Journal of Engineering Physics and Thermophysics, Vol. 66, No. 1, 1994

EFFECT OF DIFFERENT PARAMETERS ON THE FRAGMENTATION OF A VISCOELASTIC LIQUID COLUMN EJECTED FROM A CIRCULAR CHANNEL BY A COMPRESSED GAS

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UDC 532.525

A fractional factorial experiment is performed to investigate the efficiency of the fragmentation of a viscoelastic liquid column ejected from a circular channel by a compressed gas. As a result, regression relations are constructed that take into account the effect of the geometric dimensions of the channel, the difference between the pressures of the ejected liquid and of the environment, and the physical properties of both the homogeneous and the heterogeneous viscoelastic liquid at the mean level of "discreteness" of the droplets forming a spray cone.

The application of viscoelastic liquids for solving different engineering problems necessitates a quantitative evaluation of the effect exerted by the parameters that determine the process of their fragmentation on the sizes of the droplets formed. In [1], the main theoretical principles on which the process of fragmentation of a viscoelastic column is based are presented. The conditions for the practical realization of the process of fragmentation vary in a wide range; therefore the necessity arises for further experimental investigations to specify the existing theoretical concepts and estimate their adequacy to real processes.

Based on the theoretical concepts presented in [1] as applied to the conditions of the problem in question, the parameters that affect the process of fragmentation were determined. These are: τ_0, the limiting internal stress of the spatial structure; D, the diameter of the channel; L, the length of the channel; and Δp, the difference between the pressures of the ejected liquid and the environment. The totality of these parameters, without account for the properties of the gas affecting the destruction, fully characterize the process of fragmentation of a homogeneous viscoelastic liquid column. For a heterogeneous viscoelastic liquid it is necessary to take into account additionally such a parameter as Π, which is the percentage condensed phase (powdery additives).

As an output parameter for estimating the efficiency of fragmentation, the mean level of the "discreteness" of the droplets formed was selected, which is calculated from the relation

$$\gamma = \frac{\sum_{i=1}^{n_0} S_{k_i}}{\sum_{i=1}^{n_0} V_{k_i}} = \frac{\sum_{i=1}^{n_0} S_{k_i}}{V_{\text{col}}}.$$

The experimental setup incorporates an air receiver, a test pressure gauge, a solenoid-operated pneumatic valve, a test channel, a device for fixing the test channels, and a screen collector. Through the pneumetic valve, the test channel is connected with the receiver whose pressure is controlled by the gauge. The volume of the receiver ensures a constant pressure difference between the ejected liquid and of the environment in the process of viscoelastic fluid column motion through the channel. The relative change in the volume of the pneumatic system does not exceed 0.5%. Throttling on the open pneumatic valve is absent. At a distance of 2.0 m from the tip of the test channel a screen collector with a graticule is installed.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 1, pp. 24-29, January, 1994. Original article submitted February 22, 1993.

Arriving at the screen collector, the droplets formed in the fragmentation of the viscoelastic liquid column are sheared and are stably preserved in such a form.

The size of the droplets is determined from their deformed imprints in the following sequence:

- grouping of the deformed droplets together by characteristic sizes and calculation of their quantities in groups;
- selection of a control batch from each group for weighing on an analytical balance;
- calculation of the volume of droplets by their mass assuming that they are spherical in shape;
- control of the accuracy of statistical processing by comparing the overall volume of droplets and the volume of the ejected viscoelastic liquid column.

The experimental investigation was divided into two stages. In the first stage we investigated the fragmentation of a column of homogeneous viscoelastic liquid. As the basic levels of the parameters affecting the process, the following values were selected: $L = 0.28$ m; $D = 0.013$ m; $\tau_0 = 0.9 \cdot 10^3$ Pa; $\Delta p = 0.75$ MPa.

With account for the conditions of the experiment, for each of the parameters the mean range of variation was selected which determined the limits of the investigated region of the factorial space: $L \in 0.20 \ldots 0.36$ m; $D \in 0.010 \ldots 0.016$ m; $\tau_0 \in (0.5 \ldots 1.3) \cdot 10^3$ Pa; $\Delta p \in 0.5 \ldots 1.0$ MPa.

To reduce the scope of investigations, we minimized the number of experiments. According to [2], from a full factorial experiment 2^4 we selected a half-replica 2^{4-1} which had the following system of mixing

$$b_1 \to \beta_1 + \beta_{234}; \quad b_3 \to \beta_3 + \beta_{124};$$

$$b_2 \to \beta_2 + \beta_{134}; \quad b_4 \to \beta_4 + \beta_{123}.$$

All of the basic effects β_1, β_2, β_3, and β_4 are evaluated independently of one another and are supplemented only with the effects of triple interaction β_{234}, β_{134}, β_{124}, β_{123}. Analysis of the prior information shows that in the investigated region of the factorial space the sought-after model should be linear; therefore all of the pairwise interactions, not to mention triple ones, will be insignificant and, consequently, $b_1 \approx \beta_1$, $b_2 \approx \beta_2$, $b_3 \approx \beta_3$, $b_4 \approx \beta_4$.

In accordance with the half-replica selected, a planning matrix was constructed and an experiment was conducted; the results are presented in Table 1.

Statistical processing of the experimental results led to a regression model of the form

$$\gamma = 9.36 - 0.89\,\overline{D} - 0.91\,\overline{L} + 1.01\,\overline{\Delta p} - 0.70\,\overline{\tau}_0, \tag{1}$$

where γ is the mean level of "discreteness" of the droplets: $\overline{D}$, $\overline{L}$, $\overline{\Delta p}$, $\overline{\tau}_0$ are the relative values of the parameters.

Checking of the regression coefficients for regression by Student's t-criterion showed that all of the coefficients are significant. The characteristic of the mean spread of experimental points about the regression line is the variance of the model adequacy, which is equal to $S^2_{\text{ad}} = 0.1$. According to the Fisher criterion, the significance of the regression model constructed amounts to 95%.

Analysis of the regression model shows that to increase the mean level of "discreteness" of the droplets, which corresponds to a decrease in their size, it is necessary to reduce the diameter D and length L of the channel, as well as the limiting internal shear stress of the spatial structure τ_0 preserving the constancy of the difference between the pressures of the ejected liquid and the environment, or to increase the difference between the pressures of the ejected liquid and of the environment preserving the constancy of the remaining parameters.

The set of parameters D, L, and τ_0 characterizes the overall "elastic" energy of the spatial structure volume which prevents the destruction of the viscoelastic liquid column. The energy of the gas jet spent for the fragmentation of the viscoelastic liquid column is determined by the relation

$$E = \frac{1}{2}(v_{\text{g}}^2 - v_{\text{d}}^2)\, m_{\text{g}}, \tag{2}$$

TABLE 1. Matrix of Planning and the Results of the First Stage of Experimental Investigations

No. of test	Random order of realization	x_1		x_2		x_3		x_4		x_0	$y \cdot 10^{-2}$, m^{-1}	$\bar{y} \cdot 10^{-1}$, m^{-1}
		code	m	code	m	code	MPa	code	Pa, 10^3			
1	2 9	+	0.016	+	0.36	–	0.5	–	0.5	+	7.41 7.21	7.31
2	6 13	–	0.010	–	0.20	–	0.5	–	0.5	+	10.65 10.35	10.50
3	1 15	+	0.016	–	0.20	–	0.5	+	1.3	+	7.87 7.67	7.77
4	7 10	–	0.010	+	0.36	–	0.5	+	1.3	+	7.92 7.68	7.80
5	3 16	+	0.016	+	0.36	+	1.0	+	1.3	+	7.59 7.45	7.52
6	8 14	–	0.010	–	0.20	+	1.0	+	1.3	+	11.61 11.45	11.53
7	4 12	+	0.016	–	0.20	+	1.0	–	0.5	+	11.38 11.14	11.26
8	5 11	–	0.010	+	0.36	+	1.0	–	0.5	+	11.27 11.03	11.15

where E is the energy of the gas jet; v_g is the initial velocity of the gas jet; v_d is the velocity of the gas jet decelerated as a result of interaction with the viscoelastic liquid column; m_g is the mass of the gas jet entering into interaction with the viscoelastic liquid column.

The initial velocity of the gas flow escaping from the channel is determined by its temperatuere and chemical composition, as well as by the channel profile. The test channel has a constant profile along its length. The process of fragmentation is investigated within the range of pressure differences $\Delta p \in 0.5 \ldots 3.5$ MPa that ensure a critical velocity of gas outflow equal to the local speed of sound [3]

$$v_g = a_{cr} = \sqrt{\left(\frac{2k}{k+1} RT_0\right)}, \tag{3}$$

where k is the specific heat ratio of the outflowing gas; T_0 is the gas jet stagnation temperature; R is the gas constant of the outflowing gas.

The mass of gas entering into interaction with the viscoelastic fluid column for the time from the instant of escape of the column from the channel to its fragmentation is determined by the relation

$$m_g = \int_{t_{es}}^{t_{fr}} \frac{\Gamma(k)\, S_{ch}}{\sqrt{RT_0}} \Delta p dt, \tag{4}$$

where t_{es} is the time of viscoelastic liquid column escape from the channel; t_{fr} is the time of fragmentation of the viscoelastic liquid; S_{ch} is the cross-sectional area of the channel; $\Gamma(k) = \sqrt{k(2/(k+1))^{(k+1)/(k-1)}}$ is the functional dependence on the specific heat ratio.

Simultaneous solution of Eqs. (2)-(4) determines the following dependence for calculating the gas jet energy spent for the fragmentation of the viscoelastic liquid column

TABLE 2. Matrix of Planning and the Results of the Second Stage of Experimental Investigation

No. of test	Random order of realization	x_1 code	x_1 Pa, 10^3	x_2 code	x_2 %	x_3 code	x_3 MPa	x_4 code	x_4 m	x_5 code	x_5 m	x_0	$\gamma \cdot 10^{-2}$, m^{-1}	$\bar{\gamma} \cdot 10^{-2}$ m^{-1},
1	2 9	+	1.4	–	70	+	3,5	+	0.006	+	0.2	+	16.69 16.53	16.61
2	6 13	–	1.0	–	70	+	3.5	–	0.002	–	0.1	+	31.25 31.05	31.15
3	1 15	+	1.4	–	50	+	3.5	+	0.006	–	0.1	+	16.31 16.15	16.23
4	7 10	–	1.0	–	50	+	3.5	–	0.002	+	0.2	+	22.67 22.49	22.58
5	3 16	+	1.4	–	70		2.5	–	0.002	–	0.1	+	27.75 27.55	27.65
6	8 14	–	1.0	–	70		2.5	+	0.006	+	0.2	+	18.41 18.27	18.34
7	4 12	+	1.4	–	50		2.5	–	0.002	+	0.2	+	18.75 18.61	18.68
8	5 11	–	1.0	–	50		2.5	+	0.006	–	0.1	+	17.70 17.56	17.62

$$E = \left(\frac{k}{k+1} RT_0 - \frac{1}{2} v_d^2 \right) \int_{t_{es}}^{t_{fr}} \frac{\Gamma(k) S_{ch}}{\sqrt{RT_0}} \Delta p dt . \qquad (5)$$

Analysis of relation (5) shows that as applied to the conditions of the investigations carried out, the difference between the pressures of the ejected liquid and of the environment Δp characterizes the impact energy of the gas jet spent for the fragmentation of the spatial structure of the viscoelastic liquid column.

It was established from the results of the first stage of investigations that the relationship between the "elastic" energy of the space structure of the column and the destruction energy of the gas jet is the determining factor in the evaluation of the efficiency of the homogeneous viscoelastic liquid column fragmentation.

In the second stage, the fragmentation of the heterogeneous viscoelastic liquid was investigated. As the basic levels of the parameters, the following values were selected: $L = 0.15$ m; $D = 0.004$ m; $\tau_0 = 1.2 \cdot 10^3$ Pa; $\Delta p = 3.0$ MPa; $\Pi = 60\%$.

In selecting the basic level of the parameter Π, the fact that the ultimate admissible value of powdery additives amounts to about 80% was taken into account. When this value is exceeded, destruction of the internal space structure occurs; therefore, with account for the possible range of variations, the value $\Pi = 60\%$ is used in investigations in the most widely used range of content of the powdery additives.

The assignment of the range of variation for each of the parameters forms the region of the factorial space investigated: $L \in 0.1 \ldots 0.2$ m; $D \in 0.002 \ldots 0.006$ m; $\tau_0 \in (1.0 \ldots 1.4) \cdot 10^3$ Pa; $\Delta p \in 2.5 \ldots 3.5$ MPa; $\Pi \in 50 \ldots 70\%$.

As a matrix for planning the experiment, the quarter-replica 2^{5-2} was selected which has the following system of mixing

$$b_1 \to \beta_1 + \beta_{34} + \beta_{235} + \beta_{1245}; \quad b_2 \to \beta_2 + \beta_{45} + \beta_{135} + \beta_{1234};$$

$$b_3 \to \beta_3 + \beta_{14} + \beta_{125} + \beta_{2345}; \quad b_4 \to \beta_4 + \beta_{13} + \beta_{25} + \beta_{12345};$$

$$b_5 \to \beta_5 + \beta_{24} + \beta_{123} + \beta_{1345}.$$

In accordance with the planning matrix selected, an experiment was conducted whose results are presented in Table 2.

After the statistical processing of the results, a regression model of the following form was obtained:

$$\gamma = 21.1 - 3.91\,\overline{D} - 2.05\,\overline{L} + 0.54\,\overline{\Delta p} - 1.32\,\overline{\tau}_0 + 2.33\,\overline{\Pi}. \qquad (6)$$

where $\overline{D}$, $\overline{L}$,$\overline{\Delta p}$, $\overline{\tau_0}$, and $\overline{\Pi}$ are the relative values of the parameters.

All of the coefficients entering into Eq. (6) are significant. The variance of the adequacy of the model is $S^2_{\text{ad}} = 0.035$. The significance of the regression model (6) is 95% according to the Fisher criterion.

Analysis of relation (6) confirms the lines of the effect of the parameters $\overline{D}$, $\overline{L}$, $\overline{\tau_0}$, and $\overline{\Delta p}$ revealed in the first stage of investigations and shows that an increase in the percentage of powdery additives leads to an increase in the mean level of "discreteness" of the droplets, i.e., to a decrease in their size.

This fact is explained by the decrease in the limit of the elastic deformation of the spatial structure on the introduction of a condensed phase into it. The reduction of the limit of elastic deformation leads to the decrease of the "elastic" energy that prevents the destruction of spatial structure.

As a result of the experimental investigations carried out, regression models are constructed which take into account the lines and intensity of the effect of geometric dimensions of the channel, the difference in pressure between the ejected liquid and the environment, as well as the physical properties of the viscoelastic liquid on the mean level of "discreteness" of the droplets formed during the fragmentation of its column ejected from a circular channel by a compressed gas. The application of the regression models constructed allows one, with a probability of 0.95, to predict the mean level of "discreteness" of the droplets from the values of the parameters in the investigated regions of factorial space. Analysis of the regression models shows that the relationship between the "elastic" energy of the internal spatial structure and the impacting energy of the gas jet affecting the destruction is the determining factor in the evaluation of the fragmentation of a viscoelastic liquid column ejected from a circular channel by a compressed gas.

NOTATION

τ_0, limiting internal shear stress of spatial structure; D, channel diameter; L, channel length; Δp, difference between pressures of ejected liquid and environment; Π, percentage of condensed phase (powdery additives); γ, mean level of "discreteness" of the droplets; V_{k_i} and S_{k_i}, volume and area of i-th droplet surface assuming that it has the shape of a sphere; V_{col}, volume of ejected viscoelastic liquid column; n_0, total number of droplets in spray cone; b, computed value of the coefficient of regression; β, true value of the coefficient of regression; E, gas jet energy; v, gas jet velocity; m_g, mass of gas jet entering into interaction with viscoelastic liquid column; k, specific heat ratio; a_{cr}, local speed of sound; T_0, gas jet stagnation temperature; R, gas constant; t, time; S_{ch}, cross-sectional area of channel; $\Gamma(k)$, functional dependence on specific heat ratio.

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