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VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

216 NORRIS HALL
BLACKSBURG, VIRGINIA 24061

Telephone: (703) 961-6824
TLX: EZLINK 9103331861
VPI-BKS

CHEMISTRY MATERIALS MECHANICS

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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA - Langley Research Center

Transonic Aerodynamics Division

Hampton, VA 23665

D. Somers

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from

Chemistry Department and Mechanical Engineering Department

Virginia Polytechnic Institute and State University

Blacksburg, VA 24061

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I. INTRODUCTION

Previous work showed that the total number of insects sticking to an aluminum surface was reduced by coating the aluminum surface with elastomers (1). Due to a large number of possible experimental errors, no correlation between the modulus of elasticity, the elastomer and the total number of insects sticking to a given elastomer was obtained. One of the errors assumed to be introduced during the road test is a variable insect flux so that the number of insects striking one surface might be different from that striking another sample. To eliminate this source of error, the road test used to collect insects was simulated in a laboratory by development of a new insect impacting technique using a pipe and high pressure compressed air. The insects are accelerated by a compressed "air gun" to high velocities and are then impacted with a stationary target on which the sample is mounted. The velocity of an object exiting from the pipe was determined and further improvement of the technique was achieved to obtain a uniform air velocity distribution.

II. LITERATURE REVIEW

If the shear force per unit area of any fluid is proportional to the negative of the local velocity gradient, then the fluid is defined as a Newtonian fluid. All gases and most simple liquids are Newtonian fluids (2). The axial velocity profile of the flow through a circular tube can be obtained by the equation of motion in cylindrical coordinates for a Newtonian fluid from a momentum balance and Newton's law of viscosity. For this derivation, constant density and viscosity of the fluid that are independent on the radial position in the tube are assumed. The circular tube must be long enough so that end effects can be ignored; and, a steady state air flow must be achieved so that the velocity v_z is only a function of radial position in the tube.

The dimensionless Reynolds Number (Re) for flow in a circular tube is defined as:

$$Re = D * \langle v_z \rangle * \rho / \eta$$

where

D = tube diameter

$\langle v_z \rangle$ = average axial velocity

ρ = density of fluid

η = viscosity of fluid

The flow in a very smooth circular tube is laminar when Re is < 2,100 and turbulent when Re is > 2,100 (2). The velocity of the turbulent flow fluctuates over a period of time as shown in Figure 1, so that the time-smoothed velocity by taking an average of velocity over a time interval is considered. In the immediate region of the tube wall, the velocity fluctuations in the axial direction are greater than in the radial direction. Newton's law of viscosity is used to describe the fluid flow as a function of radius. As the distance from the tube wall increases (approaching the center of the tube), the velocity fluctuations are very random and turbulent flow is fully developed (2).

For both types of flow (laminar and turbulent) the velocity distributions over a tube cross section are developed as shown in Figure 2. Thus, the axial velocity (v_z) is a function of radius (r), and the average axial velocity is obtained by:

$$\langle v_z \rangle = \frac{\int_0^{2\pi} \int_0^{R} v_z(r)dr\, d\theta}{\int_0^{2\pi} \int_0^{R} rdrd\theta}$$

where R is the radius of the tube and v_z (r) is the axial velocity which is a function of r. As shown in Figure 2, the velocity distribution over a tube cross section for turbulent flow is more uniform than for laminar flow.

III. EXPERIMENTAL

A. Determination of the Velocity

To determine the feasibility of using a controlled insect impacting method, an "air gun" was developed (1). A preliminary design was used to measure the attainable velocity for a small object accelerated by the "air gun". It consists of a PVC pipe (length: 5 feet, diameter: 1 inch), a T connector, and a nozzle as shown in Figure 3. Compressed air is passed through a nozzle placed along the axis of the PVC pipe within the T connector slightly in front of the feed chute. The high velocity of air exiting from the nozzle creates a suction behind the nozzle which induces a large inflow of air through the feed chute (T connector). This large volume of air is accelerated as it flows past the nozzle creating a high velocity flow of air in the down stream section of the pipe. Any small object which is placed in the feed chute is sucked into the pipe and ejected from the end of the pipe at high velocity. The position of the nozzle along the pipe axis is very critical, since it will determine the amount of air sucked into the pipe. The optimum position must be determined by measuring air velocity at different nozzle positions.

The exact velocity of an object exiting from the end of pipe was determined using a camera, a spherical particle, and a strobe lamp. In a completely dark environment, the light reflected from a white object illuminated by the strobe lamp used may be recorded on 3200 ASA film if the object is about 5 feet away from the strobe, operated at a frequency of 400

Hz. Spherical polyethylene particles (about 0.1 inch diameter) - were coated with chrome to achieve the maximum reflection of the light from the strobe lamp. The experiment was carried out in darkness with illumination of the particles provided by a strobe lamp. A 35 mm camera was focused on the plane of the path of the particles exiting from the end of the pipe. A sheet of black velvet was placed approximately 6 feet away from the front of the camera and behind the path of the particles to create a dark background. The position of the strobe lamp requires adjustment until the brightest image of the particle appeared in the camera viewfinder without light reflected from other surfaces interfering with the image. The final set-up of the apparatus is shown schematically in Figure 4.

First a photograph of a ruler placed along the path of particles exiting the pipe was taken using a constant (un-strobed) light source. Then keeping the position of the camera fixed, photographs of exiting particles were obtained with strobed lighting on successive frames of film. When a particle is dropped into the feed chute, the shutter of the camera is opened, and as a particle exits the end of the pipe it forms images on the film as it crosses the path of the strobed light. Since the light from the strobe is fired at a fixed frequency, the particle appears as a sequence of equidistant bright dots. The actual distance between two dots is calculated by measuring the distance between two successive dots appearing in a photograph and scaling up by the ratio between an actual distance indicated by the ruler and the distance measured in the photograph of the ruler. By measuring the distance between successive dots and the frequency of the light from the strobe lamp, the velocity of the particle was calculated. Tests were made using compressed air at pressures of 5 and 10 psig passing through the nozzle.

B. <u>An Improved "Air Gun"</u>

After the velocity of the particle exiting from the end of the air-gun was determined to be reasonably high, further development of the air-gun was done to obtain more uniform velocity distributions over the entire sample target. A larger PVC pipe (length: 12 feet; diameter: 3 inch) was used. Increasing the diameter and the air velocity should increase the degree of turbulence and create a more uniform velocity distribution. The length of the pipe was increased so that the end effects would be negligible and the air flow inside of the pipe would reach steady state. As shown in Figure 5, a 4 inch X 8 inch x 5 foot rectangular plexi glass duct was placed at the end of the circular PVC pipe. An additional amount of air is sucked into the gaps between the circular and the rectangular pipes, and further improvement of the velocity distribution should be achieved. The target which is a polymer sample glued on an aluminum strip will be placed at the center of the cross section of the rectangular duct along its axis and toward the exit where fully developed turbulent flow is present, and the radial velocity distributions are most uniform.

A small quantity of baking flour was used to study the air flow profile inside the second pipe. Since the density of flour is low and the particle size is small, the path of flour passing through the rectangular duct will be the same as that of the air flow. After the air flow is fully developed, a small quantity of flour was introduced into the feed chute and the path of flour was observed.

The determination of the particle velocity within the rectangular duct using the same technique as described above was difficult. The reason was that too much strobe light was reflected from the plexi glass surfaces into the camera. The air velocity within the rectangular duct was measured using a pitot tube. In addition, an approximate particle velocity within the duct was obtained by using a strobe lamp to illuminate a particle passing through the duct, and visually determining the distance travelled by the particle between successive firings of the strobe lamp. Distances were estimated using a ruler placed behind the duct and in the plane of the particle path.

C. A Study of the Insect Flux Using Aluminum Strips

Insects have been collected by road tests in past studies. The polymer samples were glued on the aluminum strips and mounted on either an aluminum or a PVC half cylinder. These cylinders were then mounted on the top of a car, and driven at high speed where a large number of insects were present (1). Unfortunately, a large experimental error could be introduced during the road test caused by a variable insect flux. To eliminate these errors, the improved insect impact technique using the air gun was developed, but it is desired to carry the road test for comparison with the new technique.

To detect the presence of such errors the road tests were performed on May 27, July 9, and July 20, 1987 by driving from Blacksburg, Virginia to Princeton, West Virginia and back. Twenty-six 3/4 inch X 6 inch aluminum strips were mounted on the car in the same manner as in previous tests. The number of insects sticking on each strip were counted visually and recorded. By comparing the number of insects sticking on each aluminum strip the insect density distribution across the half-cylinder could be obtained.

IV. RESULTS AND DISCUSSION

A. Determination of the Particle Velocity and an Air Velocity Profile

A spherical particle exiting from the end of the pipe appears as a sequence of bright dots as shown in the photograph in Figure 6. The velocity

(v) of the particle ejecting from the end of the pipe was calculated by:

v = (distance between successive dots)*(strobe frequency)

The average velocities from 13 velocity measurements using a compressed air supply of 5 psig and from 4 measurements at 10 psig are listed in Table I. The velocity is determined to be 63 mi/hr at 10 psig. In the improved "air gun", a compressed air supply of up to 75 psig may be used.

The streamlines of air flow through the rectangular duct section of the "air gun" were obtained by examining the traces in the duct of baking flour introduced into the feed chute. As shown in Figure 7, there was no flow seen close to the walls of the duct even at the exit. The expansion of air from the 3 inch PVC pipe into the rectangular duct will induce an additional flow of air into the duct as illustrated in Figure 5. The study of the streamlines showed that the eddies created by this air flow entering the high velocity stream from the PVC pipe were quickly dampened and had no effect towards the exit end of the duct.

If a "pulse" of flour was introduced into the "air gun", a sharp vertical front could be observed using strobed lighting which passed through the duct indicating a well-developed turbulent flow, with a uniform velocity distribution extending to 6 inches along the height of the duct and practically all 4 inches along the width. Therefore if a sample of $\leq$ 6 inches high is mounted close to the exit of the duct and along its axis, the velocity of insects carried by the high velocity stream and impacting the sample will be uniform along the height and width of the sample.

Using a compressed air supply of 25 psig in the improved "air gun", an approximate particle velocity of 70 mi/hr was visually determined as described in the experimental section. Higher velocities can be obtained since a compressed air supply of 75 psig is possible. At 70 psig, the air velocity within the rectangular duct was determined to be 110 mph using a pitot tube.

The Reynolds numbers (Re) for two different diameter cylindrical tubes at various air flow velocities were calculated to check if the air flow inside of the tube was turbulent. For these calculations the viscosity and density of air, which are functions of temperature and pressure, are assumed to be constant since changes of these physical properties are smaller compared with other variables in calculation of Re. As shown in Table III, turbulent flow was developed even with the smaller diameter tube and at the lowest velocity used.

D. A Study of the Insect Flux Using Aluminum Strips

The results from two road tests are given in Table II and Figure 8. Nonuniform insect distributions across the cylinder resulted in both tests. The total number of insects sticking on each aluminum strip from the two road tests were determined, but again nonuniform distributions were observed. However, to detect the presence of possible experimental errors from the past study at least three more road tests should be performed.

C. Further Data Analyses of the Previous Study

The elastomers used in the past study were fluorocarbon elastomers with two different fluorine compositions, Viton^R, neoprene, and polyurethane of two different thicknesses. As indicated in Table IV, the fluorocarbon elastomers gave similar contact angles with deionized water and low concentration aqueous ethanol solutions. The results of ESCA analysis given in Table V and VI showed the presence of the same elements and very similar atomic compositions for each fluorocarbon sample. The main difference between these samples was the modulus of elasticity with the exception of samples B and E. Contact angle measurements on neoprene surface were close to the fluorocarbon samples, but ESCA analysis showed a large difference from the fluorocarbon samples - no detectable fluorine and different atomic percentages of each element presented. Viton[R] gave almost the same contact angle results as neoprene, but a significant percentage of fluorine on the surface, which was less than for the fluorocarbon elastomers. Polyurethane samples gave much lower contact angle and different ESCA atomic compositions than any of the other samples.

A past study by Siochi (3) showed that the surface energy of a polymer coating has an important effect on the number of insects sticking to the surface. Thus, it is unreasonable to attempt to correlate the number of insects sticking on each sample surface with the modulus of elasticity of each sample, when surface properties (surface energy, presence of different elements with different surface compositions) of each sample are very different. All the elastomers used in the past study were divided into three groups. The first group consists of fluorocarbon elastomers which gave the same contact angle measurements and very similar ESCA atomic compositions but different values for the modulus of elasticity. The second group is made up of polyurethanes which have different thickness and moduli of elasticity. The third group is neoprene and Viton[R] where no comparison is possible due to different contact angles, compositions, and moduli of elasticity from any other samples or each other.

A practically linear relationship with positive slope between the total number of insects sticking on the sample surface and the modulus of elasticity of the first group is obtained as shown in Figure 9. Similar results were obtained for the second group as shown in Figure 9. As the modulus of elasticity decreases, the elastic property of a polymer increases so that there are more chances for insects to bounce off the surface during impact.

V. SUMMARY

The polyethylene particles exiting the end of the "air gun" had velocities as high as 65 mi/hr at 10 psig of compressed air, and higher velocities could be obtained by increasing the compressed air pressure. The air flow developed in the improved "air gun" using a larger and longer circular pipe and a plexi glass rectangular duct was fully developed turbulent flow with uniform velocity distribution across the pipe and duct. Particle velocities of approximately 70 mi/hr were visually measured using a compressed air supply of 25 psig. At 70 psig, air velocity in the rectangular duct reached 110 mi/hr.

The insect distribution across the half cylinder was shown to be nonuniform from two road tests using only aluminum strips, which indicates an experimental error due to a variable insect flux. The improved "air gun" can be used as a new controlled insect impacting technique, so that the experimental error introduced during the road test caused by a variable insect flux can be reduced and comparison of lab results with ones from the road test is possible.

A linear relationship between the total number of insects sticking on the surface and the modulus of elasticity was obtained for the samples with similar surface properties. It is believed that some of the impacted insects bounce off during impact with the elastomers, so as the modulus of elasticity increases, the number of insects sticking also increased.

VI. FUTURE WORK

The following recommendations for future work are listed:

1. Coat the elastomer, which have different moduli of elasticity, with a thin layer of another material sufficient to obtain the same surface

energy of the elastomers, but leaving the modulus of elasticity of the elastomer unaffected.

2. Coat a given elastomer with different materials which will give different surface energies, so that the effect of the surface energy on the insects sticking on the surface for a given modulus of elasticity can be obtained.

3. Increase the number of aluminum strips for the road test and compare the percentage of the insects sticking on the sample polymer surface by normalizing with the average number of insects sticking on all aluminum surfaces.

4. Design a new technique to determine the velocity of an object within the duct of the improved "air gun".

5. Simulate the insect impact process using the improved "air gun" and model particles and/or insects.

VII. REFERENCES

1. Yi, O., **Factors Affecting the Sticking of Insects on Modified Aircraft Wings**, First Semi-Annual Report, &vt., 1987.

2. Bird, R. B., W. E. Stewart, and E. N. Lightfoot, **Transport Phenomena**, John Wiley, New York, 1960.

3. Siochi, M., **A Fundamental Study of the Sticking of Insect Residues to Aircraft Wings**, M. S. Thesis, &vt., Blacksburg, 1985.

4. Perry, R. H. and C. H. Chilton, **Chemical Engineers' Handbook**, Fifth Edition, McGraw Hill, New York, 1973.

Table I. AVERAGE VELOCITY MEASURED USING POLYETHYLENE PARTICLE AT TWO DIFFERENT PRESSURES

Pressure (psig)	Avg. Speed (mi/hr)
5.0	51
10.0	65

Table II. INSECT DISTRIBUTION ACROSS THE HALF CYLINDER USING ALUMINUM STRIPS

Position of the Aluminum Strips from Left Edge of the Half Cylinder	Number of Insects		
	May 28	July 9	Total
1	6	17	23
2	9	25	34
3	5	12	17
4	3	9	12
5	5	17	22
6	2	29	31
7	6	21	27
8	3	19	22
9	4	23	27
10	3	23	26
11	7	23	30
12	6	12	23
13	8	28	36
14	6	18	24
15	6	18	24
16	6	14	20
17	10	13	23
18	7	27	34
19	8	23	32
20	7	18	25
21	6	15	21
22	4	17	21
23	4	25	29
24	4	19	23
25	4	15	19
26	3	12	15

Table III. REYNOLDS NUMBERS CALCULATED AT ROOM TEMPERATURE AND ATMOSPHERIC PRESSURE

Diameter (inch)	Velocity (mi/hr)	Reynolds No.
1.0	51	38,300
	65	48,800
3.0	70	157,600
	110	247,600

viscosity = 0.016 cp density = 0.074039 lb./ft^3 (14)

TABLE IV. CONTACT ANGLE MEASUREMENTS WITH WATER/ETHANOL SOLUTIONS

Sample	Water/Ethanol (v/v)						
	100/0	90/10	70/30	50/50	40/60	30/70	80/20
FCE - A	92	85	66	50	48	40	25
FCE - B	94	84	70	53	46	39	28
FCE - C	93	78	64	51	48	36	---
FCE - D	96	84	65	47	46	34	23
FCE - E	96	84	67	50	38	31	---
PU	70	60	48	28	23	---	---
NEOPRENE	102	93	75	61	57	39	44
VITON	103	95	76	62	55	49	39

TABLE V. ESCA ATOMIC COMPOSITION (%) AND RATOS DETERMINED ON ELASTOMER SAMPLES AT A TAKE-OFF ANGLE OF 20°

	Photopeak						
Sample	C 1s	O 1s	F 1s	Si 2p	N 1s	Cl 2p	Pb 4f
FCE - A	59.	2.9	37.	0.7	---	---	---
FCE - B	55.	5.5	37.	2.4	---	---	---
FCE - C	57.	3.7	38.	0.9	0.1	---	---
FCE - D	53.	3.3	43.	0.7	---	---	---
FCE - E	57.	5.1	36.	1.7	---	---	---
PU	81.	17.	---	0.9	---	---	---
NEOPRENE	58.	20.	---	22.	---	0.6	---
VITON	41.	24.	13.	20.	0.7	---	0.4

	Ratio					
Sample	O/C	F/C	Si/C	N/C	Cl/C	Pb/C
FCE - A	0.049	0.63	0.012	--	--	--
FCE - B	0.10	0.67	0.044	--	--	--
FCE - C	0.065	0.67	0.016	0.002	--	--
FCE - D	0.062	0.81	0.013	--	--	--
FCE - E	0.089	0.63	0.030	--	--	--
PU	0.21	--	0.011	--	--	--
NEOPRENE	0.34	--	0.38	--	0.010	--
VITON	0.58	0.32	0.49	0.017	--	0.010

TABLE VI. ESCA ATOMIC COMPOSITION (%) AND RATIOS DETERMINED ON ELASTOMER SAMPLES AT A TAKE-OFF ANGLE OF 90°

	Photopeak						
Sample	C 1s	O 1s	F 1s	Si 2p	N 1s	Cl 2p	Pb 4f
FCE - A	53.	3.2	33.	0.5	---	---	---
FCE - B	64.	6.7	28.	1.9	---	---	---
FCE - C	60.	4.0	36.	0.2	0.2	0.2	---
FCE - D	59.	4.3	36.	0.3	---	---	---
FCE - E	60.	5.4	34.	0.7	---	---	---
PU	81.	16.	---	0.4	2.4	---	---
NEOPRENE	62.	20.	---	18.	---	1.1	---
VITON	46.	23.	12.	18.	0.5	---	1.0

	Ratio					
Sample	O/C	F/C	Si/C	N/C	Cl/C	Pb/C
FCE - A	0.060	0.62	0.009	--	--	--
FCE - B	0.10	0.44	0.030	--	--	--
FCE - C	0.067	0.60	0.003	0.003	0.003	--
FCE - D	0.073	0.61	0.005	--	--	--
FCE - E	0.090	0.57	0.012	---	--	--
PU	0.20	--	0.005	0.030	--	--
NEOPRENE	0.32	--	0.29	--	0.018	--
VITRON	0.50	0.26	0.39	0.011	--	0.022

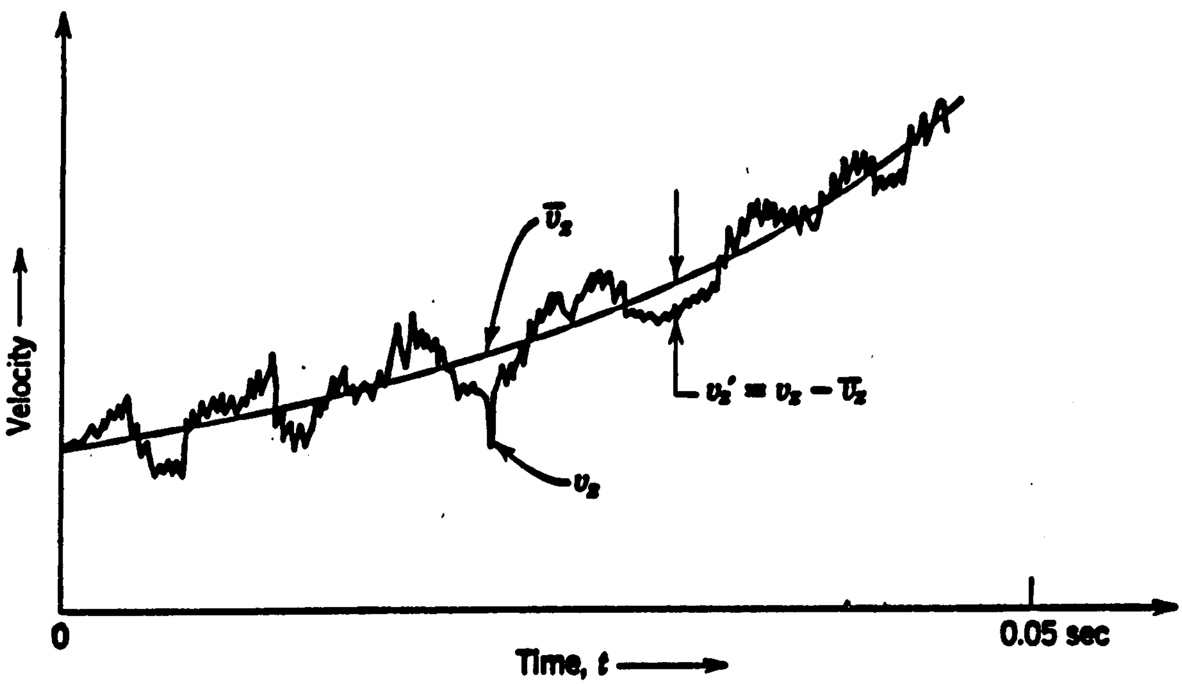


Figure 1. Oscillation of velocity component about a mean value ($\bar{v}_z$ = time smoothed velocity) (2).

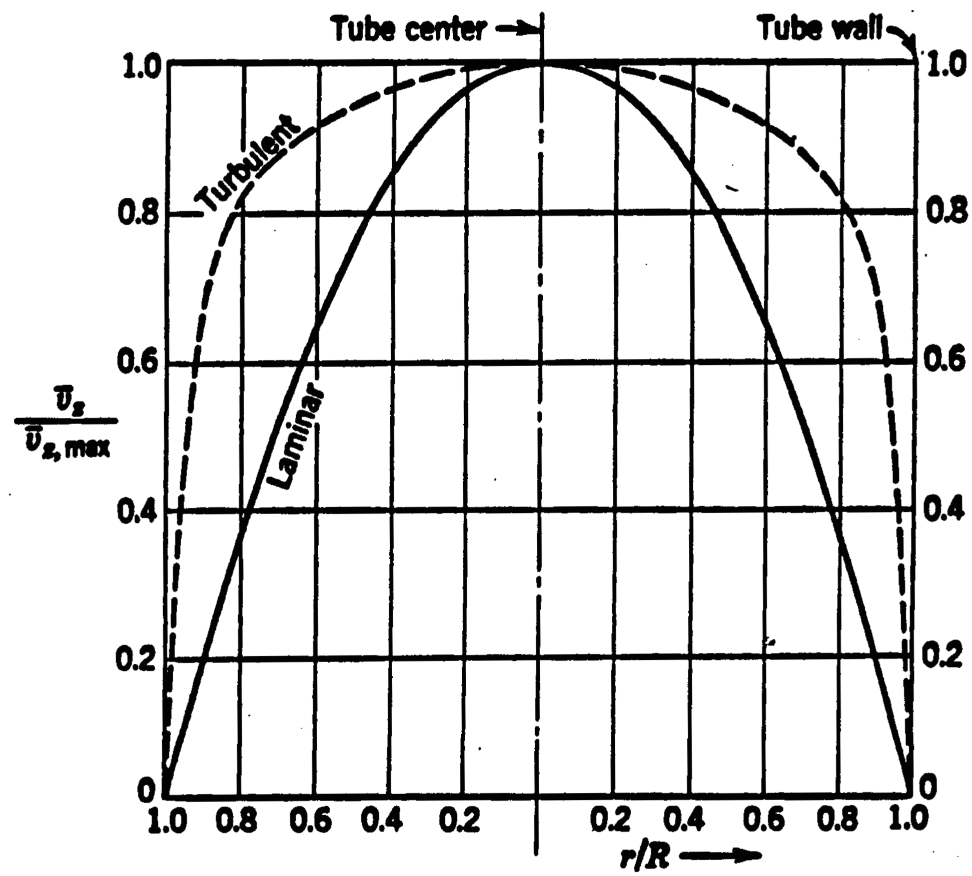


Figure 2. Qualitative comparison of laminar and turbulent velocity distribution (2).

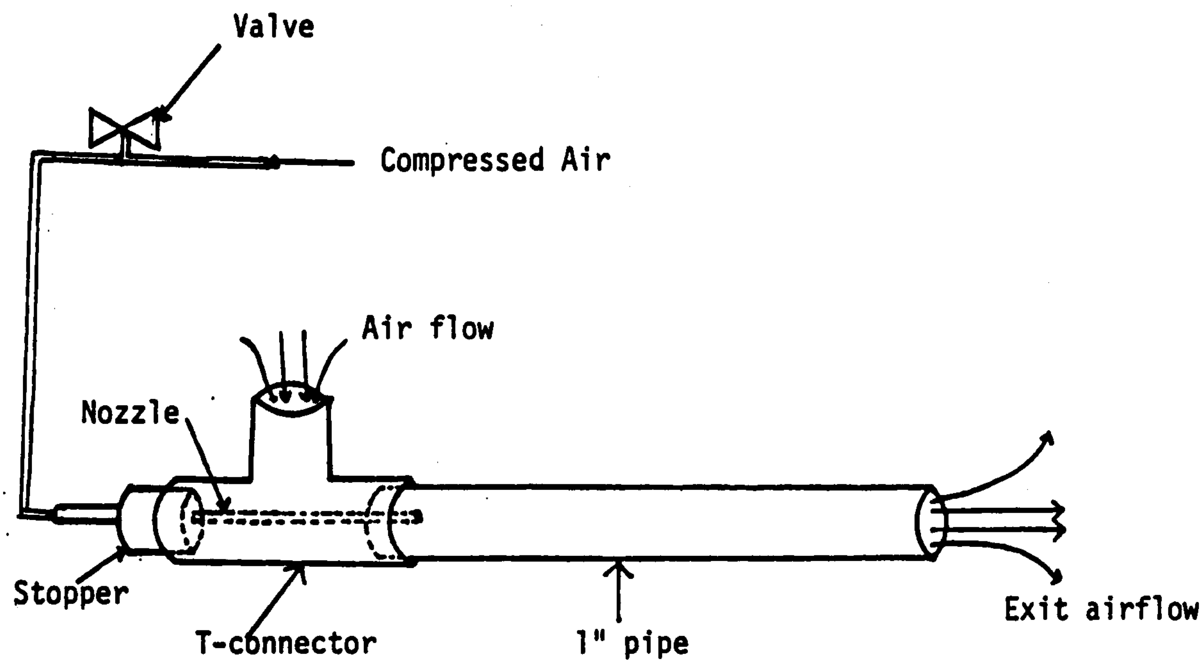


Figure 3. Simplified diagram of "Air-Gun" (1).

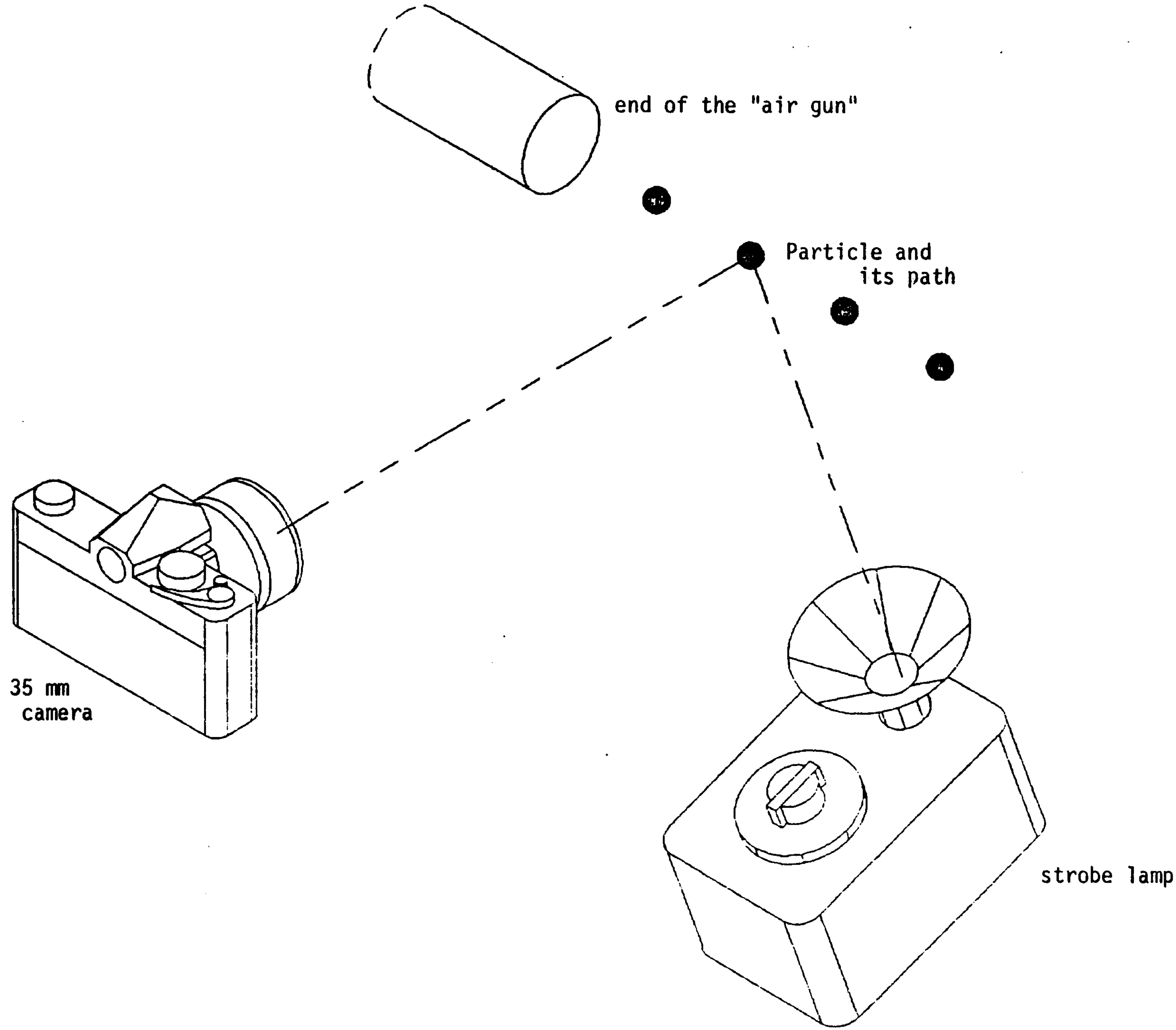


Figure 4. Photographic technique used to determine the velocity of a particle exiting from the "air gun".

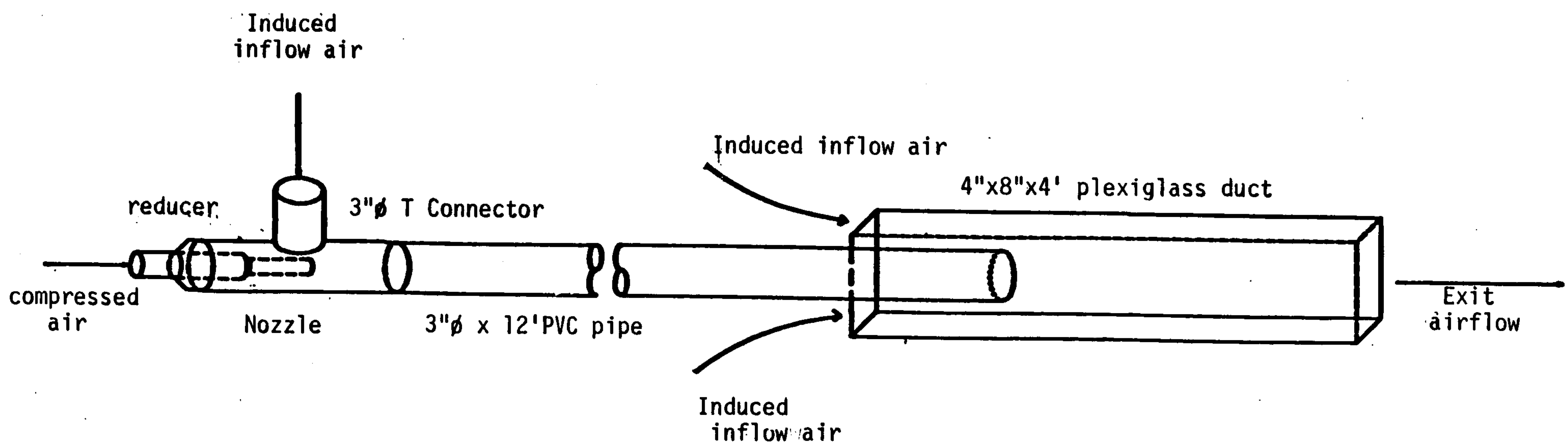
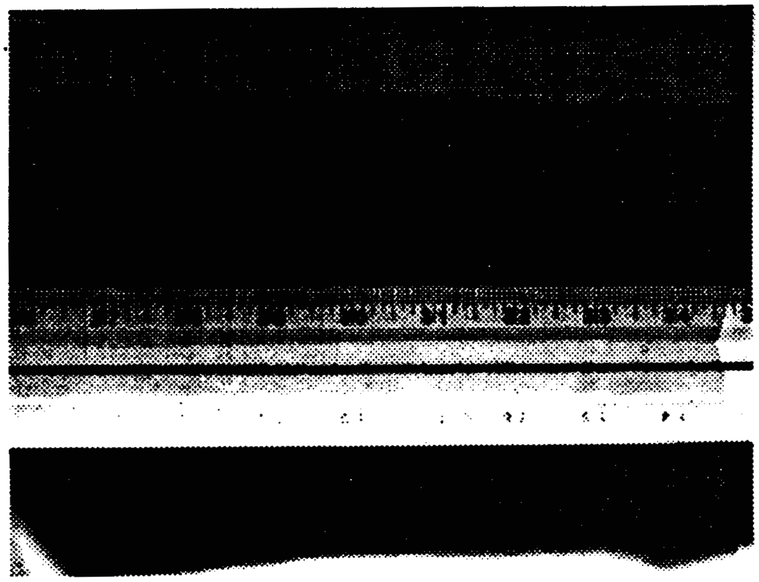
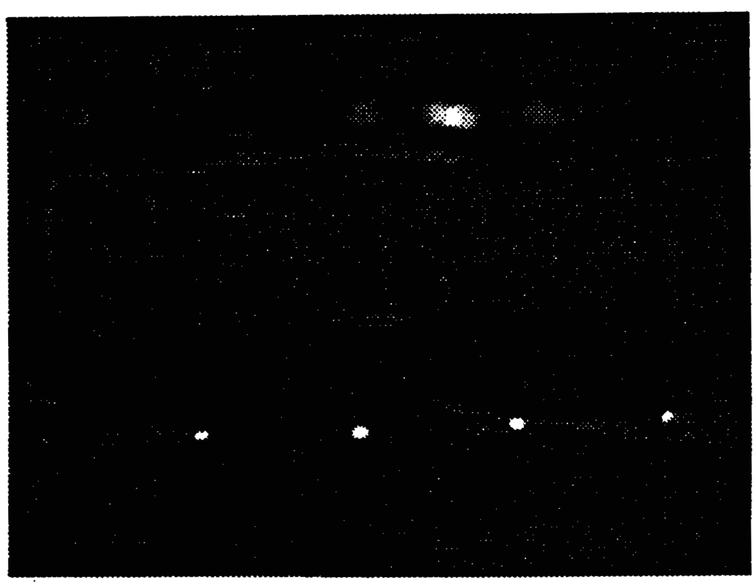


Figure 5. Simplified diagram of improved "Air-Gun".



(a)



(b)

Figure 6. Photographs of (a) a ruler (b) a particle trace at 5 psig.

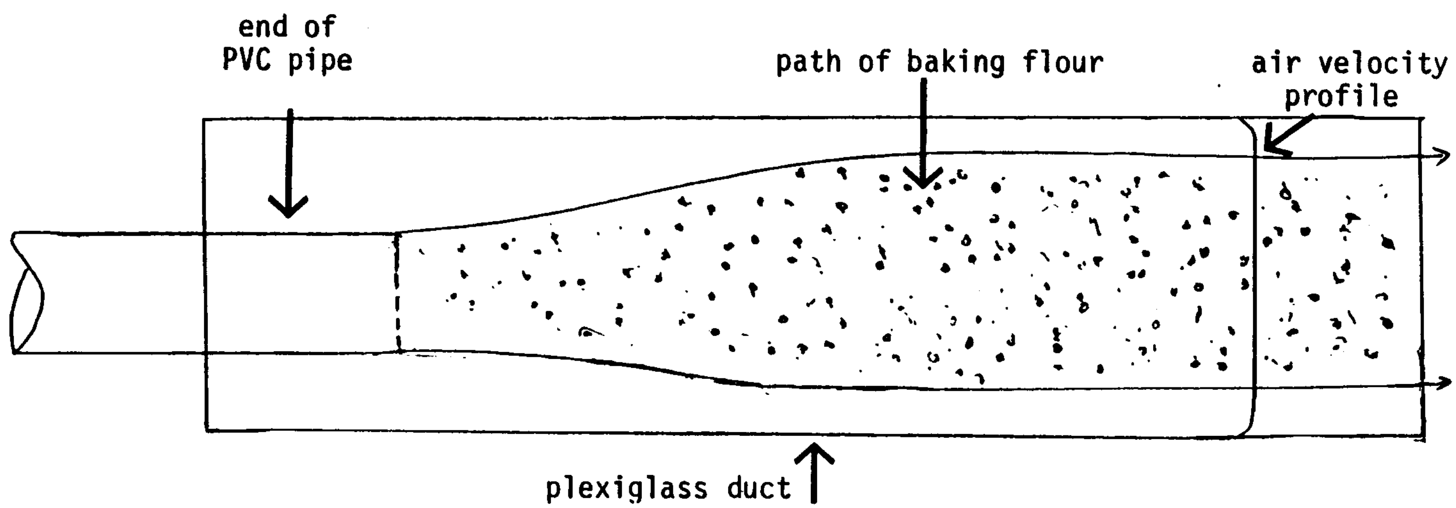


Figure 7. Air profile deduced from the path of flour in the plexiglass duct.

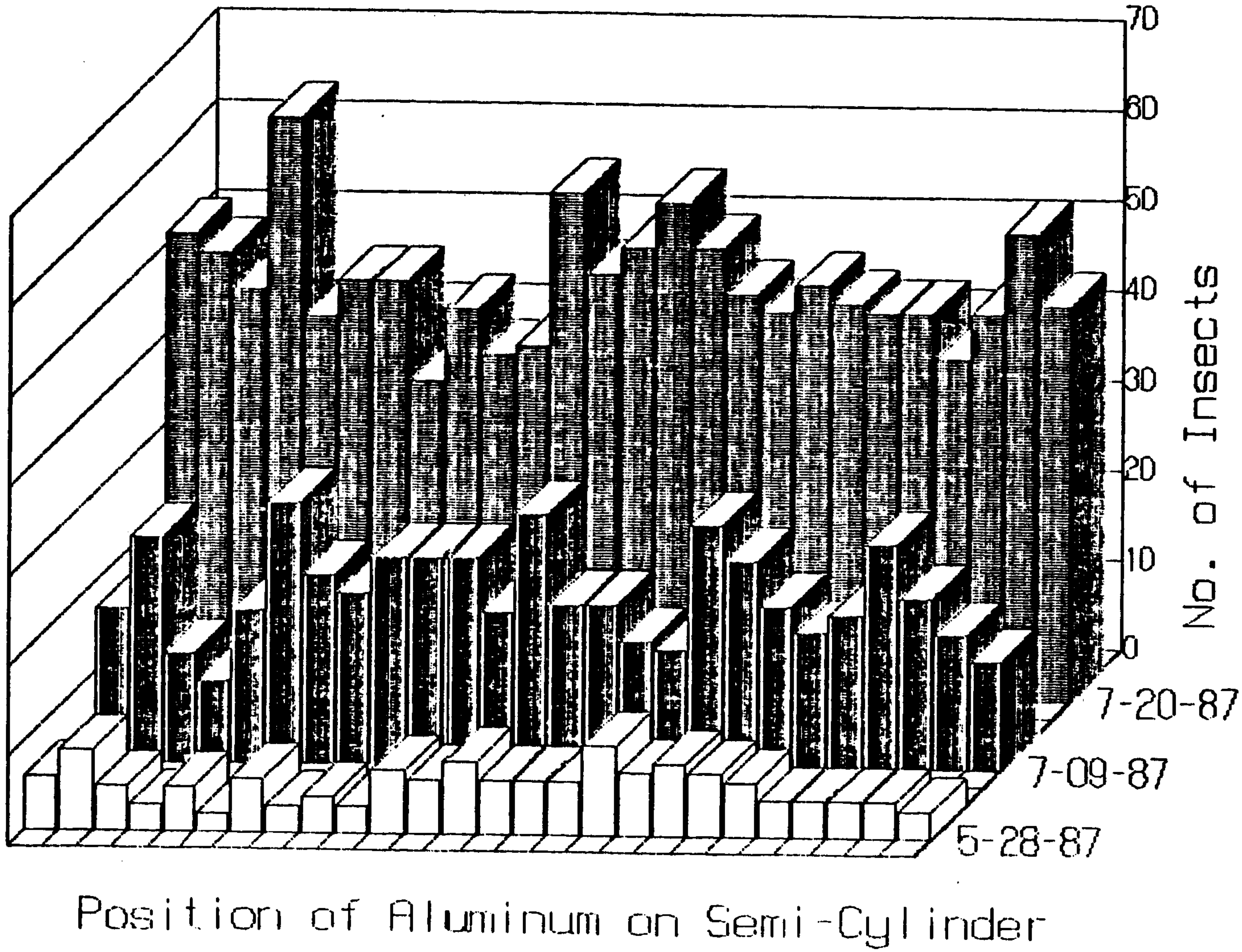


Figure 8(a). Insect distribution across the semi-cylinder obtained from the three road tests using aluminum strips.

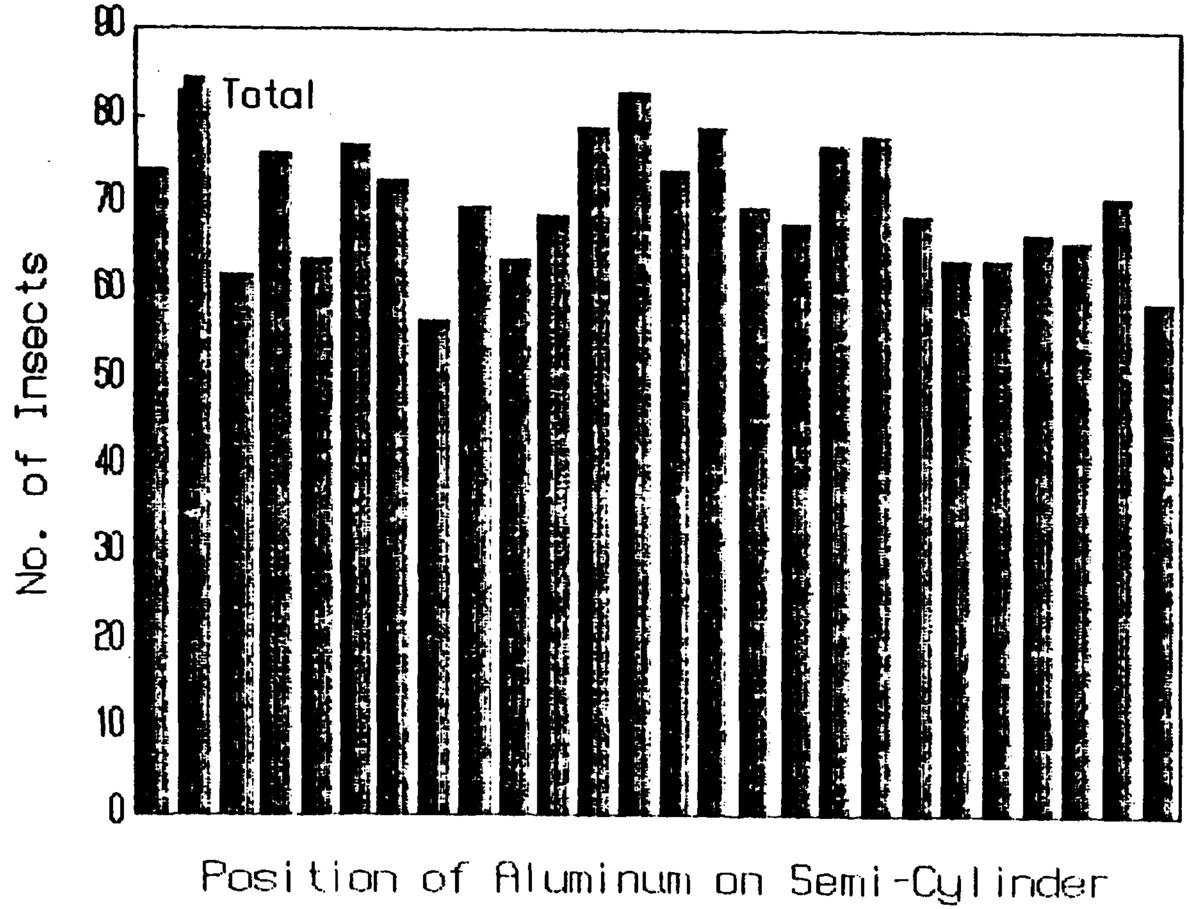
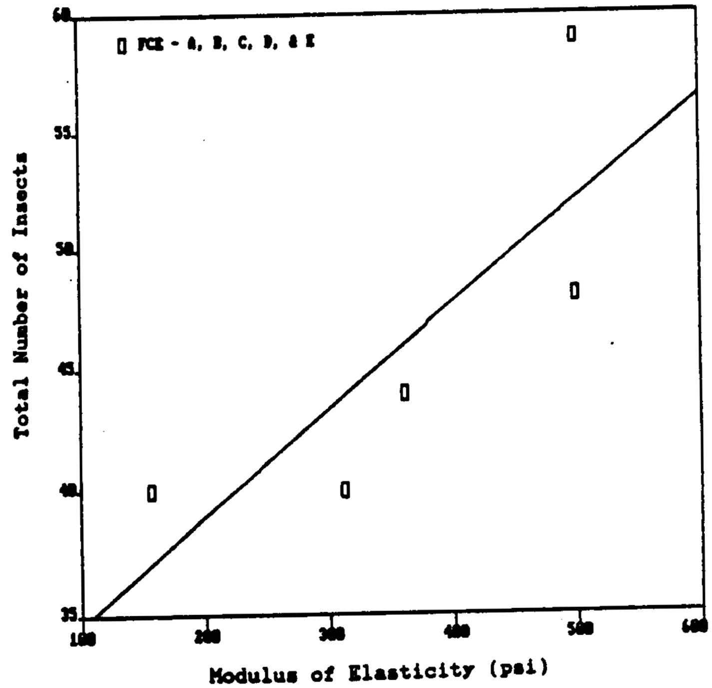
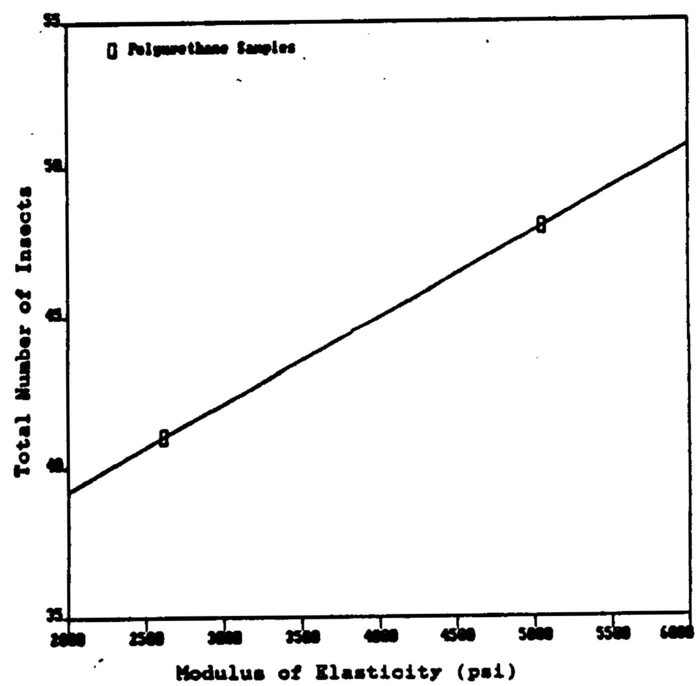


Figure 8(b). Total number of insects on the aluminum strips summed from the three road tests.



(a)



(b)

Figure 9. Total number of insects sticking on the surface as a function of modulus of elasticity (a) group 1 (b) group 2.