

An experimental investigation into the dimension-sensitive viscosity of polymer containing lubricant oils in microchannels

David Erickson ^a, Fuzhi Lu ^a, Dongqing Li ^{a,*}, Tony White ^b, Jason Gao ^b

^a Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ont., Canada M5S 3G8

^b Imperial Oil Products and Chemicals Division, 453 Christina Street South, P.O. Box 3022, Sarnia, Ont., Canada N7T 8C8

Received 11 June 2001; accepted 9 October 2001

Abstract

In many lubrication processes, lubricating oils containing polymer additives are subject to high shear rate through very small clearance channels. While the influence of shear rate on the performance of these lubricants has been well examined, very little is known about the effects of channel size. In this study a specially designed microchannel viscometer has been used to experimentally characterize the influence of channel height on the effective viscosity of oil lubricants with two different polymer additives (a radial hydrogenated styrene–isoprene copolymer and an A–B–A block ethylene–propylene copolymer) commonly used as viscosity index (VI) modifiers. The mass concentration of the polymer solutions ranged from 0.5% to 1.5% in this study. The viscosity was measured over a range of shear rates in steel slit microchannels with heights of 4.5, 7 and 11.5 μm , respectively. For all solutions a significant viscosity dependence on channel size was observed. In the higher shear rate range the smaller channels exhibited a lower viscosity while in the lower shear rate range all solutions exhibited a significant increase in viscosity. Generally, this observed increase in viscosity is more dramatic in the smaller channels. Possible causes of these behaviors were discussed in this paper. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Viscosity; Microchannel flow; Polymer solutions; Lubrication

1. Introduction

All modern lubricants contain long chain polymer additives as rheology modifiers to increase high temperature performance. In many lubrication applications, lubricating oils are subject to high shear rates through very small clearance channels. While the mechanism of shear thinning or thickening associated with high shear rate has been well studied, the influence of channel size on the effective viscosity of these polymer solutions was not well known.

Likely the earliest interest in the “dimension-sensitive” viscosity of polymer solutions was in the mid 1960s while oil companies were studying the flow of polymer containing injection water through fine pores (of the order of 1–20 μm in size) as a method of enhancing oil recovery. Chauveteau and colleagues [1,2] studied this

effect for a number of different polymers and compared the results to bulk rheological data. In general it was found that the effective viscosity decreased with decreasing pore size, however more complex behavior was noted when the pore diameter approaches the size of the polymer chain. Chauveteau et al. proposed that this effect was the result of a depleted layer near the channel wall of constant thickness, independent of the pore size, creating an effective wall slip. Along these lines Aubert and Tirrell [3,4] developed a flow model based on a linear elastic dumbbell polymer model and showed that the presence of the wall tends to align the polymer molecules in the flow direction, reducing their overall contribution to the fluid stress. The results of their model were shown to be consistent with Chauveteau's observations, however it suggested that cross-streamline polymer migration could only occur in the presence of a curvilinear flow field. Later measurements by Metzner et al. [5] revealed that the presence of shear gradients in slit flow was sufficient to promote polymer migration across streamlines resulting in significant concentration

* Corresponding author. Tel.: +1-416-978-1282; fax: +1-416-978-7753.

E-mail address: dli@mie.utoronto.ca (D. Li).

Nomenclature		Greeks	
ΔP	pressure drop across the channel (Pa)	γ_a	apparent wall shear rate (1/s)
H	channel height (m)	γ_w	true wall shear rate (1/s)
L	channel length (m)	μ	viscosity (kg/ms)
H_{PL}	effective hydrodynamic thickness of the adsorbed/entangled polymer layer (m)	μ_a	apparent viscosity (kg/ms)
Q	volume flow rate (m ³ /s)	τ_0	yield stress (Pa)
R_g	radius of gyration (m)	τ_w	wall shear stress (Pa)
W	channel width (m)		

gradients in the channel cross-section (consistent with the depleted layer hypothesis). These cross-streamline polymer migration effects were later modeled by a number of authors, for example, see Ianniruberto et al. [6] using the “two-fluid” theory.

In addition to polymer migration there are a number of other effects, for example, surface adsorption [7–12], which may have significant influences on the effective microscale viscosity but be nearly unobservable in bulk measurements. While all these aforementioned studies have revealed that solutions with macromolecular components do exhibit dimension dependent flow properties, very little work has been done in quantifying this influence on the performance of modern viscosity improving polymer additives. Therefore, the objective of this study is to experimentally investigate the “dimension-sensitive” flow properties of a base lubricating oil with two modern viscosity index (VI) improving polymer additives by examining the effective viscosity over a range of shear rate in a series of slit microchannels varying in height from 4.5 to 11.5 μm . Solutions of a radial hydrogenated styrene–isoprene copolymer and an A–B–A block type ethylene–propylene copolymer (Imperial Oil) at mass concentrations ranging from 0.5% to 1.5% in a hydrocarbon base oil (EHC 45, Imperial Oil) will be investigated.

2. Experimental

2.1. Polymer characterization and solution preparation

As mentioned above, two VI improving polymer additives are of interest to this study: a radial hydrogenated styrene–isoprene copolymer and an A–B–A tri-block type ethylene–propylene copolymer. These polymers were selected for this study due to their use as practical significance as rheology modifiers in automotive engine oils. In a previous study [13] the high shear rate (10^4 – 10^6 1/s) behavior of both these polymers over a similar range of concentrations was examined. In that study solutions of the styrene–isoprene copolymer exhibited typical shear thinning behavior over the range of shear rates, while the ethylene–propylene copolymer showed much

more complicated behavior including a region of shear thickening. The styrene–isoprene copolymer examined here is a random copolymer of the star type that is comprised of numerous branches extending from a central point. The rheology of block styrene–isoprene copolymers have been investigated by a number of authors [14,15], however a literature review shows that other than [13] little work has been done in investigating the radial (star) form of this polymer type. The ethylene–propylene copolymer of interest to this study is comprised of approximately 60% ethylene units concentrated in the middle of the chain (the polymer is manufactured in a tubular reactor which allow the position of the ethylene units along the chain to be controlled). At low temperatures the ethylene segments tend to associate, reducing the overall hydrodynamic volume of the polymer and thus the low temperature viscosity of the solution. The rheology of similar ethylene–propylene block copolymers has been studied by a number of investigators [16–19]. For example, Han and Rao [18] measured the high shear rate behavior of such a polymer at 240 °C, while Kucks and Ou-Yang [17] studied its aggregation in different hydrocarbon solvents.

The molecular weight distribution of the two polymers was determined by using a gel permeation chromatography technique which yielded $M_w = 497\,000$ and $M_n = 472\,000$ for the styrene–isoprene copolymer and $M_w = 235\,000$ and $M_n = 205\,000$ for the ethylene–propylene copolymer. The analyses were carried out by Prof. Manners’ group in the Department of Chemistry, University of Toronto using a Waters 2690 separation unit and a Viscotek T90A dual light scattering and viscometry detector.

Using the criteria $c^*[\eta] = 1$ and the intrinsic viscosities of similar polymer solutions from Filiatrault and Delmas [19], a critical concentration of approximately 0.5% was estimated for the ethylene–propylene polymer, which is of the order quoted in Kucks et al. [17]. Therefore the higher concentrations of this polymer examined in this study are likely to enter the semi-dilute range where significant coil overlap begins. The intrinsic viscosity of the styrene–isoprene copolymer in similar solutions was not known, however the order of magnitude estimates from [20] suggest

that the solutions examined here lie within the dilute range.

Solution preparation was done by dissolving the polymers in the base oil by heating the solution to over 100 °C and intermittently stirring over the course of 48 h. At this temperature evaporative losses of the base oil were found to be very small, less than 0.1%, and did not affect the final solution concentration. All solution preparation was carried out in a fume hood.

2.2. Microchannel viscometer

The microchannel viscometer consists of a microchannel test cell, a *Validyne* DP22-70 differential pressure transducer, a *Barnant* Model 75225-00 constant pressure precision pump and a liquid reservoir. The pressure transducer was calibrated using a dead weight tester and have an accuracy of better than $\pm 0.5\%$ over the expected pressures range (0–700 kPa). After attaining a steady state, the pump pressure was stable within $\pm 2\%$ over the course of a typical viscosity measurement.

At the heart of the apparatus is the microchannel test cell that consists of an array of slit microchannels, each having the same dimensions (including width, length and most importantly height) and surface properties. The channels are formed by a series of five parallel plates separated by constant height spacers, to create four channels of equal height. This method of multiple channels was developed to increase the sample volume flow rate through the small microchannels, thereby reducing the amount of time required to make a measurement. For relatively large channels, of the order of 15 μm and greater, a well-developed technique using a thin film spacer to create the channel side walls has been used successfully in previous microchannel studies [21]. However for creating even smaller microchannels required for this study, a new technique was developed to form the spacers by directly coating two strips of thin polymer film on the surface. Using this film coating technique, the side walls of a parallel plate slit channel are built up by successively depositing thin layers of a coating substance on the edges of one plate. A specially designed high-precision dip-coating apparatus was developed for this purpose. The uniformity of the coated film thickness is better than 25 nm as examined by using a Tencor surface profilometer (TSP). By repeating this coating process, the coated film thickness can be controlled from 2 to over 12 μm . A slit microchannel is formed by putting another plate on top of this plate, holding these two plates in a specially designed clamp, and applying epoxy glue to seal the outside gap between the plates. The channel heights formed in this way were calibrated in the microchannel viscometer by using a Newtonian liquid (e.g., water and oils) of known viscosity. In this study steel surfaces were used to create the

channel array. Each fluid channel in the array was 15.4 mm wide and 11.0 mm long.

In the experiment, an oil-polymer additive solution at a desired concentration filled the reservoir container that is connected to the pump. The precision pump was set to a desired pressure and forced the oil to flow through the microchannel test cell. The pressure drop across the channels was monitored and measured by the pressure transducer. When a stable pressure reading was obtained, the system was assumed to have reached a steady state and a measurement could begin. The actual flow rate is then measured by collecting the liquid at the exit of the test cell and weighting it using a *Mettler* BB240 electronic balance, accurate to within ± 1 mg. In order to minimize the error, flow rate measurements were made over a sufficiently long time, of the order of a few hours maximum, so that the collected oil weighs from a minimum of 200 mg up to 1 or 2 g, depending on the channel size and the flow rate. The high vapor pressure of the oil minimized the evaporative losses. All measurements were carried out in a temperature-controlled environment at 25 °C that maintained the system within ± 1 °C, which was confirmed by direct measurement. The use of steel surfaces minimized the thermal resistance between the test sample and the environment and a detailed numerical analysis, see Section 3, was used to ensure that internal viscous heating did not significantly alter the sample temperature.

3. Results and discussion

Using the microchannel viscometer, tests were conducted over a series of wall shear rates, ranging from 50 to 3000 1/s, for polymer concentrations of 0.5%, 1.0% and 1.5% at three separate channel heights: 4.5, 7.0 and 11.5 μm , respectively. For comparison purpose, the 1.0% solutions were also tested in an additional 105 μm channel. In all cases the true viscosity and wall shear rate have been calculated by using the Weissenberg–Rabinowitsch equations for slit rheometry, shown below,

$$\gamma_w = \frac{1}{3}\gamma_a \left(2 + \frac{d(\ln \gamma_a)}{d(\ln \tau_w)} \right), \quad (1a)$$

$$\mu = 3\mu_a \left(2 + \frac{d(\ln \gamma_a)}{d(\ln \tau_w)} \right)^{-1}, \quad (1b)$$

where the shear stress, apparent wall shear rate and apparent viscosity are given by Eqs. (2a)–(2c),

$$\tau_w = \frac{H}{2(1 + H/W)} \frac{\Delta P}{L}, \quad (2a)$$

$$\gamma_a = \frac{6Q}{WH^2}, \quad (2b)$$

$$\mu_a = \frac{H^3 W \Delta P}{12L Q} \quad (2c)$$

As seen from these equations, the viscosity can be evaluated by measuring the pressure drop, the volume flow rate, and knowing the dimensions of the microchannel. However, proper design and data correction are essential to ensure the results' accuracy. It is well known that effects such as viscous heating, hydrodynamic entrance length and induced viscoelastic stress at the entrance (to name a few) can have significant effects on the measured quantities and can therefore induce significant errors. The latter of these two have been minimized here by design techniques adapted from capillary viscometers, such as the low height to length ratio (on the order of 1:1000 in this case).

The influence of in-channel viscosity gradients, caused by a coupling of viscous heat generation and pressure dependent viscosity, on the results obtained from pressure-driven shear viscometer are well documented, especially for the capillary tube case [13,22–25].

To examine this effect for the slit microchannel viscometer used in this work, a numerical correction procedure presented in an earlier paper [13] was extended to the slit flow geometry. The correction procedure is based on a numerical solution of the equations for continuity, momentum and energy, coupled with experimental results and an assumed viscosity transport relation to predict the in-channel viscosity profile and to reduce the data to an apparent viscosity at a common reference temperature and pressure. When applied to the results of this study the correction was shown to be insignificant (due to the relatively low shear rates and applied pressures) and thus these effects were justifiably neglected.

3.1. Results

The results of the microchannel viscosity experiments are shown in Figs. 1 and 2 for the styrene–isoprene and the ethylene–propylene copolymers, respectively, at concentrations of 0.5% (a), 1.0% (b) and 1.5% (c). In the higher shear rate range it is apparent in nearly all cases

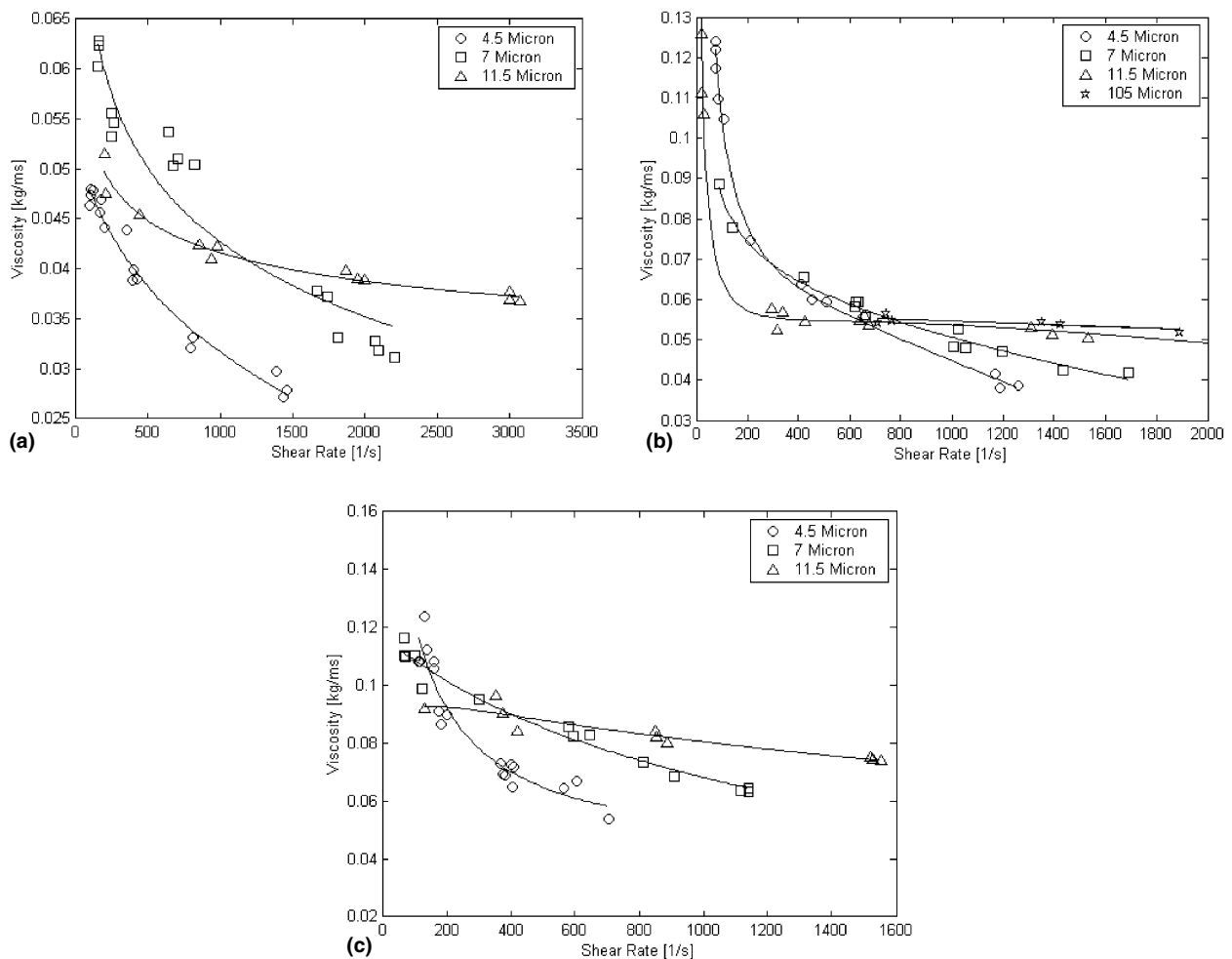


Fig. 1. Viscosity dependence on channel size for radial hydrogenated styrene–isoprene copolymer solutions at mass concentrations of (a) 0.5%, (b) 1.0% and (c) 1.5%.

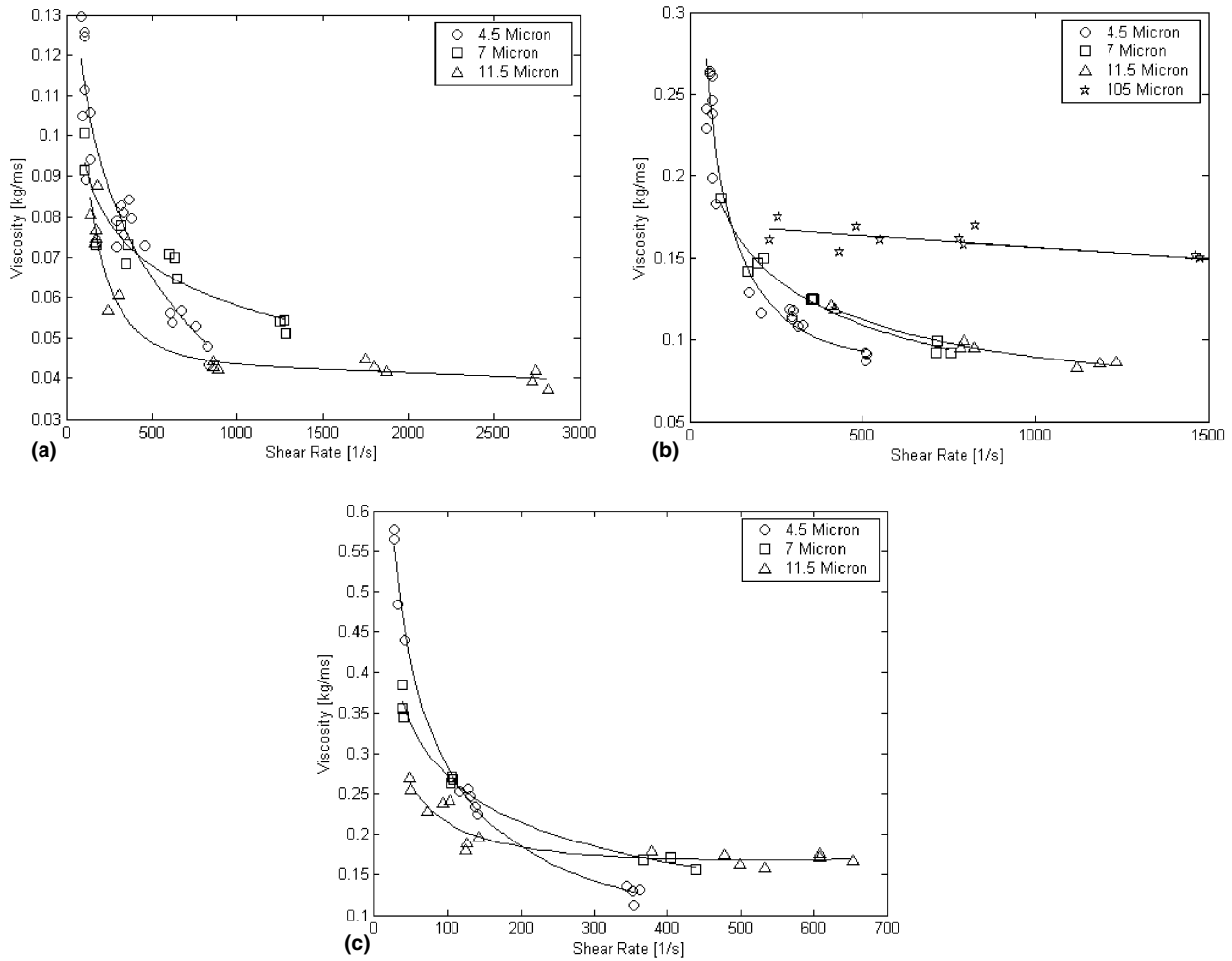


Fig. 2. Viscosity dependence on channel size for ethylene-propylene copolymer solutions at mass concentrations of (a) 0.5%, (b) 1.0% and (c) 1.5%.

that the effective viscosity of the solution decreases with channel height. It should be noted that due to an equipment limitation (namely a maximum pressure limitation to prevent dilation of the microchannel blocks) sufficiently higher shear rates could not be obtained to fully observe this behavior in the 0.5% ethylene-propylene solution. However, extrapolation from the available results in Fig. 2(a) suggests that it would follow this trend. In general this behavior became more dramatic as polymer concentration increased and appeared to be more significant in the ethylene-propylene polymer solutions. As the wall shear rate decreased, the viscosity did not reach a Newtonian plateau but rather showed an asymptotic increase. Generally, the smaller channels exhibited a more rapid increase in effective viscosity, often leading to a cross-over point below which the smaller channels began to exhibit a higher viscosity than the larger ones. Note that in Fig. 1(a) sufficiently lower shear rates were not able to obtain so that the cross-over point for the smallest channel could not be shown. However, the trend is apparent from the 7 μm channel.

In both Figs. 1(b) and 2(b) it is apparent that as channel height is increased the results for the 1.0% solutions are converging towards the bulk viscosity (measured with a 105 μm channel) over the entire range of shear rates. The slight shear thinning behavior as well as the magnitude of the viscosity observed in the 105 μm channels is consistent with the behavior reported for identical polymer solutions measured using a traditional capillary viscometer in an earlier study [13], suggesting that indeed these results do represent the true bulk viscosity.

In Fig. 3 the viscosity of the base oil alone, as measured in the three microchannels of interest, is compared with bulk rheological data (again as measured from with a capillary viscometer) from Erickson et al. [13]. Note that the capillary viscometry data shown in this figure has been corrected for the temperature difference between the two studies using the procedure outline in [13]. As can be seen very good agreement is obtained between the two results, validating the method and apparatus. As expected the base oil data does not show a viscosity dependence on shear rate suggesting that indeed the

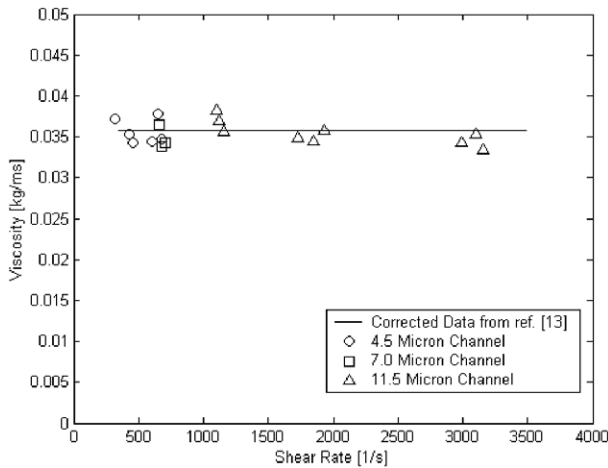


Fig. 3. Comparison between viscosity of EHC 45 base oil as measured with microchannel viscometer and capillary viscometer. Capillary viscometer data taken from [13].

anomalous viscosity observed in Figs. 1 and 2 is the result of addition of the polymers.

3.2. Discussion

The apparent thinning with channel size observed at the higher shear rates is consistent with the slip flow condition resulting from the cross-streamline migration of the polymers chains. The fact that the thinning or the slip flow appears to be enhanced (i.e., the absolute viscosity loss is greater) with the polymer concentration is in agreement with the results obtained for fine pores by Chauveteau as mentioned earlier [1,2]. As was indicated in Section 2.2 the microchannels used in this study were constructed from steel and thus it is possible that the effective thickness of this “depleted zone” was enhanced by the relative roughness of the surface, however further experiments would be required to verify this hypothesis.

In bulk rheological studies, the failure of a polymer solution to reach a Newtonian plateau and a dramatic asymptotic viscosity is usually attributed to the presence of a yield stress, below which the solution acts like a solid and thus can withstand this level of stress without shear. In slit flow, as the wall shear stress is decreased and a significant portion of the cross-sectional stress profile falls below the yield stress, a plug-flow type velocity profile is obtained. Under the plug-flow assumption the apparent viscosity in a slit microchannel is described by Eq. (3), see [26],

$$\mu = \mu_a \left(1 - \frac{3}{2} \frac{\tau_0}{\tau_w} + \frac{1}{2} \left(\frac{\tau_0}{\tau_w} \right)^3 \right), \quad (3)$$

where μ_a is the apparent viscosity as given by Eq. (2c). Since the yield stress, τ_0 , is a property of solution and not the channel, it is apparent that the plug-flow cor-

rection is a function of the wall shear stress only and should be independent of channel height. If the observed rapid increase in the viscosity values shown in Figs. 1 and 2 were purely the result of a yield stress, one would expect that a plot of the apparent viscosity, Eq. (2c), vs. wall shear stress, Eq. (2a), would show a consistent increase in apparent viscosity, independent of channel size. Figs. 4(a) and (b) show such a plot for the 1.5% solutions of the styrene–isoprene and ethylene–propylene copolymers. Apparently this is not the case as the smaller channels show a significantly more rapid increase in viscosity than the larger ones. As such the presence of a yield stress cannot fully account for the observed behavior and some other effect must be at least present, if not dominant.

As mentioned above, the formation of adsorption/entanglement layers in flowing high molecular weight polymer solutions has been discussed by a number of authors [7–12]. These multi-molecular layers are often thick (up to 100 μm have been reported) and are built

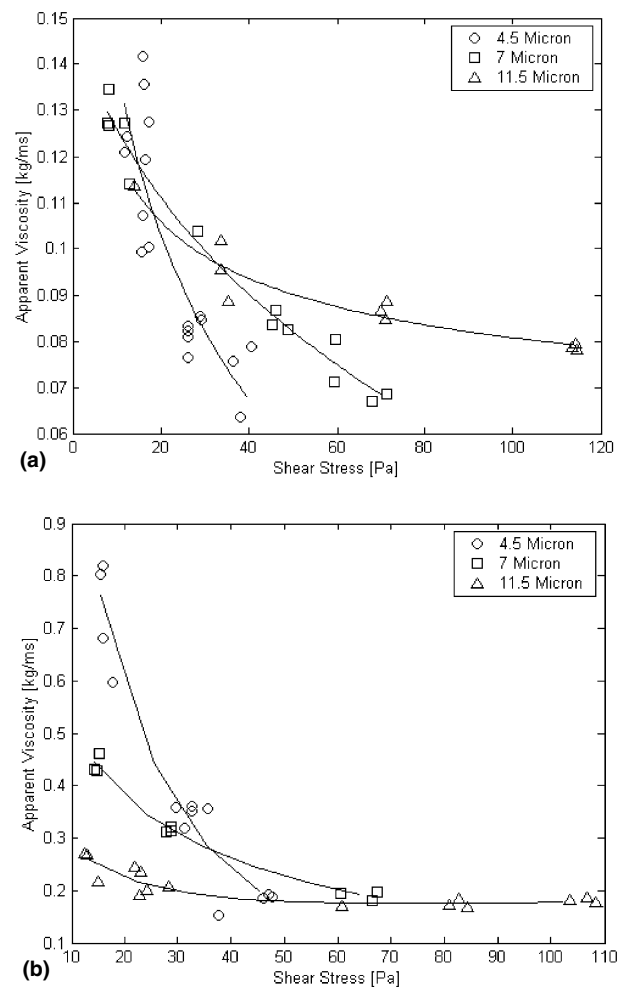


Fig. 4. Relationship between apparent viscosity and wall shear stress for 1.5% solutions of (a) styrene–isoprene copolymer and (b) ethylene–propylene copolymer solutions.

up on solid surfaces in contact with the flowing polymer solution, resulting in an effective reduction in the hydrodynamic cross-sectional area (the reader is referred to the series of papers by Barham and co-workers [7–10] for complete details of this effect). In general most studies have shown that the effective hydrodynamic thickness (EHT) of the adsorbed/entangled layer is inversely proportional to the wall shear rate. Note that some studies in ultra-fine porous media, where the pore size is near the radius of gyration of the polymer chain, have observed the opposite behavior [27]. The H/R_g ratio for the microchannels examined here is assumed to be relatively large (based on a maximum R_g estimate of 200 nm for a similar ethylene–propylene copolymer in hydrocarbon solvents from [17]) therefore, making the inverse proportionality likely more relevant in this study, however further examination of the true radius of gyration of both polymers in this particular solvent would be required to fully characterize the observed behavior. For the slit flow geometry considered in this work, the change in the apparent viscosity resulting from the presence of an adsorbed layer can be described by Eq. (4),

$$\mu_a = \left(\mu \left/ \left(1 - \frac{2H_{PL}}{H} \right)^3 \right), \quad (4)$$

which is derived from Eq. (2b) by comparing equivalent $\Delta P/Q$ ratios for the expected channel height, H , and the true channel height accounting for the thickness of the adsorbed layer, $H - 2H_{PL}$. From this equation it is apparent that at equivalent H_{PL} , the effective viscosity in smaller channels will necessarily be higher. Thus as the shear rate is decreased and H_{PL} increases, the reduced hydrodynamic mobility of the solution due to the adsorbed/entangled layer could begin to dominate over the increased mobility due to the depleted layer (i.e., effective wall slip), and the smaller channels should begin to show a higher effective viscosity than the larger ones. While such a prediction is consistent with the data shown in Figs. 1 and 2, further experiments, such as a direct measurement of the adsorbed layer thickness, would be required in order to verify the presence of this mechanism.

4. Conclusions

Using a specially designed microchannel viscometer, this study has shown that both the radial hydrogenated styrene–isoprene and block ethylene–propylene polymer additives in a hydrocarbon base oil do exhibit a significant viscosity dependence on channel height. Generally, at higher shear rates the effective viscosity decreased with the channel size, which may be attributed to cross-streamline polymer migration resulting in a “depleted

zone” near the channel wall and an effective slip velocity. At lower shear rates all solutions exhibited a sharp increase in viscosity, and in most cases a cross-over point was reached below which smaller channels began to exhibit a larger viscosity than larger channels. It was discussed that the presence of a yield stress in the solution could not fully account for the observed behavior. The cross-over may result from the reduced cross-sectional area of the channel due to the presence of an adsorbed/entangled polymer layer that becomes more significant at lower wall shear rates. While the presence of an adsorbed layer could qualitatively account for the observed behavior, further experiments are required to confirm this hypothesis.

Acknowledgements

The authors would like to thank Prof. Ian Manners and Kevin Kulbaba in the Department of Chemistry at the University of Toronto for performing the GPC analysis of the polymers used in this study. The authors also wish to acknowledge the financial support of the Natural Sciences and Engineering Research Council and Imperial Oil through scholarships to David Erickson and through a research grant to D. Li.

References

- [1] G. Chauveteau, Rodlike polymer solution flow through fine pores: influence of pore size on rheological behavior, *J. Rheol.* 26 (2) (1982) 111–142.
- [2] G. Chauveteau, A. Zaitoun, Basic rheological behavior of xanthan polysaccharide solutions in porous media: effects of pore size and polymer concentration, in: *Developments in Petroleum Science 13, Enhanced Oil Recovery: Proceedings of the Third European Symposium on Enhanced Oil Recovery*, Elsevier, New York, 1981, pp. 197–212.
- [3] J.H. Aubert, M. Tirrell, Effective viscosity of dilute polymer solutions near interfaces, *ACS Polym. Preprints* 22 (1) (1981) 82–83.
- [4] J.H. Auber, M. Tirrell, Macromolecules in nonhomogeneous velocity gradient fields, *J. Chem. Phys.* 72 (4) (1980) 2694–2701.
- [5] A.B. Metzner, Y. Cohen, C. Rangel-Nafaile, Inhomogeneous flows of non-newtonian fluids: generation of spatial concentration gradients, *J. Non-Newtonian Fluid Mech.* 5 (1979) 449–462.
- [6] G. Ianniruberto, F. Greco, G. Marricci, The two-fluid theory of polymer migration in slit flow, *Ind. Eng. Chem. Res.* 33 (1994) 2404–2411.
- [7] R.A.M. Hikmet, K.A. Narth, P.J. Barham, A. Keller, Adsorption–entanglement layers in flowing high-molecular weight polymer solutions – I. Direct observation of layer formation, *Progr. Colloid Polym. Sci.* 71 (1985) 32–43.
- [8] K.A. Narh, P.J. Barham, R.A.M. Hikmet, A. Keller, Adsorption–entanglement layers in flowing high-molecular weight polymer solutions – II. The effect of the nature of the surface, *Colloid Polym. Sci.* 264 (1986) 507–514.
- [9] P.J. Barham, R.A.M. Hikmet, K.A. Narh, A. Keller, Adsorption–entanglement layers in flowing high-molecular weight polymer

- solutions – III. Solution concentration and solvent power, *Colloid Polym. Sci.* 264 (1986) 515–521.
- [10] P.J. Barham, Adsorption–entanglement layers in flowing high-molecular weight polymer solutions – IV. The rates of layer formation and decay, *Colloid Polym. Sci.* 264 (1986) 917–923.
- [11] Y. Cohen, Hydrodynamic thickness of adsorbed polymers in steady shear flow, *Macromolecules* 21 (1988) 494–499.
- [12] Y. Cohen, A.B. Metzner, Adsorption effects in the flow of polymer solutions through capillaries, *Macromolecules* 15 (1982) 1425–1429.
- [13] D. Erickson, D. Li, T. White, J. Gao, High shear-rate behavior of radial hydrogenated styrene–isoprene and block ethylene–propylene copolymer solutions, *Ind. Eng. Chem. Res.* 40 (2001) 3523–3529.
- [14] D. Roy, B.R. Gupta, Rheological behavior of short carbon fibre filled thermoplastic elastomer based on styrene–isoprene–styrene block copolymer, *J. Appl. Polym. Sci.* 49 (1993) 1475–1482.
- [15] P. Bahadur, N.V. Sastry, S. Marti, G. Riess, Micellar behavior of styrene–isoprene block copolymers in selective solvents, *Colloids Surf.* 16 (1985) 337–346.
- [16] S. Li, P.K. Järvelä, P.A. Järvelä, A comparison between apparent viscosity and dynamic complex viscosity for polypropylene/maleated polypropylene blends, *Polym. Eng. Sci.* 37 (1) (1997) 18–23.
- [17] M.J. Kucks, H.D. Ou-Yang, I.D. Rubin, Ethylene–propylene aggregation in selective hydrocarbon solvents, *Macromolecules* 26 (1993) 3846–3850.
- [18] H.D. Han, D.A. Rao, Measurement of the rheological properties of thermoplastic elastomers, *J. Appl. Polym. Sci.* 24 (1979) 225–234.
- [19] D. Filiatrault, G. Delmas, Intrinsic viscosities and Huggins’ constant for ethylene–propylene copolymers. I. Effect of the correlations of orientations in the pure components or in the solutions on the solvent quality. Viscosities in linear alkanes and three highly branched alkanes, *Macromolecules* 12 (1) (1979) 65–68.
- [20] W.J. Freeman, Characterization of polymers, in: H.F. Mark, N.M. Bikales, C.W. Overberger, G. Menges (Eds.), *Encyclopedia of Polymer Science and Engineering*, Wiley, New York, 1985.
- [21] L. Ren, W. Qu, D. Li, Interfacial electrokinetic effects on liquid flow in microchannels, I, *J. Heat Mass Transfer* 44 (2001) 3125–3134.
- [22] J.E. Gerrard, F.E. Steidler, J.K. Appeldoorn, Viscous heating in capillaries: the adiabatic case, *Ind. Eng. Chem. Fundam.* 4 (1965) 332–339.
- [23] J.E. Gerrard, F.E. Steidler, J.K. Appeldoorn, Viscous heating in capillaries: the isothermal wall case, *Ind. Eng. Chem. Fundam.* 5 (1966) 260–263.
- [24] C.E. Davies, S.T. Pemberton, J. Abrahamson, Capillary viscometry of a New Zealand coal at high pressures and shear stresses, *Fuel* 62 (1983) 417–426.
- [25] J.L. Duda, E.E. Klaus, S.C. Lin, Capillary viscometry study of non-Newtonian fluids: influence of viscous heating, *Ind. Eng. Chem. Res.* 27 (1988) 352–361.
- [26] R.B. Bird, J.M. West, Non-Newtonian liquids, in: J.A. Schetz, A.E. Fuhs (Eds.), *Handbook of Fluid Dynamics and Fluid Machinery*, vol. 1, Wiley, New York, 1996, p. 246.
- [27] Ph. Gramain, Ph. Myard, Elongational deformation by shear flow in flexible polymers adsorbed in porous media, *Macromolecules* 25 (1981) 180–184.