渦巻노즐의 理論分析(I)
-노즐의 構造에 關하여-

Theoretical Analysis on the Swirl Type Nozzle(I)
-Structures of the Swirl Nozzle-

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摘 要

Fraser, Dombrowski, Tanasawa 그리고 Momono 等이 噴口에 對한 中子導溝 斷面積의 比에 기초를 두고 있는 Nozzle parameter가 클수록 流量係數는 增加한다고 報告하였다. 그러나 노즐의 構造는 中子導溝 및 渦室의 形狀에 따라서 特性을 가지고 있고 構造의 特性은 流量係數, 噴霧角 및 撒布度에 지대한 영향을 미친다.

노즐構造에 關한 理論分析의 結果는 다음과 같다.

中子導溝邊(d), 中子두께(t) 및 中子導溝角(θ) 等의 關係가 渦室流線角(θ_c)에 미치는 영향은

$$\tan(\theta c) = \frac{t \cdot \sin^2\theta}{d - t \cdot \sin\theta \cdot (1 - \cos\theta)}$$

또한 渦室流線角(θ_c)이 中子導溝角(θ)과 一致하는 關係는

$$\frac{d}{t} = \sin\theta$$ 이다.

渦室流線角과 渦室形狀과의 關係는

$$\tan(\theta c) \geq \frac{r_c - r_g}{L_c}$$

이며 渦室流線角은 渦室流線回轉半徑과 渦室길이의 比에 依하여 變化함을 示唆한다.

Swirl core가 Swirl plate보다는 生産費의 고려없이 壓力損失 및 마찰손실 面에서 더욱 合理的으로 考慮된다.

I. Introduction

Nozzle parameters such as

$$\Delta = \frac{A_g}{d_o d_c}, \quad K = \frac{A_g}{\pi r_o^2}\left(\frac{r_o}{r_c}\right), \qquad K = n\frac{1}{A}: \quad A = \frac{r_o r_c}{r_g^2} = \frac{1-\zeta}{\sqrt{\zeta^3/2}}: \quad \zeta = 1 - \frac{r_r^2}{r_o^2}$$

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were represented by Fraser(1959), Dombrowski(1969), Tanasawa(1951) and Momono (1987) on the basis of Bernoull's equation, the equation of continuity, the conservation of angular momentum, and the conservation of energy so as to derive their theories involving empirical data as notations in Figure 1. In the above equations, Δ and k are nozzle parameters, A_g is the cross-sectional area of the swirl groove, d_o and r_o are the diameter and the radius in the orifice respectively, d_c and r_c are the diameter and the radius in the swirl chamber respectively, r_g is the swirl groove radius, and r_r is the cavitational radius.

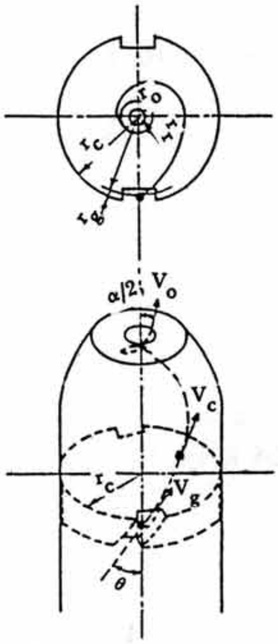

Fig. 1. Features of the swirl nozzle.

They agreed that the discharge coefficients increased with increase of the nozzle parameter.

In nozzle parameter of $\Delta = A_g / d_o \cdot d_c$, the ratio of the cross-sectional area between the swirl groove and the orifice was emphasized to increase the discharge coefficient in accordance with the nozzle parameter under the condition of $A_g > A_o$.

However, the structures of the nozzle have their own characteristics in the swirl groove, the shape of the swirl chamber, and the orifice, and they influence greatly the discharge coefficient or the spray angle and also the spray deposit pattern.

Also two factors must be treated carefully to reduce the energy loss; one is the variation of the direction of the flow depending on the shapes of the structures or the cross-sectional area of the flow to cause the pressure drop, and the other is the contact area along the path of the flow to cause the frictional loss occurring between the fluid and the inside wall in the nozzle.

The effects of the changes of the flow area and the contact area must be treated carefully on the criterion of the nozzle efficiency.

II. Theories on the swirl groove and the swirl chamber.

A) Effects of the ratio of the length to the thickness in the swirl groove on the direction of the flow.

The swirl groove has the particular function to produce tangential velocity by the liquid passing through it so that the rotational velocity is sufficiently high in the swirl chamber.

The rotational velocity is essential not only to separate the bulk liquid into fine threads or the large droplets into the fine droplets in the disintegration process by shearing function opposed to the surface tension but also to affect the spray angle and the discharge coefficient.

The rotational velocity will be greatly influenced by the position of the swirl groove at the swirl plate and by the direction of the flow which is governed by the shape of the swirl groove, although the high efficiency of the nozzle performance needs the constant direction of the rotational flow from the swirl groove to the swirl chamber.

The siwrl groove consists of the opening, the depth (or the thickness of the swirl plate), and the swirl groove angle.

The upper surface of the opening of the swirl groove is opened to the same level of the pressure or the velocity in the nozzle axial direction on the assumption of frictionless flow and the opening of the swirl groove is made in a regular square having the same width as shown in Figure 2.

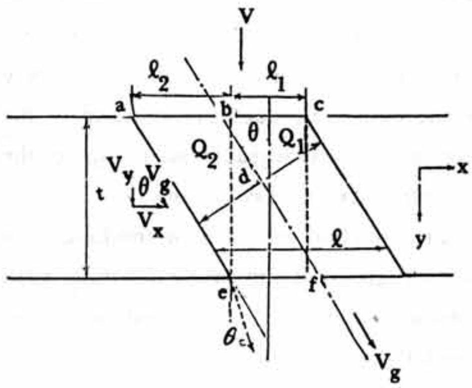

Fig. 2. Characteristics of flow in the swirl groove.

The discharge Q_1 = □ bcef is free to flow directly through the opening in a parallel to the nozzle axial direction, but the discharge Q_2 = Δabe flows along the line with a swirl groove angle to the nozzle axial direction.

The resultant direction of the flow after passing the swirl groove is changeable according to the balance resulting from two ingredients of Q_1 and Q_2.

Also the discharge Q_1 varies according to the ratio of the length d to the thickness t in the swirl groove.

In order to determine the resultant direction θ_c, two axial forces are arranged as follows;

In the block of □ bcef,

$$F_y = \rho Q_1 V_g \qquad (1)$$

In the block of Δ abe,

$$F_x = \rho Q_2 V_x = \rho Q_2 V_g \sin\theta \qquad (2)$$

$$F_y = \rho Q_2 V_y = \rho Q_2 V_g \cos\theta \qquad (3)$$

where, F_y = Y − axial force
F_x = X − axial force
ρ = liquid density
V_g = swirl groove velocity
V_x = X − axial component of V_g
V_y = Y − axial component of V_g

Therefore, the resultant direction can be represented as the following equation,

$$\tan\theta_c = \frac{\Sigma F_x}{\Sigma F_y} = \frac{\text{Eq.(2)}}{\text{Eq.(1)} + \text{Eq.(3)}} = \frac{\rho Q_2 V_g \sin\theta}{\rho Q_1 V_g + \rho Q_2 V_g \cos\theta} = \frac{Q_2 \sin\theta}{Q_1 + Q_2 \cos\theta} \qquad (4)$$

Since Q_1 and Q_2 pass the same width, Eq.(4) is reformed by replacing by ℓ_1 for Q_1 and ℓ_2 for Q_2 respectively,

$$\tan\theta_c = \frac{\ell_2 \sin\theta}{\ell_1 + \ell_2\cos\theta} = \frac{\ell_2\sin\theta}{(\ell - \ell_2) + \ell_2\cos\theta} = \frac{\ell_2\sin\theta}{\ell - \ell_2(1-\cos\theta)} \qquad \text{——(5)}$$

The relationships among the length d, the thckness t and the swirl groove angle θ are as follows;

$$\ell_2 = t.\tan\theta$$
$$\ell = d/\cos\theta \qquad \text{——(6)}$$

substituting Eq. (6) into Eq. (5),

$$\tan\theta_c = \frac{t.\tan\theta\sin\theta}{\frac{d}{\cos\theta} - \tan\theta\,(1-\cos\theta)t} = \frac{t\sin^2\theta}{d - t\sin\theta(1-\cos\theta)} \qquad \text{——(7)}$$

In practical applications, θ_c is generally getting smaller with decrease of the thickness t on criterion of the length d, and θ_c is called 'the swirl chamber flow angle' in this study.

From Eq. (7), the conditon of $\theta = \theta_c$ can be derived to find the reasonable ratio of the length d to the thickness t in order to keep a constant direction of the flow from the swirl groove to the swirl chamber to increase the nozzle efficiency.

$$\tan\theta_c = \frac{t\sin^2\theta}{d - t\sin\theta\,(1-\cos\theta)} = \tan\theta$$

$$t\sin^2\theta = \tan\theta\,[d - t\sin\theta(1-\cos\theta)]$$
$$d/t = \cos\theta\,[\sin\theta + \tan\theta(1-\cos\theta)]$$
$$d/t = \sin\theta \qquad \text{——(8)}$$

This equation shows that the siwrl chamber flow angle equals the swirl groove angle θ when ℓ_1 in Figure 2 becomes zero.

B) Relationships between the swirl chamber flow angle and the shape of the swirl chamber.

The direction of the flow must be maintained constantly or changed smoothly and slowly along the path of the flow in the nozzle from the inlet of the swirl groove to the orifice without a suddenly alterable current so as to increase or keep up the efficiency of the nozzle, although the direction of the flow may be changeable according to the characteristics of the swirl groove.

The direction of the flow resulting from the swirl groove is also changeable in the swirl chamber according to the relationship between the swirl chamber flow angle and the shape of the swirl chamber as follow;

$$\tan\theta_c \geq \frac{r_c - r_g}{L_c} \qquad \text{——(9)}$$

where, θ_c = swirl chamber flow angle
r_c = swirl chamber radius
r_g = swirl groove radius
L_c = swirl chamber length

This equation implies that the swirl chamber flow angle resulted originally from the swirl groove must be same as the value of $[(r_c-r_g)/L_c]$ or it must be slightly larger than the value, considering the frictional loss owing to the inside surface of the wall on the conditon that the liquid flow is assumed to be constant in the swirl chamber from the outlet of the swirl groove to the orifice.

In the case of $\tan\theta_c \geqq (r_c-r_g)/L_c$, the flow in the swirl chamber can be very stable and maintain a constant direction from the outlet of the swirl groove to the orifice, and also $L_c \geqq (r_c-r_g)/\tan\theta_c$ suggests that the short way of the flow needs the swirl chamber length L_c at least without alteration of currents.

However, in the case of $\tan\theta_c < (r_c - r_g)/L_c$, the direction of the flow will be changed towards the orifice quickly along the dotted line in Figure 3 in accordance with decrease of the swirl chamber length L_c.

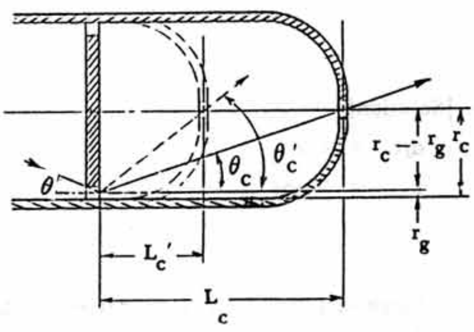

Fig. 3. The swirl chamber flow angle to the shape of the swirl chamber.

This new direction of the flow will make a new angle of the direction of the flow, $\tan\theta'_c = (r_c - r_g)/L_c'$ which is named the swirl chamber flow angle in this study.

The equation (9) seemed to be generally fitted to the experimental results of many previous relevant researches.

This sudden change of the direction of the flow in the swirl chamber may cause the turbulent flow and the energy loss, and also it affects the spray angle and the discharge coefficient.

C) The flow area and the contact area in the swirl groove

In order to produce a tangential velocity to cause the rotational velocity in the swirl chamber, the liquid must pass through tangential or helical passages of the swirl core or the swirl plate.

As a consequence of passing along the tangential or helical passages, pressure drop and frictional loss will be arised due to the variations of the flow area and the contact area which are changeable depending on the shape of the swirl groove, although the tangential velocity will be needed basically at a certain level.

Since most present theories have been developed on the assumption of frictionless flow, the theoretical results are not generally in accord with the experimental results.

Some useful references pointed out importance on frictional loss(1959) due to the quality of the inner surface finish and importance on energy loss owing to the variation of the nozzle parameter of

$$\Delta = A_g / d_o \cdot d_c$$

However, the pressure drop is greatly concerned to the degree of change of the flow area depending on the shape of the swirl groove and the frictional loss is happened along the contact area depending on the overall geometry of the swirl groove.

Previous relevant researches have led that the contact area along the path of the flow must be as shortened as possible for less frictional loss and the changes of the cross-sectional area of the flow must be as small as possible so as to reduce pressure drop for keeping of the nozzle efficiency at a certain level.

Especially the sudden change of the cross-sectional area causes the energy loss greatly as expressed in Weisbach's empirical equation for sudden shortening cross-sectional area pipe and Borda-Carnot water head loss for sudden enlarging cross-sectional area pipe being more than Gibson water head loss which was derived in the gradual change of the cross-sectional area in a pipe.

$$h_{Lc} = \left(\frac{1}{C_c} - 1\right)^2 \frac{V_2^2}{2g} \qquad (10)$$

where, h_{Lc} = water head of loss

C_c = vena contracta coefficient

V_2 = vena contracta velocity

area ratio A_2/A_1	0.1	0.2	0.3	0.4	0.5
C_c	0.624	0.632	0.643	0.659	0.681

areara tio A_2/A_1	0.6	0.7	0.8	0.9	1.0
C_c	0.712	0.755	0.813	0.892	1.00

III. Applications of theories and discussion

Illustrative example 1 to determine the swirl chamber flow angle θ_c under the conditions;

swirl groove length, d = 2 mm
swirl groove thickness, t = 2 mm
swirl groove angle, $\theta = 51°$

[Solution]

$$\tan\theta_c = \frac{t \sin^2\theta}{d - t\sin\theta(1-\cos\theta)}$$

$$= \frac{2(\sin 51)^2}{2-2(\sin 51)(1-\cos 51)} = 0.848236$$

$$\theta_c = 40°20'$$

Illustrative example 2 to determine the swirl groove (swirl plate) thickness when the swirl chamber flow angle equals to the swirl groove angle under the conditions;

swirl groove length, d = 2 mm
swirl groove angle, $\theta = 51°$

[Solution]

$d/t = \sin\theta$

$t = 2/\sin 51°$

$= 2.574$ mm

Illustrative example 3 to determine the swirl chamber flow angle θ_c according to changes of the swirl groove length d under the conditions;

swirl groove thickness, t = 3 mm
swirl groove angle, $\theta = 40°$
swirl groove length, d = 1, 2, 3, 4, 5, 6 mm

$$\ell_2 < \ell$$

[Solution]

d(mm)	1.928	2	3	4	5	6
θ_c(°′)	40°	38°40′	26°	19°20′	15°10′	12°40′

The swirl chamber flow angle θ_c varies in accordance with changes of the swirl groove length d against the swirl groove thickness t as shown in Figure 4.

To compare the results obtained in this work with previous works, the discharge coefficients which were measured from the same dimensions of the length d and the thickness t for the swirl groove which was used in Momono's experiments(1987) were plotted together in Figure 4.

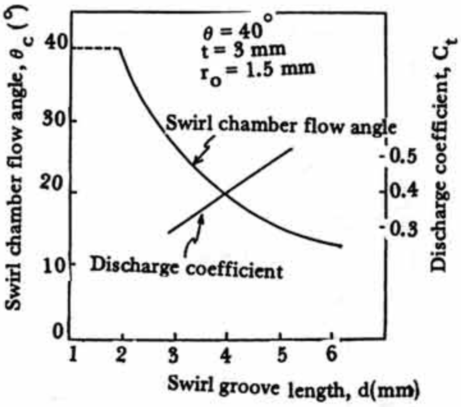

Fig. 4. Variations of θ_c and C_t against d.

Figure 4 shows that the discharge coefficient increases and the swirl chamber flow angle decreases in accordance with increase of the swirl groove length since the longitudinal velocity is getting larger with decrease of the swirl chamber flow angle or with increase of the swirl groove length on the base of the constant thickness of the swirl plate.

Namely, the direction of flow resulting from the swirl groove at the inlet of the swirl chamber changes gradually to a certain extent towards the nozzle axial direction with increase of the opening area based on the constant thickness of the swirl plate.

Illustrative example 4 to determine the swirl chamber flow angle θ_c depending on changes of the swirl chamber length under the conditions;

swirl chamber radius, $r_c = 12.5$ mm
swirl groove radius, $r_g = 2$ mm
swirl groove angle, $\theta = 40°$
swirl chamber length, $L_c = 3$ to 18 mm

[Solution]

L_c(mm)	3	4	5	6	7
θ_c	74°	69°10′	64°30′	60°20′	56°20′

L_c(mm)	8	10	12	12.5
θ_c	50°40′	46°20′	41°10′	40°

The swirl chamber flow angles θ_c were determined according to the changes of the ratio of $[(r_c-r_g)/L_c]$ as shown in Figure 5. It was obvious that the swirl chamber flow angles increased with decrease of the swirl chamber length based on a certain diameter of the swirl chamber.

To compare the present results with previous experimental works, the spray angles which resulted from the same dimensions of the swirl chamber studied in Momono's woks (1987) were plotted together in Figure 5.

Figure 5 shows that both the swirl chamber flow angle and the spray angle increase together with decrease of the swirl chamber length, which implies that the swirl groove angle and the swirl chamber flow angle must

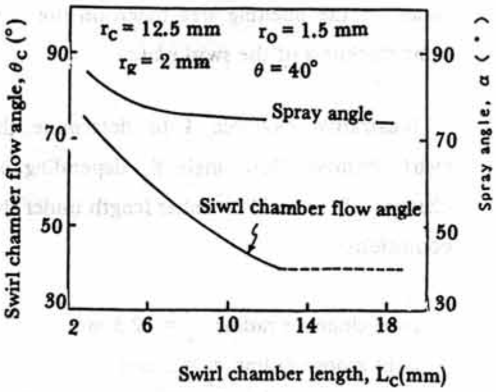

Fig. 5. Variations of θ_c and α against L_c.

be designed according to the shape of the swirl chamber, and also that the position of the swirl groove is concerned to the shape of the swirl chamber.

In other words, the shape of the swirl chamber determines finally the degree of the effect of the swirl groove angle to cause the rotational velocity which affects the spray angle and the discharge coefficient as well as the disintegration process. Therefore the nozzle efficiency necessitates the combined effects of the position and the shape of the swirl groove, and the shape of the swirl chamber.

In order to examine the shape of the swirl groove, many different designs have been used for various experimental investigations with their different flow characteristics in overall geometry of swirl grooves.

However, two types are probably the commonest type of the swirl groove to be found in industry and numerous fundamental studies, one is a swirl core (Figure 6) and another is a swirl plate (Figure 7).

Therefore, the two types were examined in this study on the viewpoints from both the contact area and the cross-sectional area to check the sources which cause the frictional

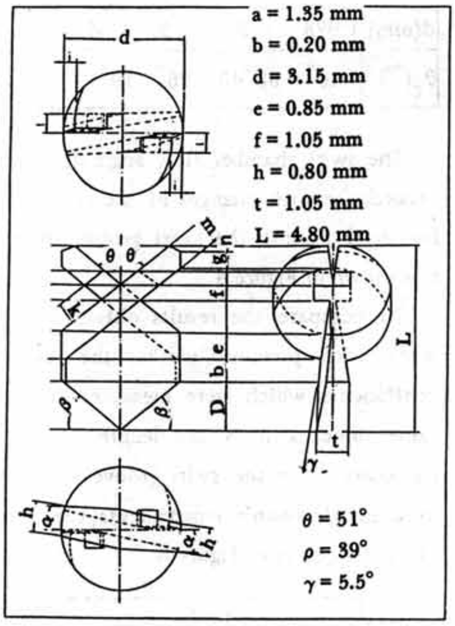

Fig. 6. Dimensions of the swirl core

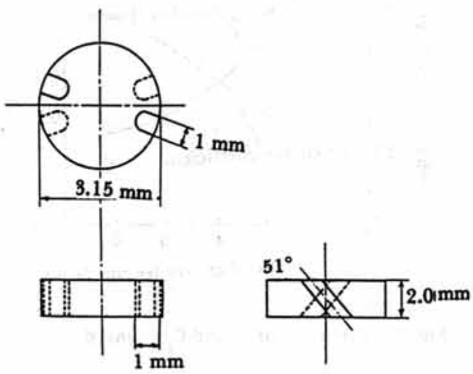

Fig. 7. Dimensions of the swirl plate

loss and the pressure drop.

In the flow area or the cross-sectional area as shown in Figure 8, the swirl core seemed to be more smooth and reasonable than the swirl plate from the viewpoint of the degree of the variation of the flow area to reduce the pressure drop.

Especially, the twice sudden changes of the flow area in the swirl plate seemed to be evaluted to cause greatly the pressure drop at the high levels of the velocity owing to

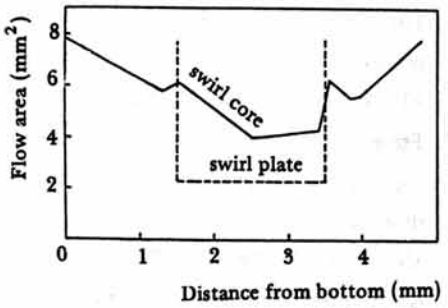

Fig. 8. Flow area responding to the distance from the bottom

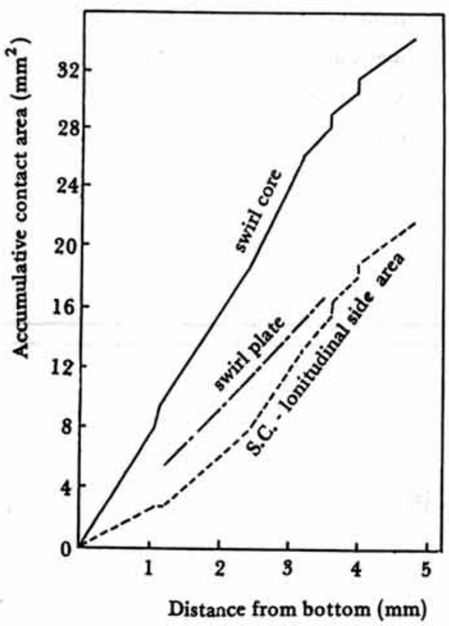

Fig. 9. Accumulative contact area responding to the distance from the bottom

Weisbach's empirical equation and Borda-Carnot water head loss.

In the contact area as shown in Figure 9, the swirl plate was smaller than the whole contact area of the swirl core but the swirl plate was nearly same as the swirl core excluding the longitudinal side area to be convered by the angle of γ as shown in Figure 6.

The longitudinal side area of the swirl core was tried to cover it with liquid films to lower frictional loss.

The swirl core has a particular function to divide easily the entire flow into two parts at the large size inlet of the opening so that the symmetrical flow is achieved in the swirl chamber.

However the swirl plate is relatively difficult to hold the symmetrical flow in the swirl chamber at high levels of the pressure because the entire flow has to pass through the small size inlet of opening.

The structures of the swirl plate are simple and easy in the make, but the structures of the swirl core are complex and relatively difficult in the manufacturing because of having various angles and surfaces.

Consequently the swirl core may be evaluated to be more reasonable than the swirl plate from the viewpoints of pressure drop and frictional loss regardless of cost benefit of manufacturing.

IV. Conclusion

The relationships among the swirl groove lgngth d, the swirl groove thickness t and the swirl groove angle θ were expressed in the swirl chamber flow angle θ_c,

$$\tan\theta_c = \frac{t \sin^2\theta}{d - t\sin\theta(1-\cos\theta)}$$

In order to keep a constant direction of the flow from the swirl groove to the swirl chamber, the relationship equation was related to,

$$d/t = \sin\theta$$

The relationships between the swirl chamber flow angle and the shape of the swirl chamber were as the following equation,

$$\tan\theta_c \geqq \frac{r_c - r_g}{L_c}$$

which suggests that the swirl chamber flow angle is changeable according to the ratio of the turning radius of swirl chamber to the swirl chamber length.

The swirl core seemed to be evaluated to be more reasonable than the swirl plate from the viewpoints of pressure drop and frictional loss regardless of cost benefit of manufacturing.

References

1. Dombrowski, N. and D. Hasson. 1969. The flow characteristics of swirl spray pressure nozzles with low viscosity liquids. AIChE Journal, Vol. 15, No. 4, p.604-611.
2. Fraser, R.P. 1959. The fluid kinetics of application of pesticidal chemicals. London, England.
3. Momono, H. 1987. Ph.D. Thesis, Studies on hollow cone nozzle for farm sprayer. Faculty agriculture, Hokkaido University, Sapporo, Japan.
4. Tanasawa, Y. and S. Kobayashi. 1951. Potential theory on the injection valve design method. Collection of thesis, the soc. of Mechanical Eng., Japan, Vol. 17, No. 58, p.107-111.

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