THE DEVELOPMENT OF AN ARTIFICIAL ENERGO-TECHNOLOGICAL PROCESS WITH THE INDUCED HEAT AND MASS TRANSFER

Обґрунтовано перспективність пошуку «штучних» енерготехнологічних процесів. Розкрито феномен індукованого тепломасообміну. Описано необхідні та достатні умови для спостереження даного ефекту. Складено балансні рівняння ефекту індукованого тепломасообміну. Встановлено, що тепловий потік, який розсіюється при даному ефекті за рахунок виносу потоку маси в навколишнє середовище, визначається фізичними властивостями рідини, способом заповнення об'єму термостата і конструкцією обтюратора

Ключові слова: штучний енерготехнологічний процес, термостат, обтюратор, індукований тепломасообмін

Обоснована перспективность поиска «искусственных» энерготехнологических процессов. Раскрыт феномен индуцированного тепломассообмена. Описаны необходимые и достаточные условия для наблюдения данного эффекта. Составлены балансные уравнения эффекта индуцированного тепломассообмена. Установлено, что тепловой поток, рассеиваемый в данном эффекте за счет выноса потока массы в окружающую среду, определяется физическими свойствами жидкости, способом заполнения объема термостата и конструкцией обтюратора

Ключевые слова: искусственный энерготехнологический процесс, термостат, обтюратор, эффект индуцированного тепломассообмена

M. Pogozhikh
Doctor of Technical Sciences,
Professor, Head of Department*
E-mail: m.pogozhikh@hduht.edu.ua

A. Pak
PhD, Associate Professor*
E-mail: a.pak@hduht.edu.ua
*Department of physical and mathematical and engineering-technical disciplines
Kharkiv State University of
Food Technology and Trade
Klochkivska str., 333, Kharkiv, Ukraine, 61051

1. Introduction

The intensive development of industries and the industrialization of the world have made it necessary to find solutions to the problems of an efficient use of energy resources and to define their scientific basis. Moreover, it is essential to comply with the increasing requirements for environmentally friendly production.

In the problem solving framework, it is important to consider the so-called energy technology processes [1], which are artificial human actions that at certain sequences of the laws of nature lead to a final product due to the use and/or the transfer of some types of energy into others (the first law of thermodynamics) [2]:

$$\delta Q = dU + \delta A, \tag{1}$$

where Q, U and A are heat, internal energy, and work, respectively, J. However, it is insufficient to use this approach only from the viewpoint of the law of conservation and transformation of energy (1) because it does not "determine" the direction of redistributing energy, mass, or charge, for it only establishes a balance. Once the balance has been established, the directional effects of these processes are regulated by the second law of thermodynamics – an entropy increase [3]:

$$dS > 0, \tag{2}$$

where S is the entropy, J/K. Then, if we consider the energy balance within an isolated system, this balance can be sustained: if (2) is true, the entropy production tends to zero, and the potential (free) energy E_p approaches the minimum value [4]:

$$\frac{dS}{d\tau} \to 0; \quad E_p \to min. \tag{3}$$

We can assume that conditions (1)–(3), as well as the laws of conservation of mass, charge, and energy, limit the scope of human knowledge in solving the problem [5].

It should be noted that any transfer of heat is irreversible, which means that it leads to an increase in the entropy (a disorder). It is this fact that largely determines the eco-friendliness of energy technology processes in which there happen primary phase transitions of matters [6]. It is noteworthy that truly "artificial" energy technology processes are those for which the beginning in natural conditions does not correspond to expression (3). For example, these can be the technologies of growing crystals [7] and making semiconductors [8], as well as catalytic reactions [9]. For these cases, it is common that at least one or more parameters or properties of the system can have no "affinity" with the environment and acquire an equilibrium value only after overcoming a certain energy activation barrier – E_A. These processes are usually characterized by high energy efficiency and eco-friendliness. Thus, the search for and development of the theoretical foundations of "artificial" energy technology processes are important tasks in the framework of the world politics in the field of energy efficiency [10].

2. Literature review and problem statement

It is particularly interesting to consider such an energy technology process as drying. Such a phenomenon as the water cycle [11] depends on conditions (1)–(3), atmospheric

pressure and temperature, as well as the chemical composition of the atmosphere and the Earth surface. From a practical point of view, it is assumable that in the Earth's environment everything can get dry (moistened or frozen), which means that for water primary phase transitions in the Earth's environment happen freely, naturally. Consequently, it should be assumed that most of the industrial methods of drying are only an intensification of the natural process by creating certain conditions.

It can be proved by analyzing (2):

$$dS = \frac{\delta Q}{T} = \frac{r\delta m}{T} + \frac{\delta E_B}{T},\tag{4}$$

where r is the specific heat of a phase transition, J/kg; δm is the mass of water that has changed from one aggregate (phase) state to another, kg; δE_B is the ballast energy to create conditions that intensify and ensure a phase transition, J; T is the absolute temperature, K.

The first term $\frac{r\delta m}{T}$ in formula (4) describes energy expenditure directly used to evaporate moisture. This energy expenditure depends on two factors. The first factor, natural, is determined by the laws of conservation of mass and energy, the laws of thermodynamics. The quantity of evaporated water is limited by the equilibrium moisture content of a raw material $w_p(\phi)$, which in turn is limited by the relative humidity ϕ (under convective drying – by the humidity of the drying agent). The second factor is determined by the temperature T and the relative humidity of the environment ϕ, which can be artificially changed, for example, to reduce the length of the dewatering process or to diminish the equilibrium moisture content.

Let us consider, in this respect, the drying processes that are used in food-manufacturing, microbiological and pharmaceutical industries. Commonly, in the convective drying process, there is a tendency to intensify the dewatering process by increasing the evaporation area and reducing the thickness of the diffusion layer of the raw material [12]. The intensification of the process by increasing the heat efficiency is achieved with infrared drying [13] and with drying in a microwave field [14]. An advantage of spray drying is the high rate of the dehydration process and the short duration of the effects of oxidation and temperature on raw materials [15]. This advantage is achieved by increasing the evaporation area and by organizing effective heat supply.

However, it should be noted that in any process the rate of entropy changes decreases (3) in the course of reaching an equilibrium, so most of drying methods are aimed at only increasing the entropy change speed by increasing or decreasing the amount of artificial components in formula (4).

Consequently, these methods make it possible not so much to control the dewatering process as to accelerate it, so they should be considered only as an intensification of natural drying.

Then, in the ideal case, expression (4) for phase transitions during drying should be transformed into:

$$dS = \frac{r\delta m}{T} + \frac{\delta E_A}{T}.\tag{5}$$

Herewith, scientific solutions in the field of energy efficiency of human activity should be sought from the condition:

$$E_A < E_B.\tag{6}$$

The essence of E_A is that this is some activation energy, i. e. some "artificial" barrier. Thus, "artificial" methods of drying include such heat and mass transfer processes in which it is possible to control the beginning (start), maintenance (course) and the end of the process.

One of these artificial methods is a method of drying with a mixed heat supply (MHS drying). The method of MHS drying was developed at the Kharkiv State University of Food Technology and Trade (Ukraine) [16], and it has never been investigated elsewhere except in the scientific schools of the organization. MHS drying is based on the creation of conditions for active hydrodynamic and thermal interaction of the object of drying with the drying agent. The "artificiality" of MHS drying is that there is an intensive mass transfer if the necessary conditions to implement the MHS drying process in a special heat transfer module containing a wet raw material and a drying agent [17].

MHS drying is described with notions such as a "startup" and a "breakdown" of the process. The "start-up" and the "breakdown" as well as the nature of the dewatering process can be managed by roughly distinguished external and internal factors [18]. It is particularly important that a variation of the external and internal factors makes it possible to control the specific energy consumption for the dehydration process [19], the intensity of the heat and mass transfer [20], and the quality of the manufactured products [21].

The MHS drying process has been studied at the Kharkiv State University of Food Technology and Trade for 30 years. However, there are still open issues as for the physical mechanism of the organization, start-up and breakdown of the MHS drying process.

The present-day research on MHS drying and the generalization of the experimental and theoretical data of the above-described studies make it possible to assert that the MHS drying process is a special case of a more general effect. We believe that this effect has not been registered before. So, being the first observers of this effect, we have called it the effect of an induced heat and mass transfer (hereinafter referred to as InHMT). It should be noted that the development of the physical mechanism of the InHMT process can help reveal the possibility of using it in various technologies and techniques.

3. The purpose and objectives of the study

The purpose of this study is to determine the necessary and sufficient conditions for developing balance equations for technical applications of the InHMT process on the basis of generalizing the theoretical and experimental data obtained so far. The purpose can be achieved by doing the following tasks:
– to disclose the phenomenon of the InHMT effect;
– to develop balance equations for the InHMT effect on the basis of observed facts about fluctuations of the concentration of particles in a continuous gaseous medium inside a thermostat. Herewith, it is essential to consider a case in which these fluctuations are caused by particle concentration fluctuations in the volume of an obturator under the effect of an external continuous gaseous medium.

4. The research materials and methods

We introduce the concept of a dynamical system [22], which is understood as any object or process with a clearly

defined notion of the state as a set of certain values at a time and with a law that is established to describe changes in the initial state over time.

The dynamic system in the InHMT process is understood as a system consisting of a thermostat with a wet colloidal capillary-porous matter and an air-vapor mixture. A thermostat entails a system in which the temperature is kept constant through the creation of some necessary and sufficient conditions for the occurrence of processes that can help maintain the constant temperature.

Thus, there is a thermostat the walls of which cover an area S_t to contain a volume V_t. The thermostat wall temperature T_t is maintained constant. The thermostat contains liquid of a volume V_{liquid} and gas of a volume V_{gas}; the latter is a mixture of air and vapor. The thermostat may also contain a solid matter of a volume V_{solid}, insoluble or partially soluble in the liquid, lyophilically active or not, with or without a specific structure. Pressure in the thermostat is stable and equal to atmospheric pressure p. The atmosphere (the environment of any temperature) is related to the thermostat through some obturator, which has a volume that is much smaller than the volume of the thermostat $V_{obt} \ll V_t$ and an area (an opening in the thermostat) that is much smaller than the area of the thermostat surface $S_{obt} \ll S_t$.

The effect of InHMT is observed using an apparatus that is shown in Fig. 1. The numbers in Fig. 1 denote:

1 – the thermostat;

2 – tubes through which an air flow is blown from the ambient environment;

3 – a matter, consisting of three phases: gaseous, liquid, and solid;

4 – thermocouples;

5 – obturators.
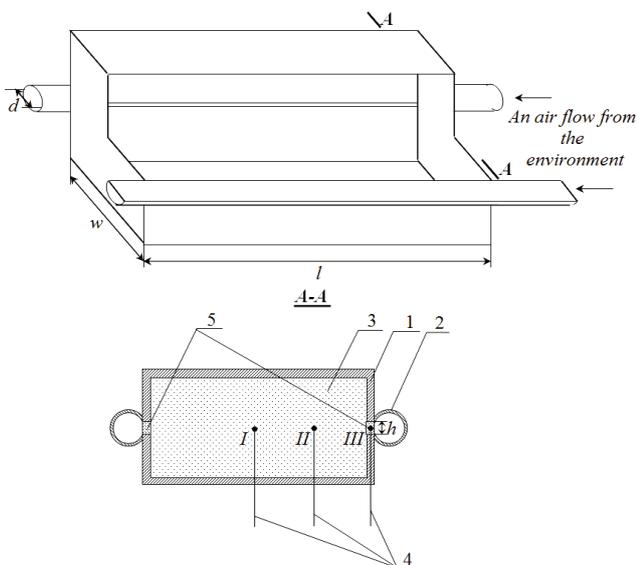
Fig. 1. An apparatus for monitoring the effect of an InHMT system of the characteristic dimensions, mm: l=100; w=20; d=10; h=1

The "start-up" of the InHMT process can be judged by the kinetics of the temperature at various points within the thermostat, which is obtained by recording the signal from the thermocouples.

5. Observation and disclosure of the InHMT effect

The organization of the experiment to monitor the InHMT process is as follows. Inside the thermostat, there is a matter consisting of solid, liquid and gaseous phases (a wet colloidal capillary-porous matter). After some time, the temperature of the matter inside the thermostat takes a value equal to its equilibrium temperature, i. e. the temperature of the thermostat walls. Further, through the tubes shown in Fig. 1, ambient air is blown in at a rate at which the turbulent regime creates a fluctuation of the transverse component of the air flow rate. The InHMT process is "started up". The thermograms obtained during the InHMT process are shown in Fig. 2.
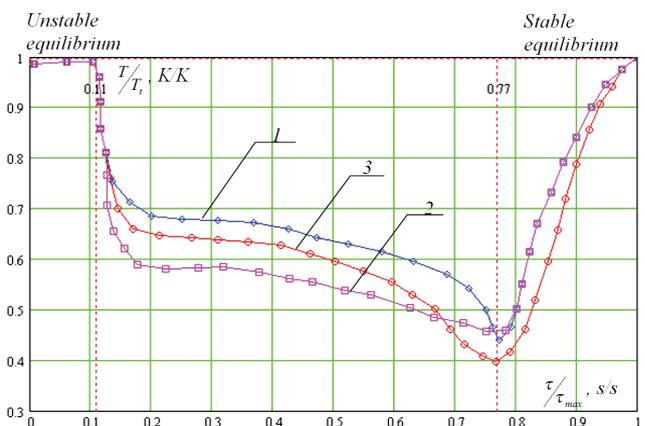
Fig. 2. The temperature kinetics of the matter during the InHMT process, obtained from the thermocouples

The thermogram shows that the process "start-up" corresponds to a drop in the temperature, which is marked with a dotted line in Fig. 2. After the removal of the liquid phase inside the thermostat (the minimum temperature kinetics), the temperature of the matter again begins to approach the equilibrium temperature of the thermostat.

Thus, during the InHMT process, there occur two equilibrium states:

– the temperature of all parts of the dynamic system tends asymptotically to the general equilibrium temperature, with almost no mass transfer with the environment, which means an unstable equilibrium;

– the temperature of all parts of the dynamic system is equal to the equilibrium temperature, with no liquid phase inside the thermostat, which means a stable equilibrium.

The InHMT effect itself consists in removing the liquid phase from the volume of the thermostat when the system is moving from an unstable equilibrium to a stable equilibrium (Fig. 3).

The air-vapor medium (the gaseous mixture) inside the thermostat during the InHMT process should be considered continuous. A continuous medium is understood as a continuous substance for which any small part (supramolecular level) thereof has the properties of the whole. Using the concept of a continuous medium eliminates the consideration of the molecular motion (i. e. takes into account only the average characteristics of the molecular motion, for example, pressure, density, and temperature), and only the movement caused by external forces is actually studied. The smallest

amount of a continuous medium inside the thermostat is much bigger than the intermolecular distances, but it is much smaller than the volume of the thermostat. All the characteristics of the continuous medium are continuous functions of spatial coordinates and time in addition to the boundaries with a solid or liquid phase. For the continuous medium, the essentials are: an equation of the medium movement or equilibrium, findings obtained as the basic laws of mechanics, a continuity equation, and the law of conservation of energy.
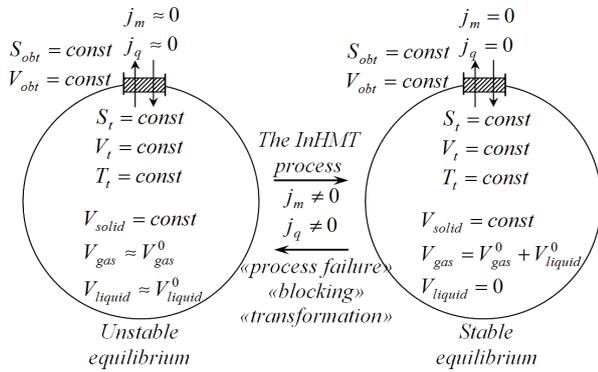
Fig. 3. The movement of the system from an unstable equilibrium to a stable equilibrium

Inside, the thermostat may integrally contain three phases – solid, liquid and gaseous, which are interconnected in equilibrium. The continuous gaseous medium is formed because the thermostat wall material is vapor-proof, and the mass exchange with the surroundings is possible only through the obturator, the area of which at least an order of magnitude smaller than the surface area of the thermostat through which heat transfer can take place. The deviation of any parameter from its equilibrium value makes the continuum oppose changing it. That is, if for any reason there is a change in the equilibrium vapor content in the air-vapor mixture within the thermostat, it will cause a change in the quantity, composition and distribution of liquid water due to its transition from liquid to gaseous. The transition of liquid water into the gaseous state by vapor diffusion occurs in the continuous gaseous medium.

Thus, as the continuous gaseous medium is inside the thermostat, the partial pressure of vapor in the medium is equal to the pressure of saturated vapor at the given temperature. The InHMT effect can be observed in case of a created fluctuation of, for example, the concentration of particles of liquid in the continuous gaseous medium inside the thermostat by removing a part of the continuous gaseous medium through the obturator. To such a fluctuation, the system will "react" by restoring the partial pressure of the vapor to the level of saturated vapor by transferring the liquid to a gaseous phase. The result of the described process is removal of the liquid phase from the thermostat, and that is an InHMT effect.

Herewith, the obturator of the thermostat contains no or only part of liquid and, in general, is characterized by the gas flow filter coefficient k_p, satisfying the condition:

$$-k_p \nabla p \cong j_{mdif}, \qquad (7)$$

where j_{mdif} is a diffusive gas flow through the obturator; ∇p is a pressure gradient in the obturator.

In this case, for dp in the obturator, the true condition is:

$$dp \ll p. \qquad (8)$$

The E_A can be represented by the work of an ambient air flow near the obturator, defined by its kinetic and potential energy:

$$dE_A = d(pV) + \xi \cdot dE_k, \qquad (9)$$

where ξ is a dimensionless coefficient that shows part of the kinetic energy dissipated in the volume of the obturator: $\xi < 1$.

What is clear is that $E_A < E_B$, since it concerns the mechanical energy of the flow rather than the amount of the mechanical energy and the heat content, as in the intensification of natural processes.

These conditions are necessary to monitor the InHMT effect that appears when the system is on its way to achieving a stable equilibrium. However, a stable equilibrium is achieved only when the mass of liquid in the thermostat is zero: $m_{liquid} = 0$.

The additional conditions (sufficient for monitoring and regulating the effect) are the following:

1) the presence of fluctuations in the parameters of the gas in the volume of the obturator;

2) the heat capacity of the thermostat must be big enough to satisfy the condition:

$$m_t c_t \Delta T_t \gg \Delta Q \quad \text{at} \quad \Delta T_t \to 0, \qquad (10)$$

where ΔQ is the amount of heat, "removed" from the thermostat with the gas of the vaporized liquid for the observation duration $\Delta \tau$;

3) the thermostat temperature can differ across the liquid limit cycle:

$$T_{cryst} < T_t < T_{boil}, \qquad (11)$$

where T_{cryst} and T_{boil} are the temperatures of crystallization and boiling of the liquid at the given pressure p (of the thermostat and the environment);

4) the effect is observed during the final (laboratory) time interval $\Delta \tau$:

$$\Delta \tau \ll \Delta \tau_{dif}, \qquad (12)$$

where $\Delta \tau_{dif}$ is the duration of the observation, corresponding to the loss of the liquid mass Δm_{liquid} without a fluctuation of the parameters of the gas in the volume of the obturator, i.e. due to the diffusive mass flow;

5) during temperature fluctuations at the boundary "the obturator – the environment", the obturator must be able to "remove" the liquid into the environment by means of, for example, capillary forces.

Fluctuations in the volume of the obturator V_{obt} may be spatial and/or temporal. However, if it is assumed that the gas in this volume has properties that make it close to the ideal, the fluctuations are closed lines on the coordinates p, V, T, and ν, with the center in k, i. e.:

$$\delta \left(\frac{p}{nT} \right) \to k, \qquad (13)$$

where k is the Boltzmann constant.

In this case, the fluctuations δ are created by an environment that is external as to the thermostat, but relaxation happens due to the inner system of the thermostat and its heat content. Based on the condition of an infinitely large enthalpy of the thermostat, relaxation of the fluctuations in the obturator will depend on the thermal properties of the gaseous and liquid phases of the thermostat. Thus, relaxation of such fluctuations in any case will be accompanied by phase transition phenomena, heat and mass transfer, and consequently, an occurrence of respective driving forces: gradients of temperature and partial pressures of air and vapor in the volume of the thermostat V_t.

It is the above-described notions that disclose the observed InHMT effect: it consists in the system moving towards a stable equilibrium, accompanied by removal of the liquid phase from the volume of the thermostat.

6. Discussion of the results: balanced equations for the InHMT effect in the case of fluctuations in the concentration of particles in the continuous gaseous medium inside the thermostat

Phenomenologically, the mass transfer process between the thermostat and the environment, which is in this case the air surrounding the thermostat, can be written as follows:

$$I_m^\infty = I_m^{ind} = I_m^{FC}, \qquad (14)$$

where I_m^∞ is the mass flow that is taken by the environment, kg/s; I_m^{ind} is the induced mass flow passing through the obturator, kg/s; I_m^{FC} is the conditional mass flow of the continuous gaseous medium in the thermostat volume due to the evaporation (condensation) of the liquid phase, kg/s.

Let us calculate the mass flow I_m^{ind} passing through the obturator. The mass flow through the obturator is equal to the mass N_{ind} of the molecules m_{ind} passing through it per unit of time $d\tau$:

$$I_m^{ind} = \frac{dm_{ind}}{d\tau} = \frac{\mu}{N_A} \cdot \frac{dN_{ind}}{d\tau}, \qquad (15)$$

where μ is the molar mass of the liquid, kg/mol; N_A is Avogadro's number, $N_A = 6,02 \cdot 10^{23}$, 1/mol; dN_{ind} is the number of particles passing through the obturator in a gaseous state or in the form of particles of liquid (mist), pieces of molecules.

We assume that the mass flow is caused by fluctuations in the environment at the external surface of the obturator. For example, in a flow of air moving along the exterior surface of the obturator, there appear fluctuations of the outer transverse component of the gaseous medium flow rate. As a result, such fluctuations produce a take-away of some volume out of the obturator into the environment. This volume (Fig. 4), indicated by the symbol V_{ind}, is calculated as follows:

$$V_{ind} = x_{ind} \cdot y_{ind} \cdot z_{ind}, \qquad (16)$$

where y_{ind} is equal to the width of the obturator surface h_{obt} that borders on the environment, m; z_{ind} is equal to the length of the obturator surface l_{obt} that borders on the environment, m.

Thus, the product of y_{ind} and z_{ind} is equal to the surface area of the obturator S_{obt} that borders on the environment:

$$y_{ind} \cdot z_{ind} = h_{obt} \cdot l_{obt} = S_{obt}. \qquad (17)$$

It is assumed that S_{obt} is defined through the structural features of the thermostat, so this value does not change with time and does not depend on any parameters of the thermostat's external or internal environment. The value of X_{ind} depends on the magnitude of fluctuations of the transverse component of the flow rate of air, moving along the exterior surface of the obturator, and the properties of the material from which it is made. The properties of the obturator, to a first approximation, are understood as resistance to the flow of vapor into or from the thermostat. The same applies to a certain part of the total air flow moving along the outer surface of the obturator, which is caused by the fluctuation of its transverse component. This resistance is determined by the filtration properties of the dry skeleton of the obturator and the amount of liquid and air-vapor mixture that it contains, as well as the condition p=const.
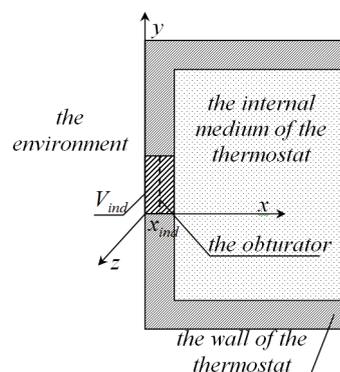
Fig. 4. A cross-section of the thermostat

During the InHMT process, the amount of dry substances of the obturator can be considered constant, and the amount of the liquid and gaseous phases that it contains may vary due to the system moving towards a dynamic equilibrium or due to changes in the parameters of the continuous gaseous medium inside the thermostat. Thus, the obturator resistance is determined by its current moisture content and the thermophysical properties of its dry skeleton.

Since the current moisture content of the obturator and the amplitude of the fluctuations of the transverse component of the air flow moving along the mass transfer gap change over time, it can be assumed that x_{ind} also changes over time. Then, using (17), we can write:

$$V_{ind} = x_{ind}(\tau) \cdot S_{obt}. \qquad (18)$$

The number of particles taken out with the volume V_{ind} is:

$$N_{ind} = V_{ind} \cdot \langle n_{ind} \rangle, \qquad (19)$$

where $\langle n_{ind} \rangle$ is the average concentration of particles in V_{ind}, pieces of molecules/m³.

The concentration of water molecules has a specific distribution in the volume V_{ind}. In this case, we assume that along the axes Oy and Oz the concentration is constant, and along the axis Ox there is a concentration gradient that is described by the specific function $f_n(x)$ (Fig. 5). Then, the average concentration of particles in the volume V_{ind} is calculated as follows:

$$\langle n_{ind} \rangle = \frac{1}{\left(n^*\left(x_{ind}(\tau) \right) - n_\infty \right)} \cdot \int_0^{x_{ind}(\tau)} f_n(x)dx, \qquad (20)$$

where n_∞ is the concentration of particles at the outer edge of V_{ind}, that is, on the border of the volume with the environment, pieces of molecules/m³; $n^*(x_{ind}(\tau))$ is the concentration of particles at the inner border of V_{ind}, that is, on the border of the volume with the continuous medium inside the thermostat, pieces of molecules/m³.
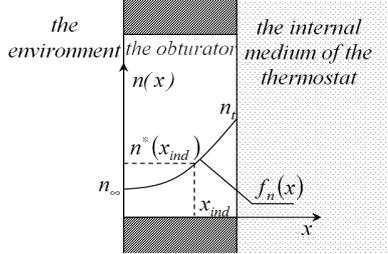
Fig. 5. A distribution of the concentration of particles of the continuous gaseous medium in the obturator

From (20), it follows that $\langle n_{ind} \rangle$ is a function of x_{ind}.

Let us write the total differential for the number of molecules of water taken out with the volume V_{ind} (formula (19)):

$$dN_{ind} = \frac{\partial \left(V_{ind} \cdot \langle n_{ind} \rangle \right)}{\partial \tau} d\tau \qquad (21)$$

and let us transfer $d\tau$ to the left side of the equation:

$$\frac{dN_{ind}}{d\tau} = \frac{\partial \left(V_{ind} \cdot \langle n_{ind} \rangle \right)}{\partial \tau} = \frac{\partial V_{ind}}{\partial \tau}\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial \tau}V_{ind}. \qquad (22)$$

Taking into account (18), we have:

$$\frac{dN_{ind}}{d\tau} = S_{gap}\left(\frac{\partial x_{ind}}{\partial \tau}\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial \tau}x_{ind} \right). \qquad (23)$$

Let us integrate (23) into (15):

$$I_m^{ind} = \frac{dm_{ind}}{d\tau} = \frac{\mu}{N_A} \cdot S_{gap}\left(\frac{\partial x_{ind}}{\partial \tau}\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial \tau}x_{ind} \right). \qquad (24)$$

We transform expression (24) into the following:

$$I_m^{ind} = \frac{\mu}{N_A} \cdot S_{gap}\left(\frac{\partial x_{ind}}{\partial \tau}\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial x_{ind}}\frac{\partial x_{ind}}{\partial \tau}x_{ind} \right) =$$
$$= \frac{\mu}{N_A} \cdot \frac{\partial x_{ind}}{\partial \tau}\left(\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial x_{ind}}x_{ind} \right)S_{gap}. \qquad (25)$$

From this expression, it is clear that the mass flow density through the obturator is:

$$j_m^{ind} = \frac{\mu}{N_A} \cdot \frac{\partial x_{ind}}{\partial \tau}\left(\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial x_{ind}}x_{ind} \right). \qquad (26)$$

Thus, if we consider the internal task for the gaseous medium inside the thermostat to remain continuous, the same number of particles must evaporate. This condition is always satisfied as evaporation depends only on temperature, and the relative vapor content in a gaseous medium is the essence of partial pressure.

The mass of the liquid that evaporates per unit of time, i. e. the mass flow in the continuous gaseous medium inside the thermostat, which is formed by the evaporation while the system is striving for a dynamic equilibrium and which flows at the diffusion rate, is calculated by the formula:

$$\frac{dm^{evapor}}{d\tau} = f_{evapor}(p,T)\frac{\mu}{N_A} \cdot S_{evapor}, \qquad (27)$$

where $f_{evapor}(p, T)$ is a function that depends on the pressure and temperature inside the thermostat and defines the speed of the liquid evaporation from the surface area unit per unit of time, pieces of molecules/(m²·c); S_{evapor} is the evaporation area, m².

Hence, it is obvious that the mass flow density into the continuous gaseous medium inside the thermostat, formed by the transfer of the liquid to the gaseous state, will be equal to:

$$j_m^{evapor} = f_{evapor}(p,T)\frac{\mu}{N_A}. \qquad (28)$$

We assume that because of the system striving for a dynamic equilibrium, the mass of the liquid that is taken out into the external environment is offset by the transition of the liquid phase inside the thermostat into the gaseous phase, which supports the continuity of the gaseous medium. Then, we equate (25) and (27):

$$\frac{dm_{ind}}{d\tau} = \frac{dm_{evapor}}{d\tau} \qquad (29)$$

and explicitly:

$$\frac{\mu}{N_A} \cdot \frac{\partial x_{ind}}{\partial \tau}\left(\langle n_{ind} \rangle + \frac{\partial \langle n_{ind} \rangle}{\partial x_{ind}}x_{ind} \right)S_{gap} = f_{evapor}(p,T)\frac{\mu}{N_A}. \qquad (30)$$

Taking into account (26) and (28),

$$S_{gap} \cdot j_m^{ind} = S_{evapor} \cdot j_m^{evapor} \qquad (31)$$

or

$$j_m^{ind} = \frac{S_{evapor}}{S_{gap}} \cdot j_m^{evapor}. \qquad (32)$$

If the mass flow density (28) in the continuous gaseous medium inside the thermostat, which is formed by the liquid transferring to the gaseous state, is multiplied by the specific heat of the vaporization, we will obtain the density of the heat flow that is spent on the evaporation of the liquid inside the thermostat:

$$j_q^{evapor} = r \cdot j_m^{evapor} = f_{evapor}(p,T)\frac{\mu}{N_A} \cdot r. \qquad (33)$$

Let us multiply and divide the right side of (32) by the specific heat of the vaporization:

$$j_m^{ind} = \frac{S_{evapor}}{S_{gap}} \cdot j_m^{evapor} \cdot \frac{r}{r}, \qquad (34)$$

taking into account (32), we obtain the following for the InHMT process:

$$ j_m^{ind} = \frac{1}{r} \cdot \frac{S_{evapor}}{S_{gap}} \cdot j_q^{evapor}. \tag{35} $$

Thus, on the basis of the obtained expressions (30) and (35), we can draw the following conclusions. From (30), it is seen that the fluctuations – temporal $\left(\frac{\partial x_{ind}}{\partial \tau} \right)$ and spatial $\left(\frac{\partial \langle n_{ind} \rangle}{\partial x_{ind}} \right)$ – in the volume of the obturator "induce" the mass flow, which is determined by the partial pressure of the saturated vapor dependence on temperature. Consequently, the heat flow, dissipated by the removal of the mass flow into the environment, is determined by the physical properties of the liquid, the method of filling the volume of the thermostat, and the obturator design. Based on the initial conditions, the heat flow must be negligible compared to the heat content of the thermostat walls. When there is a complete removal of the liquid phase volume out of the thermostat, the system reaches a stable equilibrium.

The undertaken tests have shown that the possibility of the practical use of the InHMT effect is broader than only for dewatering wet materials. An example of a broader application of this effect in the food industry is the use of InHMT for hydrothermal processing of cereals [23]. In [24], there is a technology that is described as consisting of two stages. In the first stage of processing cereals, the InHMT process is used only for temperature control. This involves technological processing of raw materials until their semi-finishing. In the second stage, there occurs dehydration of the resulting semi-finished product. The result of this treatment is an instant hot cereal that does not require cooking.

Another possibility for a practical use of the InHMT process, as follows from the balance equations, is a technology of using it for cooling systems. As shown above, starting from balance equation (35), heat energy dissipation during the InHMT process in a thermostat will occur as long as it is present in the liquid phase. Dissipation of heat in this case is so effective that the temperature difference between the walls of the thermostat and its internal environment can reach 40...50 °C (Fig. 2). This difference is 40...50 % of the maximum wall temperature of the thermostat. It should be noted that all this is within the liquid limit cycle, i. e. between its crystallization temperature and the boiling point at atmospheric pressure. The thickness of the layer on which this difference in temperature is observed is 5...7 mm.

At present, work is underway on the hardware implementation of the research results on the InHMT effect in processing food raw materials for a variety of purposes of the food processing industry.

7. Conclusions

1. The study has disclosed the phenomenon of a new "artificial" energy technology process – InHMT, which is observed in a thermostat and consists in inducing an intensive removal of the liquid phase from the thermostat volume as well as in an intense dissipation of heat when the system is moving from an unstable equilibrium to a stable equilibrium.

2. Balance equations on the InHMT effect have been developed on the basis of the observed facts in the case of fluctuations in the concentration of particles in a continuous gaseous medium inside the thermostat due to fluctuations of the concentration of particles in the volume of the obturator under the impact of an external continuous gas medium. These equations have helped determine that the heat, which is dissipated during the InHMT process due to the removal of the mass flow into the environment, depends on the physical properties of the liquid, the way of filling the thermostat volume, and the structure of the obturator.

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