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Hydrodynamic Investigation of Bubble Formation in Non-Newtonian Fluids in Waste Water Filtration Aeration Tanks Using CFD

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ABSTRACT

The present research investigates numerically the bubble formation process by inserting air in a submerged orifice in a cylindrical container which contains a non-Newtonian fluid. First, we discuss the importance of bubble formation and then we review literature. This is important because we face non-Newtonian fluids infiltration of waste water in aeration tanks. Therefore, hydrodynamic study of bubble formation is important in waste water study. In the subsequent sections, we deal with numerical methods and equations which govern bubble formation process. Solution algorithm which is SOLA-VOF calculation code is explained in detail. Simulation was conducted by means of SOLA-VOF method. In this code, momentum conservation law equations for non-Newtonian fluids (of power law type) were used by finite difference method and in two-dimensional format. In this research, the influence of inserted air rate on bubble size and its formation time in very low rates of gas are also studied.

KEYWORDS: two-phase flow, bubble formation, numerical simulation, dynamics of calculation fluids, SOLA-VOF

INTRODUCTION

Multiphase systems play important roles in a large number of industrial and natural processes like copper refining, chemical reactors, power plants, internal combustion motors and cleaning. Heat and mass transfer in these systems are characterized by fluid motion. Therefore, study of their motion is very important for designing [1]. Two-phase flow is a subset of multiphase flow regimes and explains interactive motion of two different kinds of materials or media. Difference between matters can be resulted from thermodynamic state called phase (gas, liquid, solid) and chemical elements. Modeling and analysis of two-phase flow is an important challenge in classic sciences [2]. Periodical formation of bubbles by inserting a gas into an orifice submerged in liquid is considered as a two-phase phenomenon [1]. Since formation of bubble by inserting gas flow in a container plays an important role in designing gas-liquid contact devices, this process has received a lot of attention [3]. Bubble production column is a device in which gas flow spreads all over the liquid phase in the form of small bubbles. Spreading gas in liquid in this device aims to make contact between two phases. Mixing by air is important in extraction of radioactive liquids and is a sample of a two-phase process [4]. Chemical reactors, biological for monitors and polymer production tanks are other examples of bubble formation in liquid containers. Moreover, the most fundamental method for gas dispersion is formation of bubble via orifice (or nuzzle). Therefore, it seems necessary to make research on impacts of different factors on the form and formation of bubble in an orifice submerged in liquids [5]. Therefore, many studies have been conducted on the impacts of different factors like gas chamber volume, orifice diameter and gas rate.

RESEARCH LITERATURE

Many researchers have conducted studies on the process of bubble formation and its hydrodynamics. Davison et al (1960) studied both experimental and theoretical cases for formation of bubble in a non-viscous liquid. They found equations between bubble volume and rate for when gas rate or pressure is constant. Park, Taylor and Norres (1976) conducted many studies on mutual impacts of chamber and orifice in formation of bubbles. They presented a mechanical model of mutual impact based on a simple mass balance and an approach to pressure-time figure in formation of bubble. Their device included a gas feed system in which pre-saturate gas entered a gas chamber in steady state after measurement of rate and then entered liquid column via an orifice. At that report, the influence of gas chamber on bubble volume had been explained and the equations obtained were dedicated to Newtonian fluids [3]. Ulbercht et al (1977) investigated prediction of bubbles volumeexited from a nuzzle in non-Newtonian fluids under constant-flow conditions. They showed that

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equations of type can be used for prediction of volume of bubbles in non-Newtonian liquids with rates higher . They used Davison and Schuler (1960) and Kumar-Kuloor models (1967) for obtaining the above equation. The value of the coefficient without dimension C is equal to 1.387 for the first model and equal to 0.976 for the second model. They conducted some experiments using non-Newtonian fluids of type power law (like CMC aquatic solutions) for investigation of precision of equation. They obtained relatively acceptable results in a specified range of gas rate by assuming C equal to 0.976 and drawing experimental volume curve V_{exp} versus theoretical volume V_{the} [6]. Traska, Tsuge (1990) measured bubble volume, bubble shape and gas chamber pressure during bubble growth in order to clarify mechanism of bubble formation. They used power lawmodel liquids. The liquids were PAA and CMC aqueous solutionsas non-Newtonian liquids and Glisirolaqueous solution as a Newtonian liquid. They investigated the influence of m and n coefficients of power law model, influence of gas chamber, orifice diameter and gas rate on bubble volume and shape during bubble formation process. They proposed an adjusted non-spherical model both for Newtonian and non-Newtonian liquids in order to explain mechanism of bubble formation. This model was proposed for Newtonian liquids with high viscosity by adjusting pinczewski model (1981). In this non-spherical model, bubble level is divided into a large number of elements (figure 1). Gas flows at a constant rate towards gas chamber so that gas chamber pressure increases. When pressure of gas chamber exceeds sum of hydrostatic pressure and surface tension, the gas inside the chamber flows towards the liquid via orifice and bubble start growing. Two motion equations are solved for every element in radial and vertical directions so that radial and vertical speeds are specified and then bubble surface places are determined. This calculation ends when bubbles gets free from orifice head. These calculations were conducted by assuming symmetry of bubble with respect to vertical axle and ineffectiveness of other bubbles on the motion of the bubble. Finally, a good agreement between the results of the model and experimental values was reached [6].

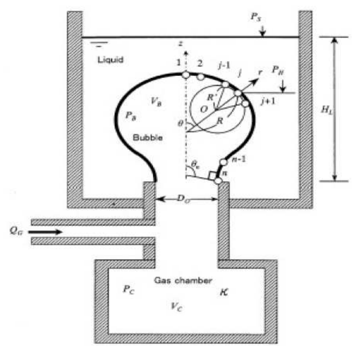


Figure 1.non-spherical bubble formation model [6]

Zhang and Tan (2000) presented a theoretical model for formation of bubble and spill phenomenon in their report. In fact, they needed to study bubble formation process in a submerged orifice completely in order to be able to calculate spill rate. This phenomenon is one of the main problems in distillation and absorption operation when using porous trays. They assumed that bubbles remain in the shape of sphere during formation process. This assumption allowed them to use analytical terms of flow potential theory for modeling pressure of liquid surrounding orifice. They considered gas phase as being ideal and compressible gas followed an adiabatic equation. Moreover, they ignored gas momentum impacts. Therefore, they presented equations for formation of bubble and spill theory and solved the problem by Runge-Kutta-Verner numerical method (ranks 5 and 6) and assuming appropriate primary and boundary conditions. They investigated their model by experimenting for a cylindrical column including an orifice in air-water system and predicted an acceptable agreement for bubble [7]. Within the past few years, some models have been developed based on dynamics of calculation fluids (CFD) in order to study flow phenomena during formation, ascend and accumulation process. Volume of fluid (VOF) model has been presented for explaining motion of re-formable gas bubbles in a Newtonian fluid. VOF model solves transitional motion of gas and liquid using Navier-Stocks equations and indicates gas-liquid surface changes using relative motion of liquid. Chen and Li (1998) used an adjusted VOF method for calculation of accumulation and ascend of bubble towards liquid surface. Krishna et al studied ascend of bubbles in a two-dimensional coordinates using VOF method. They used CFX for Navier-Stocks equations. They also investigated bubble-bubble mutual impact and found that large bubbles may break or join each other during their ascends. Some recent studies have been conducted on the impacts of electrostatic potential on dynamics of bubble formation process. They aimed to use electrostatic potential hey aimed to use electrostatic potential for controlling bubbling. Sarnobat et al (2003) studied bubble formation process experimentally in glycerol liquid under electrical potential. They used dry nitrogen for dispersing phase and showed that if electrical potential goes above zero, bubble size will reduce, bubble shape becomes more spherical and frequency of bubble production is also increased, although more research in this regard is necessary for obtaining more exact results [8]. Anyway, many studies have been conducted on formation of bubble process both via semi-empirical models and numerical simulation. In the present research, we use SOLA-VOF numerical model to investigate process of bubble formation exited from a nozzle submerged in a non-Newtonian liquid.

SIMULATION AND RESULTS

Statement of problem

Formation of gas bubbles in submerged nozzles is one of the most difficult and complex two-phase problems and many researchers have studied this phenomenon. Many experimental and theoretical studies have been conducted on the size of bubble, frequency, buoyancy effect and heat and also impact angle. In this study, process of bubble formation, growing and releasing has been conducted via Nicole calculation code and the impact of input gas rate change on bubble diameter and formation time was also investigated. Geometry of the study has been shown schematically in figure 2. This cylindrical container (diameter equal to 4 centimeters and height equal to 5 centimeters) has been filled with waste water up to a height equal to 3 centimeters. An orifice with a diameter equal to 2.5 millimeters or 1.5 millimeters has been placed at one end of the container and air enters it at a constant rate.

Calculation format, primary and boundary conditions

The calculation grid was two-dimensional and makes use of Cartesian coordinates. This code is very sensitive to grid size and bubble formation process can be conducted only at one special range of grid. In this study, grids size are 80*140. The walls of the container have non-slip boundary conditions and the nozzle has a fixed air flow inwards the container. Speeds and accelerations of all elements are assumed to be equal to zero in primary state and distribution of primary pressure in calculation grid is summarized only in hydrostatic pressure. Time step is of rank 10^{-5} which changes automatically by the code itself.

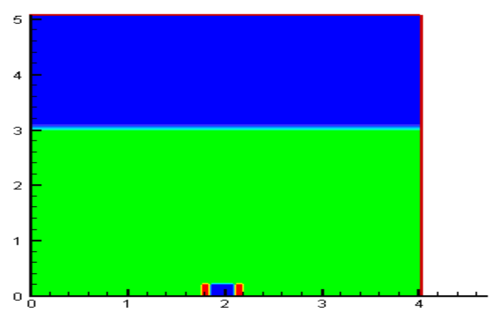


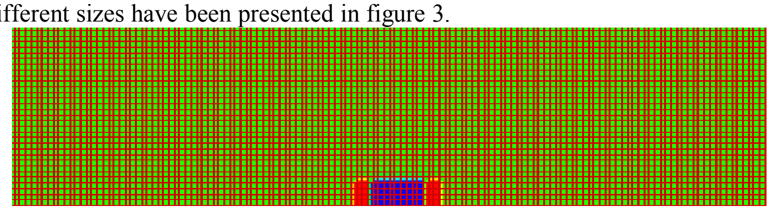
Figure 2.calculation format

Formation of the first bubble

Bubbles formed in a nozzle ascend in a liquid column and break in liquid surface. During ascend, bubbles may join each other and larger bubbles can form or may break and smaller bubbles may form. On the other hand, bubble size in the middle of column is not the same as that of ends of the nozzle [9]. Anyway, most models reported in papers and references are based upon formation of bubble in single nozzles, although it is obvious that bubble formation phenomena are made up of multi-nuzzle systems. In this research, we used a single-nozzle system and process of bubble formation at the end of the nozzle was simulated via SOLA-VOF calculation code.

Dependence of results on grid size

After conduction of numerous experiments on grids with different sizes we specified that making grids finer than that size considered in the research will increase the number of calculations but it does not have any considerable impact on precision of results. Therefore, a fixed grid was used for was used for all experiments. Two grids with different sizes have been presented in figure 3.



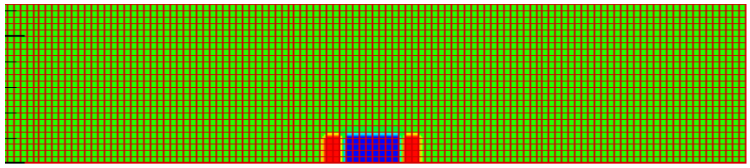


Figure 3.comparison of two grids with different sizes

Calculations, results and comparison

In this research, waste water was used as fluid and data required [10] for modeling of a non-Newtonian fluid has been presented in table 1.

Table 1.rheological parameters of power law model in different MLSSs for waste water [19]

Model	MLSS(g/l)	Parameter	Parameter	R^2
Power law		K	n	
	2.75	0.171	0.0706	0.983
	5.08	0.658	0.0873	0.989
	7.43	0.687	0.0113	0.968
	10.22	0.937	0.2060	0.979
	16	1.750	0.0956	0.997
	20	921	0.229	0.991

We investigated two states. The first state concerns orifices with diameter 2.5 millimeters and the second state concerns orifices with diameter 1.5 millimeter. The speed of air entered the nozzle was equal to 0.5, 1, 1.5 and 2centemeters per second. This experiment was conducted to determine the influence of dynamic viscosity variations and cinematicviscosity on the process of bubble formation in a non-Newtonian fluid. In the first stage, it was specified that cinematicviscosity has a basic role in this process. In other words, both dynamic viscosity and density of fluid influence formation of bubble and diameter of bubble. In the first stage, an experiment was conducted to determine the impacts of cinematicviscosity on process of bubble formation for a Newtonian fluid and the following results were obtained. In this experiment, a sample fluid was assumed with a particular cinematicviscosity and in both cases, the time of bubble formation (separation of bubble from orifice) and also diameter of bubble formed for two different diameters of orifice with an input speed of one centimeter per second was measured.

Table 2.a comparison of bubble speed and cinematicviscosity for two different diameters

2.5 mm =Orifice diameter		V=1.0 cm/s
υ=0.00171	Bubble diameter	2.0666
	Bubble formation (s)time	0.06829
υ =0.00658	Bubble diameter	2.1147
	Bubble formation (s)time	0.06999
υ =0.00687	Bubble diameter	2.1163
	Bubble formation (s)time	0.06976
υ =0.00937	Bubble diameter	2.1456
	Bubble formation (s)time	0.07220
υ =0.0175	Bubble diameter	2.1183
	Bubble formation (s)time	0.07224

1.5mm =Orifice diameter		V=1.0 cm/s
υ=0.00171	Bubble diameter	1.0019
	Bubble formation (s)time	0.0524
υ =0.00658	Bubble diameter	1.003
	Bubble formation (s)time	0.0547
υ =0.00687	Bubble diameter	1.003
	Bubble formation (s)time	0.0547
υ =0.00937	Bubble diameter	1.003
	Bubble formation (s)time	0.0552
υ =0.0175	Bubble diameter	1.0638
	Bubble formation (s)time	0.0593

Considering the above data, it can be concluded that an increase in cinematicviscosity-it both includes change in density and change in dynamic viscosity-reduces speed of bubble formation (an increase in the time needed for formation of bubble) and increases bubble diameter slightly. Of course, it must be noticed that the range of viscosity variations is limited and relatively small both in experiment on Newtonian fluid and both in experiment on non-Newtonian fluid. As it was expected, variations in bubble diameter and the time of bubble formation must be also small. The aim of the present research is to determine the influence of dynamic viscosity on the process of formation of bubblefor waste water as a non-Newtonian fluid. In order to clarify the result, the influence of density variations was eliminated from the experiment and we only investigated the influence of variations in dynamic viscosity. As it was mentioned before, we used power law model for calculation of forces resulted from fluid viscosity. Variations in dynamic viscosity have been modeled by changing (K) coefficient and power (n) in relationships between stress and strain.

The influence of gas rate on bubble diameter

Tables 3 and 4 indicate the influence of input gas on diameter of bubble. Furthermore, the influence of changes in coefficients of power law equation on bubble diameter can be also observed. If we ignore the influence of surface tension, bubble size is determined by balancing buoyancy, inertia and viscosity forces.

Table 3.a comparison of bubble diameter for orifice with diameter equal to 2.5 mm

V=2.0 cm/s	V=1.5 cm/s	V=1.0 cm/s	V=0.5 cm/s	K , n	MLSS(g/l)
3.33	2.84	2.08	1.02	k=0.171 n=0.0706	**2.74**
3.32	2.85	2.07	1.01	k=0.658 n=0.0873	**5.08**
3.33	2.86	2.07	1.02	k=0.687 n=0.0113	**7.43**
3.32	2.88	2.11	1.01	k=0.937 n=0.206	**10.22**
3.34	2.82	2.09	1.01	k=1.75 n=0.0956	**16**
3.33	2.80	2.09	1.03	k=921 n=0.229	**20**

Table 4. A comparison of bubble diameter for orifice with diameter equal to 1.5mm

V=2.0 cm/s	V=1.5 cm/s	V=1.0 cm/s	V=0.5 cm/s	K , n	MLSS(g/l)
1.47	1.305	1.04	0.98	k=0.171 n=0.0706	**2.74**
1.45	1.32	1.04	0.98	k=0.658 n=0.0873	**5.08**
1.48	1.44	1.03	0.98	k=0.687 n=0.0113	**7.43**
1.48	1.31	1.04	0.99	k=0.937 n=0.206	**10.22**
1.46	1.29	1.03	0.98	k=1.75 n=0.0956	**16**
1.43	1.05	0.92	0.90	k=921 n=0.229	**20**

The results of tables 3 and 4 indicate that as nozzle input gas speed increases, bubble diameter and bubble volume are also increased. Furthermore, it can be concluded that as orifice diameter increases, bubble diameter is also increased. Another point is that as MLSS increases from 2.74 to 20, bubble diameter increases and then decreases in both diameters and all speeds considered for orifice. The results show that diameters of the bubbles created in MLSS values between 7.43 and 10.22 are greater than bubbles formed in other cases. This shows that if waste water under experiment is considered as Newtonian fluid, waste water with MLSS values between 7.43 and 10.22 have the highest dynamic viscosities and an increase or decrease in MLSS reduces viscosity.

The influence of rate on the time of bubble formation

Tables 5 and 6 indicate the influence of nozzle input gas speed in nozzles with diameters equal to 2.5 and 1.5 millimeters. Furthermore, the influence of variations in power law equation confines on the time of bubble formation can be observed.

Table 5.a comparison of bubble formation time in orifice with a diameter equal to 2.5 millimeters

V=2.0 cm/s	V=1.5 cm/s	V=1.0 cm/s	V=0.5 cm/s	K , n	MLSS(g/l)
0.0616	0.0658	0.0683	0.0804	k=0.171 n=0.0706	**2.74**
0.0614	0.0664	0.0681	0.0805	k=0.658 n=0.0873	**5.08**
0.0625	0.0669	0.0681	0.0804	k=0.687 n=0.0113	**7.43**
0.0613	0.0667	0.0691	0.0806	k=0.937 n=0.206	**10.22**
0.0633	0.0653	0.0685	0.0805	k=1.75 n=0.0956	**16**
0.0621	0.0659	0.0683	0.0804	k=921 n=0.229	**20**

Table 6.a comparison of bubble formation time in orifice with diameter equal to 1.5mm

V=2.0 cm/s	V=1.5 cm/s	V=1.0 cm/s	V=0.5 cm/s	K , n	MLSS(g/l)
0.0448	0.0477	0.0523	0.0707	k=0.171 n=0.0706	**2.74**
0.0447	0.0479	0.0525	0.0707	k=0.658 n=0.0873	**5.08**
0.0451	0.0476	0.0526	0.0706	k=0.687 n=0.0113	**7.43**
0.0450	0.0477	0.0524	0.0707	k=0.937 n=0.206	**10.22**
0.0450	0.0477	0.0520	0.0707	k=1.75 n=0.0956	**16**
0.0435	0.0462	0.0517	0.0707	k=921 n=0.229	**20**

The results obtained from tables 5 and 6 indicate that as nozzle input gas speed increases, bubble formation time is reduced. In other words, as bubble volume increases, its formation time decreases. Another result is that as MLSS increases from 2.74 to 20, bubble formation time first increases and then decreases in all speeds and in both diameters considered for the orifice. By comparing the results, it can be concluded that as diameter of the bubble increases, more time is necessary for its separation from orifice. In practical applications, bubble formation process is used for filtering waste water and sewage in treatment plant, as one of the stages in filtering process is aeration of waste water by creation of bubbles. To this end, many orifices are installed at the bottom of waste water tank and air is pumped with high pressure into orifices in order to create bubbles and dissolving gases existing in air. Since the final favorable result in this process is dissolution of air into waste water, formation of more bubbles at a time is very good. Furthermore, small bubbles in a fixed output rate increases the contact surface of air inside bubble with waste water and increases dissolution. Finally, diameter of orifices should be reduced in order to have smaller bubbles and increase bubble formation speed. Moreover, the number of orifices should be increased. Moreover, input air speed should be kept at an optimal interval because low speed slows down trend of formation of bubble and high speed increases bubble diameter.

Bubble shape comparison

Figures 4 and 5 indicate bubble formation process for orifices with diameters equal to 2.5 and 1.5 millimeters and speeds equal to 0.5, 1, 1.5, and 2 centimeters in states K=0.658 and n=0.0873. these images indicate step-by-step trend of gas exit and way of formation of bubble in different time periods. As it can be observed, orifice diameter and also speed-and consequently rate- of the gas have direct impacts on the shape of the created bubble.

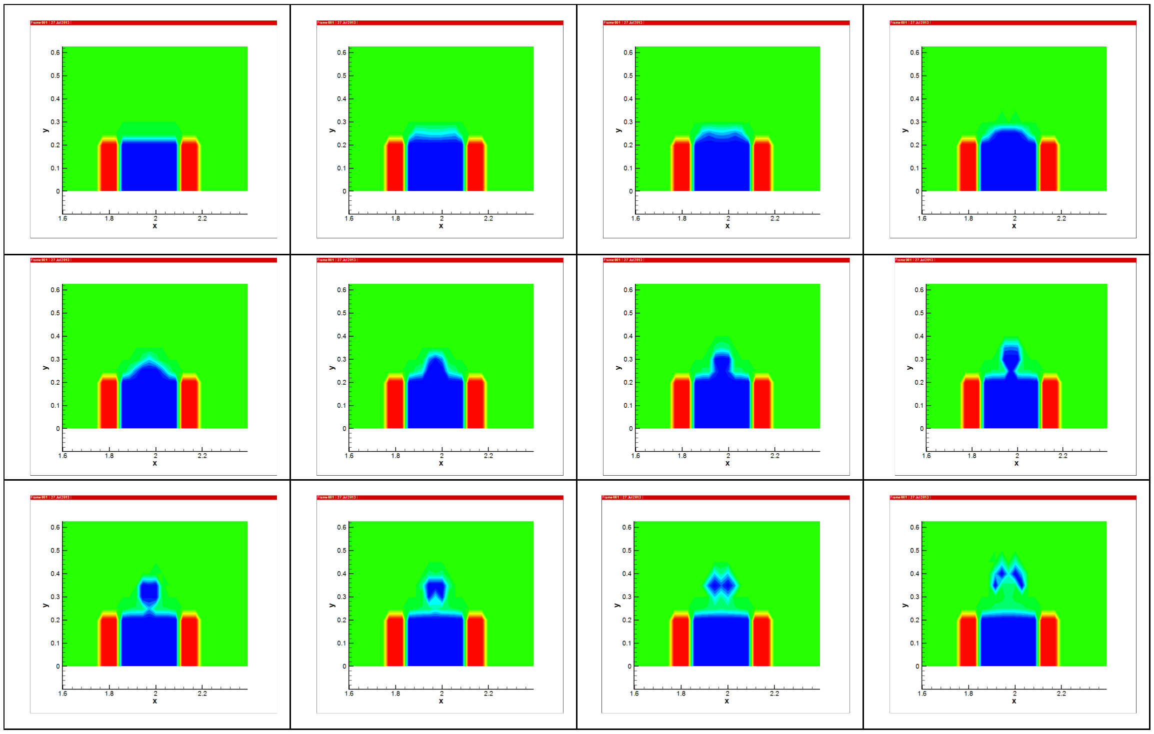


Figure 4.trend of formation of the first bubble for D_{or}=2.5mm and U_{or}=0.5cm/s

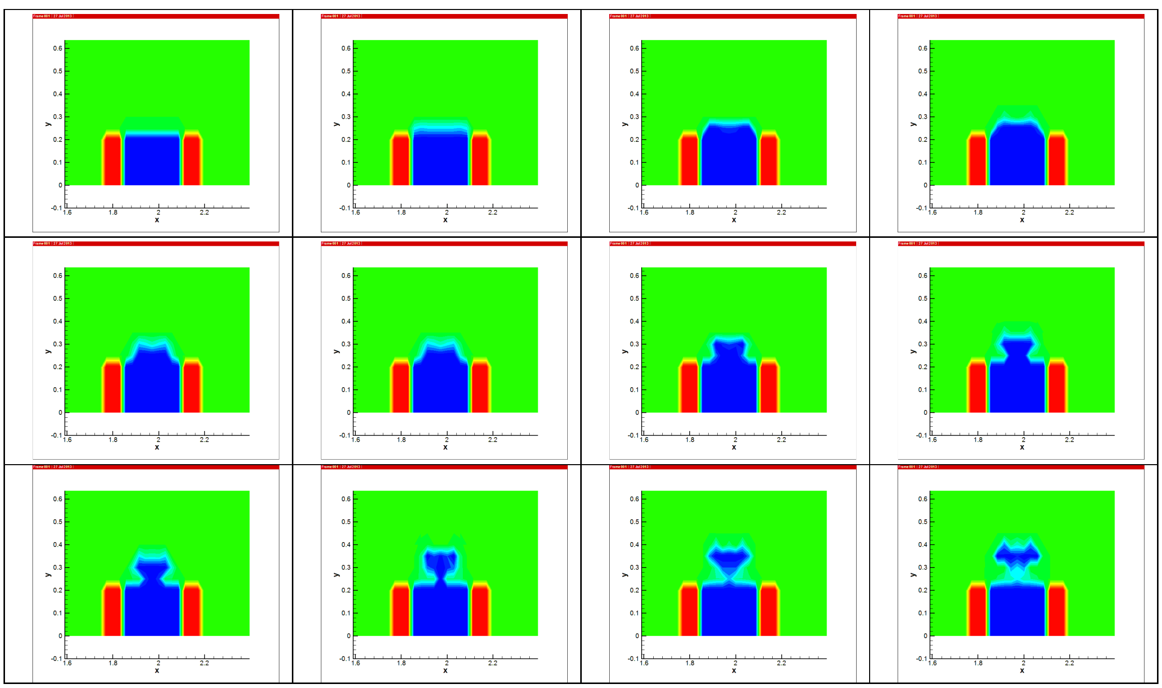


Figure 5.trend of formation of the first bubble for Dor=2.5mm and Uor=1 cm/s

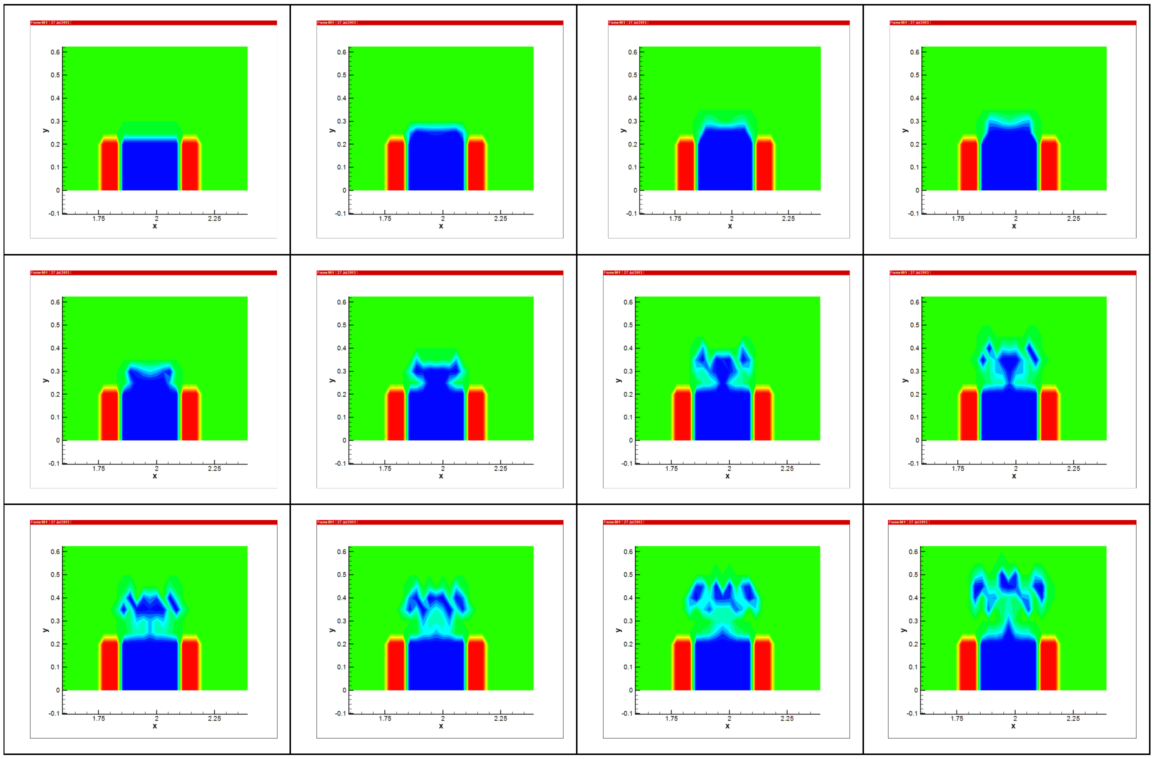


Figure 6.trend of formation of the first bubble for D_{or}=2.5mm and U_{or}=1.5cm/s

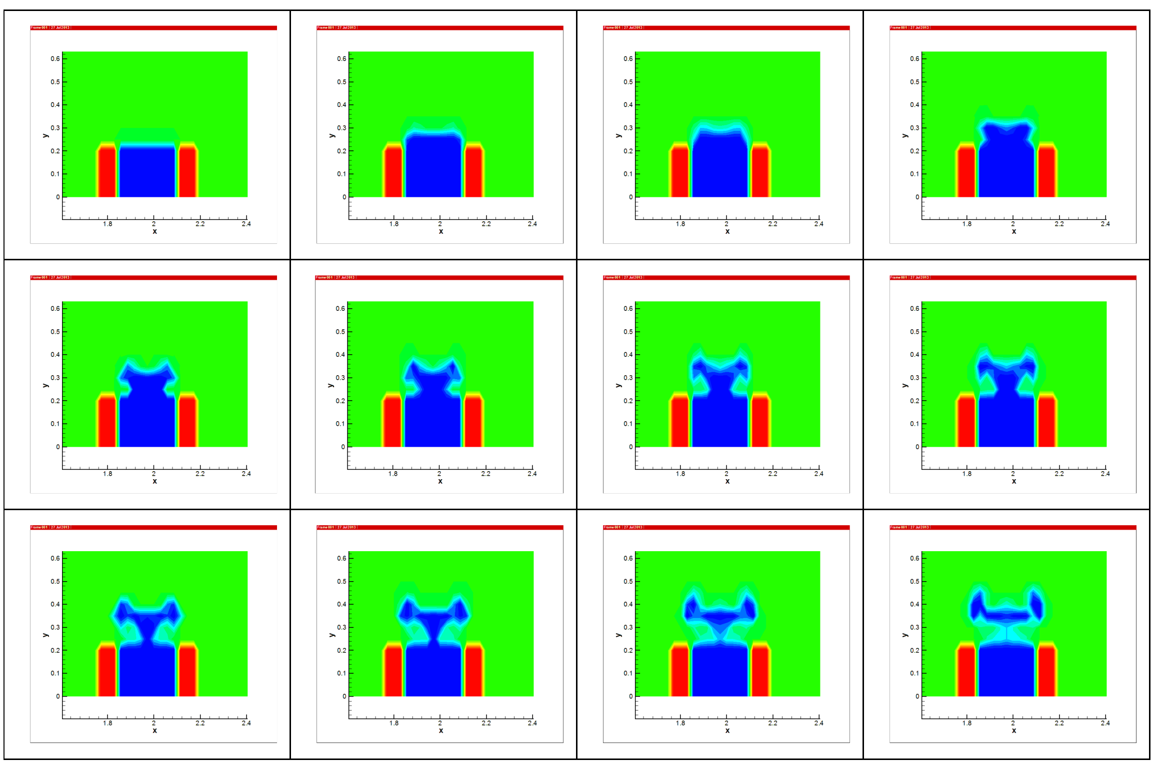


Figure 7.trend of formation of the first bubble for Dor=2.5 mm and Uor=2 cm

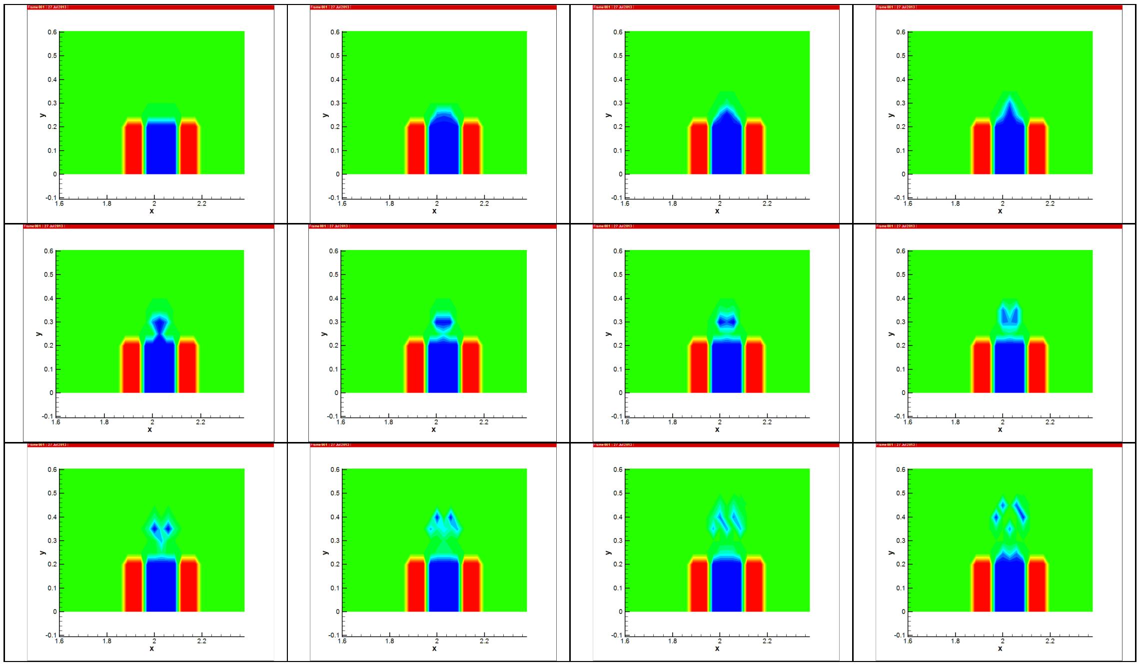


Figure 8.trend of formation of the first bubble for Dor=1.5 mm and Uor=0.5 cm/s

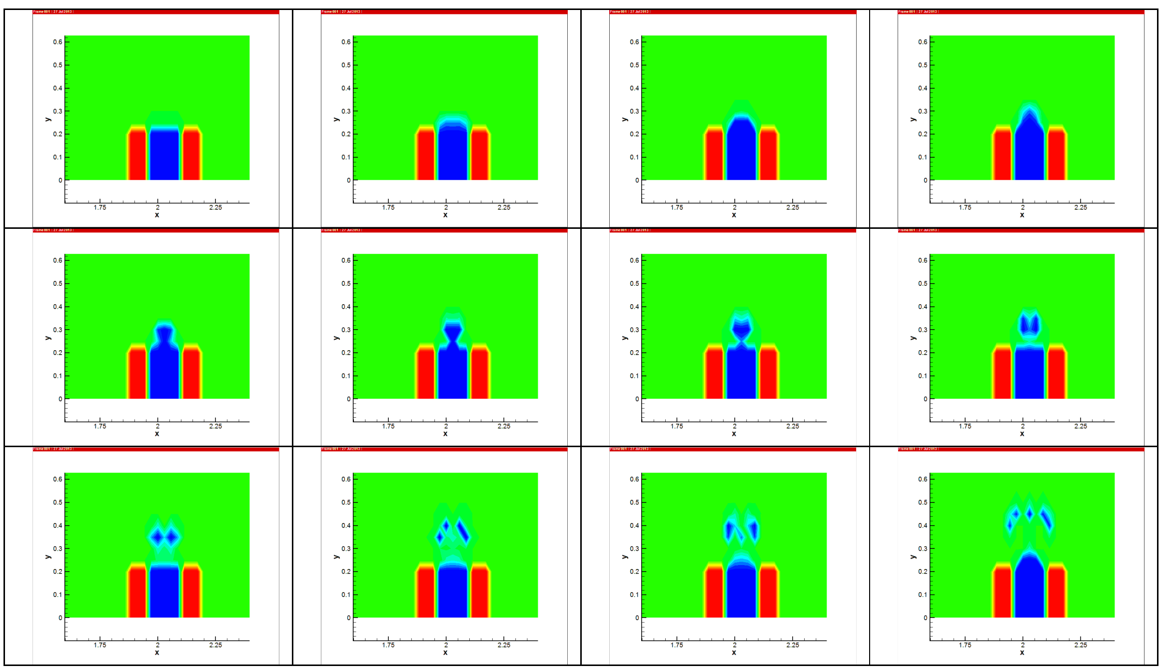


Figure 9.trend of formation of the first bubble for Dor=1.5mm and Uor=1 cm/s

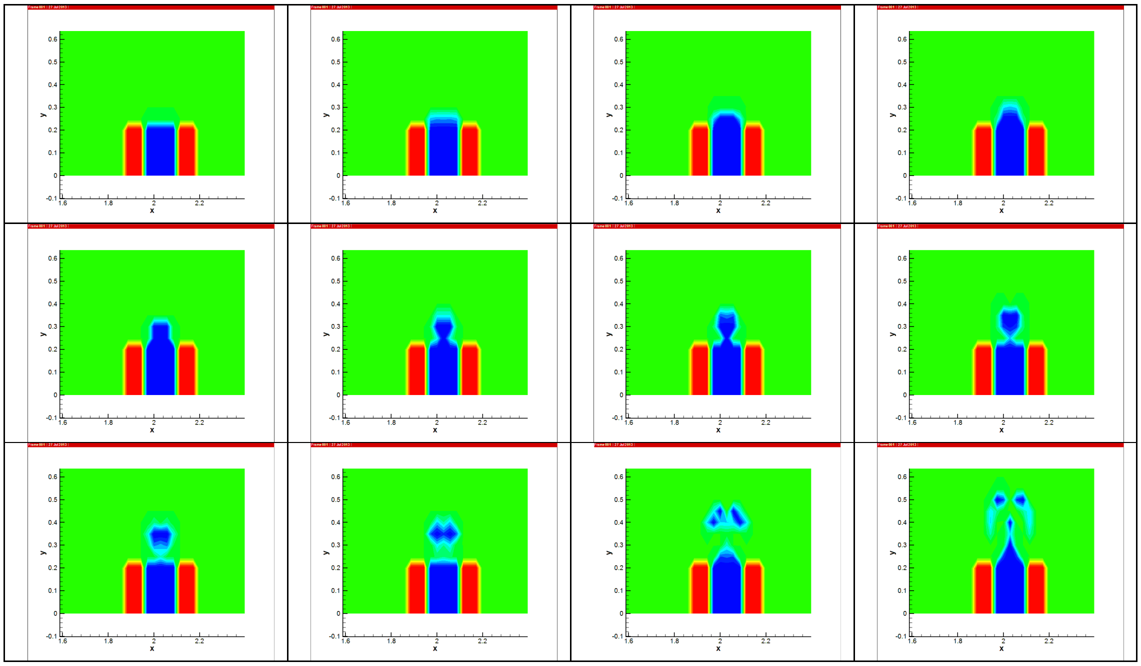


Figure 10.trend of formation of the first bubble for Dor=1.5mm and Uor=1.5 cm/s

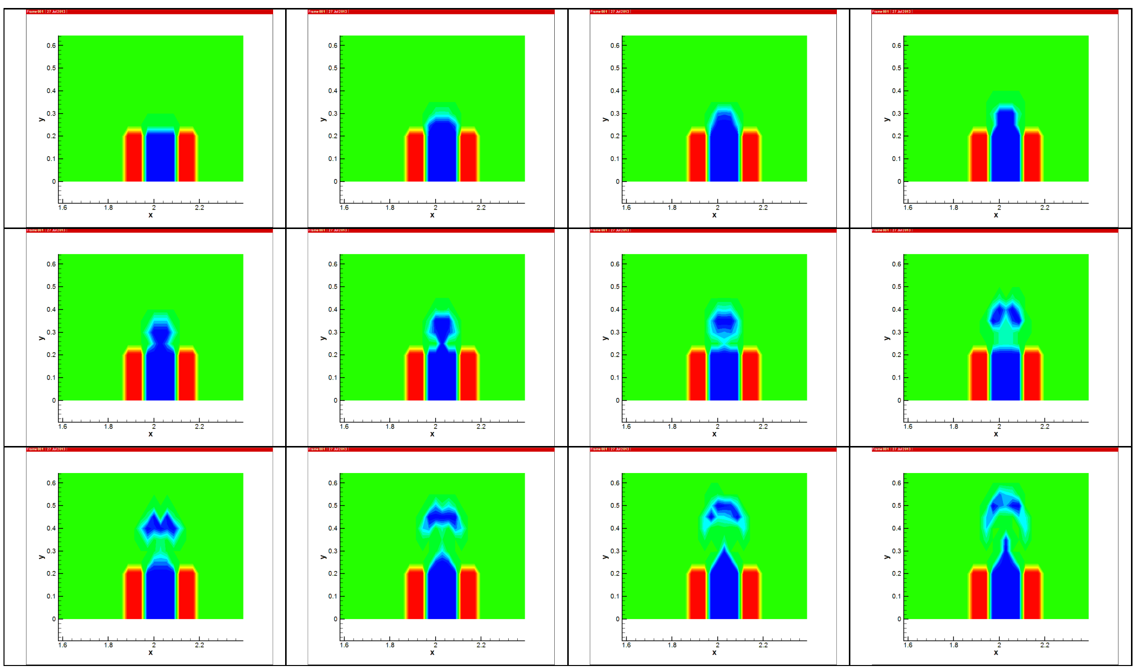


Figure 11.trend of formation of the first bubble for Dor=1.5mm and Uor=2 cm/s

Figures above indicate trend of formation of bubble from start of process and insert of air into fluid till separation of bubble from orifice and its ascend in fluid. As it can be seen, after separation of the first bubble, the second bubble starts forming immediately. Further, the bubble is fragmented and moves upwards in the next stage but it does not happen in action possibly. This might be as a result of accumulation of rounding error in numerical solution process. This phenomenon takes place in all computer programs which model a transient process after conduct of a large number of solution stages.

Conclusion

In this process, bubble formation process was simulated in a cylindrical container including an orifice submerged in waste water. This simulation made use of SOLA-VOF numerical method and Nicole's numerical code. In this process, two orifices with diameters equal to 2.5 and 1.5 millimeters and input gas rate was assumed to be very low and equal to 0.5, 1, 1.5 and 2 centimeters per second. Furthermore, the influence of change in coefficient and power of power law (in power law method for non-Newtonian fluid) on the process of bubble formation was investigated. The following results were obtained:

1. As speed increases, bubble volume increases and bubble formation time is decreased.
2. As nozzle diameter increases at a fixed rate, bubble volume is increased.
3. Trend of reduction in bubble formation time by increasing speed in nozzles with 2.5 millimeters is smaller than that of nozzles with diameter equal to 1.5 centimeters.
4. The figure obtained from SOLA-VOF code indicates that as bubble is separated from orifice head, bubble shape goes from spherical form to cap form. Ascend of the bubble in the column is continued by its breaking into several finer bubbles.

Recommendations

1. Calculation format was two-dimensional and cylindrical in this research; this research is recommended to be conducted in spherical format too.
2. Multi-nozzled systems should be studied.
3. Mass transfer and calculation of mass transfer coefficients can be investigated in this regard.
4. Other equations governing non-Newtonian fluids like Bingham and … should be studied.
5. Investigation of optimum diameter and speed for formation of bubbles which are small enough and form fast will be useful for practical cases.

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