UDC 66.047.4/.5

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RESEARCH INTO KINETICS OF FILTRATION DRYING OF ALCOHOL DISTILLERY STILLAGE

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The article describes the results of experimental studies on kinetics of the filtration drying of corn distillery stillage, which has previously proven its effectiveness in drying other crops and various dispersed materials. The experimental data are presented in the form of graphical plots describing the change of material moisture over time depending on the temperature of the drying agent (60, 70, 80 and 90^{0}C) and the layer height (40, 80, 120 and 160 mm). The obtained results are analyzed and the changes that occur on the filtration drying curves depending on the change in the material layer height and drying agent temperature are described. It is shown that the filtration drying time of alcohol distillery stillage increases with increasing the material layer height. It is determined that the drying potential remains constant at the same parameters of the drying agent. It is shown that the rate of moisture removal during the filtration drying does not depend on the material layer height. It is found that the average residual moisture of corn alcohol distillery stillage is 3.14±0.06 wt.%; this value satisfies industrial needs for an increase in its shelf life and the possibility of long-term storage and transportation.

Keywords: alcohol distillery stillage, secondary raw materials, filtration drying, kinetics, drying potential.

DOI: 10.32434/0321-4095-2021-137-4-58-65

Introduction

Alcohol distillery stillage is a by-product of ethyl alcohol production by fermentation of food raw materials (the residue after distillation from the mash). There are approximately 10–15 liters of distillery stillage per 1 liter of ethanol, depending on the production technology [1–3]. However, this value might reach 20 liters depending on the raw materials used for production [4]. The alcoholic distillery stillage is a liquid suspension of light brown color with a characteristic «bread» smell or the smell of grain. The dry matters content in this product is only up to 10% and the distillery stillage spoils quickly (in a few days). The raw product has a high humidity (about 75–80%), which shortens and limits its shelf life. In this form, the use and transportation of distillery stillage are economically unjustified, and its long-term storage is impossible. Given the above, alcohol distillery stillage can be determined as a waste product, reprocessing or utilization of which is an important industrial task because there are more than 80 distilleries in Ukraine, which produce about 4 million m^3 of molasses stillage and 3.6–3.8 million m^3 of grain distillery stillage [5].

When conducting the dehydration of alcohol distillery stillage in special separators up to 50–60%, the valuable protein food for farm animals can be received. It is known that the use of this product in the diets of dairy cows increases milk yield and improves milk quality by increasing the fat and protein content [6].

Due to a high humidity of the product, it is recommended to feed raw alcoholic distillery stillage no longer than three days after obtaining. To extend the shelf life of raw alcohol distillery stillage, it is preserved by placing it in silo pits and sleeves. In addition, in order to extend the shelf life, the alcoholic distillery stillage is dried; however, this significantly increases its cost.

As far as the chemical composition is concerned, the alcohol distillery stillage contains many valuable substances (%): sugars 0.2–0.45; glycerin 0.4–0.6; starch 0.1–0.2; hemicellulose 1.4–2.3; and cellulose 0.3–0.9 [7]. In addition, there are proteins, amino acids (tryptophan, lysine, methionine, cystine and threonine), vitamins

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(nicotinic and folic acid, biotin), macro-and micronutrients and carbohydrates in distillery stillage. The contents of some components of the alcohol distillery stillage are given in Tables 1 and 2 [6].

Note that the content of proteins, amino acids and other substances, that play an important role in metabolism and growth processes of animals, in a dry distillery stillage is ahead of the most feed products; thus, the use of dry distillery stillage in animal husbandry is the most rational.

Table 1

The content of micronutrients in alcohol distillery stillage

Micronutrient	Fe	Zn	Mn	Cu
Content, mg kg^{-1}	1570	210	75.2	8.4

Another way of the recycling of alcohol distillery stillage involves its use as a plasticizer of concrete and cement-sand mixtures. The goal is to minimize the risk of transfer of the distillery stillage to the environment. However, this area has not been developed due to low content of dry matter and the problem of transportation, which made it unprofitable to use it outside the radius of 80–100 km from the production sites [6]. In addition, studies were performed in which alcohol distillery stillage was first used for growing yeast, and later the resulting raw material was added to concrete mixtures. The addition of 0.1–0.15% of this product increased the strength of concrete by 10–15% [7].

It is also known about active laboratory and field research on fertilization of agricultural lands with alcohol waste to increase crop yields. Alcoholic distillery stillage has an acidic reaction of the environment (pH 4.8–5.2) and promotes the development of soil microflora. Such activity allowed increasing the yield by 24.9–48.1%, while the sugar content of sugar beet roots increased, and the protein content in soybeans, barley, and buckwheat increased by 3.19–31.5% [6]. It is recommended to use about 125 m^3 hectare^{-1} of alcohol distillery stillage to improve plant growth and soil characteristics. The opposite effect is observed when using more than 250 m^3 hectare^{-1} [8].

Table 2

The composition of alcohol distillery stillage obtained from various raw materials

Component of distillery stillage, % with respect to dry matters	Corn	Wheat	Rye	Barley
Dry matters content	10	10	10	10
Crude protein	21.6	20.1	16.5	23.3
Crude fat	10.7	7.6	8.2	8.2
Crude fiber	10.4	10.5	9.2	6.2
Nitrogen-free extractives	43.7	47.1	54.8	29.4
Calcium	0.17	0.18	0.13	0.24
Phosphorus	0.29	0.69	0.43	0.56
Lysine	0.71	0.83	0.52	0.49
Cystine	0.20	0.33	0.17	0.15
Methionine	0.28	0.43	0.14	0.26

Another area of the use of distillery stillage and at the same time an alternative to physicochemical processing methods is the biogas production [9]. This technology can be used for production needs by stimulating the processes of methane-forming bacteria in an anaerobic environment. The technology of waste utilization of grain processing plants was developed that provides the production of dry protein feed and biogas and the treatment of effluents to a level acceptable for their discharge into reservoirs. Here, the pellets are obtained from distillery stillage using a centrifuge, the pellets being further dried on the steam dryer.

As can be seen, the reuse of alcohol distillery stillage in optimal ways (feed additive and biogas production) requires drying of the initial product.

Drying is a complex thermophysical and mass transfer process, which is widely used at the final stages of many technological processes, and the organization of which largely affects the quality and cost of final products. It is known that 8–10% of all energy in the world is spent on drying processes and in most cases, 2.5–3 times more energy is used than is required to convert moisture into steam. Thus, when optimizing the stage of drying of the distillery stillage, one can achieve a significant economic effect on the cost, which will improve the environmental situation by reducing emissions into the environment.

Usually, three following methods of drying (dehydration) of dispersed materials are used [10]: thermal (including vacuum), sorption (contact) and mechanical methods (wringing and centrifugation). Filtration drying is a promising method of reducing grain moisture [11–13]. It is one of the most intensive methods of drying dispersed materials, which allows increasing the drying intensity, diminishing the size and metal content of the machines, reducing the specific costs of heat and electricity and improving the quality of final products.

The principle of filtration drying implies that the heat transfer agent moves under the action of pressure drop through the porous structure of the sheet gas-permeable material. The process of heat and mass transfer takes place on the intra-capillary surface, which exceeds the geometric surface of the dried material. In the process of filtration drying, there is a mechanical displacement and removal of moisture, depending on the nature of its connection with the material, achieving a high usage degree of thermal energy. There is a significant intensification of drying in comparison with the convective dehydration process; in addition, a significant reduction in specific energy consumption is observed.

Previous studies have shown the effectiveness of the filtration drying of distillery stillage [14]. However, to summarize the results and create a scientific basis for determining optimal drying parameters, it is necessary to conduct a thorough analysis of a number of the following factors:

– the quality of the distillery stillage from various food raw materials,
– grinding degree,
– initial moisture content,
– height of the material layer,
– characteristics of the thermal agent, etc.

The main task of this article is to establish the influence of some parameters (layer height and the temperature of the drying agent) on the drying process of alcohol distillery stillage. This will prolong the shelf life of test material without loss of nutrients, thereby increasing the volume and expanding the scope of usage of alcohol distillery stillage.

Experimental

To perform experimental studies of the filtration drying of alcoholic distillery stillage, an experimental laboratory installation was used (Fig. 1). It allows carrying out complex research of grain material drying at variable modes: rate and temperature of drying agent, the height of a layer of grain material, its moisture content, and an angle of inclination of a drying zone.

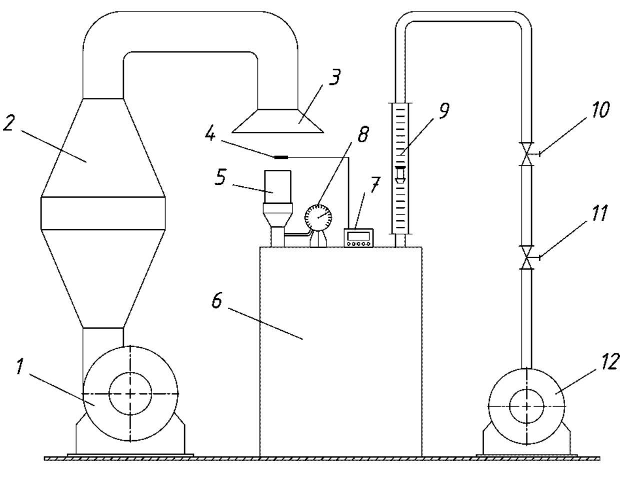

Fig. 1. The scheme of the experimental installation for filtration drying: 1 – fan; 2 – electric heater; 3 – diffuser; 4 – thermocouple; 5 – container; 6 – receiver; 7 – control and measuring device SENTOS D1S; 8 – vacuum gauge; 9 – rotameter; 10 – control valve; 11 – shut-off valve; 12 – water ring vacuum pump

The installation shown in Fig. 1 consists of a fan 1, which injects air into the electric heater 2, where it is heated to the set temperature. Passing through the diffuser 3, the air enters the container 5 with a layer of the test material. Above the container is a thermocouple 4 to determine the air temperature at the outlet of the diffuser. The thermocouple is connected to the SENTOS D1S control and measuring device, which sets and maintains a constant temperature of the drying agent. To measure the values of pressure losses in the material layer, a vacuum gauge 8 is installed. Container 5 is connected to a receiver 6, which creates liquefaction due to the water ring vacuum pump 12. In front of the previous is located a rotameter 9 for air flow measuring. In addition, a control valve 10 (to regulate the flow of heat agent) and shut-off valve 11 are installed.

We studied an alcoholic corn distillery stillage after the centrifugation process obtained on the production line of SE «Vuzlove distillery» (Vuzlove, L'viv region, Ukraine).

To determine the humidity of the alcoholic distillery stillage, a moisture analyzer RADWAG MA 50/1.R was used. A sample of the investigated raw material with a weight of about 1.5 g was placed on a special platform of the device, where the material was calcined at the temperature of 115^{0}C, that is slightly higher than the boiling point of water (to completely remove moisture from the material). To determine the humidity of the alcoholic distillery stillage more accurately, the process was performed 5 times. The drying time corresponded to the cessation of changes in the mass was 75 minutes.

The bulk density of raw materials was also determined experimentally. To this end, a certain amount of alcoholic distillery stillage was poured into a round container with a known diameter to achieve a clearly defined layer height. The next step was to determine the mass of raw materials, which was carried out on electronic scales AXIS AD3000. The calculation was performed according to the following formula:

$$\rho_b = G/(S \cdot H),$$

where G is the mass of the material layer in the container (kg); S is the cross-sectional area of the container (m^2); and H is the height of the layer of the test material (m).

To establish the effect of the temperature of the drying agent on the drying process, a series of experiments were performed at different temperatures: 60⁰C, 70⁰C, 80⁰C and 90⁰C. The height of the layer of material in the container was chosen as the closest value for industrial needs and was 120 mm.

According to the bulk density, the container was filled with distillery stillage using a fresh portion of the material for each subsequent experiment. The sample container was weighted every 60 s to determine the amount of moisture that passed into the drying agent stream. Weighting time did not exceed 15 s. A thermocouple was installed at a height of 15 cm above the container; it was connected to the SENTOS D1S control and measuring device to regulate and maintain a constant process temperature. Drying of the test sample was carried out until the weight of the container with the material in two consecutive measurements remains constant.

In addition, in accordance with the described method, a study of the effect of the material layer height on the drying kinetics was performed. The following values of heights of filling of the container with raw materials were chosen for this purpose: 40 mm, 80 mm, 120 mm and 160 mm. The temperature of the drying agent was 70⁰C (the average value of the previously specified temperatures).

Residual moisture content in the material after drying was determined according to the State Standard of Ukraine DSTU EN 14774-2: 2013 (Solid biofuels. Determination of moisture content Drying method in the oven. Total moisture).

Results and discussion

According to the methods described above, the average value of humidity of the studied distillery stillage was determined as 66.0043%. In addition, the value of the bulk density of the studied stillage was calculated: 326.86 kg m^{-3}.

The effects of the layer height (Fig. 2) and the temperature of the drying agent (Fig. 3) on the kinetics of drying process are presented as dependences of the material moisture content on the drying time, w^c vs. τ.

The obtained curves reveal two main stages of moisture removal (Figs. 2 and 3). The straight-line section determines the rate of movement in the mass transfer zone and it is called in the literature the first period of filtration drying [11]. There is a uniform removal of external moisture from the layer of the studied material during the time, which corresponds to this period. Thus, there is a direct relationship between drying time and the moisture content of the distillery stillage.

Next, there is an exponential segment in dependence w^c vs. τ, which reflects a decrease in the amount of moisture removed by the thermal agent over time. During this period, residual water will be removed from the material layer until equilibrium is established along the entire height of the layer. Such

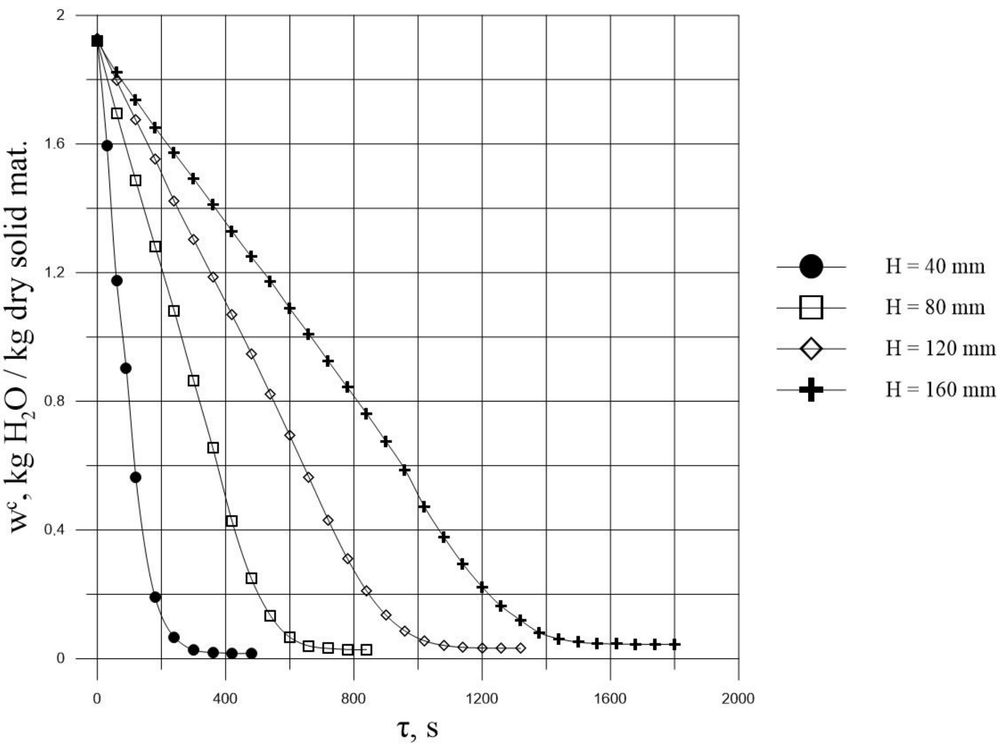

Fig. 2. Kinetics of filtration drying of corn distillery stillage at different layer heights (t=70⁰C)

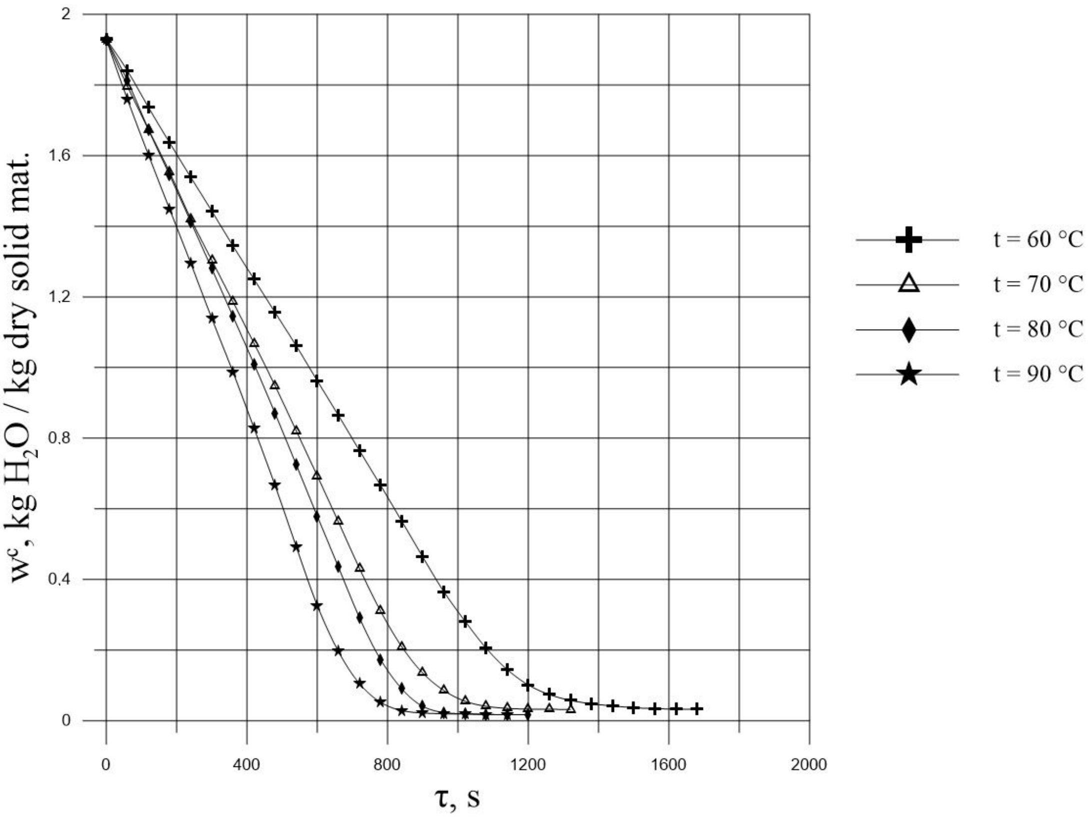

Fig. 3. Kinetics of filtration drying of corn distillery stillage at different temperatures of the heating agent (H=120 mm)

a sharp change in the moisture content of the material corresponds to the second drying period, which is also called the period of falling drying speed.

An increase in the height of the material layer is also accompanied by an increase in the amount of moisture in the sample. Since the parameters of the drying agent in parallel experiments are the same, the drying potential is limited to a certain value. Thus, a certain limited amount of moisture can be removed from the layer of material over a period of time. Figure 2 shows a proportional increase in the filtration drying time according to the height of the distillery stillage layer.

The effect of temperature change is shown in Fig. 3. With increasing this parameter, the potential of the drying agent increases, which is accompanied by a decrease in the drying time of the material at a constant speed of the heating agent. The higher the temperature values used, the closer the curves will be on the graph and the greater the slope of the straight section.

Analyzing the graphical dependences shown in Fig. 2, one can be conclude that the slope of the rectilinear sections depends on the height of the layer of the test material at the same temperature and speed of the drying agent. To explain the cause of this dependence, a graphical dependence of the residual moisture content of the material depending on the height of the layer is plotted (Fig. 4).

It is seen from Fig. 4 that the height of the layer of material does not affect the amount of moisture carried by the drying agent. This statement is confirmed by the parallelism of the straight sections of the filtration drying curves.

The drying potential of drying characterizes the rate of moisture removal from the test material. It is possible to increase this value by changing the parameters of the drying agent such as temperature or speed. The dependence of the change in the amount of moisture on the temperature of the coolant is shown in Fig. 5.

The test sample of dried alcohol corn distillery stillage was left for several days under ambient conditions. After that, the amount of residual moisture was determined. For a more accurate definition, seven parallel experiments were performed, the results of which are shown in Table 3.

Obtained values of residual moisture content of alcohol distillery stillage fully meet the industrial needs to increase the shelf life and provide its long-term storage and transportation (Table 3).

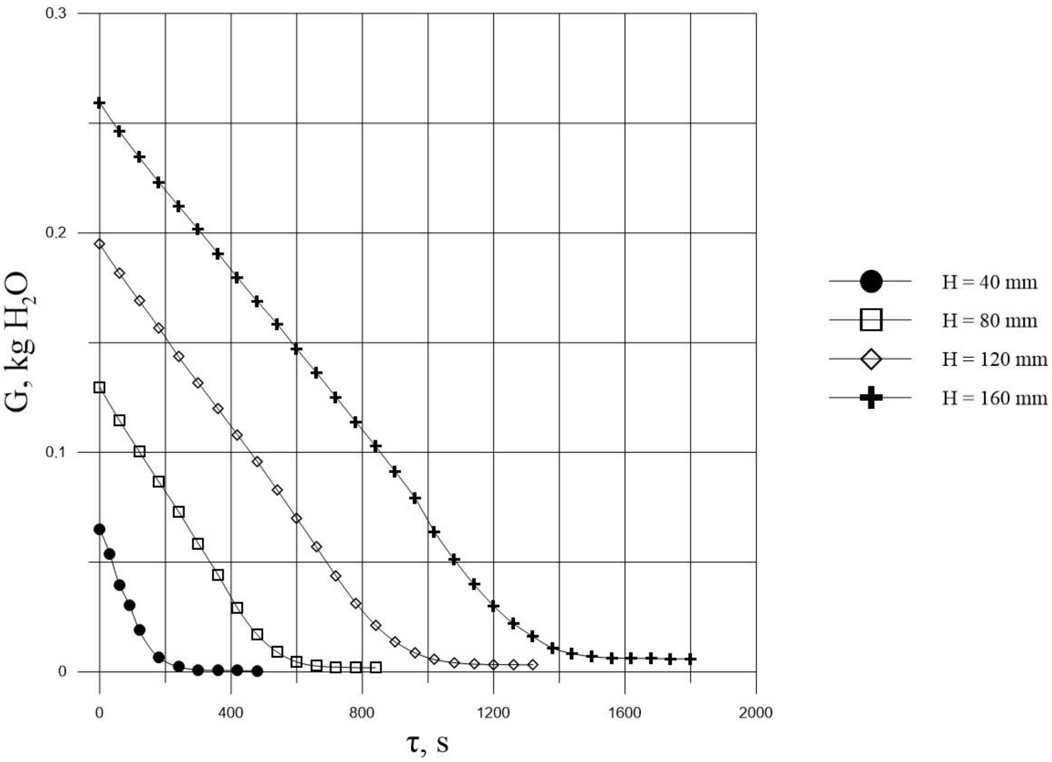

Fig. 4. The change in moisture mass of corn distillery stillage as a function of time at different layer heights at t=70^{0}C

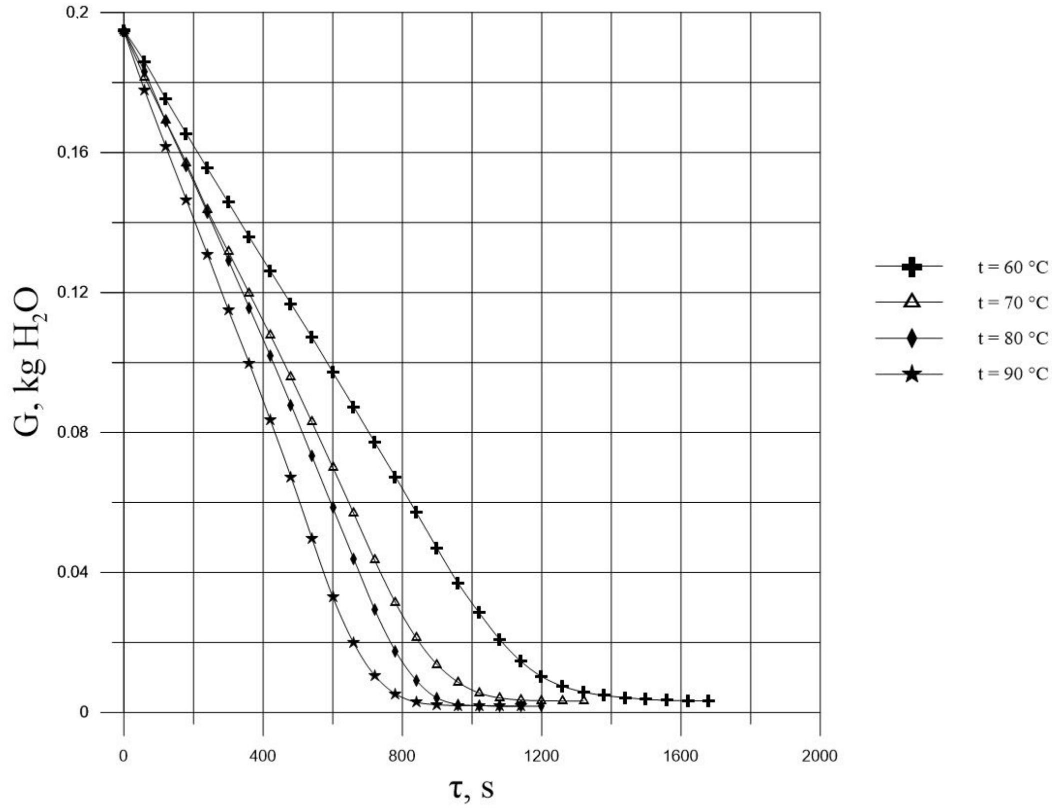

Fig. 5. Change in the moisture mass of corn distillery stillage as a function of time at different temperatures of the drying agent at a layer height H=120 mm

Table 3

The results of experimental determination of residual moisture content in corn distillery stillage

Sample No.	Moisture content, wt.%
1	2.93
2	3.10
3	3.32
4	3.09
5	3.03
6	3.13
7	3.38
Average value	3.14±0.06

Conclusions

Excessive humidity of the alcohol distillery stillage limits the time of possible operation and thus makes it a problematic product for widespread use. Because it is a by-product of ethyl alcohol production, its value is often ignored and commonly it is simply thrown out, despite its valuable chemical composition.

We proposed to dry the distillery stillage to increase its shelf life. This will expand the scope of its application and increase the area of possible transportation from production enterprises. Given this, the method involves the reduction of the cost of the product manufacturing, which will positively affect the reuse of alcohol distillery stillage.

Drying was carried out by the filtration method due to its advantages over other drying methods.

The influence of the material layer height was investigated. It was stated that the drying time of the sample increases with the increase in layer height. At the same parameters of the drying agent, the drying potential remains constant. Therefore, a study of the heat flux temperature change was done for a given layer height (H=120 mm), which is an approximate value for industrial needs.

The data on the kinetics of filtration drying of corn distillery stillage were analyzed and plotted in the form of proper dependences. The changes in curves characterizing the filtration drying with changes of the material layer height and the drying agent temperature were described. It was shown that the rate of moisture removal during filtration drying does not depend on the height of the material layer.

The value of residual moisture of the investigated material is 3.14±0.06 wt.%. This value fully satisfies the industrial requirements to increase the shelf life of the alcohol distillery stillage and provide its long-term storage and transportation.

REFERENCES

1. *Glovyn N.M.* Vplyv spyrtovoyi bardy na agrokhimichni vlastyvosti gruntu // Scientific Messenger of LNU of Veterinary Medicine and Biotechnologies. Series «Agricultural Sciences». – 2017. – Vol.19. – No. 74. – P.192-195.

2. *Treatment* of high strength distillery wastewater (cherry stillage) by integrated aerobic biological oxidation and ozonation / Beltran F.J., Alvarez P.M., Rodriguez E.M., Garcia-Araya J.F., Rivas J. // Biotechnol. Prog. – 2001. – Vol.17. – No. 3. – P.462-467.

3. *Nataraj S.K., Hosamani K.M., Aminabhavi T.M.* Distillery wastewater treatment by the membrane-based nano-filtration and reverse osmosis processes // Water Res. – 2006. – Vol.40. – No. 12. – P.2349-2356.

4. *Wilkie A.C.* Chapter 16. Biomethane from biomass, biowaste, and biofuels // Bioenergy. – 2008. – P.195-205.

5. *Mazur A.H., Tsikhanovska V.M., Hontaruk Y.V.* Perspektyvy virobnytsva biogazu na spirtovykh zavodakh Vinnyts'koyi oblasti Naukovi Pratsi Instytutu Bioenergetychnykh Kul'tur i Tsukrovykh Buryakiv. – 2013. – Vol.19. – P.245-249.

6. *Hizhnjak M.I., Tsion' N.I.* Spyrtova barda yak tsinna kormova dobavka i organichne dobryvo u sil's'komu gospodarstvi // Ribogospodars'ka nauka Ukrainy. – 2010. – Vol.2. – P.122-130.

7. *Obodovych A.N., Sydorenko V.V.* Barda spirtovykh zavodov – tsennyi othod dlya proizvodstva kormovykh drozhzhei i betona // Ceramics: Science and Life. – 2015. – Vol.4. – No. 29. – P.15-19.

8. *Mikucka W., Zielinska M.* Distillery stillage: characteristics, treatment, and valorization // Appl. Biochem. Biotechnol. – 2020. – Vol.192. – No. 3. – P.770-793.

9. *Golub N.B., Potapova M.V.* Tekhnologiya oderzhannya biogazu z pislyaspyrtovoyi bardy // Vidnovluvana energetyka. – 2018. – Vol.2. – P.70-77.

10. *Zberigannya* i pererobka produktsiyi roslynnytsva / Podprjatov G.I., Skalets'ka L.F., Sen'kov A.M., Hylevych V.S. Ed. Gorodys'ka ZA. – Kyiv: Meta; 2002. – 495 p.

11. *Atamanyuk V.M., Gumnyts'kii Y.M.* Naukovi osnovi fil'tratsiinogo sushinnya dyspersnykh materialiv. – Lviv: Vydavnytsvo Natsional'nogo Universytetu «L'vivs'ka Politekhnika», 2013. – 276 p.

12. *Modeling* of internal diffusion mass transfer during filtration drying of capillary-porous material / Gnativ Z.Y., Ivashchuk O.S., Hrynchuk Y.M.., Reutskyi V.V., Koval I.Z., Vashkurak Y.Z. // Math. Model. Comput. – 2020. – Vol.7. – No. 1. – P.22-28.

13. *Matkivska I.Y., Gumnytskyi Y.M., Atamanyuk V.M.* Kinetics of diffusion mass transfer during filtration drying of grain materials // Chem. Chem. Technol. – 2014. – Vol.8. – No. 3. – P.359-363.

14. *Doslidzhennya* parametriv sharu ta gidrodynamiky profil'trovuvannya teplovogo agenta kriz' shar pislyaspyrtovoyi bardy / Kindzera D.P., Atamanyuk V.M., Mosiuk M.I., Zdybel' B.I. // Naukovyi Visnyk NLTU Ukrayiny. – 2013. – No. 23.18. – P.86-94.

Received 17.03.2021

ДОСЛІДЖЕННЯ КІНЕТИКИ ФІЛЬТРАЦІЙНОГО СУШІННЯ ПІСЛЯСПИРТОВОЇ БАРДИ

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Наведено результати експериментальних досліджень кінетики фільтраційного сушіння кукурудзяної барди, яке попередньо засвідчило свою ефективність при сушінні сільськогосподарських культур та різних дисперсних матеріалів. Одержані експериментальні дані надані у вигляді графічних залежностей, що описують зміну вологості матеріалу в часі залежно від температури сушильного агента (60, 70, 80 і 90^{0}С) та зміни висоту шару (40, 80, 120, 160 мм). Одержані результати проаналізовано та описано зміни, які виникають на кривих фільтраційного сушіння в залежності від зміни висоти шару матеріалу та за зміни температури сушильного агенту. Показано, що час фільтраційного сушіння післяспиртової барди зростає зі збільшенням висоти шару матеріалу. Визначено, що за однакових параметрів сушильного агента, потенціал сушіння залишається сталий. Показано, що швидкість видалення вологи за фільтраційного сушіння не залежить від висоти шару матеріалу. Визначено, що залишкова вологість кукурудзяної післяспиртової барди задовольняє промислові потреби для збільшення терміну експлуатації післяспиртової барди та можливості її тривалого зберігання і транспортування і в середньому становить 3,14±0,06 мас.%.

Ключові слова: післяспиртова барда, вторинна сировина, фільтраційне сушіння, кінетика, сушильний потенціал.

RESEARCH INTO KINETICS OF FILTRATION DRYING OF ALCOHOL DISTILLERY STILLAGE

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Keywords: alcohol distillery stillage; secondary raw materials; filtration drying; kinetics; drying potential.

REFERENCES

1. Glovyn NM. Vplyv spyrtovoyi bardy na agrokhimichni vlastyvosti gruntu [Effect of alcohol on bards agrochemical soil properties]. *Scientific Messenger of LNU of Veterinary Medicine and Biotechnologies. Series «Agricultural Sciences»*. 2017; 19(74): 192-195. (*in Ukrainian*). doi: 10.15421/nvlvet7442.

2. Beltran FJ, Alvarez PM, Rodriguez EM, Garcia-Araya JF, Rivas J. Treatment of high strength distillery wastewater (cherry stillage) by integrated aerobic biological oxidation and ozonation. *Biotechnol Prog*. 2001; 17(3): 462-467. doi: 10.1021/bp010021c.

3. Nataraj SK, Hosamani KM, Aminabhavi TM. Distillery wastewater treatment by the membrane-based nanofiltration and reverse osmosis processes. *Water Res*. 2006; 40(12): 2349-2356. doi: 10.1016/j.watres.2006.04.022.

4. Wilkie AC. Chapter 16. Biomethane from biomass, biowaste, and biofuels. In: Wall JD, Harwood CS, Demain A, editors. *Bioenergy*. ASM Press; 2008. p. 195-205.

5. Mazur AH, Tsikhanovska VM, Hontaruk YV. Perspektyvy virobnytsva biogazu na spirtovykh zavodakh Vinnyts'koyi oblasti [Prospects of the production of biogas at the factories of Vinnyts'ya region, Ukraine]. *Naukovi Pratsi Instytutu Bioenergetychnykh Kul'tur i Tsukrovykh Buryakiv*. 2013; 19: 245-249. (*in Ukrainian*).

6. Hizhnjak MI, Tsion' NI. Spyrtova barda yak tsinna kormova dobavka i organichne dobryvo u sil's'komu gospodarstvi [Alcohol stillage as a valuable fodder additive and organic fertilizer in agriculture]. *Ribogospodars'ka Nauka Ukrainy*. 2010; 2: 122-130. (*in Ukrainian*).

7. Obodovych AN, Sydorenko VV. Barda spirtovykh zavodov – tsennyi othod dlya proizvodstva kormovykh drozhzhei i betona [Distillery slops of distilleries as a valuable raw material in the production of feed yeast and concrete]. *Ceramics: Science and Life*. 2015; 4(29): 15-19. (*in Russian*).
doi: 10.26909/csl.4.2015.2.

8. Mikucka W, Zielinska M. Distillery stillage: characteristics, treatment, and valorization. *Appl Biochem Biotechnol*. 2020; 192: 770-793. doi: 10.1007/s12010-020-03343-5.

9. Golub NB, Potapova MV. Tekhnologiya oderzhann'ya biogazu z pislaspirtovoyi bardy [Fabrication of biogas from alcohol stillage]. *Vidnovluvana Energetyka*. 2018; 2: 70-77. (*in Ukrainian*).

10. Podprjatov GI, Skalec'ka LF, Sen'kov AM, Hylevych VS. *Zberigannya i pererobka produktsiyi roslynnytsva* [Preservation and processing of the products of crop production]. Kyiv: Meta; 2002. 495 p. (*in Ukrainian*).

11. Atamanyuk VM, Gumnyts'kii YM. *Naukovi osnovi fil'tratsiinogo sushinnya dyspersnykh materialiv* [Fundamentals of filtration drying of dispersed materials]. Lviv: Vydavnytstvo Natsional'nogo Universytetu «L'vivs'ka Politekhnika»; 2013. 276 p. (*in Ukrainian*).

12. Gnativ ZY, Ivashchuk OS, Hrynchuk YM, Reutskyi VV, Koval IZ, Vashkurak YZ. Modeling of internal diffusion mass transfer during filtration drying of capillary-porous material. *Math Model Comput*. 2020; 7(1): 22-28. doi: 10.23939/mmc2020.01.022.

13. Matkivska IY, Gumnytskyi YM, Atamanyuk VM. Kinetics of diffusion mass transfer during filtration drying of grain materials. *Chem Chem Technol*. 2014; 8(3): 359-363.
doi: 10.23939/chcht08.03.359.

14. Kindzera DP, Atamanyuk VM, Mosiuk MI, Zdybel' BI. Doslidzhennya parametriv sharu ta gidrodynamiky profil'trovuvannya teplovogo agenta kriz' shar pislyaspyrtovoyi bardy [Research into parameters of a layer and hydrodynamics of filtration of thermal agent through a layer of alcohol stillage]. *Naukovyi Visnyk NLTU Ukrayiny*. 2013; 23.18: 86-94. (*in Ukrainian*).