EFFECT OF SOLVENT CHEMISTRY ON CRITICAL WEISSENBERG NUMBERS

E. Y. KWACK and J. P. HARTNETT

Energy Resources Center, University of Illinois at Chicago Circle, P.O. Box 4648, Chicago, IL 60680, U.S.A.

Abstract—The critical Weissenberg number for the friction factor was earlier reported to be approx. 5–10 for turbulent pipe flow of 1000 wppm polyacrylamide dissolved in Chicago tap water, while the corresponding critical Weissenberg number for the dimensionless heat transfer coefficient, j_H, was found to be approx. 200–250 for this same solution. It is known that the chemistry of the solvent generally influences the friction and heat transfer behavior of a polymer solution. Experiments have been performed using 100 wppm sodium hydroxide as an additive to the aqueous polyacrylamide solution (Separan 1000 wppm) and reveal that the critical Weissenberg numbers are unaffected. It is tentatively concluded that the chemistry of the solvent does not influence the critical Weissenberg numbers for aqueous polyacrylamide solutions.

Preliminary measurements using aqueous solution of polyethylene oxide (Polyox 5000 wppm) yield critical Weissenberg numbers which are in reasonable agreement with the values reported earlier for aqueous solutions of polyacrylamide.

NOMENCLATURE

c_p,	specific heat of fluid;
d,	tube diameter;
f,	Fanning friction factor, $\tau_w/(\rho V^2/2)$;
h,	convective heat transfer coefficient, $q/(T_w - T_m)$;
j_H,	dimensionless heat transfer coefficient, $St\, Pr_a^{2/3}$;
k_l,	thermal conductivity of fluid;
l,	total tube length;
Nu,	Nusselt number, hd/k_l;
Pr_a,	Prandtl number based on the viscosity at wall, $\eta c_p/k_l$;
q,	heat transfer per unit time per unit area;
Re_a,	Reynolds number based on the viscosity at wall, $\rho V d/\eta$;
St,	Stanton number, $Nu/(Re_a Pr_a)$;
T_m,	local mean fluid temperature;
T_w,	local wall temperature;
V,	average velocity;
Ws,	Weissenberg number, $\lambda V/d$;
Ws_{cf},	critical Weissenberg number for friction;
Ws_{ch},	critical Weissenberg number for heat transfer;
x,	axial distance.

Greek symbols

$\dot{\gamma}$,	shear rate;
η,	apparent viscosity evaluated at wall;
η_0,	zero shear rate viscosity;
η_∞,	apparent viscosity at infinite shear rate;
ρ,	density of fluid;
τ_w,	wall shear stress;
λ,	characteristic time of fluid.

INTRODUCTION

RECENTLY, it has been reported that the solvent chemistry affects the rheological properties [1–3],

drag reducing performance [4–11] and heat transfer behavior [6, 12] of aqueous solutions of high molecular weight polymers. The solvent chemistry effects on the rheological properties of aqueous solutions of high molecular weight polymers have been studied by adding base or acid additives to the polymer solution [2, 3]. Generally, the low shear rate viscosity of the solution decreases with increasing concentration of acid in the solvent. On the other hand, the addition of a base increases the low shear rate viscosity up to a certain point which corresponds to a pH value of approx. 9–10 for the polymer solution. Further addition of the base will result in a decrease of the low shear rate viscosity.

In general, an increase of the low shear rate viscosity resulting from the addition of a base is accompanied by an increase in the first normal force difference (i.e. an increase in the elasticity of the polymer solution) [3]. In turn, this influences the friction factor and heat transfer. Evidence of the changes in the drag reducing behavior resulting from the addition of an acid or a base to an aqueous polymer solution is given by White and Gordon [9] and Kwack *et al.* [10]. The limited experimental data available on solvent chemistry effects on turbulent heat transfer performance with high molecular weight polymer solutions confirm the conclusion that the addition of a base results in a decrease in the heat transfer coefficient [12].

In a recent paper we have reported that the friction factor, f, and the dimensionless heat transfer coefficient, j_H, for aqueous solutions of polyacrylamide in turbulent flow are a function only of the Reynolds number and the Weissenberg number for fully established hydrodynamic and thermal conditions. Additionally, it was found that a critical Weissenberg number (which was weakly dependent on Reynolds number) existed for the friction factor. Above this critical Weissenberg number, Ws_{cf}, the magnitude of which is approx. 5–10, the friction factor is at its

minimum asymptotic value and is a function only of the Reynolds number. A critical Weissenberg number also exists for heat transfer, Ws_{ch}, which is of the order of 200–250, above which the dimensionless heat transfer coefficient, j_H, is at its minimum asymptotic value [13].

Since the solvent in these experiments was Chicago tap water [10], the question arises whether the addition of a base or an acid to the polymer solution will alter these results. To give some insight into this question a set of experiments was carried out with 1000 wppm of polyacrylamide in Chicago tap water with 100 wppm sodium hydroxide. This choice was made inasmuch as the earlier experiments involved 1000 wppm of polyacrylamide; furthermore the addition of 100 wppm of NaOH yielded a solution with a pH of 9.2 which should correspond approximately to the maximum value of the low shear rate viscosity (i.e. the highest elasticity) [3].

Another obvious question is whether the critical Weissenberg numbers vary greatly from polymer to polymer. Consequently, a solution of 5000 wppm of polyethylene oxide in Chicago tap water was prepared, the rheology determined and the necessary friction factor and heat transfer measurements were undertaken.

EXPERIMENTAL SETUP

A schematic diagram of the recirculating flow system is shown in Fig. 1. A positive displacement Moyno pump discharges the test fluid into the horizontal test section having an inside diameter of 1.30 cm ($l/d = 475$).

In the present flow system, the hydrodynamic and thermal entrance regions develop simultaneously from the beginning of the test section. To provide the boundary condition of constant heat flux at the wall, the test tube was heated electrically by a DC power supplier. Some 13 pressure taps were installed along the length of the test tube. Forty 30 gauge copper–constantan thermocouples were cemented with copper oxide along the length of each tube to measure the local outside wall temperature. A shell and tube type heat exchanger was installed in the flow loop to maintain a constant inlet temperature of the test fluid.
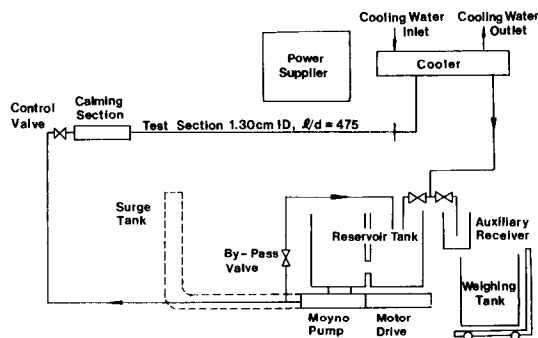
The pressure drop was measured by a set of parallel water manometers of length 1.8 m with an adjustable air pressure head to offset the pressure in the tube. Thermocouple readings and the voltage drops across the heat transfer section of the test tube were measured with a precision digital voltmeter having a resolution of 1 μv. Flow rates were measured by direct weighing. Calibration measurements of pressure drop and heat transfer for the flow loop were made with tap water.

Two different polymer solutions were used in the current study for comparison with earlier results obtained with polyacrylamide in Chicago tap water. One was a 1000 wppm aqueous solution of polyacrylamide (Separan AP-273 from Dow Chemical Company) with 100 wppm NaOH. To make this polyacrylamide solution, NaOH was first mixed with Chicago tap water and allowed to stand for one day. Subsequently, an amount of Separan powder corresponding to 1000 wppm was sprinkled on the solvent surface which was gently stirred with a glass rod. The other polymer solution is 5000 wppm of polyethylene oxide (Polyox WSR-301 from Union Carbide Corporation) dissolved in Chicago tap water.

The Separan solution was continuously circulated in the flow loop for a period of 74 h. The heat transfer coefficient and friction factor were measured simultaneously at regular time intervals. The apparent viscosity of samples of test fluid removed from the recirculating flow system at regular time intervals was measured using the Weissenberg rheogoneometer (R-18) with Couette geometry. Measurements were also made with the capillary tube viscometer (0.05334 cm I.D. and $l/d = 375$).

On completion of the Separan experiments, the flow loop was flushed and the Polyox solution was then circulated for a period of 24 h. Measurements of the viscosity, friction factor and heat transfer, as described above, were then carried out.

PROPERTIES OF POLYMER SOLUTIONS

The apparent viscosity of the 1000 wppm Separan solution in Chicago tap water reported earlier is shown in Fig. 2 [13]. Figure 3 shows the apparent viscosity of the 1000 wppm Separan solution in Chicago tap water with 100 wppm NaOH taken at different hours of

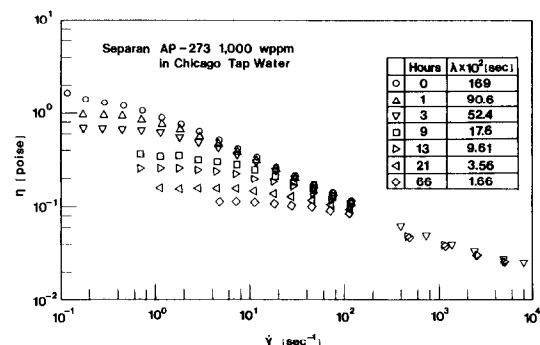Fig. 1. Schematic diagram of the recirculating flow system.

Fig. 2. Apparent viscosity vs shear rate for 1000 wppm Separan in Chicago tap water [13].

FIG. 3. Apparent viscosity vs shear rate for 1000 wppm Separan in Chicago tap water with 100 wppm NaOH.
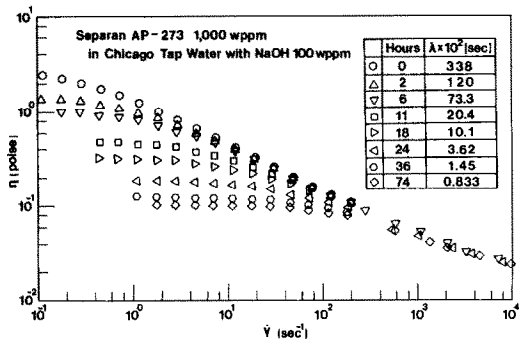

FIG. 5. Apparent viscosity vs shear rate for 5000 wppm Polyox in Chicago tap water.

shear (ranging from 0 to 74 h) during the degradation run in the recirculating flow system. The general trend of the apparent viscosities of the 1000 wppm Separan solution with sodium hydroxide additive is similar to that of 1000 wppm Separan solution without the base additive. The characteristic time of each sample solution was calculated using the Powell–Eyring model which yields the characteristic time using steady shear viscosity data only. The Powell–Eyring model is defined as follows [14]:

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)\left(\frac{\sinh^{-1} \lambda\dot{\gamma}}{\lambda\dot{\gamma}}\right) \qquad (1)$$

where λ is the characteristic time. The measured viscosity data for a given sample are used in conjunction with equation (1) to determine the value of λ which gives the best fit to the viscosity measurements over the entire shear rate range. The resulting values of characteristic time are tabulated in Figs. 2 and 3 with corresponding hours of shear.

Figure 4 shows the values of the characteristic time vs zero shear rate viscosities of 1000 wppm Separan

solution with sodium hydroxide and of 1000 wppm Separan solution without sodium hydroxide. This figure shows that the characteristic time has an approximately linear relation with the zero shear rate viscosity on a logarithmic graph. Since lower values of the characteristic time are associated with lower values of elasticity, these results are consistent with the earlier observation that a decrease in the zero shear rate viscosity reflects a decrease in the elastic force of a polymer solution.

The apparent viscosity of 5000 wppm Polyox in Chicago tap water is also shown in Fig. 5. The zero shear rate viscosity of the 5000 wppm Polyox solution is much lower than that of 1000 wppm Separan in Chicago tap water, while the viscosity of the Polyox solution is larger than that of the Separan solution in the high shear rate region. It is interesting to note that the viscosity of the 1000 wppm Separan solution at high shear rate (10^3–10^4) remains relatively constant, while that of 5000 wppm Polyox in Chicago tap water demonstrates substantial changes in that high shear rate region. These high shear rates are in the range of the wall shear rates encountered in the flow loop. Thus, the change in rheological properties of the 5000 wppm Polyox solution can be detected even using a capillary tube viscometer, whereas it is not possible to detect any substantial change of viscosity of the Separan solution using the capillary tube viscometer.
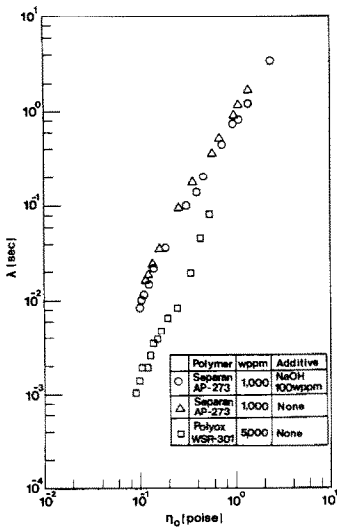

FIG. 4. Characteristic time vs zero shear rate viscosity for 1000 wppm Separan in Chicago tap water, 1000 wppm Separan in Chicago tap water with 100 wppm NaOH and 5000 wppm Polyox in Chicago tap water.
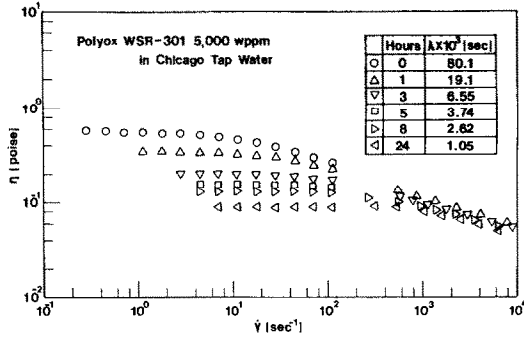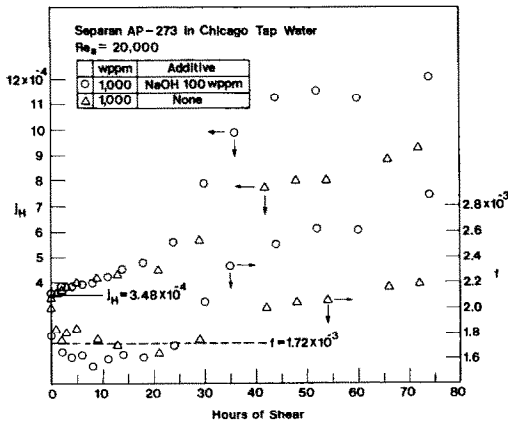

FIG. 6. Fanning friction factor and dimensionless heat transfer coefficient vs hours of shear for Re_a of 20 000.
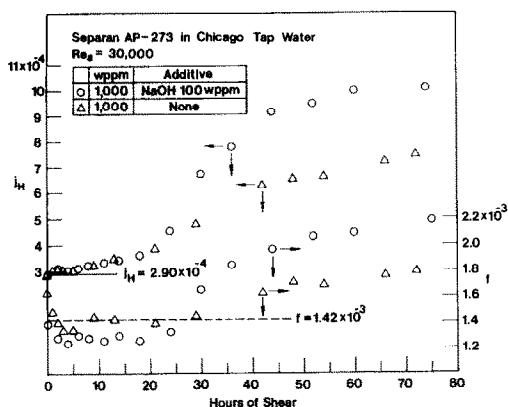
FIG. 7. Fanning friction factor and dimensionless heat transfer coefficient vs hours of shear for Re_a of 30 000.

RESULTS AND DISCUSSIONS

The measurements of friction factor and heat transfer coefficient were conducted simultaneously at regular time intervals in the recirculating flow system. The friction factors were measured at values of x/d larger than 110 to obtain the hydrodynamically established Fanning friction factor [15]. The heat transfer coefficient measurements were made at an x/d ratio equal to 430 which should yield values approximating established thermal conditions [16, 17].

To investigate the effect of solvent chemistry on the critical Weissenberg numbers for friction and heat transfer in turbulent pipe flow, pressure drop and heat transfer measurements of 1000 wppm Separan in Chicago tap water with 100 wppm NaOH were compared with those of 1000 wppm Separan solution without NaOH [13]. Figs. 6 and 7 present the dimensionless heat transfer coefficient, j_H, and the corresponding Fanning friction factor, f, as a function of hours of shear. The minimum friction asymptotic values and the corresponding minimum heat transfer values as shown on Figs. 6 and 7 were calculated as a function of the measured Reynolds numbers using the previously reported empirical relations [17–19]. In the case of the 1000 wppm Separan solution with sodium hydroxide, the dimensionless heat transfer coefficient, j_H, is seen to remain relatively constant at its minimum asymptotic

value for 6 h at a Reynolds number of 20 000 and for 8 h at a Reynolds number of 30 000, after which times the heat transfer coefficients begin to increase monotonically. On the other hand, the friction factors start to increase from the minimum value after some 25 h of circulation for both Reynolds numbers. These results confirm earlier findings that the dimensionless heat transfer coefficient, j_H, departs from its asymptotic value much earlier than the friction factor does [12, 13, 20]. These pressure drop and heat transfer measurements are replotted in Figs. 8 and 9 as a function of the Weissenberg number. The earlier reported values for the 1000 wppm Separan aqueous solution without sodium hydroxide are also shown for comparison. These two figures reveal that the friction factor, f, and the dimensionless heat transfer coefficient, j_H, show the same relationship with the Weissenberg number at a fixed Reynolds number relatively independent of the solvent chemistry. This suggests that the influence of solvent chemistry on the friction factor and on the dimensionless heat transfer coefficient is adequately accounted for in the Weissenberg number and the Reynolds number under fully established hydrodynamic and thermal conditions.

To obtain the critical Weissenberg numbers for a different polymer for comparison with results obtained with polyacrylamide, the pressure drop and heat transfer were measured in the recirculating flow system with a solution of 5000 wppm Polyox in Chicago tap water. Figure 10 shows the dimensionless heat transfer coefficient, j_H, and the corresponding Fanning friction factor, f, as a function of the hours of shear at a Reynolds number of 10 000. The minimum drag asymptotic value and the minimum heat transfer asymptotic value are also indicated in Fig. 10 for comparison. The Fanning friction factors begin to increase after 3 h of circulation, while the dimensionless heat transfer coefficient, j_H, departs from its initial value from the initiation of circulation. A direct comparison of these results with those of the Separan solution yields the fact that the Polyox solution is much more sensitive to mechanical degradation than the Separan solution. These pressure drop and heat transfer measurements are replotted as a function of the Weissenberg number in Fig. 11. These Polyox
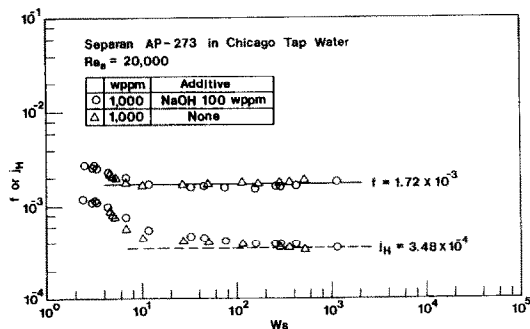

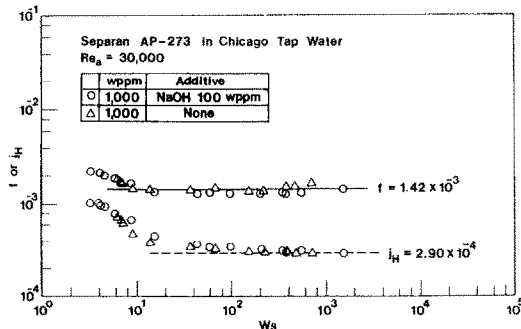FIG. 8. Fanning friction factor and dimensionless heat transfer coefficient vs Ws for Re_a of 20 000.

FIG. 9. Fanning friction factor and dimensionless heat transfer coefficient vs Ws for Re_a of 30 000.
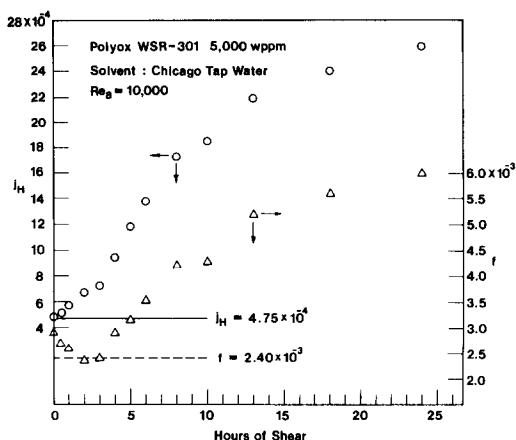
FIG. 10. Fanning friction factor and dimensionless heat transfer coefficient vs hours of shear for Re_a of 10,000.

results are compared with earlier measurements obtained in a once-through system using Separan in Chicago tap water. These earlier measurements involved the measurements of heat transfer and friction for various concentrations of Separan at a flow rate corresponding to a Reynolds number of 10 000, with the fluid making a single pass through the flow loop [13]. The friction and heat transfer results of 5000 wppm Polyox in Chicago tap water are in good agreement with those of Separan solutions using Chicago tap water as solvent. Based on these results, it may be tentatively concluded that the critical Weissenberg numbers for Polyox solution are the same as those for Separan solutions.

CONCLUSIONS

(1) The addition of a base additive to an aqueous polyacrylamide solution does not affect the critical Weissenberg numbers for friction and heat transfer.

(2) Preliminary experimental data indicate that the critical Weissenberg numbers for friction and heat transfer for aqueous Polyox solutions are very close to those for Separan solutions.

Acknowledgements—The authors wish to express appreciation to Mr. W. Y. Lee and Mr. M. Ng for their assistance in the experimental program.
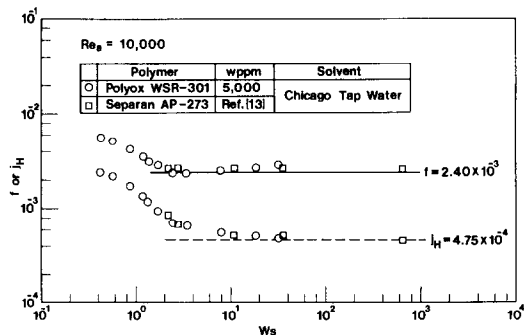

FIG. 11. Fanning friction factor and dimensionless heat transfer coefficient vs Ws for Re_a of 10 000.

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EFFET DE LA CHIMIE DU SOLVANT SUR LES NOMBRES CRITIQUES DE WEISSENBERG

Résumé—Le nombre de Weissenberg critique pour le frottement a été donné approximativement égal de 5 à 10 pour l'écoulement turbulent dans un tuyau avec 1000 ppm en masse de polyacrylamide dissous dans l'eau ordinaire de Chicago, tandis que le nombre critique correspondant pour le coefficient adimensionnel de transfert thermique j_H est approximativement de 200 à 250 pour cette même solution. On sait que la chimie du solvant influence généralement le frottement et le transfert thermique d'une solution de polymère. Des expériences faites avec 100 ppm d'hydroxyde de sodium comme additif à une solution aqueuse de polyacrylamide (Separan 1000 ppm) révèlent que les nombres critiques de Weissenberg ne sont pas modifiés. On en déduit provisoirement que la chimie du solvant ne modifie pas les nombres critiques de Weissenberg pour des solutions aqueuses de polyacrylamide.

Des mesures préliminaires avec une solution aqueuse d'oxyde de polyéthylène (Polyox 5000 ppm) donnent des nombres critiques qui sont en accord raisonnable avec les valeurs déjà connues pour les solutions aqueuses de polyacrylamide.

EINFLUSS DER LÖSUNGSMITTELZUSAMMENSETZUNG AUF DIE KRITISCHE WEISSENBERG-ZAHL

Zusammenfassung—Die kritische Weissenberg-Zahl für den Widerstandsbeiwert liegt, wie früher berichtet, für eine turbulente Rohrströmung von 1000 wppm Polyacrylamid gelöst in Leitungswasser bei 5 bis 10, während die entsprechende kritische Weissenberg-Zahl des dimensionslosen Wärmeübergangs-Koeffizienten, j_H, mit näherungsweise 200 bis 250 für die gleiche Lösung ermittelt wurde. Es ist bekannt, daß die Zusammensetzung des Lösungsmittels allgemein das Widerstands- und Wärmeübertragungsverhalten einer Polymerlösung beeinflußt. Versuche mit 100 wppm Natriumhydroxid als Zusatz zu einer wäßrigen Polyacrylamidlösung (Separan 1000 wppm) zeigten, daß die kritischen Weissenberg-Zahlen dadurch nicht beeinflußt werden. Daher wird versuchsweise der Schluß gezogen, daß die chemische Zusammensetzung des Lösungsmittels die kritischen Weissenberg-Zahlen von wäßrigen Polyacrylamidlösungen' nicht beeinflußt. Vorläufige Messungen, bei denen wäßrige Lösungen von Polyäthylenoxid (Polyox 5000 wppm) verwendet wurden, ergaben kritische Weissenberg-Zahlen, die in guter Übereinstimmung mit früher angegebenen Werten für wäßrige Polyacrylamidlösungen stehen.

ВЛИЯНИЕ ХИМИЧЕСКОГО СОСТАВА РАСТВОРИТЕЛЯ НА КРИТИЧЕСКИЕ ЧИСЛА ВЕЙССЕНБЕРГА

Аннотация—Известно, что для турбулентного трения в трубе критическое число Вейссенберга находится в диапазоне от 5 до 10. Эти данные относятся к раствору 1000 ппм вес. полиакриламида в обычной водопроводной воде района Чикаго. Соответствующее критическое число Вейссенберга для теплопереноса в этом же растворе составляет приблизительно 200–250. Обычно химический состав растворителя может оказывать влияние на трение и теплоперенос полимерных растворов. В опытах использовалась добавка 100 ппм вес. гидроокиси натрия к водному раствору полиакриламида (Сепаран 1000 ппм вес.). Оказалось, что критические числа Вейссенберга не изменяются. На этом основании сделан вывод об отсутствии влияния химического состава растворителя на критические числа Вейссенберга для водных растворов полиакриламида.

Как показали предварительные опыты, для водных растворов полиэтиленоксида (Полиокс 5000 ппм вес.) критические числа Вейссенберга хорошо согласуются со значениями, полученными ранее для водных растворов полиакриламида.