.

The specific energy consumption ranges from 4000 to 6300 kJ per 1 kg evaporated moisture, depending on the capacity (90—400 t/h), wear and efficiency of the dryers. The energy consumption in Ukraine for coal and peat drying is about 1.4 million tons of conventional fuel, with 9.5 million tons of water vapor emitted into the environment.

Energy-efficient configurations of pneumatic dryers with combined motion of the heat carrier and intermediate grinding (Fig. 8) have been designed [12]. They allow reducing the specific energy consumption by up to 20%.

The energy saving potential for the drying of fuels is up to 0.4 million tons of conventional fuel. The water vapor emissions into the environment are expected to decrease by about 2 million tons.

In Ukraine, there are many forests, which allows for the annual production of about 2 million m^3 lumber. At sawmills, drying makes up, at least, 80% of the total manufactured lumber. In the domestic market, they are subject to complete de-

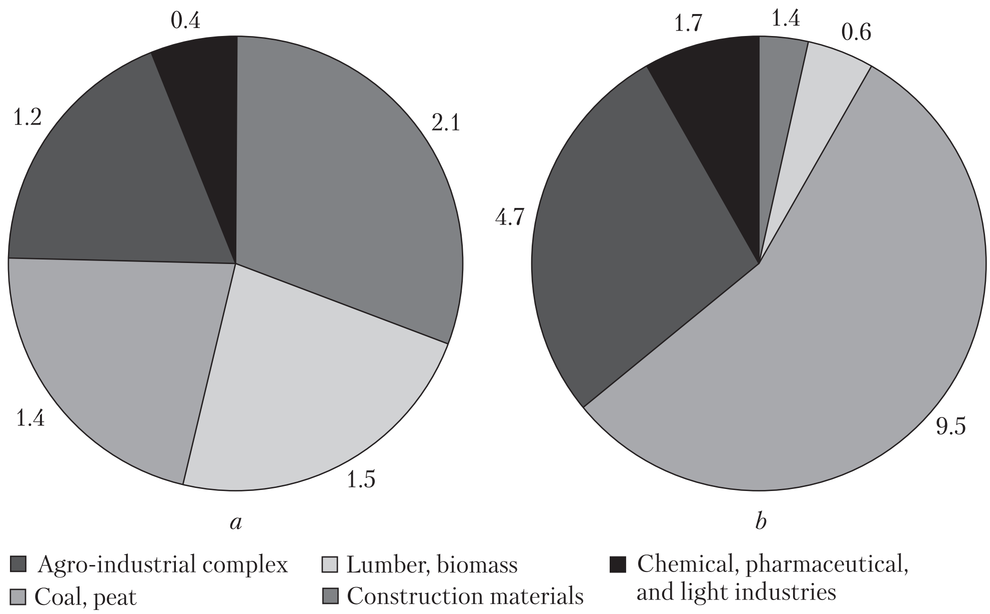


Fig. 10. Energy consumption and environmental safety of drying processes in various industries: *a*) energy consumption for drying in industries (million tons of conventional fuel); *b*) emissions of water vapor into the environment (million tons)

hydration. The drying equipment of this industry mainly consists of outdated periodic or continuous action dryers with a capacity ranging from 10—20 m^3 to 200—300 m^3. The specific heat consumption for evaporation of 1 kg moisture ranges from 4000 to 8000 kJ. The total heat consumption in this industry is about 1 million tons of conventional fuel, with approximately 0.6 million tons of water vapor released into the environment.

The Institute has designed an energy-efficient geothermal tunnel-type dryer on water heaters, with thermal water at a temperature of 45—70 °C used as fuel. In this dryer, the energy is consumed only to drive the fan and the circulation pump for geothermal water. Therefore, the energy consumption is lower than in the similar dryers operating on vapor heaters (Fig. 9).

The condensation drying method with the use of a heat pump is the most effective in the world today for dehydrating both lumber and other materials. It is the most heat-labile in relation to dehydrated materials, with its parameters fully corresponding to natural drying. The energy consumption per 1 kg evaporated moisture in many cases is lower than the theoretically possible one for thermal drying and is equal to 2000—2200 kJ due to a high energy conversion coefficient that may reach 5. This is the only environmentally safe method of drying, because all the moisture evaporated from the material condenses in the heat pump evaporator and is collected in the form of water, without polluting the environment. This method is the future of the drying technology.

The energy saving potential for this industry is estimated at 0.3 million tons of conventional fuel, with the water vapor emissions into the environment decreasing by about 0.2 million tons.

The largest estimated energy costs for drying in various branches of industry of Ukraine have been reported for the production of construction materials (approximately 2.1 million tons of conventional fuel), lumber, wood and agricultural biomass (1.5 million tons of conventional fuel), coal and peat (about 1.4 million tons of conventional fuel), agro-industrial complex (about 1.2 million tons of conventional fuel), chemical, pharmaceutical materials, paper, fabrics, etc. (0.4 million tons of conventional fuel). Together, they total 6.6 million tons of conventional fuel (Fig. 10, *a*).

The largest greenhouse gas emissions have been reported for the coal and peat industry (9.5 million tons of water vapor); the agricultural industry (4.7 million tons of water vapor); lumber, wood, and agricultural biomass (1.7 million tons of water vapor); the manufacture of chemical, pharmaceutical materials, paper, fabrics, etc. (1.4 million tons of water vapor); and construction materials (0.6 million tons of water vapor). Together, they total 17.9 million tons of water vapor annually (Fig. 10, *b*).

The analysis of energy consumption and environment indicators has shown that drying processes are quite energy-intensive and dangerous for environment. About 10% of energy resources by the industry, population, transport, service sector, and agriculture are consumed for the drying processes today. About 28% of energy is spent on the drying processes in the industry alone.

The largest amount of energy is consumed for the drying of construction materials, lumber, wood, and agricultural biomass, coal and peat, and in agriculture (6.6 million tons of conventional fuel); 17.9 million tons of water vapor (which is equal to 7 % of CO_2-equivalent greenhouse gas emissions in Ukraine) are emitted into the environment.

It is obvious that these industries have the greatest potential for energy saving, which is estimated at 2.0—2.1 million tons of conventional fuel per year, while the environmentally hazardous water vapor emissions may be reduced by, at least, 4 million tons per year.

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ЕНЕРГЕТИЧНІ ТА ЕКОЛОГІЧНІ ОСОБЛИВОСТІ ПРОЦЕСІВ СУШІННЯ

Вступ. Глобальними на сьогодні є проблеми енергоресурсозбереження та екології. Енергетична потужність світового виробництва зростає швидше, ніж обсяги промислового виробництва. Наразі у світі існує дефіцит енергії та збільшується забруднення навколишнього середовища, оскільки за останні роки промислове навантаження на довкілля зросло в декілька разів. Тому нині підвищується значимість енергоресурсозбереження та екології.

Проблематика. Сушіння належить до складних енергоємних технологічних процесів. Виробництва, які використовують процеси сушіння, є значимими серед інших промислових підприємств за кількістю використовуваних енергоресурсів. Використання застарілого сушильного обладнання та недосконалих технологічних процесів призводить до витрат значної кількості енергоносіїв та забруднення середовища водяною парою, яка входить до складу парникових газів. Тому актуальним є пошук шляхів зменшення цих негативних наслідків.

Мета. Визначення та аналіз тенденцій зменшення витрат енергоресурсів та небезпечних викидів водяної пари в процесах сушіння.

Матеріали й методи. Використано аналітичні та практичні методи, порівняльно-аналітичний і системний підходи. Матеріалами слугували наукові праці й розробки українських науковців, присвячені зазначеній проблематиці.

Результати. Узагальнено основні способи енергозбереження та зменшення викидів водяної пари під час сушіння. Розробки науковців України, які працюють в Інституті технічної теплофізики НАН України, дозволяють отримати значний потенціал енергозбереження, який оцінюється в 2,0—2,1 млн т.у.п., та зменшення екологічно небезпечних викидів водної пари щонайменше на 4 млн т на рік.

Висновки. Створення та впровадження нового енергоефективного й екологічнобезпечного обладнання і технологій не тільки дозволить зменшити енергозатрати й викиди небезпечної водяної пари в навколишнє середовище, а й дасть змогу оптимізувати використання сировини та отримання якісної продукції у процесах сушіння.

Ключові слова: енергозбереження, сушіння, екологія.