Chemical Engineering & Processing: Process Intensification 131 (2018) 125–130

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Breakup of immiscible liquids at the interface using high-power acoustic pulses

O.M. Gradov[a,*], Yu.A. Zakhodyaeva[a], A.A. Voshkin[a,b]

[a] Kurnakov Institute of General and Inorganic Chemistry, Russian Academy of Sciences, Leninsky prospect 31, Moscow, Russia
[b] Moscow Technological University, Prospect Vernadskogo 78, Moscow, Russia

ARTICLE INFO

Keywords:
Solitons
Pulses
Sound velocity
Pressure drop
Acoustics
Solitary waves
Nonlinearity
Extraction
Interphase distribution
Intensification

ABSTRACT

A method has been developed for the approximate analytical description of the properties of acoustic solitary waves that have a large difference between the values of spatial gradients of their parameters along different coordinates. In the presence of two- or three-dimensional nonuniformity of the initial perturbation, these waves maintain their spatial structure unchanged when propagating to large distances and make it possible to regulate pressure drop at the front and the rate of their movement. All of this ensures a wide range of the possibilities of producing special force action or organizing long-distance information exchange. In particular, the sequence of such compression or rarefaction pulses can break up immiscible liquids at their interface, which is of great importance for the intensification of mass transfer in extraction processes.

1. Introduction

In recent years, the ability of nonlinear acoustic techniques to produce force action has been increasingly frequently used in various spheres of applied character, for example, in the development of ultrasonic miniextractors using liquid pseudomembranes [1–3], in the field of oil well stimulation [4,5], or for the reinforcement of the basic structure of materials [6]. There are studies [7,8] in which ultrasonic irradiation is used for the intensification of such fine mechanism of extraction as interphase mass transfer using the dynamic layer, which is controlled by self-organization and self-assembly processes. Even the simple creation of the cavitation region by different direct methods in the working zone of extraction leads to positive results [9]. Successful testing of power and resonance methods of the use of ultrasound in extraction processes suggests that the other nonlinear acoustic technique, such as the generation of solitary waves (solitons), can also have an effect on the intensification of mass transfer. The study of acoustic solitons [10,11] made it possible to determine some various aspects of the development of this nonlinearity in liquids and indicated new useful possibilities of its application. In particular, of special practical importance can be the use of acoustic solitary pulses in the treatment of molten metals [10]. The study of specific features of the generation and spatiotemporal structure of high-power acoustic pulses [11] is aimed at finding ways to produce special force action on the material being processed in a liquid medium. The specificity and conditions of the existence of such waves in plasma have also been well studied at present [12–14]. At the same time, a number of the important features of these waves, including the localization of force action in a limited volume, controllability by process parameters, and ability to propagate to long distances even in a dissipative medium, continue to attract well-founded scientific and applied interest in the study of these waves and their properties in liquids.

This study considers the specific features of the propagation of acoustic solitary waves in an ideal liquid in the case where there is a large difference between the values of the spatial gradients of their parameters along different coordinates, as applied to their interaction with the interface of immiscible liquids. When the multidimensionality of their spatial structure is ensured, which is the necessary condition of their existence, the movement of a soliton leads to the transport of the rarefaction or compression region in the given direction, thus producing the required force action. The performed calculations on the accurate determination of the character of the interaction between acoustic solitons and the surrounding medium are based on the separate description of the motion of a liquid in different directions that have a considerable difference in characteristic scales along the corresponding axes.

* Corresponding author.
E-mail address: lutt.plm@igic.ras.ru (O.M. Gradov).

https://doi.org/10.1016/j.cep.2018.07.011
Received 18 May 2018; Received in revised form 12 July 2018; Accepted 13 July 2018
Available online 25 July 2018
0255-2701/

2. Theoretical part

2.1. Original equations and approximate nonlinear solutions

The motion of an ideal liquid is described by the following well-known [15,16] system of the equations of fluid dynamics:

$$\rho[\partial_t \mathbf{v} + \mathbf{v}\nabla\mathbf{v}] = -\nabla p, \tag{1}$$

$$\partial_t\rho + \mathrm{div}\,\rho\mathbf{v} = 0, \tag{2}$$

$$p = A_0\left(\frac{\rho}{\rho_0}\right)^{\gamma} - A_1. \tag{3}$$

Here, the functions $\mathbf{v}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$, and $p(\mathbf{r},t)$ are the distributions of the liquid velocity, density, and pressure, respectively, along the spatial coordinates described by the radius vector $\mathbf{r}$ and their variation with time t under the conditions when the constants A_0, A_1, and γ, which appear in Tait equation of state (3), weakly depend on the temperature of the medium. The subscript «0» denotes the equilibrium values of parameters in the absence of motion (the case $\mathbf{v}(\mathbf{r},t) = 0$) when perturbations in density $\delta\rho(\mathbf{r},t)$ and pressure $\delta p(\mathbf{r},t)$ are equal to zero.

By restricting the discussion to the study of potential perturbations, for which the velocity potential $\Psi(\mathbf{r},t)$ ($\mathbf{v} = \nabla\Psi$) is usually introduced, system of Eqs. (1) and (2) can be rewritten in the form that takes into account the relative smallness of deviations from the initial state [15,16]:

$$\partial_t\Psi + (\nabla\Psi)^2/2 = -c^2\delta\rho/\rho_0 - (\gamma/2 - 1)c^2\delta\rho^2/\rho_0^2, \tag{4}$$

$$\partial_t\delta\rho + \mathrm{div}[(\rho_0 + \delta\rho)\nabla\Psi] = 0,\ c^2 = \gamma A_0/\rho_0 \tag{5}$$

Concentrating on the consideration of the wave process that propagates along the 0Z axis, in the simplest approximation, the process can be assumed to be azimuthally symmetric in the radial plane for the cylindrical coordinate system ($\mathbf{r} = \{r',\theta,z\}$) in the limit when there is no dependence on the azimuth angle. In this case, the behavior of a perturbation along the direction of its propagation at a velocity of v_0 in the coordinate system that moves with this wave is described by the dependence on the variable $\xi' = z - v_0 t$ (v_0 = const), and system of Eqs. (4),(5) becomes simpler. Since the study of only a solitary wave is of practical interest, in order to obtain the corresponding solution from system of Eqs. (4),(5), a method can be used that ensures the isolation of this special form of a function from the total number of different solutions that exist for the original system of nonlinear equations. This isolation is particularly noticeable in the case where there are different-scale motions of a liquid in different directions, when the characteristic size of a pulse in the radial direction R is much higher than the value z_0, which determines its length along the direction of propagation, i.e., when there is a small parameter $\varepsilon << 1$, where $\varepsilon = z_0 / R$. In this case, it is more convenient to write system of Eqs. (4),(5) in the dimensionless form by introducing the new variables $r = r'/R$ and $\xi = \xi'/z_0$ and the sought functions $\varphi = \Psi/cz_0$ and $n = \delta\rho/\rho_0$:

$$\partial_\xi\varphi - \frac{1}{2w}\{(\partial_\xi\varphi)^2 + \varepsilon^2(\partial_r\varphi)^2\} = n + \frac{\gamma - 2}{2}n^2,\ w = \frac{v_0}{c}, \tag{6}$$

$$w\partial_\xi n - \partial_{\xi\xi}^2\varphi - \partial_\xi(n\partial_\xi\varphi) - \frac{\varepsilon^2}{r}\partial_r[r(n + 1)\partial_r\varphi] = 0 \tag{7}$$

In the presence of a small parameter $\varepsilon << 1$, when the characteristic sizes of a solitary wave in different directions considerably differ in magnitude, the simplifying assumption $\partial_r\varphi \sim \varphi$ can be used without substantial detriment to the correctness of consideration. The point is that, in this case, the specific features of a large-scale change in the wave profile in the radial direction cannot affect the origination and propagation of a solitary wave, and the acceptability of the proposed condition can be ensured with any desired accuracy by specifying initial-boundary conditions. Therefore, by replacing approximately fit radial gradients with the value of the function itself and excluding the quantity $n(\mathbf{r},t)$ from system of Eqs. (6),(7), we can finally derive the single equation for the velocity potential:

$$\partial_\xi\varphi - \beta_0(\partial_\xi\varphi)^2 - \varepsilon_0^2\varphi^2 = -a^2,\ \varepsilon_0^2 = \frac{\varepsilon^2}{w^2 - 1}, \tag{8}$$

$$a^2 = \beta_0 v_{00}^2 - v_{00},\ v_{00} = \frac{v_z(\xi = 0)}{c}, \beta_0 = \frac{\gamma w^2 - 2w^2 + 3}{2(w^2 - 1)}$$

As the results of numerical calculation have shown [11], Eq. (8) has a quite accurate approximation of the solution in the form of the following simple formula:

$$u = \partial_\xi\varphi(\xi) \approx \frac{k\varphi_0}{\mathrm{ch}^2(k\xi)}. \tag{9}$$

$$k = a\varepsilon_0,\quad \varphi_0 = -\alpha/\varepsilon_0.$$

From Eq. (9), it can be seen that the parameters of a nonlinear signal are substantially related to nonuniformity in the radial plane, which is proportional to ε_0. It follows from passage to the limit $\varepsilon_0 \to 0$ that the solitary waves under consideration with the structure described by formula (9) do not exist in a homogeneous medium. This means that solution (9) derived using simple approximations is a new type of acoustic solitary waves that exist only due to the anisotropy of conditions for their excitation.

2.2. Increasing the contact area of immiscible liquids using high-power acoustic pulses

Generalizing the results of calculating the form of acoustic solitons and the conditions of their propagation, it can be stated that a liquid can maintain the movement of perturbations with a certain profile of spatial distribution and a specific form of time dependence. All of the specific features of spatial structure and interrelationship between the parameters of the nonequilibrium region that are required for this purpose are produced in a special manner in the zone of the generation of these nonlinear acoustic signals. The corresponding quantitative relationships are represented in formula (9). As was shown in [10–12], when these relationships are satisfied, a solitary perturbation, which is the original cavity of compression or rarefaction, can propagate without changing a shape to large distances even in the presence of substantial dissipation, i.e., in media with high viscosity and thermal conductivity. These properties of the wave forms under consideration can be used to achieve objectives that are hard to reach under other conditions in special practical applications.

One of these interesting applications can be associated with extraction by the liquid pseudomembrane method in miniextractors. The microemulsion used in this method consists of liquids with restricted mutual solubility; therefore, extraction takes place through their interface and, accordingly, the intensity of the process is proportional to the area of this interface. The point is that, when two such liquids are mixed, the droplets of the heavier liquid are dispersed in the lighter liquid, and the total area S of the surface of these droplets with the equal radius R, which completely fill some volume V_0, is inversely proportional to this radius:

$$S = 3V_0/R \tag{10}$$

From formula (10), it can be seen that the smaller the radius of droplets into which the liquid is broken, the larger the contact area of liquids and the higher the intensity of extraction. Solving the problem of the breakage of emulsion droplets can be taken to a new considerably higher level by using acoustic pulses under consideration. The point is that each of these pulses is the original cavity of compression or rarefaction, i.e., the moving region of increased or decreased pressure. To elucidate the mechanism of the formation of small droplets from the volume of the heavier fraction under the effect of a soliton that propagates in the light liquid, Fig. 1 shows a special example of such