Cavitation Suppression by Polymer Additives: Concentration Effect and Implication on Drag Reduction

ROBERT Y. TING

Naval Research Laboratory, Washington, D.C. 20375

In recent years the interest in the flow properties of dilute solutions of high molecular weight polymers mainly involved their drag reducing characteristics in turbulent flow. Large effects on the frictional drag clearly manifested the capability of polymer additives to influence the overall hydrodynamic regime. In an exploratory effort, Ellis et al. (1970) observed the suppression of flow generated cavitation in dilute solutions of polyethylene oxide and guar gum on hemispherically-nosed cylinders. The effect was demonstrated in terms of the incipient cavitation number,

$$\sigma_i = \frac{P - P_v}{\frac{1}{2}\rho U^2} \tag{1}$$

which designates the state of liquid flow at the instant cavitation commences. Over a Reynolds number range of 7×10^4 to 3×10^5, these investigators found that with the presence of polymer additives the incipient cavitation number might be reduced to 30% of its value for tap water. Recently, a similar, definitive inhibition of the inception of jet cavitation was also demonstrated by Hoyt (1971). By using dilute polyethylene oxide solutions (Polyox-WSR-301) at different concentrations, the effect on jet cavitation was studied in turbulent jets through test nozzles with different turbulence-inducing grids. Independent of the grid sizes, the incipient cavitation number was greatly influenced by the presence of polymer. The major results of Hoyt's study are shown in Figure 1.

CONCENTRATION EFFECT

Figure 1 shows a steady increase of cavitation inhibition with polymer concentration until about 20 ppmw. If the percent reduction of incipient cavitation number is defined as

$$R_I = \frac{\sigma_i^w - \sigma_i^p}{\sigma_i^w} \times 100\% \tag{2}$$

where σ_i^w are values in water and σ_i^p in polymer solutions, then the data up to this concentration may be presented as shown in Figure 2. It is now attempted to develop a correlation function to describe the concentration dependence of this effect since the development of even an empirical relation may well reveal the mechanism involved in the cavitation suppression phenomenon.

It can be seen in Figure 2 that initially the effect of cavitation suppression increases rapidly with increasing concentration. Then the effect becomes saturated as R_I approaches a certain limiting value at higher concentrations. In other words, the rate of increase of R_I is large at small concentrations. As the concentration increases, this rate becomes smaller and smaller, eventually approaching zero. If one examines the cavitation suppression per unit concentration and its variation with concentration, it becomes obvious that the cavitation suppression effect becomes less efficient on a unit concentration basis as the concentration increases. This concentration dependence may be best described by an equation of the classical Langmuir type in surface chemistry (Langmuir, 1918):

$$\frac{R_I}{R_{I-m}} = \frac{c}{[c]_I + c} \tag{3}$$

The intrinsic concentration, or the concentration required to achieve $(\frac{1}{2})R_{I-m}$, is a measure of how rapidly the cavitation suppression effect increases with increasing concentration. If the experimental data obey Equation (3), then a linear relationship should exist between c/R_I and c because the rearrangement of Equation (3) shows

$$\frac{c}{R_I} = \frac{[c]_I}{R_{I-m}} + \frac{1}{R_{I-m}} \cdot c \tag{4}$$

The data of jet cavitation were tested by plotting c/R_I vs. c in Figure 3, where indeed this linearity was obtained. The intercept value of c/R_I at $c = 0$ yields the quantity $[c]_I/R_{I-m}$, which has a physical significance. If one examines the limit

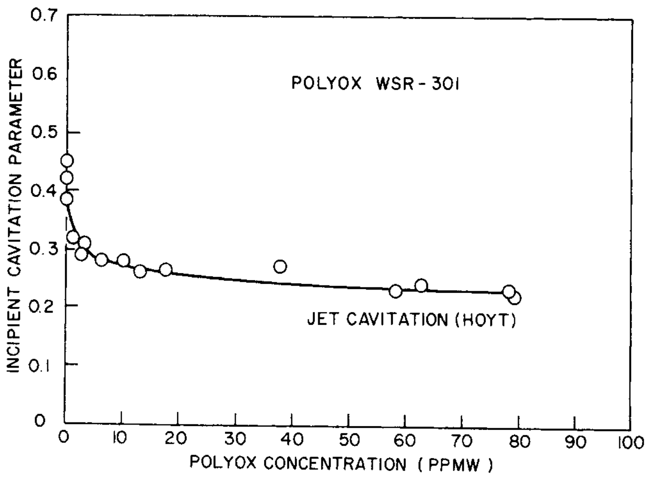

Fig. 1. Concentration dependence of incipient cavitation number.

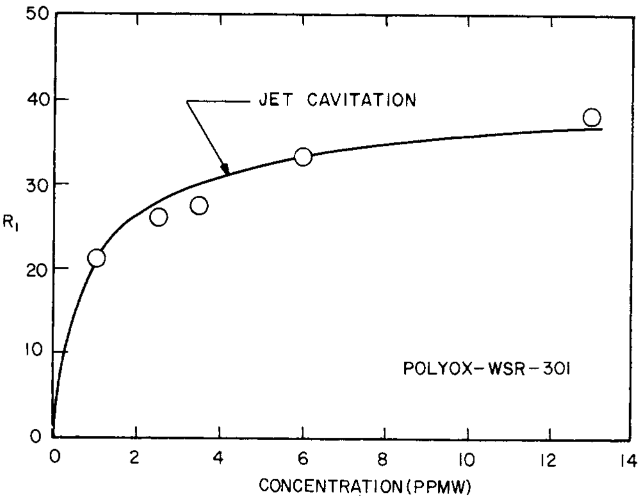

Fig. 2. Percent reduction of σ_i vs. concentration.

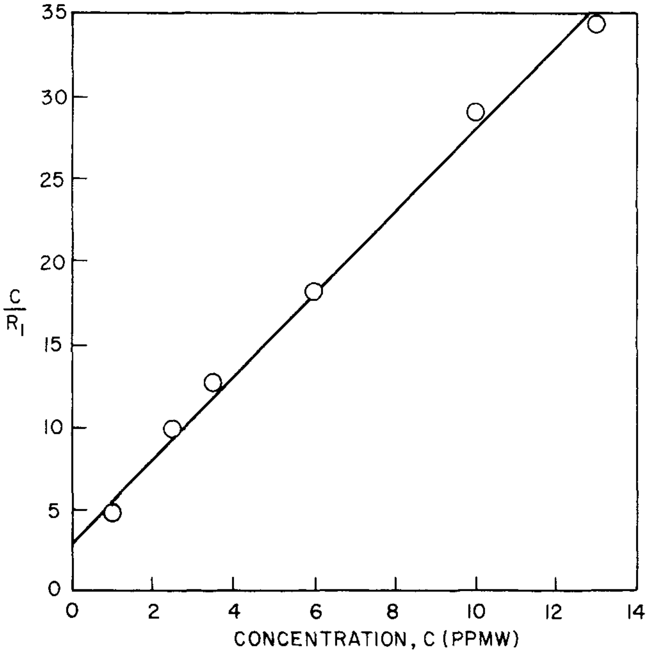

Fig. 3. Linearity between c/R_I and c.

$$\lim_{c\to 0}\frac{R_I}{c}=\lim_{c\to 0}\frac{R_{I-m}}{[c]_I+c}=\frac{R_{I-m}}{[c]_I} \qquad (5)$$

it shows that $R_{I-m}/[c]$ is a measure of the effectiveness of the polymer additives in suppressing incipient cavitation on a unit concentration basis at infinite dilution. Therefore, once the concentration dependence of R_I is experimentally determined, the parameter $R_{I-m}/[c]_I$ may be easily evaluated and successfully used as an index for rating the effectiveness of different polymer compounds. The utility of this parameter will be further discussed in the next section.

DRAG REDUCTION

The fact that the data of jet cavitation suppression obey Equation (3) is interesting. Earlier, Little (1971) derived an equation of similar form for the concentration effect in turbulent drag reduction,

$$\frac{DR}{DR_m}=\frac{c}{[c]+c} \qquad (6)$$

If one applies Equations (3) and (6) to Hoyt's results of jet cavitation and the simultaneous drag reduction measurements, one obtains the following values:

$$\frac{R_{I-m}}{[c]_I}=2.98 \qquad \frac{DR_m}{[c]}=2.29$$

for Polyox-WSR-301 compound. These values are clearly of the same order of magnitude. This result, together with the existing similarity between Equation (3) and Equation (6), seems to suggest that cavitation suppression and drag reduction are strongly related phenomena. The basic mechanisms involved in both these hydrodynamic phenomena may therefore have much in common. For example, extremely high viscoelastic resistance of polymers to elongational strains has been proposed as a possible explanation for drag reduction (Lumley, 1969; Everage and Gordon, 1971; Ting, 1972). In the case of jet cavitation, it may be possible that the stress-strain balance was also strongly affected by the presence of the polymer additives. Since in the jet flow the fluid elements are accelerating in the streamwise direction, polymer solutions may exhibit very high elongational viscosity. This influences the overall pressure level and the incipient cavitation is hence suppressed. This explanation is specially attractive in view of the experimental results of James and Acosta (1970) and Gadd (1965). When compared with a water jet, these investigators reported striking differences in jet appearance in polymer solutions for both laminar and turbulent jets.

The usefulness of the effectiveness indices $R_{I-m}/[c]_I$ and $DR_m/[c]$ may also have a bearing on the basic mechanism of these phenomena. The effects of polymer homology, solvent power, and molecular conformation on drag reduction have been demonstrated by correlating appropriate molecular parameters with $DR_m/[c]$ (Ting and Little, 1973; Kim et al., 1974). Such studies relate the macroscopic flow information to the microscopic molecular properties and may eventually bring a detailed molecular-level explanation for these interesting phenomena. Future experimental work on cavitation suppression toward this direction is therefore recommended.

NOTATION

c = polymer concentration
$[c]_I$ = intrinsic concentration for cavitation suppression
$[c]$ = intrinsic concentration for drag reduction
DR = percent drag reduction
DR_m = maximum drag reduction
P = static pressure
P_v = liquid vapor pressure
R_I = percent reduction of σ_i
R_{I-m} = maximum value of R_I
U = free stream velocity

Greek Letters

ρ = liquid density
σ_i = incipient cavitation number

LITERATURE CITED

Ellis, A. T., J. G. Waugh, and R. Y. Ting, "Cavitation Suppression and Stress Effects in High-Speed Flows of Water with Dilute Macromolecule Additives," *ASME J. Basic Eng.*, 3D, 459 (1970).

Everage, A. E., and R. J. Gordon, "On the Stretching of Dilute Polymer Solutions," *AIChE J.*, **17**, 1257 (1971).

Gadd, G. E., "Turbulence Damping and Drag Reduction Produced by Certain Additives in Water," *Nature*, **206**, 463 (1965).

Hoyt, J. W., "Effect of Polymer Additives on Jet Cavitation," presented at the 16th Am. Towing Tank Conf., Sao Paulo, Brazil (1971).

James, D. F., and A. J. Acosta, "The Laminar Flow of Dilute Polymer Solutions around Circular Cylinders," *J. Fluid Mech.*, **42**, 269 (1970).

Kim, O. K., R. C. Little, and R. Y. Ting, "The Correlation of Drag Reduction Effects with Polymer Intrinsic Viscosity," *J. Colloid Interface Sci.*, **47**, 530 (1974).

Langmuir, I., "The Adsorption of Gases on Plane Surfaces of Glass, Mica and Platinum," *J. Am. Chem. Soc.*, **40**, 1361 (1918).

Little, R. C., "Drag Reduction in Capillary Tubes as a Function of Polymer Concentration and Molecular Weight," *J. Colloid Interface Sci.*, **37**, 811 (1971).

Lumley, J. L., "Drag Reduction by Additives," *Ann. Rev. Fluid Mech.*, **1**, 367 (1969).

Ting, R. Y., "On the Mechanisms for Drag Reduction—A Viscoelastic Evaluation Based on a Bead-Spring Model," *J. Appl. Polym. Sci.*, **16**, 3169 (1972).

———, and R. C. Little, "Characterization of Drag Reduction and Degradation Effects in the Turbulent Pipe Flow of Dilute Polymer Solutions," *ibid.*, **17**, 3345 (1973).

Manuscript received January 28, 1974; revision received March 26 and accepted April 5, 1974.