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EXPERIMENTAL INVESTIGATION OF A THRUST AUGMENTING EJECTOR

by

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December 1985

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The present investigation concerns the performance of a two-dimensional ejector with its primary jet excited by a novel method. A constant area duct was used in this experiment. The velocity of the jet at the exit was subsonic. Maximum thrust was obtained when the ejector to jet exit area ratio was about 35. Under this condition a thrust augmentation ratio of 1.65 was achieved, with the jet excited at 20 Hz, whereas without excitation it was only 1.40. The mixing characteristics of the jet under excitation was examined using flow visualization techniques. Smoke filaments illuminated by a sheet of powerful light and schlieren optics with the jet heated were used for the above purpose. Excitation

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ABSTRACT

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NOMENCLATURE

A	Mixing area
A_j	Primary inlet flow area
A_e	Exit area
C_p	Pressure coefficient
f	Frequency of applied oscillation
H	Height of nozzle
P_a	Ambient pressure /exit pressure
P_1	Secondary inlet static pressure
S	Distance between upper and lower surface
T	Total thrust
T_j	Thrust at primary nozzle
u	Velocity component in x direction
U_e	Exit velocity
U_j	Velocity of jet nozzle
U_1	Inlet velocity
v	Velocity component in y direction
x	Longitudinal distance from the inlet of the ejector
x_L	Distance between the nozzle and the ejector duct
y	Coordinate perpendicular to x axis
z	Coordinate along span of ejector

α	Jet to ejector area ratio (Aj/A)
β	Exit to ejector area ratio(Ae/A)
ϕ	Thrust augmentation ratio (T/Tj)
ρ	Air density
ψ_s	Stream function
δ	Wall boundary layer thickness

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Innumerable thanks to Professor Max F. Platzer and Professor Badri Narayanan for their advice and assistance, making it a pleasure to study in the Gas Dynamics Laboratory.

Finally, I am grateful to my wife and children for their patience, understanding and encouragement.

I. INTRODUCTION

In the past two decades the ejector technology has received considerable attention on account of its application to vertical and short take-off and landing (V/STOL) aircraft. The immediate plausible application is to achieve V/STOL capability of a flying machine. Special wing configurations with ejector systems are now under extensive study with the goal of improving the design of the next generation aircraft. An ejector is a simple device capable of generating additional thrust to an already existing free jet [Ref. 1], hence a highly sought after gadget by engineers. However, a large number of technological problems are yet to be solved to promote the ejector from the experimental stage to an actual operating aircraft system.

The first V/STOL aircraft to use the ejector principle was the Lockheed XV-4A Hummingbird. This machine achieved a thrust augmentation ratio of 1.24 [Ref. 2], considerably less than what was anticipated. A later industrial development was the Rockwell XFV-12A. A low thrust augmentation ratio of only 1.1 was achieved by this aircraft.

An ejector is basically a jet pump in which the kinetic energy of the jet is made to impart motion to the fluid surrounding it. ~~[Ref.~~ 3]. During this process, in a well designed system, the ejector as a whole experiences a thrust much higher than that of the jet alone. Thus the ejector can be classified as a thrust augmentor. In principle, an ejector is nothing but a jet surrounded by a shroud. The system has no moving parts unlike other thrust augmentors, e.g fan-jets, prop-jets. Laboratory experiments indicate that an ejector can easily produce 40 percent more thrust over a simple free jet. The main disadvantage of the device is the losses involved in the nozzle and the duct system. To strike a favourable balance between the gain and the

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losses an increase in thrust augmentation is required. This calls for additional mixing between the jet and the surrounding air for inducing more flow. The aim of the present research work is to achieve the above result employing an excited primary jet which has a greater mixing capability. This investigation forms part of the ejector project already undertaken by the Department of Aeronautics, Naval Postgraduate School, Monterey California.

II. THEORETICAL CONSIDERATION

A simple control volume analysis without considering the details of the flow can be used to illustrate that an ejector can produce more thrust than the primary jet (Figure.2.1) [Ref. 4].

Assumption :

1. The jet has uniform velocity at the exit
2. The induced flow has uniform velocity at station (1)
3. Between region (1) and (2) the jet and the induced flow mixes completely resulting in uniform velocity at station (2)
4. Static pressure Pa ahead and downstream of the ejector
5. The flow is incompressible.

Continuity equation :

$$U1(A - Aj) + Uj\ Aj = Ue\ A \qquad (1)$$

Momentum equation :

$$A(P1 - P0) = \rho Ue^2 A - \rho U1^2 (A - Aj) \qquad (2)$$

Using Bernoulli's equation :

$$P1 = Pa - 1/2\ \rho\ U1^2 \qquad (3)$$

Eliminating P1 and U1 it can be shown that :

$$U_e = U_j \left[\frac{-\alpha(1-2\alpha) + \sqrt{2\alpha - 6\alpha^2 + 6\alpha^3 - 2\alpha^4}}{1 - 2\alpha + 2\alpha^2} \right] \qquad (4)$$

where $\alpha = Aj/A$

(Thrust of the total system)/(Thrust of the jet alone) :

$$\phi = \frac{\rho\, Ue^2 A}{\rho\, Uj^2 A_j} = \frac{(U_e/U_j)^2}{\alpha} \qquad (5)$$

Where ϕ is known as thrust augmentation ratio. The variation with Aj/A is plotted in Figure.2.2. As alpha

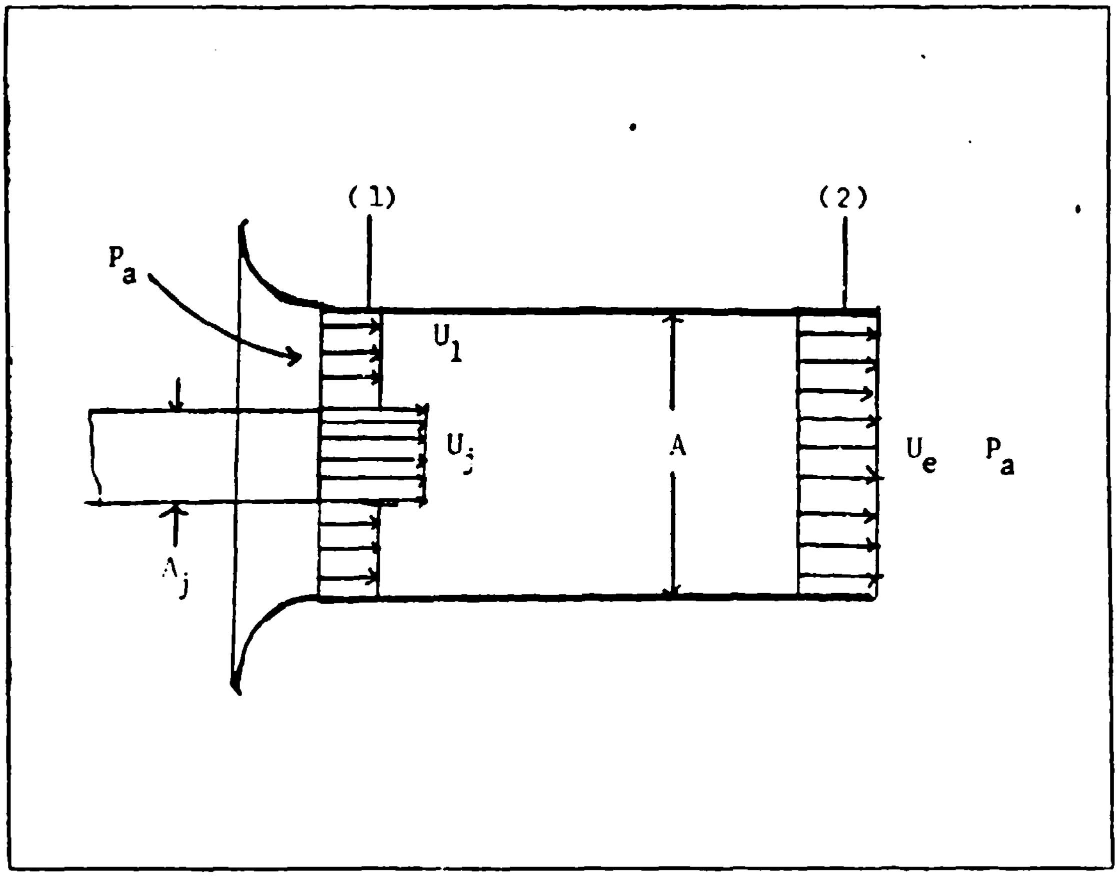

Figure 2.1 Ejector Configuration With a Straight Duct.

approaches zero ϕ tends towards 2.0 [Ref. 2].

The thrust of the ejector can be further increased by attaching a diffuser to the parallel duct as shown in Figure.2.3. Pressure recovery in the diffuser is responsible for this phenomenon. In this system both the area of the parallel duct, the area of the jet and the diffuser configuration are involved in determining the thrust augmentation. Using a simple one-dimensional flow analysis the thrust augmentation can be estimated. The relation is given by :

$$\phi = (\rho Ue^2 Ae)/(\rho Uj^2 Aj) = (Ue/Uj)^2 (\beta/\alpha)$$

where $\beta = Ae/A$

The variation of ϕ with α and β is shown in Figure.2.4.

The theoretical approach to the ejector problem is so far confined to simple analysis without considering viscous effects and details of the mixing process. In the last few years attempts have been made to examine the ejector flow characteristics using a simple mixing length model for turbulent stresses [Ref. 5]. It is interesting to note that the pressure distribution along the ejector duct estimated by the above method is in close conformity with the experimental results (Figure.2.5), indicating the success of the approach. Since the analysis involves an extensive computer based program it is not convenient to give all the details in the report. Only the basic approach is described below. For simplicity the flow is considered to be two-dimensional, the momentum equation for streamwise momentum is :

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + (\mu - \rho\overline{u'v'})\frac{\partial^2 \bar{u}}{\partial y^2} \qquad (7)$$

Using the stream function ψ_s for convenience :

$$\frac{\partial \psi_s}{\partial y} = \rho\bar{u} \qquad , \qquad \frac{\partial \bar{u}}{\partial \psi_s} = \frac{1}{\rho\bar{u}}\cdot\frac{\partial \bar{u}}{\partial y} \qquad (8)$$

The momentum equation can be written as :

$$\bar{u}\frac{\partial \bar{u}}{\partial x} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \bar{u}\frac{\partial \tau}{\partial \psi_s} \qquad (9)$$

(It is convenient to solve the problem if streamwise coordinate is used)

$$\tau = (\mu\frac{\partial \bar{u}}{\partial y} - \rho\overline{u'v'}) = (\mu + \rho\varepsilon)\frac{\partial \bar{u}}{\partial y} \qquad (10)$$

where ε is the eddy viscocity.

The following models were used for eddy viscocity. For the sake of simplicity the flow is divided into three parts and each region is treated with a separate model (Figure.2.6) [Ref. 6],

$$\varepsilon = l_m^2\frac{\partial \bar{u}}{\partial y} \qquad (11)$$

where l_m is Prandtl's mixing length

Region :

a. Shear layer adjacent to the potential core region of the primary jet, $l_m = 0.08\,\delta_1$, where δ_1 is the width of the shear layer.

b. Fully developed portion of the jet flowing coaxially with a secondary potential stream, $l_m = 0.108\,\delta_2$, where δ_2 is the half width of the jet.

c. The wall boundary layer divided into inner and outer layers, for the outer layer $\delta_m = 0.09\,\delta_3$, where delta_3 is the boundary layer thickness. For the inner layer the Van Driest model is used :

$$l_m = 0.41\left[1 - e^{-(y^*/26)}\right] y \qquad (12)$$

where y^*= The dimensionless wall coordinate

The time averaged Navier-Stokes equation is solved using the above different mixing length models for each distinctive region of the flow.

It can be observed that even in the case of a steady jet ejector system the success of the analysis depends on the models used for turbulence. The models were based on experimental information already available for various steady flows such as jets, boundary layers and internal flow in the duct. The situation is more complicated in the case of an excited jet. It calls for time dependent flow characteristics and such information is not available at present. Hence it will be a long way before an excited jet and its influence on an ejector could be analytically examined. Hence this investigation was experimental in nature. It is the aim of this research activity to gather information not only on the overall performance of the system but also to provide some insight on the mixing process.

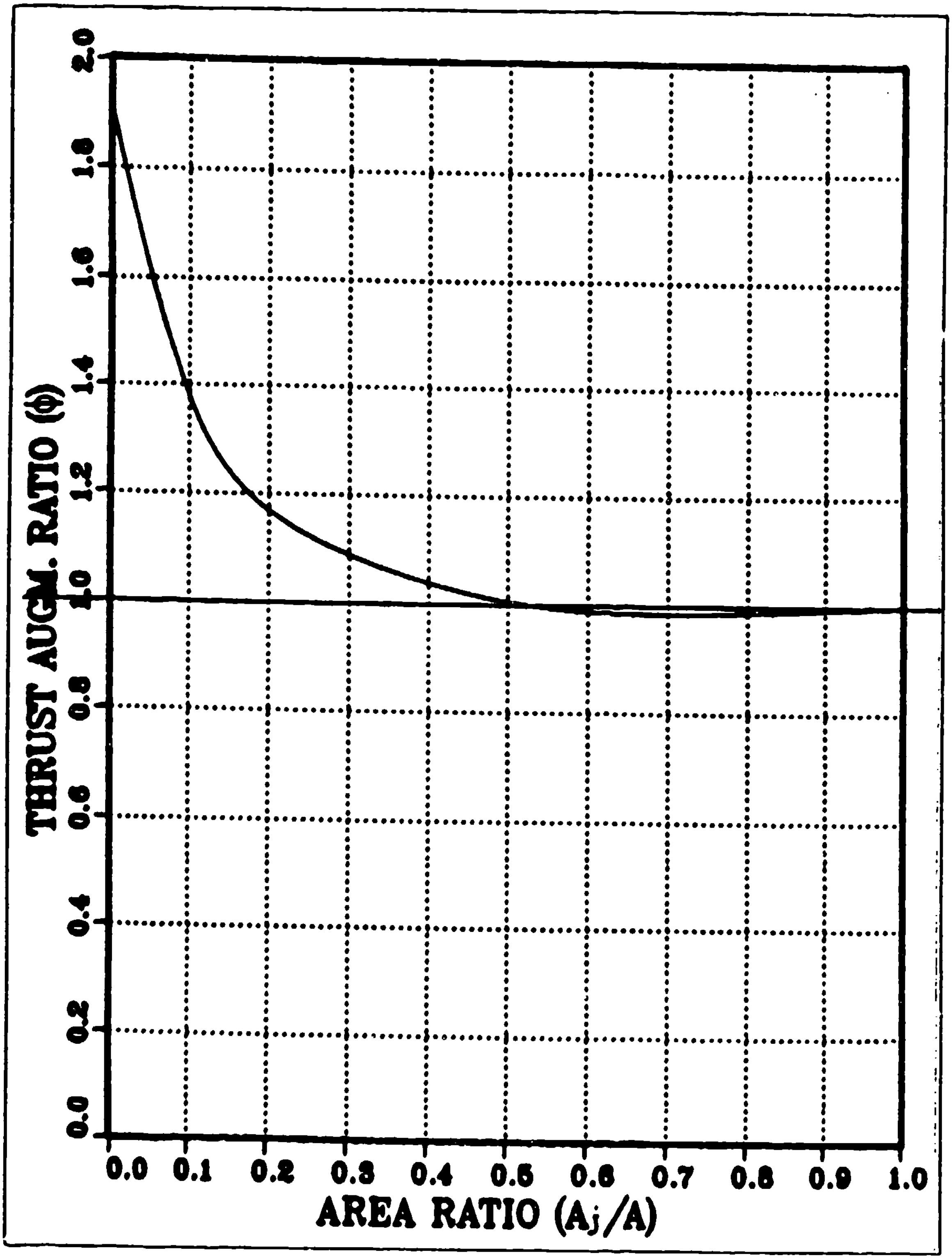

Figure 2.2 Thrust Augmentation Ratio vs Aj/A(Ref.2).

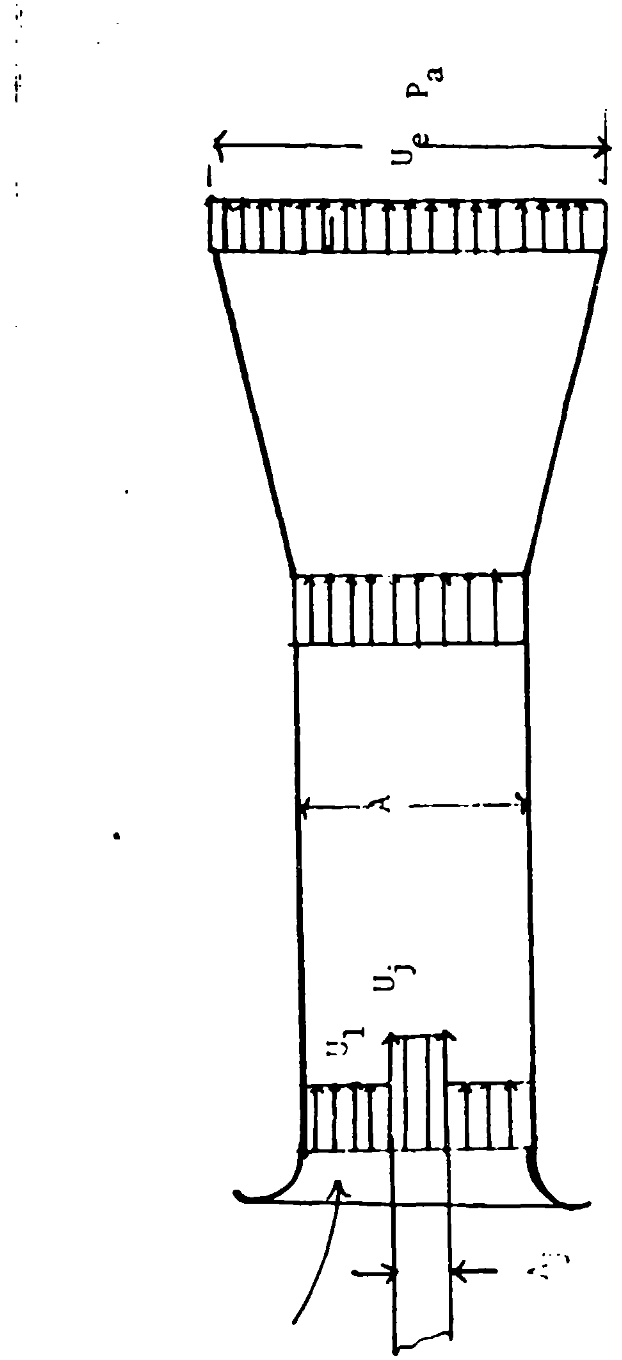

Figure 2.3 Ejector With Diffuser.

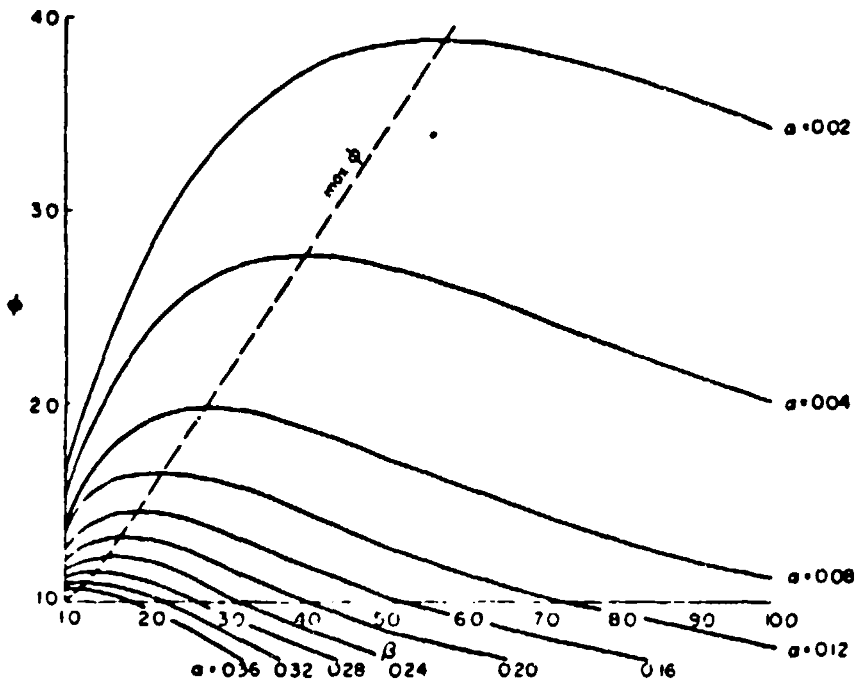

Figure 2.4 Thrust Augmentation as a Function of α & β (Ref.2).

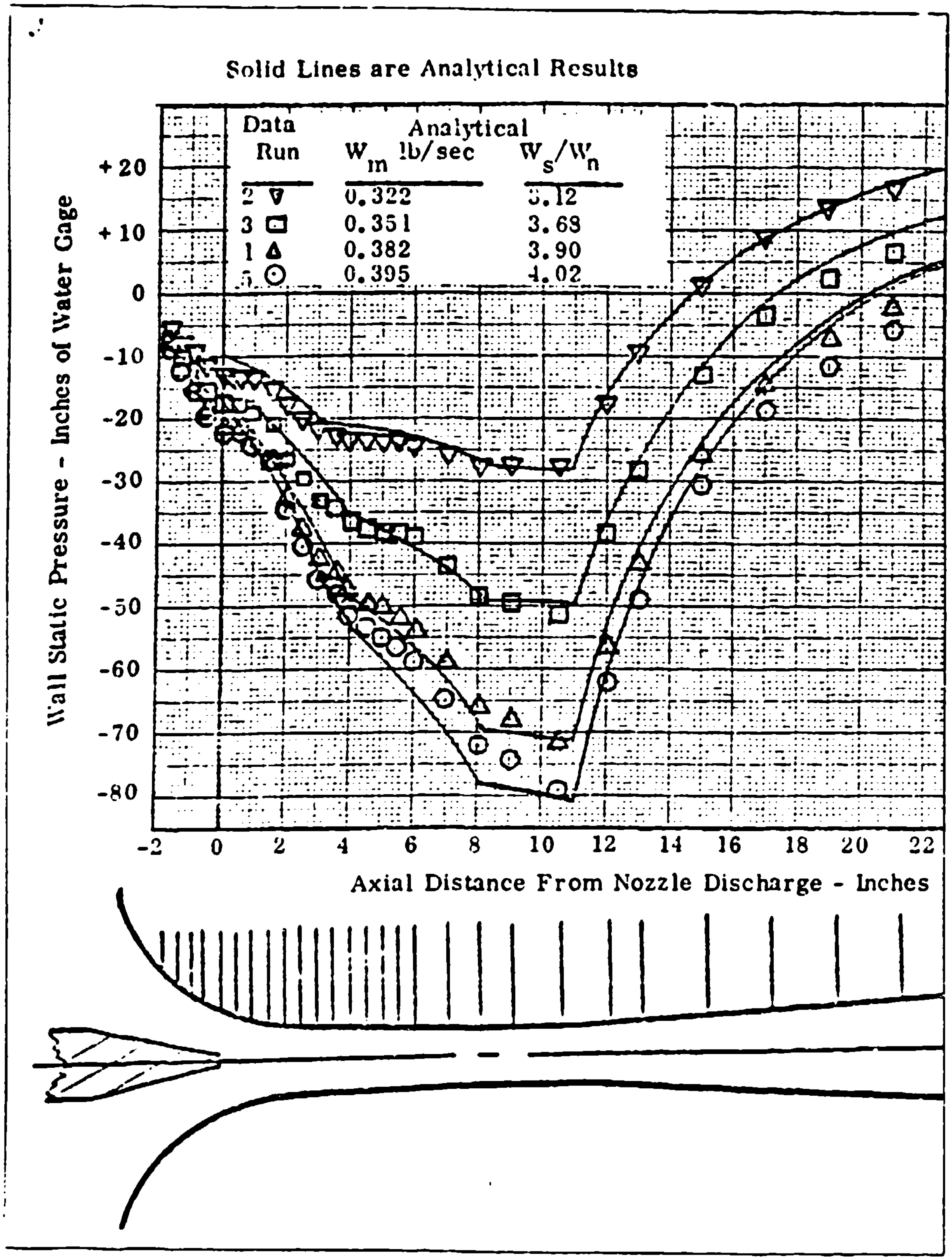

Figure 2.5 Pressure Distribution Along The Ejector (Ref.5).

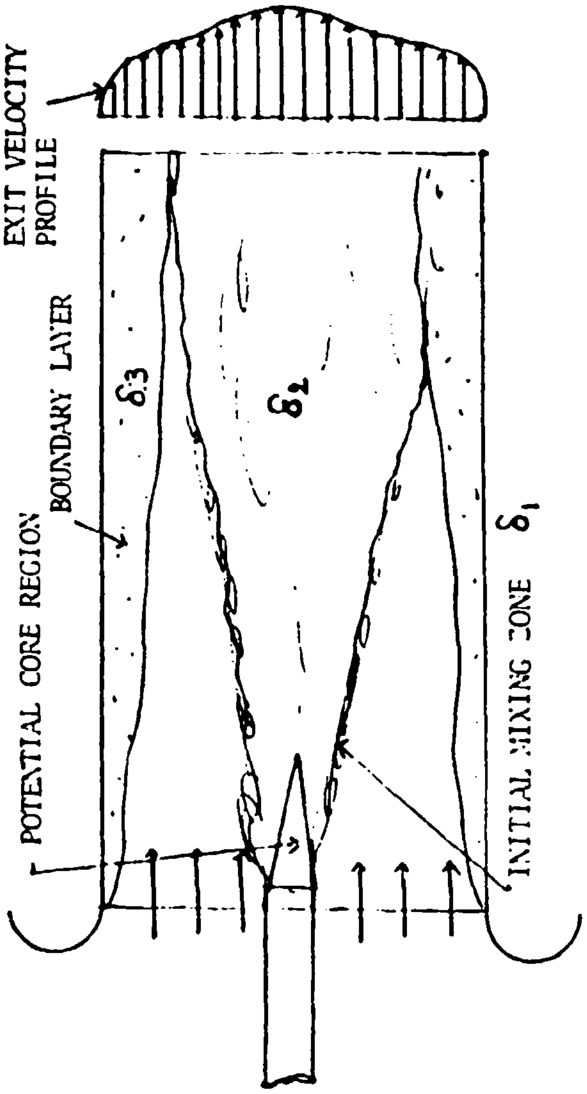

Figure 2.6 Flow Inside The Duct(Viscous Flow Pattern).

III. EXPERIMENTAL SETUP

A. PRIMARY NOZZLE WITH EXCITATION MECHANISM

The jet was produced by a converging nozzle to which high pressure air was supplied by a compressor. In between the compressed air supply and the jet was incorporated a large plenum chamber and a settling chamber containing a set of screens and honeycombs (Figure.3.1 and Figure.3.2). The jet was excited by moving two small segments, which form the exit of the nozzle in a reciprocating manner using a gear cam mechanism operated by a variable speed motor. By suitably positioning the cams, the lips of the nozzle could be made to move in opposition with a phase difference of 180 degrees. This enabled the jet to flip up and down with maximum throw (Figure.3.3). The nozzle width was 0.5 cm when the lips were in neutral position and 38 cm long.

B. EJECTOR DUCT

Since the experiments were exploratory in nature a simple rectangular duct was employed as the ejector shroud. Originally the width of the shroud was 50 cm, larger than that of the jet nozzle. It was observed that this duct induced side flow which had an unfavourable effect on ejector performance. The ejector thrust was found to be very sensitive to alignment of the system. Later the width of the duct was reduced to 40 cm by inserting solid liners on the sides. The inlet region of the shroud was provided with a pair of semicircular entry lips for the smooth entry of the flow without separation (Figure.3.4 & Figure.3.5) Figure.3.6 shows a picture of nozzle and the mixing duct.

C. INSTRUMENTATION

The jet nozzle with the settling chamber was mounted on very low friction needle bearings restraining movement only in the axial direction. A similar arrangement was used for the ejector shroud. Both the jet assembly and the ejector duct were provided with force measuring devices using strain gauges. The systems were calibrated and it was observed that both of them had linear behavior and the repeatability was excellent. A set of pitot rakes was employed for determining the velocity profiles in the ejector duct (Figure.3.7). A multitube inclined alcohol manometer was used to measure the pitot and local wall static pressure. The flow pattern of the steady as well as oscillating jet was visualized by introducing smoke filaments into the flow. Smoke was generated by electrically heating a spiral wire filament coated with wax. Photographs were taken using a polaroid camera. Flow visualization studies were conducted only at low speeds, say 6.0 m/sec. At higher velocities smoke dispersed and patterns were not distinctly observable. The jet was turbulent in this experiment.

A Schlieren system was also used for flow visualization. The density gradient was produced by placing a thin heated wire along the outer boundary of the jet.

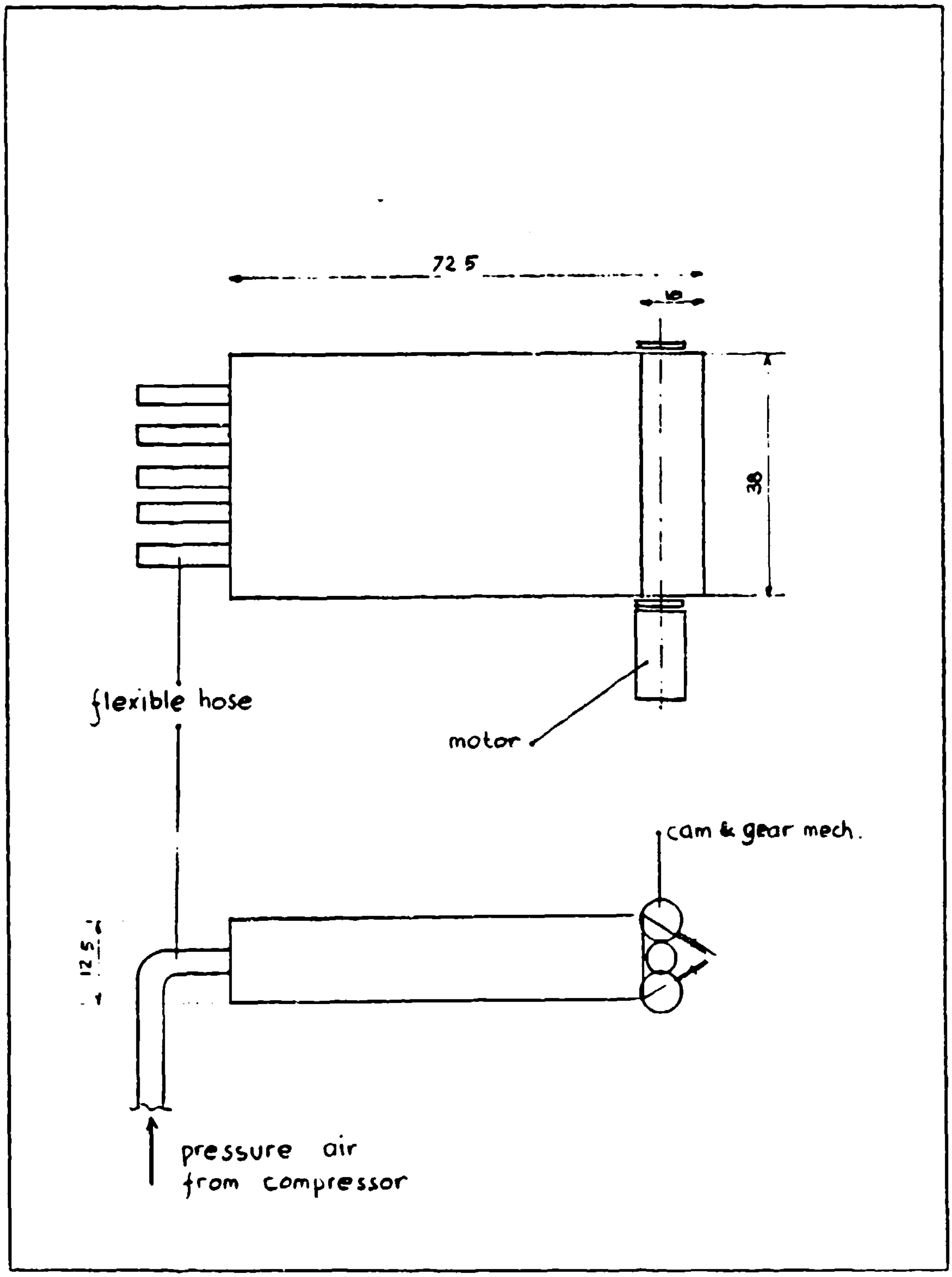

Figure 3.1 Schematic of Primary Nozzle.

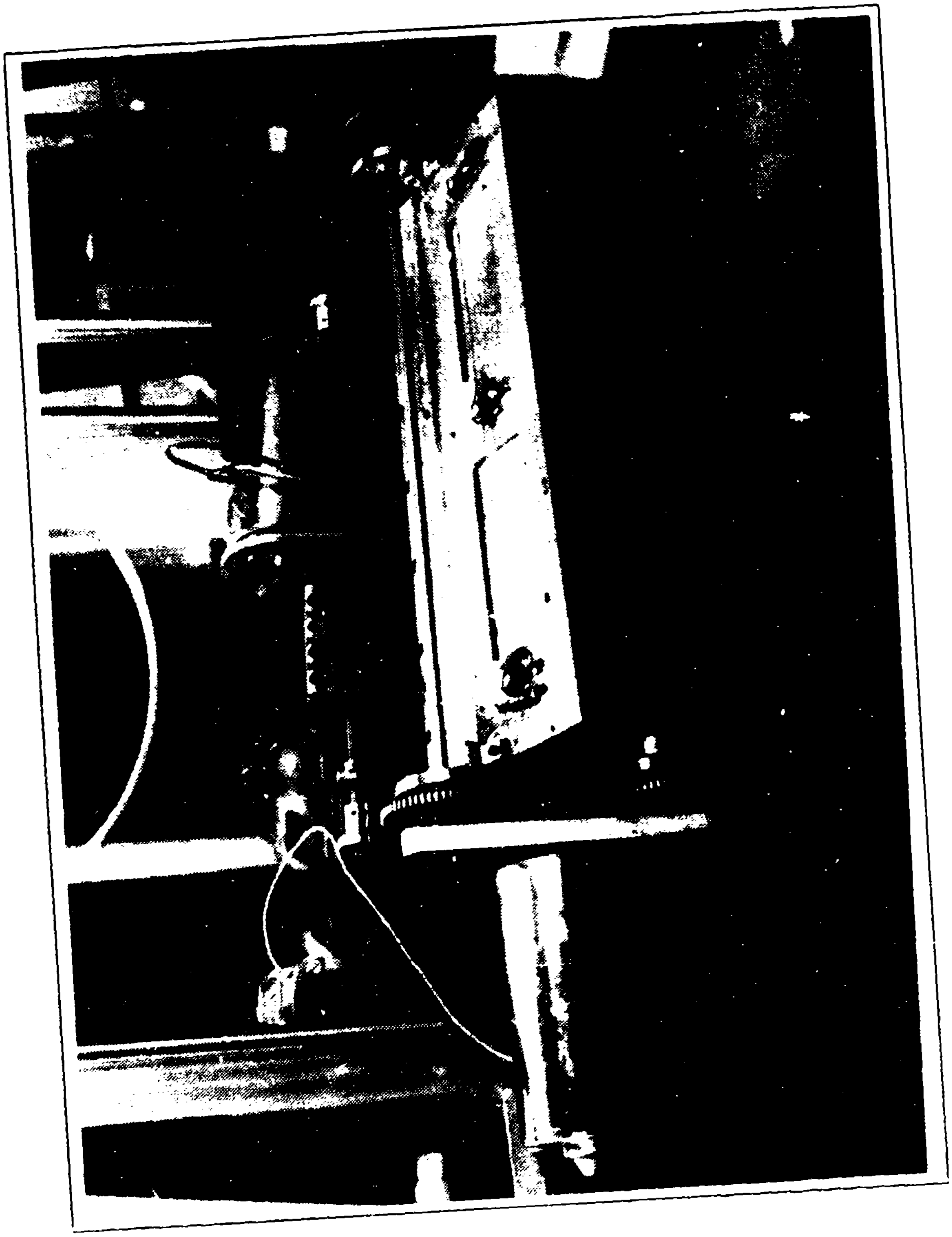

Figure 3.2 Picture of Primary Nozzle.

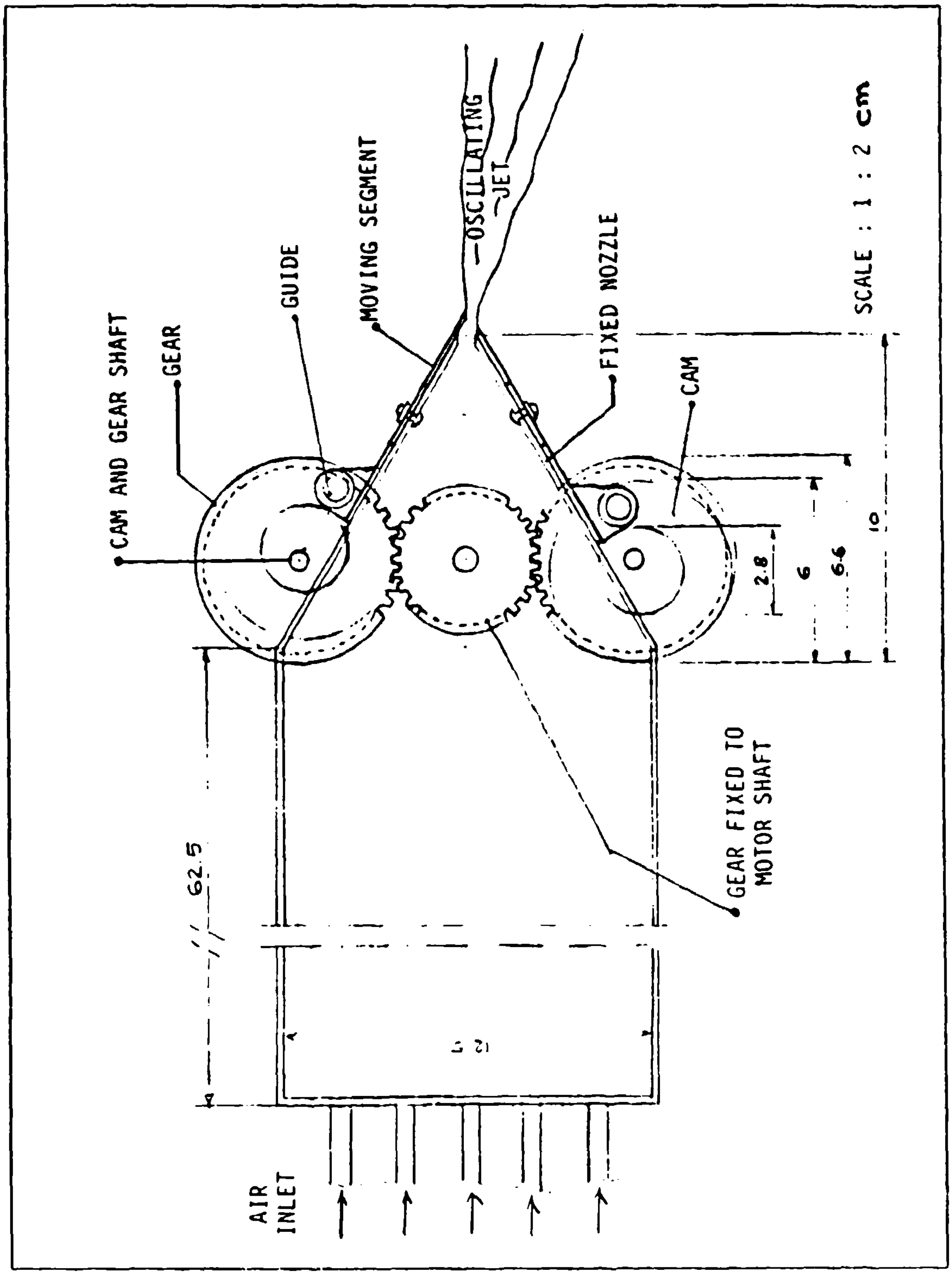

Figure 3.3 Cam Gear Mechanism at Nozzle.

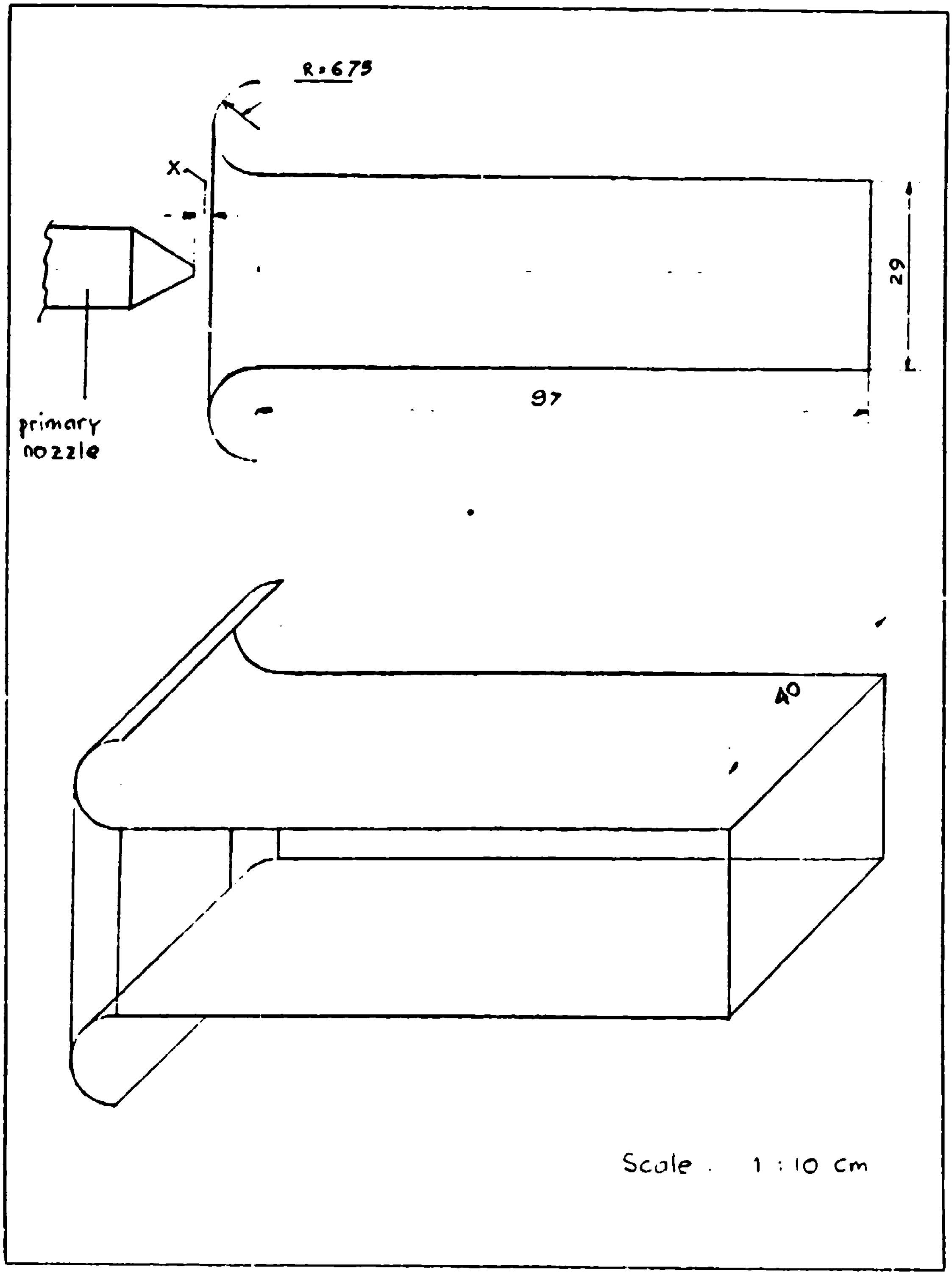

Figure 3.4 Schematic of Constant Area Ejector.

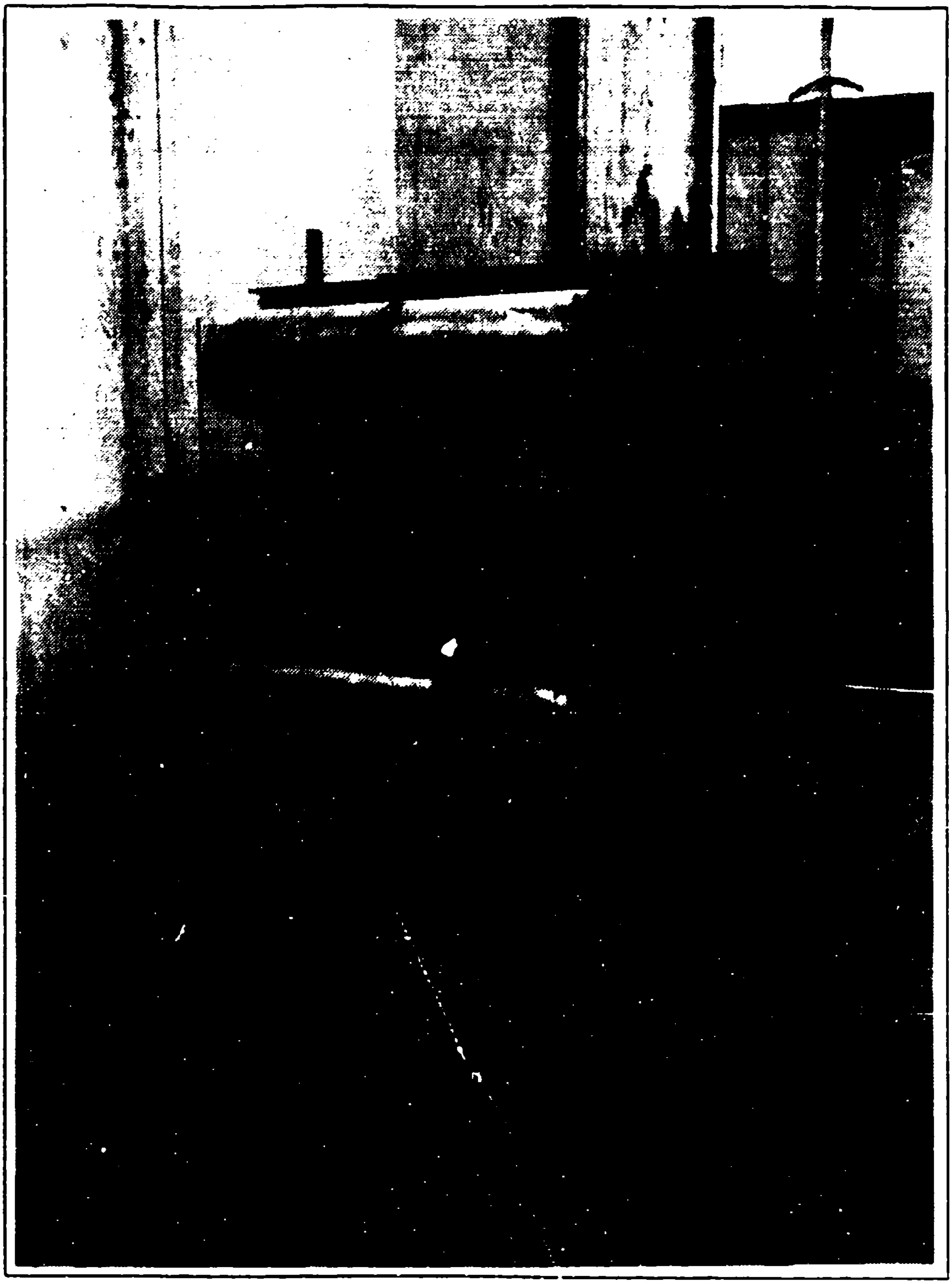

Figure 3.5 Picture of Constant Area Ejector.

Figure 3.6 Picture of Nozzle and The Mixing Duct.

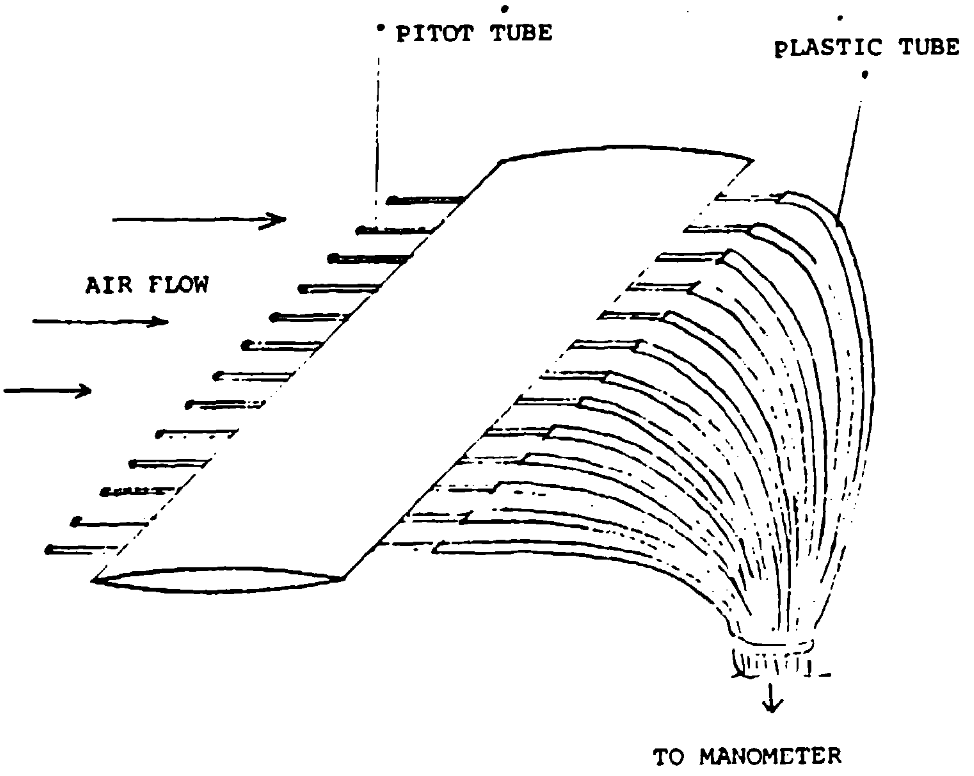

Figure 3.7 Schematic of Pitot Rake.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. THRUST

All the experiments were conducted with a total pressure of 4.1 inches of mercury above atmosphere. A thrust of 4.61 Newton was produced by the jet as recorded by the force measuring device (Figure.4.1 & 4.2). The thrust as estimated assuming isentropic expansion was 5.13 Newton. The details of the calculation are given below.

Static pressure/total pressure = 0.8797
This corresponds to a Mach number of 0.435
Speed of sound = 340 m/sec
Exit velocity $U_j = 0.435 \times 340 = 148$ m/sec
Area of the jet exit $A_j = 0.5 \times 38 = 19$ sq. cm
Density of air $\rho = 1.12$.kg/m
Mass flow rate $m = A_j U_j \rho = 0.315$ kg/sec
Thrust = $m U_j$ = 5.13 Newton

It is difficult to measure thrust with accuracy in the laboratory. The air admitted into the settling chamber produces some reactions and they interfere with the axial force. These additional forces are difficult to measure or account for, hence the measured thrust of the jet is generally less than the actual value. It is for this reason that the isentropic thrust is employed as the standard one in most investigations, the same procedure is followed in the present investigation.

B. EFFECT OF BASIC PARAMETERS ON EJECTOR PERFORMANCE

The effect of the following parameters on thrust augmentation was investigated

1. Frequency of excitation

2. Height of the ejector duct
3. Distance between the jet nozzle and the ejector duct

Thrust of the duct was measured exciting the jet at different frequencies varying from 0 to 25 hz. Initially there was an increase in thrust as the frequency was changed from zero to a higher value (Figure.4.3). It reached a saturation around 17 Hz beyond which there was no appreciable increase in ϕ . Based on this observation the subsequent experiments were conducted at an excitation frequency of 20 Hz.

The distance between the nozzle and the duct had noticeable effect on ejector thrust (Figure.4.4). For the case of the steady jet thrust was maximum for $x = 5$ cm and with excitation the above distance reduced to 2 cm. Thrust decreased for both cases when x was more than 5.0 cm. The above experiments were conducted for an ejector height of 30 cm, i.e $S/H = 50$. With excitation the maximum value of phi was 1.65 and 1.4 for the steady jet using isentropic thrust for the jet. Thrust augmentation ratio estimated with measured jet thrust is shown in Figure.4.5.

The effect of height of the ejector duct on thrust augmentation (Figure4.6) was appreciable. In the case of the steady jet ϕ was maximum for $x/H = 40$ and 50 for the jet excited at 20 Hz.

C. VELOCITY DISTRIBUTION INSIDE THE DUCT

The velocity distribution inside the ejector duct was measured with pitot rakes specially designed for this purpose. Wall static pressure (Ps) at the pitot tube location was used to determine the mean velocity

$$U = \left[(P - Ps)2/\rho\right]^{1/2}$$

Only a limited number of profiles were measured to examine the three- dimensionality of the flow. Figure.4.7 shows the spanwise velocity distribution along the center of the jet without the duct and the jet was found to be nearly two-dimensional in the potential core region.

Three sets of velocity profile measurements were made inside the duct for the case of steady jet. With the jet in the excited state it was found difficult to hold the pitot rake steady. Hence no attempt was made to measure profiles under this condition except in one case near the exit of the ejector. The spanwise velocity distribution along the duct at y = 15 is shown in Figure.4.8. The jet which was nearly uniform near the entrance of the duct loses its two-dimensionality as it mixes with the entrained flow. A set of velocity profiles measured along y at different spanwise location at x = 66 cm (Figure.4.9) shows the true three-dimensionality of the flow. It is interesting to note that these profiles exhibit near similarity when local maximum velocities are used for scaling. The velocity profiles measured along the height of the duct at x = 90 cm with and without excitation (Figure.4.10) indicated a tendency for the flow to become uniform with excitation.

D. FLOW VISUALIZATION

The structure of the flow was visualized using smoke filaments. Long duration exposure photographs taken with a steady jet in the neutral and extreme position of the lips when compared with the one taken with the excited jet indicated a larger spread in the latter case (Figure.4.11). The angle of spread of the excited jet was 48 degrees. For the steady jet the maximum spread was only 24 degrees revealing that excitation produced additional spread of the jet.

The instantaneous structure of the flow was examined by exposing the photographic film for a shorter duration less than 1/fe. At low velocities and low frequencies the flow was found to flip up and down (Figure.4.12), as the excitation frequency was increased there was a tendency for the flow to curl up and form vortices (Figure.4.13). These vortices were found to form in an alternating fashion and as they were convected downstream of the exit the vortices lost their identity and merged with the flow forming some kind of large scale motion spanning the entire width of the jet. It is the opinion of the author that these vortex like patterns are responsible for mixing when the jet is excited.

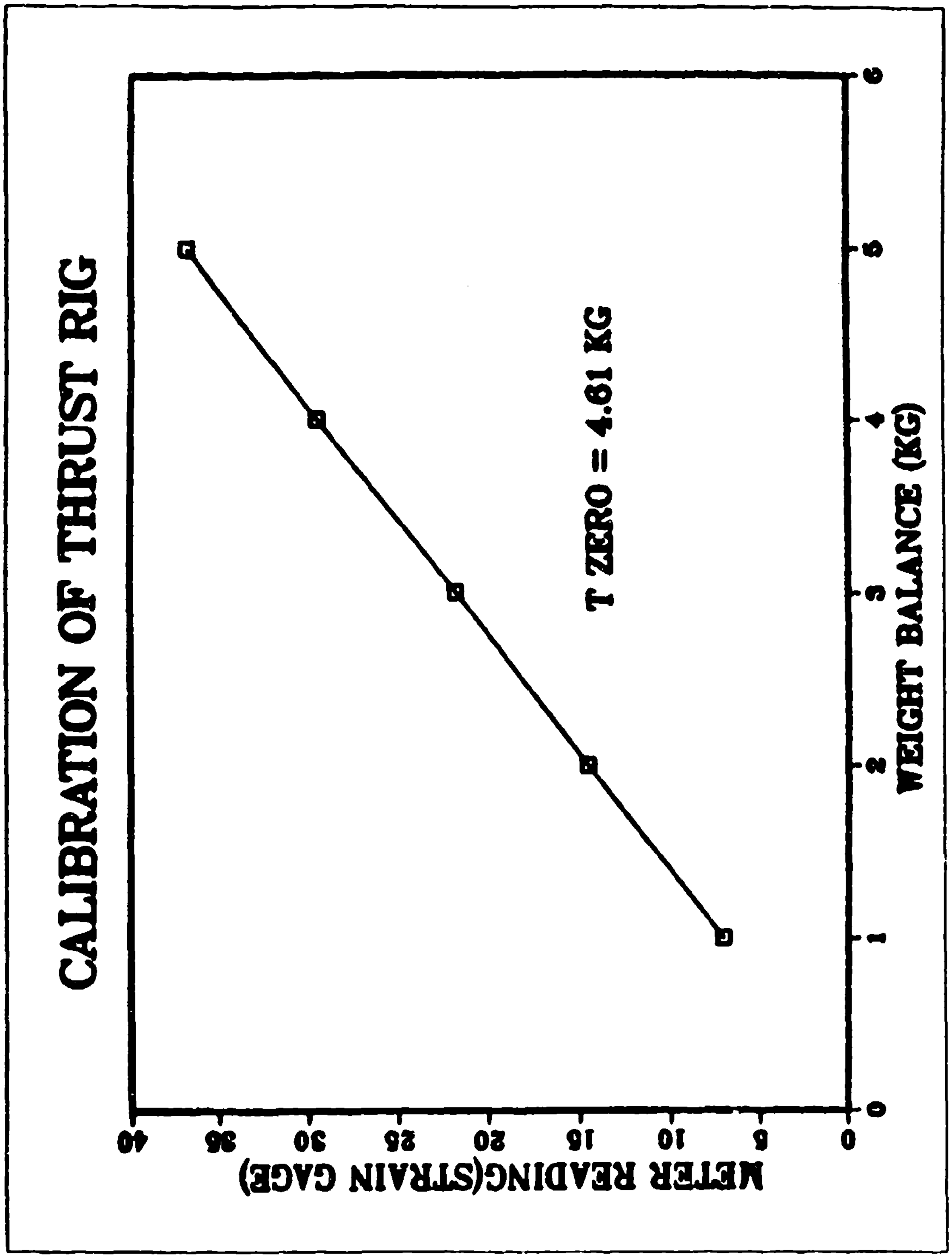

Figure 4.1 Calibration of The Thrust Rig.

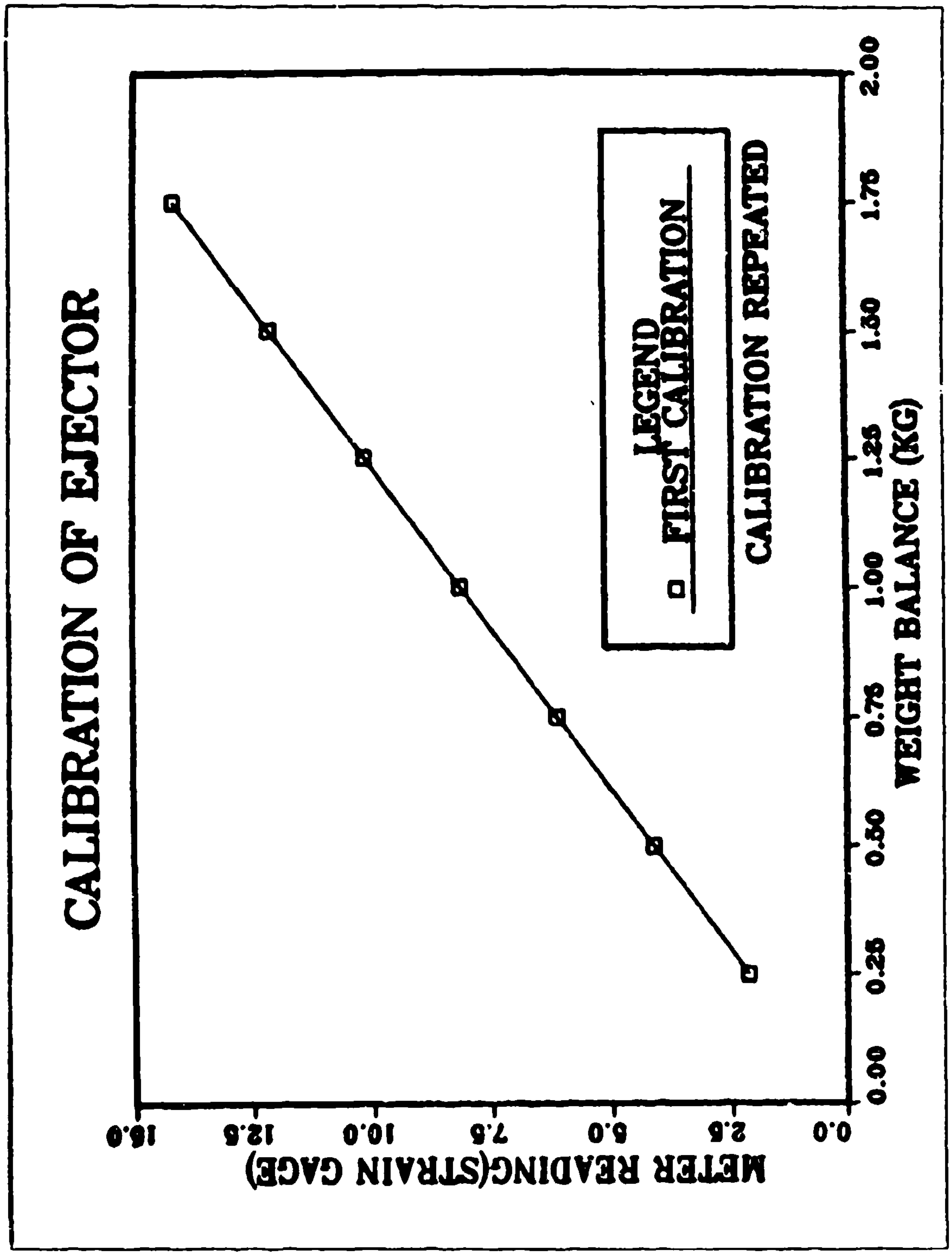

Figure 4.2 Calibration of Ejector Thrust Rig.

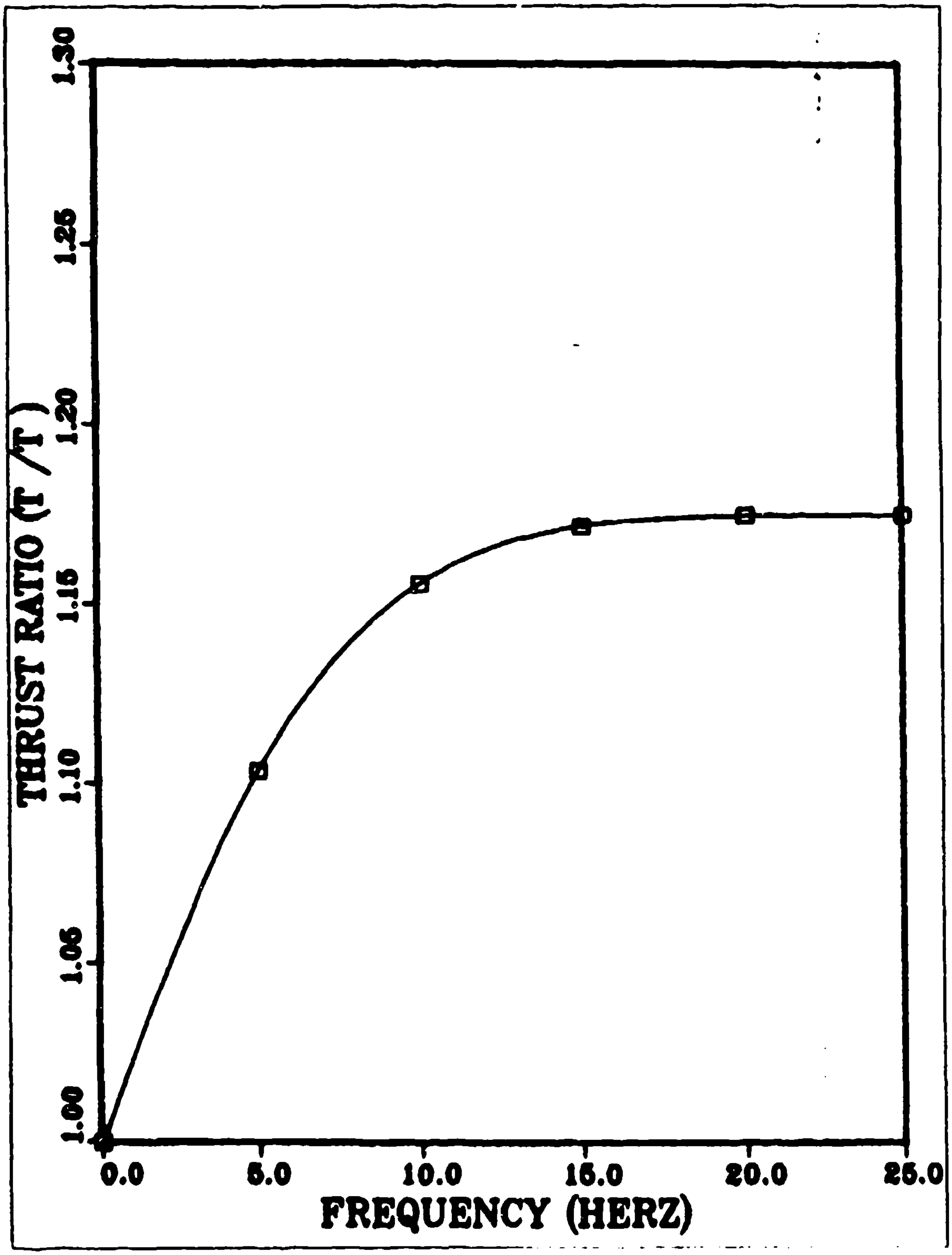

Figure 4.3 Ejector Thrust vs Frequency.

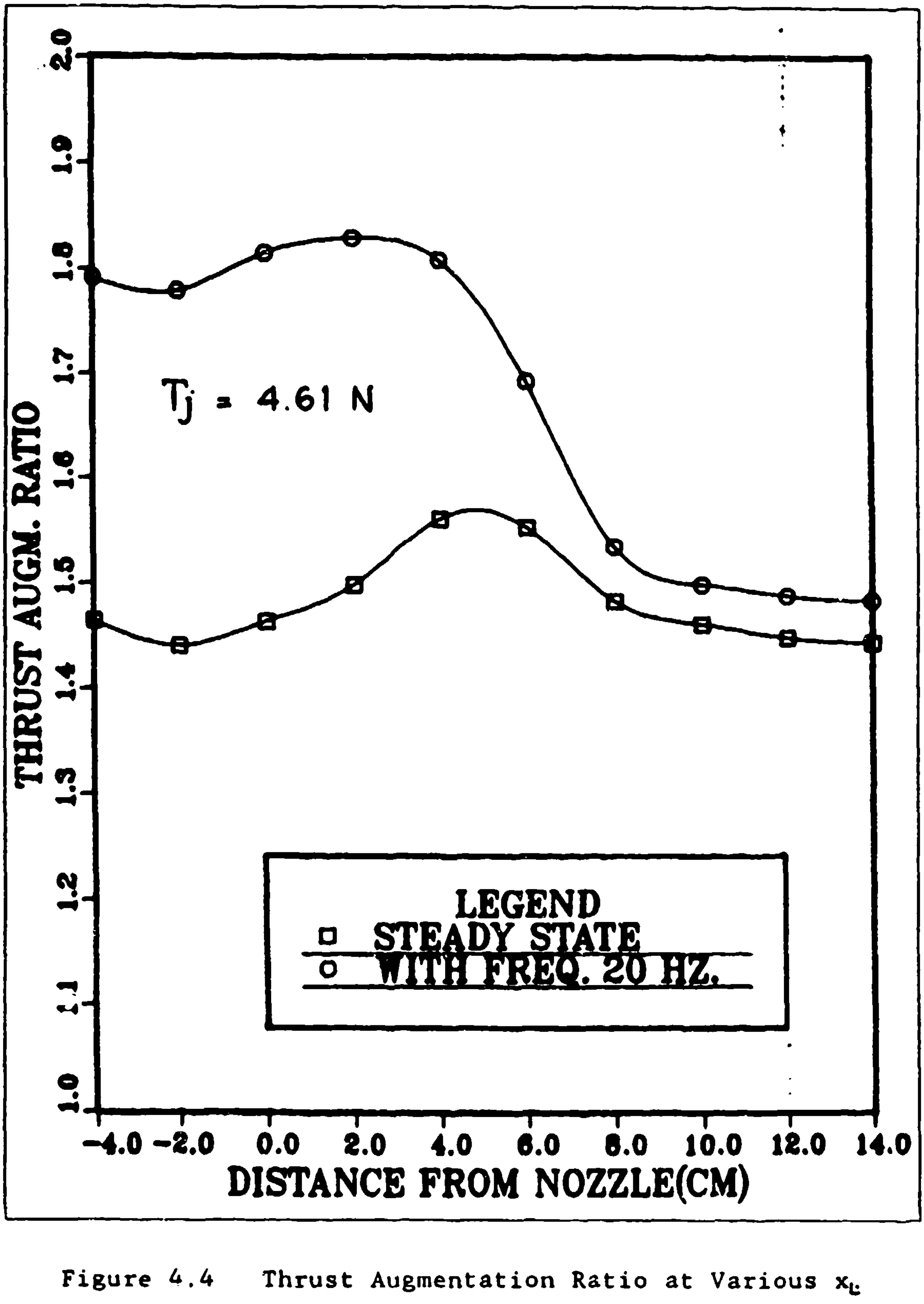

Figure 4.4 Thrust Augmentation Ratio at Various x_L

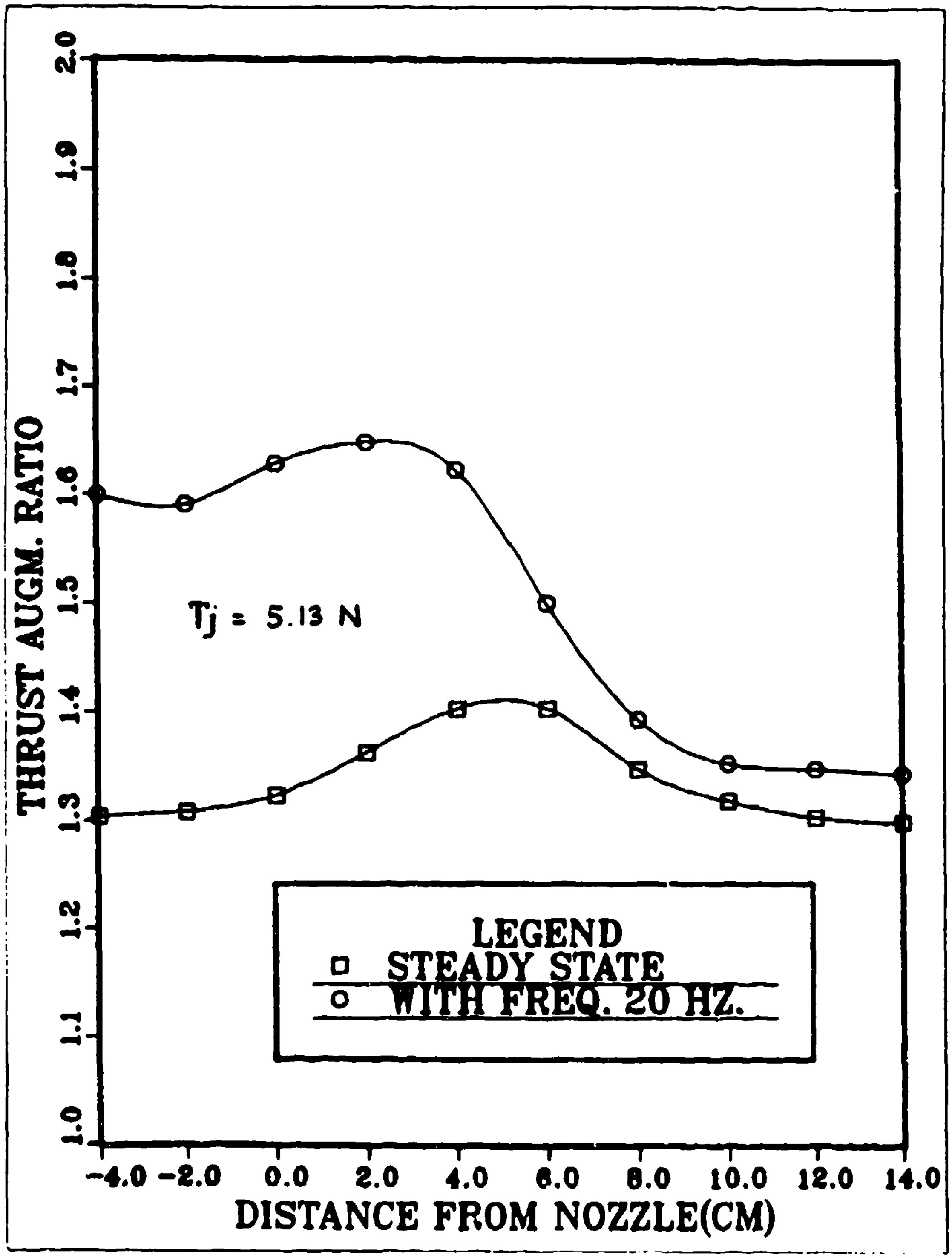

Figure 4.5 Thrust Augmentation Ratio vs x_L

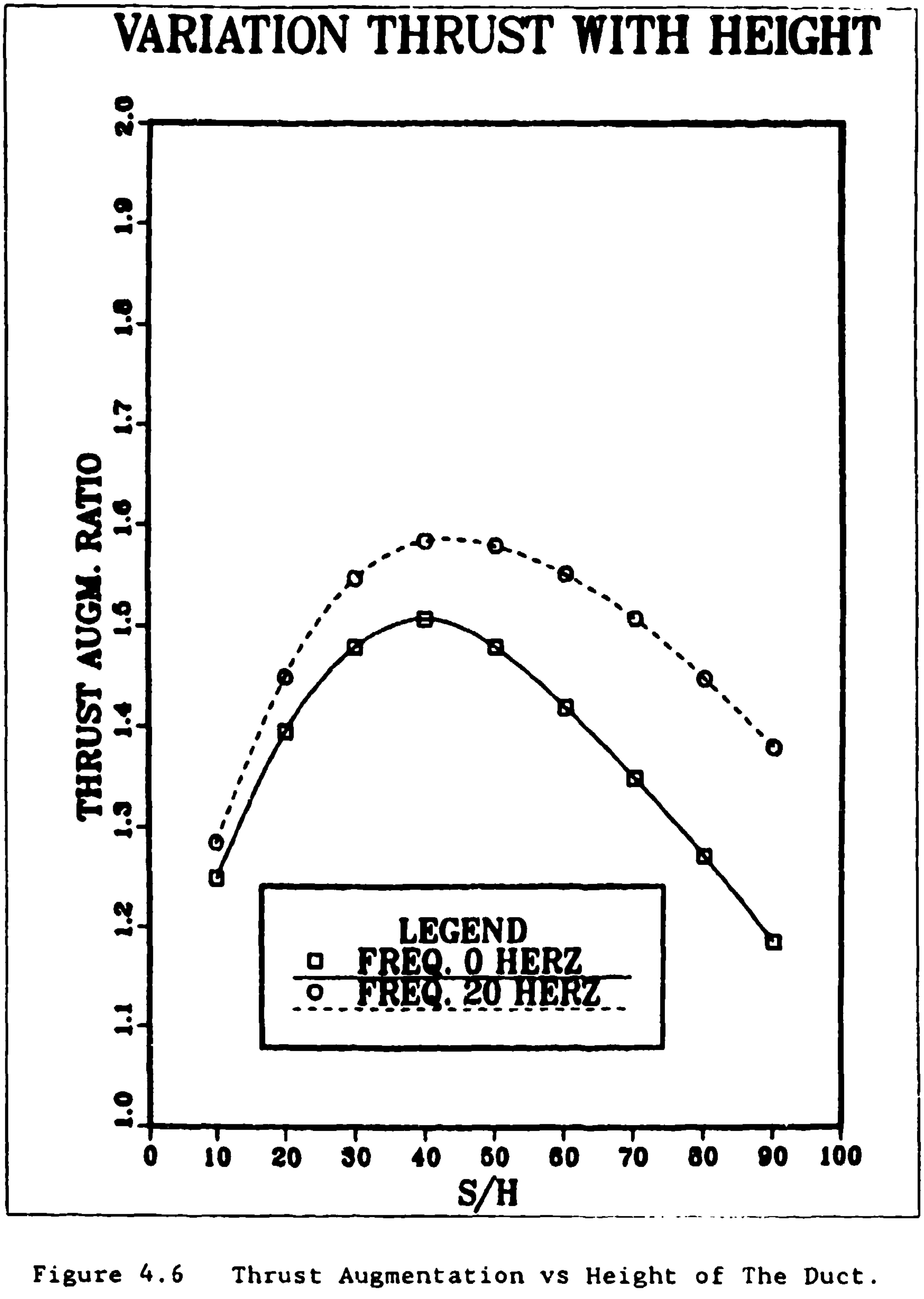

Figure 4.6 Thrust Augmentation vs Height of The Duct.

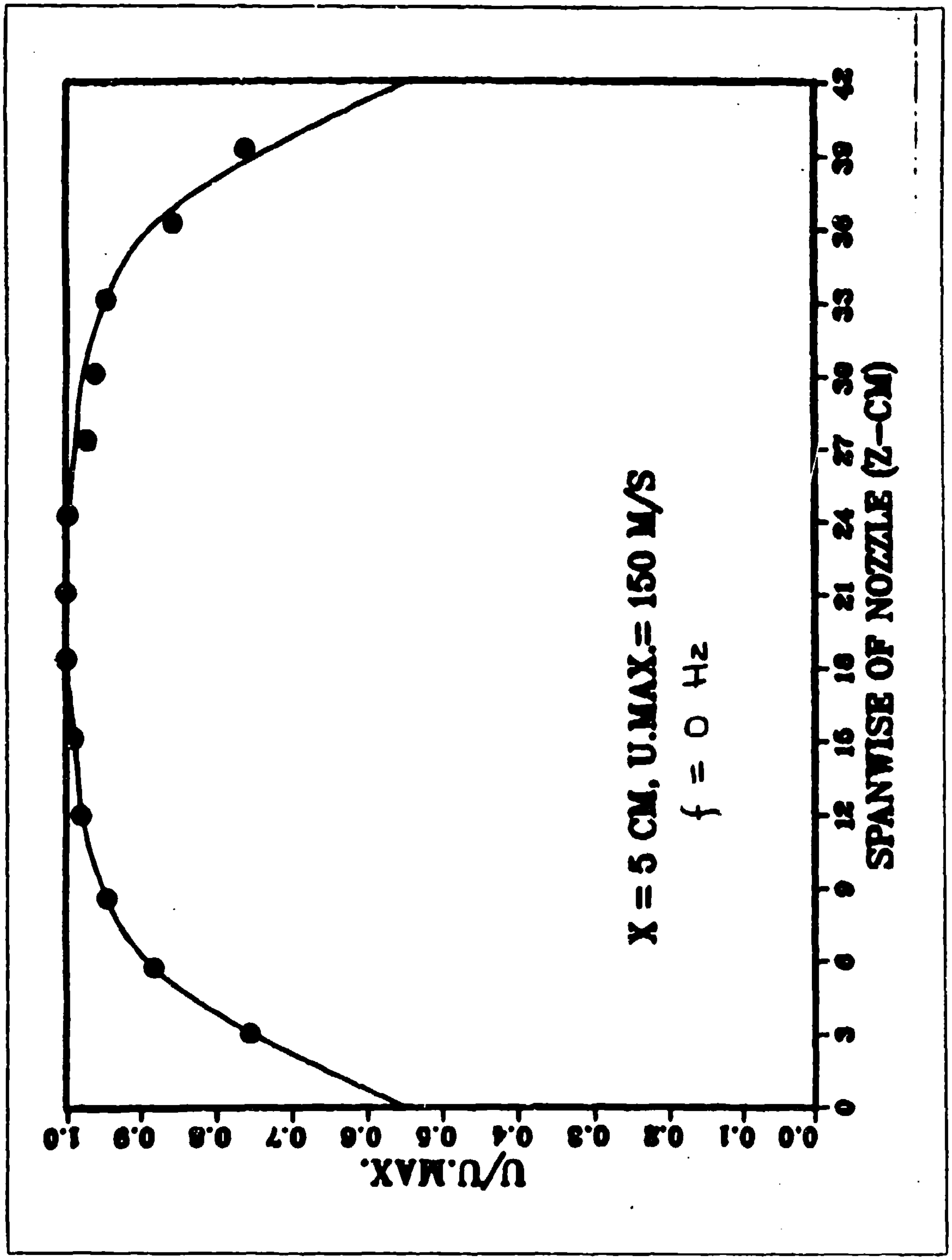

Figure 4.7 Spanwise Velocity Profiles.

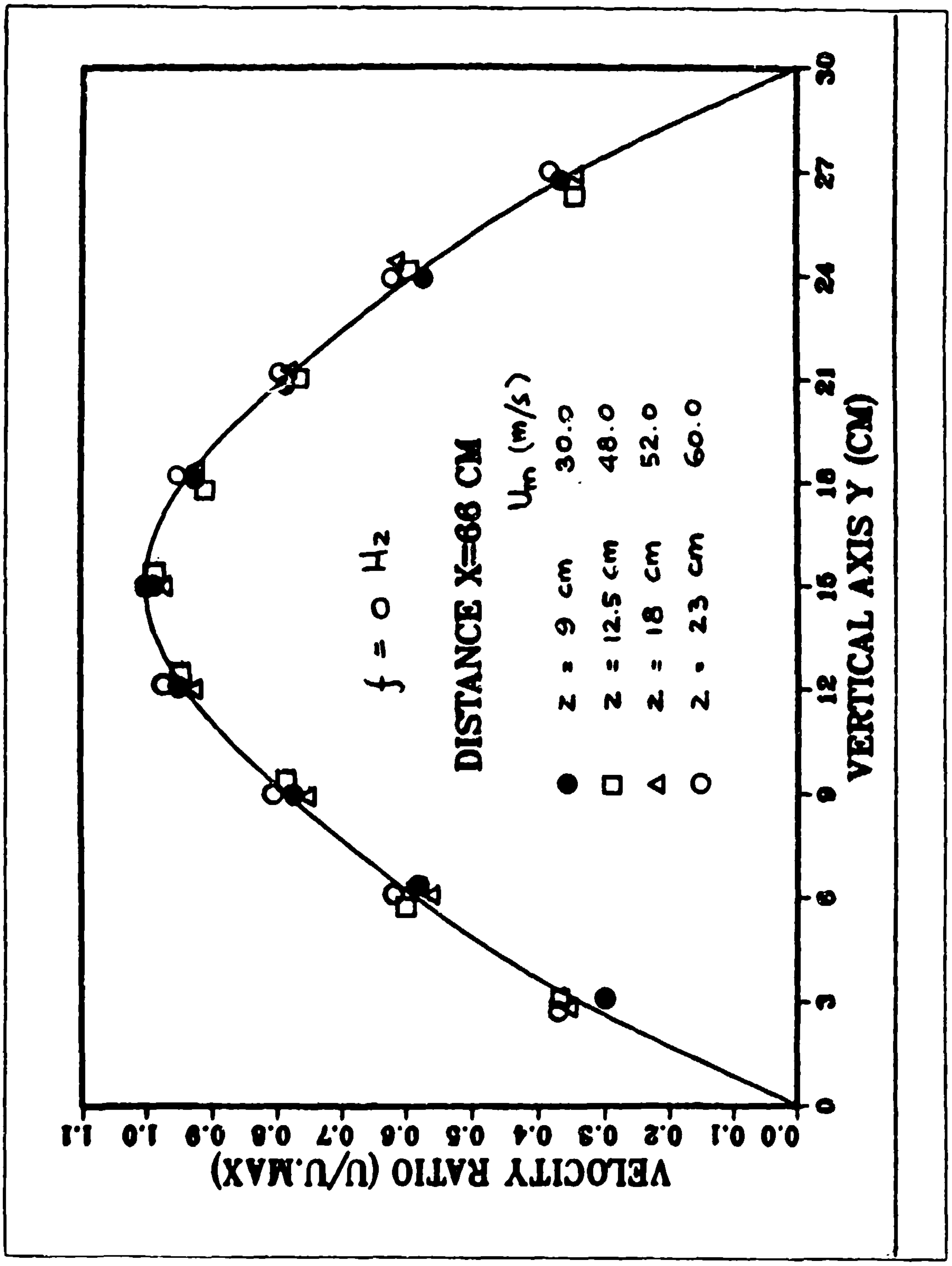

Figure 4.8 Velocity Profiles Across The Ejector.

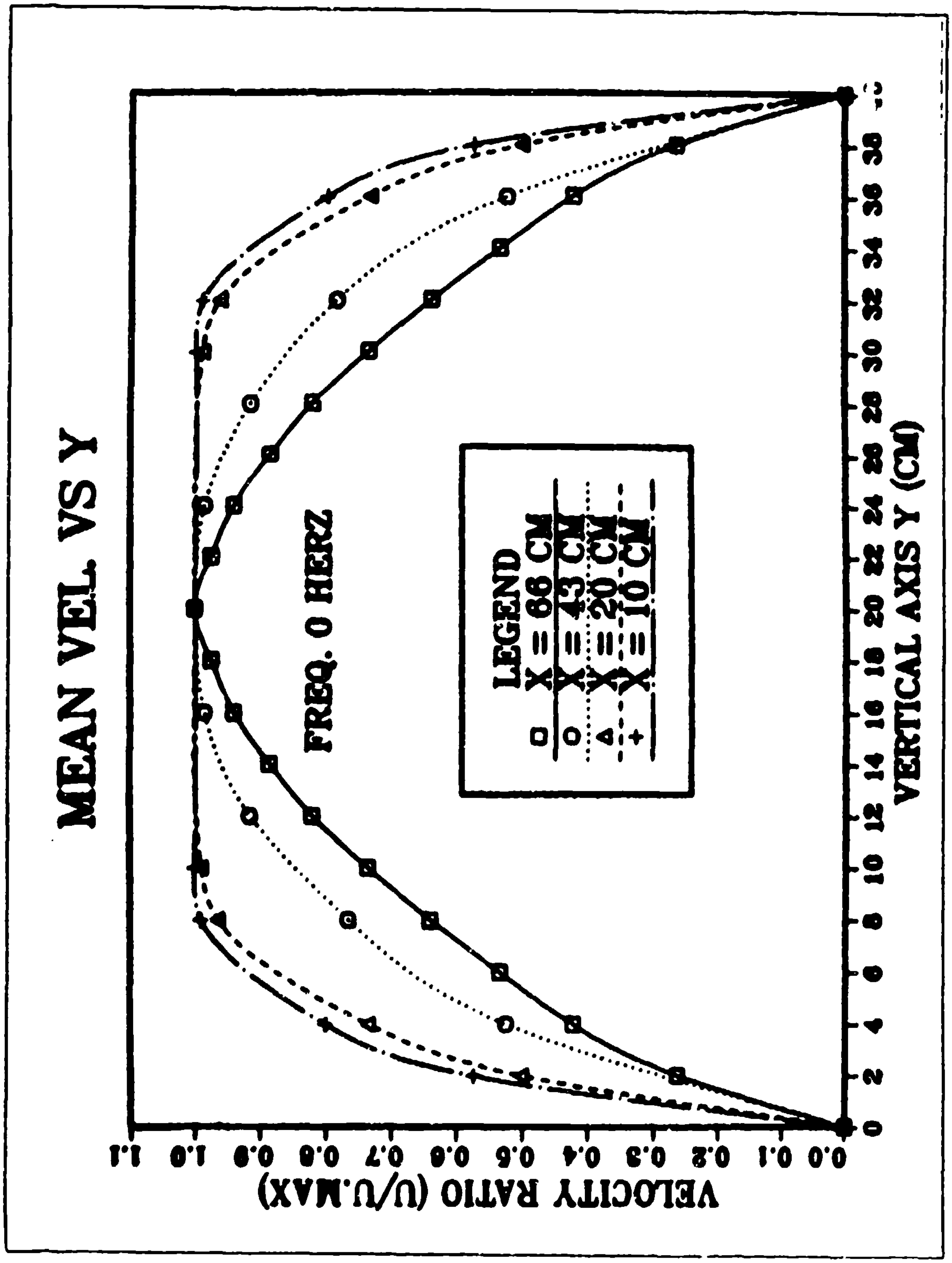

Figure 4.9 Spanwise Velocity Profiles.

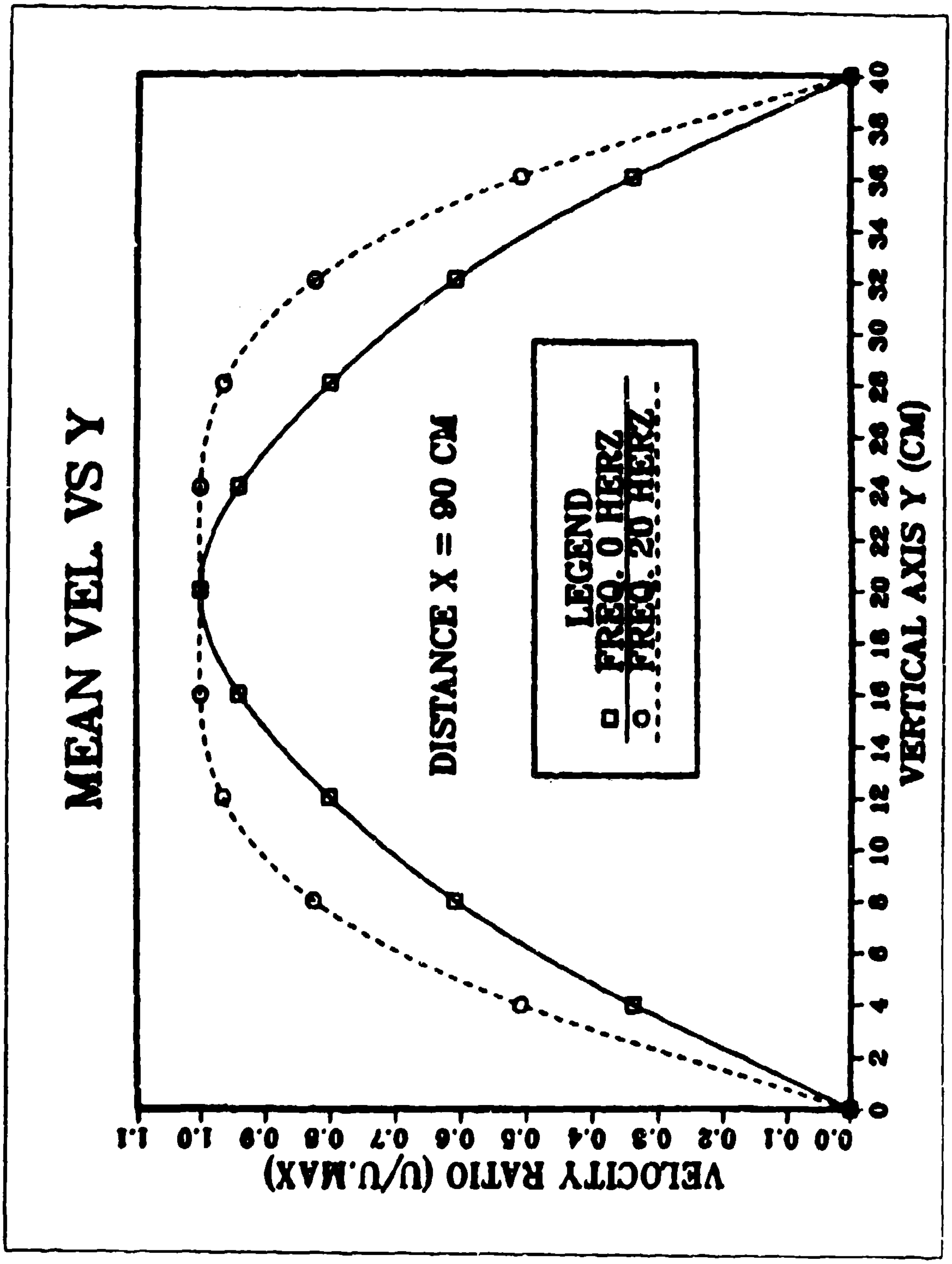

Figure 4.10 Velocity Profiles at x=90 cm.

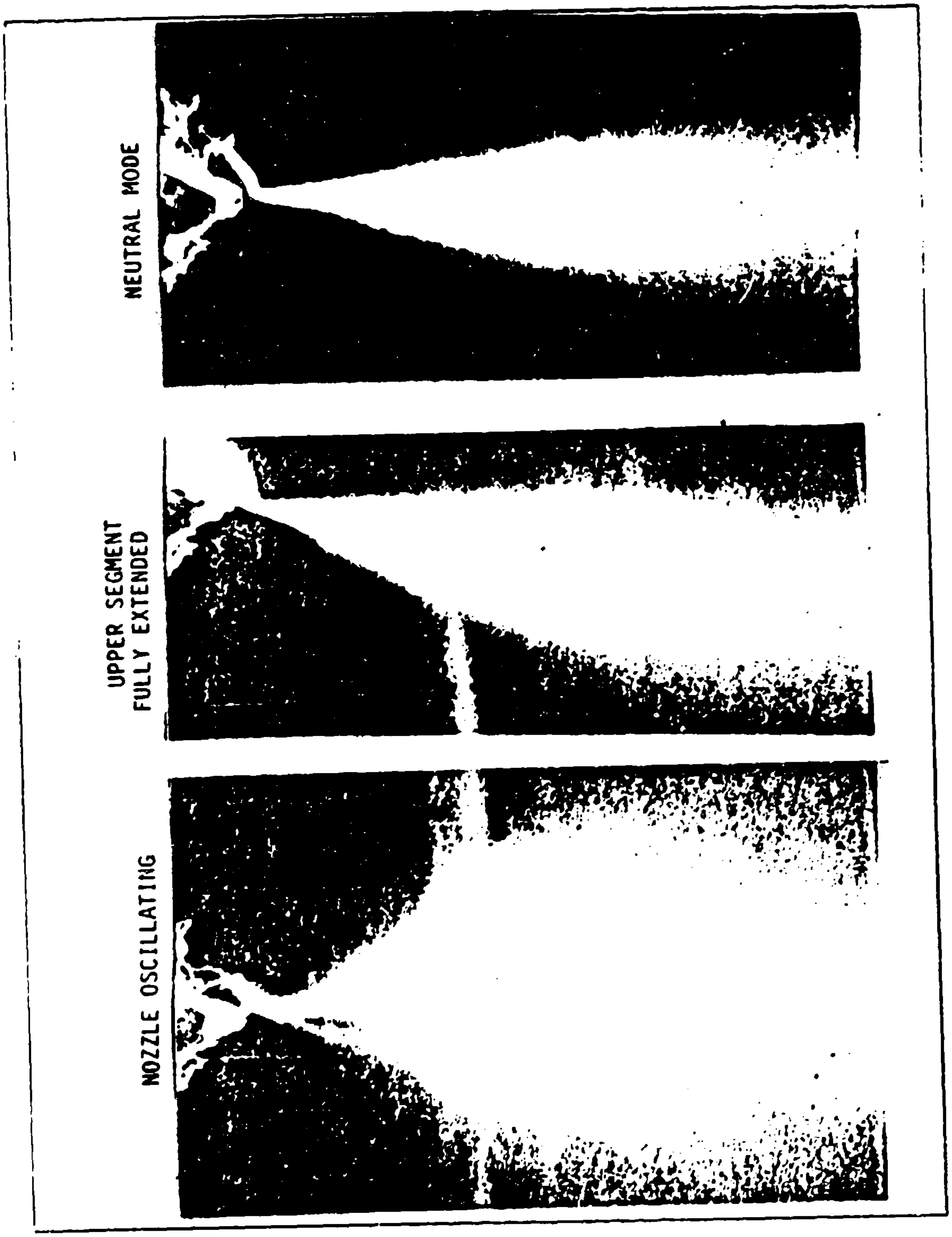

Figure 4.11 Primary Flow in Different Nozzle Mode.

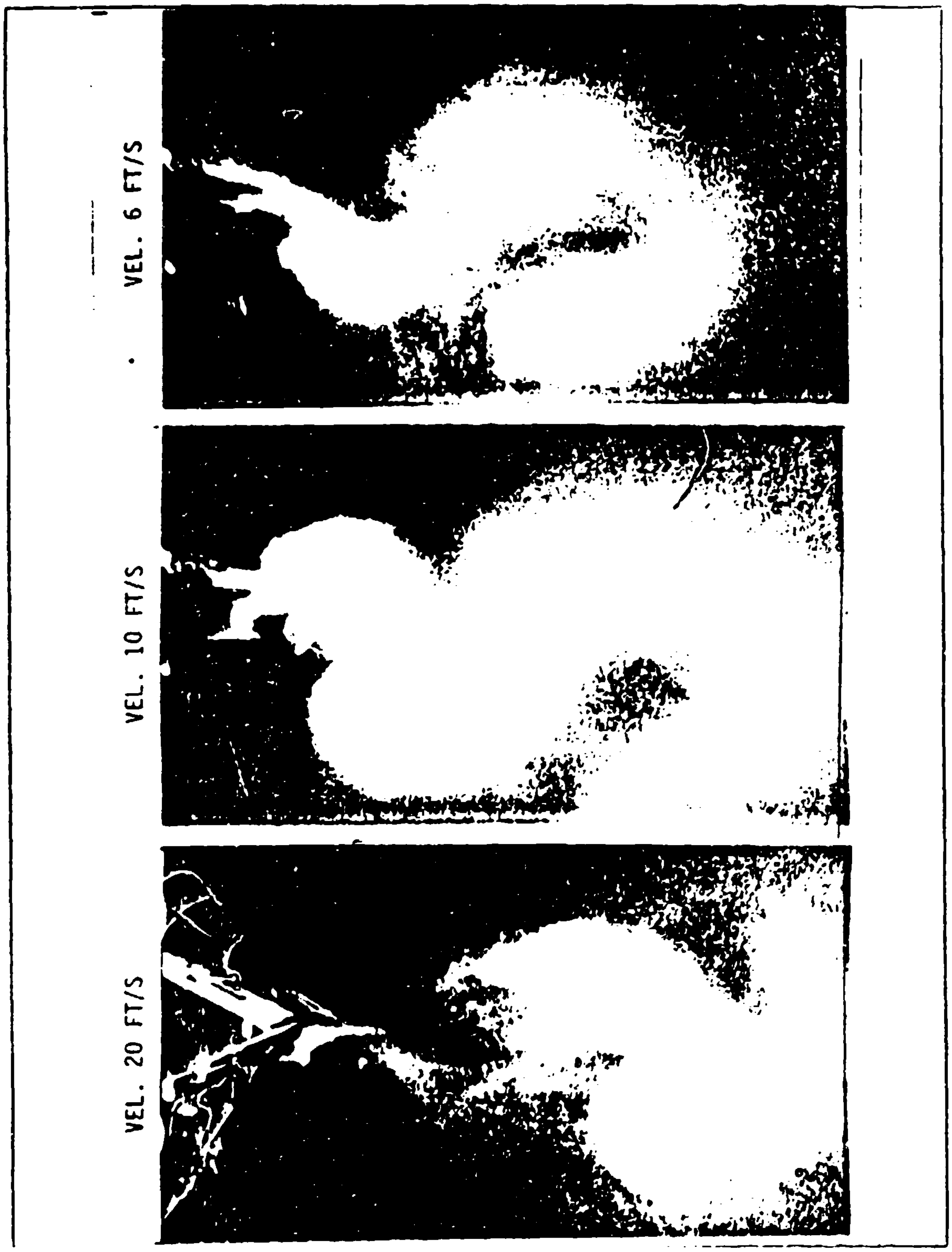

Figure 4.12 Change in Flow Pattern at Freq. 10 Hz.

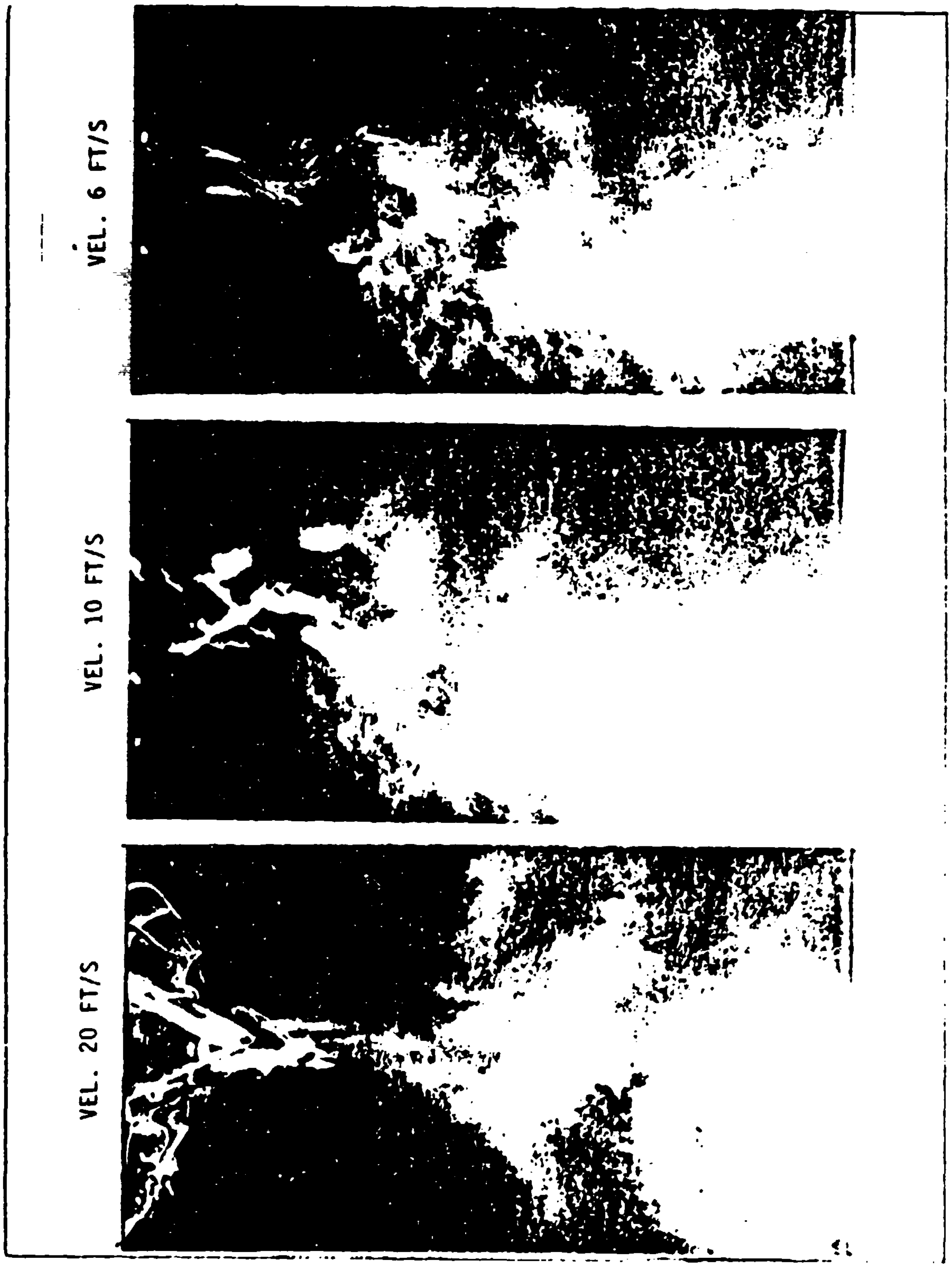

Figure 4.13 Change in Flow Pattern at Freq. 20 Hz.

V. CONCLUSIONS AND RECOMENDATIONS

A. CONCLUSIONS

1. In the present method of excitation the maximum thrust could be obtained beyond an oscillating frequency of 15 Hz. This indicates that mixing is efficient even at lower frequencies in this system. It is a great advantage from the mechanical design point of view.
2. A thrust augmentation ratio (ϕ) of 1.65 was achieved at an excitation frequency of 20 Hz. For a steady jet thrust augmentation ratio was 1.40. These values are based on jet thrust values derived from isentropic expansion calculations.
3. The thrust was maximum when the ratio of the duct to nozzle height was around 50.
4. Maximum thrust was produced when the inlet of the ejector duct was placed about five nozzle heights (x /H) from the nozzle.
5. Excitation produced periodic large scale structures. They are considered to play a major role in the mixing process.

B. SUGGESTION FOR FURTHER RESEARCH

Based on the observations made in the present investigation the following suggestions are made for further understanding of the problem.

1. Overall performance of the ejector system varying the maximum throw of the lips of the reciprocating nozzle. The present movement is one centimeter which is large compared to the width of the jet (.6 cm). This calls for the design of a set of cams for each throw.
2. Ejector performance with a lower duct height, say S/H = 20,which is more practical for aircraft design.
3. Three dimensionality of the flow for lower S/H
4. High speed photography of the flow using a high intensity light source of microsecond duration.
5. A diverging duct or a diffuser to increase thrust.

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