J. Indian Inst. Sci., 64 (A), Oct., 1983, Pp. 203-218

An experimental investigation of the internal flow in an ejector with flap-excited primary jet

M. A. BADRI NARAYANAN AND KAMAL PODDAR
Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560 012, India.

Abstract

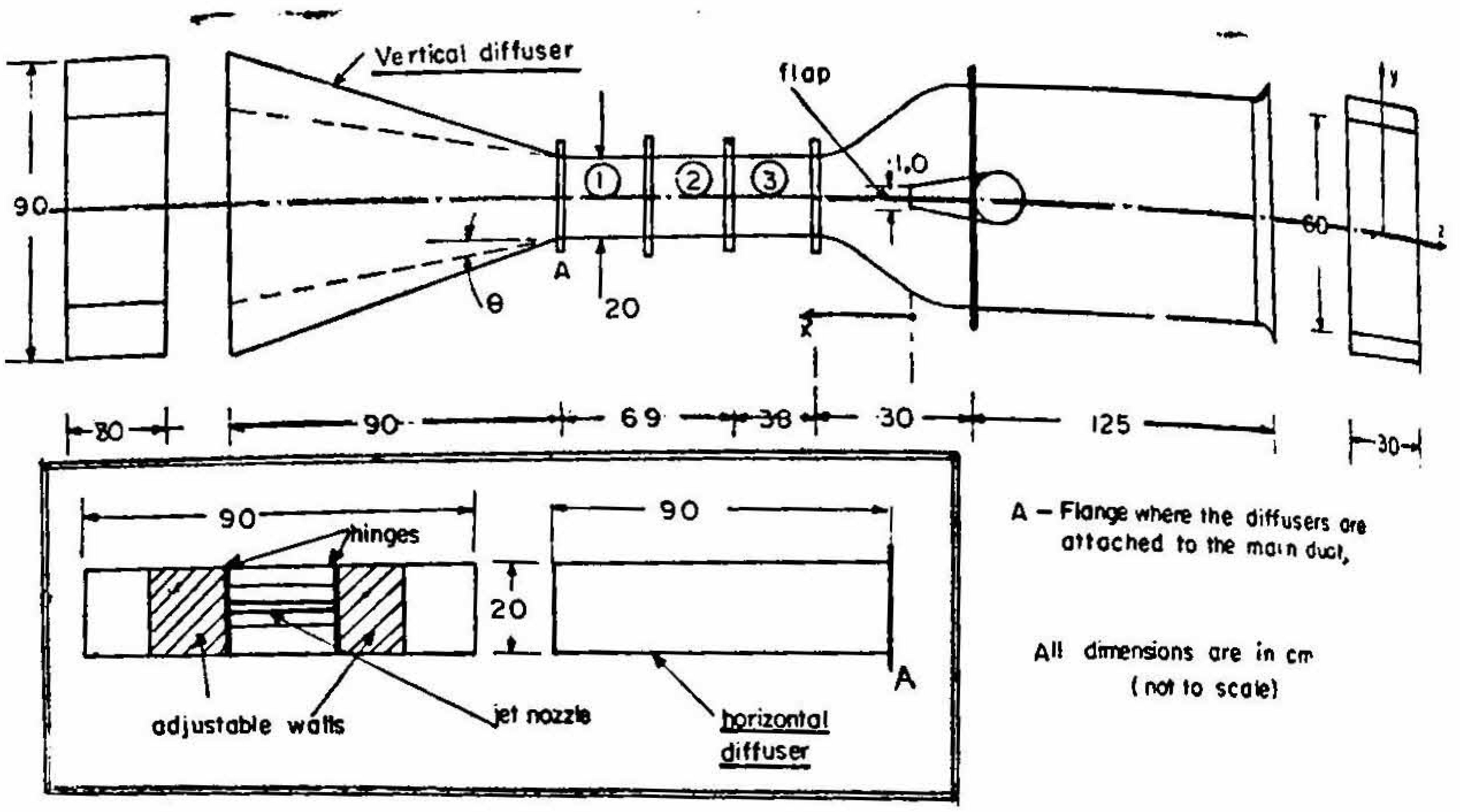
The internal flow in a two-dimensional ejector was investigated with the main jet subjected to excitation by an oscillating flap located just downstream of the jet exit. Mean velocity profiles measured in the constant area mixing duct indicated appreciable increase in mixing due to excitation. However, excitation had only a minor effect on induced mass flow. The performance of the ejector was examined with a two-dimensional diffuser attached to the constant area mixing duct in two different modes, namely divergence perpendicular and parallel to the nozzle of the jet. The rate of induced mass flow was maximum at $\theta = 8°$ for vertical diffuser and at $\theta = 12°$ for horizontal diffuser. By segmenting the primary jet into a multi-jet configuration it was possible to increase the entrainment ratio by 40%.

Key words: Propulsion, fluid dynamics, aerodynamics.

1. Introduction

In the past decade attempts were being made to improve the thrust of an ejector so that it could be employed for practical applications. Using the simple momentum theory one can show that the thrust augmentation depends on the inlet area ratio (α) and the diffuser angle (θ). It is assumed in the above analysis that the mixing between the primary jet and the secondary flow is complete[1]. However, in practice, when it is integrated with an aircraft, the size of the ejector is severely restricted. Often the length of the mixing duct has to be short and in addition a wide angle diffuser has to be employed to derive the maximum benefit. In such a situation, the mixing between the primary jet and the secondary flow is only partial and the flow in the wide angle diffuser is prone to separation which is detrimental to the performance of the ejector.

The above defects could be overcome by increasing mixing and controlling flow separation by artificial means. It has been observed that the mixing characteristics of a turbulent jet could be considerably increased by introducing controlled disturbances



A – Flange where the diffusers are attached to the main duct,

All dimensions are in cm (not to scale)

FIG. 1. Experimental set-up.

in the flow. Pulsating the main incoming flow of a free jet in a periodic fashion or by introducing small oscillations near the exit of the jet, the flow in the jet could be excited; resulting in a spectacular spread of the jet followed by a large entrainment of the fluid from the surroundings[2,3].

It is natural to expect that the use of any of the above methods in an ejector system should enhance mixing and entrainment resulting in greater thrust augmentation. But experiments carried out in such a set-up did not yield favourable results[4,5]. The reason for this behaviour is yet to be understood. It is conjectured that the enclosure of the jet in the ejector shroud modifies the turbulent mixing pattern in such a manner that additional entrainment is not possible.

The aim of the present investigation is to examine the flow in the mixing region in an ejector system with and without the excitation. Even though the experiments are preliminary in nature and restricted to the measurement of mean velocity profiles, the results do throw some light on the basic features of the flow.

2. Experimental set-up

An ejector of rectangular cross-section was designed and fabricated for the present investigation (fig. 1). The ejector consists of a 60 × 30 cm rectangular intake to which is attached a 20 × 30 cm constant area duct with a converging section in between. Downstream of the constant area duct, provision was made to incorporate a two-dimensional diffuser in the horizontal or vertical position. The flow diffuses in y direction in the vertical configuration whereas in the horizontal mode it spreads in the Z direction. The angle of the diffuser (θ) could be varied from 0 to 20° for both the diffusers. The constant area mixing duct was made in three sections so that its length could be varied in steps.

The primary jet which was placed in the converging section of the ejector was 30 cm long and 1·0 cm wide at the exit and was attached to a 10 cm diameter and 30 cm long cylindrical settling chamber through a converging nozzle. Dry air was supplied to the system from a large reservoir of nearly 15 cubic meter capacity through a 10 cm diameter pipe through a control valve. A precision Bourdon pressure gauge was used to measure the total pressure (P_0) in the settling chamber.

The mean velocity profiles in the mixing duct as well as near the exit region of the diffuser were estimated from the pressures measured using pitot rakes. A multi-tube water manometer was used to measure these pressures. Static pressure holes (1 mm dia) were drilled along the diffuser and the mixing duct at suitable locations. In the entry section, the velocity of the induced flow was estimated from the static pressures measured all along the periphery at a distance of 60 cm from the entry. It was observed that the velocity in this section was uniform within 2%.

The excitation of the jet was produced by the self-induced oscillations of a thin rubberised fabric fixed near the exit of the jet. This device oscillated in a two-dimensional flapping mode. The amplitude as well as the frequency of oscillations could be varied by changing the length of the flap. In the present experiments, the amplitude and frequency of the oscillations were 4 mm and 60 Hz respectively.

3. Results and discussion

3.1 *Effect of blowing pressure on entrainment*

The induced rate of mass flow (m_i) was measured for different blowing pressures (P_0) (fig. 2). Up to 0·15 kg/cm^2 gauge m_i increased nonlinearly and beyond this value the variation of m_i was linear with P_0. In all the latter experiments P_0 was maintained at a constant value of 0·211 kg/cm^2 gauge which lies just above the nonlinear range.

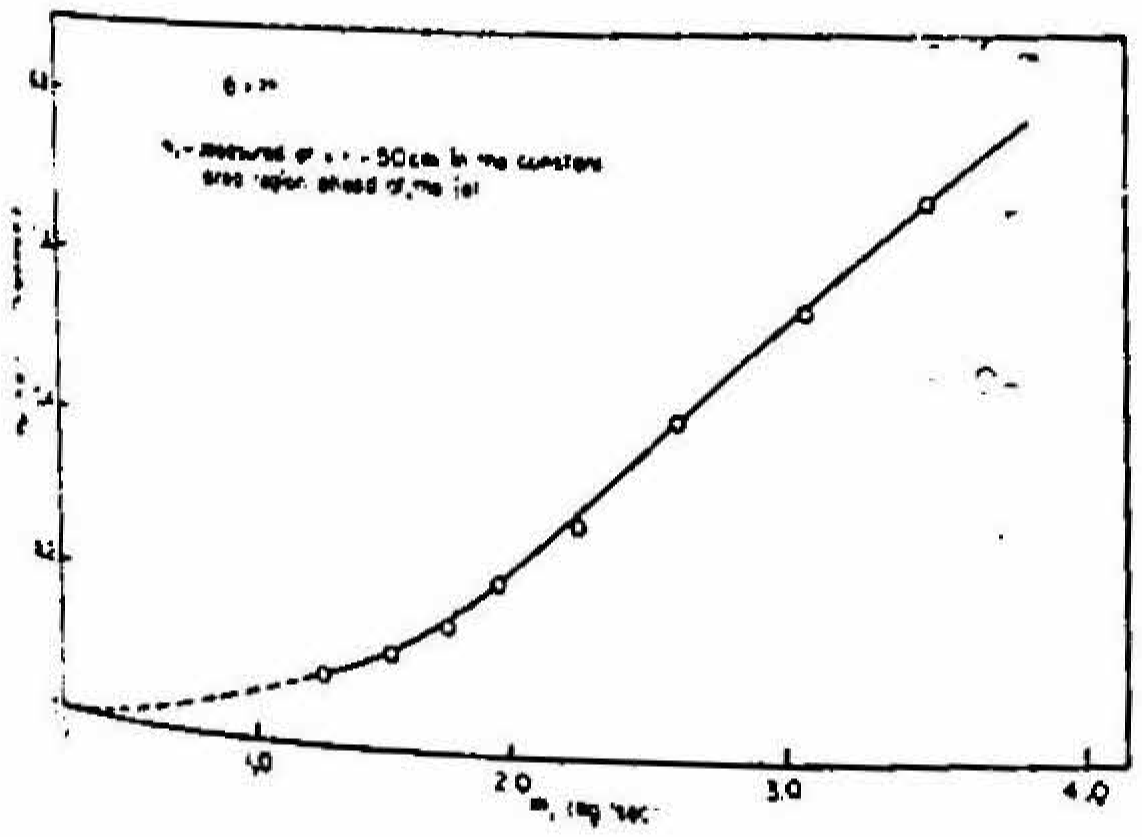
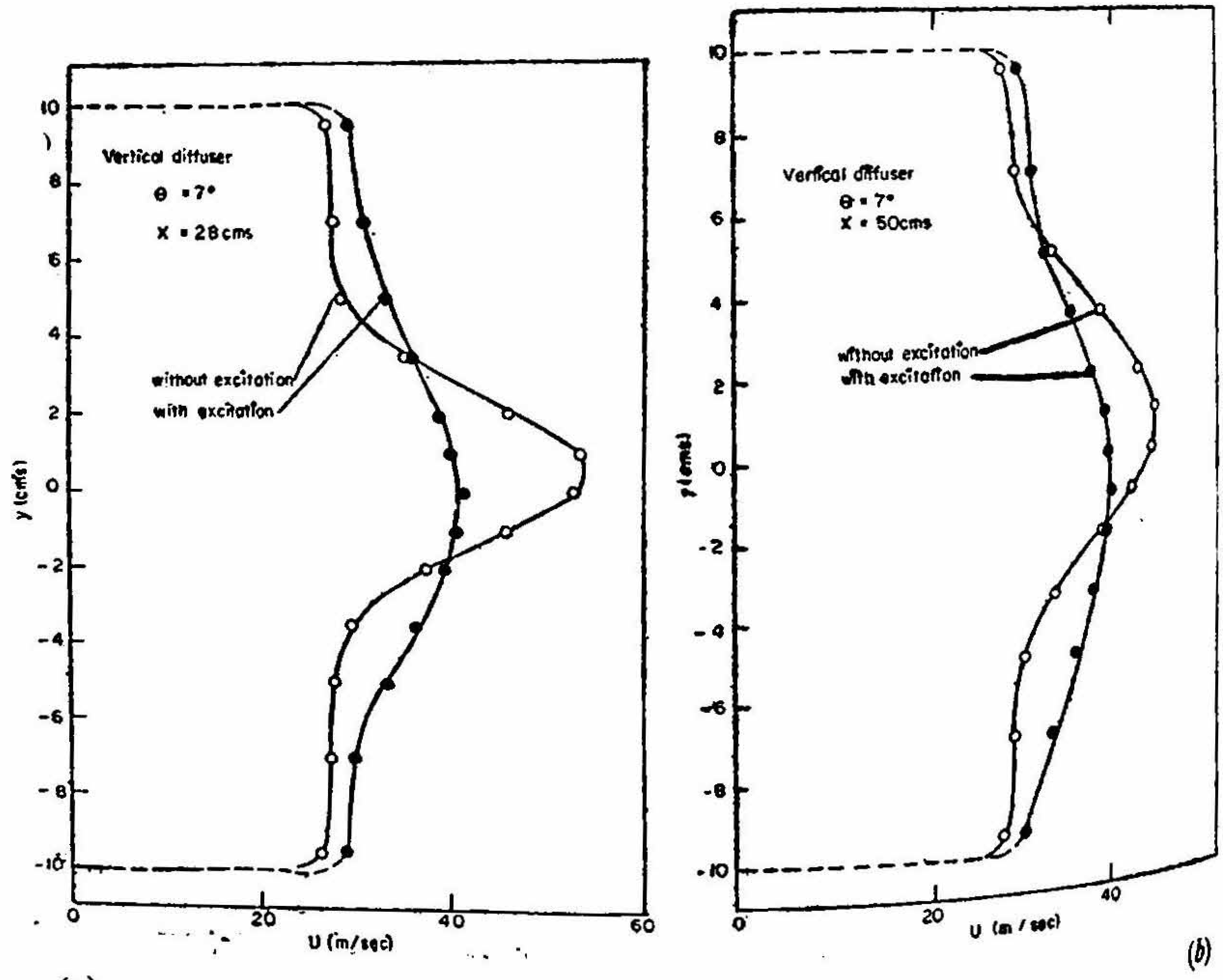


FIG. 2. Variation of induced mass flow rate with primary nozzle pressure.

This value was chosen to obtain maximum operating time for the experiment with a single reservoir charge but at the same time avoiding the nonlinear regime.

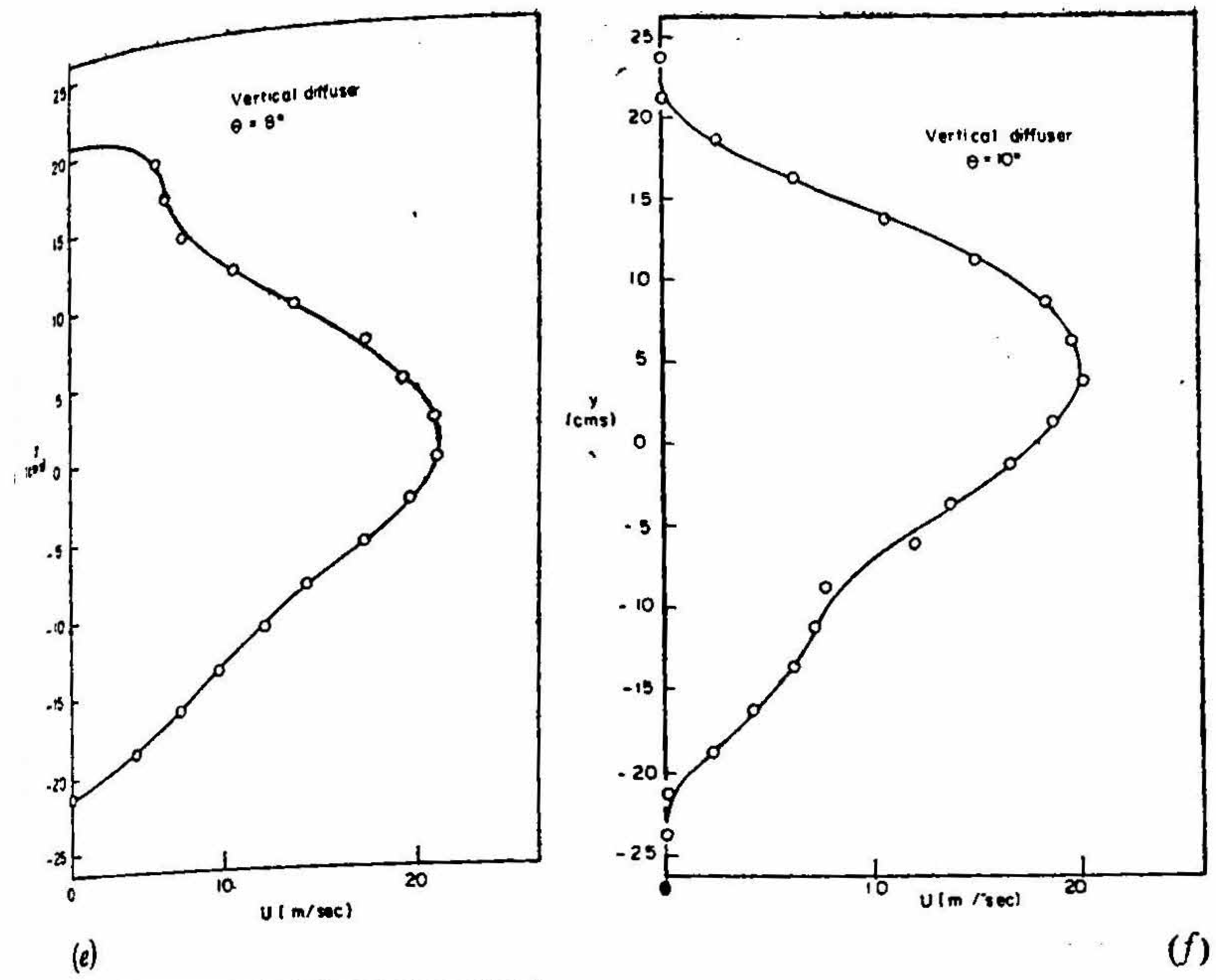
3.2 *Flow in the ejector with vertical diffuser*

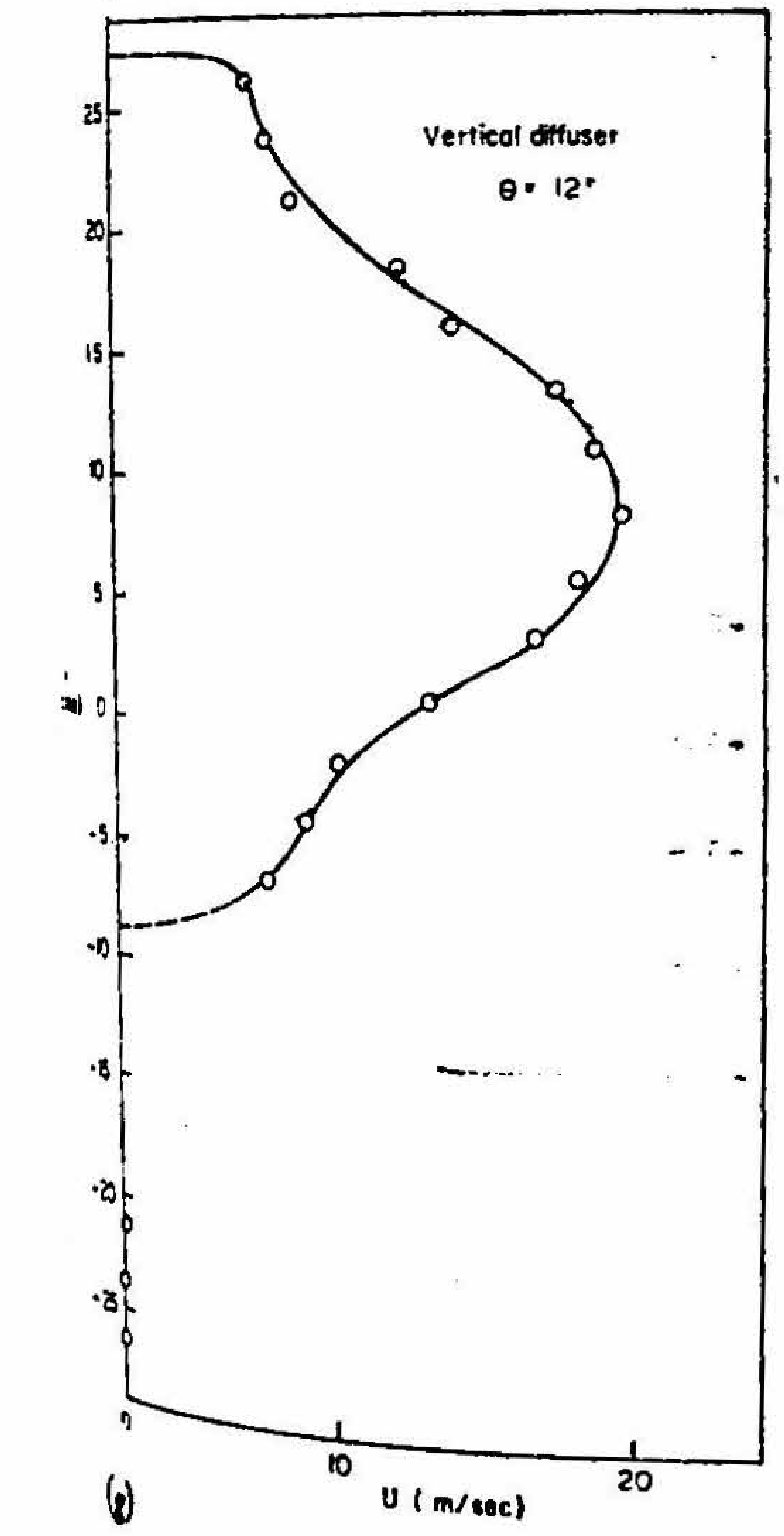
The mean velocity profiles in the mixing duct of 107 cm long (known as long duct hereafter) with vertical diffuser were made at five different stations namely, $x = 28$, 50, 66, 90 and 120 cm with and without the excitation of the primary jet. These experiments were made with a diffuser angle (θ) of 7° which is optimum for this configuration (fig. 6). A comparison of the mean velocity profiles clearly indicates that excitation does affect the flow in a significant manner (figs. 3 *a* to *e*). The velocity distribution which is highly non-uniform across the duct with a steady jet has become almost uniform with excitation. This shows that there is a considerable increase in mixing in the latter case. The width of the jet ($\delta_{0 \cdot 5}$) based on half the maximum velocity at a given station, is more in the case of excitation (fig. 16) which further supports the above view. Under the above condition one would naturally expect an enhancement in induced rate of mass flow but the experiments do not indicate



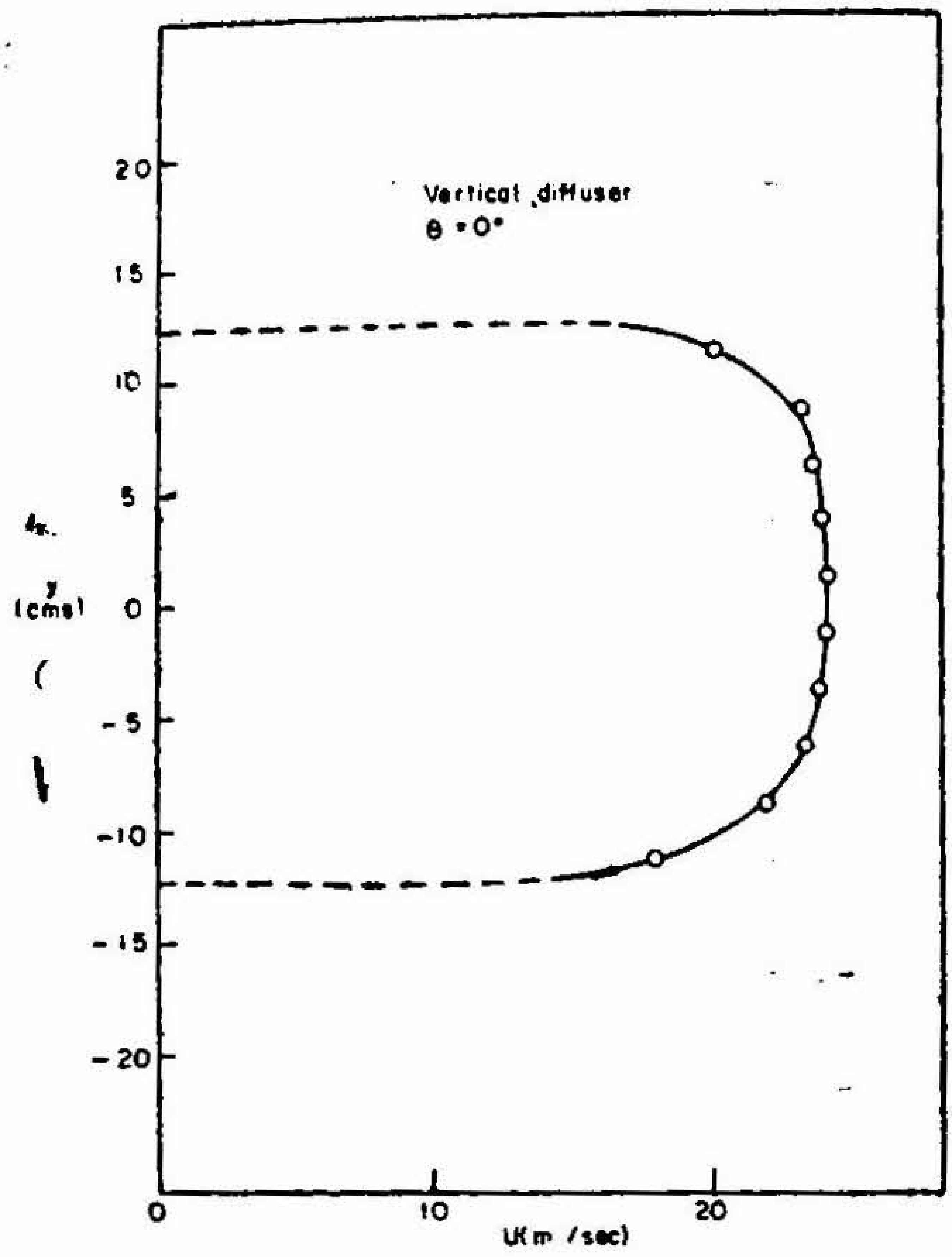
(*a*)

(*b*)

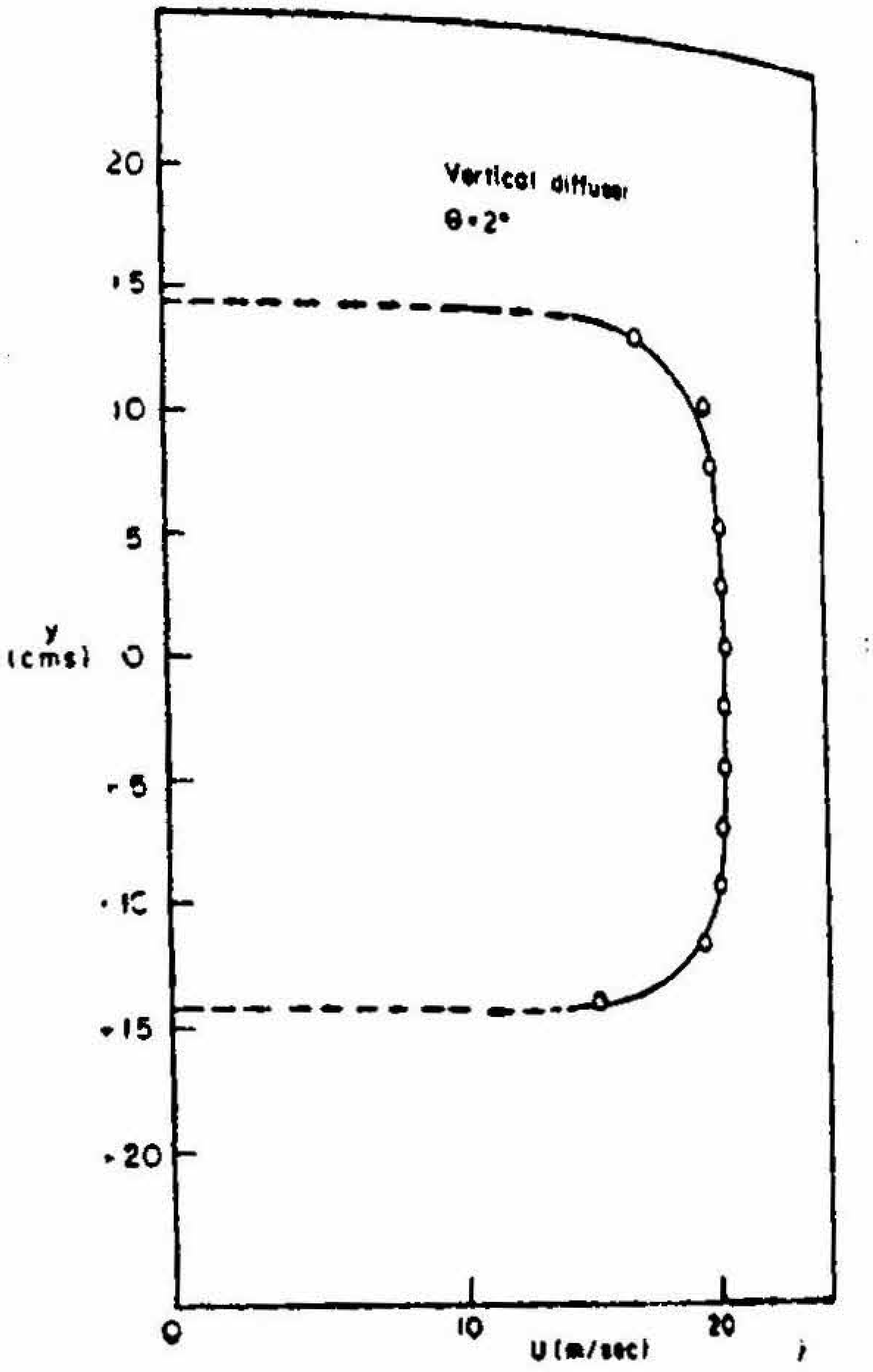




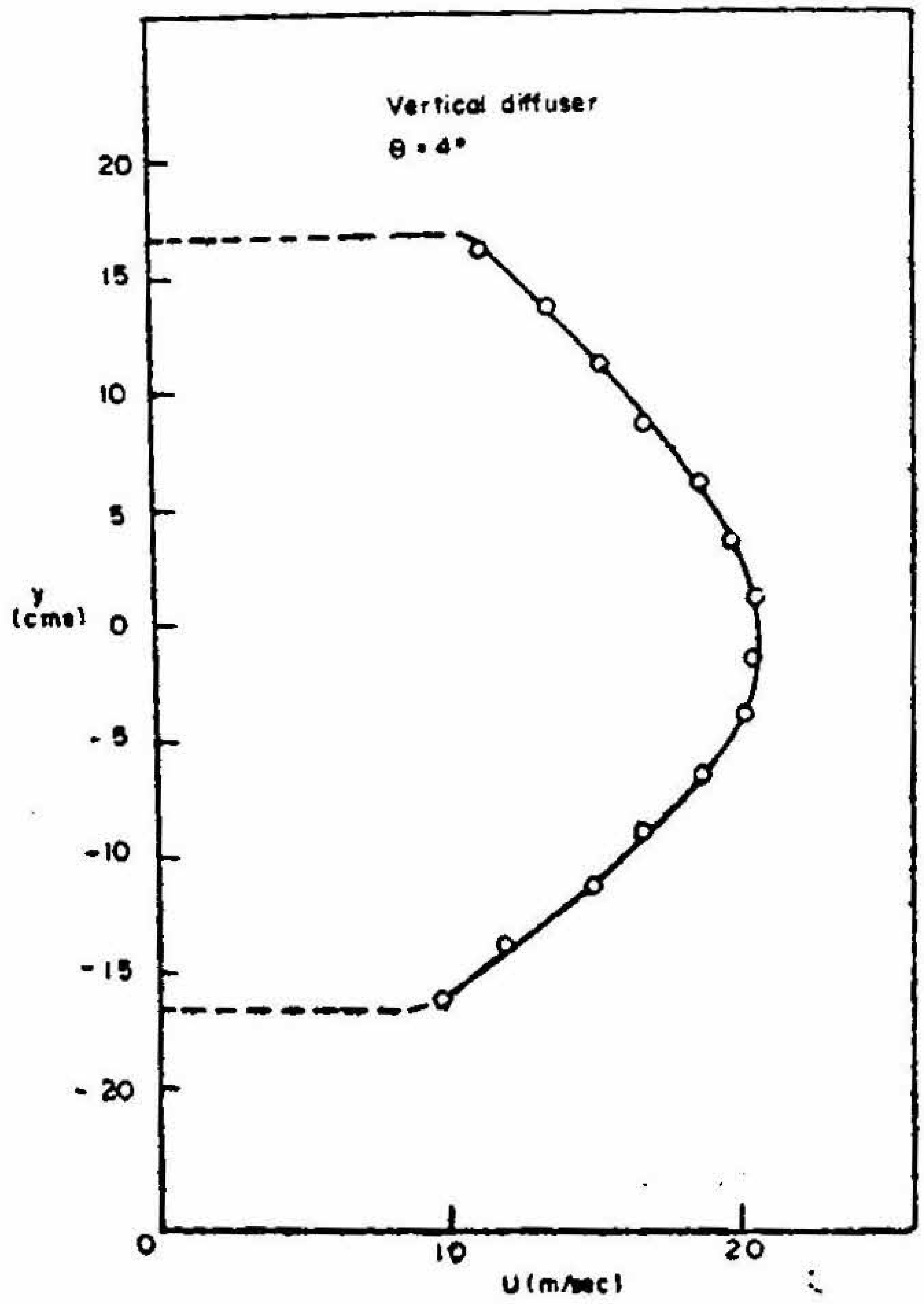
FIGS. 4 *a* to *g*. Mean velocity profiles at the exit of the diffuser with long mixing duct.


Vertical diffuser
θ = 0°
y (cms)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
U(m /sec)

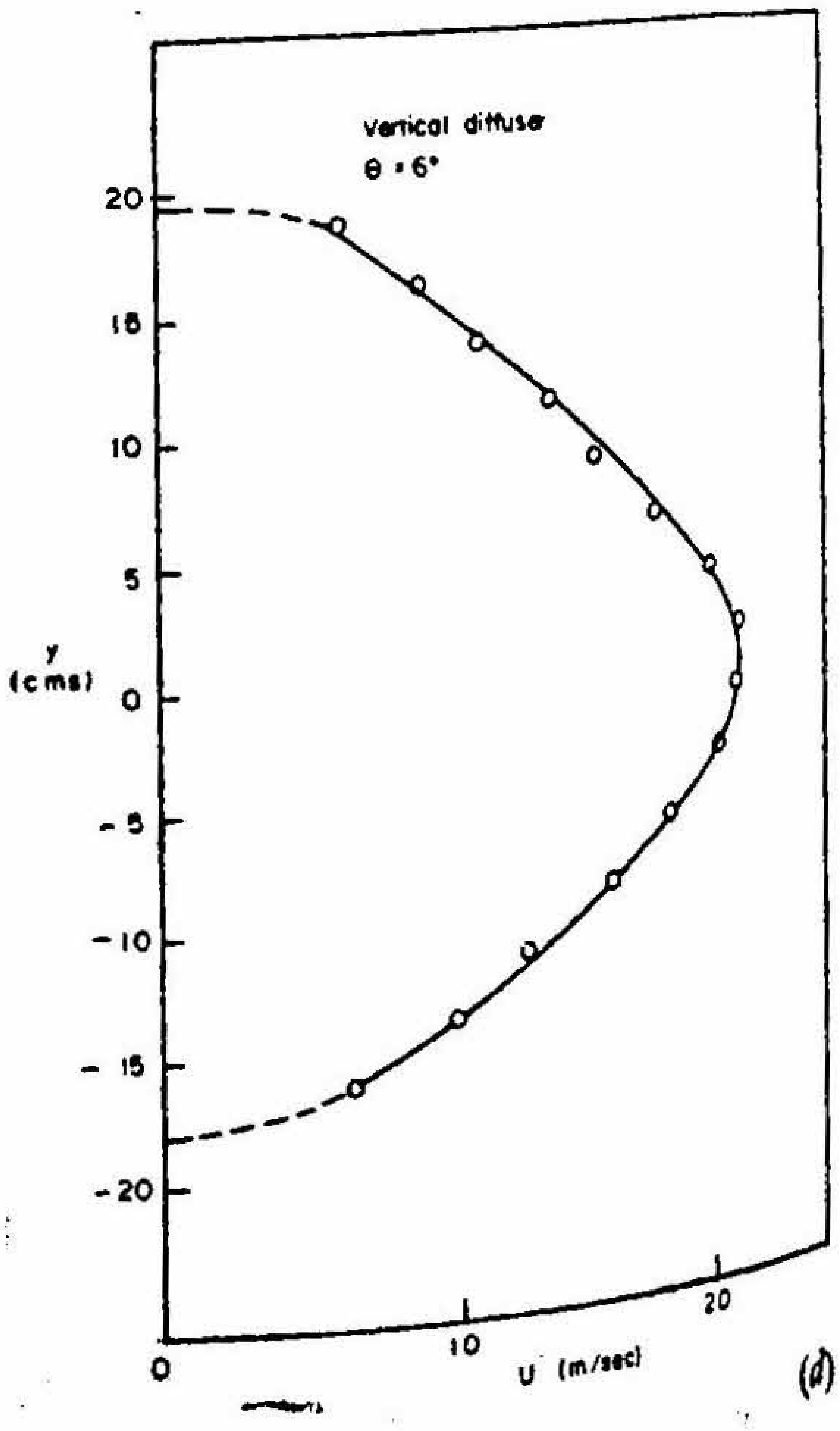
(a)


Vertical diffuser
θ = 2°
y (cms)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
U (m/sec)

(b)


Vertical diffuser
θ = 4°
y (cms)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
U (m/sec)

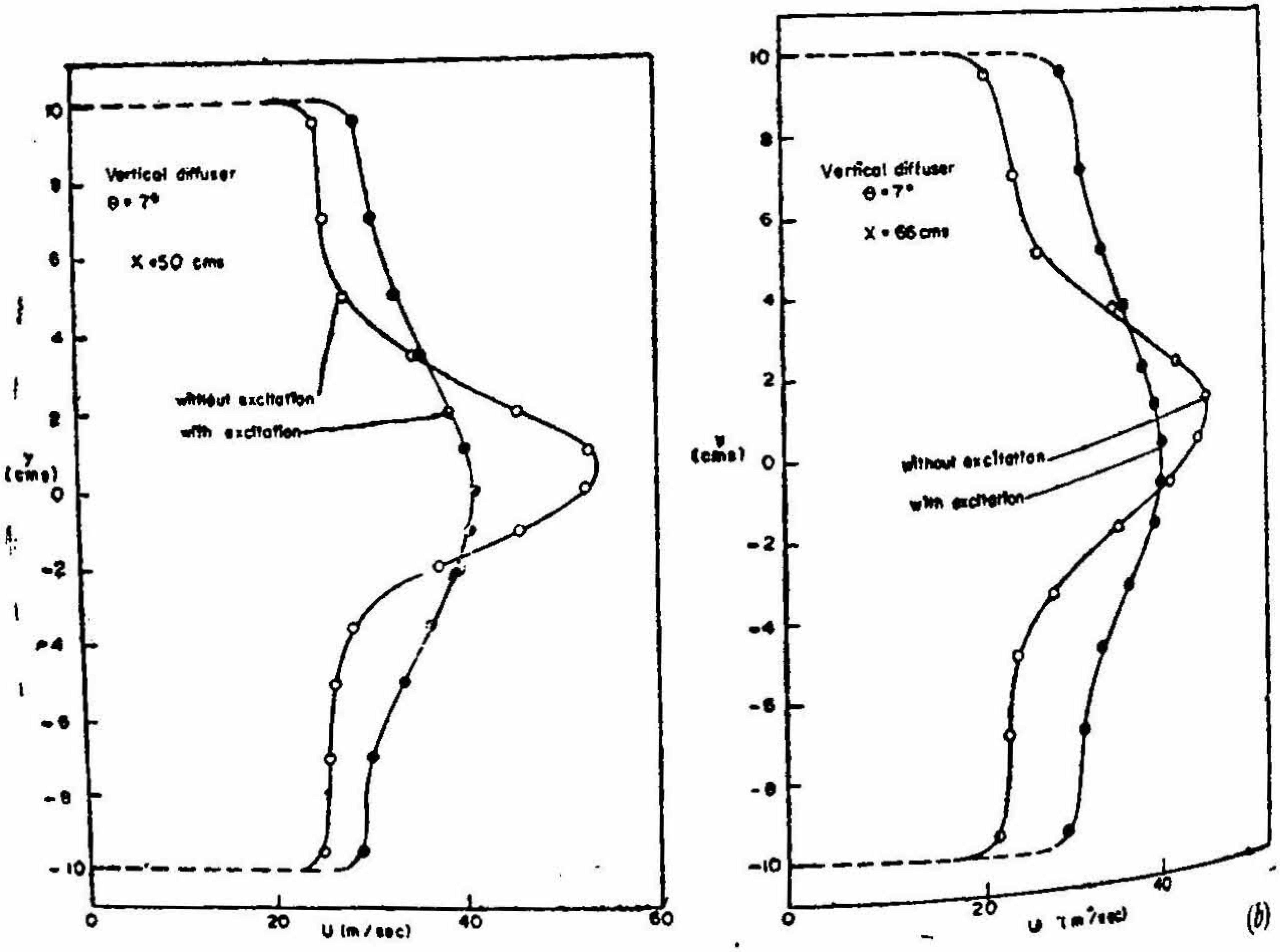
(c)


Vertical diffuser
θ = 6°
y (cms)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
U (m/sec)

(d)

any such trend. Similar result was observed earlier by Badri Narayanan and Raghu[4]. An estimate of the total mass flow rate (m_0) across the duct based on the measured mean velocity profiles indicates that the mass flow is same in both the cases even though the velocity distributions are quite different (fig. 17). This result further confirms that there is no net increase in the rate of mass flow in the system due to the excitation; however, there is a local redistribution with a reduction in the central region, which is compensated by an increase in the outer region.

An estimate of the momentum distribution also exhibits a similar trend. For example, the distribution of momentum across the duct at $x = 28$ cm is shown in fig. 13. The total momentum ($\bar{M}$) remains almost constant along the length of the mixing duct for both the steady and the excited jet (fig. 15). This means that the flow under excited condition transfers momentum across the duct in the y direction alone and not in the direction of the flow. In the case of the excited jet there is a slight reduction in $\bar{M}$ as the flow moves downstream but this could not be ascertained considering the errors involved in making measurements in an oscillating flow. A comparison of momentum distribution with and without excitation at $x = 28$ cm shows that there is a decrease in momentum in the central region between $y = -3$ and 3 cm and this loss is compensated by the gain in the outer region (fig. 14).



(a) (b)

FIG. 5 *a* and *b*. Mean velocity profiles in the short constant area mixing duct.

The turbulence mechanism involved in an ejector flow is not quite clear; however, it seems to be different from that of a free jet. In the case of a free jet, excitation in the above manner considerably increases not only the spread of the jet but also the entrainment of the fluid from the surroundings. Excitation of the jet in an ejector configuration no doubt increases mixing; however, it is unable to induce more flow. The reason for this behaviour is to be examined.

The above result suggests that in order to induce more mass flow the turbulent mixing pattern should be suitably oriented ; otherwise, only local redistribution will be the end result. In the case of an ordinary steady jet the entrainment is due to the large scale organised structure which scours the surrounding fluid in a near periodic fashion. When excited externally, the input oscillations are advantageously made use of by the jet, most probably, by forming large scale organised structures which induce more fluid from the surroundings. This could be considered as a kind of pumping action in periodic fashion, the periodicity depending on the input frequency.

When the jet is confined in a duct the entrainment is affected by the area ratio between the jet exit and the shroud. Simple momentum theory is able to explain this on the assumption that the mixing between the primary and secondary flows is complete[1]. In this approach, the mechanism of turbulence is not explicitly considered; however, it is assumed that at the end of the duct the mean velocity is uniform due to complete mixing. In actual practice, the profile at the exit of the mixing duct is hardly uniform due to the limited length of the duct (fig. 3 *e*) and this results in lesser induced mass flow. But when the jet is excited, the mean velocity profile becomes nearly uniform

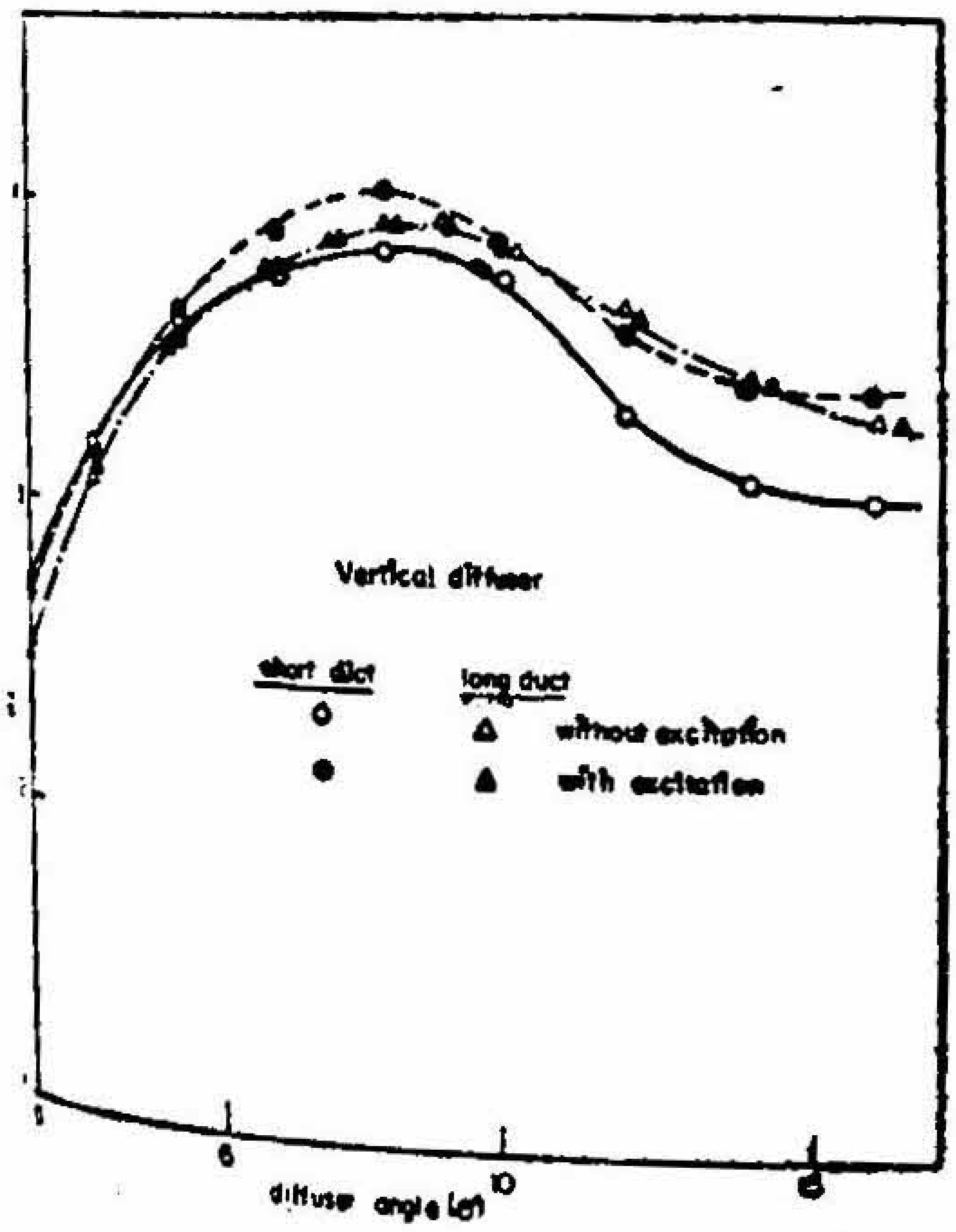


FIG. 6. Variation of entrainment ratio with diffuser angle with and without excitation.

and one would expect, under such conditions, greater induced mass flow. The experimental results indicating a trend contrary to this expectation calls for an examination of the boundary conditions assumed in the momentum balance approach. An understanding of the dynamics of the flow will be highly beneficial for this purpose. It is conjectured that there will be appreciable modification in the structure of the large scale eddies in the above situation.

Mean velocity profiles in the short mixing duct (26 cm) with the vertical diffuser were made at two stations—namely, $x = 28$ and 50 cm with and without excitation. Results indicate the same trend as that of the long duct. Excitation increased the value of $\bar{m}$ by small amount from 3·8 to 4·1 (fig. 6) on account of the improvement in the diffuser flow.

The mean velocity profiles at $Z = 0$ in the y direction, at the exit of the vertical diffuser with the long mixing duct, were measured for various values of diffuser angles namely, $\theta = 0, 2, 4, 6, 8, 10$ and $12°$. Results (figs. 4 a to g) indicate that the flow

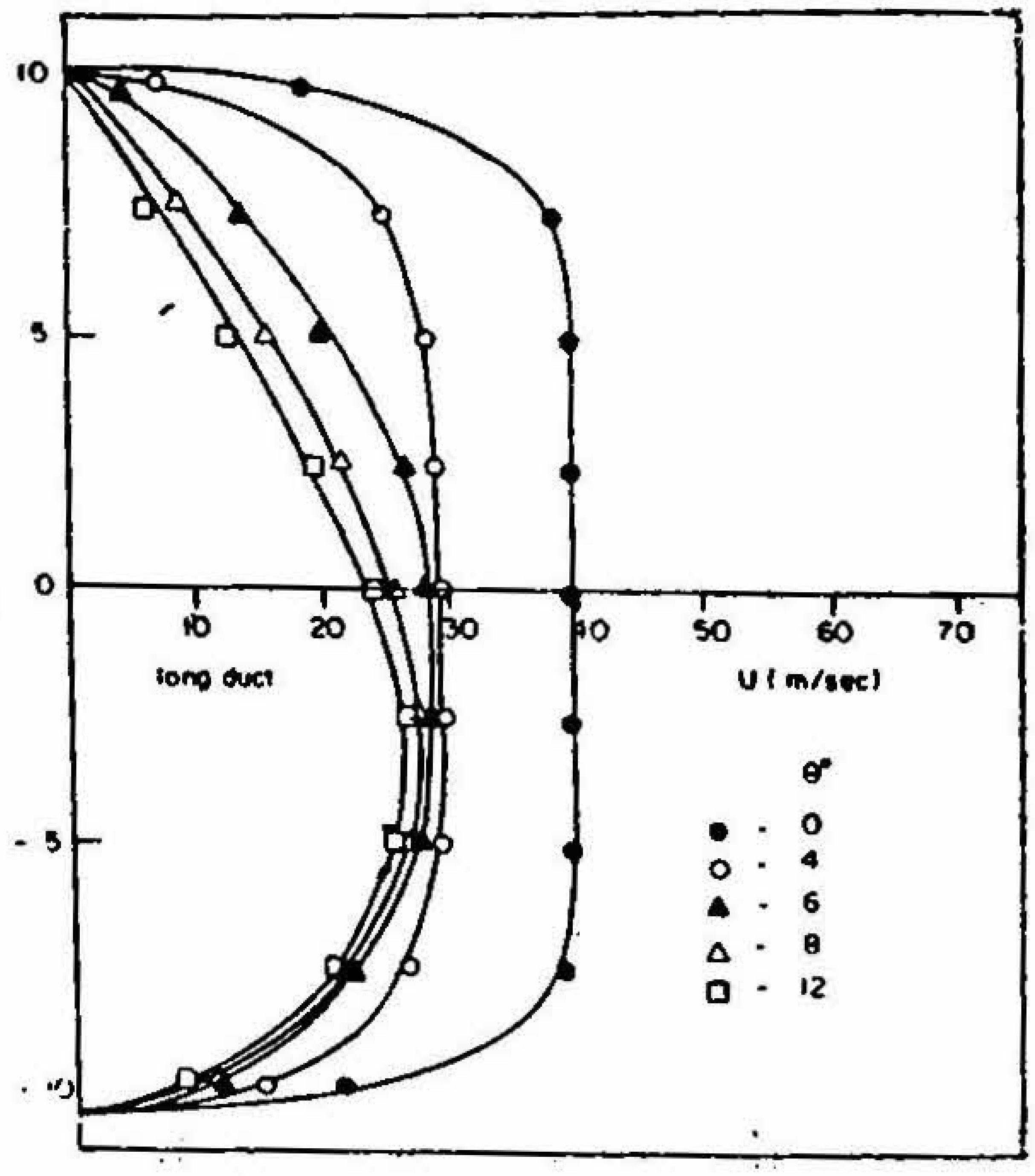


FIG. 7 a. Mean velocity profile at $z = 0$ in the y direction at the exit of the horizontal diffuser.

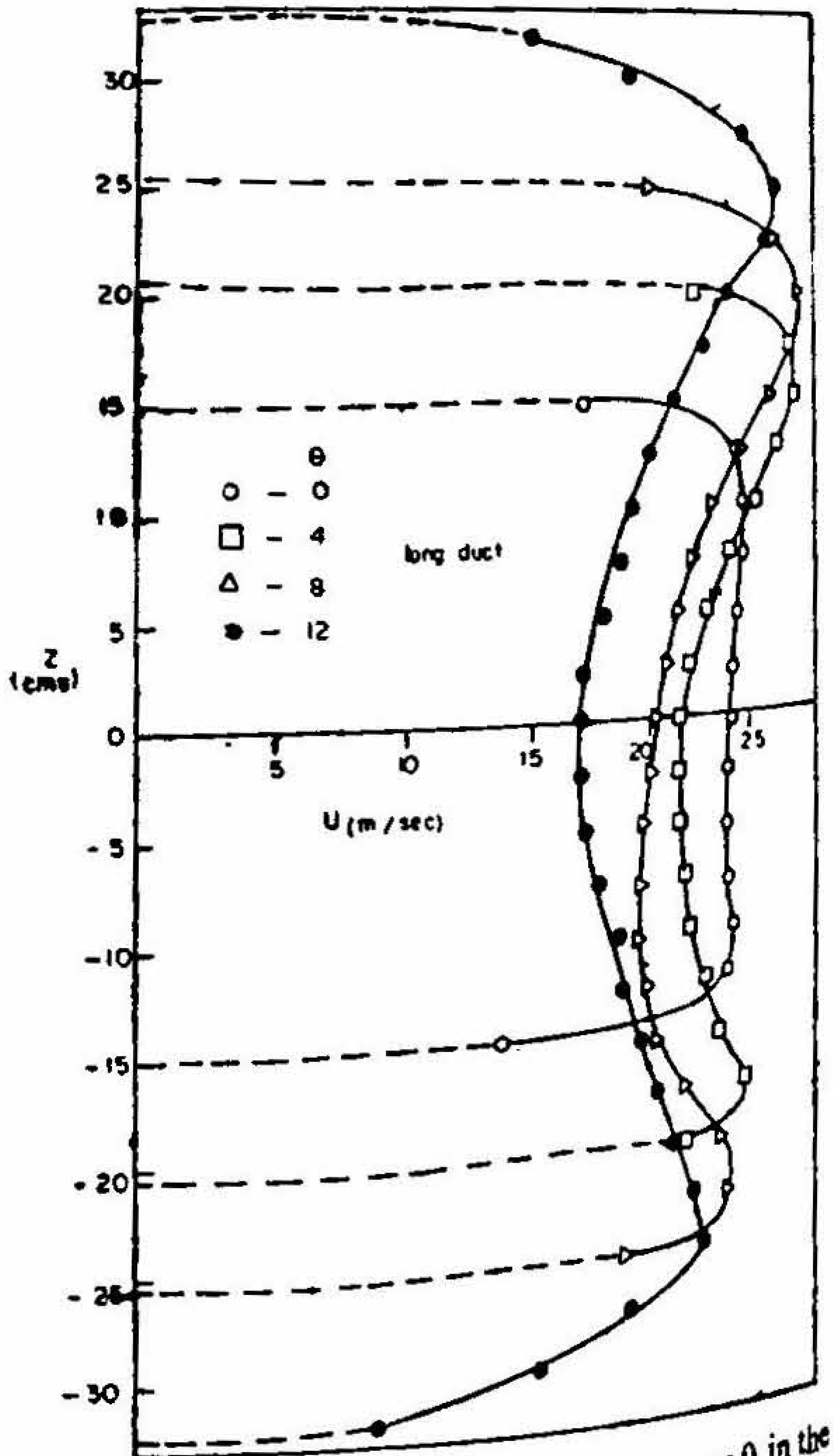


FIG. 7 b. Mean velocity profile at $y = 0$ in the z direction at the exit of the horizontal diffuser.

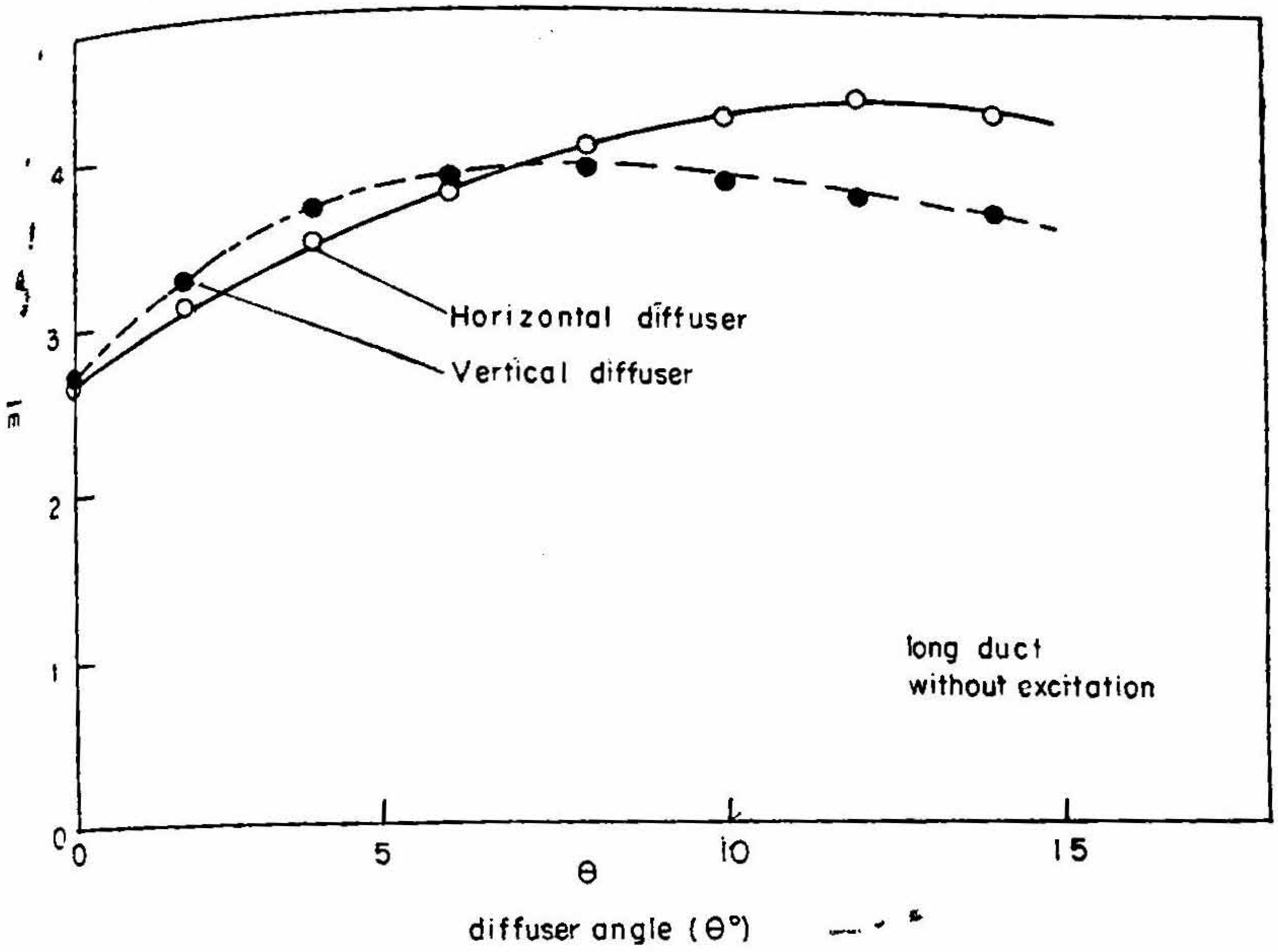


FIG. 8. Variation of entrainment ratio with diffuser angle.

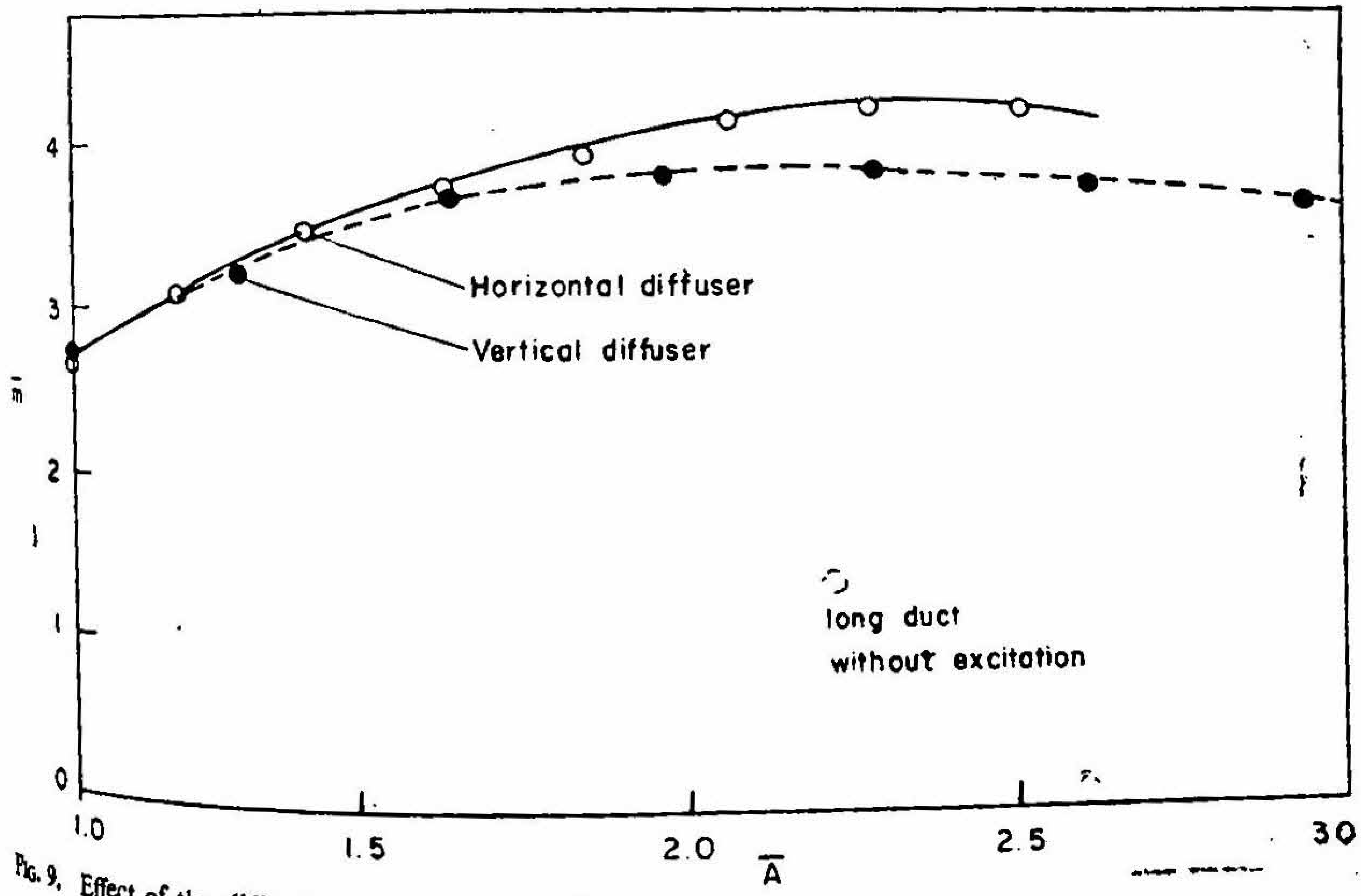


FIG. 9. Effect of the diffuser exit area on entrainment ratio.

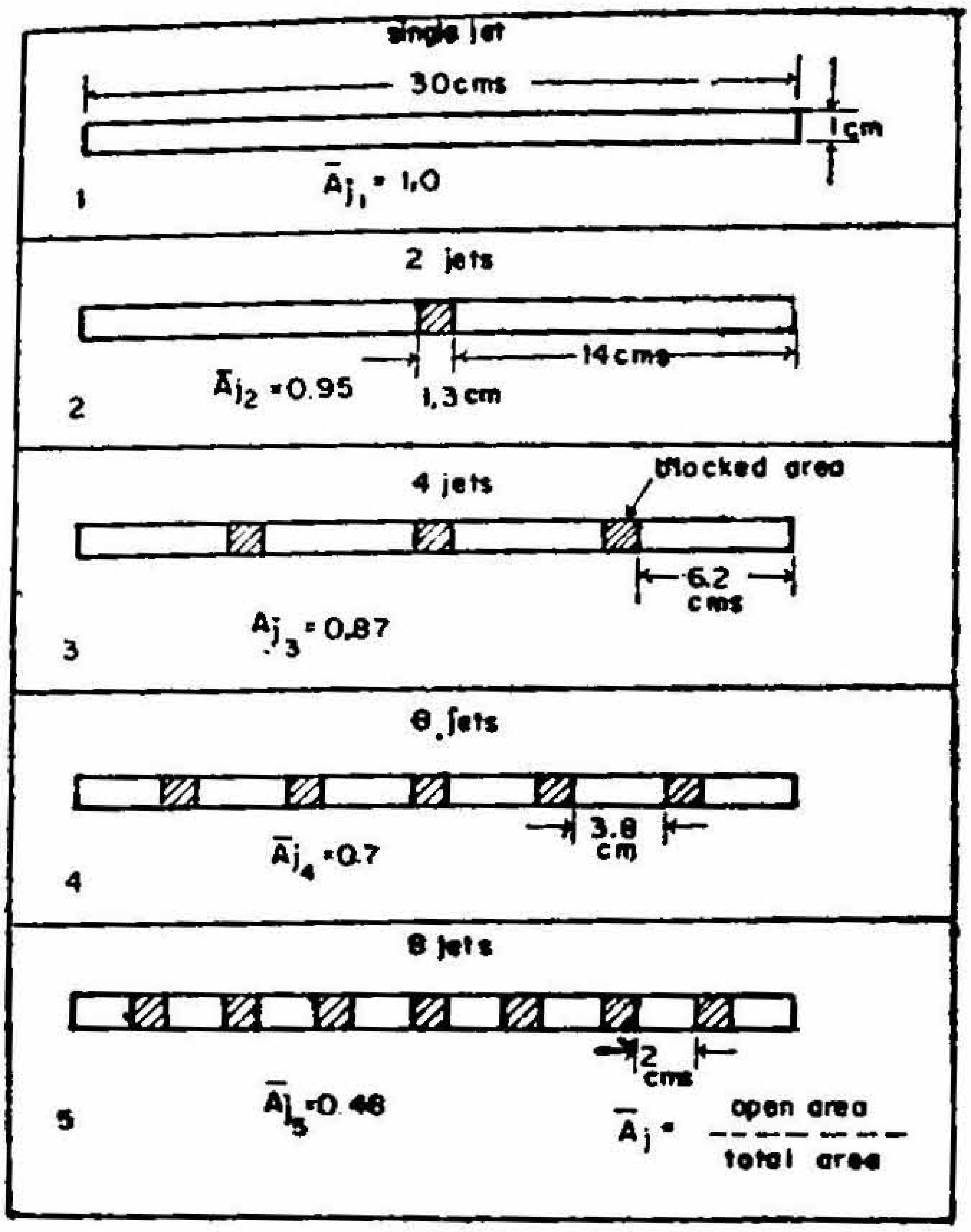


FIG. 10. Various modes of segmentation of the primary jet.

diffuses uniformly up to $\theta = 6°$. Beyond $\theta = 6°$ the flow tends to deviate towards one of the side walls even though great care was taken to align the main jet along the center line. Even though the flow tends to deviate towards one of the side walls of the diffuser, no reverse flow was observed up to $\theta = 10°$ (fig. 4f). At $\theta = 12°$, the flow in the diffuser gets attached completely to one of the walls and there was reverse flow (fig. 4 g).

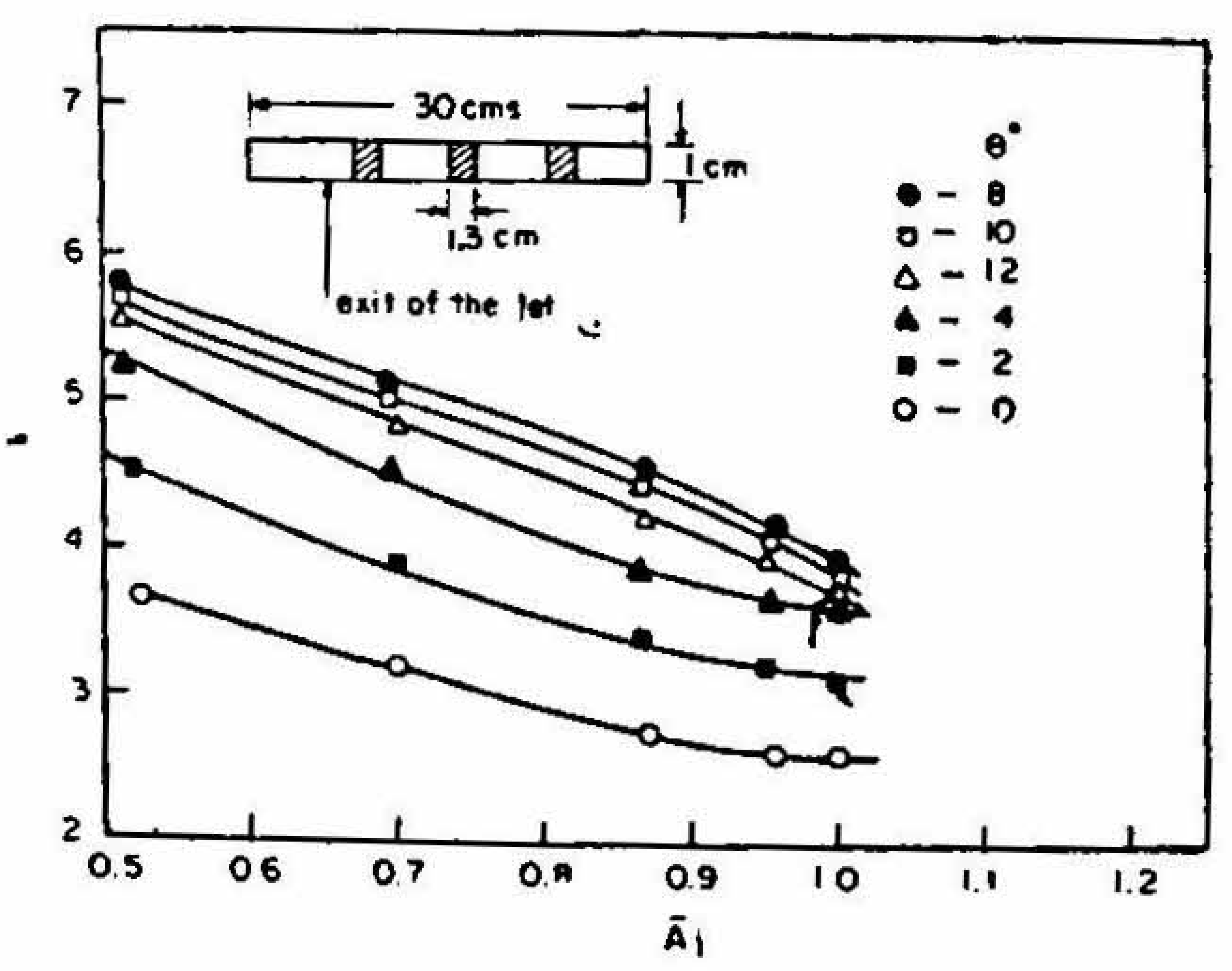


FIG. 11. Effect of exit area of the jet on the entrainment ratio with vertical diffuser.

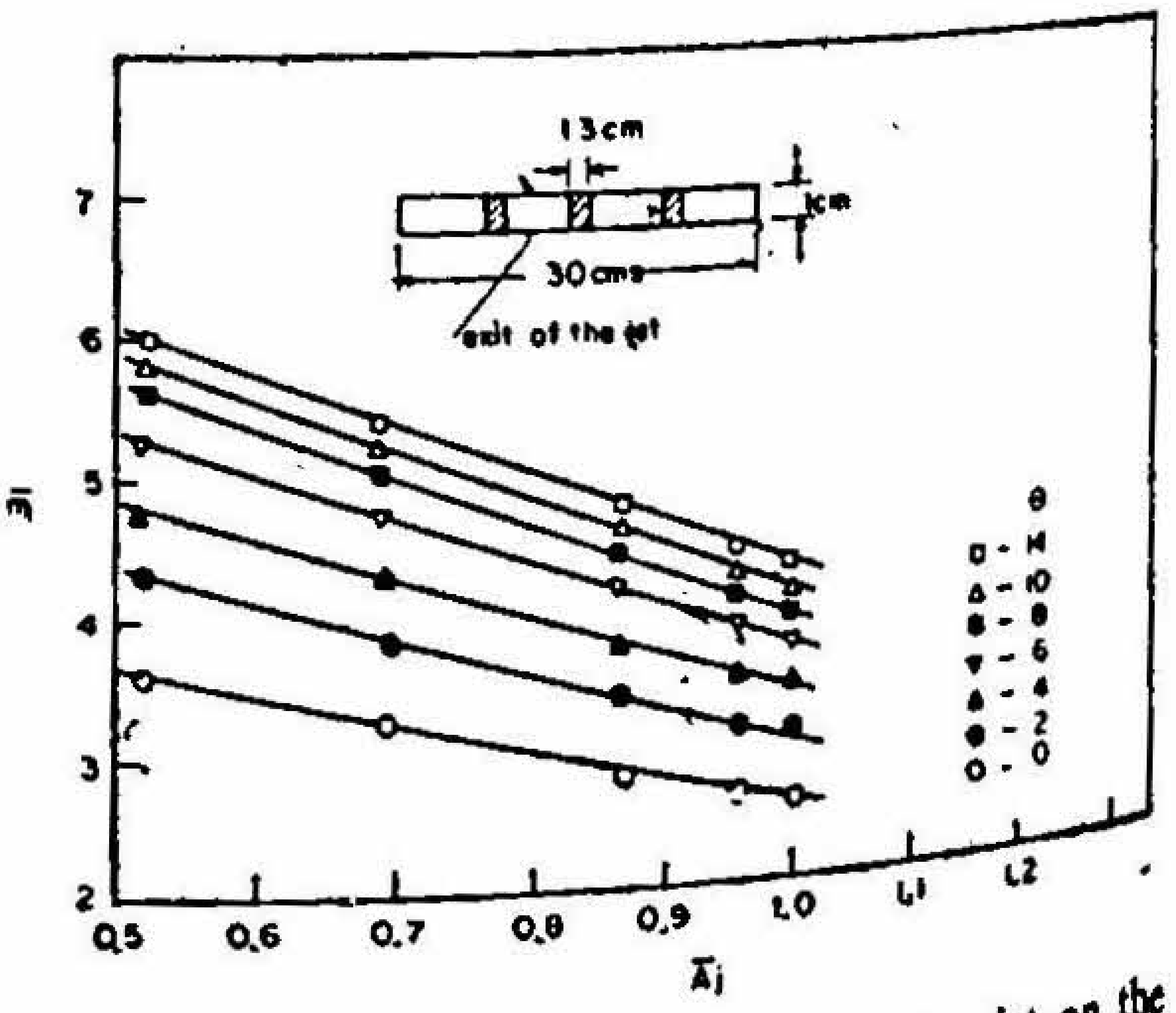


FIG. 12. Effect of exit area of the jet on the entrainment ratio with horizontal diffuser.

Both the long and the short ducts show a decrease in $\overline{m}$ beyond $\theta = 7°$; however, it is more pronounced for the short duct. Flow visualization indicated that flow in the diffuser with the short duct is more sensitive to separation. Excitation delayed separation of the above diffuser flow restoring the induced mass flow rate to that of the long duct up to $\theta = 14°$. Beyond this angle the separation was always present resulting in large unsteadiness in the flow.

3.4 *Effect of multi-jet configuration in the ejector flow*

The nozzle of the two-dimensional jet was segmented into a multi-jet configuration by closing uniformly as shown in fig. 10. Five different jet configurations were used in the experiments with open area ratio ($\bar{A}_j$) of 1·0, 0·95, 0·87, 0·76 and 0·48. These experiments were conducted at a fixed blowing pressure (P_0) of 0·211 kg/cm^2 gauge using both the horizontal and vertical diffusers in conjunction with the 107-cm long constant area duct. The results are shown in figs. 11 and 12. For both the diffusers entrainment ratio ($\overline{m}$) increased as the exit area of the nozzle was reduced. In all the cases it was observed that the induced rate of mass flow remained almost constant ; however, the mass flow rate of the primary jet decreased resulting in an increase in $\overline{m}$. For the vertical diffuser the maximum in $\overline{m}$ occurred for $\theta = 8°$ as observed earlier

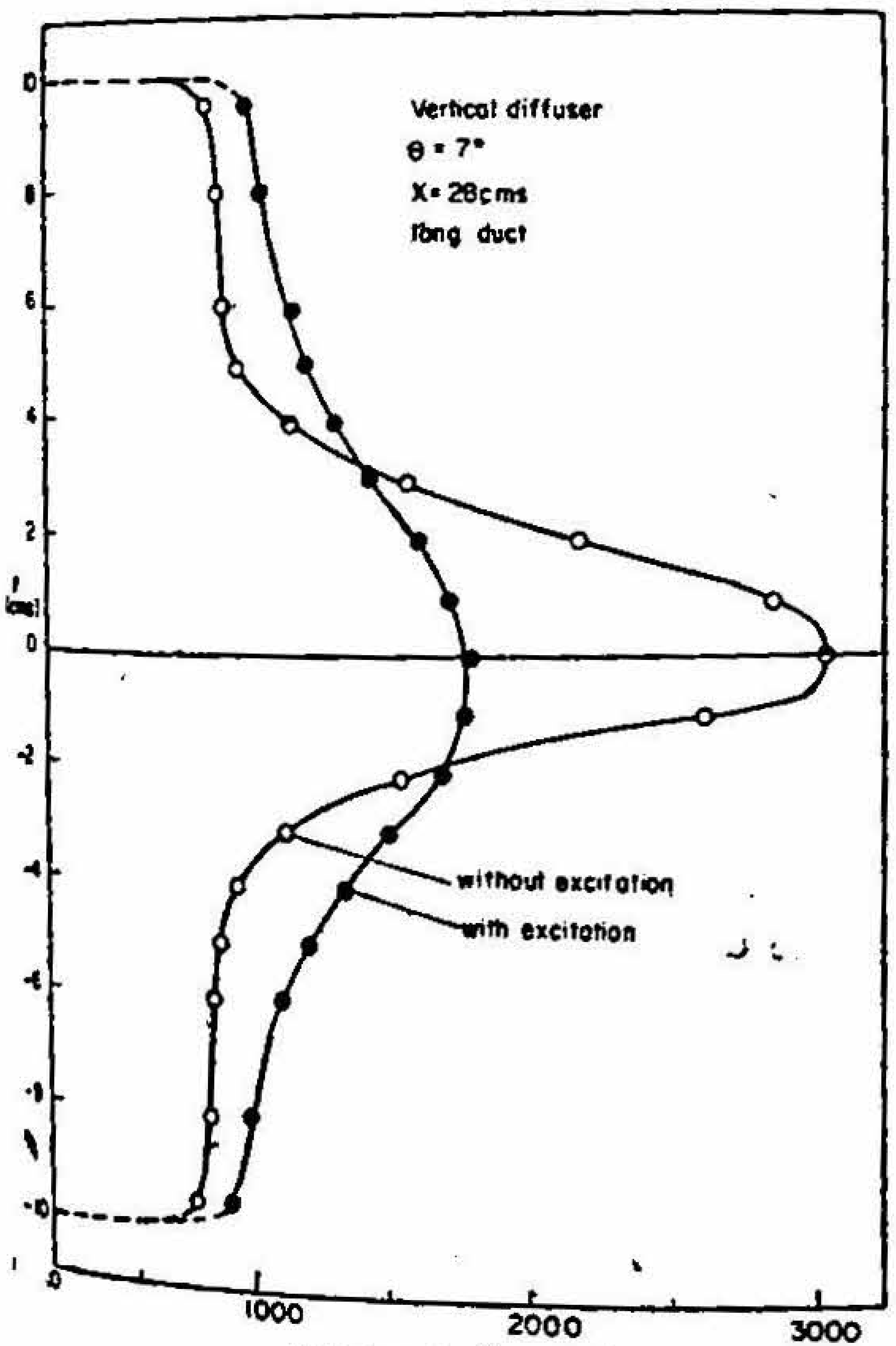


FIG. 13. Distribution of momentum across y at $x = 28$ cm with and without excitation.

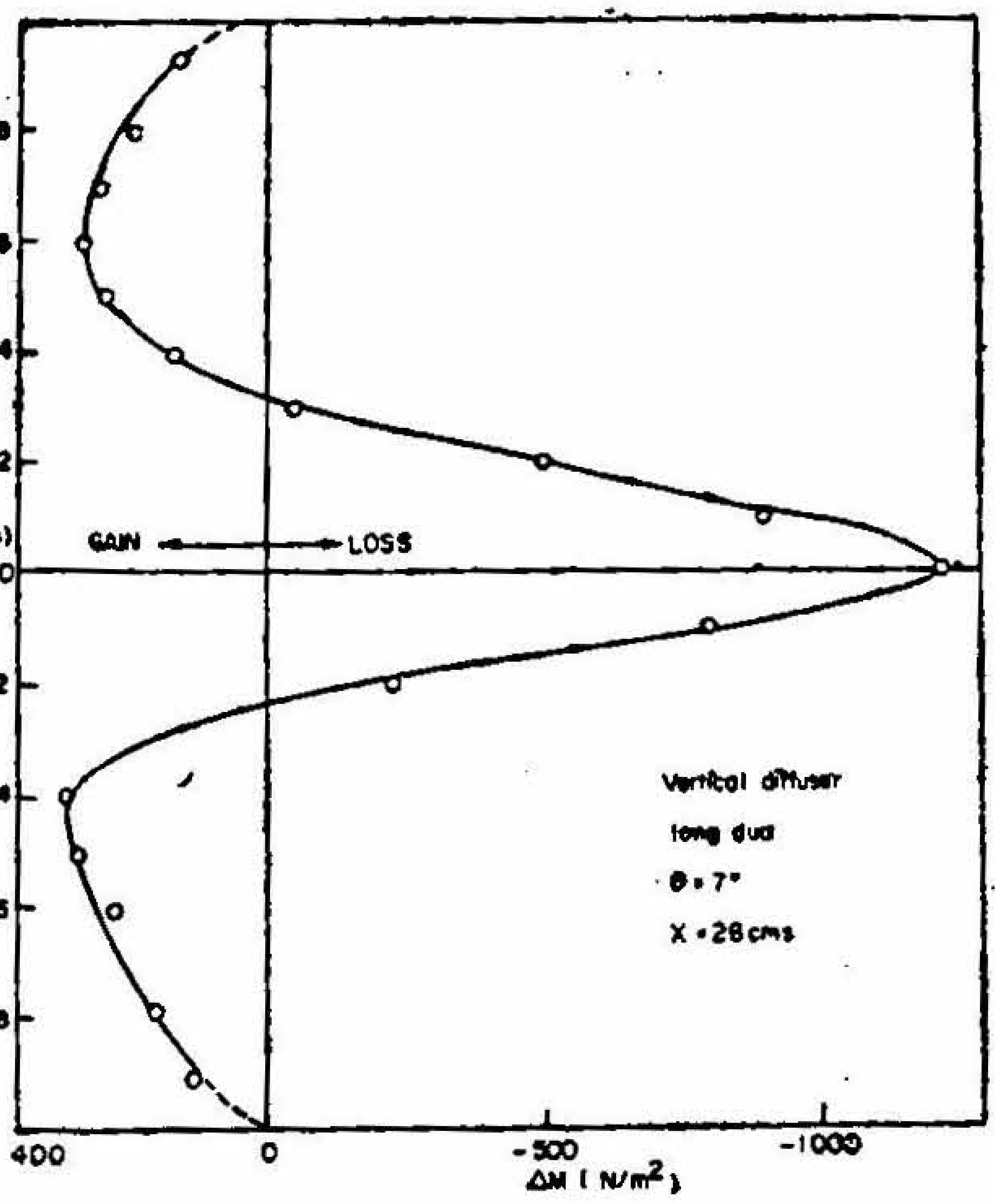


FIG. 14. Momentum exchange in the mixing duct at $x = 28$ cm due to excitation.

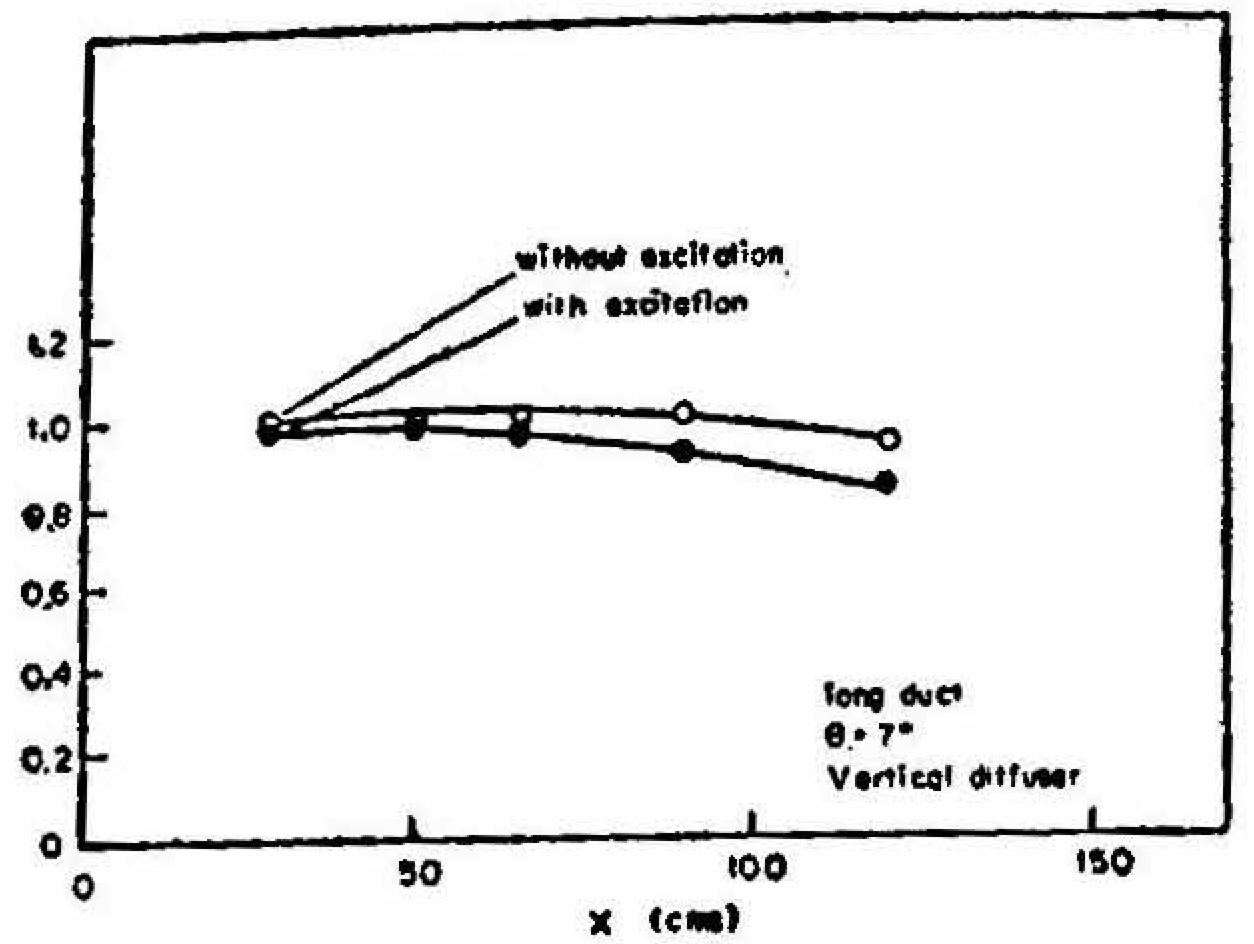


FIG. 15. Variation of total momentum per unit span along x with and without excitation.

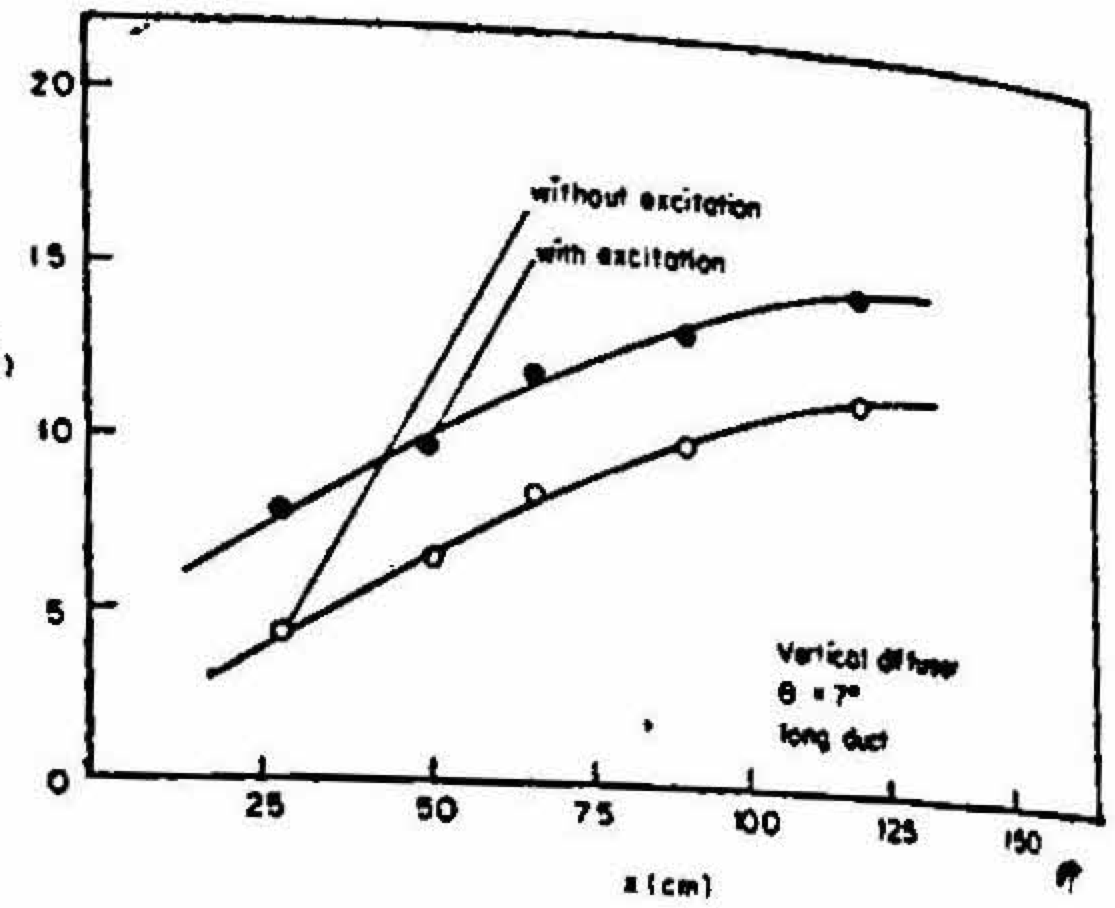


FIG. 16. Spread of the jet with and without excitation.

whereas for the horizontal diffuser the mass flow increased with θ up to $\theta = 14°$. The variation of $\bar{m}$ with $\bar{A}_j$ is nearly linear in all the cases except around $\bar{A}_j = 1 \cdot 0$. Excitation had negligible effect on $\bar{m}$ even for the multi-jet configurations.

The above results suggest that the mode of mixing with a multi-jet configuration is more effective than that by flap excitation. Hence, in an ejector, it is essential not only to enhance mixing but also to control mode of mixing to increase the efficiency. In a multi-jet configuration, the introduction of additional shear produces large eddies which seem to be oriented in such a way as to induce flow from the surroundings whereas mixing due to excitation by a vibrating flap is locally confined. Further studies are required to understand the details of the mixing process by different mechanisms.

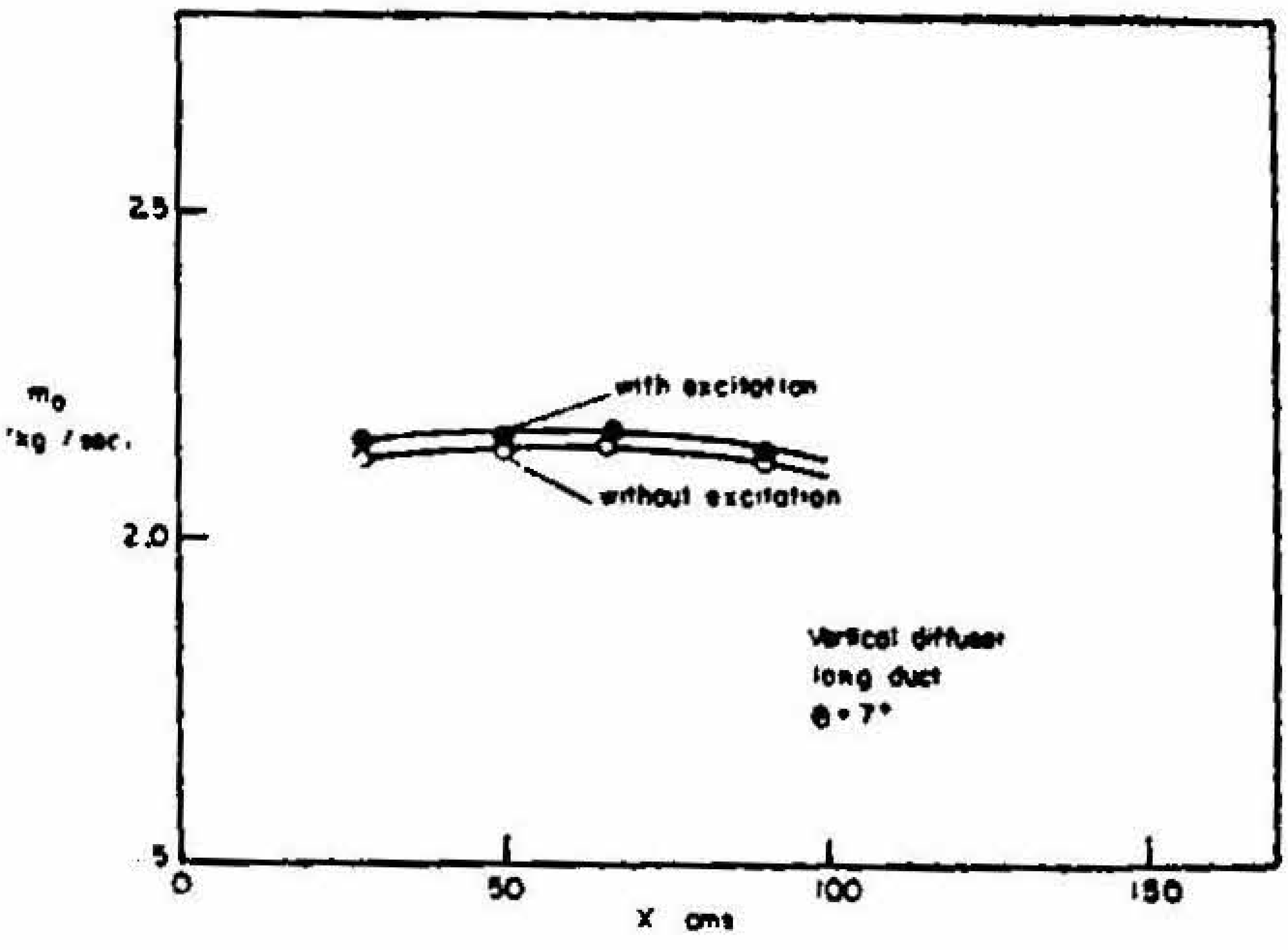


FIG. 17. Variation of total mass flow rate along the duct.

4. Conclusions

Experiments were carried out in a two-dimensional ejector with a flap excited primary jet. The following are the main conclusions :

(*a*) Excitation enhances mixing in the ejector flow ; however, its effect on induced mass flow is negligible.

(*b*) The flow in the diffuser is more stable with the long duct than the short one ; however, excitation restores this defect in the case of the latter.

(*c*) Diffusion of flow parallel to the jet nozzle is more effective than in the perpendicular direction.

(*d*) Segmentation of a single two-dimensional jet into a multi-jet configuration seems to increase the entrainment ratio.

Nomenclature

A_1	Cross-sectional area of the mixing duct
A_E	Diffuser exit area
A_j	Jet exit area
$\bar{A} = \frac{A_1}{A_E}$	Ratio of area of the mixing duct to the exit area of the diffuser
$\bar{A}_j$	Ratio of open area of the jet nozzle with partition to the open area of the jet nozzle without partition
$a = \frac{A_1}{A_j}$	Inlet area ratio
M	Momentum (ρU^2)
$\bar{M}$	Average value of the momentum across the jet at a given station
m_t	Total mass flow rate
m_i	Induced rate of mass flow
m_j	Rate of mass flow of the primary jet
$\bar{m} = \frac{m_i}{m_j}$	Entrainment ratio
P_t	Blowing pressure
U	Mean velocity
x	Co-ordinate in the direction of the flow ; $x = 0$ at the exit of the jet
y	Co-ordinate perpendicular to x axis in the vertical direction ; $y = 0$ along the central line of the ejector
z	Co-ordinate perpendicular to x axis in the horizontal direction ; $Z = 0$ along the central line of the ejector
ρ	Density
$b_{\frac{1}{2}}$	Half width of the jet based on half the maximum velocity at a given station
θ	Half angle of the diffuser

References

1. McCormick, B. W.	*Aerodynamics of V/STOL flight*, Academic Press, New York, 1967.
2. Simmons, J. M., Lai, J. C. S. and Platzer, M. F.	Jet excitation by an oscillating vane, *AIAA J.*, 1981, **19** (6), 672–676.

3. Badri Narayanan, M. A. and Raghu, S. — Two-dimensional jet subjected to periodic oscillations in the potential core region, Report No. 82 FM 2 (1982). Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560 012 India.

4. Badri Narayanan, M. A. and Raghu, S. — Effect of excitation of the primary jet on ejector thrust augmentation, Report No. AE 82 FM 11 (1982). Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560 012, India.

5. McClellan, T. R. — Experimental investigation of thrust augmenting ejectors using vane excited primary jets. Master's thesis, Naval Postgraduate School, Monterey, California 93940.