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REGULAR ARTICLE

Theoretical Aspects and Engineering Approaches to Energy-Saving Liquid Atomization Technologies

O.V. Khomenko[1,*], M.V. Naida[1], K.P. Khomenko[1], A.A. Biesiedina[1], S.O. Hodlevsky[2], I.A. Chelnokov[1]

[1] *Sumy State University, 40007 Sumy, Ukraine*
[2] *Educational and Scientific Institute of Vocational Education of the National Academy of the National Guard, 61000 Kharkiv, Ukraine*

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This article explores modern approaches to liquid atomization with a focus on energy efficiency, enhanced interfacial heat and mass transfer, and a deeper understanding of the physical nature of the liquid state. Particular attention is given to the concept of the hole structure of liquids as a key factor influencing the disintegration mechanisms during atomization. The study examines how fundamental liquid properties - such as density, viscosity, and specific heat capacity – affect multiphase interactions in liquid-gas systems, which are crucial for the performance of various industrial processes. The paper reviews major atomization methods, including static and centrifugal nozzles, emphasizing their ability to generate droplets of con-trolled dispersity while minimizing energy consumption. The role of nozzle geometry and flow parameters in reducing energy demand without compromising atomization quality is critically assessed. Additionally, the potential of thin-film atomization technologies is highlighted, as they enable uniform droplet distribution and significantly improve heat and mass transfer efficiency. Based on current scientific literature, physical-technical models, and experimental findings, the study presents a comparative analysis of energy-saving atomization technologies. The importance of an interdisciplinary approach is underlined – one that integrates the physics of liquids with design and operational considerations of atomizing systems. The results support the development of next-generation atomization methods that offer both economic advantages and environmental sustainability for industrial applications. This opens up the possibility not only to extend the service life of sprayers in difficult conditions, but also to increase the overall efficiency of cooling systems, which is strategically important for ensuring the reliability of modern equipment.

Keywords: Heat and mass transfer, Static atomizers, Centrifugal atomizers, Thin-film technologies

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1. INTRODUCTION

The process of dispersing liquids, in particular their atomization in the form of finely dispersed aerosols, plays a critically important role in a large number of natural and man-made processes. The efficiency of heat and mass transfer in heat exchangers, the productivity of spraying in agriculture, the efficiency of fuel atomization systems in internal combustion engines, the level of gas purification in power plants, as well as the quality of painting, humidification, cooling or dust removal in industrial technologies depend on the quality and controllability of this process. Technological interest in liquid atomization is enhanced by the need to increase energy efficiency, reduce substance losses, as well as environmental requirements for reducing harmful emissions and secondary pollution.

In general, the process of liquid atomization is a complex multi-stage phenomenon that includes the destruction of a continuous flow or film of liquid, the formation of fragments (primary drops), their further destruction, interaction with the gas flow, possible collision and coalescence of drops, and, finally, the inclusion of the dispersed phase in the flow. The final characteristics of the aerosol, such as the size and distribution of drops, their speed, surface density, duration of existence in the gas medium, determine the effectiveness of a particular technological task. Despite significant progress in the development of atomization systems, a deep understanding of the physical foundations of the formation of a droplet medium still needs to be clarified. This is especially true of the issue of mechanisms for the destruction of the liquid phase. In this context, the concept of the hole structure of the liquid is gaining increasing attention, which forms a new view of the processes of destruction of the liquid volume.

According to modern ideas, any liquid, despite its seemingly continuous structure, has microscopic cavities – holes, which are formed due to density fluctuations, thermal motion of molecules and surface effects. These holes play the role of primary centers of instability in the volume of the liquid, which are activated under the action of external forces: hydrodynamic pres-

* Correspondence e-mail: o.khomenko@mss.sumdu.edu.ua

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sure, ultrasonic vibrations, centrifugal acceleration, etc. Actually, the growth, merger and collapse of these cavities cause the destruction of the liquid medium into individual fragments and drops. This approach opens up new possibilities for controlling the dispersion process at the level of the liquid structure, in particular by changing its rheological properties, composition, temperature, pressure and external perturbation. A detailed study of the hole structure requires the use of methods of molecular dynamics, mathematical modeling, hydrodynamic analysis of instabilities and experimental studies on a microscale. This field of knowledge is currently one of the promising areas of fundamental physics of liquids and interphase interaction.

In parallel with the fundamental analysis, it is important to understand the technological implementation of liquid dispersion. Modern technology offers a wide range of methods and devices for spraying - mechanical, hydraulic, pneumatic, centrifugal, ultrasonic, electrohydrodynamic, etc. Each of these methods has its own advantages, limitations and energy costs. For example, hydraulic spraying allows you to achieve a sufficiently high dispersion with a relatively simple device design, but is often accompanied by significant energy losses to overcome hydraulic resistance. Pneumatic spraying provides a finely dispersed aerosol, but requires powerful compressor systems. Centrifugal nozzles are able to work with viscous liquids, but have limitations in terms of uniformity of droplet distribution.

In each case, the key characteristics remain the degree of dispersion (average droplet diameter, distribution spectrum), energy consumption (energy consumption for the formation of a unit volume of aerosol), spray stability (variability in time and space), as well as technological compatibility with other elements of the system. A careful comparison of the main dispersion methods allows not only to select the optimal method for a specific task, but also to lay the foundation for the creation of new hybrid or adaptive spray systems.

The most urgent task of modern engineering is to reduce energy consumption when spraying liquids, which is especially important in large systems with continuous supply. In this context, active research is being conducted in the direction of creating energy-saving spraying systems that allow reducing energy losses by optimizing the design of nozzles, using pulsed or resonant supply modes, as well as the active use of external fields (electric, magnetic, acoustic).

Another promising direction is the intensification of interphase heat and mass transfer by improving the parameters of the formed aerosol: reducing the average diameter of droplets, increasing their specific surface area, controlled interaction with gas flows or hot surfaces. This is possible thanks to an integrated approach - a combination of modern CFD modeling methods, the use of high-speed video recording of spraying processes, as well as improving the materials and shapes of active elements of sprayers.

Thus, the topic of this work covers a wide range of fundamental and applied aspects of the process of dispersing liquids. The article sequentially considers:

- the structure of the liquid at the microlevel, in particular its hole nature, as a factor determining the mechanisms of destruction during spraying;
- analysis of the dispersibility and energy efficiency of various methods and devices for spraying;
- prospects for the development of energy-saving methods of dispersion and technologies for intensification of interphase heat and mass transfer.

A comprehensive study of these aspects allows not only to deepen the understanding of the physical and technical essence of liquid spraying, but also to form a basis for the design of new effective engineering solutions aimed at minimizing costs and increasing the functional reliability of dispersion systems.

2. HOLE STRUCTURE OF THE LIQUID

Solving many questions and problems necessary to substantiate the search for the most promising methods and directions of energy-saving intensification of heat and mass transfer in contact devices is possible only if we carefully analyze the theories and models of the liquid state and use everything useful that they contain. Therefore, let's get acquainted with the main elements of modern theories of the gaseous and liquid states and the theory of liquid destruction.

The theory of the liquid state has achieved some success. However, to date, there is no single generally recognized model of the liquid state that would allow obtaining clear mathematical definitions of the main thermophysical characteristics of liquids. To construct a model of the liquid state based on molecular kinetic theory, it is necessary to take into account two directly opposite conditions: the liquid state is characterized, on the one hand, by the chaotic arrangement of particles, characteristic of gases, and, on the other hand, by the relatively strong intermolecular interaction, characteristic of solids.

A consistent molecular theory of the liquid state can be built only on the basis of quantum mechanics, taking into account the nature of the interaction and the properties of individual molecules and their groups [1, 2]. This theory should be built taking into account the quantum statistics of the motion of liquid particles [3]. However, the mathematical problems involved are enormous. Therefore, such a consistent theory has not yet been created. This forces the use of theories that offer models from different aspects of the liquid state of matter. All such theories are usually based on the results of experimental studies of the thermophysical and hydrodynamic properties of liquids and in most cases are not applied to all liquids, but to a certain class. Many of the proposed models can be considered classical to some extent, since many useful relationships between the physical and thermophysical characteristics of liquids have been established with the help of these models.

What features of the liquid state are most often taken into account in modern theories? Most of them proceed from the fact that a liquid is a state intermediate between a solid and a gaseous one, and therefore has a number of transitional properties. For example, at high temperatures, properties characteristic of the gas phase appears, and at low temperatures, properties characteristic of solids. If we accept the postulate that a liquid is closer in structure to a solid, then we can expect that when solids melt, there should be no sharp

change in many physical characteristics in the liquid state compared to the solidified state of this substance. Theoretical ideas about the close relationship between the crystalline and liquid states of matter were first clearly formulated by Ya.I. Frenkel and G. Green. Let us discuss some of the ideas that underlie modern models of the liquid state, which serve to explain experimental results. Several structural general theoretical models of liquids are known. They can be divided into three main groups: structurally inhomogeneous, structurally homogeneous, and holey.

Structurally heterogeneous models of the liquid state show the model of the liquid as a cluster of many ultramicroscopic significantly deformed aggregates – "crystalline islands", separated by regions of chaotic arrangement of particles. Such structures do not have sharp boundaries, the molecules in them, performing thermal motion, smoothly and continuously pass into neighboring regions with a disordered arrangement of molecules.

Structurally homogeneous models are based on experimental data on NMR and comparative X-ray structural analysis. They are based on a model that shows that each molecule in a liquid is surrounded by neighboring molecules, which are located around it in almost the same way as they are located in a crystal of the same substance. However, deviations from order already appear in the nearest layers, which increase as the molecule is removed. At a large distance from the molecule under consideration, the deviation from the correct arrangement becomes significant. It can be generally said that a liquid has a short-range order.

Of particular importance for the processes of liquid spraying are hole theories of liquids. Let us turn to them. There is a group of theories of the liquid state, which are called "hole theories". This group of theories proceeds from the main important differences between the liquid state and the gaseous state: fluidity and a free surface are manifested in liquids. The fluidity of liquid media is manifested in their ability to change their shape with minimal effort without changing the total volume. Fluidity is explained by the ability of a system of particles in a liquid to move independently relative to their "individual" movement. Such individual movement of particles relative to other surrounding particles is possible if there is at least a small amount of free space between the molecules of the liquid - free volume.

Free volume ($V - V_0$) is the difference between the volume V occupied by the particles and its minimum volume V_0. The minimum volume of a substance is considered to be the one at which all the molecules of the liquid are closest to each other, similar to their placement in an ideal crystal. This concept found its first application in the theory of real gases, starting with the Van der Waals theory. To explain the properties of single crystals, M. Born put forward the principle of close packing, according to which the particles in the crystal are closest to each other as much as possible.

In an ideal crystal, there should be no space for particles to move. But it is known from production practice that plastic deformations occur in any real single crystals. This circumstance indicates that even inside real single crystals there should be volumes free of particles ("holes"). Such free volume in crystals is realized in the form of defects of crystal lattices: vacancies - unoccupied nodes (microholes), dislocations and many others [4, 5]. As noted earlier, the liquid formed at the moment of melting of crystals inherits the structure of the corresponding crystal. The observed slight jump in the volume of the liquid suggests that additional free volumes of liquid arise at the moment of melting. These can be microcracks, microcavities and even microbubbles. All of them constitute what can be called holes, and in general, fluctuations in the concentration of particles and the density of matter. Macrofluctuations of particle concentration behave normally. They gradually turn into microscale ones due to molecular chaotic motion.

From such ideas arose the theory of the hole structure of the liquid (Altar, Furth, Bridgman, etc. [6]), supported and developed mainly by Frenkel. Hole theory determines the behavior of an ensemble of holes according to classical statistics and probability theory (Gaussian distribution). According to classical statistics, holes in a liquid are not distributed uniformly throughout the volume of the liquid, but represent discrete microcavities that arise as a result of fluctuations in the concentration of molecules according to the laws of the theory. Later, some theorists established an analogy in the behavior of fluctuation cavities and cavitation bubbles, and therefore they are often called cavitation fluctuations (cavitation holes).

The emergence of fluctuation bubbles, i.e. fluctuations in the concentration of particles, can be explained theoretically from an energy point of view. Indeed, any particles or their ensembles are in a more stable state if they are in a deeper potential well [5]. It follows that if the particles are not located at equal distances from each other, but in the form of compact discrete groups separated by fluctuating "cracks" that form the walls of the potential barrier, then the entire macrosystem, consisting of molecules, atoms, ions, is in a state of stable dynamic equilibrium. Conversely, if the particles are located "correctly", i.e. symmetrically, as in an ideal single crystal, the system is in a less stable state.

The presence of any microcavities in a liquid is confirmed by Bridgman's experiments. He investigated the dependence of the modulus of comprehensive compression of a liquid on external pressure. At low pressures, the modulus of comprehensive compression of a liquid is 10-15 times greater than that of the corresponding solid. When the pressure increases to 150-200 MPa, the compressibility of liquids decreases sharply, and with a further increase in pressure, the compressibility is almost constant and close to the compressibility of the corresponding crystalline substance.

Of great interest in finding ways of energy-saving dispersion of liquids and intensification of contact heat and mass transfer is the modernized model of hole theory [6], aimed at explaining the increase in the diffusion rate in liquids. According to this model, the diffusion mechanism is that a particle, due to fluctuations in kinetic energy, moves from its initial position to a neighboring position through a "hole" without colliding with other particles and, therefore, without additional energy consumption. The intensity of internal processes of the liquid in such a fluctuating nonequilibrium state of the internal structure of the liquid increases significantly compared to its equilibrium state. And this is beneficial for the intensification of heat and mass

transfer, especially if such fluctuating states occur near the phase interface – the phase contact surface.

From here we can draw the following conclusion and conclusion for practice: to accelerate diffusion processes, the liquid must be brought to the maximum nonequilibrium state with the largest number of fluctuations in particle concentrations, the appearance of many vacancies, micro-ruptures, microcracks, etc.

The origin of fluctuations can be different. They can be caused by the action of both purely mechanical loads and other reasons, for example, the action of gravitational, electromagnetic, sound fields. In this case, macrocavities, which under normal conditions are in equilibrium with the environment, can increase, develop [7], turn into cavitation macrocavities, ultimately leading to liquid rupture, that is, to irreversible destruction of the liquid.

Similar phenomena of an even sharper, jump-like increase in the size of microcavities in liquids are observed under resonant loads on the liquid. From the point of view of the theory of fluctuations, the resonant increase in cavities - holes in this case is an example of how microfluctuations with increasing intensity can turn into irreversible macrofluctuations. Using the concept of cavitation bubbles, from all that has been considered, we can come to an unfortunate conclusion: the low-energy dispersion of the liquid is facilitated by the existence of cavitation bubble nuclei, which are the weak link in the structure of the liquid from which its destruction begins.

3. DISPERSION AND ENERGY CONSUMPTION IN BASIC METHODS AND DEVICES FOR ATOMIZING LIQUIDS

Considering the internal structure of liquids, it is clear that the crushing of a liquid occurs when mechanical stress is applied to it. As a result, negative pressure arises, which stretches the liquid and transfers its molecular structure to a metastable state. The slightest impact on a liquid in a metastable state leads to a rapid avalanche-like growth of fluctuation microcavities inside the liquid up to critical sizes, which immediately leads to irreversible rupture of the solid liquid.

According to the hole theory, even in the absence of dissolved gas, there are always microcavities in the liquid - "holes", which are filled with individual free molecules of the liquid. The cavities originate at points where the forces of attraction between the molecules of the liquid are weakened, and this primarily occurs in holes, in microbubbles of gas, which is always present in the liquid in the form of a solution, and other similar formations.

Under the influence of external mechanical or other stress, microcavities expand until the liquid molecules on the walls of the cavity completely lose their mutual bonds, after which the liquid structure is irreversibly destroyed. Since the rupture voltage is determined by the size of the gas bubble, the presence of holes or suspended particles, in reality the rupture can occur at very small, practically zero voltages. It can be confidently stated that the rupture voltage will never exceed the limit value experimentally determined for many well-purified liquids.

The technology of the process, as a result of which a metastable or nonequilibrium state of the liquid is created, differs from each other existing and newly developed methods of spraying (dispersing) liquids. Searches and justification of each new method of spraying liquids require deep theoretical and experimental research. Comparison of different methods of spraying, dispersion and their features allows to assess their advantages and disadvantages, that is, to choose reasonable criteria for improving known and proposed new methods of dispersion.

All currently known methods of dispersing liquids can be divided into the following main classes: mechanical, pneumatic (or gas) ultrasonic and electric spraying. These classes, in turn, are divided into groups, subgroups according to more specific design or other characteristics. Methods of spraying, collected in the class of mechanical spraying, based on the use of both nozzles and centrifugal spray mechanisms.

Nozzles [8-12] in turn are divided into pressure nozzles (jet, with colliding jets and others), centrifugal nozzles and nozzles with rotating disks or nozzles inside them. The simplest type of pressure nozzle is a jet nozzle, which is a cylindrical nozzle from which a jet of liquid flows under pressure [9, 13]. In centrifugal nozzles, the liquid, before leaving the nozzle, acquires intense rotation in the swirl chamber, where it enters through tangential or other channels on a drop.

As is shown in Fig. 1 centrifugal atomizers [8, 10-24] mainly come in the following three modifications: with smooth or ribbed discs, nozzle and slit. In a smooth centrifugal disc, the liquid enters closer to the axis of rotation, and a liquid torus appears on the edge of the rotating disc or drum, which, as the liquid flow rate increases, turns into thin jets and threads flowing from the edge of the sprayer [18, 19]. The number of such threads increases with increasing flow rate. Liquid threads at a certain distance from the edge of the disc break up into drops similar to the breakup of free jets.

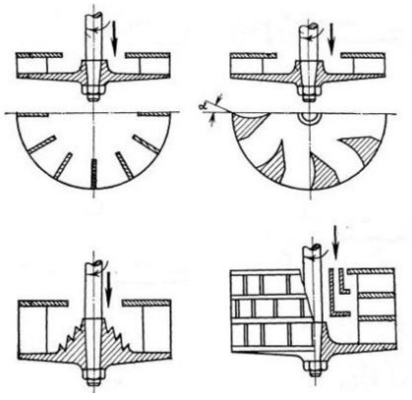


Fig. 1 – Centrifugal atomizer

In nozzle centrifugal atomizers, the liquid enters a cylindrical nozzle, in which, due to centrifugal forces, pressure is imparted to it, as in pressure nozzles. In slotted centrifugal atomizers, the liquid stream enters the blades and is transformed into a thinner film than in smooth discs [10, 14, 20]. Slotted centrifugal discs provide high performance, and therefore they are used much more often than smooth discs.

Pneumatic atomizers are often called pneumatic nozzles, because they often use designs that resemble

mechanical nozzles. Fig. 2 shows that in pneumatic nozzles of the first type, a liquid jet is directed into a coaxial gas flow. At the contact surface, the liquid is turbulized. After exiting the nozzle, unstable waves determine the pattern of disintegration of the jet or microfilm on the droplet.

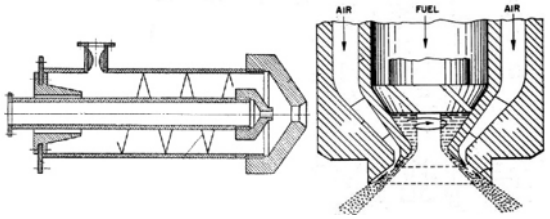


Fig. 2 – Pneumatic atomizer

In pneumatic nozzles of the second type, the liquid jet exits at a certain angle to the direction of the gas flow [9, 17, 19]. There are nozzle designs that contain rotating spray disks or turbines [14], and the liquid enters the internal cavity of these mechanisms. Breaking off from the edges of the disk or turbine, the liquid film enters the nozzle and, interacting with gas (air), loses stability and breaks up into droplets. Atomizers of this type have not found widespread use in industry due to very low productivity and clogging of nozzles with untreated liquids.

As is shown in Fig. 3 in ultrasonic atomizers [13], the liquid is crushed under the action of rapid vertical ultrasonic vibrations of the plate on which it moves. Standing waves of different modes appear on the surface of the liquid layer under the influence of the ultrasonic emitter. Drops break off from the crests of these waves. In other ultrasonic nozzle schemes, the liquid jet flowing from the gap is exposed to the influence of ultrasonic vibrations of air or gas created by a special high-frequency generator [15].

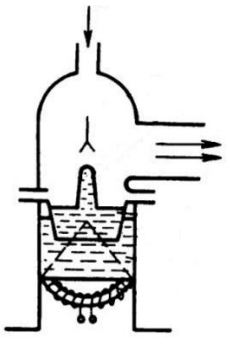


Fig. 3 – Ultrasonic atomizer

Fig. 4 represents that in electric atomizers (dispersion), an electric field is applied to the jet moving from the nozzle [16]. Under the action of the electric field on the surface of the jet, due to the electric polarization of the substance in the electric field, a certain redistribution of voltage occurs inside the liquid, which causes the repulsion of individual groups of molecules inside the liquid and the associated loss of stability of the jet, its disintegration and the formation of drops.

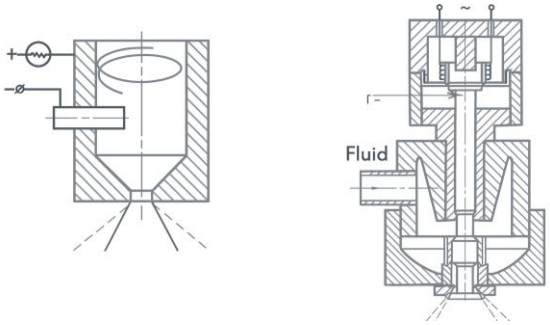


Fig. 4 – Electric atomizer

Analysis of the schemes of devices and methods of spraying liquids confirms what was said earlier that in any spraying methods the liquid turns into an unstable state and after leaving the sprayer, even without additional energy input or with minimal energy input, breaks up into fragments, which are immediately recrushed and sprayed. It should be noted that in many of the considered spraying methods, unstable liquid states are accompanied by the formation of wave processes on the surface of the liquid.

Let us consider in more detail the concept of dispersion, which is necessary in comparing spraying devices and interpreting theoretical and experimental data.

4. PROMISING RESEARCH DIRECTIONS FOR ENERGY-SAVING DISPERSION OF LIQUIDS AND INTENSIFICATION OF INTERPHASE HEAT AND MASS TRANSFER

The rate of heat and mass transfer processes can be characterized by the following generalized value:

$$\frac{dm}{dt \cdot dF}, \qquad (1)$$

where m is the mass or other quantity transferred per unit time through a unit surface of phase contact (for example, the amount of mass transferred or heat) (1).

The basis of the engineering solution to the problem of increasing the intensification of contact atomization heat and mass transfer processes between a liquid and a gas is to determine the conditions under which the process of atomization (dispersion) of a liquid can be purposefully enhanced, spending a minimum of energy.

The theories of the structure of liquids considered in the review allow us to estimate the upper limit values of mechanical stresses sustained by a liquid, to understand the processes that can be used to implement low-energy atomization contact heat and mass transfer between a liquid and a gas, and thereby establish research directions for solving the problem. The main conclusion from all of the above is that introducing macrofluctuations into a liquid reduces the energy consumption for dispersing liquids and at the same time increases the rate of atomization heat and mass transfer by orders of magnitude [21, 22].

To intensify the heat and mass transfer processes, as the discussion of the concept of the rate of change of the phase contact surface reminds, it is necessary to create conditions when, during the conduct of thermophysical processes, the rate of change (renewal) of the phase contact surface is maintained at the maximum

for as long as possible. Carrying out any heat and mass transfer process in this mode allows the process to be carried out "to the end" and thereby obtain a high economic, including energy effect and reduce environmental damage. The latter consists in preventing environmental pollution from various emissions directly from the contact apparatus, but also in the fact that reducing energy consumption reduces environmentally harmful emissions at power plants.

What are the main directions for solving these problems?

From the previous discussion it follows that in all methods of liquid dispersion, the size of the drops is directly proportional to the thickness of the liquid film flowing into the gas medium. Therefore, it is necessary to learn how to obtain thin liquid films.

Hence, the first direction of solving this problem is to theoretically substantiate and experimentally prove that low-energy processes of thin film formation are real. The second direction is to create industrial designs of large-capacity low-energy film formers, which will allow to reliably solve most of the problems associated with energy-saving liquid dispersion and contact heat and mass exchange.

In the following presentation, two possible methods of low-energy conversion of liquid jets into thin films on static rotating film formers will be considered and substantiated. In parallel, the methods and results of theoretical and experimental studies of low-energy film formation processes will be discussed [23-29].

The static low-energy pneumatic film method of liquid spraying and contact heat and mass exchange devices designed on its basis are analyzed first. To solve the problem of reducing energy consumption in centrifugal spraying while maintaining the required dispersion, centrifugal dispersion with a preliminary low-energy transformation of the liquid jet into thin films on rotating film-forming blades of various geometries is considered in detail.

Then, the results of laboratory and industrial research of the developed highly efficient low-energy heat and mass exchange contact devices with static and rotating film sprayers are discussed, which provide conditions for the most intensive contact heat and mass exchange with the required dispersion of the sprayed liquid flame and maximum liquid productivity.

5. CONCLUSIONS

The conducted analysis allows us to draw several important theoretical and practical conclusions regarding the atomization of liquids from the perspectives of energy efficiency, the physical nature of the liquid state, and the intensification of heat and mass transfer processes. It has been established that the conventional macroscopic hydrodynamic approach to modeling atomization is insufficient for a precise understanding of the mechanisms governing liquid disintegration. In this context, the concept of the hole structure of liquids offers significant scientific value, enabling the interpretation of the liquid phase as a nonuniform medium containing microvoids. These voids contribute to the emergence of instabilities and act as initiation points for flow rupture under external forces.

The study of basic liquid properties (such as viscosity, density, surface tension, and specific heat capacity) reveals their critical influence on droplet formation and subsequent behavior in multiphase systems. These properties directly affect not only the atomization efficiency but also the degree of interfacial heat and mass exchange, which is essential in a wide range of industrial processes, including cooling, humidification, gas cleaning, and combustion. Therefore, accounting for the physicochemical characteristics of liquids should be an integral component in the design and optimization of modern atomizing systems.

The comparative analysis of different atomizer types (particularly static, centrifugal, and thin-film or impulse-driven systems) demonstrates that the most promising technologies in terms of energy saving are those capable of producing high-dispersity droplets with minimal energy consumption per unit volume of liquid. These systems ensure stable droplet size, uniform spatial distribution, and adaptability to various types of liquids, including viscous, foaming, or multicomponent fluids.

Notably effective are hybrid systems that combine optimized structural designs with active external control mechanisms (such as electrostatic, ultrasonic, or aerodynamic fields), as well as thin-film atomization techniques. In these systems, the liquid is first transformed into a film and then dispersed, which allows for significantly reduced energy input, improved droplet uniformity, and enhanced interfacial heat and mass transfer performance.

The synthesis of literature, theoretical modeling, and experimental data confirms that energy efficiency in liquid atomization can be improved not only through nozzle design but also via a fundamental reevaluation of the atomization process itself. This includes structural modification of liquids, utilization of novel instability-inducing mechanisms, optimization of feed regimes, and better management of phase transition conditions.

In conclusion, the findings support the relevance and promise of continued interdisciplinary research that integrates liquid-state physics, thermodynamics, energy engineering, and applied design. Such an approach paves the way for the development of next-generation atomization systems that are economically efficient, technologically flexible, and environmentally sustainable offering significant advantages for industrial-scale implementation.

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DECLARATION OF COMPETING INTEREST

The author declares that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

Data will be made available on request.

AUTHORS CONTRIBUTION STATEMENT

O.V. Khomenko: Conceptualization, Methodology, Investigation, Reviewing, Writing Original Draft and Editing; Analysis, Visualization and Supervision. **M.V. Naida:** Conceptualization, Investigation, Reviewing, Writing Original Draft and Editing. **K.P. Khomenko:** Investigation, Writing Original Draft, Analysis. **A.A. Biesiedina:** Investigation, Writing Original Draft, Analysis. **S.O. Hodlevsky:** Investigation, Writing Original Draft, Analysis. **I.A. Chelnokov:** Investigation, Writing Original Draft, Analysis.

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Теоретичні аспекти та інженерні підходи до енергозберігаючих технологій розпилення рідини

О.В. Хоменко[1], М.В. Найда[1], К.П. Хоменко[1], А.А. Бесєдіна[1], С.О. Годлевський[2], І.А. Челноков[1]

[1] *Сумський державний університет, 40007 Суми, Україна*
[2] *Навчально-науковий інститут професійної освіти, Національна академія Національної гвардії України, 61000 Харків, Україна*

У цій статті досліджуються сучасні підходи до розпилення рідини з акцентом на енергоефективність, покращений міжфазний тепло- та масообмін та глибше розуміння фізичної природи рідкого стану. Особлива увага приділяється концепції діркової структури рідин як ключового фактора, що впливає на механізми розпаду під час розпилення. У дослідженні розглядається, як фундаментальні властивості рідини, такі як густина, в'язкість та питома теплоємність, впливають на багатофазні взаємодії в рідинно-газових системах, які мають вирішальне значення для виконання різних промислових процесів. У статті розглядаються основні методи розпилення, включаючи статичні та відцентрові форсунки, з акцентом на їхній здатності генерувати краплі контрольованої дисперсності, мінімізуючи споживання енергії. Критично оцінюється роль геометрії форсунок та параметрів потоку у зниженні енергоспоживання без шкоди для якості розпилення. Крім того, підкреслюється потенціал технологій тонкоплівкового розпилення,

оскільки вони забезпечують рівномірний розподіл крапель та значно покращують ефективність тепло- та масообміну. На основі сучасної наукової літератури, фізико-технічних моделей та експериментальних даних у дослідженні представлено порівняльний аналіз енергозберігаючих технологій розпилення. Підкреслюється важливість міждисциплінарного підходу, який інтегрує фізику рідин з конструктивними та експлуатаційними міркуваннями систем розпилення. Результати підтримують розробку методів розпилення наступного покоління, які пропонують як економічні переваги, так і екологічну стійкість для промислового застосування. Це відкриває можливість не лише подовжити ресурс роботи розпилювачів у складних умовах, але й підвищити загальну ефективність систем охолодження, що є стратегічно важливим для забезпечення надійності сучасних зразків техніки.

Ключові слова: Тепло- та масообмін, Статичні розпилювачі, Відцентрові розпилювачі, Тонкоплівкові технології.