



**ФАН ВА ТЕХНОЛОГИЯЛАР
ТАРАҚҚИЁТИ**
**РАЗВИТИЕ НАУКИ И
ТЕХНОЛОГИЙ**



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ИЛМИЙ – ТЕХНИКАВИЙ ЖУРНАЛ

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Ушбу журналда чоп этилган материаллар тахририятнинг ёзма рухсатисиз тўлиқ ёки қисман чоп этилиши мумкин эмас.

Тахририятнинг фикри муаллифлар фикри билан ҳар доим ҳам мос тушмаслиги мумкин. Журналда ёритилган материалларнинг ҳаққонийлиги учун мақолаларнинг муаллифлари ва реклама берувчилар масъулдирлар.

МУНДАРИЖА - СОДЕРЖАНИЕ – CONTENT

ТЕХНИКА, ТЕХНОЛОГИЯ ВА ЖИҲОЗЛАР	
Яхяев Н.Ш. Эксплуатация нефтяных месторождений с трудноизвлекаемыми запасами....	5
Назаралиева Н. Дезодорациялаш жараёни гидродинамикасини яхшилашда секцияларга ажратиш истиқболлари.....	12
Mansurov O.A. Improving the drying process of fruits using convective method.....	17
Urinov A.A. Magistral quvurlari himoya qoplamalarini modifikatsiyalashda uglevodorod xomashyosi va bitum piroliz chiqindilarini qo'llash salohiyati.....	21
Норбоев О.Н., Улжаев Э. Расчет основного параметра емкостного датчика.....	25
Tog'aymurodov S.Z, Rasulova B.I. Yuklama tokining o'zgarishini transformatorlarning ichki izolyatsiyasiga bog'liqligini tekshirish.....	30
Berdiyev D.M., Komilova G.M. Shtamp asboblarning termik ishlov berish harorat rejimlarini optimallashtirish.....	34
Зокирова Д.А. Свободных и вынужденных колебаний на установке - ТМ 155.....	38
Bibutov N.S., Hojiyev A.X., Xabibov F.Yu., Xamroyev X.X. Metall konstruksiyalar.....	42
Shukrullayev J.O., Jo'rayev X.F. Barabanli quritgichda gidrodinamik rejimlarini nazariy tadqiq qilish.....	51
КИМЁ ВА КИМЁВИЙ ТЕХНОЛОГИЯЛАР	
Беккулов Дж.Ш. Адаптивный виртуальный анализатор на основе метода “движущегося окна”, предназначенный для определения и анализа качественных показателей хлорида калия в режиме реального времени, постоянно адаптирующий свой алгоритм работы на основе последних данных.....	56
Mahmudov G'B., Ravshanov F.A., Qalandarov A.F. Sianlash jarayonida ionsektiv elektrodi usuli yordamida sian konsentratsiyasini o'lchash aniqligini oshirish.....	63
Obidov H.O. Gazni qayta ishlash zavodlarida turli xildagi absorbentlarning tahlili va jihoz, qurilmalarning korroziyalanishini oldini olish.....	72
Tilloeva Sh., Sharipov K. Improvement of the demercaptanization process based on kerosene production technology.....	77
Jo'rayeva D.Sh., Jumayev J.H., Atoev E.X. Sintez qilib olingan 1-(defenilamino)butanon-2 ning xromato-mass spektri tahlili.....	81
Ахмедова О.Б., Мустафоев Б.Ж. Риформинг жараёни учун янги авлод катализаторини танлаш.....	85
Сафаров Ё.Т., Гуро В.П., Расулова С.Н., Рузиев У.Н., Абдуллаев Ф.Р., Асадов А.И. Совершенствование технологии получения высокочистого вольфрамового ангидрида.....	90
Tojiyev O.O., Sharipov Q.Q., Yaminov F.F. Neft va gaz quduqlarining mahsuldorligini oshirish uchun tarkibi yaxshilangan kislota eritmasini olish.....	95
Фозилов Ҳ.С., Туробжонов С.М., Фозилов С.Ф. Этил спирти куб қолдиғи сивуш мойи асосида дизел ёқилғилари учун мойловчи ва едирилишга қарши присадкаларни олиш.....	100
Ranoyev E.R., Do'stov H.B., Nurnazirova G.D. Buxoro neftni qayta ishlash zavodidagi mazut xomashyosining fizik – kimyoviy tahlili va undan moy va koks olish jarayonini tahlil qilish.....	107
Soatov B.Sh., Xasanov A.S., Hakimov K.J., Muhammadiyev E.M. Xondiza polimetall ma'danlarining kollektiv-selektiv flotatsiyasini optimallashtirish va mis boyitmasini ajratib olishning samaradorligini oshirish	113
Ниезов С.А., Умиров Ф.Э., Номозова Г.Р., Махмудов.Р.А., Худойбердиев Ф.И. Калий хлориди ва натрий гипохлорит конверсияси асосида калий хлоратини олиш.....	119
Savriyev M.S., Do'stov H.B., Tilloyev L.I. Unconverted oil (uco) ning kimyoviy tarkibini gaz xromatografiya–mass-spektrometriya yordamida tahlil qilish.....	127

МАШИНАСОЗЛИК ВА ЭНЕРГЕТИКА	
Qo'ziyev Z.E. Quyosh fotoelektr panellarining asosiy parametrlarini tahlili va modellari.....	134
Tovboyev A.N., Tog'ayev I.B. Konveyer elektr yuritmalarida garmonik buzilishlarni kamaytirish hamda mexanik nosozliklarning elektr energiyasi sifatiga ta'sirini baholash texnologiyalari..	139
Sadullayev N.N., Murtazoyev F.F. Neft va gaz sanoatida energiya samaradorlikka ta'sir etuvchi omillar va energiya samaradorlikni oshirish imkoniyatlari.....	146
Жалилов Р.Б., Шарипова Н.О. Перспективы комбинированного производства электроэнергии, тепла и холода – актуальное направление в энергетике в условиях цифровой трансформации	150
Гафуров К.Х., Рахманов Ш.Б. Механизм влияния низкочастотного электрического поля на процесс сушки плодов (обзор).....	157
Ахмедов Х.И. Комплексное исследование химического состава, морфологии и эксплуатационных характеристик белых высокохромистых чугунов.....	161
Sayfiddinov Q.E. Ikki rotorli shamol turbinasini matlab/simulink tizimida modellashtirish va optimal parametrlarini aniqlash.....	168
Tovboyev A.N. Elektr tarmoqlarida ko'ndalang kompensatsiya tizimining funksional tahlili.....	174
Mamadjanov A.B., Akmalov J.X. Gravitatsion girdobli mikroges konussimon havzasining maqbul konstruksiyasini asoslash orqali energiya samaradorligini oshirish.....	180
Maxmudov B.M. Key factors in selecting drying process parameters and their impact on product quality and energy efficiency.....	189
ИНФОРМАТИКА ВА АХБОРОТ – КОММУНИКАЦИОН ТИЗИМЛАР	
Тураев Х.С. Повышение надёжности и безопасности сложных технологических процессов с использованием принципов условной обратной связи.....	196
Sobirov M.N. Intelktual qurilmalarning internet tarmog'i (internet of things) ga asoslangan oziq - ovqat ishlab chiqarish va qayta ishlash korxonalarining umumiy modelini ishlab chiqish...	204
Sultonov S. Mathematical modeling of the output power of a mobile power plant with a garland turbine.....	212
ОЗИҚ-ОВҚАТ САНОАТИ ТЕХНОЛОГИЯЛАРИ	
Dehqonova N.A., Majidov K.X. Paxta moyini rafinatsiyalash jarayonlarida zamonaviy innovatsion texnologiyalarni qo'llash va ularning matematik modelini ishlab chiqish.....	218
Абдуллаева Г.У., Курбанов М.Т. Влияние лекарственных растений и их смеси на микро-биологические показатели комбикормов при хранении.....	226
Sharipov N.Z., Qo'ldosheva F.S. Gilos danagidan moy olish jarayonini ultratovushli maydonida jadallashtirish.....	232
Kuliyeva N.G'., Sharipov N.Z. Qovoq mag'zini quritish jarayonini ultratovush ta'sirida jadallashtirishning nazariy asoslari.....	236
Кабулов Н.А., Сабиров У.К., Окилов А.К. Машинное зрение для автоматизации контроля качества продукции.....	242
Садуллаев С.Х., Шахридинов Ф.Ф. Сравнительный анализ аминокислотного состава белков, полученных из местного зерна тритикале для помола хлебопекарной муки.....	245
ТЎҚИМАЧИЛИК ВА ЕНГИЛ САНОАТ ТЕХНОЛОГИЯЛАРИ	
Темирова Г.И. Табiiй мўйна хом ашёсининг физик-механик хусусиятларини иқтисодий харажатларга таъсирларини ўрганиш усуллари.....	253
Темирова Г.И. Аёллар устки кийими тайёрлашда фойдаланиладиган табiiй мўйна пакетининг физик-механик хоссалари.....	259

Uzoqova L.P. Tabiiy va sintetik charmlardan tayyorlangan ustki poyabzallarning shaklbardoshligini oshirish uchun shakllantirish rejimlarini ilmiy asoslash.....	264
Mirzaboyev J.B. Turli rusumli pnevmomexanik yigirish mashinalarida olingan ip sifat ko'rsatkichlarini tahlili.....	269
To'xtayeva Z.Sh., Abulova P.U. O'smirlar modasi talablari asosida antropometrik muvofiqlikning ergonomik ko'rsatkichlarini baholash.....	275
Azimova G.A., Kadirova D.N. Jun aralash tarkibli kiyimbop to'qimalarning texnologik ko'rsatkichlari tadqiqi.....	281
Gaybullayeva N.Z. Zamonaviy maxsus ish kiyimlari uchun innovatsion matolarning xususiyatlari va qo'llanilishi.....	285
Abduraxmanova F.A. Bikr qobiq yordamida poyabzal maketini barpo etish usullari.....	291
Uzoqova L.P. Poyabzal ishlab chiqarishda bichuvchi malakasining charmdan foydalanish koeffitsiyentiga ta'sirining ilmiy tahlili.....	296
Ихтиярова Г.А., Рахматова Г.Н., Асадова С.С. Исследования техники мокрого валяния - нунофелтинг на различных шелковых тканях.....	301
Эргашева Н.Д., Нигматова Ф.У., Шомансурова М.Ш., Музаффарова Ф. Модульное проектирование одежды как основа ресурсосбережения.....	306
Toshpulotov L.I., Xamrayeva S.A., Mardonov S.E. Ikki qatlamli ko'ylakbop matoning fizik-mexanik xususiyatlarini aniqlash uslublari.....	315
Kadirova D.N., Azimova G.A. Kiyimbop to'qimalarning tolaviy tarkibini aniqlash.....	320
Совутов М.Э., Мусаев Н.М., Гуляева Г.Х., Мукимов М.М. Иссиқлик сақлаш хусусияти юқори бўлган трикотаж тўқималарининг сифатини баҳолаш.....	324
Xodjayeva M.E., Gafurova N.T. Yigiruvchilar uchun maxsus kiyim yaratishda o'tkazilgan tajribalarni matematik rejalashtirish va ratsional qiymatlarini aniqlash.....	329
Toshpulotov L.I., Xamrayeva S.A., Mardonov S.E. Turli o'rilishli ikki qatlamli ko'ylakbop matolar olish texnologiyasini ishlab chiqish.....	336
Нодирова М.Н., Танибердиев Ф.Р., Исломова М.С., Хамраева С.А. Ипларнинг узиш кучини аниқлаш усулини такомиллаштириш.....	342
Turdiyev B.E. Chigit shikastlanishini kamaytirish tajriba-sinov natijalari.....	345
Avezov M.F., Kuliyeva D.R. Yengil sanoat sohasida bazalt tolali matolardan foydalanishning ilmiy-asosiy tahlili.....	350
Musayev S.S., Qodirov T.J. Maxsus poyabzal tagligi uchun etilen propilen kauchuk va polipropilen asosidagi termoplastik elastomer kompozitsiyalarning mexanik xossalarini tadqiq etish.....	353
Muxammedova M.O. Boldir-tovon bo'g'imlari shikastlangan bemorlar uchun ilmiy asoslangan ortopedik poyabzal konstruksiyasini ishlab chiqish.....	360
Fayziyev S.H., Ibodullayev O.O. Paxta tozalash mashinasini yangi konstruktsiyasini ishlab chiqish.....	365
АНИҚ ВА ИЖТИМОИЙ-ИҚТИСОДИЙ ФАҢЛАР	
Burxonov Z.A. Kutubxonada ish jarayonida avtomatlashtirilgan intellektual dezinfektsiyalovchi qurilmani ishlab chiqish.....	372
Xolova Sh.A. Effectiveness of implementing internet of things devices in occupational safety: real time monitoring approach.....	377
Мухамедбаев Аг.А. Легкий пористый заполнитель автоклавного генезиса.....	381
Gadoeva O.P. Bazalt asosidagi yangi qurilish materiallarini ishlab chiqarish texnologiyalari.....	388
ЭКОЛОГИЯ ВА АТРОФ МУҲИТ МУҲОФАЗАСИ	
Xaitov R.A., Axmedova M.B., G'ulomov I.G'. Ikkilamchi xomashyolaridan foydalanib ekologik toza qurilish materiallari ishlab chiqarish	394

Xaitov R.A., Axmedova M.B., Xalikova N.S. O‘simlik xomashyolaridan foydalanib ekologik toza mahsulot yetishtirish usullari.....	399
Pirimov R.R., Juraqulov A.X. Buxoro viloyati hududida qayta tiklanadigan energiya manbalaridan foydalanish imkoniyatlari.....	403
Yunusova G. R., Nabiyev A.A., Ro‘ziyev I.X. Chiqindi suvlar tarkibidagi AL, GA, TL ionlarini aniqlash usullari.....	411
Yaminov F.F., Obidov H.O. Oltingugurt-ishqorli oqova suvlarni tozalashning kimyoviy va kompleks usullari.....	417

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KEY FACTORS IN SELECTING DRYING PROCESS PARAMETERS AND THEIR IMPACT ON PRODUCT QUALITY AND ENERGY EFFICIENCY

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Abstract. This article analyzes the selection and optimization of key technological parameters of the drying process for raw materials and products in light industry. Drying is considered as a coupled heat and mass transfer process, and the effects of temperature, air velocity, relative humidity, pressure, and drying time on product quality and energy consumption are investigated. The study demonstrates that improperly selected drying conditions can lead to deterioration of physical and mechanical properties of materials and increased energy usage. The constant-rate and falling-rate drying periods, energy-saving strategies in industrial dryers, heat recovery technologies, and modern drying methods are discussed. In addition, the potential of solar energy as a renewable source for drying applications and the prospects for using solar dryers under the climatic conditions of Uzbekistan are examined. The results provide scientific and practical recommendations for achieving high-quality and energy-efficient drying processes in light industry.

Keywords: drying process, light industry, temperature, air velocity, relative humidity, energy efficiency, drying time, solar energy.

QURITISH JARAYONLARI PARAMETRLARINI TANLASHDAGI ASOSIY OMILLAR VA ULARNING MAHSULOT SIFATI HAMDA ENERGIYA SAMARADORLIGIGA TA'SIRI

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Annotatsiya. Ushbu maqolada yengil sanoat xomashyolari va mahsulotlarini quritish jarayonining asosiy texnologik parametrlarini tanlash va optimallashtirish masalalari tahlil qilingan. Quritish jarayoni issiqlik va massa almashinuvi jarayoni sifatida ko'rib chiqilib, harorat, havo tezligi, nisbiy namlik, bosim va quritish vaqti kabi omillarning mahsulot sifati hamda energiya sarfiga ta'siri yoritilgan. Tadqiqotlarda noto'g'ri tanlangan quritish rejimi mahsulotning mexanik, fizik va kimyoviy xossalari yomonlashishiga, ortiqcha energiya sarfiga olib kelishi ko'rsatib berilgan. Maqolada quritish jarayonining doimiy va kamayuvchi tezlik bosqichlari, sanoat quritkichlarida energiya tejash usullari, issiqlikni qayta tiklash texnologiyalari hamda zamonaviy quritish usullari tahlil qilingan. Shuningdek, qayta tiklanuvchi energiya manbai sifatida quyosh energiyasidan foydalanish imkoniyatlari va O'zbekiston sharoitida quyosh quritkichlarini qo'llash istiqbollari ko'rib chiqilgan. Tadqiqot natijalari yengil sanoatda yuqori sifatli va energiya tejamkor quritish jarayonlarini tashkil etish uchun ilmiy-amaliy tavsiyalar beradi.

Kalit so'zlar: quritish jarayoni, yengil sanoat, harorat, havo tezligi, nisbiy namlik, energiya samaradorligi, quritish vaqti, quyosh quritkichi.

ОСНОВНЫЕ ФАКТОРЫ ВЫБОРА ПАРАМЕТРОВ ПРОЦЕССОВ СУШКИ И ИХ ВЛИЯНИЕ НА КАЧЕСТВО ПРОДУКЦИИ И ЭНЕРГОЭФФЕКТИВНОСТЬ

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Аннотация. В данной статье рассмотрены вопросы выбора и оптимизации основных технологических параметров процесса сушки сырья и продукции легкой промышленности. Процесс сушки проанализирован как процесс тепло- и массообмена, при котором изучено влияние температуры, скорости воздуха, относительной влажности, давления и времени сушки на качество продукции и энергопотребление. Показано, что неправильно выбранный режим сушки приводит к ухудшению физических и механических свойств продукции, а также к избыточным затратам энергии. В работе рассмотрены периоды постоянной и убывающей скорости сушки, методы энергосбережения в промышленных сушильных установках, технологии рекуперации тепла и современные методы сушки. Особое внимание уделено использованию солнечной энергии как возобновляемого источника и перспективам применения солнечных сушилок в условиях Узбекистана. Полученные результаты могут быть использованы для повышения энергоэффективности и обеспечения высокого качества продукции в легкой промышленности.

Ключевые слова: процесс сушки, легкая промышленность, температура, скорость воздуха, относительная влажность, энергоэффективность, время сушки, солнечная энергия.

Introduction. The drying process is an important stage in the preparation of products for storage and maintaining their quality in industry. Drying various raw materials and products extends

their shelf life, prevents microbiological deterioration, and provides the necessary moisture level for subsequent technological processing. Drying is relevant in light industry (for example, in food, pharmaceuticals, and agricultural products), and directly affects product quality and energy consumption.

Drying processes are characterized by high energy demands in industry - some studies have found that at least 7–15% of the total energy consumption of industry falls on drying processes [1]. Therefore, in light industry, optimizing drying technology, i.e., correctly selecting and controlling parameters such as temperature, air velocity, humidity, and drying time, is an important task to achieve energy efficiency while maintaining high product quality. However, choosing the wrong parameters during the drying process can cause a number of problems. For example, overdrying raw materials such as cotton fiber (moisture content < 6%) makes the fiber brittle and prone to breakage; on the contrary, if the moisture content is high (> 8%), the fibers become sticky, making the cleaning and shearing processes difficult [2,3]. Similarly, drying foods at very high temperatures or for long periods of time can reduce their nutritional value [4]. Therefore, it is necessary to choose the optimal drying mode for each product: this mode should ensure fast and efficient drying without compromising the quality of the product.

To model and analyze the drying process, it is first necessary to understand its physical foundations. Drying is essentially a heat and mass transfer process, in which thermal energy is supplied to evaporate water from a moist material and the resulting vapor is carried away by the air flow. Drying usually occurs in two stages: a constant rate period (constant) and a decreasing rate period (decreasing). During the constant rate period, external factors - the temperature of the drying medium, air velocity and relative humidity - determine the removal of moisture; during the decreasing period, internal diffusion processes prevail, and moisture from the interior of the material moves to the surface (tends to the surface). Theoretical models are often used to accurately model the drying process using experimental data [5]. In addition, in modern approaches, the drying process is modeled using numerical methods (e.g., computational fluid dynamics – CFD) and the effects of process parameters are predicted in advance [6].

This article examines the main technological parameters used in drying light industrial raw materials and their importance, as well as the possibilities for energy saving and the use of solar energy.

Method. The factors (parameters) that affect the drying process are a guarantee of the quality of the dried product. In order to study how to improve the quality of drying, it is necessary to establish and analyze each method (parameter) that affects drying one by one.

Temperature (T) is the most influential parameter in the drying process. Increasing the temperature accelerates the evaporation process by transferring more heat to the material. It is known that at higher temperatures, air can hold more moisture and evaporate more quickly from a moist material [7]. However, increasing the temperature beyond the norm can lead to unpleasant consequences: the surface of the product dries out too quickly, causing a "crust" phenomenon (it becomes difficult for internal moisture to escape). Also, excessively high temperatures lead to a decrease in strength and elasticity in light industrial (fiber) products, easy breakage of fibers, and deterioration of quality through yellowing [4]. Therefore, the optimal temperature is selected individually for each material: for example, for fruits and vegetables, a temperature of around 50–60 °C is optimal for quality and speed, while some fibrous products (for example, cotton fabrics) can be dried at temperatures up to 70–90 °C, since their structure is resistant to such heat [8]. Scientific studies often test temperatures between 45–65 °C, and it is also noted that this range provides a balance between efficient drying and quality preservation [9].

Drying time is the total time required for a given reduction in moisture content of a material and is one of the most important parameters in industrial drying processes. Incorrect selection of drying time directly affects product quality, energy consumption and efficiency of drying equipment. There are no exact values for drying time, since the optimal value of drying time

directly depends on factors such as air temperature, air velocity, relative humidity, pressure, material thickness and structure, and initial moisture content of the material.

The optimal drying time preserves the internal structure of the product (molecular bonds, interfiber capillaries) and especially increases technical aspects such as energy consumption and dryer efficiency. Shorter drying time leads to insufficient drying of the product, while longer drying time leads to overdrying, energy consumption, and quality deterioration.

Air velocity (V) plays an important role in drying equipment. Increasing air velocity helps to remove evaporated moisture from the product surface more quickly, i.e. the moisture boundary layer around the product becomes thinner. As a result, higher air flow increases the evaporation rate during the constant velocity stage of drying [7]. For example, in a study on hot air drying of wood, it was observed that the drying rate increased significantly by increasing the air velocity from 0.5 m/s to 4.0 m/s [10, 7]. However, increasing the air speed excessively is not always beneficial - after a certain limit, the process begins to be limited by internal diffusion, and a very strong air flow does not provide additional efficiency, but only increases energy consumption. Therefore, in practice, air speeds of about 1.5–2.5 m/s are often used, these values significantly increase the drying speed and are economically justified [5].

Relative humidity (RH) of the air determines the moisture capacity of the drying environment. Dryer air (low RH) is more likely to absorb moisture from the product, which speeds up drying. Conversely, if the air has a high RH, it becomes saturated and cannot absorb new moisture, which slows down or stops drying. Studies have shown that when the air RH is low, the final equilibrium moisture (the remaining moisture content of the product) is also lower, while high RH leaves more moisture in the product [7]. Therefore, in industrial dryers, the air is first heated and its relative humidity is reduced - for example, air heated to 60 °C is dried to about 15–20% RH, depending on the atmospheric humidity. The optimal RH value depends on the type of material: in some cases, it is also necessary not to dry the air too much to maintain product quality. In general, heat exchangers and dehumidifiers (e.g. desiccant rotors) are used in dryers to maintain air in the range of 10–30% RH in industry.

Pressure (P) is another parameter that affects the drying process, and is especially important in vacuum drying technologies. It is known that at atmospheric pressure, water evaporates at 100 °C, and reducing the pressure lowers the boiling point of water. Vacuum dryers operate at low pressure, which allows drying the product at relatively low temperatures (for example, 40–60 °C). For thermolabile products, vacuum and even freeze-drying (lyophilization) methods can be used to remove water while preserving their valuable substances. For example, pharmaceutical and biological products are dried in a vacuum, limiting thermal damage that would otherwise occur under normal conditions [12]. Vacuum dryers can also be used in some areas of light industry (food, medicinal herbs), but due to their high energy consumption and complex design, their economic efficiency is often low. Nevertheless, accelerating the drying process and maintaining product quality through pressure control is a current area of scientific research.

Results. If we look at the results of drying quality through the variation of drying parameters, industrial practices have provided a lot of information on the effect of drying parameters on efficiency. In general, increasing the temperature significantly reduces the drying time: for example, while drying of fibers at 60 °C is quite slow, drying at 80–90 °C can be completed several times faster.[9] However, increasing the temperature to higher values (°C) provides little additional benefit in terms of drying rate, as internal diffusion often becomes the limiting step at higher temperatures. However, excessive temperatures have a negative impact on product quality.

The effect of air velocity varies depending on the nature of the material and the drying stage. For thin and permeable materials (e.g. fabrics or fibers), increasing the air flow will quickly remove moisture at the beginning of the drying process, reducing the drying time. When air velocities are tested at higher speeds, the speed increases the initial rate of moisture evaporation. However, in the

second, decreasing stage of drying, the effect of air velocity decreases as internal moisture diffusion becomes the main limitation [14]. By supplying air at a higher speed, the drying rate is initially faster, but then it does not change. This is due to the diffusion of moisture exchange in the material. Therefore, when choosing the optimal air speed, energy consumption is also taken into account: too high a speed requires a large flow capacity. Most industrial dryers use air speeds around 2 m/s, at which point convective heat and mass transfer are good and no excess energy is consumed. For thicker or denser materials (wooden boards, grain layers, etc.), slightly higher speeds (3–5 m/s) can be used, since in them the air flow must penetrate deeper into the material and transfer heat [10].

The effect of air humidity is in the opposite direction: the drier the drying environment, the more efficient the drying. Air humidity is one of the main factors that has a very strong influence on the drying process. Drying is mainly a process of evaporation of moisture, and air humidity directly controls the rate of evaporation. At low humidity, the drying rate increases, because dry air has the ability to absorb more moisture. This increases the humidity difference between the surface of the material and the surrounding air, and the moisture evaporates faster. In the opposite case, i.e. at high humidity, the air is already saturated with moisture, so it hardly absorbs new moisture. The evaporation process slows down or may stop altogether.

Changing the drying rate directly affects energy consumption. In low humidity conditions, drying is faster, which saves energy. In high humidity conditions, the process takes longer and the dryer has to work extra, which increases operating costs. Air humidity has a profound effect not only on the drying rate, but also on the quality of the dried product. In high humidity conditions, the outer shell of the material can dry out, leaving moisture inside. This uneven drying leads to subsequent mold, rot, or deformation of the product. In addition, the color and composition of some materials change, or the likelihood of microorganisms multiplying increases. In industrial drying methods, it is possible to control the air humidity in the drying chamber or reduce it using special dryers. Analyzing the results, it is recommended that most drying systems do not exceed 20–30%. If the air humidity is 50% or higher, the drying time will be much longer, and in the end, the product may contain more moisture than allowed.

Drying time is closely related to the above parameters and is considered an indicator of efficiency. The goal is to achieve the desired moisture level in the shortest possible time. Experiments show that, for example, a thin layer of fruit and vegetables (3–5 mm) can be dried in 6–8 hours at a temperature of 60 °C and an air speed of 2 m/s, while the same product will have to be dried for 15–20 hours at 40 °C and slower ventilation [16]. In industrial continuous drying processes, the time is determined by the time the product is held in the conveyor belt or drum. For example, textile fabrics can be dried in conveyor dryers in a few minutes because the temperature is very high (80–120 °C), the air flow is strong, and the fabric is thin. In the case of granular or granular materials (grain, tea leaves), the drying time depends on the layer thickness: the thicker the layer, the longer it takes for the moisture in the lower layer to evaporate. In this case, the total time is reduced by mixing or moving the layer (fluidization). It is clear that there is an optimal combination of drying times for each product, and it can be determined experimentally. Regarding the drying time, it should be noted that the drying process is carried out slowly at a lower temperature, which serves to preserve the quality of the product. However, this, in turn, reduces the efficiency of the device and increases energy consumption. Since drying processes are seasonal depending on the product, it is also necessary to dry them faster (without mold, rot, or fungus).

Summarizing the above results, the most effective drying regime in industrial drying processes is achieved by selecting a specific combination of temperature, air velocity and humidity. The drying time depends on the type of product, its thickness and the value of the moisture content required to remain in it. In the textile industry, although higher temperatures (70–90 °C) are used depending on the type of fabric, the drying time is very short and humidification operations (e.g. steaming) are also used to avoid damaging the quality of the product. For raw materials such as cotton fiber, it is important to maintain the ideal moisture level: leaving cotton in the moisture range of about 6–8% after drying gives the best results - in this case the fibers have optimal strength and

elasticity [2]. If cotton fiber is dried more than normal (for example, to 3–4% moisture), it will have to be re-wetted later, which is an additional cost and a loss of quality [17].

Discussion. Maintaining balance during the drying process is one of the main tasks. As mentioned above, drying too quickly (with high temperature and strong air flow) sometimes leads to the product becoming hard on the surface and preventing the internal moisture from escaping. On the contrary, drying too slowly (with low temperature and humid air) can create conditions for bacterial or fungal growth, which can spoil the product, and also waste energy. When choosing the optimal mode, it is necessary to adjust each parameter proportionally: for example, if a slightly higher temperature is used, it is time not to increase the air speed too much, or vice versa - when drying at a low temperature, it is possible to compensate for the time by increasing the air flow. Often, a multi-stage drying strategy is used: in the first stage, the main part of the moisture is removed with high temperature and speed (constant speed period), in the next stage(s) the temperature is slightly reduced and the internal moisture of the product is gradually removed (decreasing speed period). This method helps to save energy and maintain quality.

Energy saving strategies are becoming an integral part of drying technology. It is known that drying processes release a large amount of heat into the air, especially in traditional convective dryers, where the efficiency is only around 30–60% [18]. Therefore, modern drying systems are equipped with heat recovery (utilization) capabilities: for example, using the hot and humid air leaving the dryer to absorb energy using heat exchangers and heat the incoming fresh air. One study showed that using dryer exhaust air can increase the overall energy efficiency by 60–80% [1][19]. Energy consumption can also be reduced by further improving drying equipment: for example, heat pump dryers consume significantly less energy than traditional gas or electric dryers because they operate in a closed cycle, recovering heat from the air [12]. Technologies such as microwave drying and infrared drying generate heat directly in the product itself, dramatically reducing drying time and thereby achieving energy savings [12]. But such methods sometimes result in uneven drying of the product or technological complexity, so they are used more in special cases.

Another important approach is to optimize the organization of the drying process. For example, energy consumption can be reduced by evenly distributing the material being dried inside the dryer, ensuring that air reaches every part of it, and by properly insulating the dryer walls and air ducts [20]. It is also important not to set the drying time incorrectly: the process should be stopped as soon as the product reaches the required moisture content, continuing it too much is a waste of energy and time. Many modern dryers have automatic control, which determines the end of the process based on the humidity level of the exhaust air. It should be noted that by replacing electric motors and fans with energy-efficient ones, and installing inverter control (VFD), it is also possible to save about 5–15% of electricity [21].

One of the promising future directions of drying in light industry is the use of solar energy. Solar energy has great potential as a cheap and environmentally friendly source, especially in regions with a sunny climate. Traditional open-air solar drying has been used for a long time, but its serious drawback is the inability to fully control the process (dependence on weather, contamination with dust and insects, etc.). A modern approach is the use of solar dryers. Solar dryers have special designs that pass air heated by concentrating sunlight or the greenhouse effect through the product. For example, in tunnel-type solar dryers, air is heated under a transparent cover, creating temperatures of up to 50–60 °C inside [22]. It has been found that the temperature inside a solar dryer chamber exposed to direct sunlight is twice as high as the outside temperature – for example, when it is 32 °C outside, the temperature inside the dryer reaches around 70 °C [23][24]. Another study reported that a hybrid dryer with a solar collector and battery achieved daytime temperatures of up to 73 °C [25]. Such systems dry much faster and more efficiently than conventional open drying: for example, a maximum temperature of 57.6 °C was observed in a direct solar dryer, which dried the wet material faster than in conventional solar drying, while a relatively high temperature of 55.4 °C was achieved in an indirect (collector) dryer, which ensured more stable drying (at the

same time, the temperature in open air drying was at most 38 °C) [26]. Hybrid solar-electric dryers have also been developed, allowing the process to continue uninterrupted at night or when the sun is low, using an electric heating system; such dryers have been shown to be capable of reaching temperatures above 60 °C with solar energy during the day and maintaining temperatures of 40–50 °C at night using a heat accumulator [27]. In Uzbekistan, scientific research is even studying the issue of optimizing drying systems using solar concentrators, that is, analyzing ways to achieve maximum efficiency when sunlight is focused and directed to the dryer [28]. Of course, the widespread introduction of solar dryers faces some limitations - weather variability, the need for night time, the problem of uniform drying of large volumes of products, etc. Nevertheless, the prospects for using solar energy in terms of energy saving and environmental friendliness are very high.

Conclusion. When drying light industrial raw materials, the correct selection and control of technological parameters such as temperature, air speed, humidity and time determine the success of the drying process. The above analyses and examples show that there is an optimal drying regime for each type of product, and achieving this regime requires a scientific approach and experimental tests. By taking into account the interaction of parameters and adjusting them in a balanced way, the following achievements are achieved: drying time is reduced to a minimum, product quality (taste, color, consistency, nutritional value) is maintained, and energy consumption is optimized.

For example, in fibrous materials, it is advisable to keep the moisture content in the range of 6–8% (in the case of cotton fiber) [2]. By following such optimal parameters, it is possible to reduce excessive energy consumption and the risk of obtaining poor-quality products. Measures such as automating the drying process, controlling temperature and humidity in real time, and improving the design of the dryer reduce the human factor and facilitate the achievement of stable results.

Renewable energy sources, in particular solar energy, are expected to play an important role in increasing the energy efficiency of industrial drying in the future. Dryers using solar energy can reduce traditional fuel consumption and reduce greenhouse gas emissions. In the conditions of Uzbekistan, there is a possibility of widespread use of solar dryers in the processing of light industrial products and drying agricultural raw materials, and scientific research is being conducted in this regard [28].

In conclusion, scientifically based optimization of drying parameters is an important condition for ensuring competitive and sustainable production in light industry. A correctly selected drying mode maintains high product quality, reduces energy consumption and costs, and makes the process more environmentally friendly. At the same time, by introducing innovative technologies using solar energy, drying processes can be made more economical and environmentally friendly in the future. This will not only bring economic benefits to industrial enterprises, but also make a positive contribution to the overall energy efficiency and environmental sustainability of the country.

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