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Pulsating flow type apparatus: Energy dissipation rate and droplets dispersion

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ABSTRACT

Hydrodynamics of pulsating flow type apparatus (PFA), namely droplet disintegration, was investigated by use of theoretical approach and experimentally. Impact of several mechanisms on droplet sizes: Kelvin–Helmholtz instabilities, turbulence in the bulk of liquid and near walls of apparatus, dynamic and inertial mechanisms as well as high shear stresses are studied. It was found that oil droplet sizes in water in PFA (mean diameter of 20 μm and the maximum diameter of 35 μm) are 1.8 times smaller than in the stirred tank with Rushton turbine (maximum diameter about 70 μm) at the same level of energy dissipation rate. By other words, according to the Kolmogorov theory the stirred tank with Rushton turbine needs 4.5 times more dissipated energy to get the same sizes of droplets (1800 W/kg for Rushton turbine and 400 W/kg for PFA). Comparison of PFA with tubular turbulent apparatus (baffled pipe) has shown similar advantages of PFA.

It has been revealed that these effects attributed to the generally other mechanisms of droplet dispersion in PFA compared with usual apparatuses like stirred tanks, where the turbulence plays the main role in the droplet disintegration. Among these mechanisms are pulsations of velocity, acceleration and pressure, high shear stresses rate, and some instabilities.

1. Introduction

Emulsification processes are widely used in the chemical and petrochemical industry, for example in the products refining by removing aromatics from the gasoline by means of liquid extraction. In addition, emulsions are widely used in food products, cosmetics, pharmaceuticals. Another field of industrial application of emulsions is their use as a means for carrying of active compounds such as flavors, vitamins, antioxidants, nutraceuticals, phytochemicals, drugs, and chemicals within droplets. The introduction of these components requires the use of suitable means for transferring the effective amount of the active ingredient in the desired location and effective, energy saving methods for disintegration of droplets is one of the challenges.

The most studied and applied in industrial practice are following physical impacts on heterogeneous media: powerful shear flows (jet mixers, agitators, rotary apparatus), centrifugal field, ultrasound and electromagnetic waves (including microwave), pressure pulsations and velocity. One of a new generation of equipment is the pulsating flow type apparatus (PFA) (RF Patent, 2005) characterized with main idea – generation of pulsations along the streamlines due to the special form of a longitudinal section of the apparatus without any mechanical actuator like piston.

In recent decades, there has been a tendency to develop one of the promising areas of intensification of interphase transfer in heterogeneous media in mainly by the input of energy in the immediate vicinity of the boundary between the phases (Dolinsky and Ivanitsky, 1997; Dolinsky and Nakorchevskii, 1997; Abiev, 2003a,b; Abiev and Galushko, 2013). Obviously, this method of energy conversion should lead to an increase in the efficiency of heat and mass transfer processes, which will be expressed, for example, by sharp increase in specific surface area of the dispersed phase at equal energy dissipation rate.

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The main idea of the functioning of PFA is to create conditions to maximize the direct conversion of energy introduced into the apparatus, first, to the surface energy of the bubbles or droplets (in the process of dispersion), and secondly, to the kinetic energy of the relative motion of a continuous and dispersed phases to accelerate mass transfer processes, both on the surface of the bubbles or droplets, as well as within the volumes of continuous as dispersed phases. Dissipation of energy due to turbulence occurring at the same time is seen by us as a side effect; though it is inevitable, but partly controlled (Abiev and Galushko, 2013).

Interest in the use of devices with periodically varying cross-section (PFA) or looking like that for use in chemical engineering has increased in recent years. In some studies investigations of the apparatus partly similar to PFA, but with additional oscillatory flow (oscillatory baffled flow reactors) generated by mechanical piston are described (Harvey et al., 2003; Harvey and Stonestreet, 2002; Smith and Mackley, 2006; Gaidhani et al., 2005). It should be noted that baffled flow reactors – BFR (or baffled tubes) have generally other geometry and other principles of working (the baffles are necessary to generate turbulent vortices behind of them). Nevertheless, although they have significant differences from PFA, it should be mentioned that for the classification purposes BFR, PFA and TTA (see (Minsker et al., 2001; Danilov et al., 2011) for TTA – tubular turbulent apparatus) could be regarded as related apparatuses in contrast with usual batch reactors with stirrers, and even with well-known static mixers having insertions of special form (e.g. Kenics Static Mixer).

Some basic aspects of hydrodynamics of pulsating flow type apparatus has been studied both experimentally and theoretically in (Abiev and Galushko, 2013). At the same time the problems in droplets dispersion in PFA have not been studied yet.

The aim of this work is an experimental and theoretical study of the quality of the emulsification process in the pulsating flow apparatus and comparison of the quality of dispersion for the PFA and other types of devices at the same level of energy dissipation rate. It was also necessary to investigate the effect of various devices by the characteristics of dispersion depending on the kinetic energy of the flow. The particular task was to identify how significant the role of turbulent eddies is in the process of splitting drops compared to other factors in the pulsating flow type apparatus.

2. Experimental

A schematic of the pulsating flow type apparatus is shown in Fig. 1. The device can be used in chemical, petrochemical, pharmaceutical, food and other industries in the process of dispersing gas in a liquid, emulsifying (drops dispersion), with the concomitant heat and mass transfer processes like the dissolution of the solid phase (RF Patent, 1996; Abiev, 2012b), extraction (Vasilev and Abiev, 2014), the gas–liquid reactions (Galushko and Abiev, 2008) and absorption.

Set out in Abiev and Galushko (2013), Abiev (2012a), the results of calculations of pressure, velocity and acceleration, as well as the distribution of the turbulent kinetic energy and dissipation of energy (for k-ε model) arising in pulsating flow type apparatus suggests that there are conditions favorable for the dispersion of bubbles and drops in PFA.

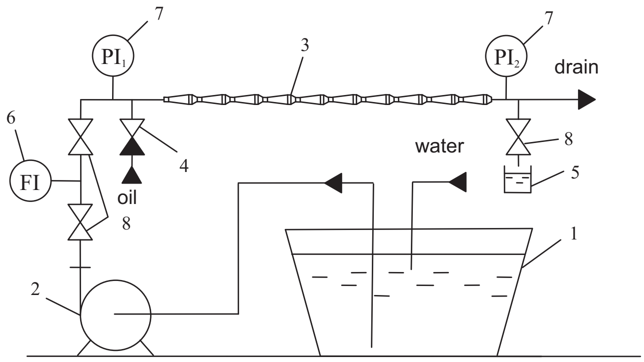

Fig. 2 – Draft of experimental set-up for oil droplets dispersion in water in pulsating flow type apparatus. 1 – feeding tank; 2 – pump; 3 – PFA; 4 – non-return valve; 5 – container to collect samples; 6 – mass flow meter; 7 – pressure gauges; 8 – flow rate control valves.

PFA consists of Venturi tubes disposed in series (Fig. 1), therefore the cross-section of apparatus is periodically varies along the axial coordinate of the apparatus, i.e. along direction of flow.

Heterogeneous system, passing through portions PFA with varying cross-section, are excited by variations in velocity, acceleration and pressure change due to the variation of cross-section of the pipe having the shape of Venturi tubes elements. The oscillations role and other mechanisms will be discussed further in Sections 3.2 and 3.3.

Experiments on the oil in water dispersion were performed at the set-up shown in Fig. 2. The water supplied from the tank 1 by a centrifugal pump 2 into the horizontal PFA 3 – a thick-walled glass tube consisted of ten elements of the “Venturi tube” (linear dimensions of the structural elements specified in Fig. 1 are: $d = 9$ mm, $D = 20$ mm, $L_1 = 15$ mm, $L_2 = L_4 = 10$ mm, $L_3 = 50$ mm, $\alpha = 36°$, $\beta = 11.5°$). The oil supply is performed in the point 4 upstream to the first diffuser through a check valve with a medical syringe of volume 20 ml. The sampling of oil-water mixture treated passing the through PFA has been performed by vessel 5 containing 5 ml pre-filled solution of surfactants; this was performed to avoid unnecessary coalescence of dispersed droplets during analysis of their sizes distribution. As the surfactant commercially available detergent ‘Fairy’ was used. Mixture flow rate was measured by electromagnetic mass flow meter 6 ‘VZLET ER ERSV-540M’ with a relative error of measurement ±2.0%, the pressure before and after the apparatus measured by a pressure gauges 7 ‘Elemer AIR-20/M2-DI’ with a relative error of measurement ±0.6%.

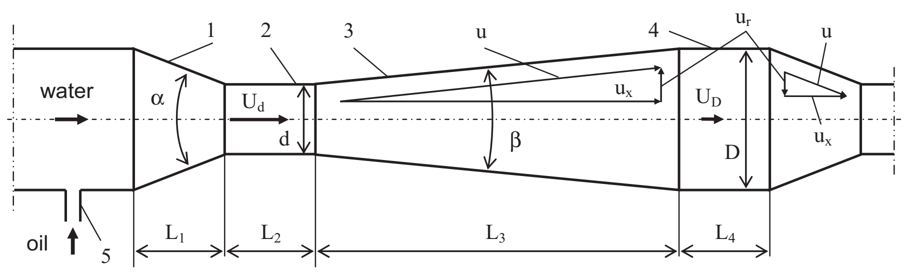

Fig. 1 – Schematic of Venturi tube element of PFA with typical dimensions. 1 – confuser; 2 – neck; 3 – diffuser; 4 – wide part of apparatus; 5 – oil feed point (for first element of PFA only); u – flow velocity vector, u_r – radial velocity, u_x – axial velocity.