Title	The experimental study on pneumatic ejector, with special reference to the effect of distance, from nozzle exit section to the entrance of the parallel part of the mixing tube, upon performance characteristics (2nd report)
Sub Title	
Author	渡部, 一郎(Watanabe, Ichiro) 渡辺, 剛男(Watanabe, Takeo) 仲田, 哲郎(Nakata, Tetsuro) 中川, 洋(Nakagawa, Hiroshi)
Publisher	慶應義塾大学藤原記念工学部
Publication year	1955
Jtitle	Proceedings of the Fujihara Memorial Faculty of Engineering Keio University Vol.8, No.31 (1955.) ,p.94(1)- 103(10)
JaLC DOI	
Abstract	Among the factors which affect the performance characteristics of a pneumatic ejector, the effect of the distance a' from the nozzle exit section to the entrance of the parallel part of the mixing tube was dealt with experimentally in the present paper. It was found that the optimum distance a' for the highest vacuum and the highest ejector efficiency was a'= 15 mm, so long as the present ranges of experiments were concerned. As the inner diameter e of the parallel part of the mixing tube was selected like e= 9.55 mm, the optimum value above-mentioned yields to a' /e= 1.57, which coincides with the results obtained previously by L. J. Kastner and J. R. Spooner for a pneumatic ejector. Besides, the present authors have measured the pressure distributions in the mixing tube, the results of which we compared with the theories of W. Tollmien and A. M. Kuethe. Further, we compared the results of the present paper with the results hitherto published on the steam ejectors.
Notes	
Genre	Departmental Bulletin Paper
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001004-00080031-0001

The Experimental Study on Pneumatic Ejector, with Special Reference to the Effect of Distance, from Nozzle Exit Section to the Entrance of the Parallel Part of the Mixing Tube, upon Performance Characteristics (2 nd Report)

(Recieved September 15, 1956)

Itirō WATANABE*
Takeo WATANABE**
Teturō NAKATA***
Hirosi NAKAGAWA****

Abstract

Among the factors which affect the performance characteristics of a pneumatic ejector, the effect of the distance a' from the nozzle exit section to the entrance of the parallel part of the mixing tube was dealt with experimentally in the present paper. It was found that the optimum distance a' for the highest vacuum and the highest ejector efficiency was $a'=15$ mm, so long as the present ranges of experiments were concerned. As the inner diameter e of the parallel part of the mixing tube was selected like $e=9.55$ mm, the optimum value above-mentioned yields to $a'/e=1.57$, which coincides with the results obtained previously by L. J. Kastner and J. R. Spooner for a pneumatic ejector. Besides, the present authors have measured the pressure distributions in the mixing tube, the results of which we compared with the theories of W. Tollmien and A. M. Kuethe. Further, we compared the results of the present paper with the results hitherto published on the steam ejectors.

I. Introduction

Experiments on the effects of area ratio m, i. e. the ratio of cross-sectional area

* 渡部一郎 Dr. Eng., Professor at Keio University
** 渡辺剛男 Assistant at Keio University
*** 仲田哲郎 Master Course Student at Keio University
**** 中川 洋 Engineer at Nissan Kagaku Co.

of the parallel part of the mixing tube to the nozzle exit area, on performance characteristics of a pneumatic ejector were conducted previously by the present authors.[1] A convergent nozzle was used, and the driving pressure, i. e. the pressure just upstream to the nozzle, was held constant ranging from 50 mmHg to 450 mmHg above atmospheric pressure. The results of the survey were that, the highest vacuum p_2, obtained when the weight flow of the secondary flow $G_2 = 0$, attained to the absolute maximum at $m = 1.72$, and further, the absolute maximum of the ejector efficiency η was obtained when $m = 2.14$.

Another factor, which is conceived to have serious effects upon performance characteristics of the ejector, seems to be the distance from the nozzle exit section to the inlet of the parallel part of the mixing tube. Although various theoretical considerations concerning the pneumatic ejector are available at present [2], the effect of the above-mentioned distance a' seems to be beyond the scope of the theoretical treatment. Thus, the present authors have conducted experimental studies on the effect of the distance a' upon performance characteristics.

The results were that, the maximum vacuum in the secondary flow as well as the maximum ejector efficiency were obtained when the distance $a' = 15$ mm, so far as the present experiments were concerned. As the inner diameter e of the parallel part of the mixing tube amounts to $e = 9.55$mm, the optimum condition may be represented as $a'/e = 1.57$. This optimum value coincides approximately with those obtained experimentally for a pneumatic ejector by L. J. Kastner and J. R. Spooner.[3] Further, the discussions and the comparisons of the results of the present experimental study with those for steam ejectors hitherto published are described in the present paper.

II. The Experimental Apparatus and the Method.

The schema of the experimental set is shown in fig. 1. The compressed air delivered by a Roots blower enters to the distribution tank, and then arriving at the pressure tank via valve V_2, exhausts finally out of the convergent nozzle. The pressure p_1 at the pressure tank or the driving pressure may be held constant by a valve V_1 fitted to the distribution tank as shown. The valve V_2 is left full

1) I. Watanabe, T. Watanabe, S. Iso, T. Kawahito, This Proceedings, vol. 7, no. 26, 1954, pp. 51/60

2) J. H. Keenan, Jour. App. Mech. 1950/9, pp. 299/309; H. G. Elrod, Jour. App. Mech. 1945/9, pp. A-170/174; J. A. Goff, C. H. Coogan, Jour. App. Mech. 1942/12, pp. A-151/154; W. Tollmien, Z. A. M. M. Bd. 6 Heft 6, 1926/12, pp. 468/478; S. I. Pai, Jour. App. Mech. 1955/3, pp. 41/47 and Ueda, Ikeno, Science of Machine vol. 5 no. 7, 1953/7 pp. 425/429

3) L. J. Kastner, J. R. Spooner, Proc. Inst. Mech. Engrs., vol. 162, 1950, pp. 149/159

open. The secondary flow of air is sucked into the mixing chamber via the round

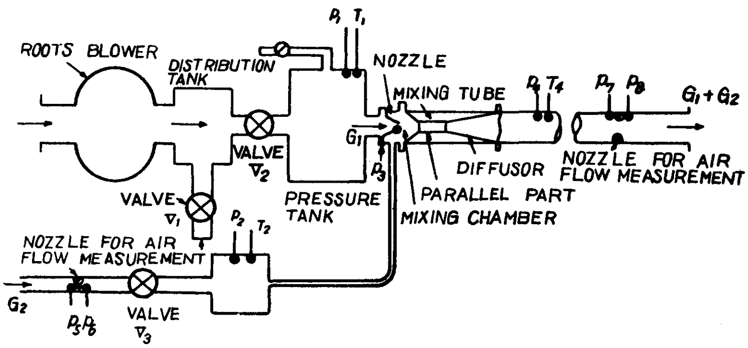

Fig. 1. Schema for Experimental Apparatus

type nozzle and the valve V_3. The weight flow of air for the secondary flow G_2 is measured by this round type nozzle, while the vacuum p_2 at the secondary flow is measured at the tank provided just downstream of the valve V_3. The weight flow G_2 may be altered by means of the valve V_3. The driving stream from the nozzle is mixed with the secondary stream of air, and thence delivered to the surrounding atmosphere after passing through the mixing tube. The weight flow of air $G_1 + G_2$ (G_1 denotes the weight flow of the driving air) is measured by means of the round-type nozzle fitted downstream to the diffuser.

The nozzle used in the present experiment is of convergent type as shown in fig. 2, while the mixing tube is shown in fig. 3. This mixing tube is one of the

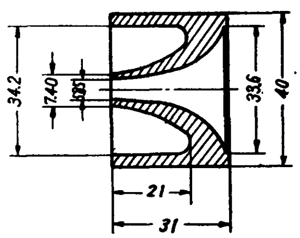

Fig. 2. Nozzle

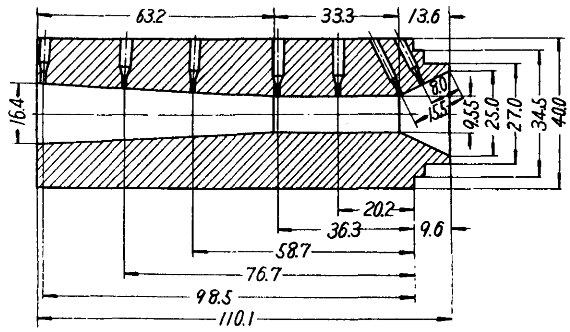

Fig. 3. Mixing Tube and Holes for Pressure Measurement

six mixing tubes employed in the previous experiments, and, as the inner diameter e of the parallel part amounts to $e = 9.55$mm, the area ratio m yields to 2.67. Several holes are provided in the mixing chamber, parallel part and diffuser of the mixing tube, so that the pressure distributions along the tube may be observed. The ring, as shown in fig. 4, are provided between the nozzle and the mixing tube. Thus, the distance a' from the nozzle exit to the entrance of the parallel part of the mixing tube may be varied as $a' = 4$mm, 8.5mm, 15mm and 20mm. The driving pressure p_1, in the present experiments, was kept constant from 150mmHg to 450mmHg above atmospheric pressure, and the experiments were conducted by altering the weight flow of the secondary air.

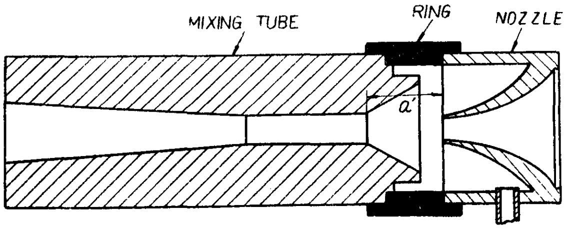

Fig. 4.

III. The Experimental Results and the Considerations.

If we denote the vacuum (absolute pressure) obtained at the secondary flow as p_2, and the atmospheric pressure as p_0, the relations between the pressure ratio p_2/p_0 and the distance a', with weight flow ratios G_2/G_1 as parameters, are represented in fig. 5, in case of the driving pressure (gauge pressure) $p_1 = 150$mmHg, 250 mmHg, 350 mmHg and 450 mmHg respectively. It is observed from the figure, that the highest vacuum is obtainable, in other words, the pressure ratio p_2/p_0 becomes minimum at $a' = 15$ mm, for the predominant ranges of G_2/G_1 and p_1. As the diameter of the nozzle exit section $d_n = 5.85$mm and the diameter of the parallel part $e = 9.55$mm, the above-mentioned optimum condition may be

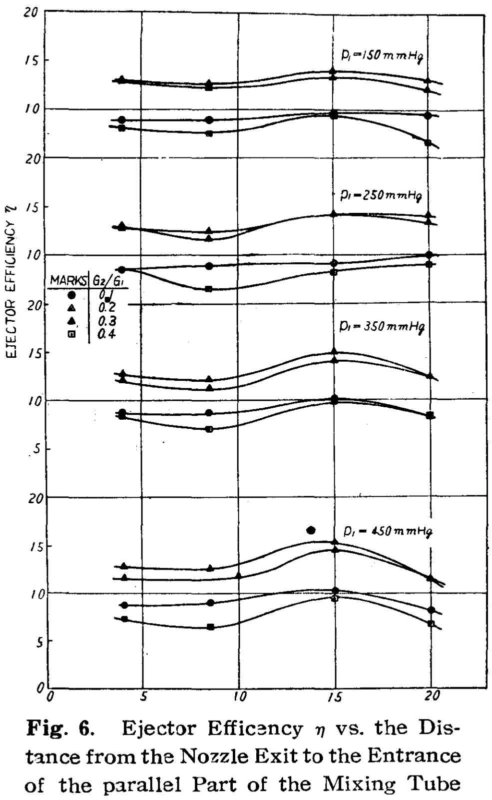

Fig. 6. Ejector Efficiency η vs. the Distance from the Nozzle Exit to the Entrance of the parallel Part of the Mixing Tube a'

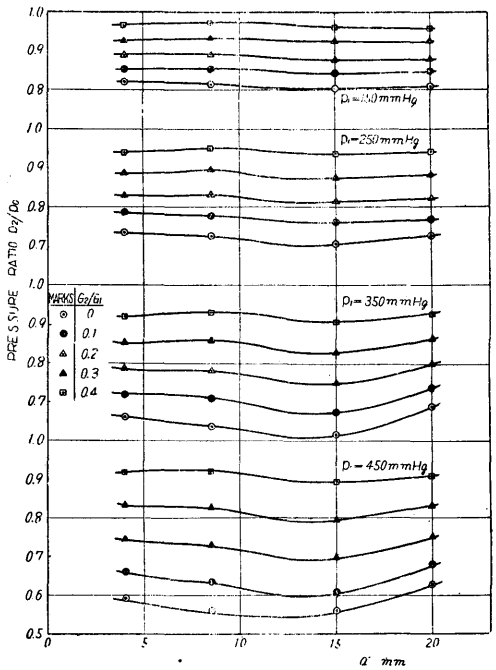

Fig. 5. Pressure Ratio p_2/p_0 vs. the Distance from the Nozzle Exit to the Entrance of the parallel Part of the Mixing Tube a'

represented as $a'/d_n=15/5.85=2.56$ and $a'/e=15/9.55=1.57$. Further, if we evaluate the ejector efficiency η by the expression quoted in the first report, the relations between the ejector efficiency η versus the distance a' with G_2/G_1 as parameters are represented as in fig. 6, in case of $p_1=150$mm, 250mmHg, 350mmHg and 450mmHg respectively. It is observed from the figure, that the optimum condition $a'=15$mm holds also in the present case.

The pressure distributions in the mixing tube were observed in case of $a'=4$mm, 8.5mm, 15mm and 20mm, the results of which are shown in fig. 7 to fig. 10 respectively. While the pressure distributions along the mixing tube when $G_2/G_1=0$, 0.1, 0.2, 0.3 and 0.4 in case $a'=15$mm, 8.5mm and 4mm (fig. 8 ~ fig. 10) are represented in monotonous curves, the curves in fig.7 in case $a'=20$mm are rather stepwise. W. Tollmien had previously conducted a theoretical investigations[4] of the case of issuing homogeneous air jet into the still air of the same density by means of the theory of turbulent mixing. According to his theory, the boundaries, which bisect the issuing jet from the surrounding air, expand linearly with the distance along the issuing jet (fig. 11). It is conceivable, therefore, in the present case, that the driving fluid may partly be reflected at the entry of the parallel part, by the above-mentioned expanding boundaries. The inhibited flow at the entry of the parallel part, thus, produces a reversed flow, and so, it is conceivable that the stepwisely increasing pressure rises are due to the worse

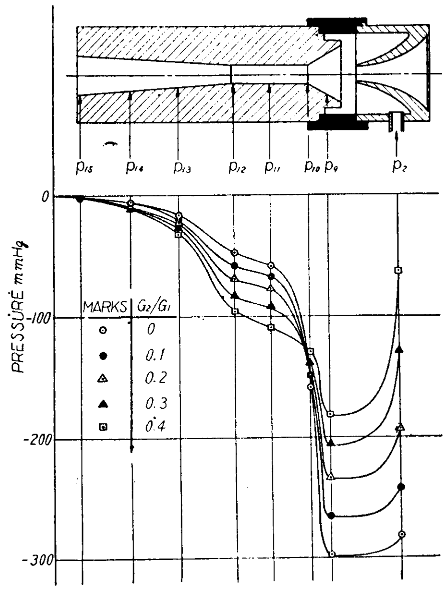

Fig. 7. Pressure Distributions along the Mixing Tube
($a'=20$mm, $p_1=450$mmHg)

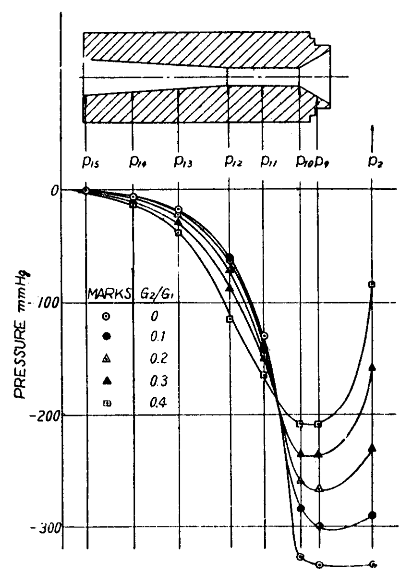

Fig. 8. Pressure Distributions along the Mixing Tube
($a'=15$mm, $p_1=450$mmHg)

4) W. Tollmien, Z. A. M. M. Bd. 6, Heft 6, 1926/12, pp. 468/478

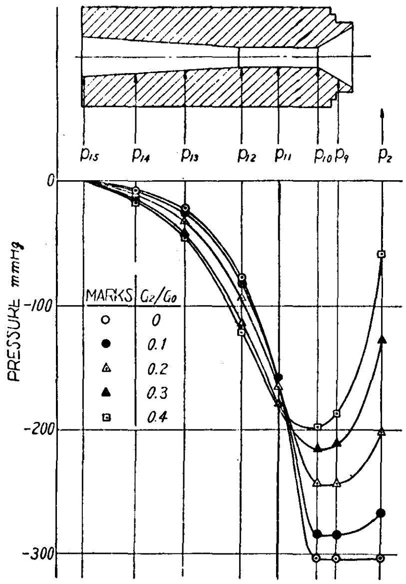

Fig. 9. Pressure Distributions along the Mixing Tube
(a'=8.5mm, p_1=450mmHg)

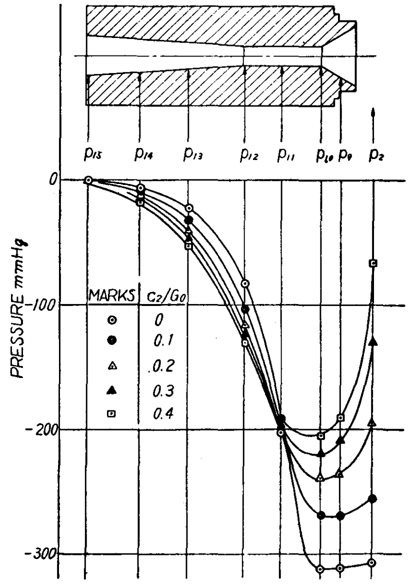

Fig. 10. Pressure Distributions along the Mixing Tube
(a'=4mm, p_1=450mmHg)

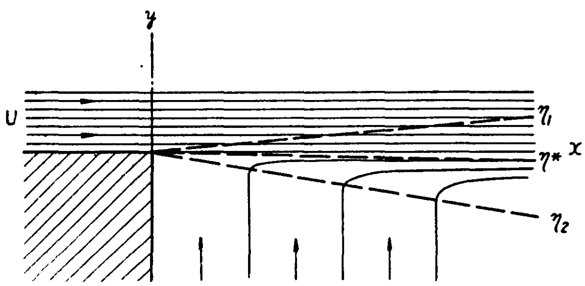

Fig. 11. Stream Lines obtained by W. Tollmien

flow conditions in the parallel part of the mixing tube. The occurrence of the reverse flow at the entry is clearly shown in fig.7 by the fact that the pressure p_{10} is higher than the pressure p_9, while in case of no reverse flow, the pressures p_9 and p_{10} become nearly equal (figs. 8 ~ 10). W. Tollmien performed a numerical calculus for the jet as shown in fig. 11, to find $\eta^*/a = -0.1855$ and $\eta_2/a = -2.0353$. In these expressions, η^* denotes the parameter that represents the boundaries to which the driving fluid and the secondary fluid approach asymptotically, and η_2 denotes the parameter that represents the boundaries for $u=0$, u being the x-component of the velocity. Further, $\eta = y/x$ and $a = (2c^2)^{\frac{1}{3}}$, and c is a constant which may be determined experimentally. W. Tollmien had, further, found that the theoretical velocily distributions coincided near exactly with experimental results, if $a=0.0845$, which had been determined by comparison with the experimental results in the large wind tunnel at the Göttingen Aeronautical Institute, would be introduced into the above expressions. Putting $x = a' = 20$mm, evaluation of the present case with the above- mentioned value $a=0.0845$ yields to $y = -0.01568 \times 20 = -0.3135$mm, by the fact that $\eta^* = -0.1855 \times 0.0845 = -0.01568$.

In case of η_2, using the value $\eta_2=-2.0353\times 0.0845=-0.172$, we obtain $y=-0.172\times 20=-3.44$mm. As the nozzle exit diameter d_n is equal to 5.85mm and the inner diameter of the parallel part e is equal to 9.55mm, the radial difference between d_n and e amounts to -1.85mm. Therefore, although the line η^* does not impinge at the entry of the parallel part, the line η_2, on the other hand, covers completely the inlet, and hence it is conceivable that the secondary air may be restricted in some degrees. As mentioned above, the theory by W. Tollmien assumes that the surrounding air is still initially. Concerning the case of the secondary stream flows parallel with the driving stream, A. M. kuethe[5] brought it to light. He assumed that the mixing length l was proportional to the breadth of the mixing region or the distance x, and in addition to this, he assumed that the driving stream and the secondary stream were of equal densities. Thus, putting $l=cx$, in which c being the constant which may be determined by experiments, he solved a numerical example in case that $c^2=0.00496$.[6] Comparison of this example by A. M. Kuethe with the line η_2 or the boundaries on which $u=0$ by W. Tollmien, explains to us that the boundaries for $u=0$ expand wider in the former case. Thus, the present results shown in fig. 7, may be explained qualitatively by the above considerations. It is noticed, however, that the present problem differs from the above-mentioned theories in the point of the driving fluid as well as the secondary fluid are of different densities.

IV Comparisons of the present Results with those in various Literatures

Available data of the various literatures concerning the effect of the distance a' are confined principally to the steam ejectors, *i. e.* the ejectors that employ steam for the driving fluid, air being employed for the secondary stream. Few data on the pneumatic ejectors are available.

As to the steam ejctors, K. Hayami performed series of experiments on the steam ejectors having area ratios 72.9 and 23.8 with steam pressures ranging from 14kg/cm^2 to 17kg/cm^2. He altered the distance x from the nozzle exit section to the entrance of the mixing tube as -20mm, 0mm and $+40$mm for area ratio 72.9, and -10mm and $+20$mm for area ratio 23.8, and found that, although the appropriate increment in x yielded to the increase of the highest suction vacuum and the lowest exit vacuum, further increment of x made the function of the steam ejector unstable. These tendency resembles to the results of the present survey.

F. R. B. Watson[7] also conducted experiments on the steam ejectors by changing the distance a' from the nozzle exit section to the entrance of the parallel part of the mixing tube as well as the distance L from the nozzle exit section to

5) A. M. Kuethe, J.App. Mech. 1935/9, vol. 2, no 3, pp. A87-95

6) Fig. 11 in reference 5).

7) F. R. B. Watson, Proc. Inst. Mech. Engrs., vol. 124, 1933/2, pp. 231/261

the outlet of the parallel part of the mixing tube. He found that, although the distance a' affected primarily on the vacuum generated, the adjustment of L under the correct value of a' brought a slight improvement in vacuum. The optimum values of a' were found to lie in the range $a'=68.6$mm$\sim$38.1mm for steam pressures (guage) ranging from 9.84kg/cm^2 to 5.62kg/cm^2. For instances, the optimum value of a' was 38.1mm when steam pressure was 5.62kg/cm^2. As the nozzle exit diameter d_n and the diameter of the parallel part e were of the values $d_n=22.225$mm and $e=19.05$mm respectively, it follows that $a'/d_n=1.71$ and $a'/e=2.0$ respectively. On the other hand, $a'/d_n=2.56$ and $a'/e=1.57$ in the present case. It became clear that a' decreases as the driving pressure becomes smaller,[8] and so, it is observed that the former value $a'/e=2.0$ has a tendency to approach to the value of the present study. F. R. B. Watson had, further, taken photographs of the jet issuing from the nozzle, and as the expansion ratio, in his case, was under critical pressure, the photographs showed wave-formed flow because of the lateral expansion followed by the lateral contraction of the stream. He stated that the optimum length a' may be represented by the multiples of the wave-length thus obtained. Thus, for example, he showed that a' equalled to twice the wave length when the driving pressure amounted to 9.84kg/cm^2 gauge. In the present experiment, however, the working regions of the pneumatic ejector belong to the expansion ratio greater than the critical value,[9] and so the flow from the convergent nozzle is of smooth flow accompanied with no lateral expansions and contractions. Hence, in the present case, the expression just mentioned above has no significant meanings, and it is rather practical to obey to the considerations described at the latter half of article III.

R. Royds and E. Johnson[10] had also performed an experimental study on the steam ejectors. Their conclusions were that, although the distance a' affected largely on the performance characteristics as well as the efficiencies of the ejector, the distance a' appeared to be independent of the nozzle dimensions, weight flow ratio and the shape or dimensions of the mixing tube and parallel part.

L. J. Kastner and J. R. Spooner[11] conducted experimental surveys on two pneumatic ejectors having smaller area ratios and larger area ratios in case of driving pressures less than 2.81kg/cm^2 abs., the area ratios and the pressure ratios ranging from 1.44 to 1110 and from 3 to about 1.001 respectively. Their conclusions were as follows. As for the pneumatic ejector with area ratio 2.25, the optimum value of a'/e was about 1.5 for pressure ratios $1.2\sim2.0$. It was found, however, that a'/e became larger than 1.5 when the ratio L/e became too small, where L

8) This tendency is stated in the closure of F. R. B. Watson's paper 7), and is remarkable in fig. 3 and 4 on pp. 241 and 243 in the same literature.
9) loc. cit. 1).
10) R. Royds, E. Johnson, Proc. Inst. Mech. Engrs., vol. 145, pp. 193/209.
11) loc. cit. 3).

and e denote the length and the diameter of the parallel part respectively. For area ratio 683, the optimum value of a'/e was found to be $0\sim1.0$ so long as the ratio L/e had a correct value. When L/e were too small, the optimum ratio a'/e showed an increment. In the present study, the result is $a'/e=1.57$ for area ratio 2.67 to find the coincidence with the above-mentioned results by L. J. Kastner and J. R. Spooner. Further, L. J. Kastner and J. R. Spooner showed a relation between the area-ratios and a'/e which renders the pressure ratio maximum.[12] This relation also shows fair coincidence with the present results.

V. Conclusions.

The following conclusions are derived from the present experimental study.

(1) The optimum value a'/e both for the pressure ratio and the ejector efficiency was found $a'/e=1.57$ for the driving pressure (guage pressure) $p_1=150\text{mmHg}\sim450\text{mmHg}$ and area ratio 2.67. This optimum coincides near exactly with that obtained previously by L. J. Kastner and J. R. Spooner.

(2) In the present experiments, the area ratio is confined to a fixed value ($m=2.67$). The optimum value, however, coincides near exactly with that in the diagram by L. J. Kastner and J. R. Spooner,[12] which shows relations between a'/e and the area ratio. Hence, the diagram in the literature may be available in the present case. Thus, the optimum value for a'/e increases closely in linear relation with the area ratio m, provided the discontinuity at $m=10$ be omitted.

(3) If the distance a' increases beyond the optimum value, the pressure distributions along the parallel part of the mixing tube become somewhat irregular. This phenomenon may be well explained qualitatively by means of the theories developed by W. Tollmien and A. M. Kuethe.

VI Appendix —— The Infiuence of the Shape of the Entrance of the Mixing Chamber.

The present authors have performed the experimental survey using the conical entrance mixing chamber, as shown in fig. 3. It is conceivable, however, that the sharp corner thus produced at the transfer point from the entrance to the parallel part would cause enormous losses from the hydrodynamical point of view. L. J. Kastner and J. R. Spooner conducted their surveys using two inlet types, i. e. the conical entrance and the nozzle type or round type entrance. The results were that the ejector performance showed no significant differences, and they recommended the former on account of easiness for construction. The present authors, also, made a nozzle type inlet mixing chamder, as shown in fig. 12, and compared this with the conical one. The comparison is not strictly exact, because the inner diameter of the parallel part shown in fig. 12 amounts to 10mm, while in the

12) Fig. 10 on p. 155 on the literature cited in 3).

conical inlet type the diameter is 9.55mm. The other dimensions, such as the diameter of the inlet of the mixing chamber as well as the length of the parallel part, however, are equal, and further, the distance $a'=8.5$mm is employed for both types. The present comparison, therefore, has a value from the practical point of view. The results of comparison are shown in fig. 13. It is observed that the ejector with the nozzle type inlet shows somewhat superior characteristics for the almost entire ranges of G_2/G_1.

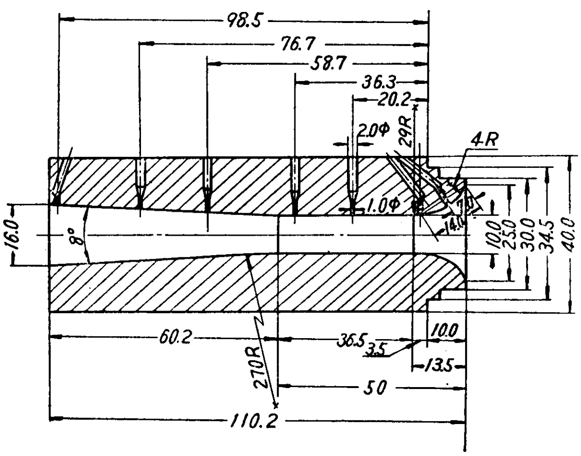

Fig. 12. Mixing Chamber having Nozzle Type Entrance

This fact will be due to the fact, that the losses are reduced by the continuity of the profile at the entry to the parallel part in the nozzle type inlet. Hence, the present authors recommend a nozzle type inlet rather than the conical one.

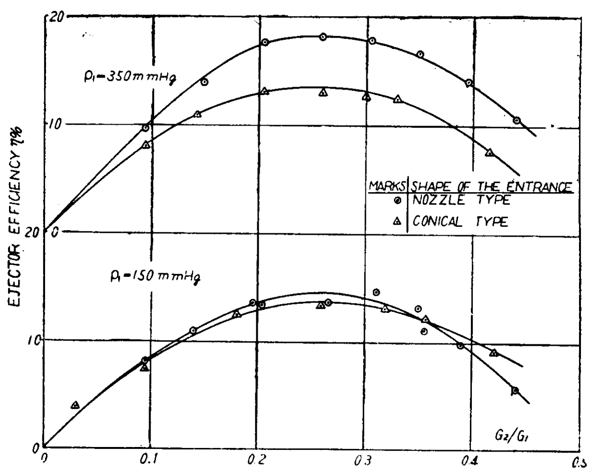

Fig. 13. Influence of the Shape of the Entrance to the Mixing Tube upon Ejector Efficiencies