 

# Effects of Polymeric Additives on Vapor Bubble Dynamics in Thermal Ink Jet Printing

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## Abstract

We have reported earlier (IS&T's NIP13) the stabilisation of the ink jet in the flight by means of polymeric additives. On the other hand it was shown theoretically that polymeric additives can influence on vapor bubble dynamics, in particularly they can reduce the bubble growth and (or) collapse. In dependence on different factors this reduction may lead to some jet velocity losses but in the same time it may lead to suppression of cavitation damage of the heater surface. To experimental observation of discussed phenomena the visualisation of vapor bubble growth and collapse in different polymeric fluids was carried out. The polyacrylamide solutions of molecular mass of 500,000 -11,000,000 and concentrations of 0 - 6 % were studied. It was found that only high concentrations of polymer solution causes the considerable reduction of bubble growth and collapse in comparison with pure solvent. These concentrations far exceed the concentrations which provide the most appropriate stabilisation effect on jet flight. In all other investigated cases the bubble dynamics is well described by Rayleigh theory and does not differ significantly from one of pure solvent. Therefore there is the range of polymer parameters which provides the jet stabilisation without the variance in vapor bubble dynamics.

## Introduction

Polymeric additives cordially modify the process of microjet ejection from the nozzle [1]. Usually the jet of standard ink consists of the prime drop and the long thin tail which then can disintegrate into the number of secondary small droplets (Fig. 1a). The polymeric additives can cause the long jet to compress into the single drop without any losses of the liquid in the flight (Fig. 1b). On the other hand in thermal ink jet printing the jet ejection results from rapid vapor bubble growth and its following collapse. The polymeric additives can modify this cavitation process too. In particular the effect of polymeric additives will be negative if some jet velocity losses take place. In the same time the some retardation of the final stage of the bubble collapse may have positive effect because probably the cavitation damage of the thermoheater is the dominant factor which defines the lifetime of printhead [2].


*Figure 1. The jets of the standard ink (a) and polyacrylamide solution of concentration of 100 p.p.m. and molecular mass of 2,000,000 (b). Jet motion is from right to left. Longitudinal frame size corresponds to 2 mm. The flight time is 140 μs.*

It is well known that high molecular polymeric additives to water affect cavitation phenomena [3]. Available experimental data are contradictory. In particular, polymeric additives increase the rate of vibrator cavitation erosion of materials [4], but suppress the cavitation erosion in bulk flow [5]. Two mechanisms of polymeric influence were suggested. First one is the change of the flow velocity field. The second one is the suppression of individual bubble collapse. A number of theoretical studies predict the arrest of bubble collapse at the final stage [6-8]. However, the direct observations of bubble collapse do not detect the collapse retardation. For instance, it was concluded that the collapse rate in a concentrated polymer solution is larger than in a viscous liquid of the same viscosity [6]. Observations of the growth and collapse of bubbles generated by a laser pulse in a polymer solution indicated the bubble behaviour similar to a pure solvent [9]. To account for the contradiction between the theory and experiment, G. Ryskin proposed that experimental conditions did not correspond to the situation when fluid elasticity dominates the process. He remarked that the bubble radius should be much smaller in order that the predicted effect could be detectable [6].

The present work was undertaken to investigate the growth and collapse of bubbles of relatively small diameters. The small bubble scales lead to very high extensional rates in the bubbles' collapse. So there is the hope that a strong extension will cause the appearance of significant elastic stresses in the fluid, which will have a pronounced effect on bubble collapse process.

 

## Theory

To estimate the influence of polymeric additives on the process of bubble collapse, the spherically symmetric motion is considered. Present consideration is similar to the one for a viscous fluid [10] and some models of elastoviscous fluids [6-7]. The flow is radial in the spherical coordinate system $(r,\theta,\varphi)$: $v_r = v(r)$, $v_\theta = v_\varphi = 0$, $dR/dt = v_R$, where $v$ is the fluid velocity, and $R = R(t)$ is the bubble radius. The equations of motion are:

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r}\right) = -\frac{\partial p}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{rr}) - \frac{\tau_{\theta\theta} + \tau_{\varphi\varphi}}{r}, \quad \tau_{\theta\theta} = \tau_{\varphi\varphi},$$

$$\frac{\partial}{\partial r}(r^2 v) = 0, \tag{1}$$

where $p$ is the pressure, $\tau$ is the deviatoric stress tensor.

The Oldroyd-B model is used for modelling of the polymer solution rheological behavior. Stress tensor is connected with deviatoric stress tensor by relation:

$$\sigma = -p\boldsymbol{I} + \tau = -p\boldsymbol{I} + 2\mu\boldsymbol{E} + G\boldsymbol{A} \tag{2}$$

The elastic strain tensor $\boldsymbol{A}$ is defined by the kinetic equation

$$\frac{D\boldsymbol{A}}{Dt} = \boldsymbol{A}\bullet\nabla\boldsymbol{v} + \nabla\boldsymbol{v}^T\bullet\boldsymbol{A} - \frac{1}{\theta}(\boldsymbol{A} - \boldsymbol{I}), \tag{3}$$

where $\sigma$ is the stress tensor, $p$ is the pressure, $\mu$ is the shear viscosity, $G$ is the elasticity modulus, $\boldsymbol{E}$ is the strain rate tensor, $\boldsymbol{I}$ is the unit tensor, $t$ is the time, $\nabla v$ is the velocity gradient, and $\theta$ is the relaxation time.

A strong convergent flow in the final stage of the bubble collapse causes the appearance of axial elastic stresses that act against the collapse. Deformation and stress states are described by tensors $\boldsymbol{E}$, $\boldsymbol{A}$ which have the components:

$$\boldsymbol{E} = \begin{vmatrix} \frac{\partial v}{\partial r} & 0 & 0 \\ 0 & \frac{v}{r} & 0 \\ 0 & 0 & \frac{v}{r} \end{vmatrix} \qquad \boldsymbol{A} = \begin{vmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix} \tag{4}$$

Boundary conditions are:

$r = \infty \quad p = p_\infty \quad v = 0$

$$r = R \quad \sigma_{rr} = -p + 2\mu\frac{\partial v}{\partial r} + GA = \frac{2\alpha}{R} - p_v,$$

where $\alpha$ is the surface tension, $p_\infty$ is the pressure far away from the bubble, $p_v$ is the pressure within the bubble.

Integrating Eq.(1) from $r = \infty$ to $r = R$ and taking into account Eqs. (2), (4) and boundary conditions, one can obtain the equation of bubble motion:

$$\frac{1}{2R^2}\frac{d}{dR}(R^3\dot{R}^2) = -\frac{4\mu}{\rho}\frac{\dot{R}}{R} - \frac{2\alpha}{\rho}\frac{1}{R} + \frac{p_v - p_\infty}{\rho} - \frac{2G}{\rho}\int_\infty^R \frac{A}{r}dr \tag{5}$$

The solution of Eqs. (5) and (3) gives the description of the process of bubble collapse. The influence of elastic stresses is described by the last term of Eq. (5). It follows from Eq. (5) that elastic stresses prevent from an acceleration of bubble collapse. The numeric calculations show that there is a small influence of polymeric additives on bubble dynamics for large radius of bubble, whereas a final stage of bubble collapse strongly depends on the polymer effect. A simple estimate for the final stage of bubble collapse may be obtained without explicit solution of Eq. (5). Indeed, let us consider the final stage of the bubble collapse when $R << R_0$, where $R_0$ is the initial radius of the bubble. In this stage very high deformation rates take place. Therefore it is possible to suppose that high elastic deformations are stored in the liquid: $\boldsymbol{A} >> 1$. In this case the following estimate takes place:

$$R(t) \geq \frac{GR_0\exp(-t/\theta)}{\frac{2}{3}(p_\infty - p_0) + \frac{2\alpha}{R_0}} \tag{6}$$

Hence, the final stage of bubble collapse lasts down to infinity. It means that the kinetic energy is dissipated intensively on the final stage. Of course, other real physical factors modify the developed model, and a bubble lifetime is finite. But it is clear from the presented analysis that polymeric additives further an additional dissipation of the kinetic energy at the final stage of bubble collapse. Therefore the resulting pressure waves in the liquid can be relaxed and consequently the cavitation damage of the thermoresistor can be made weaker.

## Experiment

Our goal was to produce and observe a single vapor bubble of relatively small size. The experimental apparatus is shown schematically in Fig. 2. The main unit is a bowl filled with the tested fluid. A small heater is mounted in the bottom of the bowl. The heater is a plane thermoresistor 100×100 μm square. It can supply a heat pulse of a few tens microJoules. The heat pulse provides the superheating of the fluid in close vicinity to the heater. The vapour bubble is generated as a result of fluid superheating. The bubble growth is eliminated by very fast heat losses. The temperature in the bubble becomes close to the ambient temperature after a few microseconds after the process begins.

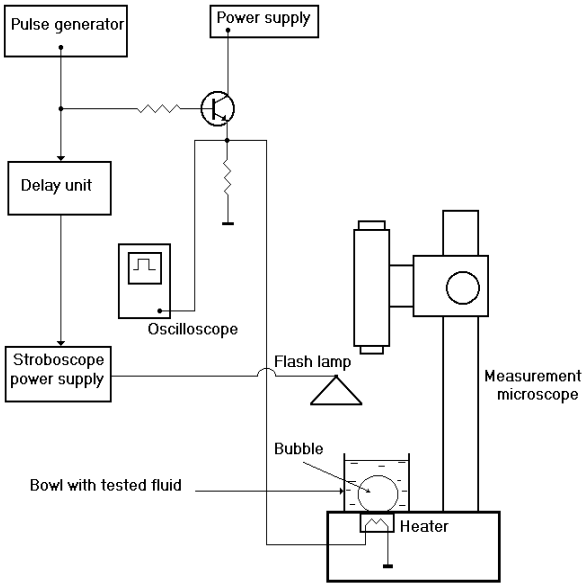


*Figure 2. The principal scheme of experimental set up.*

The transistor triggered by the pulse generator applies the voltage to the heating element. This pulse is monitored at the oscilloscope. Lighting includes flash lamp controlled by the generator. The signal from the pulse generator passing the variable delay unit triggers the flash lamp. The duration of strobing flashes is 1 μs approximately, and the frequency is up to 1500 Hz.

Due to a constant phase shift between the heat and light pulses, the different stages of bubble growth and collapse were visualised. The bowl is mounted on an x/y stage (with 1 μm accuracy of positioning) of a measurement microscope. The microscope was used for direct measurements of the bubble diameter. To avoid an accumulation of gas and a formation of gas bubbles, all experiments were carried out under low frequency (1 Hz and lesser) of pulse repetition.

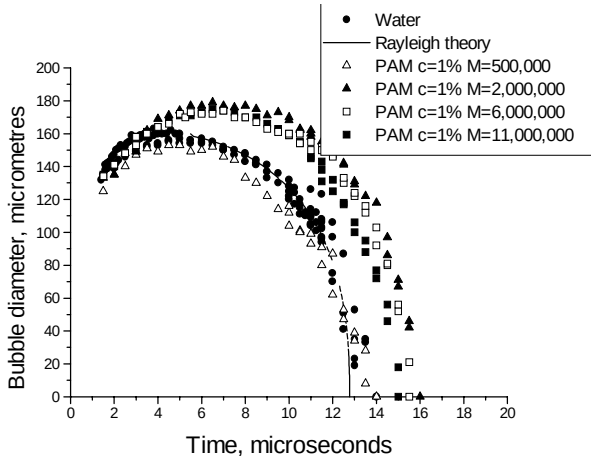


*Figure 3. The dependence of vapor bubble diameter versus time for polyacrilamide solutions of concentration of 1% and different molecular masses.*

Hence the empty cavity of a very small dimension is created in the fluid. The presented technique allows the monitoring of the bubble collapse history. The result of the observations are shown in Fig. 3 and Fig. 4. They represent the dependencies of the measured bubble diameters as a function of time.

## Results and Discussion

The comparison of the results with ones for pure water and predictions of the Rayleigh theory shows good interdependencies. The established fact states the possibility of modeling of a single bubble collapse by means of the presented method.

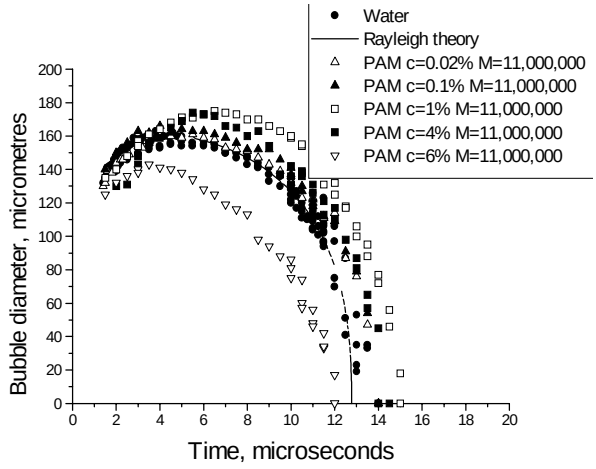


*Figure 4. The dependence of vapor bubble diameter versus time for polyacrilamide solutions of molecular mass of 11,000,000 and different concentrations.*

The water solutions of polyacrylamide of a wide range of molecular masses and concentrations were investigated. The experiments did not detect a significant retardation of the collapse. Fig. 3 represents the influence of molecular mass, and Fig. 4, the influence of concentration. As it is seen from the graphs, there are no significant differences between the behavior of the bubbles in the water and in the polymeric fluid. Some increase of bubble maximum diameter, in the case of intermediate concentrations, is probably connected with the difference of the thermo-physical properties of the polymeric fluid and water. However, the further decrease of the maximum diameter with increasing concentrations can be considered as some indication of retardation of bubble collapse under the action of elastic stresses. The same conclusions can be made with respect to the decrease of the maximum diameter with the decrease of molecular mass. Indeed, it is well-known that elasticity modules grow with the increase of concentrations and the decrease of molecular mass. Hence, the above mentioned feature of the experimental curves may be considered as a qualitative confirmation of the prediction of the formula (6). Therefore the polymeric additives do not influence on vapor bubble growth and consequently on ejection velocity. Observed difference in displacement of the jets of ink and polymeric liquid (Fig. 1) is caused by

compression of the whole polymeric liquid into a single drop and by some velocity losses resulting from isolation of the jet from the nozzle. The isolation occurs no sooner than after 50μs from beginning of the ejection (see Fig. 5).

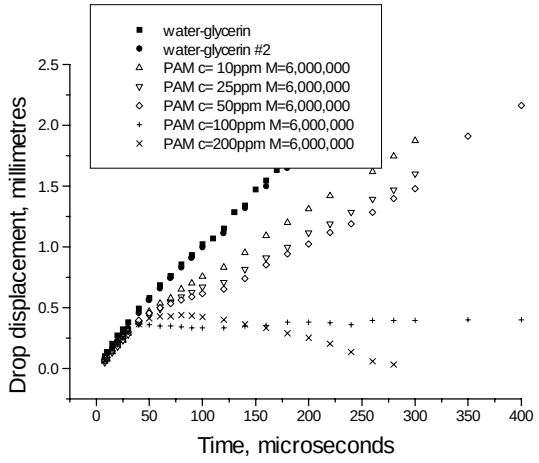


*Figure 5. Flight displacement of a drop of polyacrylamide solution of molecular mass of 6,000,000 and different concentrations.*

It should be mentioned that the formation and collapse of the bubble in the vicinity of the rigid wall leads to some axial non-uniformity of the fluid deformation. It is possible to consider only average values. In particular, it is possible to suggest that the deformation distribution in the fluid in the experimental situation is close to one which takes place in the case of an infinite sea of fluid, if the initial diameter of the bubble is equal to $R_0 \approx a/2\pi$ ($a$ is the size of heater).

Let us estimate the magnitude of the possible polymeric additives effect using available rheological data. Previously, the experiments with a polyacrylamide solution (molecular mass is 11,000,000) [11] give the values of an elasticity modulus of 87-285 Pa for concentrations of 2-6%. In accordance with (6), the retardation of the collapse can take place at the level of $R/R_0 \approx 0.03$. Consequently, the predictions based on numerical data of [11] do not predict the effects which can be observed by means of available technique.

## Conclusions

The theoretical and experimental investigations show that the polymeric additives (in the range of molecular parameters which provides the stabilisation of jet) do not influence on the bubble growth and jet expelling. On the other hand the theoretical estimates show that polymeric additives can decrease the cavitation damage of the thermoheater.

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## Biography

Aleksey Rozhkov received his M.S. in Physics from Moscow Physical Technical Institute in 1978 and Ph.D. in Fluid Mechanics from The Institute for Problems in Mechanics of Russian Academy of Sciences in 1985. His current research interests include rheology, processes of jet and film high speed flows, flows through porous media, shock disintegration of viscous and elastoviscous liquids,foam motion; development of devices for rheology and capillary testing. He is currently head of Laboratory of Applied Continuum Mechanics at The Institute for Problems in Mechanics of Russian Academy of Sciences.

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