Title	Experimental study on pneumatic ejector, with special reference to the effect of area ratio on performance characteristics (1st report)				
Sub Title					
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Publisher	慶應義塾大学藤原記念工学部				
Publication year	1954				
Jtitle	Proceedings of the Fujihara Memorial Faculty of Engineering Keio University Vol.7, No.26 (1954. ) ,p.51(1)- 60(10)				
JaLC DOI					
Abstract	Experiments on pneumatic ejectcr have been conducted to ascertain the effect of the area-ratio, i.e. the ratio of the cross-sectional area of the parallel part of the mixing tube to the nozzle exit area, upon the perfomance characteristics. The compressed air delivered by a Roots blower was employed as a driving fluid, and the air sucked in from the surrounding atmosphere was used as a driven fluid. Experiments were performed under constant driving pressure with varying weight flow of the secondary air. The results were that, (1) there exists an optimum area-ratio and (2) the mixing in the mixing chamber took place at nearly constant pressure and so on.				
Notes					
Genre	Departmental Bulletin Paper				
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001004-00070026- 0001				

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# Experimental Study on Pneumatic Ejector, with Special Reference to the Effect of Area Ratio on Performance Characteristics (1st Report)

(Received February 25, 1955)

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## Abstract

Experiments on pneumatic ejector have been conducted to ascertain the effect of the area-ratio, i.e. the ratio of the cross-sectional area of the parallel part of the mixing tube to the nozzle exit area, upon the perfomance characteristics. The compressed air delivered by a Roots blower was employed as a driving fluid, and the air sucked in from the surrounding atmosphere was used as a driven fluid. Experiments were performed under constant driving pressure with varying weight flow of the secondary air.

The results were that, (1) there exists an optimum area ratio and (2) the mixing in the mixing chamber took place at nearly constant pressure and so on.

### I. Introduction

Various theoretical researches and experimental studies have been performed on ejectors, and especially as to the steam ejectors, many a survey was conducted that the performance characteristics and the functions of them have been thoroughly understood. Further, ejectors using oil vapor have been studied recently by Prof. S. Sugawara.<sup>1)</sup> The theoretical and experimental studies on pneumatic ejectors have also been conducted recently, and the results <sup>233)4)</sup> obtained are available to some extent. The present authors have conducted experimental study on pneumatic ejectors with special reference to the effect of area ratio, i.e. the ratio of the cross sectional area of the parallel part of the mixing tube to the nozzle area and have endeavoured to obtain performance data not available

4) Ueda, Ikeno; Science of Machine, Vol. 5 No. 7, July 1953, pp. 425~429

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<sup>1)</sup> S. Sugawara; Trans. Japan Soc. Mech. Engrs, Vol. 29 No. 16, 1954, pp. 542 and 548

<sup>2)</sup> L. J. Kaster, J. R. Spooner; Proc. Inst. Mec'h. Engrs. Vol. 162 1950, pp. 149~159

<sup>3)</sup> J. H. Keenan; Jour. App. Mech. Sept. 1950, pp. 299~309

from the preceding literatures. In our experiment, the compressed air delivered from a Roots lower was employed as driving fluid, and the air sucked in from the surrounding atmosphere was used as driven fluid. The nozzle used in the present experiment is of convergent type, and six mixing tubes having parallel part or throat of different cross-sectional areas were constructed to vary the above-mentioned area ratio of the ejector. The weight flow of the secondary air was allowed to vary by a valve, and the experiments were conducted by varying the weight flow of the secondary air for every constant upstream-pressure or the driving pressure of the nozzle. Further, pressure distributions were measured at the mixing chamber, parallel part and the diffuser downstream to the parallel part for a specified ejector.

#### II. Experimental Apparatus and the Experimental Method

Fig. 1 represents the schematic drawing for experimental apparatus on pneu-



Fig. 1. Schema for Experimental Apparatus

matic ejector. The compressed air delivered by a Roots blower enters to the ditsribution tank, and then arriving at the pressure tank via valve  $V_2$ , exhausts finally out of the convergent nozzle. Another pipe provided with by-pass valve  $V_1$  is fitted to the distribution tank, and thus the pressure in the pressure tank may be varied by the operation of the value  $V_1$ . The value  $V_2$ , on the other hand, has the purpose for checking the air flow when the experimental set is Thus, for the present case, the value  $V_2$  was left utilized for another purpose. full open. The secondary air or the driven fluid is sucked into the pipe shown below in the figure. The weight flow of this secondary air  $G_2$  is to be measured by round type nozzle, and the air is sucked into the mixing chamber via valve  $V_3$ . The weight flow  $G_2$  may be varied if the opening of the value  $V_3$  is altered. Mixing of the secondary air with primary air is undertaken at the mixing chamber, from which the air is delivered to the surrounding atmosphere after passing through the parallel part and the diffuser of the mixing tube. At the downstream of the diffuser, the total amount of air, i.e. the sum of the weight flow of primary air  $G_1$  and secondary air  $G_2$ , is measured by another air flow meter.

The nozzle used in our experiment is of convergent type as shown in Fig. 2.

Six mixing tubes shown in Fig. 3 are used to vary the area ratio. As shown in Fig. 3, each mixing tube is constructed of the mixing chamber, parallel part and the diffuser or diverging part, and is so constructed that the nozzle exit section situates the distance a' apart from the entrance section AA of the parallel part. The values of a' are shown below in the figure.



Fig. 2. Nozzle

As the inner diameter of the parallel part varies as shown in Fig. 3, we are able to vary the area ratio m, i.e. the ratio of the cross-sectional area of the parallel part to the cross-section-

You A
 b

Test Ejector a mm	Distance between nozzle exit and section AA, a'mm	b mm	c mm	d mm	e mm	f mm	Area ratio m
ED-1950 13.6	8.5	46.9	110.1	25.0	9.55	16.4	2.67
ED-1850 15.0	8.5	49.4	110.4	25.0	8.55	14.8	2.14
ED-1750 18.0	8.5	50.7	110.2	25.0	7.60	13.0	1.72
ED-1100 13.5	8.5	48.9	110.2	25.0	10.0	16.0	2.93
ED-1200 18.0	8.5	<b>50.0</b>	110.0	25.0	12.0	18.0	4.22
ED-1600 18.0	8.5	50.0	110.0	25.0	6.00	14.0	1.05

al area of the nozzle exit. The mixing tube ED-1950 is especially provided with several holes for pressure measurement as shown in Fig. 4. Further, the static pressures at the nozzle exit were observed by a hole drilled as shown in Fig. 10.

The situations at which the pressures and tempera-





Fig. 4. Mixing tube provided with holes for pressure measurement

tures were measured for the present experimental set are shown in Fig.1. Pressures were read by manometers filled with water or mercury, and the temperatures were observed by thermometers. The Roots blower used was driven by a 15HP electric motor of induction type, and experiments were conducted under a constant driving pressure ranging from 50mmHg to 450mmHg varying the weight flow of the secondary air from zero to maximum value.

## III. The Experimental Results and the Considerations

3.1 Pressure ratio  $p_2/p_0$  and weight flow ratio  $G_2/G_1$ .

The pressure ratio  $p_2/p_0$  in which  $p_2$  means the vacuum pressure in the tank (Fig. 1) and  $p_0$  expresses the pressure of the surrounding atmosphere as well as the weight flow ratio  $G_2/G_1$  in which  $G_1$  and  $G_2$  mean the weight flow of the primary and the secondary air respectively are calculated and the relations between  $p_2/p_0$ 



Fig. 5. Pressure Ratio vs. Weight Flow Ratio (Area ratio m=2.93, Mixing Tube ED-1100)

and  $G_2/G_1$  are plotted. Fig. 5 shows an example of such a diagram for the case of m=2.93. The parameters of pressure  $p_1$  is ranging from 50mmHg to 450mmHg. Fig. 6 represents the same relationships for m=1.05. When m is relatively large such as in Fig. 5,  $p_2/p_0$  becomes smaller as the driving pressure increases, and



Fig. 6. Fressure Eatio vs. Weight Flow Ratio (Area ratio m=1.05, Mixing Tube ED-1100)

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further  $p_2/p_0$  increases uniformly with  $G_2/G_1$  for every driving pressure  $p_1$ . For smaller values of *m*, such as 1.05, the tendency of the curves becomes somewhat different as shown in Fig. 6.<sup>5</sup>

When m=1.05 (Fig. 6), the exit area of the nozzle amounts nearly equal to the cross-sectional area of the parallel part, and thus it is conceivable that the choking phenomena of the flow at the entrance of the parallel part are liable to occur as the driving pressure  $p_1$  increases, that is as the nozzle exit velocity and hence the weight flow of the secondary air increases. Hence we may suggest



**Fig. 7.** Pressure Ratio vs. Weight Flow Ratio  $(p_1=250 \text{ mmHg})$ 



Fig. 8. Fressure Ratio and Weight Flow Ratio ( $p_1 = 450 \text{mmHg}$ )

that  $p_2/p_0$  increases or in other words the vacuum  $p_2$  collapses rapidly as  $G_2/G_1$  increases. For greater values of m as in Fig. 5, however, no choking phenomena are liable to occur, so that the curves show uniform tendency with respect

<sup>5)</sup> The diagrams for m=4.22, 2.67, 2.14 and 1.72 are not cited in the present paper. It is seen that the diagrams yield to tend gradually from the tendency shown in Fig. 5 to that in Fig. 6 as the value of m becomes smaller.

to  $G_2/G_1$ . The replotting of the curves shown in Fig. 5 and 6 for constant values of  $p_1$  with parameters of *m* renders to the diagrams shown in Fig. 7 and 8. The values of  $p_2/p_0$  corresponding to the critical value of  $p_1/p_2=1.89$  amount to 0.702 (Fig. 7) and 0.842 (Fig. 8) respectively. Therefore, in the regions below these values of  $p_2/p_0$ , it is considered that the nozzle exit velocity amounts to the local sonic velocity along each curve, while in the regions above these values of  $p_2/p_0$ , the exit velocity remains subsonic and decreases gradually along respective curve as  $p_2/p_0$  increases. Hence, notwithstanding with constant values of  $p_1$ , the nozzle exit velocity varies on each curve in Fig. 7 and 8. The choking phenomena appear clearly in these diagrams, that is, in Fig. 7, the slope of the curves becomes steeper as *m* decreases. In Fig. 8 where the driving pressure  $p_1=450$ mmHg, the choking tendency is more exaggerated compared with Fig. 7 in which  $p_1=250$ Hgmm.

Further replotting from these diagrams yields to the curves shown in Fig. 9



Fig. 9. Pressure Ratio vs. Area Ratio ( $p_1 = 450$ mmHg)

for the case of  $p_1=450$  Hgmm. The theoretical considerations <sup>6)</sup> and the present experimental results both show that the maximum vacuum is obtained with no secondary flow. In the theoretical analysis,  $p_2/p_0$  decreases as *m* becomes smaller.

The experimental results, however, show that  $p_2/p_0$  tends initially to smaller value as *m* decreases until it reaches a minimum, then tending to larger value again. This phenomenon is conceivable because of the choking phenomena within ranges for smaller values of *m*. For larger values of  $G_2/G_1$ , the value of *m* which renders  $p_2/p_0$  to a minimum removes towards larger values of *m*, as may be expected easily.

3.2 Pressure distributions within the mixing tube.

An example of pressure distributions within the mixing tube is shown in Fig. 10. The mixing tube used is of type ED-1950, and the pressure distributions along

6) Same as 2).

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(6)

mixing chamber, parallel part and diffuser are plotted for the case of  $G_2/G_1 = 0.4$ . The pressures  $p_2$  are also plotted in the same figure. In the theoretical treatment<sup>7</sup> cited above, the method of assuming constant pressure mixing in the mixing chamber has been developed. As is clear from Fig. 10, the pressures in the mixing chamber  $p_9$  and  $p_{10}$  differ so little so far as the driving pressure

is kept within the range of the present experiment, that the above method of calculus for constant pressure mixing is found to be allowable.

In the present experiment, it was found further that the static pressure at nozzle exit section  $p_3$  shows greater value than the surrounding pressure such as  $p_9$ , even if the critical pressure ratio has not yet exceeded.

3.3 Ejector efficiencies and the weight flow ratio  $G_2/G_1$ .

The energy of the driving fluid is found to be



Fig. 10. Pressure Distributions within Mixing Tube

 $G_1\left\{k/(k-1)\right\}RT_0\left\{\left(\frac{p_1}{p_0}\right)^{\frac{k-1}{k}}-1\right\}$  if  $G_1$  represents weight flow of the driving fluid,  $p_1$  expresses the driving pressure and  $p_0$  and  $T_0$  mean the pressure and absolute temperature of the surrounding atmosphere respectively. Further, let  $G_2$  be the weight flow of the secondary air,  $p_2$  and  $T_2$  be the static pressure and absolute temperature of the secondary air before mixing. Then it is seen that the pressure of the secondary air is compressed from  $p_2$  to  $p_4$  i.e. the delivery pressure at the diffuser outlet (Fig. 1). Thus, if we put the velocity of the nixing stream as  $w_4$  at the cross-section corresponding to  $p_4$ , the energy given to the secondary air yields theoretically to

$$G_2 \frac{k}{k-1} R T_2 \left\{ \left( \frac{p_4}{p_2} \right)^{\frac{k-1}{k}} - 1 \right\} + G_2 \frac{w}{2g}$$

Therefore, we may define the ejector efficiency as follows.

$$\eta = \frac{G_2 \frac{k}{k-1} R T_2 \left\{ \begin{pmatrix} p_4 \\ p_2 \end{pmatrix}^{\frac{k-1}{k}} - 1 \right\} + G_2 \frac{w_4^2}{2g}}{G_1 \frac{k}{k-1} R T_0 \left\{ \begin{pmatrix} p_1 \\ p_0 \end{pmatrix}^{\frac{k-1}{k}} - 1 \right\}} = \frac{G_2 T_2 \left\{ \begin{pmatrix} p_4 \\ p_2 \end{pmatrix}^{\frac{k-1}{k}} - 1 \right\}}{G_1 T_0 \left\{ \begin{pmatrix} p_1 \\ p_0 \end{pmatrix}^{\frac{k-1}{k}} - 1 \right\}}$$

7) Same as 3).

(7)

Fig. 11 shows the relations between  $\eta$  and  $G_2/G_1$  thus obtained, when m=2.93. As is clear from the figure, the efficiency  $\eta$  falls off as the driving pressure  $p_1$ 



Fig. 11. Ejector Efficiency vs. Weight Flow Ratio (m=2.93)

becomes larger. The increase in  $p_1$  corresponds to the increase in exit velocity from the nozzle so far as the subcritical pressue ratio regions are concerned,<sup>8)</sup> and thus it is considered that  $\eta$  falls off as  $p_1$  increases. It is also found that the values of  $G_2/G_1$ , which give maximum  $\eta$  become smaller as  $p_1$  increases.



Fig. 12. Ejector Efficiency vs. Weight Flow Ratio ( $p_i = 450 \text{mmHg}$ )

Fig. 12 shows the relations between  $\eta$  and  $G_2/G_1$  for the case of  $p_1=450$  mmHg,

8) The values of  $p_2/p_0$  corresponding to the critical pressure ratio of the nozzle amount to  $p_2/p_0=0.599$  and  $p_2/p_0=0.633$  for  $p_1=100$  mmHg and 150 mmHg respectively. Therefore, in these cases, the regions in the present experiments belong to the subsonic regions of the exit velocities. Thus, the exit velocity increases gradually as  $p_1$  increases until  $p_1=450$  mmHg is reached, where as is seen from Fig. 8, the exit velocities amount to local sonic ones in the major part of the regions of the present experiment.

(8)

*m* being taken as parameter. As *m* tends from 1.05 to larger values, the efficiency  $\eta$  improves until the maximum efficiency  $\eta = 16.8\%$  is reached at m = 2.14. For values of *m* larger than 2.14,  $\eta$  tends gradually to lower values. The values of  $G_2/G_1$  which make  $\eta$  maximum tend as a whole to larger values of  $G_2/G_1$  as *m* increases. These phenomena show qualitatively the same tendency as the theoretical results obtained by Ueda and Ikeno.<sup>9)</sup>

#### **IV.** Conclusions

In the present experimental study, the effect of the area ratio on the perfomance characteristics has been investigated, and the following conclusions were obtained.

(a) The relations between  $p_2/p_0$  and  $G_2/G_1$  differ as *m* varies. When *m* is small such as m=1.05, the higher values of  $p_1$  produce choking of the flow at the inlet of the parallel part of the mixing tube so that  $G_2$  saturates to some value. The saturated value of  $G_2/G_1$  tends to smaller value as  $p_1$  increases for the same value of *m*. In the case of large values of *m*, this saturation phenomenon is not observed.

(b) In both cases, the minimum  $p_2/p_0$  or the maximum vacuum is obtained whenever the weight flow of the secondary air  $G_2$  vanishes, and the vacuum is weakened as  $G_2$  increases.

(c) As is clear from Fig. 7 and 8, there exists some value of m which gives maximum vacuum or least  $p_2/p_0$  corresponding to  $G_2=0$ . In our experiments, this aboslute maximum vacuum is obtained at m=1.72 both for  $p_1=250$ mmHg (Fig. 7) and  $p_1=450$ mmHg (Fig. 8).

(d) The relations  $p_2/p_0$  vs. *m* for parameters of  $G_2/G_1$  (Fig. 9) show that the value of *m* which gives maximum vacuum tends to larger values of *m* as  $G_2/G_1$  increases. That is, if we want ejectors for small values of  $G_2/G_1$ , the lower value of *m* is preferable and vice versa.

(e) From the observations of the pressure distributions along the mixing tube, we are able to support the assumption of constant pressure mixing in the mixing chamber so far as the ejectors such as used in the present experiments are concerned.

(f) At a fixed area ratio m, the relations  $\eta$  vs.  $G_2/G_1$  with parameters of  $p_1$  show that the maximum value of  $\eta$  is obtined at smaller values of  $p_1$ . As  $p_1$  increases  $\eta$  becomes smaller, and the value of  $G_2/G_1$  corresponding to this maximum removes to smaller values of  $G_2/G_1$ .

(g) The relations  $\eta$  vs.  $G_2/G_1$  as parameter of *m* reveal us that,  $\eta_{max}$  is affected by *m*, and at a certain value of *m* maximum  $\eta_{max}$ . or the absolute maximum of

9) Same as 4)

(9)

 $\eta$  is obtained. For values of *m* larger than this critical value,  $\eta_{mix}$  becomes smaller. The values of  $G_2/G_1$  which correspond to  $\eta_{mix}$  become larger as *m* increases.

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