The break-up of jet in non-Newtonian systems

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Abstract

The phenomenon of break-up of jet into drops has been applied mainly to separation technologies in chemical, pharmaceutical, and metallurgical industries. The addition of polymers to a solvent can affect the breakup of jets. The length of jet is very important parameter for description of dispersion effect. Knowledge of the jet length has practical significance in fire fighting and cleaning of boiler pipes, where the large length of jet is desirable, as well as in combustion engine, where the short length of jet is recommended. The paper deals with the experimental analysis directed on the breakup of flexible, semi-rigid and rigid polymers solutions flowing through a ring-shaped orifice nozzle. Non-Newtonian effects on the break-up of a liquid jet into drops was studied using microphotography method. In the experiments the various aqueous solutions of carboxymethylcellulose sodium salt, polyacrylamide and xantan gum, have been used. The polymer solutions studied were inelastic power-law fluids. The observations were carried out at equivalent Reynolds number values in power-law fluids changed from 25 to 5900. An analysis of the photos of the jets break-up showed that the length of jets depends on both, liquid flow rate and type of polymer solutions used. High molecular polymers added to a solvent involve the changes in the rheological properties of liquid and the length of break-up of jets. For all polymer solutions used the length of jets was a function of Reynolds number for power-law fluids.

Keywords: break-up, jet, polymer solution, non-Newtonian system, nozzle

1. Introduction

The addition of polymers to a solvent can affect the breakup of jets. The break-up length is defined as the length of the continuous portion of the jet, measured from the nozzle to the break-up point where drop formation occurs. The length of jet is very important parameter for description of dispersion effect (Mun *et al*., 1998-1999, Harrison *et al*., 1999, Akimoto *et al*., 2004, Broniarz-Press *et al*., 2004). Knowledge of the jet length has practical significance in fire fighting and cleaning of boiler pipes, where the large length of jet is desirable, as well as in combustion engine, where the short length of jet is recommended.

The breakup of Newtonian jets is well understood and widely described by Levebvre (1989) and Orzechowski and Prywer (1991). The most striking difference observed for the breakup of non-Newtonian jets is the greatly increased breakup length. Investigations (Mun *et al*., 1998-1999, Liu H., 1999, Broniarz-Press *et al*., 2004-2006) have shown that jets of aqueous solutions of polymers unlike the Newtonian fluid jets do not break into drops, but form long threads of liquid connecting drops along the length of the jet. These threads are thinning further and finally break at distances much greater than for the Newtonian fluids. The analysis of literature data showed that the length of jets depends on both, liquid flow rate and type of polymer solutions used. High molecular polymers added to a solvent involve the changes in the rheological properties of liquid and the length of break-up of jets. A shorter breakup length was observed for an aqueous solution of polyacrylic acid, as Kroesser and Middleman (1969) have also reported, a shorter breakup length for a solution of polyisobutylene in tetraline.

2. Experimental

In the paper the experimental analysis directed to the break-up of polymers solutions flowing through a ring-shaped orifice nozzle, has been presented.

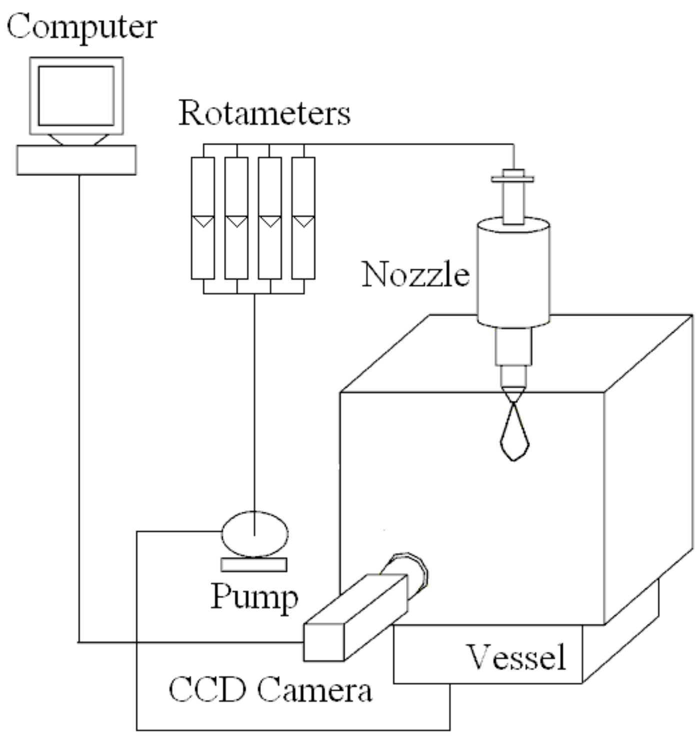

Fig. 1. Simplified scheme of test installation

The main elements of the test installation (Fig. 1) were ring-shaped orifice nozzle, reservoir, pump, measurement units of liquid flow and digital camera. The camera was a Konica-Minolta Dimage A-200 with exposure time of 1/1000 s placed directly in front of the nozzle at a distance of approximately 0.7 m. The automatic flash was used to provide a short period of illumination sufficient for a clear photograph to be taken. The Image Pro-Plus and Corel Draw 11 programs were used to analyze the length of jet. All experiments were conducted at 293±2 K. The surface tension was measured by tensiometer K9 manufactured by Krüss GmbH.

Three types of polymer molecule were considered in this work. Xantan gum (XG) was a rigid polymer, a semi-rigid was carboxymethylcellulose sodium salt (Na–CMC), and a flexible chain was characteristic for polyacrylamide (PAA) (Harrison *et al.*, 1999). The various aqueous solutions studied were power-law fluids

$$\tau_w = K(\gamma_w)^n \tag{1}$$

where τ_w is the wall shear stress, K describes the consistency index, γ_w is the shear velocity at a wall and n describes the flow index. These solutions presented different rheological behaviour. The characteristics of the media used is presented in Table 1.

Table 1. Characteristics of the media used

Liquid	Concentration	Density	Surface tension	Viscosity	Flow index	Consiste-ncy
	c_p [w.ppm]	ρ [kg·m^{-3}]	σ [N·m^{-1}]	η [Pa·s]	n	K [Pa·s^n]
Water	-	998.2	72.6	$1.0 \cdot 10^{-3}$	–	–
Aqueous solutions of Na–CMC	1000	998.4	72.0	–	0.63	0.075
	2000	998.4	70.2	–	0.61	0.217
Aqueous solutions of PAA	1000	998.4	71.2	–	0.68	0.031
	2000	998.4	70.8	–	0.52	0.174
Aqueous solution of XG	1000	998.4	69.3	–	0.59	0.071

Na–CMC – carboxymethylcellulose sodium salt, molecular weight of 700,000, producer PCC Rokita S.A.,
PAA – polyacrylamide (Rokrysol WF1), molecular weight of 4,400,000, producer PCC Rokita S.A.,
XG – xantan gum, producer Hortimex

The observations were carried out at Reynolds number values $Re_L \in (25, 5900)$ determined by formula (Metzner and Reed, 1955):

$$Re_L = \frac{u^{2-n} d^n \rho}{8^{n-1} K} \left(\frac{4n}{3n+1} \right)^n \tag{2}$$

where u is the mean volume velocity of a flow, d describes the nozzle diameter and ρ is the fluid density.

3. Results and discussion

The exemplary photographs illustrating the effects of polymer on the jet breakup are shown in Figs. 2, 3 and 4.

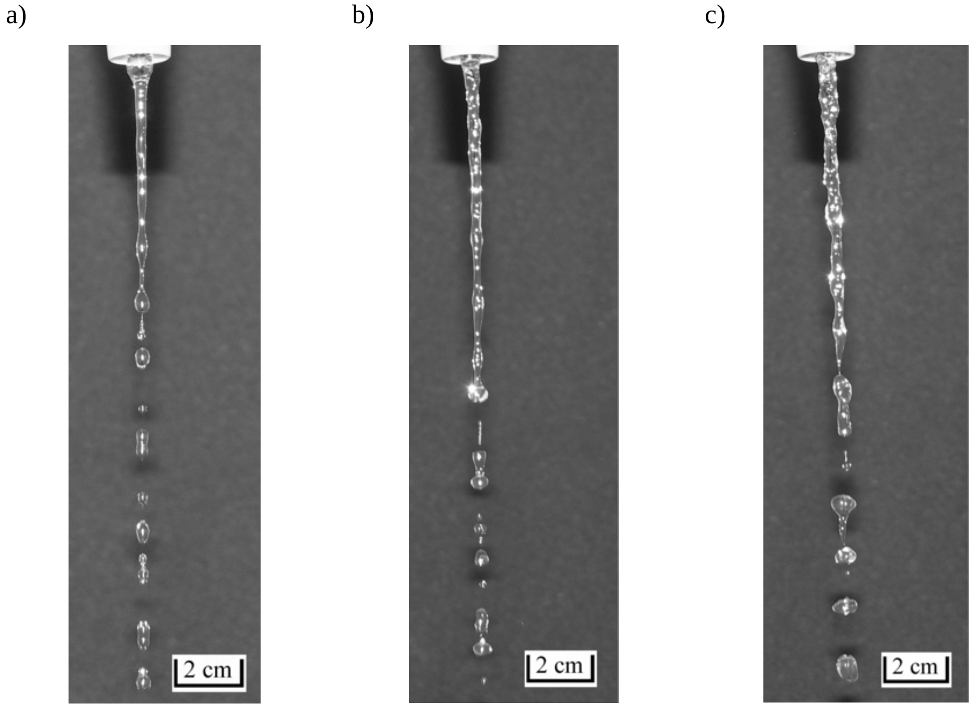

Fig. 2. Water jets: a) Re_L = 980, b) Re_L = 2940, c) Re_L = 4900

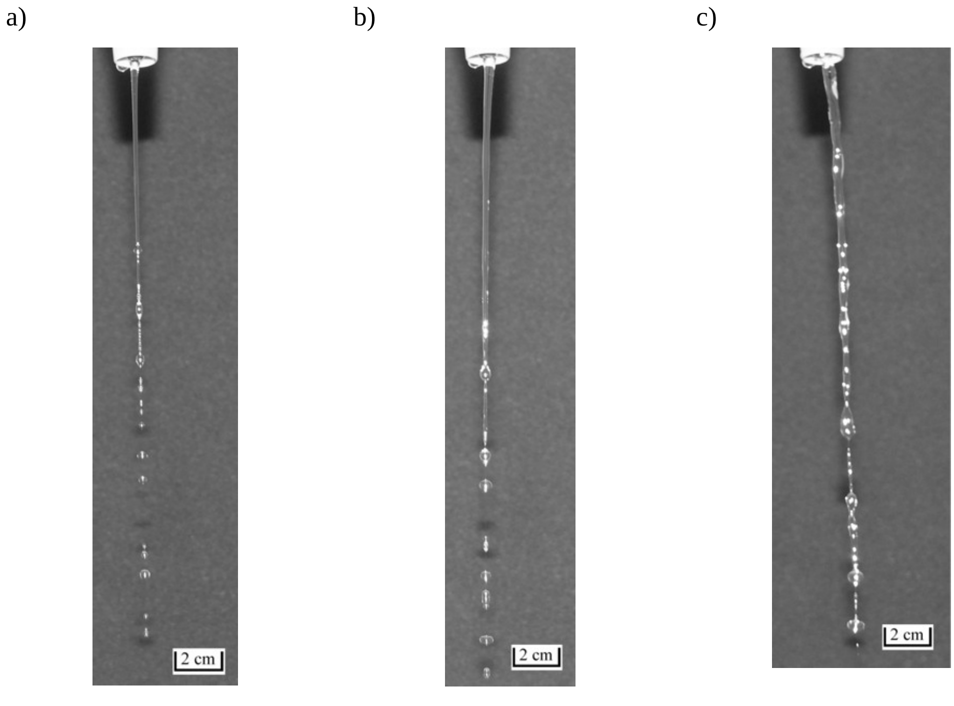

Fig. 3. 2000 w.ppm aqueous solution of PAA jets: a) Re_L = 25, b) Re_L = 230, c) Re_L = 1150

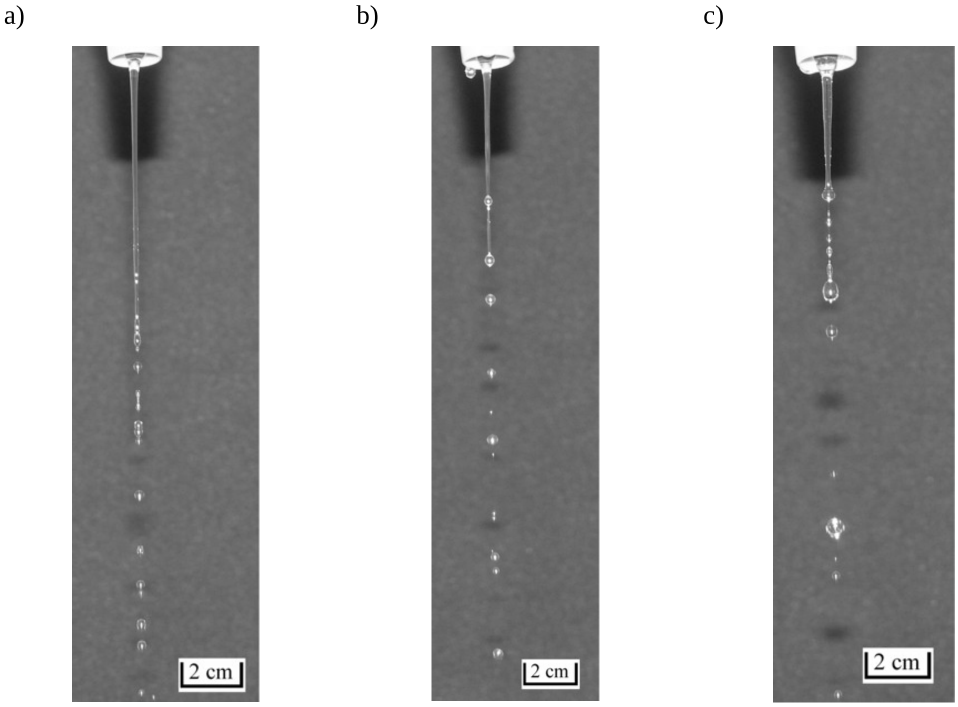

Fig. 4. Jets of aqueous solutions of polymers used: a) 2000 w.ppm solution of Na–CMC at Re_L = 30, b) 1000 w.ppm solution XG at Re_L = 165, c) 1000 w.ppm solution of PAA at Re_L = 290

The break-up length was measured on three or more photographs for each Reynolds number. The value shown in Fig. 5 is the averaged break-up length obtained for investigated nozzle for all Reynolds numbers studied, while individual measurements varied by up to 10% from the averaged value. The break-up length is defined as the length of the continuous portion of the jet, measured from the nozzle to the break-up point where drop formation occurs. Analysis of the photos of jet break-up showed that the break-up length depends on both, liquid flow rate and properties of liquid. Larger values of jet break-up lengths have been observed for all investigated solutions in comparison with water. It has been found that the break-up length can be determined from the following correlation relationship:

$$\frac{L_L}{d} = CRe_L^A \tag{3}$$

where the values of C and A were dependent on the type of polymer in a solution and its rheological behaviour. Values of coefficient C and exponent A are presented in Table 2.

High molecular weight of polymers added to spray solvent (water) involves the changes in the viscosity of liquid and in character of flow (Harrison *et al.*, 1999). The results show that there are complex, but qualitatively predictable interactions between the rheological properties of the liquids and the jet break-up length. Further, it is clearly demonstrated that low concentrations of polymer additives may have profound effects on the spray pattern produced by spray nozzles.

For all investigated liquids an increase in the break-up length relative to Newtonian fluid was observed. This increase in break-up length occurred at all Reynolds numbers studied. The effects of concentration and molecular weigth on the break-up of viscoelastics jets were observed. The break-up length increased with concentration of polymer in solution.

Table 2. Values of coefficient *C* and exponent *A* in Equation (3)

Liquid	Concentration of a solution	Correlation values	
	c_p [w.ppm]	*C*	*A*
Water	0	2.272	0.34
Aqueous solutions of Na–CMC	1000	8.661	0.23
	2000	17.155	0.23
Aqueous solutions of PAA	1000	6.022	0.27
	2000	13.385	0.27
Aqueous solutions of XG	1000	4.731	0.34

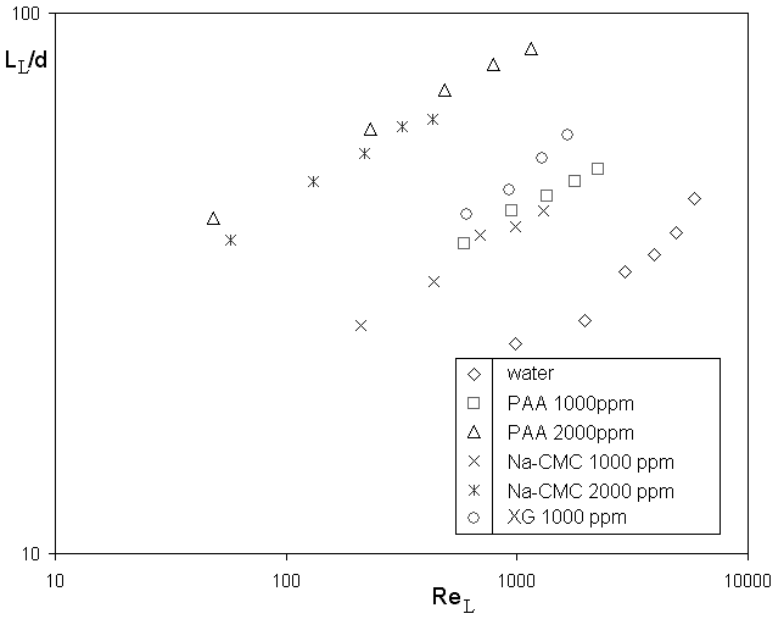

Fig. 5. Effect of liquid flow rate and type of polymer solution on break-up length

An analysis of the photos of the jets break-up showed that the length of jets depends on both, liquid flow rate and type of polymer solutions used. High molecular polymers added to a solvent involve the changes in the rheological properties of liquid and the length of break-up of jets. It has been shown that the increase in break-up length increased with polymer concentration at any molecular weight of added polymer.

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