Title	Experimental study on pneumafil (I)
Sub Title	
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Publisher	慶應義塾大学藤原記念工学部
Publication year	1951
Jtitle	Proceedings of the Fujihara Memorial Faculty of Engineering Keio University Vol.4, No.14 (1951.) ,p.61(1)- 69(9)
JaLC DOI	
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Notes	
Genre	Departmental Bulletin Paper
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001004-00040014-0001

Experimental Study on Pneumafil (I)

(Received Sept. 25, 1952)

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Abstract

Two types of pneumafil are considered practical in textile industries. The first type is a pipe of variable cross-sectional area with holes of constant area fitted to the suction side of a blower to maintain the weight flow of air through each hole constant, and the second type is a pipe of constant cross-sectional area with holes of variable area to maintain the weight flow of air through each hole constant.

Experiments were conducted concerning to the above-mentioned two types of pneumafil provided with three holes. Besides, the authors have made theoretical analysis to obtain the simple formulae which coincide fairly well with experimental results.

I. Introduction

Pneumafil used in textile industries is a device or pipe having several small holes fitted at the suction side of a blower and the object of the device is to keep the weight flow of air sucked in through each hole constant. Two types of pneumafil are considered practical. In the first type, the pipe fitted to the suction side of the blower is of variable cross-sectional area, while the holes remain of same diameter. In the second type, the pipe is of constant cross-sectional area with holes of variable diameter.

Experiments were performed for the two types of pneumafil, the numbers of the holes remaining three in each case. Further, theoretical formulae were derived approximately as to obtain the simple expressions for each type of pneumafil. The comparison of the experiments and theory showed fair coincidence as far as the number of holes remained three.

II. Theoretial Derivation of the Expressions for Pneumafil

(1) Pneumafil fitted with pipe of variable cross-sectional area with holes of constant diameter

Fig. 1 represents the pneumafil having pipe of variable cross-sectional area with

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holes of constant diameter. Let A be the constant area of each hole, and further F_1, F_2, ⋯⋯, F_n represent the cross-sectional areas of the pipe at the center lines of the successive holes, the subscripts denoting the numbers of the holes derived from the farthest end of the pipe relative to the blower. Further, let p_1, p_2, p_3, ⋯⋯, p_n; T_1, T_2, T_3, ⋯⋯, T_n and w_1, w_2, w, ⋯⋯, w_n be the static pressures, absolute temperatures and the velocities of air at the above-mentioned sections respectively. The weight flow of air sucked in through each hole at these sections is shown as G_1, G_2, G_3, ⋯⋯, G_n respectively. In addition, we represent pressure and absolute temperature of the surrounding atmosphere as p_0 and T_0. In the case of pneumafil, p_1, p_2, ⋯⋯, p_n are usually smaller than p_0 by the amount of 100～300mm Aq, and hence the assumption $T_1=T_2=T_3=\cdots\cdots=T_n \doteqdot T_0$ is considered permissible. To obtain the relations satisfying the condition $G_1=G_2=G_3=\cdots\cdots=G_n$ in this case, we may proceed as follows.

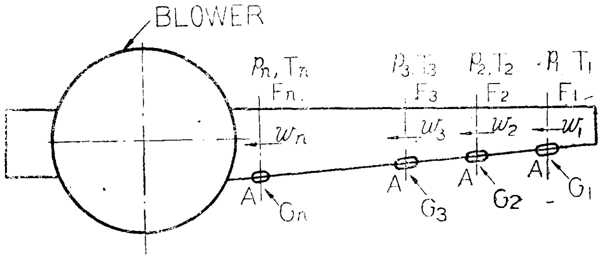

Fig. 1. Pneumafil fitted with pipe of variable cross-sectional area with holes of constant diameter

The weight flow equation through the first hole may be expressed as $G_1 = \alpha A\sqrt{2g\gamma_0(p_0-p_1)}$,where α denotes the discharge coefficient of the hole. In the above expression, the correction factor for pressure ε is considered to be unity on account of small pressure differences. Putting $\gamma_0=p_0/RT_0$ into the above equation, we have

$$G_1 = \alpha A\sqrt{2g\frac{p_0}{RT_0}(p_0-p_1)} = \alpha A\sqrt{\frac{2g}{RT_0}p_0(p_0-p_1)} \qquad (1)$$

Substituting $w_1=G_1/\gamma_1F_1$ and $\gamma_1=p_1/RT_0$ into the above equation, we obtain

$$\frac{w_1^2}{2g}\gamma_1 = \frac{\alpha^2A^2}{F_1^2p_1}p_0(p_0-p_1) \qquad (2)$$

On the other hand, we have the relation $p_0=p_1+(w_1^2/2g)\gamma_1$. Putting this relation into eq. (2), we get

$$p_1 = \frac{\alpha^2A^2}{F_1^2}p_0 \qquad (3)$$

Substituting eq. (3) into eq. (1), we find

$$G_1 = \alpha Ap_0\sqrt{\frac{2g}{RT_0}\left(1-\frac{\alpha^2A^2}{F_1^2}\right)} \qquad (1.1)$$

As for the second hole, the weight flow equation becomes to

$$G_2 = \alpha A\sqrt{\frac{2g}{RT_0}p_0(p_0-p_2)} \qquad (4)$$

Hence, the expression

$$p_1 = p_2 = \frac{\alpha^2 A^2}{F_1^2} p_0 \tag{3.1}$$

must hold if the condition $G_1 = G_2$ is required. Further, we are able to write down as follows by means of the relation $G_1 = G_2$ and eq. (1.1).

$$w_2 = \frac{G_1 + G_2}{\gamma_2 F_2} = \frac{RT_0}{p_2 F_2} 2\alpha A p_0 \sqrt{\frac{2g}{RT_0}\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)}$$

Hence, we have

$$\frac{w_2^2}{2g}\gamma_2 = 4\left(\frac{F_1}{F_2}\right)^2\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)p_0 \tag{5}$$

On the other hand, we know the relation $(w_2^2/2g)\gamma_2 = p_0 - p_2 = p_0 - p_1$, and so we get

$$p_0\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right) = 4\left(\frac{F_1}{F_2}\right)^2\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)p_0$$

by eqs. (3.1) and (5). Therefore, we find finally the following expression.

$$\frac{F_1}{F_2} = \frac{1}{2} \tag{6}$$

As to the third hole, we may proceed in the same manner. Thus, we have

$$G_3 = \alpha A \sqrt{\frac{2g}{RT_0} p_0 (p_0 - p_3)} \tag{7}$$

Hence, to satisfy the condition $G_1 = G_2 = G_3$, we must have

$$p_1 = p_2 = p_3 = \frac{\alpha^2 A^2}{F_1^2} p_0 \tag{3.2}$$

According to the relation $\gamma_3 = p_3/RT_0 = (p_0/RT_0)(\alpha^2 A^2/F_1^2)$, we find

$$w_3 = \frac{G_1 + G_2 + G_3}{\gamma_3 F_3} = 3\alpha A p_0 \sqrt{\frac{2g}{RT_0}\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)} \frac{1}{F_3} \frac{RT_0}{p_0} \frac{F_1^2}{\alpha^2 A^2}$$

Calculating $(w_3^2/2g)\gamma_3$ from the above expression, we get

$$\frac{w_3^2}{2g}\gamma_3 = 9\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)\left(\frac{F_1}{F_3}\right)^2 p_0 = p_0 - p_3 = p_0\left(1 - \frac{\alpha^2 A^2}{F_1^2}\right)$$

and so we obtain finally

$$\frac{F_1}{F_3} = \frac{1}{3} \tag{6.1}$$

On repeating the same process, we find the following relation for the n th hole.

$$\frac{F_1}{F_2} = \frac{1}{n} \tag{6.2}$$

(2) Pneumafil fitted with pipe of contant cross-sectional area with holes of variable diameter.

This type of pneumafil has already been treated theoretically by Prof. Y. Niitsu and M. Kurahashi[1], but in this paper we may treat the problem so as to obtain the results in simpler expressions.

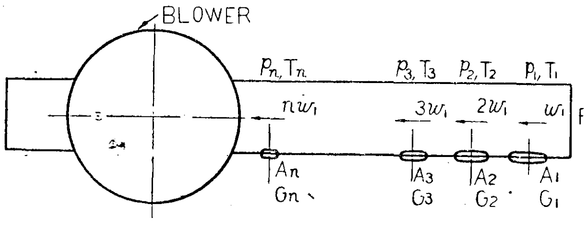

Fig. 2. Pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameter

The pneumafil in this case may be expressed as in Fig. 2. As shown in the figure, the cross-sectional area of the pipe F remains constant, while the area of each hole varies as A_1, $A_2, A_3, \cdots\cdots, A_n$. If we assume $T_1 = T_2 = \cdots\cdots = T_n \doteqdot T_0$ under the condition $G_1 = G_2 = \cdots\cdots = G_n$ as in the previous case, no great differences are considered as long as the magnitudes of the pressures $p_1, p_2, \cdots\cdots, p_n$ are concerned. Thus we are able to assume approximately that the velocities of the air at the cross-section corresponding to the center line of each hole are $w_1, 2w_1, 3w_1 \cdots\cdots nw_1$ respectively as shown in the figure.

The weight flow of air through the first hole, i. e. the farthest hole from the blower is, as eq.(1),

$$G_1 = \alpha A_1 \sqrt{\frac{2g}{RT_0} p_0 (p_0 - p_1)} \tag{8}$$

Further, remembering the relation

$$w_1 = G_1/\gamma_1 F = (RT_0/Fp_1)\alpha A_1 \sqrt{(2g/RT_0)p_0(p_0-p_1)},$$

we have

$$\frac{w_1^2}{2g}\gamma_1 = \frac{\alpha^2 A_1^2}{F^2}\frac{p_0}{p_1}(p_0 - p_1)$$

Hence we find

$$p_1 = p_0 \frac{\alpha^2 A_1^2}{F^2} \tag{9}$$

which is identical to eq.(3) in the previous case. Further, we obtain the following expression.

$$p_0 = p_2 + \frac{4w_1^2}{2g}\gamma_2 = p_2 + 4\frac{F^2}{\alpha^2 A_1^2}p_2 - 4p_2$$

In this case, it is expected that the weight flow through the second hole A_2 is smaller than that through the first hole. Because of the constant cross-sectional area of the pipe, the air flow through the second hole may be restricted on account of the air stream in the pipe already sucked in through the first hole. Thus it is natural to assume that there exists some resistance to the air stream through the second hole to adjoin with the air stream already flowing in the pipe. Taking into account of this resistance, we put

$$G_1 = \alpha\lambda A_2 \sqrt{2g\gamma_0(p_0 - p_2)} = \alpha A_1 p_0 \sqrt{\frac{2g}{RT_0}\left(1 - \frac{\alpha^2 A_1^2}{F^2}\right)} \tag{11}$$

1) Y. Niitsu, M. Kurahashi, Jour. Textile Machinery Soc., Vol.5, No.1, 1952/1

where λ denotes a coefficient which represents the resistance in question. Hence it is clear that $\lambda>1$. Substituting eq.(11) into eq.(10), we obtain easily the following expression.

$$\lambda^2 A_2^2\left(1-\frac{1}{4\frac{F^2}{\alpha^2 A_1^2}-3}\right)=A_1^2\left(1-\frac{\alpha^2 A_1^2}{F^2}\right) \tag{12}$$

Similarly, as for the third hole, we have

$$p_0=p_3+9\frac{w_1^2}{2g}\gamma_3=p_3\left(9\frac{F^2}{\alpha^2 A_1^2}p_3-8\right)$$

It is considered that the air stream which enters into the pipe through the third hole A_3 is encountered the resistance greater than for the second hole A_2. Thus, if we assume the resistance in this case correspond to λ^2, we find as shown later that the theory coincide fairly well with the experimental results. Namely, putting

$$G_1=\alpha\lambda^2 A_3\sqrt{2g\gamma_0(p_0-p_3)}=\alpha A_1 p_0\sqrt{\frac{2g}{RT_0}\left(1-\frac{\alpha^2 A_1^2}{F^2}\right)}$$

we obtain the formula as follows.

$$(\lambda^2)^2 A_3^2\left(1-\frac{1}{9\frac{F^2}{\alpha^2 A_1^2}-8}\right)=A_1^2\left(1-\frac{\alpha^2 A_1^2}{F^2}\right) \tag{12.1}$$

Generally, for the n^{th} hole, we have

$$(\lambda^2)^{n-1} A_n^2\left(1-\frac{1}{n^2\frac{F^2}{\alpha^2 A_1^2}-(n^2-1)}\right)=A_1^2\left(1-\frac{\alpha^2 A_1^2}{F^2}\right) \tag{12.2}$$

In our case, the experiments are carried on when the number of holes is three, and so it is necessary to examine the degree of coincidence of eq.(12.2) with the experimental results when n exceeds three. However, we are convinced that the formula (12.2) is applicable as long as n does not exceed five. The value of λ may vary as F/A_1 varies. In our case, the value of $\lambda=1.040$, $\lambda^2=1.081$ is found to bring the eq. (12.2) in close agreement with experimental results.

In the former case, i.e. when the pneumafil is fitted with pipe of variable cross-sectional area with holes of constant diameter, we have not taken into account the coefficient λ. The factor λ is considered to be unnecessary in the former case, where the variation of the cross-sectional area seems to allow the air to flow through the successive holes with as much easiness as with the first hole.

III. Experiments of Pneumafil

(1) Experimental set and method

The skelton drawing of the experimental set is shown in Fig. 3. The pipe of the pneumafil is fitted on the suction side of a blower driven by an electric motor

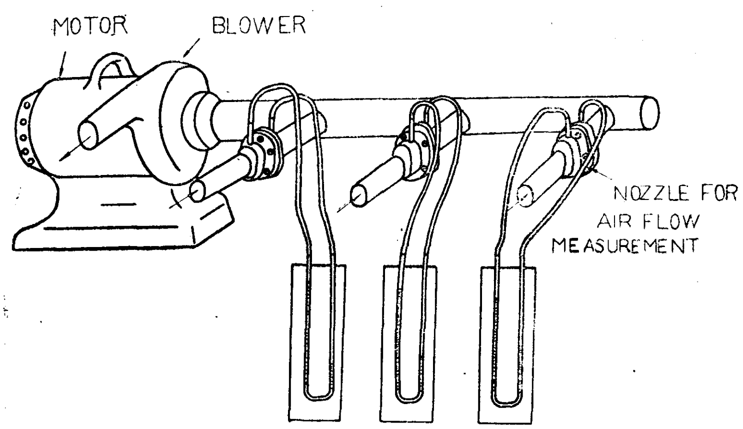

Fig. 3. Experimental set of pneumafil

of 220/200 W. The free end of the pipe is enclosed, and three small pipes fitted with round type nozzles are attached to the main pipe as shown. Thus the holes are represented by these round nozzles in our case. As the rotational speed of the electric motor is variable by an electric resistance, it is possible to alter the overall weight flow through the blower. As is shown in the figure, the weight flow is measured by round nozzles using water manometers.

The pipe of variable cross-sectional area with holes of constant diameter used in our experiments is shown[2] in Fig. 4. The values of F_1, F_2 and F_3 in this case are enumerated by eqs. (6) and (6.1), and further, as the inner diameters of the round nozzles are all d=8mm and the inner diameters of the small pipes fitted with the round nozzles are selected as 16.7mm, it follows that the value of area ratio m=0.2295 and hence α=0.847 for each nozzle. Experiments concerning to the pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameters were conducted by a pipe shown in Fig. 5. In this case, the diameters of the round nozzles used were d=8.0mm, 8.5mm, 9.0mm and 9.5mm, and the experiments were carried on by the following configuration of nozzles.

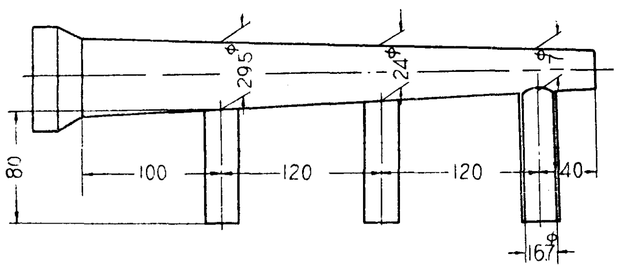

Fig. 4. Pipe of variable cross-sectional area with holes of constant diameter

(1) $d_1=d_2=d_3$=8.0mm,

(2) d_1=8.5mm, d_2=9.0mm, d_3=9.5mm,

(3) d_1=9.5mm, d_2=9.0mm, d_3=8.5mm,

2) Round nozzles are to be provided for Fig.4 as shown as for Fig.5, but in this case the nozzles are omitted in the figure.

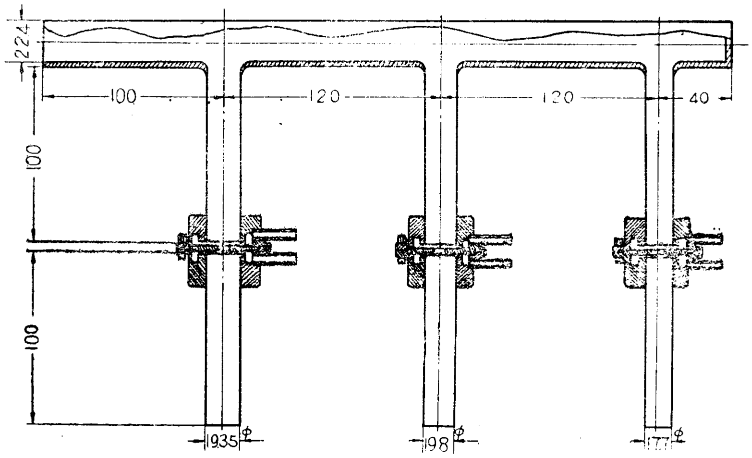

Fig. 5. Pipe of constant cross-sectional area with holes of variable diameter

From the results of these experiments, the diameter ratios relative to the diameter of the second hole d_2 were determined with respect to the condition $G_1=G_2=G_3$. In three cases cited above, the inner diameters of the small pipes to which the round nozzles are attached are determined so as to maintain the area ratios of the round nozzle m=constant, thus α=constant.

(2) Comparison of the formulae with experimental results.

The experimental results for the case of pneumafil fitted with pipe of variable cross-sectional area with holes of constant diameter are shown in Fig. 6. In this case, the cross-sectional area at each section is calculated by eqs. (6) and (6.1), and the results were that although the weight flow of air G_2 and G_3 are nearly equal, G_1 is somewhat lower than G_2 or G_3. The differences are, however, relatively small. For the case of $G_t=G_1+G_2+G_3=12.08\times 10^{-3}$kg/s, it is found from the figure that $G_2=G_3=4\times 10^{-3}$kg/s, while $G_1=3.8\times 10^{-3}$ kg/s, to find the difference of 5 per cent.

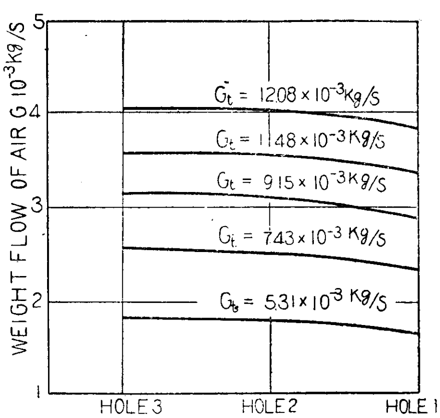

Fig. 6. Results for pneumafil fitted with pipe of variable cross-sectional area with holes of constant diameter.

As to the case $G_t=5.31\times 10^{-3}$kg/s, the deviation is about 7.7%. Hence it seems practically permissible to apply eqs.(6) and (6.1) as long as the number of holes does not exceed three.

The exprimental results for pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameters are shown in Fig. 7, Fig. 8 and Fig. 9.

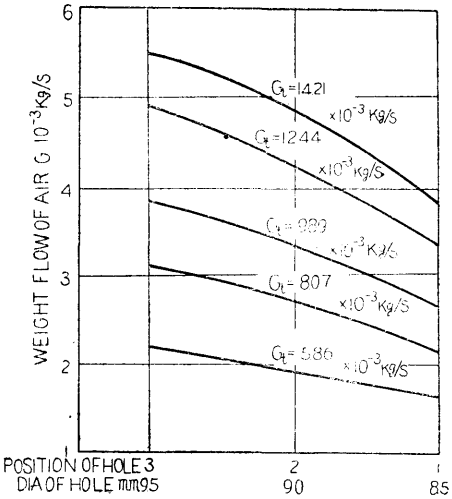

Fig. 7. Results for pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameter.

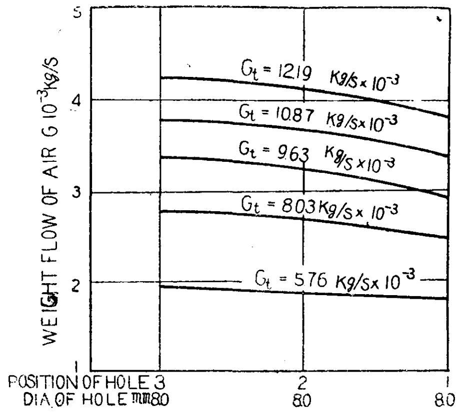

Fig. 8. Results for pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameter.

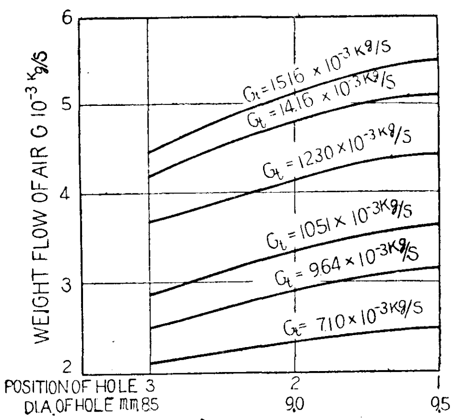

Fig. 9. Results for pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameter.

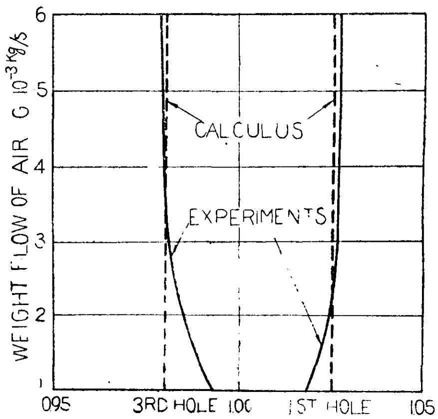

Fig. 10. Diameters of the 1st and 3rd hole when diameter of the 2nd hole is selected as unity.

Replotting these results, it is able to find the diameter of the first hole d_1 and the diameter of the third hole d_3 when the diameter of the second hole $d_2=1$ as the condition $G_1=G_2=G_3$ is required. This relation is shown in full lines in Fig. 10. On the other hand, the calculated results according to the eqs.(12) and (12.1) by putting $\lambda=1.040$ are shown in dotted lines. These evaluated values are $d_1=1.025$ and $d_3=0.98$ which are in close agreement with experimental results. Thus eqs.(12) and (12.1) give fairly accurate values so far as the number of holes remains three. Although the application of the eqs.(12) and (12.2) to the case of n holes should be examined experimentally, the equations are considered to be applicable with permissible errors for the case of $n=5$.

IV. Conclusions

The above-mentioned analysis and experimental results lead us to the following conclusions.

(1) When pneumafil fitted with pipe of variable cross-sectional area with holes of constant diameter is under consideration, eqs. (6), (6.1) and (6.2) are applicable to determine the cross-sectional area of the pipe so long as the number of holes remains three.

(2) When pneumafil fitted with pipe of constant cross-sectional area with holes of variable diameter is intended, eqs. (12), (12.1) and (12.2) are applicable for the determination of the diameter of each hole so long as the number of holes remains three. It seems permissible to apply these equations as long as the number of holes n does not exceed five.

The authors are intended to perform experiments for the case of pneumafil with larger number of holes.