# NEW CONCEPTS IN THRUST AUGMENTOR EJECTORS

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## ABSTRACT

An investigation of both an experimental and theoretical nature has been conducted into the use of a subsonic conventional ejector as a thrust augmentor.

A new effectiveness performance parameter, $E_M$, was derived in this investigation and has proved a useful tool in comparing different thrust augmentor designs.

Moderate ejector diffuser area ratios, around 1.5:1, were found to be more favourable for thrust augmentation. This discovery proves a new concept in ejector augmentor design which is more suitable in airfield applications.

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## 1.1 INTRODUCTION:

Recent developements in the field of V/STOL aircraft have stimulated an interest in the use of ejectors for augmenting thrust or lift, particularly, at take-off and landing where the propulsive efficiency of jet engines, at low vehicle velocities, is very poor.

Augmentation can be achieved either by increasing the energy level in the jet, but, this increases noise and inefficiency still further, or alternatively, by chaning the nature of the jet. It is known that thrust can be increased by judicious entrainment of surrounding fluid in order to increase the momentum flux of the jet. If this can be achieved without any substantial loss in the total pressure flux while mixing the entrained fluid with the jet fluid, then the propulsive efficiency is improved, noise is reduced and accumulative improvements in thrust to weight ratio can be achieved.

The developement of an efficient ejector is the main objective of recent investigations. The literature shows that an efficient diffuser is a necessary requirement for achieving high augmentation. Ejector compactness is necessary for technological use. The overall area ratio, $AR_T$, of an ejector is the factor that measures its compactness. In this study two new concepts are introduced. A new effectiveness performance parameter, based on the ejector overall area ratio, was derived and has proved a useful tool in evaluating and comparing different thrust augmentor design. The effect of the ejector diffuser area ratio, $A_R$, when the diffuser effectiveness was considered, was found to have an optimum diffuser area ratio between 1.5:1 to 2:1 . This result proves a new concept in ejector theory. Extensive literature review of the developement of ejector diffuser section is given in EL-BANNA [1] which shows a contradiction between investigators in optimising diffuser area ratio. Theoretical results were compared with experimental one and a good agreement was found.

## 1.2.DEFINITIONS:

### 1.2.1.EJECTOR ENERGY TRANSFER EFFECIENCY:

The transfer of energy from the primary stream to the secondary one can be evaluated using an energy transfer efficiency, $\eta_{TE}$, defined as follows :

$$\eta_{TE} = \frac{\text{System output kinetic energy flux}}{\text{System input kinetic energy flux}} = \frac{\dot{m}_3 V_3^2}{\dot{m}_o V_o'^2} = \mu \frac{(1+X)}{A_R (1-U^2)^{1/2}}$$

where, $\mu$ is the entrainment ratio.

### 1.2.2. THRUST AUGMENTATION RATIO:

The literature indicates different definitions of thrust augmentation ratio for an ejector augmentor. There are two different bases for definition. The more convenient one, which is used in this investigation, relates the ejector thrust to a reference thrust that would have resulted from the isentropic expansion into the ambient of a flow stream that identical to the ejector motivating jet by virtue of its mass and stagnation temperature and pressure. This definition has been used by ALPERIN [2] &RANSOM [3]. The other definition RESZNICK [4] used a reference thrust of a nozzle of equal cross sectional area to that of the ejector primary nozzle. Although the stagnation pressure and temperature as considered to be identical to the ejector supply nozzle, the mass flow rate would not be identical because of the effect of the depression at the ejector inlet. However, this variation in definition complicates the problem of optimising thrust augmentaion.

## 2. TYPICAL EJECTOR ONE-DIMENSIONAL, INVISCID, MATHIMATICAL MODEL:

The following model was derived to study the effect of the diffuser effectiveness, $E_D$, on the performance of a typical ejector (FIG.1) using the following assumptions:

(i) Mixing of primary and secondary flows is completed at plane (2), (FIG.1).

(ii) The thrust plane is plane (3)

(iii) The diffuser exit flow static pressure is equal to the ambient static pressure ( $p_3 = p_A$ ).

### 2.1. Governing equations:

(1) continuity equation:

$$\rho A_o V_o + \rho A_1 V_1 = \rho A_2 V_2 = \rho A_3 V_3 \qquad (2.1.1)$$

Introducing the non-dimensional variables, $U = V_1/V_o$ , $X = A_1/A_o$ & $A_R = A_3/A_2$ , and puting $A_2 = A_1 + A_o$ , therefore gives:

$$\frac{V_2}{V_o} = \frac{1 + XU}{1 + X} \qquad (2.1.2)$$

and,

$$\frac{V_3}{V_o} = \frac{1 + XU}{A_R(1+X)} \qquad (2.1.3)$$

From the definition of the entrainment ratio, $\mu = \dot{m}_2/\dot{m}_o = \dot{m}_3/\dot{m}_o$ ;

$$\mu = 1 + \dot{m}_1/\dot{m}_o = 1 + \frac{\rho A_1 V_1}{\rho A_o V_o} = 1 + X U \qquad (2.1.4)$$

(2) Momentum balance: Applying Newtons second law of motion to the control volume starting at the mixer inlet and ending at the diffuser inlet gives:

$$p_2 A_2 - p_o A_o - p_1 A_1 = \dot{m}_o V_o + \dot{m}_1 V_1 - \dot{m}_2 V_2 \qquad (2.1.5)$$

The following relationships can be written which are based on the previous assumptions

$$p_2 = p_A - 1/2.\rho.V_2^2.C_p \qquad (2.1.6)$$

where, $C_p = E_D\,(1 - A_R^{-2})$

$$P_1 = p_A + \frac{1}{2}\rho V^2 \qquad (2.1.7)$$

$$P_1 = p_1 + \frac{1}{2}\rho V_1^2 \qquad (2.1.8)$$

Equations (2.1.6 to 2.1.8) give:

$$p_1 = p_A + \frac{1}{2}\rho V^2 - \frac{1}{2}\rho V_1^2 \qquad (2.1.9)$$

and $p_2 - p_1 = \frac{1}{2}\rho V_1^2 - \frac{1}{2}\rho V^2 - \frac{1}{2}\rho V_2^2 C_p \qquad (2.1.10)$

Equation (2.1.5) can be written, therefore, in the form:

$$A_2(p_2 - p_1) = A_o V_o^2 \left[ 1 + XU^2 - (1 + X)\,(V_2/V_o)^2 \right] \qquad (2.1.11)$$

Substituting for $p_1$, $p_2$, $(V_2/V_o)$ and dividing through by $(A_o V_o^2)$ and rearranging give:

$$U^2 - S^2 - C_p\left(\frac{1 + XU}{1 + X}\right)^2 = 2\left[\frac{1 + XU^2}{1 + X} - \left(\frac{1 + XU}{1 + X}\right)^2\right]$$

$$\text{or, } U^2 - S^2 + (2 - C_p)\left(\frac{1 + XU}{1 + X}\right)^2 = 2\left(\frac{1 + XU^2}{1 + X}\right)$$

Rearranging in descending power of (U) and letting $K = (2-C_p)/(1+X)$, therefore gives :

$$U^2 + \left(\frac{2XK}{1-X+X^2K}\right) U + \left[\frac{K-S^2(X+1)-2}{1-X+X^2K}\right] = 0 \qquad (2.1.12)$$

$$\text{or, } \quad U^2 + B\,U + C = 0$$

where,

$$B = \left( \frac{2XK}{1-X+X^2K} \right) \text{ and } C= \left[ \frac{K-S^2(X+1)-2}{1-X+X^2K} \right]$$

2.1.2. Thrust augmentation ratio ( $\Phi$ ):

The thrust augmentation ratio as defined before can be expressed in terms of the rate of change of momentum for both the ejector and the reference nozzle as follows:

$$\Phi = \frac{m_3V_3 - m_oV - m_1V}{m_o\,(V_o' - V)}$$

therefore,

$$\Phi = \frac{m_3}{m_o}\;\frac{V_3 - V}{V_o' - V}$$

$$\Phi = u \left[ \frac{(V_3/V_o) - S}{(V_o'/V_o) - S} \right] \qquad (2.1.13)$$

The following relationship can be written according to thrust augmentation definition:

$P_o = p_A + \frac{1}{2} \rho V_o'^2 = P_1 + \frac{1}{2} \rho V_o^2$ , where, $P_o$ is the total pressure of both the reference nozzle and the primary nozzle and $V_o'$ is the discharging jet velocity of the reference nozzle expanding isentropically to the ambient.

therefore,

$$\frac{V_o'}{V_o} = (1- U^2 + S^2)^{1/2} \qquad (2.1.14)$$

Substitution for $(V_3/V_o)$ from equation (2.1.3) and for $(V_o'/V_o)$ from equation (2.1.14) therefore,

$$\Phi = \mu \frac{[\, u / A_R / (1+X) \,] - S}{(1 - U^2 + S^2)^{1/2} - S} \qquad (2.1.15)$$

From equation (2.1.15) and the definition of the energy transfer effeciency the static ejector augmentation ratio can be found as a function of the entrainment ratio and the energy transfer effeciency in the form:

$$\Phi = \sqrt{\mu\, \eta_{TE}} \qquad (2.1.16)$$

### 3. A NEW PERFORMANCE PARAMETER:

A new augmentor 'Effectiveness' parameter is derived in order to provide a basis for comparison and evaluation of augmentors. The new parameter is used to compare the measured performance with that which would be obtain from an ideal augmentor having the same overall area ratio, $AR_T$, and inlet conditions; clearly such an ideal augmentor would supply the maximum possible thrust from the available constraints. For an augmentor, the maximum thrust augmentation ratio can most simply be calculated using an analysis based upon incompressible, one-dimensional flow.

The augmentation ratio, for a static ejector can be written as follows:

$$\Phi = \mu \, ( V_3/V_o' ) \qquad (3.1)$$

and the total area ratio of an ejector, $AR_T = A_3/A_o'$, where, $A_3$, is the diffuser exit area and $A_o'$, is the area of the reference nozzle can be written as follows:

$$V_3/V_o' = \mu/AR_T \qquad (3.2)$$

Combining Equations (3.1) and (3.2) gives:

$$\Phi = \mu^2/AR_T \qquad (3.3)$$

From the definition of energy transfer efficiency:

$$\eta_{TE} = \mu \, (V_3/V_o')^2 = \mu^3/AR_T^2 \qquad (3.4)$$

then,

$$\mu = ( \eta_{TE} AR_T^2 )^{1/3} \qquad (3.5)$$

Combining Equations (3.3) and (3.4) gives:

$$\Phi = ( \eta_{TE} AR_T )/\mu \qquad (3.6)$$

Equations (3.5) and (3.6) give the maximum augmentation ratio, $\Phi_{max}$, in terms of the total area ratio, $AR_T$, and relate to the ideal condition when $\eta_{TE} = 1.0$ as follows:

$$\Phi_{max} = (AR_T)^{1/3} \qquad (3.7)$$

The performance effectiveness, $E_M$, is defined as :

$$E_M = \Phi_s / \Phi_{max}$$

where, $\Phi_s$, is the measured augmentation ratio.

### 4. EXPERIMENTAL FACILITY :

A two-dimensional test section, Fig.2, which comprises a ninty degrees Coanda surface and a two-dimensional nozzle and diffuser was used. The diffuser area ratio, $A_R$, was varied from 1.1 up to 1.9 and the thrust was measured (EL-BANNA [1]). Augmentation ratios were calculated and plotted against the diffuser area ratio, $A_R$, in fig.3 .

## 5. DISCUSSION:

### 5.1.EFFECT OF DIFFUSER AREA RATIO AND DIFFUSER EFFECTIVENESS:

The theoretical models resulted in a series of graphes, figures 4 to 9 which are instrumental in the following analysis.

It is clearly shown in FIG.4 that the entrainment ratio increases as the diffuser area ratio, $A_R$, increases. This is simply because an increase in the diffuser area ratio results in a stronger depression at the ejector inlet which in turn increase the acceleration of surrounding fluid. On the other hand, an increase in '$A_R$' was found to decrease the energy transfer effeciency Fig. 5. This means that entrainment ratio and energy transfer effeciency are affected by diffuser area ratio in opposing way which dictates that an individual increase of either component is not necessarily a sufficient condition for obtaining high augmentation ratio.

Analysing the data shown in figures 6, 7 & 8 led to the following interesting results:
(i) For an ideal ejector where diffuser effectiveness, $E_D$, equals unity, the augmentation ratio increases continuosly with the diffuser area ratio FIG.6.
(ii) When the diffuser effectiveness was included (a typical value of 0.85), moderate diffuser area ratios (in the range 1.5 to 2.0) were found to be the most favourable to give high augmentation ratios FIG.7.
(iii) An increase in the diffuser effectiveness results in an approximately similar increase in the augmentation ratio Fig.8 .

The increment in the thrust produced by the ejector configuration is due solely to the depression reaction forces on the ejector inlet. Although increasing the diffuser area ratio results in more depression at the ejector inlet, it creates also an increase in the depression on the inner walls of the diffuser and this opposes the thrust increament. This argument agrees with the present predictions in that the moderate diffuser area ratios lead to a favourable balance between the thrust on the intake and the drag loss of the diffuser.

The experimental data plotted in fig. 3 shows the same trend which clearify that the augmentation ratio increases with the diffuser area ratio up to a maximum at around $A_R$ = 1.6 and then starts to decrease for further increase of diffuser area ratio.

### 5.2 THE PERFORMANCE PARAMETER $E_M$ :

This parameter, besides its simplicity in calculating the maximum possible thrust augmentation ratio of a system given just the overall area ratio ( using equation 3.7 ), is found instrumental in three different other ways ; the first evaluates momentum by comparing the measured thrust relative to the maximum obtainable thrust from an ideal ejector having the same total area ratio, the second is to indicate the size of the augmentor used by its overall area ratio, and the third use is to provide a measure of the mixing efficiency since an ideal augmentor of a unity energy transfer efficiency is used as a basis for comparison.
beside these advantages , there are two more use of the derived equations 3.6 and 3.7;

(i) Equation 3.6 gives the ejector performance chart FIG.9 which can be used either to get data or to evaluate an existing augmentor.
(ii) equation 3.7 gives a very simple form to calculate the maximum possible augmentation ratio in terms of the overall area ratio of an augmentor.

## REFERENCES

1. R.A.M. EL-BANNA, "An investigation of new concepts in two-dimentional curved thrust augmentors", Ph.D. thesis, Cranfield Institute of Technology (1986).

2. ALPERIN M & WU J, "Recent Developement of a Jet-Diffuser Ejector", AIAA Paper 80-0231, Jan. (1980)

3. RANSOM E C P & SMY J R "Introduction and Review of some Jet Interaction Phenomena Relevant to V/STOL Aircraft", AGARDograph R-710, (1982)

4. REZNICK S G " inlet and Diffuser Effects on the Thrust Augmentation of Circular and Rectangular Ejectors", Airforce Institute of Tech. Ohio, AFB Oh 45433, (1979)

## Nomenclature:

| | |
|---|---|
| A | Area |
| X | Area ratio $A_1/A_o$ |
| V | Velocity, Ejector velocity |
| U | Velcocity ratio $V_1/V_o$ |
| S | Velocity ratio $V/V_o$ |
| $C_p$ | Coefficient of diffuser pressure rise |
| P | Total pressure |
| p | Static pressure |
| $E_D$ | Diffuser Effectiveness |

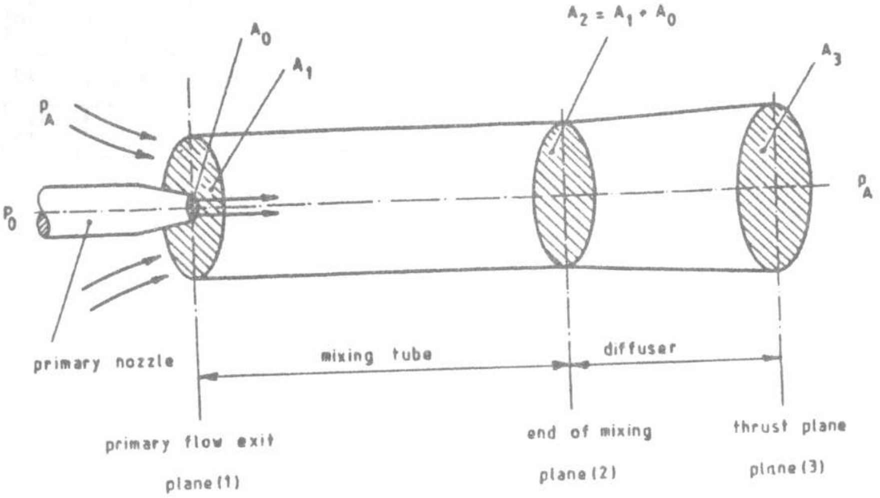

Fig.1 A typical Ejector.

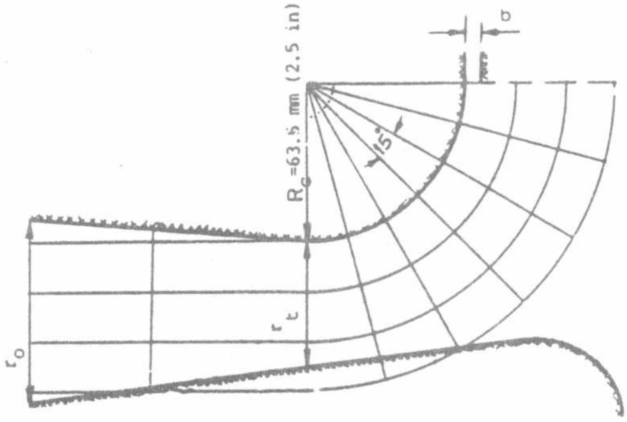

Fig.2 Two-Dimensional Test Section.

| | |
|---|---|
| b | 12.7 mm |
| $b/R_c$ | 0.20 |
| $P_o/P_A$ | 1.13 |
| $r_t$ | 53.34 mm |

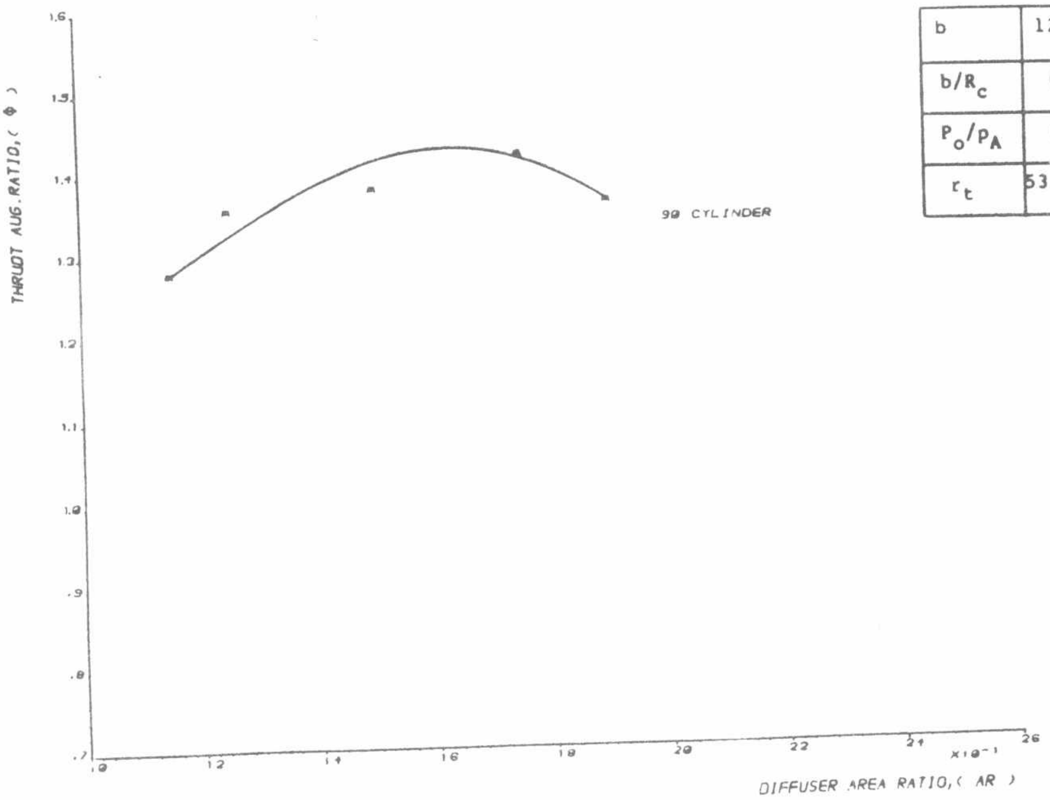

FIG.( 3 ) - EFFECT OF DIFFUSER AREA RATIO ON THRUST AUGMENTATION RATIO

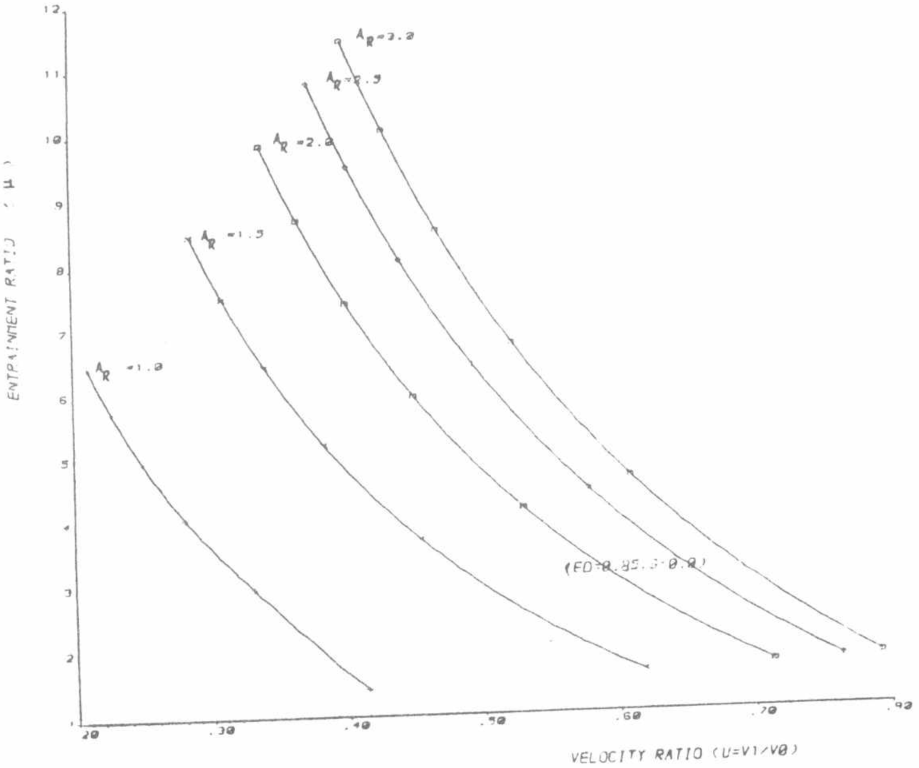

FIG.( 4 )-VARIATION OF ENTRAINMENT RATIO WITH VELOCITY RATIO (U)

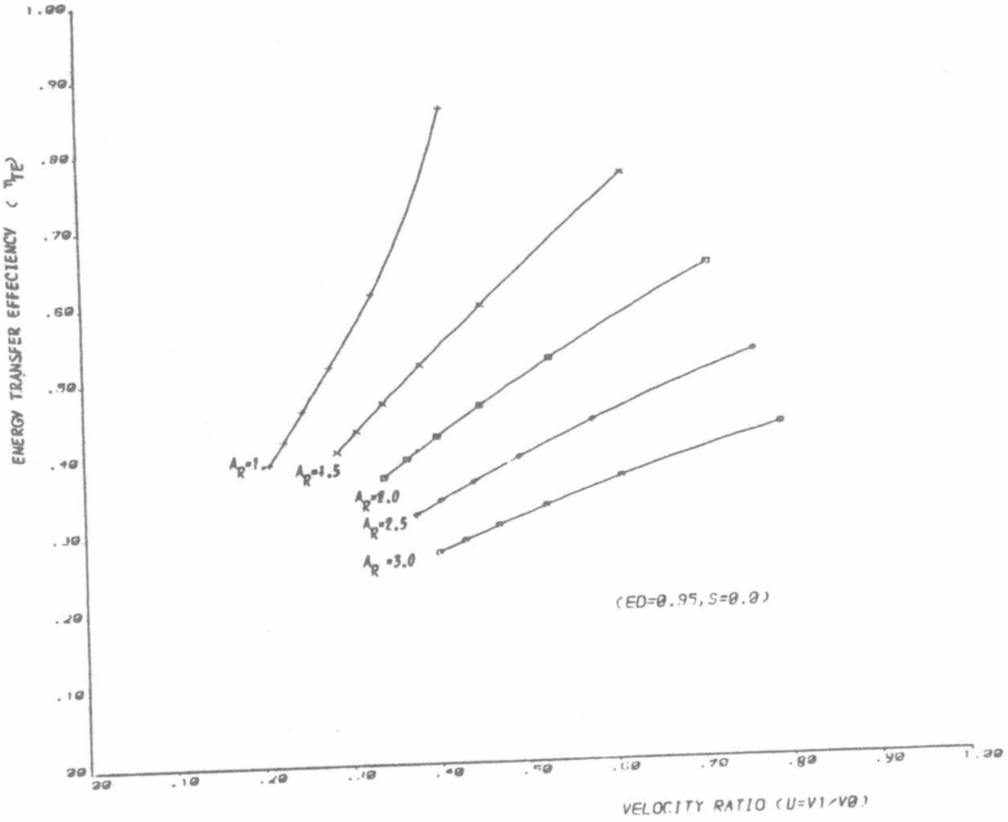

FIG.( 5 ) - EFFECT OF VELOCITY RATIO, U, ON ENERGY TRANSFER EFFECIENCY

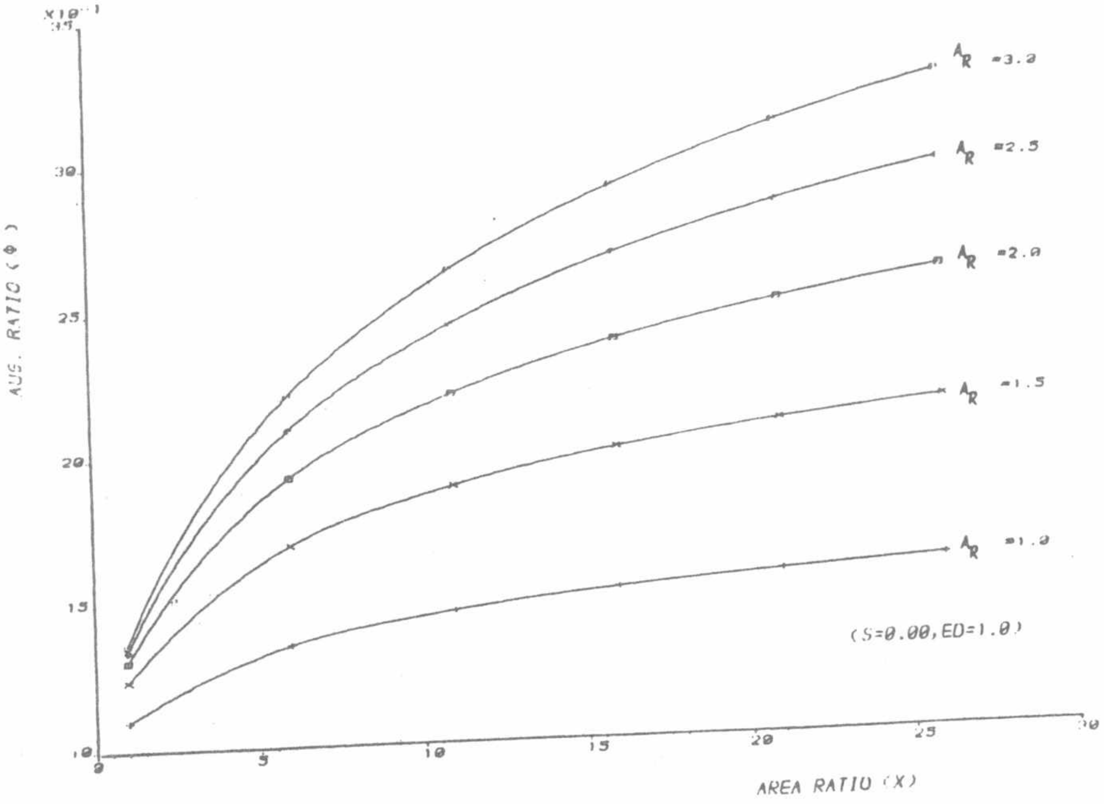

FIG.( 6 ) EFFECT OF DIFFUSER AREA RATIO $A_R$ UPON Φ

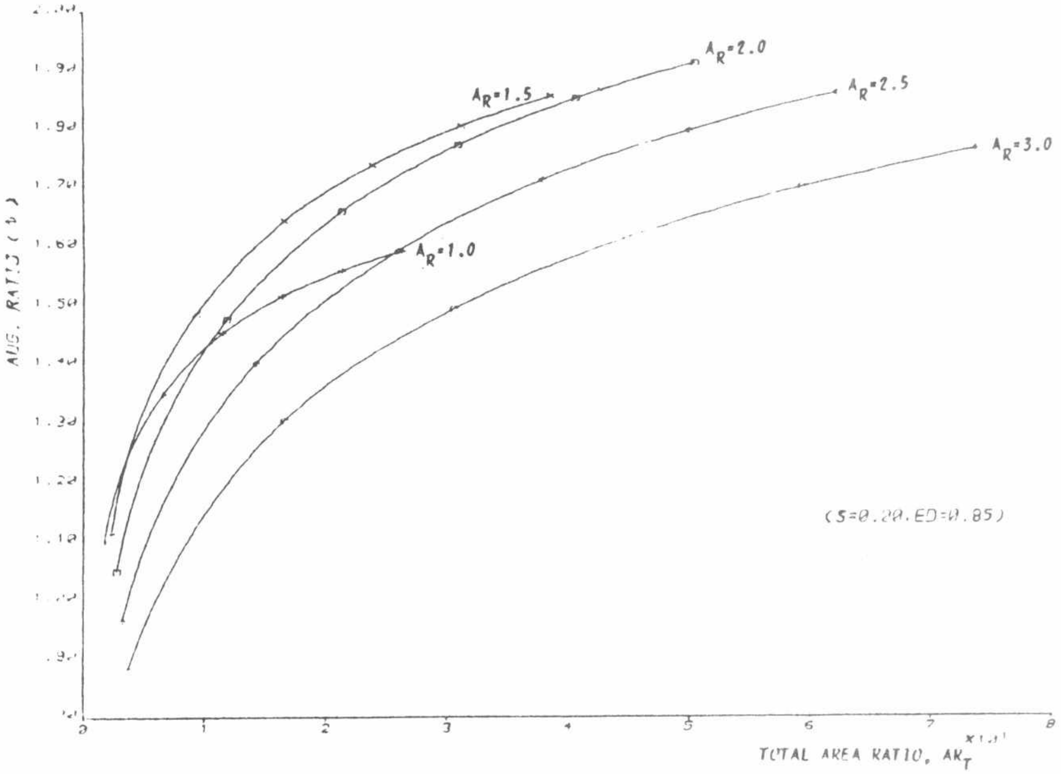

FIG.( 7 ) - EFFECT OF DIFFUSER EFFECTIVENESS ON EJECTOR PERFORMANCE

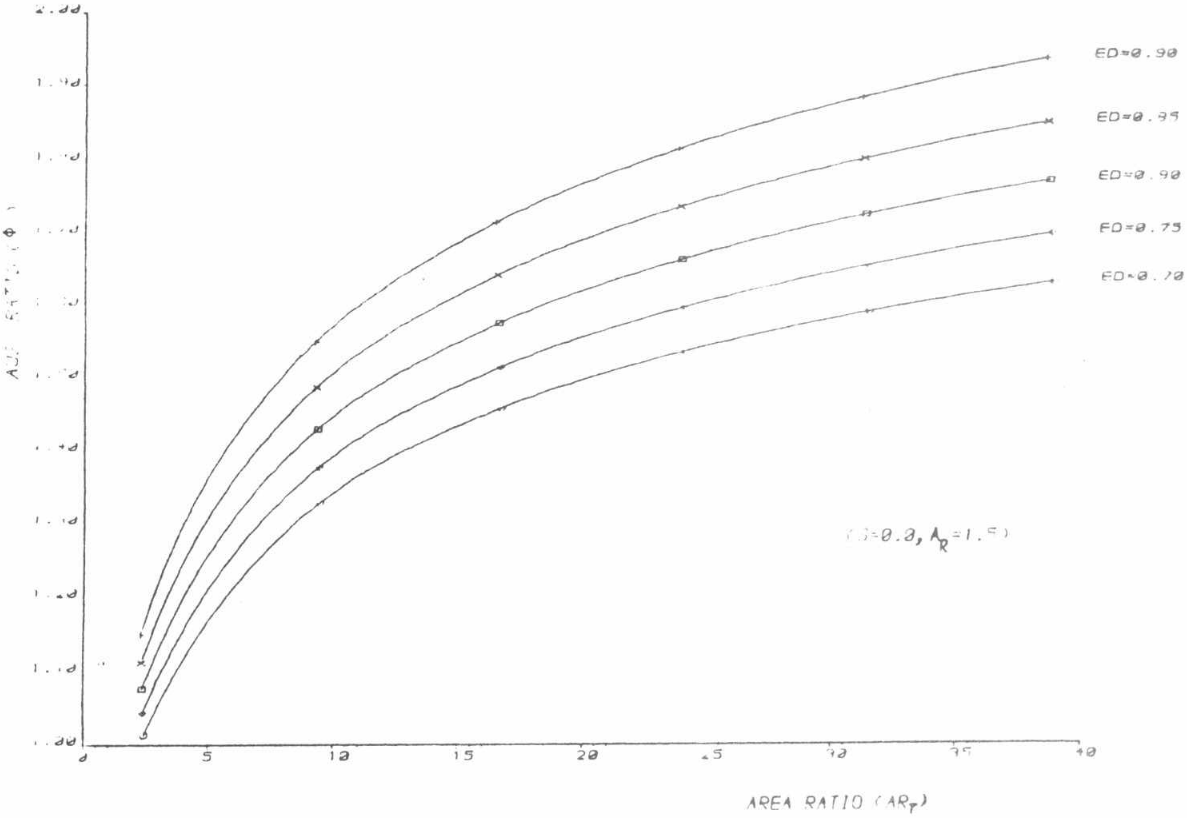

FIG.( 8 ) EFFECT OF DIFFUSER EFFECTIVNESS (ED) UPON ( Φ )

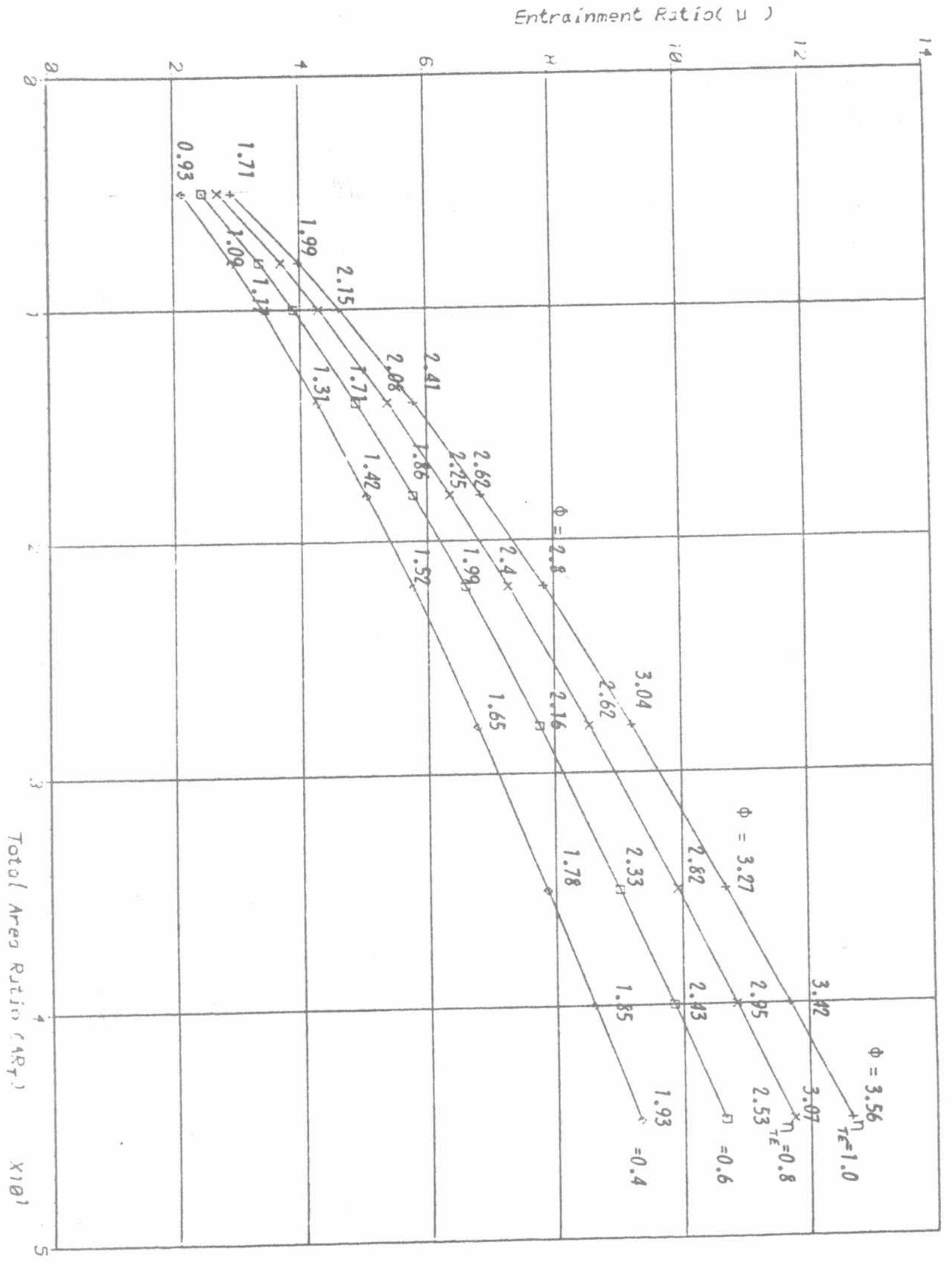

FIG.( 9 )- EJECTOR PERFORMANCE CHART.