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Experimental Study on the Squeezing Flow of Viscoelastic Fluids*

(1st Report, The Effect of Liquid Properties on the Flow Between a Spherical Surface and a Flat Plate)

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An experimental study has been made on the flow of viscoelastic liquids in thin films held between a flat plate and a spherical surface of a large radius of curvature. In particular, the case is investigated when a spherical surface begins to roll on a flat plate from stationary and contacting state. Dilute polymer solutions are used as viscoelastic fluids, whose properties are elastic but Newtonian in viscosity. Compared with non-elastic liquids, some effects are shown: The point of cavitation is far from the center of contact where the thickness of the liquid film is minimum. The thickness of the liquid film, generated with rolling movement, is larger than that of non-elastic liquids.

key Words : Viscoelastic Fluid, Squeezing Flow, Liquid Film, Cavitation, Dilute Polymer Solutions, Experimental Study, Human Joint, Non-Newtonian Fluid

1. Introduction

It is widely known that viscoelastic properties of liquid affect the stress and the velocity in various flow fields. In particular, squeezing flows of viscoelastic fluid in lubrication give such interesting effects as load enhancement and increase in liquid film thickness.(1)~(3) Also similar problems have been studied in medical engineering from the point of view of lubrication mechanism in human joints, because synovial fluids have viscoelastic properties and a squeezing flow is realized in the lubrication in human joints.(4)(5)

These studies were almost made by numerical computations and experiments on steady flows or one dimensional squeezing flows, and very few experiments have been carried out in a situation similar to the actual lubrication processes.

In this study, it is investigated how the viscoelastic property in liquids affects the unsteady squeezing flow like the one in human joints. A lubrication system between a flat plate and a spherical surface is tested, when the spherical surface begins to roll on the flat plate from a stationary and contacting state. Dilute polymer solutions are used as viscoelastic fluids, because they are viscoelastic but Newtonian in viscosity and are suitable for the purpose of examining the contribution of only the elasticity to the lubrication system with the viscosity unchanged.

2. Apparatus and Experimental Method

2.1 Apparatus

A schematic diagram of the main apparatus is given in Fig. 1. An optical flat glass ① and a convex lens ②, whose radius of curvature R_L is 1980mm, were utilized as a lubrication system between the flat plate and the spherical surface. They are 40mm in diameter. An aluminum beam was attached to the lens via a holder, and the lens was placed on the flat glass which was fixed in a reservoir ③. Some load F was applied to one end of the beam P_1 with a tip of an arm held by an accurately calibrated balance ④. The other end P_2, which was adjustable in height, was supported by a pivot connected to a micrometer head ⑥ and a shaft of a linear motor ⑤. The flat glass and the convex lens were lighted from below by He-Ne laser parallel beams from the optical system composed of holography mirrors and a half mirror. A high speed camera was utilized to observe and to film the movement of the lens.

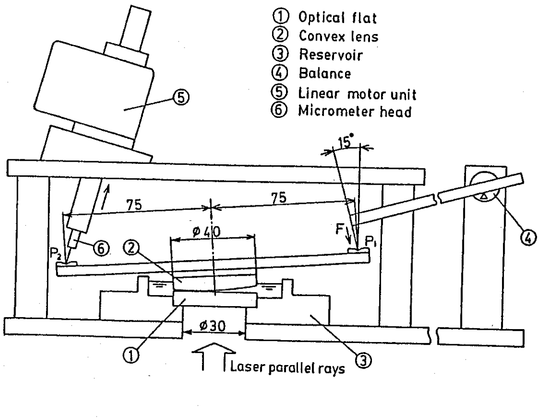

Fig.1 Schematic diagram of the main apparatus

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2.2 Experimental method

Adjustment of the pivot height was made such that the initial contact point between the flat glass and the lens was situated at some distance Xs from the center. After being held at rest, the pivot was moved from P_2 in the direction of the arrow indicated in Fig. 1. Then the lens began to roll on the plate under a load F. The moving state of lens was filmed with the high speed camera as a transformation of Newton's rings (optical interference fringes). The pictures on films were projected on a digitizer, and then the locations and diameters of Newton's rings (i.e. the lens movement) were computed by a personal computer connected to the digitizer.

Three or four initial distances Xs were taken within 10mm, and the loads F were 0.14, 0.29 and 0.44 N, for each solution.

2.3 Liquids used

Three kinds of Newtonian liquids were used as non-elastic liquids: 10% glycerol solution (on volume basis), 30% and 50% starch syrup solutions (on weight basis) in distilled water. For comparison with these, 100ppm and 200ppm polymer solutions (on weight basis) were utilized: polyethylene oxide of grade number 18 (PEO 18) manufactured by SEITETSU KAGAKU in Japan.

Average temperatures and measured properties of these solutions are shown in Table 1. Tests were performed within ±2°C of average temperatures and with a constant volume of liquids (15cc). It is known that PEO solutions have Newtonian viscosity and elastic properties over the range of concentrations and temperatures in this experiment.(6)(7) In consideration of polymer fracture with high shear flow, fresh PEO solutions were used on each occasion in this test. Solutions will be referred to as shown in Table 1.

Table 1 Properties of solutions

Solution	Temp. T °C	Density ρ g/cm^{-3}	Viscosity η $\times10^3 Pa\cdot s$
Gly. 10%	30.8	1.02	1.08
S.Syrup 30%	16.8	1.09	3.51
S.Syrup 50%	18.8	1.19	11.3
PEO 100ppm	30.6	1.00	0.857
PEO 200ppm	30.2	1.00	1.05

3. Results

3.1 Outline

Figure 2 illustrates a state of lens and liquid in the rolling movement, and a corresponding picture on the film. Following observations were made on this movement: (1) when the lens rolled along the X axis (see Fig. 2 lower), a cavity was generated behind the center of near-contact (center of Newton's rings) between the two surfaces, then developed and finally disappeared with this rolling movement; (2) simultaneously, the lens was lifted with the liquid flow by the order of sub-micron in height. In this chapter, the following comparisons will be made between 10% glycerol solution and 200ppm PEO solution of nearly the same viscosity: (1) the rolling movements; (2) the locations of the cavity; and (3) the height of lifted lens. Furthermore, in some cases, the data on 50% starch syrup solution will be shown to examine the viscosity dependence.

3.2 Rolling movement

Rolling time from the beginning of the movement is plotted against the center location of the near-contact on the X axis in Figs. 3 (a)∿(c), (for 0.44N). The rolling speeds are inverse to the slopes of the lines drawn through the data. The speeds during the initial movement have no change as shown in Fig. 3 with broken lines, and become larger as the initial contact point is shifted toward the negative X because of the increase of initial moment. Similar trends were seen for different loads and solutions (not shown here).

Comparison between glycerol solution (Fig. 3 (a)) and PEO solution (Fig. 3 (b)) shows that they are similar in values of data. For starch syrup solution, data and the slopes were about 10 times larger than those for glycerol and PEO solutions (see Fig. 3 (c)).

The meaning of arrows indicated in Fig. 3 will be described in section 3.4 together with the results of lifted lens height.

3.3 Center location of cavity

Center of the cavity generated in the rolling movement is considered to be located at the center of negative pressure region formed behind the center of near-contact. From this viewpoint, the distance dXc between the center of near-contact and the center of the cavity is plotted against the center location of near-contact in Figs. 4 (a,b). Data for 0.44N correspond to those in Figs. 3 (a,b). Since the cavity changes in shape and

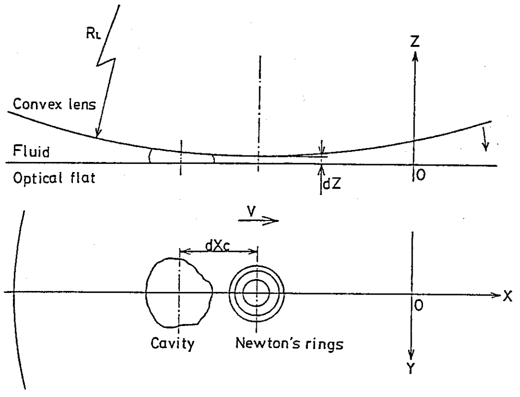
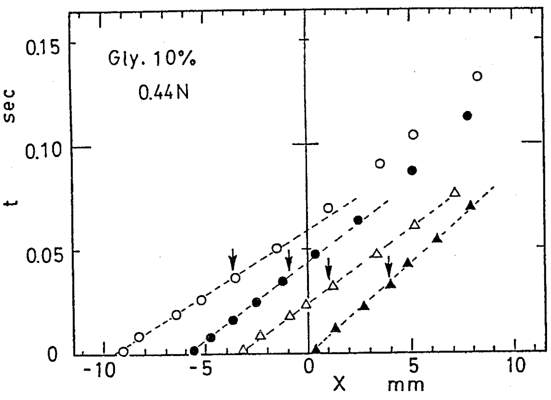


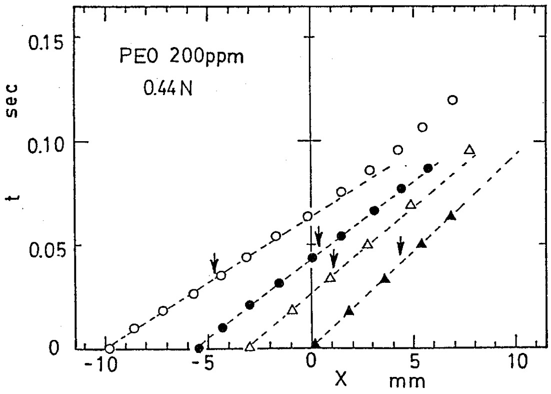
Fig.2 Schematic representation of the lens and the liquid in rolling movement, and a corresponding picture on the film

disappears at the final stage, appreciable errors are included in the values of dXc. Nevertheless the following results are revealed: The values of dXc are larger with an increasing load F. For the same load, dXc increases and approaches constant values during the initial movements by taking similar paths. Therefore it is considered that these constant values depend on the initial constant speeds which were shown in section 3.2.

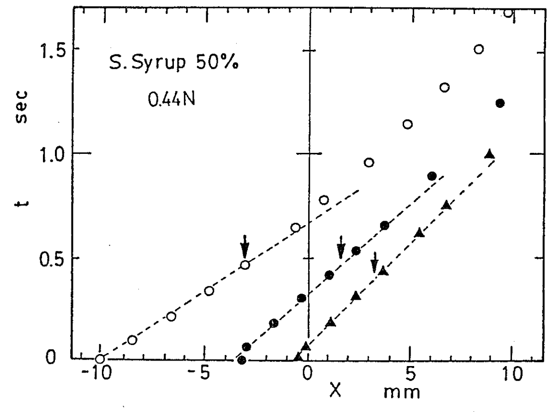
Comparison between Figs. 4 (a) and (b) shows larger values of dXc for PEO solution than those for glycerol solution under the same conditions. Then it would be expected that they had different stress fields in liquid films.



(a) Glycerol 10% solution.

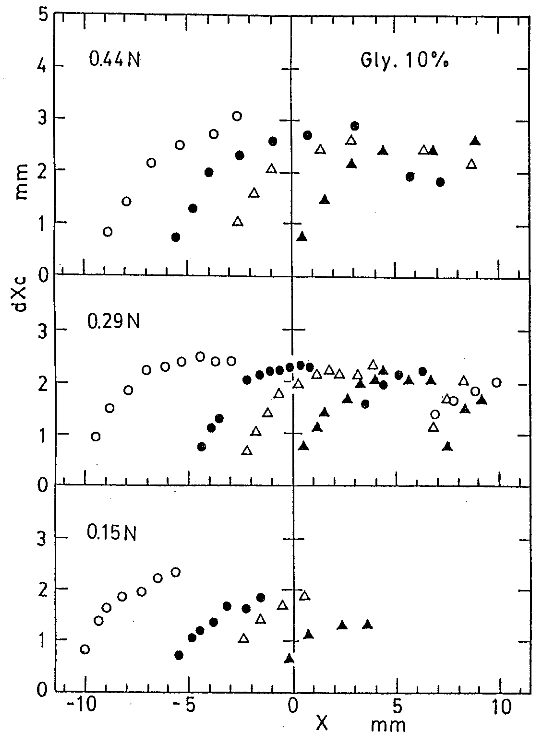


(b) PEO 200ppm solution.

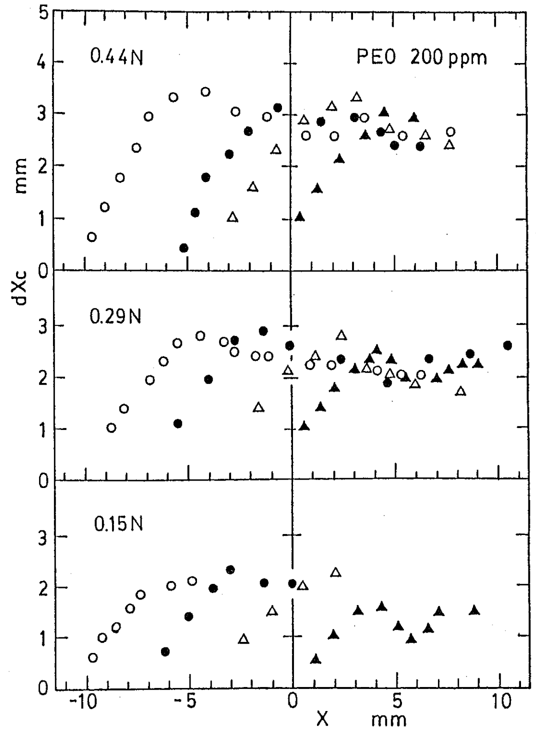


(c) Starch syrup 50% solution.

Fig.3 Rolling time against the location of the near-contact center (F=0.44N).



(a) Glycerol 10% solution.



(b) PEO 200ppm solution.

Fig.4 Center location of cavity: Distance between the center of near-contact and the center of the cavity versus the center location of near-contact.

3.4 Height of lifted lens

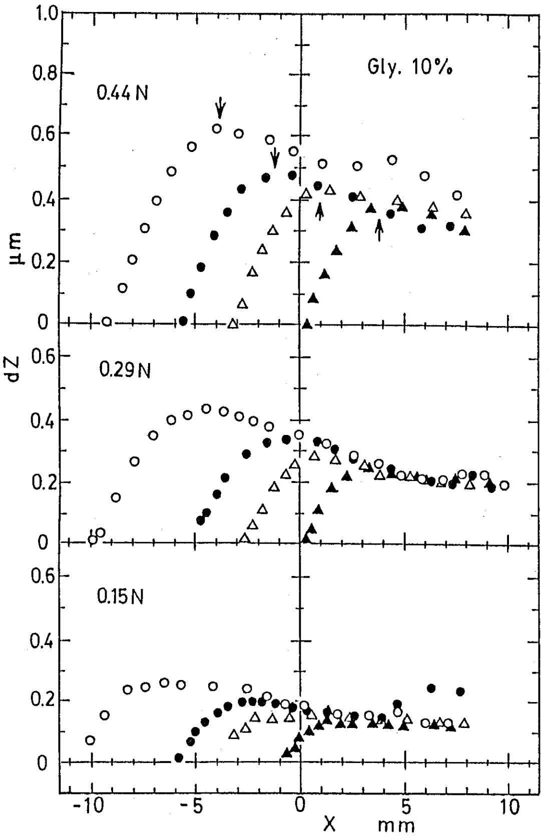
In relatively slow rolling movements as realized in this experiment, the rolling lens will be lifted by a liquid film generated by the squeezing flow. Hence, we will identify the measured height of lifted lens with the thickness of squeezing liquid film. Then, the thickness dZ is presented against the location of near-contact center in Figs. 5 (a)∿(c). Its correspondence to Fig. 3 is the same as for Fig. 4. These figures show that the thickness of liquid film increases to a maximum value during the initial movement of constant speed and then decreases slowly. The values of dZ increase with an increase in load. When the initial contact point is located at the negative coordinate X of larger value, the maximum of dZ at the same load becomes larger, but the values of dZ decrease through similar processes. Arrows point to the maxima of dZ in Fig. 5 and correspond to those indicated in Fig. 3 having the same positions on the abscissa X. Taking account of the positions of arrow in Figs. 3 and 5, it is obvious that the thickness of liquid film reaches the maximum during the movement of constant speed.

Comparison between Figs. 5 (a) and (b) shows that PEO solution has thicker liquid films than glycerol solution under the same conditions. Therefore it is supposed that PEO solution generates a different stress field from the one of glycerol solution in squeezing flows and this difference would be related to the negative pressure regions mentioned in section 3.3. The data on 50% starch syrup solution (Fig. 5 (c), for 0.44N) show that this solution has the thickness of the liquid film of the same order as the other solutions (glycerol etc.). The cause may be the high viscosity and the resulting low rolling speed in 50% starch syrup solution.

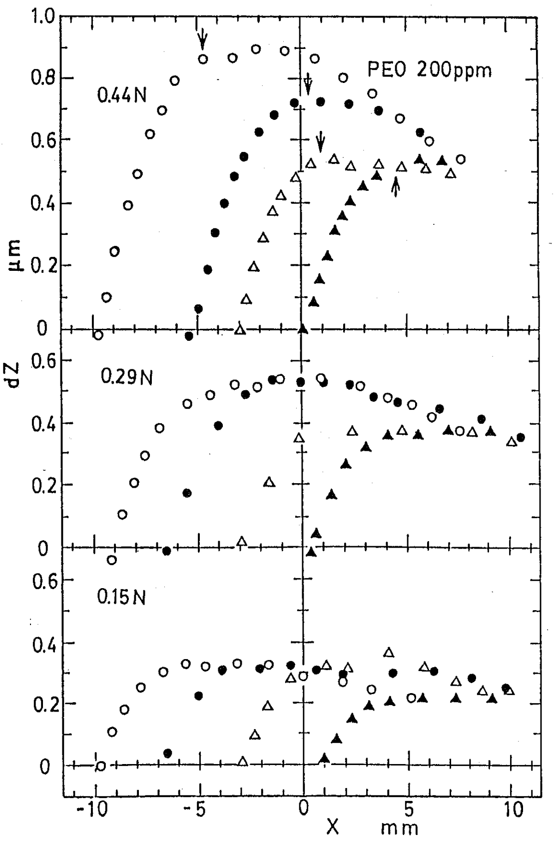
4. Discussion

4.1 Simplifications

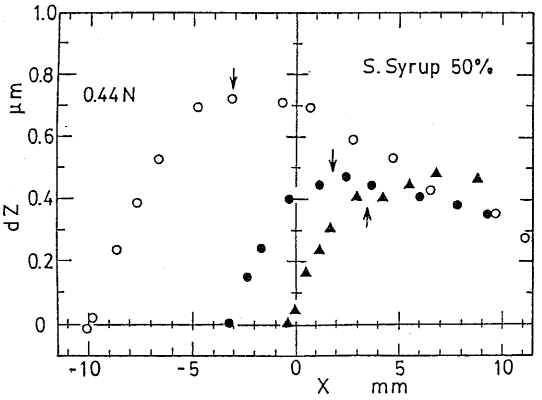
In this chapter, the dependence of viscosity on the experimental results is



(a) Glycerol 10% solution.



(b) PEO 200ppm solution.



(c) Starch syrup 50% solution (F=0.44N).

Fig.5 Thickness of squeezing liquid film against the centerlocation of near-contact.

generalized, so as to clarify the contribution of the elasticity of the liquid used. In this case, some simplifications have to be made in treating several factors which will be related with the results.

Firstly, it is shown in sections 3.2～3.4 that the distance dXc becomes constant and the thickness of liquid film reaches the maximum during the movement of constant speed, that is, the constant values and maxima depend on the initial rolling movement only. Therefore, it is assumed that the initial rolling movement is decided only by the initial moment applied on the contact point of lens at the beginning of the movement.

Secondly, indeed the results may be affected with the flow and pressure conditions near the edges of the lens and the flat glass. However, the clearance at these edges is considerably larger than that at the center, because of the spherical surface of lens. Therefore, it seems that the influences of the edges are negligibly small, and we will not deal with this point in the following discussion.

4.2 Initial rolling movement

Based upon these simplifications, the initial rolling movement of constant speed V will be related to the initial moment Mo, which is evaluated with the load F and the forces applied on the center of gravity, i.e. weight of the lens and buoyant force. Thus, a value ηVR_L, which has a dimension of force (like a viscosity force), is plotted in Fig. 6 as a function of Mo/R_L, the moment divided by the radius of curvature of the lens (that is, the force applied on the center of curvature). Figure 6 shows that data of ηVR_L correlate with Mo/R_L regardless of the elasticity of the liquid used. Therefore, it is considered that the initial rolling movement depends on the initial moment and the viscosity alone. In other words, it can be supposed that Fig. 6 represents a generalized viscosity force in liquid film versus an applied force on the spherical surface, so that we will make considerations of the other experimental data by using the factor ηVR_L.

4.3 Stress field in liquid film

It may be impossible to obtain the detail stress distribution in the squeezing liquid film from this experiment. It is, however, possible to estimate the stress field by using the data of center location of cavity which would be related with the region of effectively working stress for lifting the lens. Normalized constant distances $dXcs/R_L$ between the center of near-contact and the center of the cavity are plotted in Fig. 7 as a function of force ratio $\eta VR_L/W$, where W is the force applied on the liquid film, that is, W consists of the load F and the weight of the lens in the liquids (the weight of the lens in the air minus the buoyant force). Although these data include appreciable errors as mentioned in section 3.3, the data of non-elastic liquids are on a similar line in spite of the differences in load, initial position and viscosity. Consequently, it is supposed that non-elastic liquids have similar stress distributions. On the other hand, PEO solutions show little difference with respect to the concentration increase and give 20 percent larger values than non-elastic liquids, which means that the sizes of effectively working stress region of PEO solutions are larger than those of non-elastic liquids, because the center of cavity is supposed to be equal to the center of negative pressure region as described in section 3.3. This is due to the contribution of viscoelastic properties to the flow field.

4.4 Thickness of squeezing liquid film

In this section, we will deal with the maximum thickness of liquid film in the initial movement rather than the decreasing process of the thickness, because of the difficulty in normalizing the data in the process where the rolling speed varies. The maximum thickness may correspond to the productivity of thicker lubrication films. Figure 8 represents the normalized maximum thickness $dZmax/R_L$ against the same abscissa $\eta VR_L/W$ as in Fig. 7. The data of non-elastic liquids are on a similar line as in the case of section 4.3, that is, the normalized maximum thickness depends only on the force

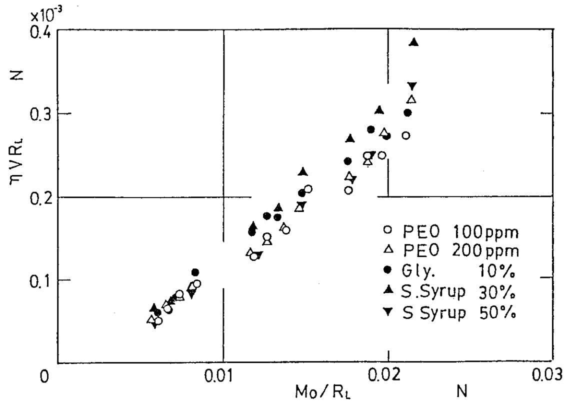


Fig.6 Generalized rolling movement

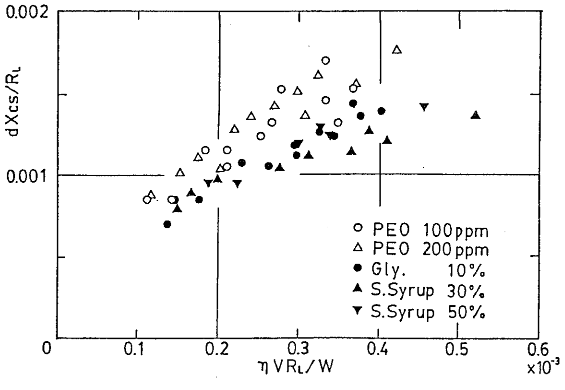


Fig.7 Normalized center location of the cavity

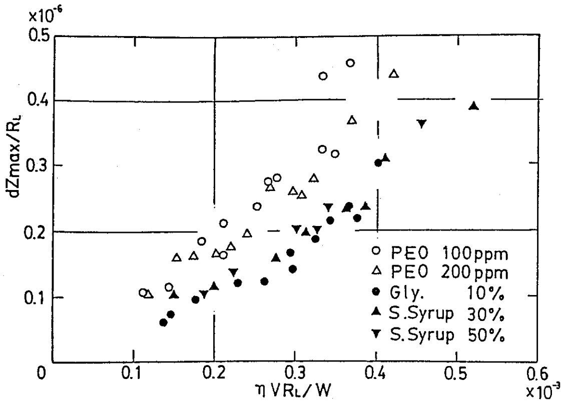


Fig.8 Normalized thickness of the squeezing liquid film

ratio of the generalized viscosity force to the applied force on liquids. On the other hand, PEO solutions show little difference between the data regardless of the concentration and give larger values than other solutions. PEO solutions may have larger productivity of squeezing liquid film in these conditions, because of an additional contribution by the elastic property. From the results in this section and the section 4.3, it is clear that the magnitude of liquid film thickness has some relation to the stress field of the liquid used.

As all the data for each solution in sections 4.2∿4.4 show no influence of the initial positions and loads, it is confirmed that, near the edges, the pressure is negligibly small and the flow is relatively slow as mentioned in section 4.1.

5 Concluding Remarks

Experiments have been made on the squeezing flow between a flat plate and a rolling spherical surface. The fluids used were dilute polymer solutions and non-elastic liquids which are Newtonian in viscosity. The following points were clarified:

(1) The initial movement of constant speed depends on the viscosity and the initial moment but it is independent of elasticity.

(2) A cavity is generated at the back of the center of near-contact and a liquid film is produced in this unsteady movement. The center location of the cavity and the thickness of liquid film were made clear.

(3) The distance between the center of near-contact and the center of the cavity depends on the initial movement, and the distances of polymer solutions are larger than those of non-elastic liquids.

(4) Thickness of liquid film reaches to the maxima in the initial movement, and the liquid films of polymer solutions are thicker than those of non-elastic liquids.

(5) The distance and the maximum thickness mentioned in (3) or (4) can be correlated with a non-dimensional factor which is related to viscosity for non-polymeric solutions. The differences between the results of polymer solutions and those of non-polymeric solutions are due to the elastic properties of polymer solutions.

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