INTENSIFICATION OF THE ABSORPTION OF OXYGEN BY WATER USING A ROTOR-PULSATING APPARATUS

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One of the important components of the quality of food products is the quality of water used. A common way to remove unwanted impurities from water is aeration, i.e. the oxidation of chemical compounds in water by oxygen. Aeration devices with mechanical energy input in comparison with other groups of devices, namely with energy input with gas phase and with liquid phase, have low power consumption and additional mixing of the processed medium. The work presents a study of oxygen absorption in water in an experimental setup with rotor-pulsating apparatus for water treatment in beverage production technology. In this paper, the energy and technological parameters of aeration of a model aqueous solution of a certain concentration of sodium sulfide in an experimental setup with a rotor-pulsating apparatus as an aerator are determined. The experimental aeration setup allows conducting research in several modes and consists in particular of a vessel, a rotor-pulsating apparatus, two ejectors - one at the entrance to the rotor-pulsating, the other at the outlet, the recirculation pipeline. Air from the atmosphere enters each of the ejectors through a separate air duct. The aeration of the studied water took place in the recirculation mode for 20 minutes. Determination of the oxygen mass transfer rate is determined by the iodometric titration method on the rate of oxidation of sodium sulfite. Experiments were conducted without using a catalyst. It is determined that when placing the ejector unit at the rotor-pulsating apparatus inlet at the angular rotor unit velocity of 240.02; 270.18, and 300.02 s^{-1}, the oxygen mass transfer rate is 1.39; 1.49 and 1.73 kg m^3/h. At the location of the ejector unit at the outlet of the rotor-pulsating apparatus, the velocity of the oxygen mass transfer under the same conditions is 1.17; 1.36 and 1.63 kg m^3/h respectively. However, the power consumption of the second scheme exceeds the power consumption by the first scheme by 50%.

Keywords: aeration, ejector, mass transfer rate, rotor-pulsating apparatus, sodium sulfite

1. Introduction

One of the important components of the food product's quality is the quality of water used. Increasingly, for industrial use, water from underground sources is used. The main disadvantage of groundwater is the presence of dissolved iron, manganese, and other nonorganic impurities in it. The most efficient method of removing these elements from water is aeration.

Devices the most commonly used for pressure aeration are conveniently classified according to the method of energy input into the apparatus: with a gas phase, with a liquid phase, with mechanical energy input, and combined (Novoselov et al., 2014). The more common of the first group are bubble aerators,

in which compressed air passes through the diffusers made of different porous materials. The second group includes airlift systems of aeration. Turbine, propeller, and blade agitators from the third group are the most often used ones, both self-suction agitators and those combined with compressor air supply. The advantage of devices of the third group is low power consumption and additional mixing of the processed media.

Alternative mass-exchange devices of liquid-liquid, gas-liquid types continue to be the object of research in the world.

M. Meeuwse from the Eindhoven University of Technology described a new multiphase reactor, the rotor-stator spinning disc reactor, which shows high rates of gas-liquid mass transfer (Meeuwse et al., 2010). The spinning disc reactor consists of cylindrical housing, with a rotating disc in the middle between the top and bottom plate of the cylinder. Liquid enters the reactor through the top wall, near the rotor axis. It flows outwards, to the rim of the reactor, and flows under the disc to the center of the reactor. Gas enters the reactor through an orifice from the center of the stator, near the rim of the disc. Gas bubbles are formed at the gas inlet and flow to the middle of the reactor in a spiraling motion. The gas-liquid dispersion leaves the reactor through the outlet in the center of the bottom plate. In further work, the author improves the design of a single reactor (Meeuwse et al., 2010) and also offers the concept of a multi-stage reactor (Meeuwse et al., 2011). A rotor–stator spinning disc reactor setup with a perforated disc containing 119 narrow channels for direct dispersal of gas into the reactor cavity was

examined by Franz Haseidl and others (Haseidl et al., 2022).

The work (Banaga et al., 2020) presents a rotating bar reactor (RBR), which consists of two concentric cylinders, has been developed. The inner cylinder of the RBR always rotates and the outer cylinder is fixed, which is different from other rotating reactors. The mass transfer study of RBR using a water-air physical absorption system was conducted by the authors of a work (Liu et al., 2022). Different internals, including gas distributor (GD) for optimizing gas dispersion and liquid disturbing pin (LDP) for promoting liquid disturbance, were employed to enhance the mass transfer. D. P. Rao with colleagues took a critical view of the transport processes in rotating packed beds (Rao et al., 2004). Rotating packing beds generally consist of a rotor with a vertical or horizontal axis. The rotor is an annular, cylindrical packed bed. It is housed in a casing and driven by a motor. The flows of vapor (or gas) and liquid are in countercurrent directions in the rotor. The angular velocities employed are in the range of 500-2000. Ways of mass transfer intensification in such units proposed by the authors of the paper, namely: higher packing surface areas, higher liquid-side mass-transfer rates, and higher gas-side mass transfer rates. A novel design rotating packed bed is presented, aiming at mitigation of liquid maldistribution commonly encountered in rotating packed beds. The design consists of three concentric, perforated rings placed in the packing, which act as liquid redistribution rings, see (Hacking et al., 2020).

Khabibrakhmanov and Mukhachev from Kazan National Research Technological University investigated apparatus with one- and

multitier perforated stirrers with inclined planes (Khabibrakhmanov & Mukhachev, 2012). The authors found that the value of efficiency oxygen mass transfer is significantly influenced by the angle of inclination of the working surface of the mixer floor.

One of the mass-exchange equipment types, which intensifies mixing, dissolution, emulsifying, etc., is equipment based on the method of discrete-pulse energy input. The efficiency of this method is proved in a number of technologies in the processing of heterogeneous media (Dolinskii et al., 2015).

Among the devices realizing this method, the most known is rotor-pulsating apparatus (RPA) or a high shear mixer, in general consisting of a perforated rotor (-s) and stator (-s) with a gap between them (Zhang, et al., 2012).

The aim of the work is to determine of efficiency of the application of rotor-pulsating apparatus with different arrangements of ejector units in aeration systems.

2. Materials and methods

2.1 Experimental setup

Experimental aeration setup allows to conduct research in several modes and consist of a vessel with a total volume of 60 L (1), rotor-pulsating apparatus (2), pair of ejectors one of them at the RPA (3) inlet, another at the outlet (4), recirculation pipe (5). Air from the atmosphere enters each of the ejectors through a separate air inlet pipeline (6) with the airflow meter installed on it (Fig.1).

The scheme is supplemented with an electrical motor (7) connected with a control unit (not shown in the figure). The control unit consists of a frequency converter, an ammeter, and an electricity meter and serves to change rotor angular velocity.

The value of the volume flow rate of the air-water mixture is measured by a flow meter, placed on the recirculation pipe. The value of the head is measured by a manometer.

A rotor-pulsating apparatus consists of a cylindrical hollow housing with a rotor-pulsating unit placed inside it and consisting of two rotors connected by screws and representing a single rotor unit, the stator and the impeller of the centrifugal pump.

The rotors have the following design characteristics: the inner radius of the small rotor $R_{sr} = 56$ mm, the inner radius of the large rotor $R_{lr} = 66$ mm, the width of the slots $a = 3.0$ mm, the angle between the slots in the shell of $6°$, the height of the slots $h_{sl} = 5$ mm, and the number of slots of rectangular shape $m = 60$.

The range of gap variation between the rotor and the stator is $\delta = 0.3$–0.5 mm.

Structural characteristics of the stator are as follows: the radius of the stator $R_{st} = 61$ mm, the width of slots $a = 3.0$ mm, the height of the slots $h_{sl} = 5$ mm, and the number of slots of rectangular shape $m = 60$ (Dolinskiy et al., 2018).
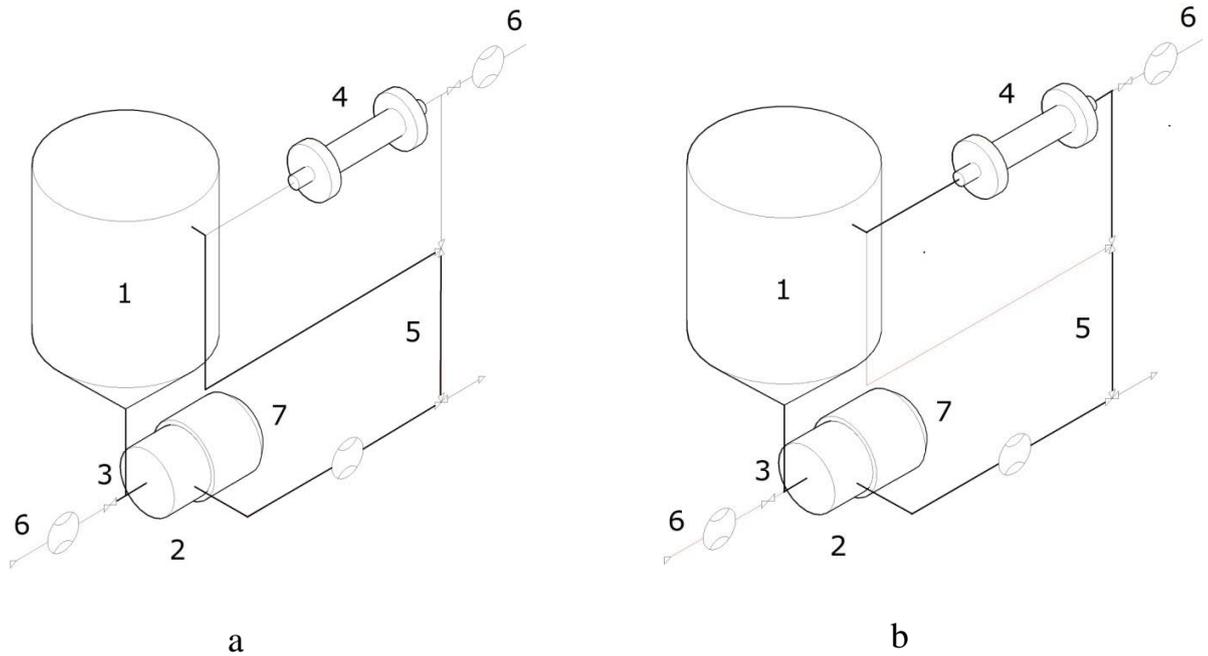
Fig. 1. *Experimental aeration setup: 1 – vessel; 2 – aerator-oxidizer; 3, 4 – ejector unit; 5 – recirculation pipeline; 6 – air inlet pipe; 7 – electric motor.*

a – scheme with ejector unit 3; b – with ejector unit 4.

The ejector unit (3) through which air fed into the working area of the apparatus in the result of self-suction is placed in an elbow connected with RPA inlet.

The ejector unit (4) placed in a pipe of 286 mm length, and an outer diameter of 60 mm.

The design of the ejector unit (4) allows, by changing the position of the nozzle, to change the liquid flow rate in the mixing chamber.
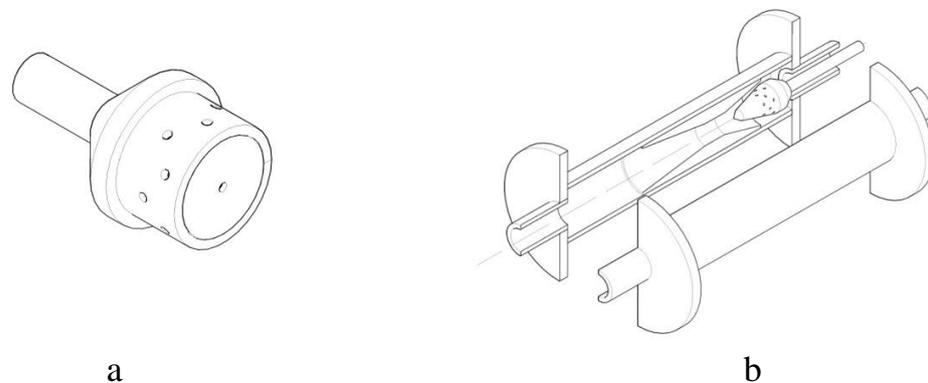
Fig. 2. *Ejector units: a – at the RPA inlet, b – at RPA outlet.*

2.2 Method

Two schemes for placing the ejector unit (before and after RPA) are shown in Fig. 1.

For the first scheme (Fig.1, a) the vessel and RPA are filled with liquid in the amount determined by the experimental conditions.

The speed of the rotor unit and the airflow are set in advance in accordance with the experimental conditions. After the start of the experiment, the liquid under investigation, under the action of centrifugal forces, moves through the inlet pipe through the ejector unit (3) to the RPA, forming a water-air mixture.

In RPA an intense mixing and additional grinding of air bubbles are taking place. After the RPA through the recirculation pipeline, the investigated mixture returns to the vessel.

The second scheme (Fig.1, b) operates in the same way as the first except that the liquid from the vessel under the centrifugal forces moves through the RPA through the recirculation pipeline to the ejector (4), where the air-water mixture is forming. The change in the position of the ejector nozzle (Fig. 2, b) regulates the area of the converting inlet diffuser, reducing the pressure to below atmospheric, and hence the airflow. The water-air mixture obtained in the ejector returns to the vessel.

All experiments were carried out under the following initial conditions: the volume of liquid was 10 L; the concentration of sodium sulfite was 10…15 g/L, temperature 15°C. Samples were taken every 5 minutes in 20 minutes. The initial sodium sulfite concentration was selected in such a way that, in relation to sodium sulfide, the reaction had a zero-order.

In other words, a certain difference in the initial concentrations of sodium sulfide in the selected range does not affect the rate of its oxidation.

The water, previously purified from impurities was settled for at least 24 hours under atmospheric pressure to achieve an equilibrium concentration of oxygen.

The determination of aeration efficiency is based on the use of chemical oxidation of sodium sulfite which is a part of the water model solution by oxygen from air feeding the setup.

Determination of oxygen absorption rate is based on two chemical reactions: the oxidation of sodium sulfite with oxygen to water-insoluble sodium sulfate and the reaction of sodium sulfite with iodine also to form sodium sulfate.

Accordingly, a solution of iodine of a certain concentration with excess is added to the test sample of aqueous sodium sulfite solution, which is evidenced by the appearance of a yellow color. The exact amount of excess iodine is determined by titration of sodium thiosulfate in the presence of starch until the blue color disappears.

3. Results and discussion

Experiments were performed for the angular velocity of rotor units of 240.02, 270.18, and 300.02 s^{-1}.

Characteristics of the setup according to the first scheme are shown in Table 1.

Characteristics of the setup according to the second scheme are shown in Table 2.

Table 1. *Characteristics of the setup according to the first scheme*

Rotor angular velocity, s^{-1}	240.02	270.18	300.02
Air water mixture flow, m^3/h	6.11…3.38	6.62…3.50	7.31…3.56
Air flow rate, m^3/h	0…0.98	0…1.17	0…1.31
Pump head, MPa	0.04	0.05	0.07
Power consumption, kWh	2.68	2.37	5.15
Power consumption, kWh (with air)	1.62	2.01	2.35

Table 2. *Characteristics of the setup according to the second scheme*

Rotor angular velocity, s^{-1}	240.02	270.18	300.02
Air water mixture flow, m^3/h	6.11…2.17	6.62…2.35	7.31…2.52
Air flow rate, m^3/h	0…1.02	0…1.17	0…1.28
Pump head, MPa	0.12	0.16	0.20
Power consumption, kWh	2.78	3.41	4.48
Power consumption, kWh (with air)	2.85	4.64	4.70

During the experiments, the catalyst was not used. Data on changes in the concentration of sodium sulfite according to the first scheme are presented in Table. 3.

Data on changes in the concentration of sodium sulfite according to the second scheme are presented in Table 4.

On the basis of the obtained values of the concentration of sodium sulfide graphically, the value of the velocity of the mass transfer of oxygen (sulfite number) was obtained.

Table 3. *Titration results of a sodium sulfite solution and its calculated concentration at different angular velocity of rotor unit (n) according to the first scheme*

Sample	Time, min	Volume of iodine solution, mL	Volume of thiosulfate solution, mL	Concentration of sodium sulfite , g/L
$\omega = 240.02\ s^{-1}$				
1	-	9	0.73	12.0
2	5	9	1.89	8.19
3	10	9	3.10	4.23
4	15	9	4.30	0.29
5	20	9	4.35	0.01
$\omega = 270.18\ s^{-1}$				
1	-	9	1.00	11.11
2	5	9	2.22	7.11
3	10	9	3.60	2.59
4	15	9	4.30	0.01
5	20	9	4.30	0.01
$\omega = 300.02\ s^{-1}$				
1	-	9	0.62	12.36
2	5	9	2.10	7.51
3	10	9	3.70	2.26
4	15	9	4.50	0.00
5	20	9	4.50	0.00

Table 4. *Titration results of a sodium sulfite solution and its calculated concentration at different angular velocity of rotor unit (n) according to the second scheme*

Sample	Time, min	Volume of iodine solution, mL	Volume of thiosulfate solution, mL	Concentration of sodium sulfite , g/L
$\omega= 240.02 \text{ s}^{-1}$				
1	-	10	0.30	15.00
2	5	10	1.50	11.07
3	10	10	2.60	7.46
4	15	10	3.65	4.02
5	20	10	4.60	0.91
$\omega = 270.18 \text{ s}^{-1}$				
1	-	10	0.50	14.35
2	5	10	1.80	10.09
3	10	10	2.90	6.48
4	15	10	4.10	2.55
5	20	10	5.50	0.01
$\omega = 300.02 \text{ s}^{-1}$				
1	-	10	0.5	14.35
2	5	10	2.1	9.11
3	10	10	3.6	4.19
4	15	10	4.9	0.01
5	20	10	4.9	0.01

The dependence of the oxygen mass transfer rate on the angular speed of the rotor unit is shown in Fig. 3. According to the schedule, the installation of an ejector at the RPA input for aeration of aqueous solutions is more appropriate than in the recirculation pipe, both in terms of the oxygen mass transfer rate, and the point of view of energy expenditure for aeration and mixing of the water-air mixture.
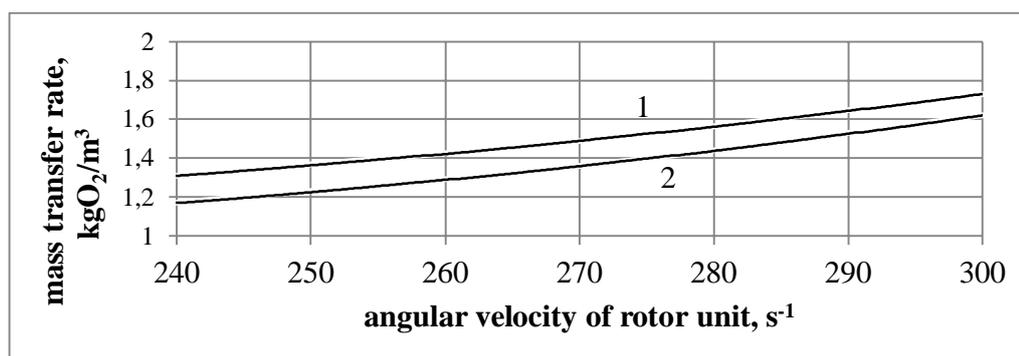
Fig. 3. *Dependence of oxygen mass transfer rate on rotor unit angular velocity: 1- first scheme; 2 – second scheme*

4. Conclusions

It has been determined that the installation of an ejector unit at the rotor-pulsating apparatus inlet for aeration of aqueous solutions is more appropriate than in a recirculation pipe in terms of the rate of mass transfer of oxygen and energy consumption for aeration of the aqueous-air mixture. Thus, the oxygen mass transfer rate according to the first scheme is 1.39; 1.49 and 1.73 kg m^3/h for the angular velocity of the rotor of 240.02; 270.18, and 300.02 s^{-1}. The oxygen mass transfer rate according to the second scheme is 1.39; 1.49 and 1.73 kg m^3/h respectively. the power consumption of the second scheme exceeds the power consumption by the first scheme by 50%.

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ІНТЕНСИФІКАЦІЯ ПОГЛИНАННЯ КИСНЮ У ВОДІ ЗАВДЯКИ ВИКОРИСТАННЮ РОТОРНО-ПУЛЬСАЦІЙНОГО АПАРАТУ

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Однією з важливих складових якості харчових продуктів є якість використовуваної води. Поширеним способом видалення з води небажаних домішок є аерація, тобто окиснення хімічних сполук у воді киснем повітря. Аераційні пристрої з механічним введенням енергії в порівнянні з іншими групами пристроїв, а саме з введенням енергії з газовою фазою, та з рідкою фазою, мають низьке енергоспоживання та додаткове перемішування середовища, що обробляється. У роботі представлено дослідження поглинання кисню водою на експериментальній установці з роторно-пульсаційним апаратом для обробки води в технології виробництва напоїв. У даній роботі визначено енергетичні та технологічні параметри аерації модельного водного розчину певної концентрації сульфіду натрію в експериментальній установці з роторно-пульсаційним апаратом в якості аератора. Експериментальна аераційна установка дозволяє проводити дослідження в декількох режимах та складається зокрема з посудини, роторно-пульсаційного апарата, двох ежекторів - один на вході в роторно-пульсаційний апарат, інший – на виході), трубопроводу рециркуляції. Повітря з атмосфери надходить до кожного з ежекторів через окремий повітропровід. Аерація води, що досліджувалась, відбувалась в режимі рециркуляції протягом 20 хв. Визначення швидкості масообміну кисню визначають методом йодометричного титрування за швидкістю окислення сульфіту натрію. Експерименти проводили без використання каталізатора. Визначено, що при розміщенні ежекторного блоку на вході роторно-пульсаційного апарата при кутовій швидкості ротора 240,02; 270,18 і 300,02 c^{-1}, швидкість масообміну кисню 1,39; 1,49 і 1,73 кг $м^3$/год. При розташуванні ежекторного блоку на виході з роторно-пульсаційного апарата швидкість масообміну кисню за тих же умов становить 1,17; 1,36 і 1,63 кг $м^3$/год відповідно. Однак споживана потужність другої схеми перевищує споживану потужність першої схеми на 50%.

Ключові слова: аерація, ежектор, швидкість масообміну, роторно-пульсаційний апарат, натрію сульфіт