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The Statical Characteristics of the Wall Reattachment Fluidic Devices

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This study is concerned with a developed method for obtaining the quantitative relations between the input or output characteristics and the geometric parameters of the wall reattachment fiuidic devices.

In this report, it is shown analytically and experimentally that the characteristics can be represented by the functions, dependent on the geometric parameters only, with non-dimensional quantities, if the Reynolds number at the main jet nozzle is sufficiently large.

Accordingly, the quantitative relations of the geometric parameters may be analyzed more easily.

§ 1. Introduction

Now, it is often said that the development of the pure fluidic devices reaches the stage of practical use. However, this means not always that every foundamental problems about them has been solved.

To cite instances, the statical characteristics of the wall reattachment fluidic devices can not yet be predicted by an analytical theory because of excessive simplification of the mathematical model, and every theory gives only some design guides. They can not also been decided quantitatively by past obtained experimental data because of indefiniteness of the relations between the geometrical variables and the characteristics, and the data have only a qualitative meaning for a modified element. Furthermore, they can give no informations about the effects on the charateristics produced by a change of the operating conditions (for instance, loaded or unloaded).

Therefore, at present we must rely in many cases on the trial and error method to design an element that satisfies a required specification. The greatest reason of the difficult state is that the mechanism of the fluid flow within such an element is affected by a large number of possible geometrical parameters. There are some studies1) which try to solve this problem, but they are not satisfactory. And the experimental studies are also troublesome for the lower impedances of the measuring apparatus for these devices.

The purpose of the present paper is to predict more definitely the characteristics of the element from its geometry. In doing this two methods may be available. One of them is a method investigating in detail analytically and experimentally the phenomena in the elementary components that construct the practical fluidic devices. This method was used in many past studies2), but it could not treat the practical devices.

The other is a method arrainging in proper shape the experimental results obtained with the practical devices by such proper means as the dimensional analysis. It is well known that the method can give the almost same results as that are obtained by solving directly the precise equations representing the phenomena. This study is based on the latter method.

§ 2. Nomenclature

a : sectional area of the nozzle or the duct, cm^2
d : width or equivalent diameter of the nozzle or the duct, cm
K : non-dimensional constant
k_f : coefficient of the entrainment
l : length of the nozzle or the duct, cm
O_f: effset, cm
P : total pressure, kg/cm^2-gauge
p : static pressure, kg/cm^2-gauge
Q : volume flow rate, cm^3/sec

t : depth of the element, *cm*
α : coefficient of discharge
ρ : density of the fluid, $kg\cdot sec^2/cm^4$
μ : viscosity of the fluid, $kg\cdot sec/cm^2$
subscript
c : control nozzle
o : output duct
s : supply or main jet

§ 3. Flows within the wall-reattachment devices

According to the results obtained by the flow visualization, the flows within the wall-reattachment fluidic devices without control flows can be classified into three patterns as follows: 3), 4)

(a) The core of the main jet bumps against the splitter.
(b) The main jet overflows from the output duct of the unattached side because of the larger splitter distance.
(c) Excepting (a) and (b), the main jet does not overflow from the output duct of the unattached side and the flow pattern does not be affected by the change of the splitter position.

This study treats the case (c) only.

§ 4. Statical input and output characteristics

4. 1 Statical input characteristics

If the partial geometries of an element are fixed, it can be assumed that the statical input characteristics are described by

$$\phi_c(Q_c, Q_s, P_c, P_s, d_c, d_s, l_c, \rho_c, \rho_s, \mu)=0. \tag{1}$$

Of cause, the forms of formulas ϕ_c's may be different on the attached and the non-attached side. And the quantities ρ_s, Q_s, and ρ_c, Q_c must be evaluated respectively at the pressure in the main jet nozzle and the control noszle.

The dimensional analysis gives the non-dimensional formula from Eq. (1)

$$\varphi_c\left(\frac{Q_c}{Q_s}, \frac{P_c}{P_s}, \frac{\rho_c Q_c}{\mu d_c}, \frac{\rho_s Q_s}{\mu d_s}, \frac{l_c}{d_c}, \frac{d_c}{d_s}, \frac{\rho_c}{\rho_s}\right) = 0. \tag{2}$$

In normal states the Reynolds number at the main jet $\rho_s Q_s/\mu d_s$ is sufficiently large. Therefore, the flow may be expected to become insensitive to variations of fluid viscosity, so that this term can be omitted from the equation. Then the Eq. (2) becomes

$$\varphi_c\left(\frac{Q_c}{Q_s}, \frac{P_c}{P_s}, \frac{\rho_c Q_c}{\mu d_c}, \frac{l_c}{d_c}, \frac{d_c}{d_s}, \frac{\rho_c}{\rho_s}\right)=0, \tag{3}$$

or

$$\frac{Q_c}{Q_s}=f\left(\frac{P_c}{P_s}, \frac{\rho_c Q_c}{\mu d_a}, \frac{l_c}{d_c}, \frac{d_c}{d_s}, \frac{\rho_c}{\rho_s}\right). \tag{4}$$

Eq. (4) can be simplified still more when the flow is assumed incompressible and the devices have the same geometries,

$$\frac{Q_c}{Q_s}=f\left(\frac{P_c}{P_s}, \frac{\rho_c Q_c}{\mu d_c}\right). \tag{5}$$

Though the funtion f may be established properly by the experiments, it may be also effective to supplement that from the other point of view. Then the control flow rate Q_c is derived approximately to estimate the function f.

Firstly, Q_c on the attached side is represented approximately by the equation5)

$$Q_c = \alpha_c a_c\left\{\frac{2(P_c-k_f P_s)}{\rho_c}\right\}^{1/2}. \tag{6}^*$$

Though the coefficient of entrainment k_f may be generally dependent upon the internal geometry of the device, the control flow rate Q_c, and the supply pressure of the main jet P_s, it does not depend upon P_s where the Reynolds number is sufficiently large.6) And the flow rate of the main jet Q_s may be written approximately

$$Q_s = \alpha_s a_s\left(\frac{2P_s}{\rho_s}\right)^{1/2}. \tag{7}$$

From Eqs. (6) and (7), a function of Eq. (4) is obtained as follows

$$\frac{Q_c}{Q_s}\left(\frac{\rho_c}{\rho_s}\right)^{1/2}=\frac{\alpha_c a_c}{\alpha_s a_s}\left(\frac{P_c}{P_s}-k_f\right)^{1/2}. \tag{8}$$

In general the coefficient of discharge α is a function of the Reynolds number, and becomes constant as the Reynolds number increases. Under the assumption to derive Eq. (4), α_s is considered a constant but α_c not always a constant. Thus α_c must be treated as a function of $\rho_c Q_c/\mu d_c, l_c/d_c$, etc. from Eq. (4).

Accordingly, from Eqs. (4) and (8) the statical input characteristics can be represented by

$$\frac{Q_c}{Q_s}\left(\frac{\rho_c}{\rho_s}\right)^n = K\alpha_c\left(\frac{P_c}{P_s}-k_f\right)^{1/2}, \tag{9}$$

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* $k_f P_s$ represents the pressure at the outlet of the control nozzle.

where $K=a_c/a_s\alpha_s$.

Secondly, on the unattached side it becomes

$$\frac{Q_c}{Q_s}\left(\frac{\rho_c}{\rho_s}\right)^{n'} = K\alpha_c\left(\frac{P_c}{P_s}-k'_f\right)^{1/2}. \tag{10}$$

Both K and α_c are not dependent upon the attachment or the unattachment.

4.2 Statical output characteristics

The output characteristics mean here the relations of the output flow rate and the output recoveery pressues. In practice, the wall-reattachment fluidic device has the vents to avoid the effect of the load to the bubble on the attached side.[7] The optimum vents can not yet design by a theoretical or a synthetic method, and they are decided on the basis of the experimental results of the device without vents.[4],[8],[9] Accordingly, this study is limited only for the devices without vents.

If the partial geometries are fixed, it can be assumed that the statical output characteristics of the device are described by

$$\phi_o(p_o, P_s, Q_o, Q_s, d_o, d_s, l_o, \rho_o, \rho_s, \mu)=0. \tag{11}$$

Using the dimensional analysis it can be rewritten as

$$\phi_o\left(\frac{p_o}{P_s}, \frac{Q_o}{Q_s}, \frac{\rho_o Q_s}{\mu d_o}, \frac{\rho_s Q_s}{\mu d_s}, \frac{l_o}{d_o}, \frac{d_o}{d_s}, \frac{\rho_o}{\rho_s}\right) = 0, \tag{12}$$

or

$$\frac{p_o}{P_s} = g\left(\frac{Q_o}{Q_s}, \frac{\rho_o Q_o}{\mu d_o}, \frac{\rho_s Q_s}{\mu d_s}, \frac{l_o}{d_o}, \frac{d_o}{d_s}, \frac{\rho_o}{\rho_s}\right). \tag{13}$$

If the Reynolde number at the main jet $\rho_s Q_s/\mu d_s$ is sufficiently large, it can be considered that the pressure loss in the main jet nozzle and the zone of flow interference does not depend upon the viscosity or the term $\rho_s Q_s/\mu d_s$. In such a case, Eq. (13) can be simplified for same devices as

$$\frac{p_o}{P_s} = g\left(\frac{Q_o}{Q_s}, \frac{\rho_o Q_o}{\mu d_o}, \frac{\rho_o}{\rho_s}\right). \tag{14}$$

Further simplification can be done, if the pressure loss in the output duct by the viscosity can be neglected. Eq. (14) becomes

$$\frac{p_o}{P_s} = g\left(\frac{Q_o}{Q_s}, \frac{\rho_o}{\rho_s}\right). \tag{15}$$

Furthermore, if the flow is regarded as incompressible, it becomes a simpler form

$$\frac{p_o}{P_s} = g\left(\frac{Q_o}{Q_s}\right). \tag{16}$$

The function g may be established experimentally, given the geometry of the device.

Where the device has the vents, the output pressure p_o depends not only upon the variables in Eq. (11), but also upon the distance between the top of splitter and the vent, the width or the equivalent diameter of vent, the directional angle of the vent to the axis of the output flow, and so on. Then, the problem becomes very complicated. However, these variables are proper to the device. Therefore, if it is considered that the function g is decided by the geometry including even the vent, Eqs. (14) and (15) are still applicable to the devices with the vents.

The analysis mentioned above indicates that the relation between the function f or g and the geometry of the device must be decided, to obtain the statical input or output characteristics of the wall-reattachment fluidic device. This study does not yet obtain the final results. Then, the remains of the paper are devoted to the experiments that show the propriety of the function f and g to represent the statical characteristics of the device.

§ 5. Apparatus and experimental procedure

The schematic diagrams of the experimental setup are shown in Fig. 1-a and 1-b, respectively for the input and the output characteristics.

In Fig. 1-a, the main or supply flow is leaded from the constant pressure tank T_c to the main jet nozzle of the wall-reattachment fluidic device E through the flow meter F_s. The main jet pressure P_s is the total pressure at the point of the manometer M_5, and the volume flow rate is evaluated at the pressure indicated by M_5.

The control flow is leaded from the constant pressure tank T_c to the control nozzle through the flow meter F_c. The control pressure is the total pressure at the point of the manometer M_1, and the control flow rate is evaluated at the pressure indicated by M_1.

In Fig. 1-b, the main flow rate is measured by a hot wire anemometer. The output recovery pressure is the static pressure indicated by the manometer M_3. The output flow rate is measured by a volumetric flow meter and

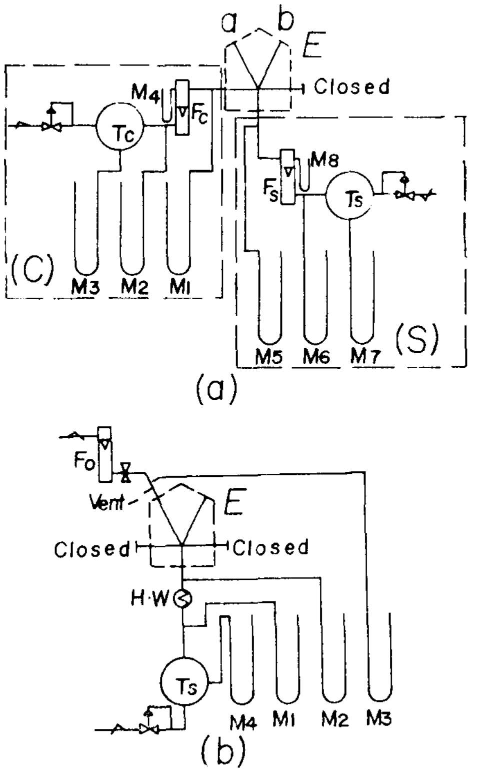

Fig. 1 Schematic diagram of test for
(a) Input characteristics
(b) Output characteristics

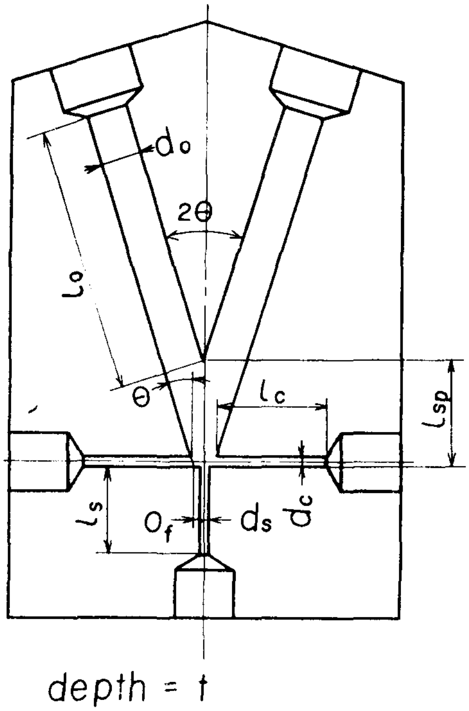

Fig. 2 Wall-reattachment bistable element

evaluated at the pressure indicated by M_3.

The tested devices and their dimensions are shown respectively in Fig. 2 and in Table 1.

Table 1, Dimensions (Unit: mm)

Elemetn No.	1	2	3
Main nozzle width (d_s)	0.70	0.60	1.0
Main nozzle length (l_s)	5	10	20
Control nozzle width (d_c)	0.77	0.59	1.80
Control nozzle length (l_c)	10	15	20
Offset (O_f)	0.55	0.59	0.50
Distance from splitter leading edge to nozzle exit (l_{sp})	7.1	8.0	9.9
Inclined wall angle in degsees (θ)	14.3	11.5	15.1
Output duct width (d_o)	2.6	2.3	3.4
Output duct length (l_o)	28	30	25
Depth (t)	4.0	4.0	6.0

§ 6. Experimental results and discussion

6. 1 Statical input characteristics

Some examples of the statical input characteristics are shown in Fig. 3 and 4. These data demonstrate strongly that n and n' in Eqs. (9) and (10) are equal to unity. Therefore, Eq. (9) can be rewritten as follows,

$$\frac{\rho_c Q_c}{\rho_s Q_s} = K\alpha_c\left(\frac{P_c}{P_s} - k_f\right)^{1/2}, \tag{17}$$

or,

$$\frac{P_c}{P_s} = \left\{\frac{1}{K\alpha_c} \cdot \frac{\rho_c Q_c}{\rho_s Q_s}\right\}^2 + k_f. \tag{17'}$$

In this equation the first term of the right side can be decided by the geometry of the control nozzle, because α_c is the quantity proper to the control nozzle, regardless of the attachment or the unattachment. The second term can be obtained as a function of the control flow rate and others from the device geometry. The results in Fig. 5 and 6 indicate a feasible relation between k_f and Q_c as follows,

$$k_f = F\left(\frac{\rho_c Q_c}{\rho_s Q_s}\right). \tag{18}$$

If k_f is known, a device of required characteristics can be designed by adjusting the control nozzle which affects the second term of the right side.

Though the switching of the device is left in the previous discussion and must be studied

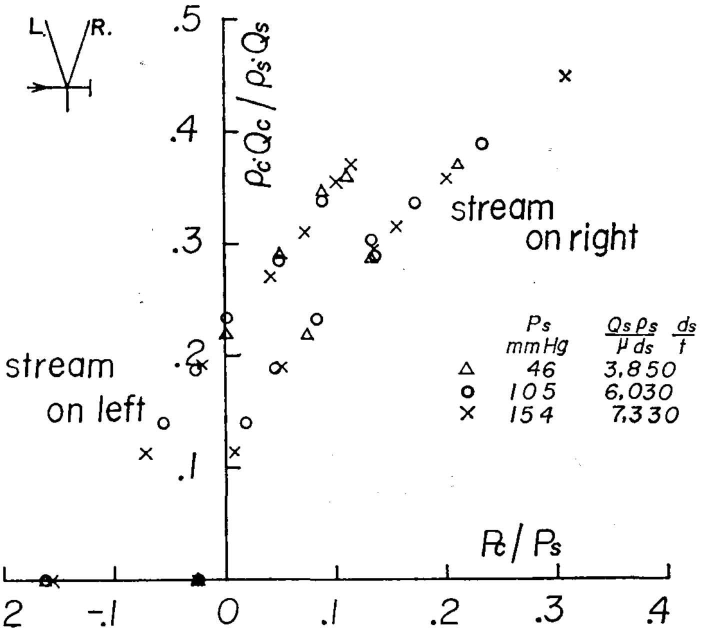

Fig. 3 Input characteristics (Element 1)
(Right control nozzle closed)

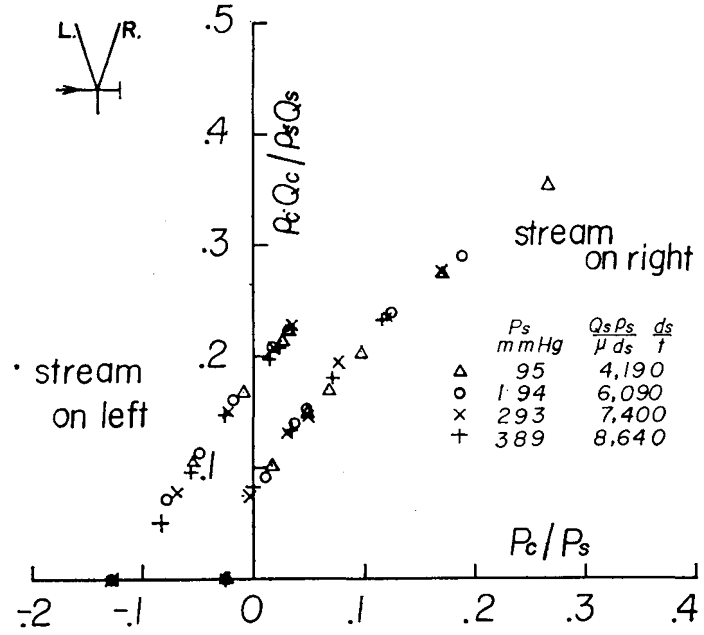

Fig. 4 Input characteristics (Element 2)
(Right control nozzle closed)

from a different view point, it is also a fact that the switching point is a point on the above-mentioned characteristic curve.

6.2 Statical output characteristics

The experimental results of the statical output characteristics are illustrated in Fig. 7. These suggest the propriety of Eq. (15). The vents of these devices are added supplementally to the output ducts of the original devices, and are optimum at those vent position.

Finally, from the experimental results and Eq. (15), the output characteristics can be

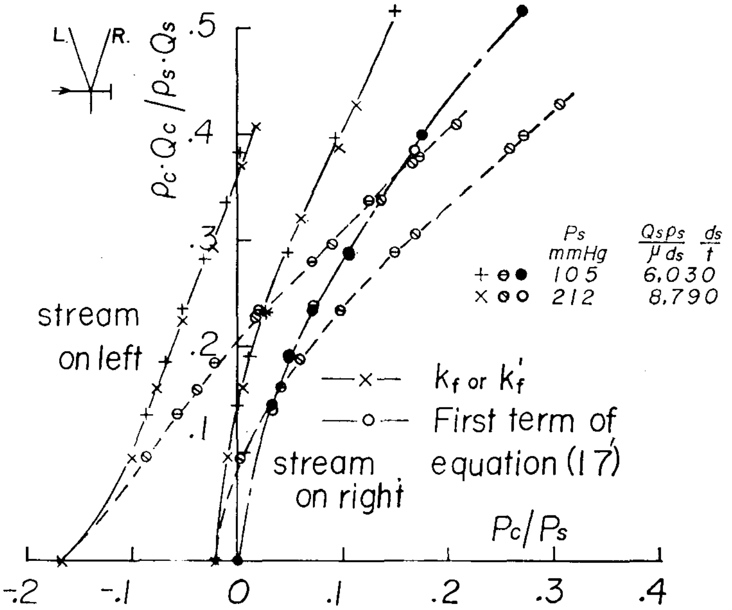

Fig. 5 Input characteristics, divided into control nozzle term and internal geometric term (Element 1)
(Right control nozzle closed)

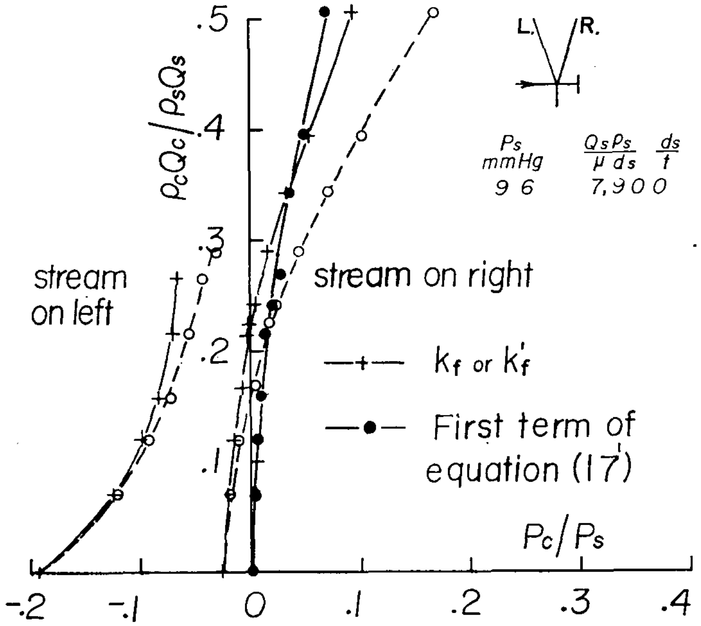

Fig. 6 Input characteristics, divided into control nozzle term and internal geometric term (Element 3)
(Right control nozzle closed)

written as follows, in spite of the presence of the vent

$$\frac{p_0}{P_s} = g\left(\frac{\rho_0 Q_0}{\rho_s Q_s}\right), \tag{19}$$

where the function g is decided by the geometry of the device involving the vents.

§ 7. Conclusion

By the dimensional analysis and the experi-

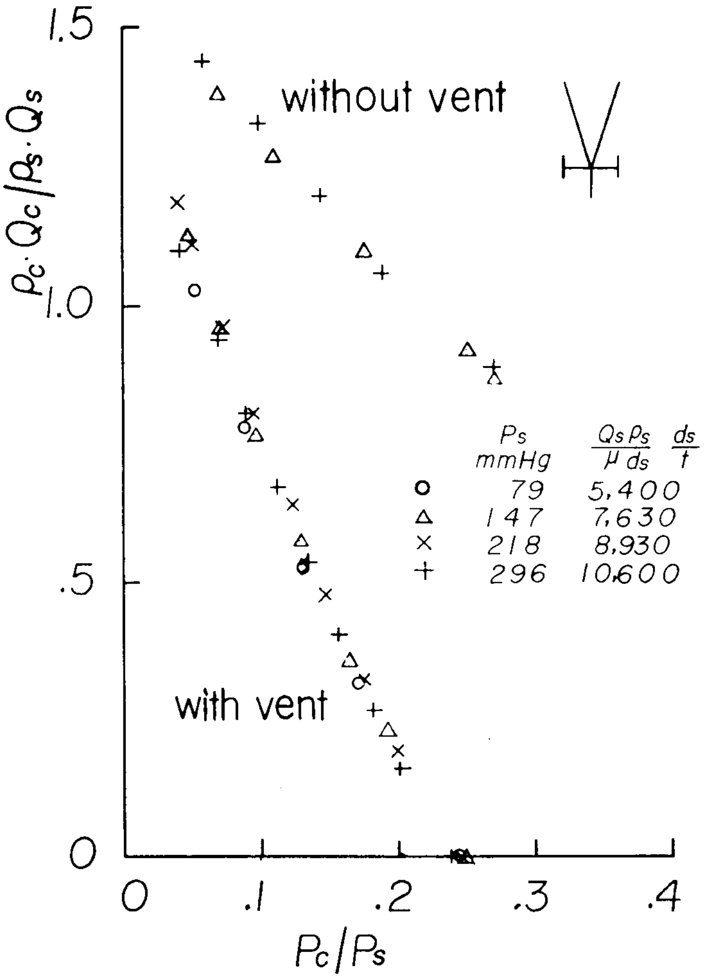

Fig. 7 Output characteristics (Element 1)
(Both control nozzles closed)

ments, it appears that the characteristics of the wall-reattachment fluidic devices can be represented by a function of the non-dimensional variables, if the partial geometry of the device is fixed. But the relation between the fixed geometrical parameters and the functional form is yet unknown.

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