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Experimental studies of hydrodynamics of two-phase gas-liquid system in the production of vegetable oils and fats

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Abstract

This paper presents a study of physical and chemical processes in two-phase multi-component gas-liquid systems at different stages of vegetable oil production and processing. One of the steps consists of determination of hydrodynamic parameters in vegetable oil bubbling, i.e. gas bubbles passing through a layer of liquid. The gas may be water steam, nitrogen, air or a combination of both of them. During this process the vegetable oil has direct contact with gas, therefore the processing time and the quality of the finished product depend to a great extent on precise determination of the parameters.

Introduction

The problems of hydrodynamics of two-phase gas-liquid system were studied thoroughly in the petroleum, gas and fuel industries and in production and use of various aerosols. Similar problems are encountered in development of modern technologies for vegetable oil processing, primarily for final distillation and deodorization as well as for introduction of gaseous media into a liquid, e.g., during nitration. Hydrodynamics of bubbling processes has not been fully studied yet. This happens due to complicacy and instability of processes in the structure of the liquid layer through which gas or steam is passed. Movement of liquid and gas masses defies accurate quantitative description for the cases in which the interface is changing continuously. The most comprehensive notion of the process of water steam bubbling through highly concentrated miscella was first presented in the monograph by Beloborodov (1966). The bubbling process was studied by many specialists including such outstanding scholars as Kutateladze (1952), Styricovich (1976), Kafarov (1979), Danilova (1986), Stabnikov (1985), Kracht (2008), Fujilawa (2003).

The structure of the hydrodynamic mode is the most important characteristic of the process. Specialists who studied bubbling problems distinguished several modes. According to Kafarov (1979) there are two modes: the first one is a bubble or barbotage mode, and the second one is a torch mode. All other modes are derivatives of these two. When it comes to vegetable oil bubbling, it is very important to know the frontiers between the modes since the goal is to maintain the bubbling or barbotage mode in the oil, because this mode provides maximum interaction between the phases. The torch mode disturbs the treatment process because it leads to unwarranted gas consumption and to possible formation of “dead zones” with untreated miscella. The most effective bubbling can be achieved with the smallest possible bubble diameters together with increase of their quantity and/or bubble detachment frequency. The number of gas formation centres or the number of openings in the bubbler remains the most important condition. However, the smallest bubble sizes lead to the risk of foaming, which is unacceptable in the majority of cases. Foaming is especially intensive if surfactants are present in the studied liquid phase.

According to Shamirzayev (2001), velocity of floating-up bubbles depends significantly on the bubble volume for volumes lower than 50 mm^3. For higher volumes it remains practically constant of approx. 4-6 cm/s for all liquids studied. It is reasonable to use the information about movement of air and steam bubbles during boiling since the hydrodynamic processes in this case are the same as during bubbling (Baltas *et al*., 1969; Sato *et al.*, 1981; Fujilawa *et al*., 2003; Sakaguchi *et al*., 1983; Thome, 1983; Yamazaki, 1986; Linn *et al*., 1988;

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Abramzon *et al.*, 1989; Sadatomi *et al.*, 2005). In the case of petroleum-containing wastewater a flotation method is widely used. In the sphere of mathematical simulation of gas bubbles movement in a liquid medium, the work of Morozov *et al*. (2000) is of interest. Results of research of behaviour of bubbles exposed to intensive electric fields are given in (Korobeinikov, 1998). An engineering method for heat- and mass-exchange calculation during steam-gas mixture condensation that allows to determine local values and to control detailed characteristics of the process such as concentration and temperature at the phases of interface and influence of transverse mass flow on transfer intensity etc., is presented in the study of Solodov (1994).

In the studies of T. Grumstrup (2007), Calderbank *et al.* (1970), Uemura *et al*. (2010) the presence of some "ripples" on the interface was noted. They report the experimental observation of a well-defined rippling of the air cavity entrained by a rapidly moving solid object entering the free surface of a liquid (water or ethanol). The ripples are fixed in the lab frame, and begin just after the pinch-off (deep seal) of the cavity, simultaneous with the acoustic emission. The acoustic emission spectrum is located in the vicinity of the bubble resonance frequency. They present an irrotational model which explains the ripples as a spatial rectification of these volume oscillations by the surface of the moving object. The study of the rippling of an air cavity attached to a rapidly moving solid object (sphere, cone, hemisphere) in both water and ethanol, initiated by the post-impact pinch-off of the cavity. Their potential flow model implies that the ripples are an acoustic phenomenon, due to a standing wave reflected from the projectile surface. Among the remaining puzzles is the asymmetry produced by certain projectiles (cone, teflon sphere). The conditions for the onset of rippling are also unclear; this could be clarified by independent control of the velocity and size of the object.

Kashinsky (2012) experimentally studied the influence of flow characteristics of liquid and gas bubbles peel from a capillary in the fluid flow. As a result they found that, ceteris paribus, the liquid and gas bubbles are smaller than the average diameter in the case of separation of the capillary located in the central region of the channel rather than at the wall during isolation. The authors believe this happens due to the fact that the velocity of the fluid in the central portion of the channel is significantly higher than that near its walls. They showed that the shape of the histogram distribution of bubble size changes qualitatively when exceeding a certain critical frequency separation.

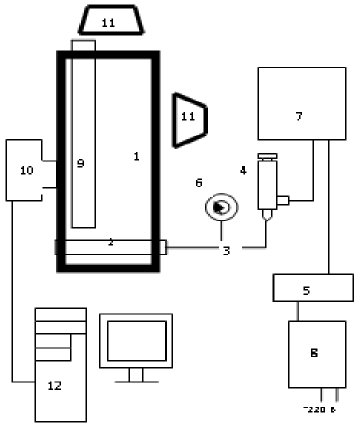

Figure 1. The experimental device for studying the bubbling hydrodynamics

Materials and Methods

Liquid and gas materials

Distilled water tinctured with iodine and unrefined non-deodorized vegetable oil was selected as studied liquid. Water was selected as a model liquid. Air was selected as gas.

Research modes and equipment

Experiments with water were conducted under different conditions with varied pressure and/or flow rate. The first mode was the bubble mode, i.e. movement of solitary bubbles (hereinafter, two terms will be used: solitary and bubble mode). In this mode bubbles have the shape described in the studies (Morozov *et al*., 2000; Shamirzayev, 2001; Kashinsky *et al*., 2012). At the moment of detachment the bubble has an spherical shape, but then it changes to an ellipsoid, the longer axis of which is perpendicular to the direction of floating-up. Trajectories of all bubbles passed through the same points. For studying the bubbling processes in vegetable oil under different conditions a special experimental device was built (shown in Figure 1).

The vessel filled with the liquid (1) is made of 6-mm thick glass in the form of a square cross-section cup with the dimensions of 200 × 200 mm and a height of 480 mm. Edges of the cup are joined by silicone adhesive that withstands heating to 180°C. Two opposite faces have holes in the lower part of the cup. A replaceable tube (2) with openings of different diameters (1, 2, 4 mm) is inserted in the holes through rubber seals. The rubber seals allow changing the positions of the openings vertically upwards, vertically downwards and horizontally. A compressor (5) feeds air to the tube through a hose (3) via a needle valve (4). Air pressure is measured by a pressure gauge (6). To eliminate pulsation of a membrane-type compressor, a receiver (7) is used.

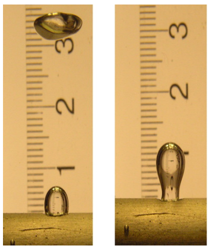

Figure 2. The moment of bubble detachment from the solid surface in water

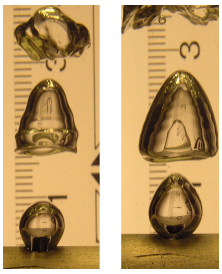

Figure 3. Changing form of the bubbles in the torch mode

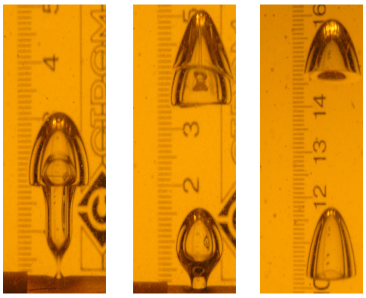

Figure 4. Changing form of the bubbles in different modes in oil

The voltage supplied to the compressor is adjusted by a constant-voltage regulator (8). The cup contains a measuring ruler (9). The process is recorded by means of a digital photo camera (10) mounted on a stand directly in front of a cup face. To provide a minimum exposure in a range of 1/500 to 1/2000, the device is equipped with several powerful lighting lamps (11). The digital photo camera is connected to a computer (12).

Air was fed by a micro-compressor through a receiver having at its outlet variable area flow meters RMA 0,063 GUZ for stabilization of the required air flow into the perforated duralumin tube. Temperature of vegetable oil in the vessel was maintained by a thermostat VEB MLW that supplied thermally stabilized heat carrying medium into a glass coil immersed into the vessel. Temperature was monitored by means of a glass mercury thermometer with a division value of 0.5°C. Though it is important to mention that even if the oxygen content is low, the raise of temperatures stimulates the accelerated oxidation of fatty acids that are the basis of the oils and fats. Protein and phosphorus-containing substances that are presented in large quantities in unrefined oils are particularly sensitive to high temperatures. As a result the vegetable oil undergoes irreversible transformations.

For determination of bubble size, a transparent measuring ruler with a division value of 1 mm was mounted at the line of bubble floating-up. The ruler was made of polycarbonate (in order to decrease temperature influence on its geometric dimensions). Photographing was performed by means of an OLIMPUS C-5060 camera in different modes such as macro photography, high-speed photography (4 frames/s). To eliminate influence of external mechanical factors, a remote control board was used for controlling the camera.

Results

Bubble diameters did not exceed 4 mm, and the openings in the bubbler had diameters of 1, 2 and 4 mm. This confirms the conclusion done by V. V. Kafarov (Kafarov, 1979) that the bubble diameter does not practically depend on diameter of openings in the bubbler. In the second mode, bubble detachment frequency grows with an increase of air flow rate (Figure 2). Bubbles retain their spherical shape at the moment of detachment, but then they get an oblong shape reminding of an ellipsoid, and their orientation changes. The long axis of the ellipsoid is directed along the bubble floating-up trajectory. It is possible that the change is due to an increase in the number of bubbles floating up and a decrease in their spacing because of mutual influence. The preceding bubble leaves behind a “trace” in the form of a lower-pressure area that sucks in the next bubble. However, they do not collide since the spacing between them is large enough. Bubble size increases to 5-6 mm.

When passing to the torch mode, the bubbles change their shape already at the moment of filling and detachment (Figure 3). The bubble has an oblong shape instead of spherical, and immediately after detachment it assumes non-regular shape. The bubbles collide continuously, merge into one bubble or coalesce, or divide into several fragments. Their trajectory becomes spiral-like. The zone occupied by the trajectory (or “the channel”) increases 3-4 times as compared to the bubble mode.

Results of the study of air bubbles movement in vegetable oil are presented in Figure 4. Optical properties of vegetable oil and water differ significantly varying the contrast of the photographs. Floating-up of solitary bubbles demonstrates complete similarity to the experiment conducted with water. At the moment of detachment, the bubble

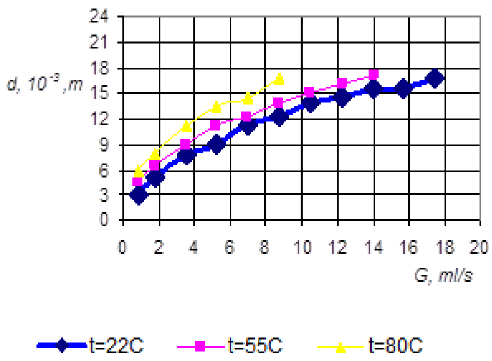

Figure 5. Dependence of bubble diameter on gas flow rate and vegetable oil temperature

has a spherical shape (Figure 4). After detachment, it becomes flattened on the poles. The long axis of the ellipsoid is transverse to the direction of the bubble floating-up, the diameter of the opening is 1 mm, and the bubble diameter does not exceed 3 mm.

As air flow rate increases, the detachment frequency of bubbles floating-up grows and their diameter increases up to 4-4.5 mm (Figure 4). The bubble shape remains the same. With further increase of air flow rate the bubble diameter increases drastically up to 7-8 mm. In this case, at the moment of detachment the bubble has an oblong cigar-like shape. Later it is transformed, and its shape reminds of a mushroom cap. An area filled with liquid is formed in the “tail” portion of the bubble. Geometrically the shape can be described as two parabolic surfaces and one plane.

The above observations and the photographs were made with the opening directed vertically upwards. As the orientation is changed, no significant changes are observed. The bubbles retain the cigar-like shape at the moment of their formation. After that, their shape becomes similar to the bubble shape with the opening directed vertically upwards. If the opening is directed vertically downwards, the initial bubble formation followed by the transformation of its shape to a mushroom-cap in a single cycle. The cap is inflated through a cigar-like neck, which follows by detachment of the bubble. In the middle and upper parts of the floating-up trajectory, bubbles have the same shape with any position of the opening. The bubble trajectory itself does not practically change.

It was the first time that measurements of floating-up air bubbles flow rate in the vegetable oil were performed. The values 0.15 to 0.30 m/s were obtained after having processed large volumes of data. The velocity is constant over the entire floating-up trajectory except the initial part. The experimental results are presented in Figure 5 showing the relationship between the flow rate of floating-up bubbles and the temperature of the liquid (vegetable oil, in this case). The diameter of the bubbler opening was 4 mm. In the case of deviation of the floating-up bubble shape from spherical one, the size was taken as an equivalent diameter that corresponds to diameter of a sphere having the same volume as the bubble of a non-regular shape.

Conclusions

The results of the study carried out show that the bubble shape and size depend on the following parameters: diameter of the bubbler opening, air flow rate, physical properties (primarily viscosity) of the liquid, surface tension and wetting angle. Diameter of the opening affects neither bubbles behaviour and shape nor the bubble size. Air flow rate influences the bubble shape and spatial position at the moment of floating-up.

If the opening diameter is increased to 4 mm, the bubble diameter in bubbles mode reaches 6 mm. However, if flow rate increases and there is change into the torch mode, the bubble diameter can reach 12-15 mm. The shape changes from a “mushroom cap” to a “cannon shell”. The “tail” portion has a zone filled with liquid and, as earlier, can be described by two parabolas and a plane. However, steepness of the parabolas increases. In the torch mode, collision of two sequential bubbles begins. This can be presumably caused by formation of a “trace” with lower pressure behind the bubble, which leads to suction of the next bubble into such a zone. However, the third bubble behind remains at a sufficient distance, so only two bubbles collide. In this process, the first bubble is deformed and covers the surface of the next bubble while the latter retains its shape until it emerges on the surface. It should be noted that, in contrast to experiments with water, the bubbles in oil do not join. This is probably due to the presence of surfactants and to higher viscosity of the liquid.

Thus, the bubble shape and size depend on the bubbler opening diameter, air flow rate, physical properties of liquid, primarily its viscosity, and surface tension. Diameter of the opening does not practically affect bubbles behaviour and shape but their size. Air flow rate influences, in the first place, the bubble shape and spatial position at the moment of floating-up. The results of this study have both fundamental importance for elucidation of the bubble origination, their detachment, movement and destruction mechanism as well as practical importance for designing devices for bubbling.

The data obtained allows calculate more accurately the geometric parameters of the equipment and process conditions in production and processing of vegetable oils and fats. It becomes possible to more accurately determine the diameters and number of openings, their configuration, the height of the liquid layer, the flow ratio of liquid and gas, such as oil miscella distillation, and deodorization of fats and oils when treated with nitrogen. This can reduce the size of equipment and decrease energy consumption, as well as increase the quality of oils and fats as a result of a more thorough treatment of the gas phase and the exclusion of local temperature overheating.

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