AD-774 968

FLOW ORIENTATION OF SHORT FIBERS IN RECTANGULAR CHANNELS

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Monsanto Research Corporation

Prepared for:

Office of Naval Research
Army Research Projects Agency

February 1974

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AD774968

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Monsanto Research Corporation

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
Flow Orientation of Short Fibers in Rectangular Channels

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*
Masaharu Takano

6. REPORT DATE

7a. TOTAL NO. OF PAGES

7b. NO. OF REFS

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
HPC 70-116

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Office of Naval Research
Washington, D. C.

13. ABSTRACT

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The effects of fiber concentration, die-geometry and flow rate on the translational and rotational motions of short fibers in concentrated suspensions are determined from cinematographic studies on model systems subjected to flow through uniform and convergent rectangular channels. Fiber concentration is varied from 60 vol. % to as low as 0.05 vol. %. The total convergence angle of the channels varies from 0 to 210 degrees; the channel thickness is comparable to or smaller than the fiber length. The viscosity of resin used is 55 p.

When fiber concentration is higher than 5 vol. %, a plug-type flow is observed in both uniform and convergent channels. However, the observed velocity of fibers is always smaller than the mean velocity of the flowing suspension. A stagnation region is observed in convergent channels when the convergence angle is larger than 120 degrees. The alignment of fibers in the flow direction exclusively occurs in convergent channels. Flow instabilities, migration of trapped air bubbles, generation of voids, deformation of fibers and flow properties are also observed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
short fibers						
composites						
fabrication						
flow orientation						
thermoset						
rheology						
rectangular channels						
model study						
concentrated suspensions						
die-geometry						
velocity profiles						
resin-fiber separation						
fiber damage						
flow instability						
stagnation						
voids						
flow resistance						
glass						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

HPC 70-116 Item A002

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February 1974

Monsanto/Washington University Association
High Performance Composites Program
Sponsored by ONR and ARPA
Contract No. N00014-67-C-0218, ARPA Order 876

Approved for Public Release: Distribution Unlimited.

FOREWORD

The research reported herein was conducted by the staff of Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled, "Development of High Performance Composites."

The prime contractor is Monsanto Research Corporation. The Program Manager is Dr. Rolf Buchdahl (Phone 314-694-4721).

The contract is funded for $7,000,000 and expires 30 June, 1974.

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INTRODUCTION

Conventional molding techniques developed for thermoplastics such as transfer-molding, injection-molding and extrusion are recently used to fabricate composites of short fibers with thermoset matrixes.[1-5] However, several difficulties arise with flow processings of short fiber composites when the operating condition established for homogeneous thermoplastics is used. The property level of short fiber composites is limited by several structural parameters,[6-12] such as fiber orientation, distribution and aspect ratio (length/diameter), void content and adhesion of resin to fiber surfaces, as well as by other constituent factors, such as fiber modulus, strength and concentration, in addition to matrix properties. Control of the structural parameters during a flow process is important if one is to utilize the superior properties of reinforcing fibers, and also to provide reproducibility and reliability of the fabricated composite. Predominant fiber-fiber interactions result in a plug-type flow in uniform channels and unsteady plug flow in convergent channels, particularly when the viscosity of dispersing medium is low. The change in orientation of fibers is mainly determined by the local velocity gradients around the fiber center. When the fiber length is comparable to the size of flow channels, both translational and rotational motions of fibers are also significantly affected by the channel wall.[13]

One way of establishing optimum conditions for a flow process of short fiber composites is a direct observation of fiber behavior in flowing concentrated suspensions as a function of operating variables.[13,14] In this study, the effects of fiber concentration, die geometry and flow rate on the fiber behavior and flow properties of concentrated fiber suspensions are observed. The viscosity of resin used in model systems is as low as 55 poises. Rectangular channels are used to eliminate the optical distortion at channel walls.

EXPERIMENTS

Displacement, orientation and deformation of tracer fibers, behavior of trapped air bubbles and generation of voids in concentrated fiber suspensions flowing through rectangular channels were cinematographically studied.

a) Apparatus and Method: One of the rectangular channels used in this study is illustrated in Figure 1. Rectangular channels were chosen in order to eliminate the optical distortion caused by channel walls. The geometry of flow channels was varied by replacing the set of interchangeable aluminum inserts between two flat Plexiglas plates. The thickness of channels is either 1/8" or 1/4". The width of the top uniform channel is 1.0". The width of the bottom uniform channel is either 1/8" or 1/4" and the length is 1.0". The total convergence angle of the convergent channel which connects the top and bottom uniform channels is varied from 0° to 210°. A tight-fitting aluminum plunger is pressed down in the top uniform channel to extrude fiber suspensions through the convergent and bottom uniform channels. The plunger speeds used were 1, 2 and 5 "/min. and the load required to produce a constant flow rate was measured by using a compression cell of Instron tester. A Hycam high-speed movie camera (Red Lake Lab., Calif.) was focused on the central x-y plane passing through the channel axis and the fiber behavior in the central x-y plane was recorded in film at the speed of 30 pictures per second. The velocity profile of tracer fibers mixed with other transparent fibers was measured to determine the mechanism of fiber orientation and resin-fiber separation in the flowing suspension. The orientation of tracer fibers was analyzed in terms of the angle, θ_z, and the asimuthal angle, ϕ_z, of the fiber axis to the observation axis (z-axis), as defined in Figure 2. Fiber deformation, void generation and migration of trapped air bubbles in flowing suspensions were qualitatively observed. All measurements were carried out at room temperature, 24°C $\pm$ 0.5°C.

b) Suspensions: To make the above cinematographic study possible, optically distortion-free, transparent concentrated fiber suspensions were prepared from heat-treated, E-glass fibers and a resin mixture of Epon Resin 828 (Shell Chem. Co.) and polyglycol oil (Ucon Oil LB-1715, Union Carbide). Commercially available, chopped E-glass fibers (1/8", 1/4" and 1/2" in length and 0.6 mil. in diameter) were heat-treated at 600°C for 30 minutes to burn the size on the fiber surfaces. Tracer fibers were made of the same glass fiber but coated with chromium oxides, and mixed with the ratio of 1:200 to other transparent fibers. Both the tracer and other transparent fibers are in loose bundles after the heat-treatment and can be easily debundled in shear flow. The viscosity of the resin mixture is 54.8 poises, which is approximated to the viscosity, 44 poises, of a typical, B-staged epoxy resin[14] (cured 52% at 125°C). The refractive index of the dispersing medium is matched to that of E-glass fiber, 1.547. The densities of E-glass fibers and the resin mixture are 2.54 and 1.13 g/cm^3, respectively. Fiber concentration was varied from 0.05 to 60% by volume. Fibers separate from the resin in several days when the fiber concentration is less than 1 vol. %. However, the separation of fibers from the dispersing medium is negligible over several months when the fiber concentration is higher than 5 vol. %. Fibers were first soaked in a dilute acetone solution of the resin mixture and the solvent was slowly evaporated. While a small amount of acetone still remained, the mixture of fibers and resin was gently stirred with a spatula. The morphology of resulting resin-fiber mixtures varies significantly as the fiber concentration increases. When fiber concentration is less than 10 vol. %, fibers are dispersed in a continuous phase of resin. A large amount of air bubbles are usually trapped in suspensions with low fiber concentrations. When fiber concentration is increased to 20 vol. %, fibers are dispersed in either continuous or discontinuous (granular) phase of resin, depending on the shearing condition used. When fiber concentration is higher than 30 vol. %, resin-fiber mixtures are in the form of granules which are similar to those used for transfer molding.[3] The resin-fiber mixture, in the form of either dispersion or granules, was packed in the top uniform channel without any attempt to align fibers in a specific direction, after one of the Plexiglas window plates was removed. When the window plate was reinstated and the resin-fiber mixture was compressed with a plunger, a transparent concentrated suspension was obtained in the top channel. Tracer fibers had nearly random orientations in the resulting suspension.

EXPERIMENTAL RESULTS

When the dispersing medium has a low viscosity and the length of dispersed fibers is comparable to the size of flow channels, a narrow exit of convergent channel is easily blocked with fibers, mostly aligned parallel to the flow direction. Such a blockage of narrow channels with fibers can be prevented by using a higher flow rate and a wider channel exit.

Presence of air bubbles and voids varies the flow rate of suspensions and also makes the visual observation of fiber behavior in suspensions difficult. Air bubbles trapped in flowing suspensions coalesce and, moving faster than fibers, migrate towards the channel axis in convergent channels and towards wall surfaces in divergent flow. Voids are generated in partially filled divergent channels[15] and at the exit of convergent channels blocked with fibers, due to a sudden drop in internal pressure. In general, transparent suspensions without air bubbles and voids were obtained in uniform and convergent channels after a steady state flow was attained.

Flow instabilities and the presence of air bubbles and voids were minimized in the following flow studies.

i) Velocity profiles:

In dilute suspensions, streamlines are parallel to the wall surfaces in uniform channels and in a straight line passing through the vertex in convergent channels. The velocity profiles observed for a 0.2 vol. % suspension of 1/8" fibers flowing through uniform and convergent channels are in good agreement with those for incompressible Newtonian fluids,[16] although fibers move slow in the vicinity of wall surfaces, compared to theoretical prediction, due to wall effects.[13]

When fiber concentration is higher than 5 vol. %, a plug-type flow is generally observed in both uniform and convergent channels. However, when the fiber concentration is as high as 40 vol. %, paths of tracer fibers frequently deviate from a straight line passing through the fiber center and the vertex in convergent channels. This deviation of fiber paths from the assumed streamline is due to the mechanical interaction between loosely bundled fibers. When the resin-fiber mixture in the form of granules is packed in the top channel for flow experiments, fibers are in loose bundles and these bundles of fibers rotate as a deformable mass in flowing suspensions.

In uniform channels all fibers move with a same velocity throughout the cross-section of the channel. The velocity, V_f, of fibers in the flow direction (x-axis) is represented by

$$V_f = \frac{Q}{W\,H} \cdot f = V_o \cdot f \qquad \ldots(1)$$

where W and H are the width and the thickness, respectively, of the channel, and Q is the flow rate, V_o the mean velocity of the suspension and f is the ratio of fiber velocity to the mean velocity. The flow rate is calculated from the speed of the aluminum plunger in the top channel.

In convergent channels, all fibers located at an axial distance, x, from the vertex of the channel move with a same velocity in the flow direction, despite the drift of fiber paths in the radial direction. The velocity, V_f, of fibers in the flow direction is represented by

$$V_f = \frac{Q}{2\alpha \times H} \cdot f = V_o \cdot f \qquad \ldots(2)$$

where 2α is the total convergence angle of the channel.

Velocity profiles observed for a 40 vol. % suspension of 1/8" fibers flowing through uniform and convergent channels are normalized with the mean velocity and illustrated in Figure 3. The observed velocity of tracer fibers is always smaller than the mean velocity of the suspension, indicating that fibers are lagging behind resin flow due to wall effects. The velocity ratio, $f = V_f/V_o$, observed for various suspensions flowing through uniform and convergent channels is shown as a function of channel size, fiber concentration and the convergence angle of the channel in Figure 4.

When the ratio of fiber velocity to the mean velocity of the suspension decreases, resin-fiber separation increases in the suspension and the possibility of blocking a narrow channel exit with fibers increases. The resin-fiber separation is significantly affected by the morphology of the resin-fiber mixture packed in the top channel prior to the flow study. Resin-fiber separation appreciably increases with a decrease in the channel size when fiber concentration is as low as 0.05 to 10 vol. %. When fiber concentration is as high as 40 to 60 vol. %, the extent of resin-fiber separation becomes insensitive to the channel size, but is affected by flow rate and the convergence angle of flow channels to a great extent. In general, resin-fiber separation decreases as the convergence angle of channels decreases. At a low flow rate, however, resin-fiber separation increased when the convergence angle was smaller than 40°.

When the convergence angle is larger than 120°, a stagnation region is observed in convergent channels, as demonstrated for a 40 vol. % suspension of 1/8" fibers in Figure 5. The actual converging angle of flowing suspensions was approximated by projecting the motion pictures onto a screen at slow speeds. The stagnation region increased as the flow rate increased.

ii) <u>Fiber orientation</u>:

In dilute suspensions flowing through uniform and convergent channels, fibers continue to rotate due to the shear and superposed hyperbolic flow fields. In the steady flow state, most of the fibers are oriented parallel to the flow direction.[13]

In concentrated suspensions which undergo a plug-type flow, the central core of fiber suspension is not subjected to any kind of deformation in uniform channels, but is subjected to a hyperbolic flow in convergent channels due to the reduction in the cross-sectional area. Consequently, dispersed fibers do not change their orientation in uniform channels, but are oriented parallel to the flow direction exclusively in convergent channels.

The change of fiber orientation in convergent channels due to the hyperbolic flow field[17] is expressed by

$$\tan\phi_z/\tan\phi_{zo} = (x/x_o)^{-\lambda} \text{ or } \tan\phi'_z/\tan\phi'_{zo} = (x/x_o)^{\lambda} \quad \ldots(3)$$

and

$$\tan\theta_z/\tan\theta_{zo} = \left\{\frac{(x/x_o)^{\lambda} + (x/x_o)^{\lambda}\tan^2\phi_{zo}}{1 + \tan^2\phi_{zo}}\right\}^{1/2} \quad \ldots(4)$$

where θ_{zo} and ϕ_{zo} are the angle and the azimuthal angle, respectively, of the fiber axis to the observation axis at the axial distance x_o measured from the vertex of the channel. θ_z and ϕ_z are the respective angles, defined in Figure 2, at the axial distance x. ϕ'_z and ϕ'_{zo} are $(90° - \phi_z)$ and $(90° - \phi_{zo})$, respectively. The parameter λ is a function of the aspect ratio of the fiber and the interaction of the fiber with surrounding fibers, resin and wall.

Changes in the orientation angles of a few tracer fibers with the axial position x, observed in a 40 vol. % suspension of 1/8" fibers, are demonstrated in Figure 6. The angle ϕ'_z was measured as the angle between the assumed streamline passing through the fiber center and the fiber axis, both projected onto a screen $(x - \psi$ plane). The angle θ_z was measured from the relative length, $\ell/\ell_o = \sin\theta_z$, of fibers projected onto a screen, where ℓ_o was the true length of the fiber. When the angle ϕ'_z is 0° and the angle θ_z is 90°, the fiber axis is oriented perfectly parallel to the streamline passing through the fiber center.

The λ-value experimentally determined has a broad distribution ranging from positive to negative values, as shown as a function of fiber concentration in Figure 7. These distribution curves were obtained from orientation measurements over 30 to 160 tracer fibers in each suspension flowing through a 60° convergent channel. Fibers are oriented parallel to the streamline passing through the fiber center when the λ-value is positive. The λ-value often becomes negative, however, when the fiber path deviates from the assumed streamline due to the predominant fiber-fiber interaction. The mean value, $\bar{\lambda}$, calculated from experimentally observed λ-values, is listed in Table I as a function of fiber concentration. The smallest value was observed in the 10 vol. % suspension which also showed the most remarked resin-fiber separation. The effect of flow rate and convergence angle on the mean value, $\bar{\lambda}$, observed in 40 vol. % suspensions, is shown in Table II. Although the mean values are scattering, there is a general trend that the mean value decreases with decreased convergence angle when the convergence angle is smaller than 60° and that the mean value generally decreases with increased flow rate.

Fiber orientation distributions, observed in the top and bottom uniform channels which are connected with a 60° convergent channel, are compared for various suspensions in Figure 8. These cumulative distribution curves of fiber orientations were obtained from orientation measurements over 40 to 170 tracer fibers in each channel. The solid line represents the random orinetation of fibers. The change in fiber orientation distributions demonstrated here is, however, affected by another factor, namely, the reorientation of fibers at the entrance and exit, in addition to the change in fiber orientation achieved inside the convergent channel.

When one assumes that all of the fibers oriented within the angle ϕ'_{zo} in the top channel will be oriented within the angle ϕ'_{ze} in the bottom channel, an "efficiency parameter," λ', of the convergent channel which takes into account the reorientation effect can be calculated from the fiber orientation distributions observed in the top and bottom uniform channels. λ' values were calculated at every ten degrees of ϕ'_{zo}, using a modified form of Eq. (3),

$$\tan\phi'_{ze}/\tan\phi'_{zo} = (x_e/x_o)^{\lambda'}$$

where x_o and x_e are the axial distances of the entrance and exit, respectively, of the convergent channel measured from the vertex. The mean value, $\bar{\lambda}'$, of these λ' values is listed in Tables I and II, in comparison with the mean value of λ which was determined from the transient state of fiber orientation in convergent channels. The effect of fiber concentration on the $\bar{\lambda}'$ value is comparable to that for $\bar{\lambda}$ values, except that the highest value is observed in 40 ~ 50 vol. % suspensions.[10] However, the $\bar{\lambda}'$ value shows a significant increase compared to the $\bar{\lambda}$ value when the convergence angle is small, indicating that the reorientation effect at the channel exit has a significant effect on the orientation efficiency of a convergent channel.

When the convergence angle is larger than 120°, the presence of stagnation region decreases the actual converging angle of suspensions flowing through the channel. The shear flow at the boundary of flowing and stagnant regions also contributes to the fiber alignment achieved in convergent channels having a stagnation region.

iii) Fiber deformation and dispersion:

In general, fibers are buckling in suspensions when fiber concentration is as high as 50 and 60 vol. %, due to the predominant, mechanical interaction between fibers. Fibers are more deformed in convergent channels than in uniform channels because a compression force is applied to the core of fiber suspension in convergent channels. In highly concentrated suspensions, fibers pressed onto wall surfaces are deformed as the geometry of the wall surface varies, indicating that some of the fibers may be broken at sharp corners. However, observation of fiber breakages is impossible in motion pictures of flowing concentrated suspensions since the broken pieces of fibers do not change the relative position and orientation due to the predominant interaction with surrounding fibers. In general, fibers are more deformed as the flow rate, the length of fibers and the fiber concentration increase. Loose bundles of fibers are most effectively stretched and debundled at the exit of convergent channels where the highest elongational force is available. Neither fiber dispersion nor buckling state of fibers changes in uniform channels when the dispersing medium has a low viscosity. Bundled fibers are less buckling than debundled fibers.

iv) Flow properties:[18]

In concentrated suspensions flowing through a narrow channel, both the translational and rotational motions of dispersed fibers are subjected to wall effects.[13] Particularly in convergent channels, a narrow exit is intermittently blocked with fibers when the length of fibers is comparable to the size of the channel exit. This flow instability is demonstrated by a fluctuation in flow resistance as illustrated in Figure 9. The flow resistance is defined here as the load required to produce a constant flow rate through the convergent and bottom uniform channel. The extent of flow instability can be decreased by increasing either flow rate or exit size.

The flow resistance, observed for 40 vol. % suspensions flowing through various convergent channels, is shown as a function of flow rate, fiber length and the convergence angle in Figure 10. All convergent channels used here had an exit of

1/4" in width and 1/8" in thickness. For a comparison of flow resistances, the first plateau in load is used, since this represents independence of load with the plunger displacement in the top channel. This value is shown by the broken line in Figure 9. The flow resistance of fiber suspensions flowing through a convergent channel decreases as the convergence angle decreases. In general, the flow resistance increases in the proportion to the flow rate used, indicating that the central core of concentrated fiber suspensions is lubricated with a thin resin layer on wall surfaces. Stankoǐ et al.[19] have reported the same observation results for flow properties of short glass fiber suspensions. The flow resistance also significantly increases when the length of dispersed fibers exceeds the width of the channel exit. Longer fibers are more buckling in the suspension and more frequently block a narrow exit.

DISCUSSION

The use of rectangular channels and optically transparent, distortion-free suspensions made the quantitative analysis of fiber behavior in flowing concentrated suspensions possible.

One of the purposes of this study is to determine a parameter which may be applicable to predict fiber orientations achieved by various flow processes. The orientation angle, θ_x, of the fiber axis to the flow direction, which is most frequently used for theoretical prediction of mechanical properties of short fiber composites, is given by

$$\cos\theta_x = \sin\theta_z \cdot \cos\phi_z'$$

in rectangular channels, where θ_z and ϕ_z' are predicted by Eqs. (3) and (4). In general, the angle ϕ_z' approaches 0° as the fiber flows through a convergent channel. However, the angle θ_z may increase or decrease during the convergent flow, depending on the initial angle ϕ_{zo}' of the fiber.

In convergent circular tubes, the central core of fiber suspensions is subjected to a uniaxially elongational flow field when a plug-type flow is generally observed.[14] The velocity of fibers in the flow direction is given as

$$V_f = \frac{Q}{2\pi x^2(1 - \cos\alpha)} \cdot f = V_o \cdot f$$

for a plug-type flow in conical tubes and the change in fiber orientation with the axial position is predicted as

$$\tan\theta_x/\tan\theta_{xo} = (x/x_o)^{3\lambda} .$$

Here α is the half angle of the cone. However, direct measurement of the angle θ_x in convergent circular tubes is impossible. The angle θ_x must be calculated from the other angles θ_z and ϕ'_z , as done for rectangular channels. In general, measurement of fiber orientation becomes unreliable near the wall in circular tubes, due to the optical distortion caused by the difference in refractive indices of suspension and tube wall.

When the relative size of fibers to the size of flow channels is comparable to that used for the measurement in rectangular channels, the parameter values, $\bar{\lambda}$ and $\bar{\lambda}'$, determined in this study may be applicable to predict fiber orientations achieved in circular tubes, without causing a significant error.

The effect of resin viscosity on velocity profiles and orientation distributions of fibers and flow properties of concentrated fiber suspensions are discussed in another paper.[20]

CONCLUSIONS

For concentrated suspensions of short fibers in a low viscosity resin, a plug-type flow is observed in both uniform and convergent rectangular channels when the fiber concentration is higher than 5 vol. %. The velocity of fibers is smaller than the mean velocity of the flowing suspension due to wall effects. The alignment of fibers in the flow direction occurs exclusively in convergent channels due to the elongational flow field. The extent of fiber alignment achieved after a convergent flow is a function of fiber concentration, flow rate and the convergence angle of the convergent channel.

In general, flow instabilities are observed in concentrated fiber suspensions flowing through convergent channels. Streamlines fluctuate with time in convergent channels and a narrow exit of convergent channel is intermittently blocked with fibers when the length of fibers is comparable to the size of channel exit.

A stagnation region is observed in convergent channels when the total convergence angle is larger than 120°. Fibers are buckling in suspensions when fiber concentration is as high as 50 and 60 vol. %. The extent of fiber buckling increases as the fiber length increases, and decreases when fibers are in bundles. The flow resistance of fiber suspensions flowing through a convergent channel generally decreases with a decrease in the convergence angle. However, the flow resistance fluctuates when the exit is blocked with fibers.

ACKNOWLEDGMENT

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Office of Naval Research under Contract No. N00014-67-C-0218.

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Table 1. The mean values of parameters λ and λ' observed for 1/8" fibers in suspensions flowing through a 60° convergent channel with 1/8" thickness, at the flow rate of 0.250 in^3/min.

Fiber concentration (vol. %)	λ^a	λ'^b
5	1.09	0.81 ± 0.32
10	0.73	0.00
20	0.94	0.76 ± 0.05
30	1.21	0.91 ± 0.33
40	1.28	1.24 ± 0.24
50	1.37	1.27 ± 0.12
60	2.05	0.67 ± 0.13

a) Measured from the transient behavior of individual fibers in convergent channel.

b) Measured from the fiber alignment achieved through the 60° convergent channel.

Table 2. The mean values of parameters λ and λ' observed for 1/8" fibers in 40 vol. % suspensions flowing through convergent channels.

	$\bar{\lambda}^a$		$\bar{\lambda}'^b$	
Flow rate (in^3/min)	0.250	0.625	0.250	0.625
2α, 20°	0.28	-0.59	1.56 ± 0.24	1.10 ± 0.19
30°	0.83	0.51	1.15 ± 0.19	1.42 ± 0.21
34.6°	0.33	1.24	-	-
43.2°	1.01	0.93	-	-
60°	0.68	0.37	1.24 ± 0.25	1.09 ± 0.30
	1.28			
90°	0.98	-	1.22 ± 0.21	-
120°	1.94	0.46	1.19 ± 0.20	1.09 ± 0.30
150°	1.42	0.80	0.99 ± 0.28	0.82 ± 0.22
180°	0.64	0.90	1.18 ± 0.27	1.20 ± 0.22
210°	-	-	0.93 ± 0.37	1.33 ± 0.13

a) Measured from the transient behavior of individual fibers.

b) Measured from the fiber alignment achieved through the convergent channel.

LIST OF FIGURES

Figure 7. Differential distributions of the λ-values measured in various suspensions flowing through a 60° convergent channel at $Q = 0.250$ in^3/min.

Figure 8. Cumulative distributions of fiber orientations in concentrated suspensions flowing through a 60° convergent channel at $Q = 0.250$ in^3/min: open circles are for the top uniform channel and closed circles for the bottom uniform channel.

Figure 9. Flow resistance of 40 vol. % suspensions flowing through a 34.8° convergent channel: The size of channel exit and flow rate are varied. A) 1/8" x 1/8", at $Q = 0.250$ in^3/min. B) 1/8" x 1/8", at $Q = 0.625$ in^3/min. C) 1/4" x 1/8", at $Q = 0.250$ in^3/min.

Figure 10. Flow resistance of 40 vol. % suspensions flowing through various convergent channels having an exit of 1/4" x 1/8":

a) Effects of convergence angle and flow rate for suspensions of 1/8" fibers; Curve A is for $Q = 0.250$ in^3/min and curve B for $Q = 0.625$ in^3/min.

b) Effects of convergence angle and fiber length, at $Q = 0.250$ in^3/min; Curve A is for 1/8" fibers, curve C for 1/4" fibers and curve D for 1/2" fibers.

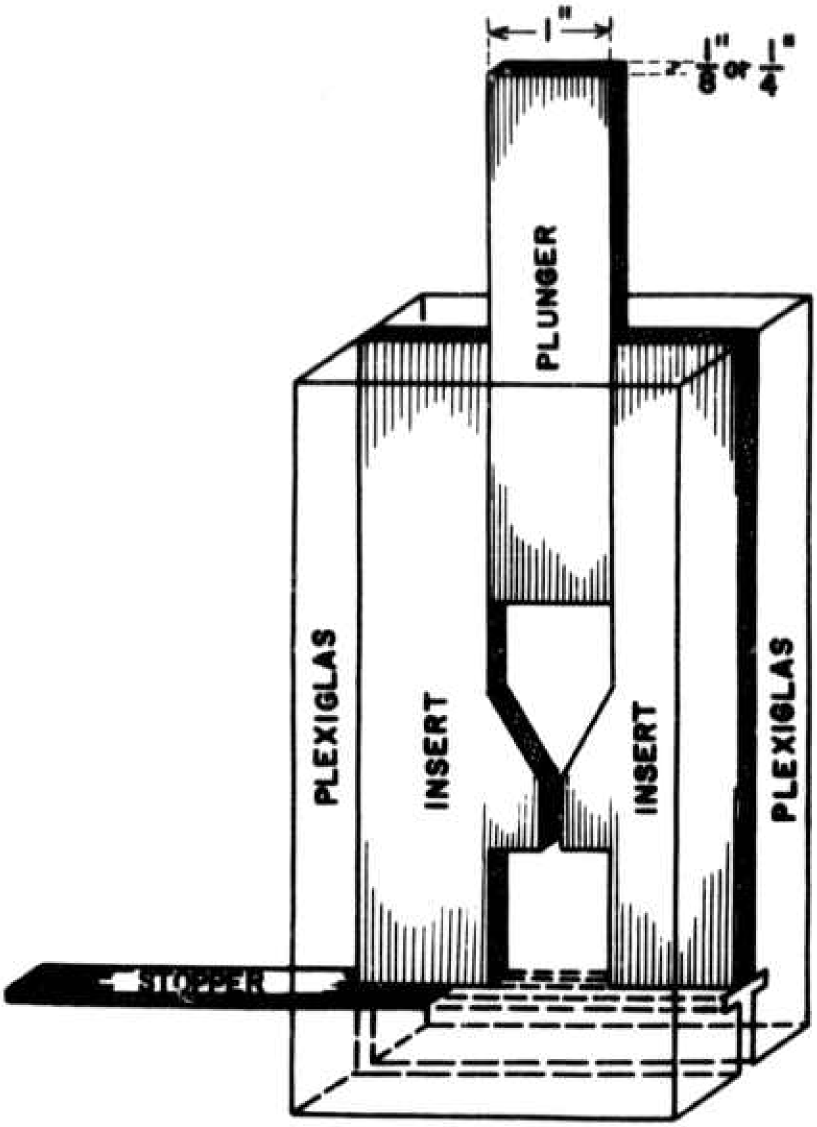
1"
1/8" or 1/4"
PLUNGER
PLEXIGLAS
INSERT
INSERT
PLEXIGLAS
STOPPER

Figure 1

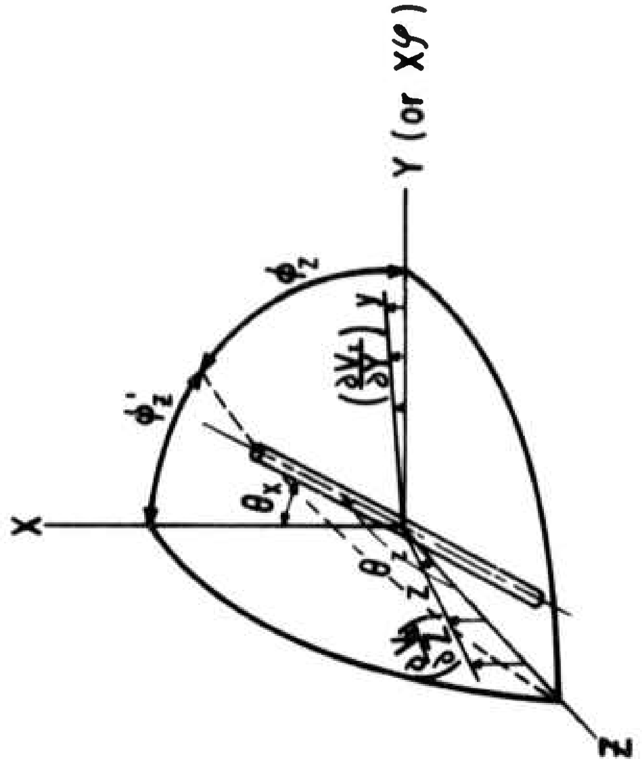

Figure 2

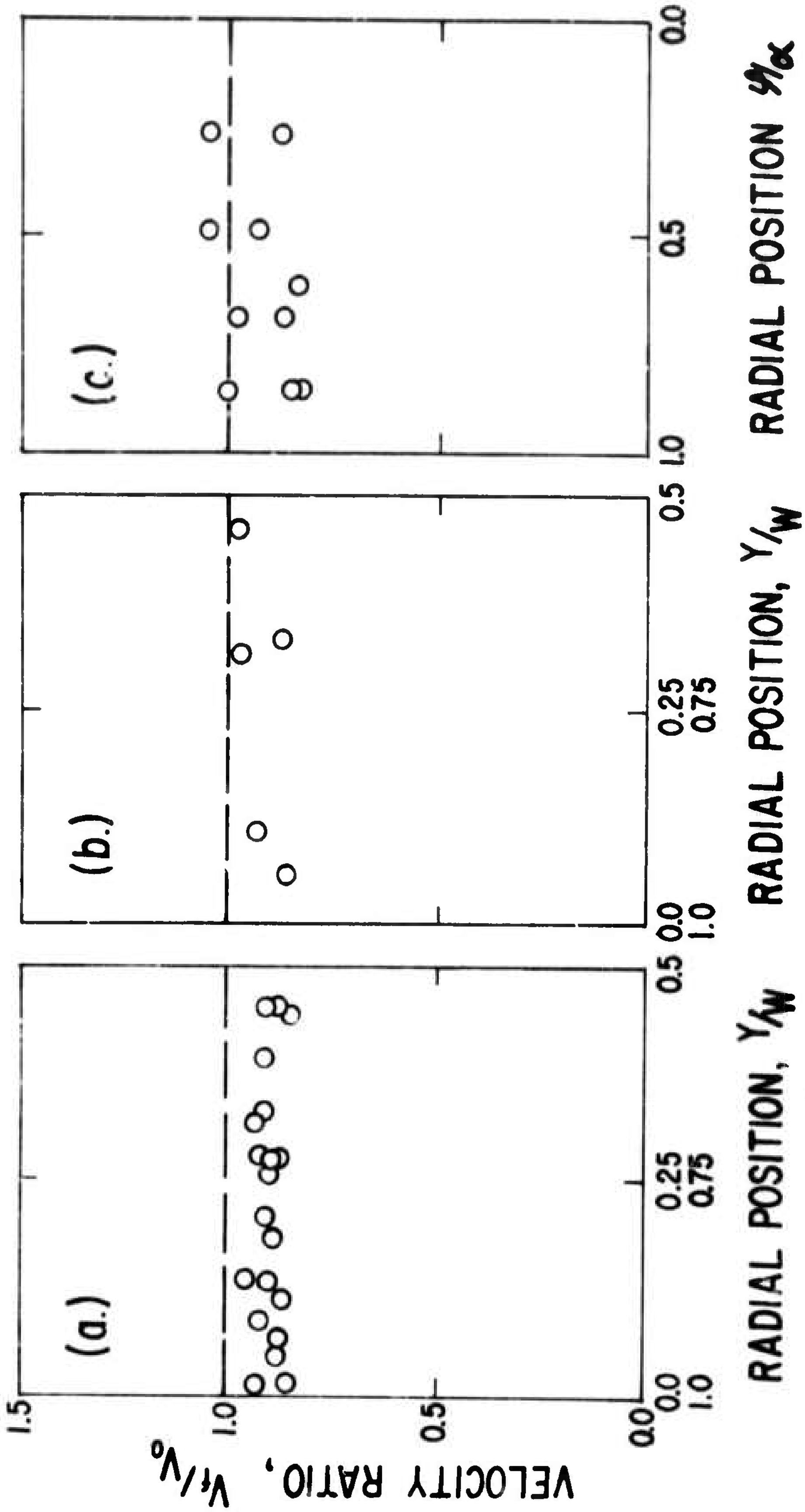
VELOCITY RATIO, V_f/V_0
1.5
1.0
0.5
0.0
(a.)
(b.)
(c.)
0.0
1.0
0.25
0.75
0.5
RADIAL POSITION, Y/W
RADIAL POSITION, Y/W
RADIAL POSITION y/α

Figure 3

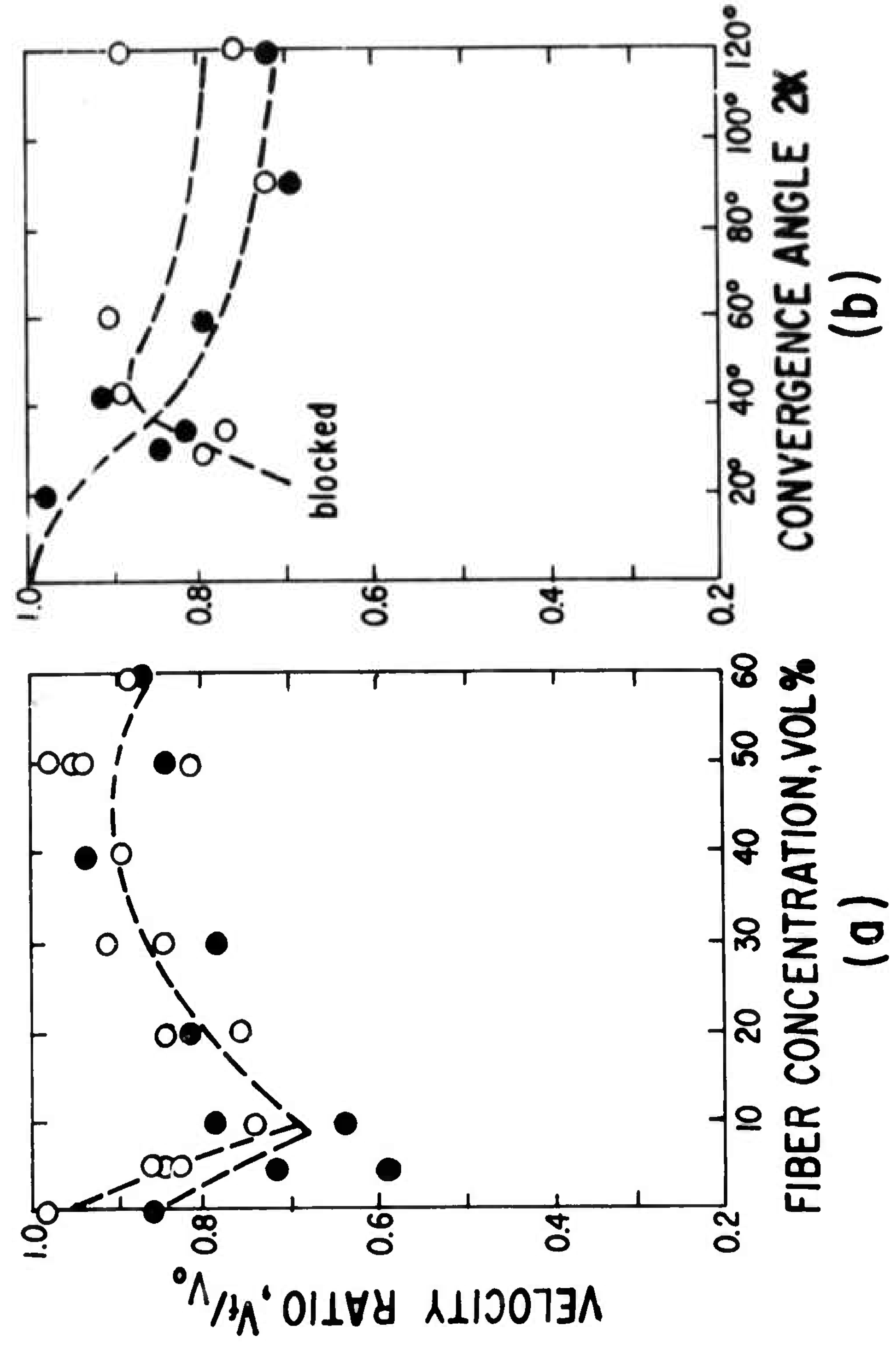
VELOCITY RATIO, V_f/V_o
1.0
0.8
0.6
0.4
0.2
10
20
30
40
50
60
FIBER CONCENTRATION, VOL %
(a)
1.0
0.8
0.6
0.4
0.2
blocked
20°
40°
60°
80°
100°
120°
CONVERGENCE ANGLE 2α
(b)

Figure 4

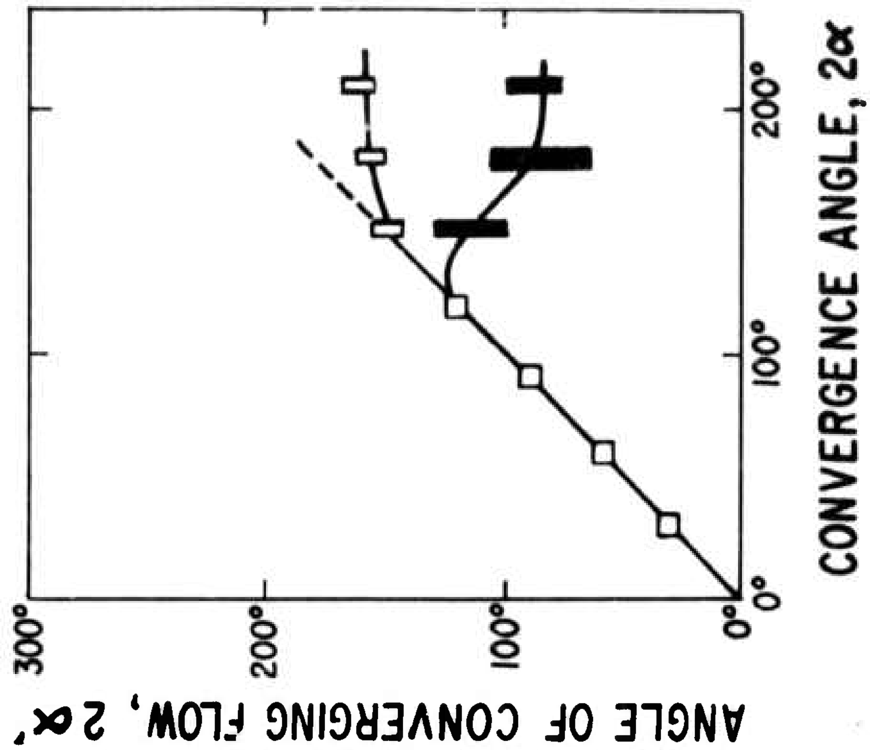
ANGLE OF CONVERGING FLOW, 2α'
300°
200°
100°
0°
0°
100°
200°
CONVERGENCE ANGLE, 2α

Figure 5

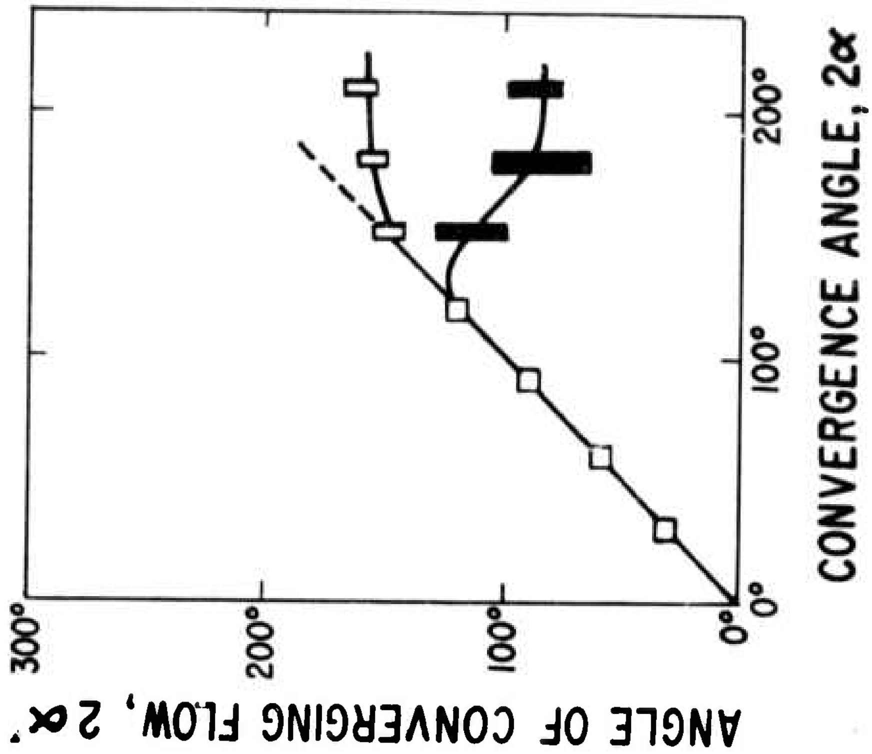
ANGLE OF CONVERGING FLOW, 2α'
300°
200°
100°
0°
0°
100°
200°
CONVERGENCE ANGLE, 2α

Figure 5

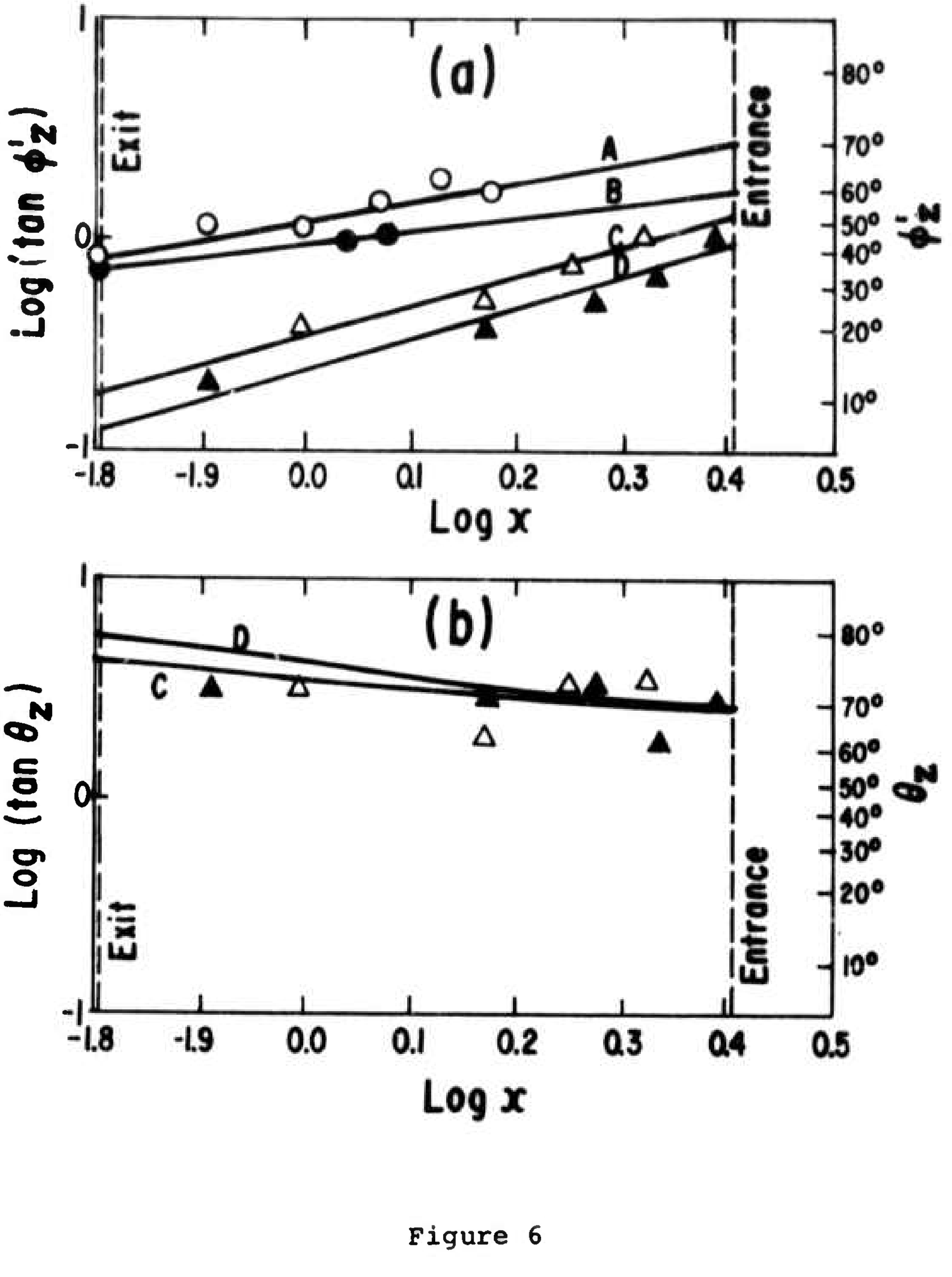
(a)
Log (tan ϕ'_z)
Exit
Entrance
A
B
C
D
1
0
-1
80°
70°
60°
50°
40°
30°
20°
10°
ϕ'_z
-1.8
-1.9
0.0
0.1
0.2
0.3
0.4
0.5
Log x
(b)
Log (tan θ_z)
Exit
Entrance
D
C
1
0
-1
80°
70°
60°
50°
40°
30°
20°
10°
θ_z
-1.8
-1.9
0.0
0.1
0.2
0.3
0.4
0.5
Log x

Figure 6

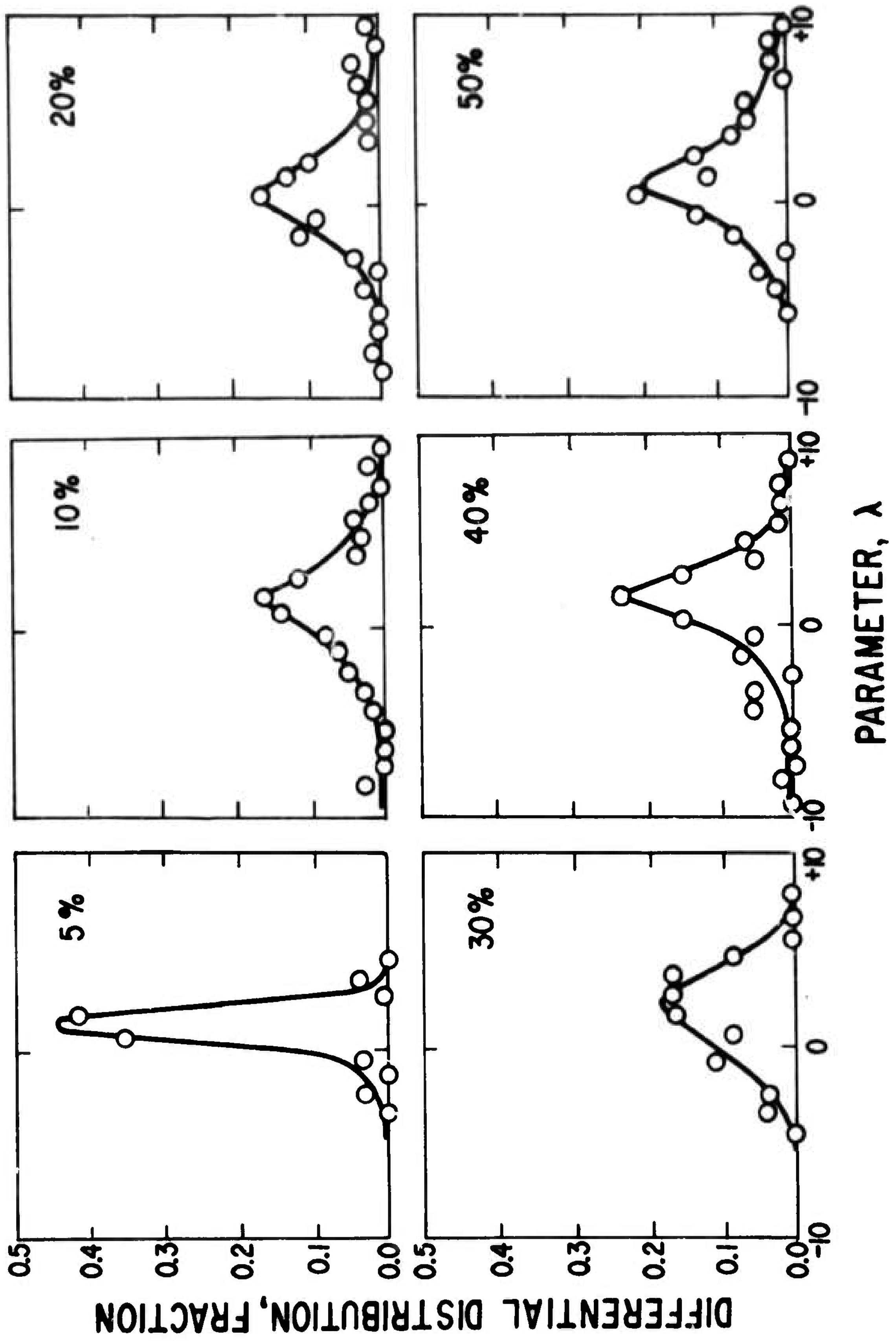
5%
10%
20%
30%
40%
50%
0.5
0.4
0.3
0.2
0.1
0.0
-10
0
+10
DIFFERENTIAL DISTRIBUTION, FRACTION
PARAMETER, λ

Figure 7

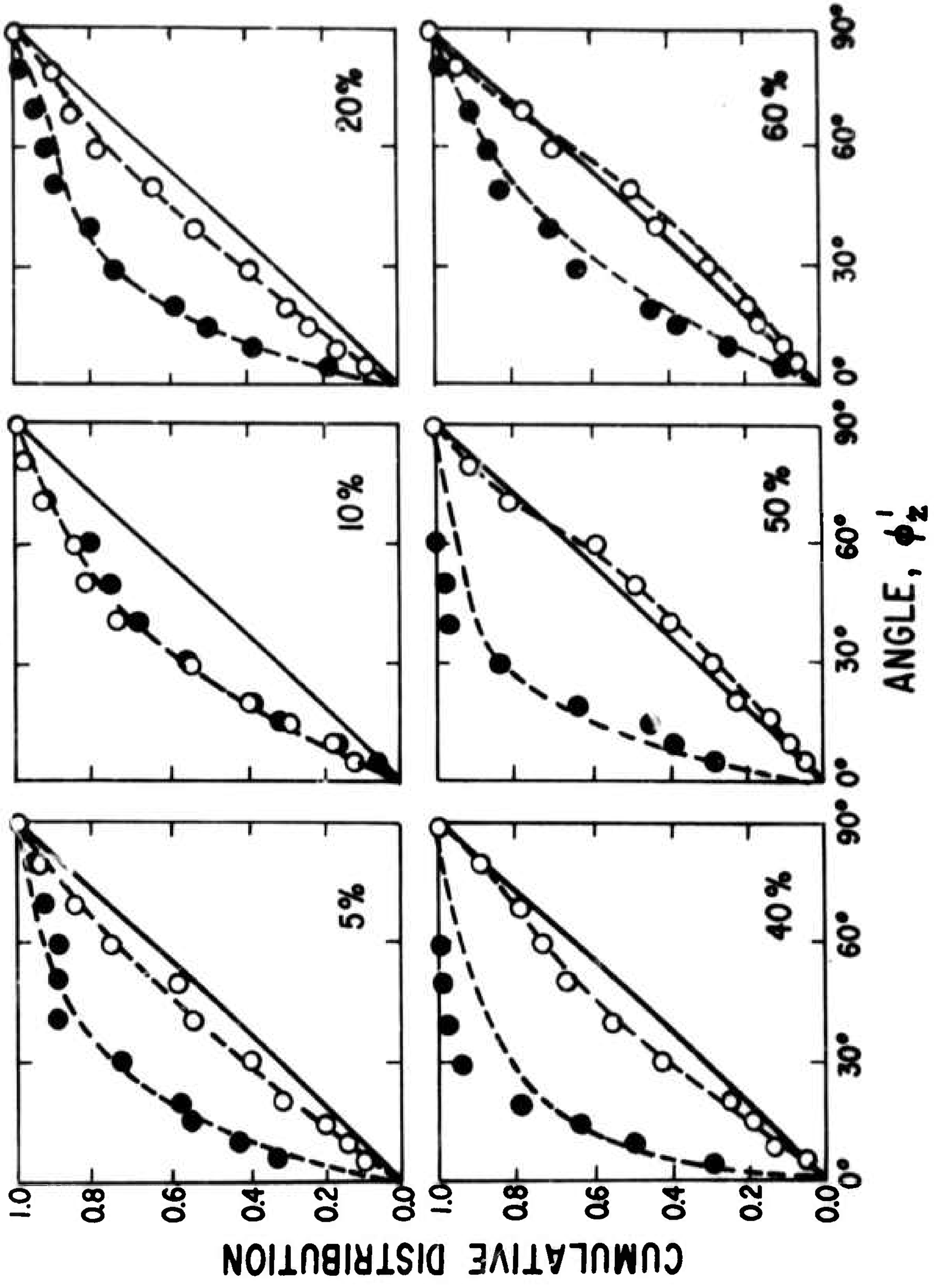
5%
10%
20%
40%
50%
60%
CUMULATIVE DISTRIBUTION
1.0
0.8
0.6
0.4
0.2
0.0
ANGLE, ϕ'_z
0°
30°
60°
90°

Figure 8

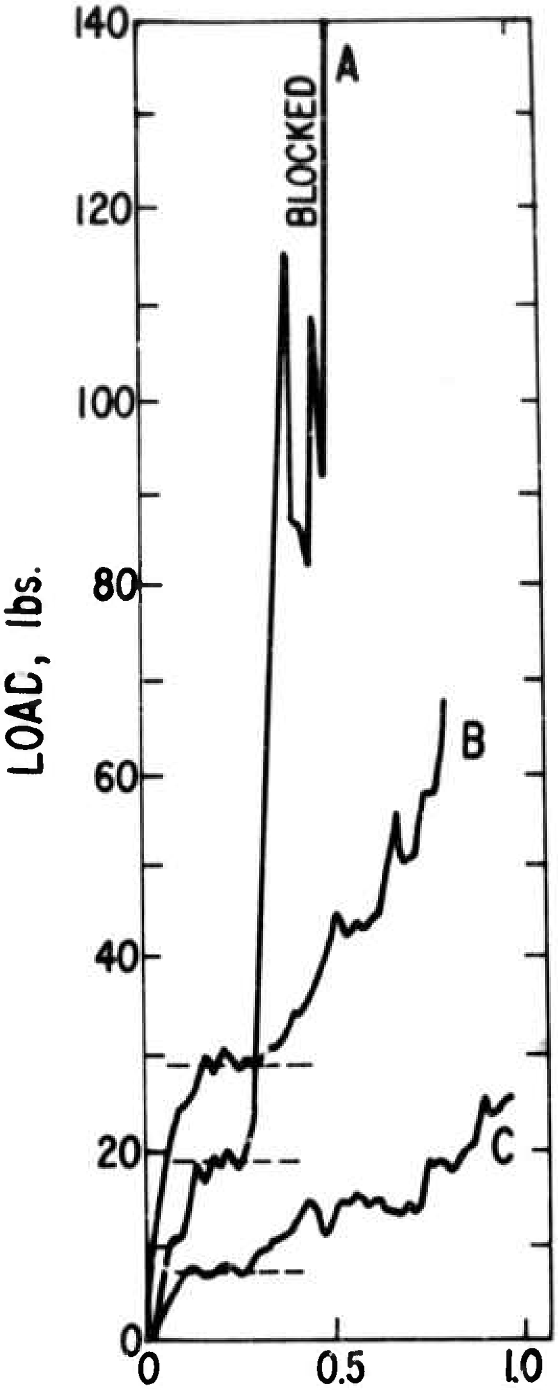

Figure 9

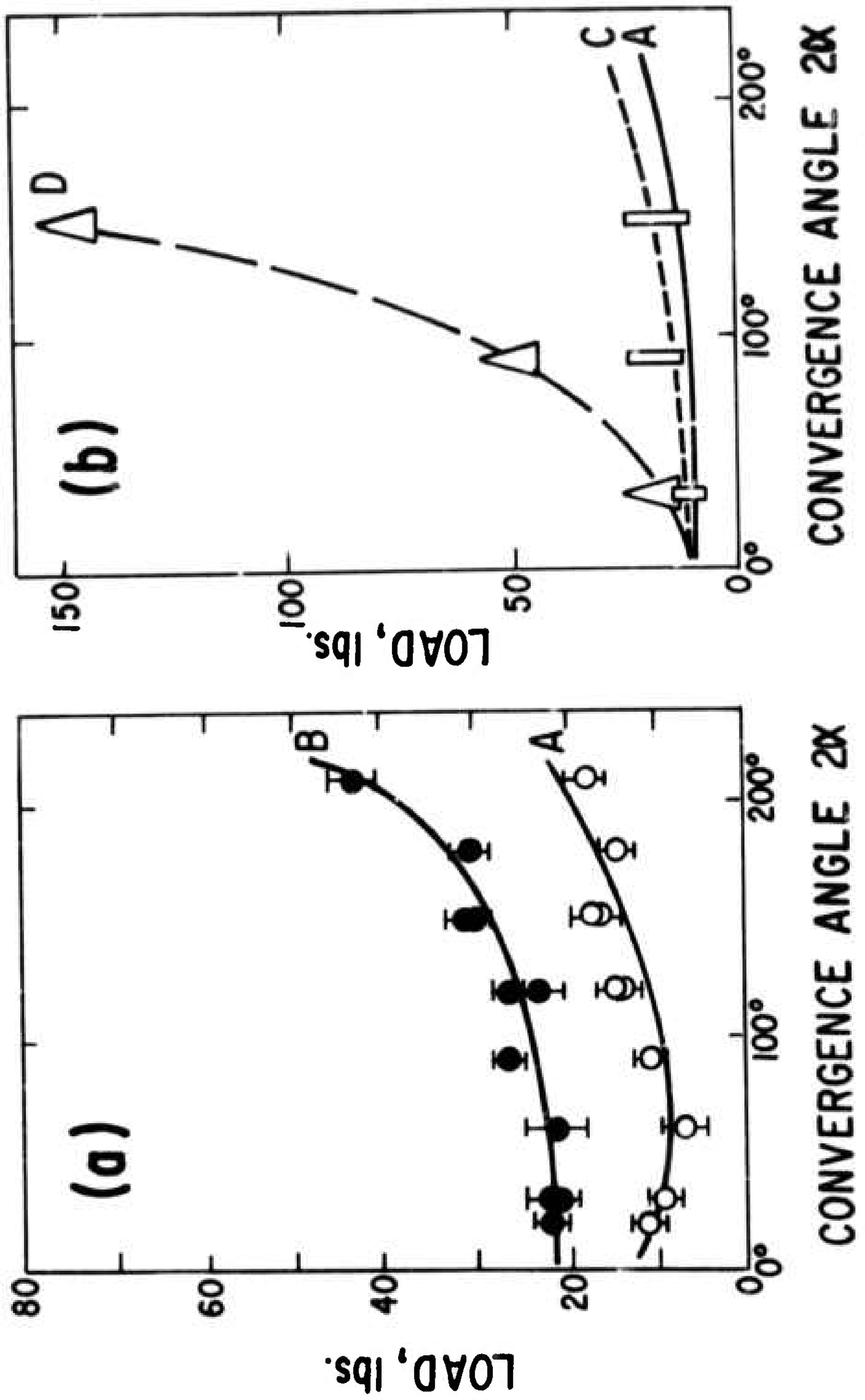
(a)
LOAD, lbs.
0
20
40
60
80
0°
100°
200°
CONVERGENCE ANGLE 2α
A
B
(b)
LOAD, lbs.
0
50
100
150
0°
100°
200°
CONVERGENCE ANGLE 2α
A
C
D

Figure 10