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Effect of Load on Characteristics of Wall Attachment Amplifier*

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The purpose of this paper is to clarify the relationship between the flow condition in the wall attachment amplifier and its characteristics. The flow patterns are observed in detail in cases of the flow divided by the splitter and the flow joined with a reversed flow from the output port of the non-attachment side, and the cause of the existence of these flow patterns and its effect on the characteristics of the amplifier are experimentally investigated. The flow models in the amplifier are proposed by referring to the experimental phenomena and the effect of load on the characteristics is theoretically investigated. The theoretical calculation on the characteristics agreed fairly well with the experimental results. It was made clear by the calculation that the flow pattern in the amplifier depends only on the load condition of the attachment side regardless of the load condition of the non-attachment side.

1. Introduction

The fluid amplifier or fluidic device, which has no moving part, is a control device, whose application to the information processing in the control system has been strongly anticipated. For such application, gas is the working fluid and liquid is not usually used. This is mainly because the high viscosity and density of liquid cause slower responses in the signal transmission and more power consumption would occur than gas. However, considering that liquid is commonly used in the conventional control element because of its large power capacity, the fluid amplifier with liquid as its working fluid should be applicable to the information processing as well as to control systems. For the application of the wall attachment amplifier as the directional control device, the minimization of the hydraulic loss of power in the amplifier and that of the switching flow rate are most required in the range of appropriate output power. These steady state characteristics of the amplifier are affected by many factors, such as the geometrical configuration and dimensions of the amplifier, the conditions of vent, load, flow, etc.

Many experimental and theoretical studies⁽¹⁾⁻⁽¹²⁾⁽²⁰⁾⁻⁽²⁴⁾*** on the Coanda effect have been done and the state of the attached flow has been clarified. Other studies⁽¹³⁾⁻⁽¹⁹⁾⁽²⁶⁾⁻⁽²⁹⁾*** on the effect of the above-mentioned factors on the

characteristics of the amplifier have been also done, but only a few⁽²⁵⁾ clarified the relationship between the flow conditions in the amplifier and its characteristics. The authors have previously reported the effects of vent and load on the characteristics of the amplifier and clarified that its characteristics depend on two flow patterns, that is, the flow divided by the splitter and the flow joined with a reversed flow from the output port of the non-attachment side⁽³⁰⁾⁻⁽³²⁾.

In this paper, the above-mentioned flow patterns are observed in detail and the cause of their existence and its effect on the characteristics of the amplifier are experimentally investigated. The flow models in the amplifier are proposed by referring to the experimental phenomena and the effect of load on the characteristics is theoretically investigated.

2. Experimental apparatus and testing procedure

Fig. 1 shows the experimental apparatus with water as the working fluid. The flow rate of working water supplied from the tank with an elevation head of 4 m is regulated by the variable throttling valve and water comes into the amplifier which is horizontally fixed. The jet from the main nozzle through S' (exit of main nozzle) is attached to one of the adjacent walls of the amplifier due to the Coanda effect. The conditions of load determine the flow through two load resistances, which are the flow resistances in the connecting pipes between O1 or O2 (pressure measuring points in output ports) and T (tank) including throttling valves.

Fig. 2 shows the internal configuration and important dimensions of the amplifier with co-ordinates and origins. The under cover and adjacent walls of the amplifier and splitter, which are made of acrylic resin, have pressure measuring

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*** References (1)-(19) and (3)-(20)-(32) use gas and liquid as the working fluid, respectively.

Fig. 1 Experimental apparatus

points with hole diameters of 1 mm (see marks ● in Fig. 2). The flow velocity profiles at points $4w_s$ and $7w_s$ downstream from the exit of the main nozzle are measured by using a cylinder-type pitot-tube with hole diameter of 0.25 mm and tube outer diameter of 1.2 mm, where w_s is the width of the main nozzle. The pitot-tube coefficient is in the range of 0.99 to 1.02 and its static pressure indication angle is 50.4° .

The oil film method⁽³³⁾ is applied to the upper cover of the amplifier to clarify the flow condition in the amplifier. The streak marks are composed of Pb_3O_4 , carbon grease and mobil or torque oil in the weight ratio 1.0 : 1.3 : 2.2-2.6. The observing time is approximately 5 to 7 minutes depending on the flow velocity.

The experiments were performed in two cases of the flow divided by the splitter and the flow joined with a reversed flow from the output port of the non-attachment side in the non-cavitation region. The magnitude of the load is regulated with reference to the experimental results of previous reports by the authors⁽³⁰⁾⁽³¹⁾. The main volume flow rate is regulated in the range of 40 to 60 l/min. The main volume flow rate and the water temperature are measured at the exit of the tank and the pressure in the amplifier and connecting pipes are measured by manometers. The experimental flow characteristics of the load resistances are used to estimate the volume flow rate in the load resistance by measuring the pressure difference.

3. Experimental results

Fig. 3 shows the non-dimensional pressure distributions on the adjacent walls of the amplifier and splitter in the case of the flow divided by the splitter. In the figures,

Fig. 2 Wall attachment amplifier used in experiment (length in mm)

Fig. 3 Non-dimensional pressure distributions on adjacent walls of amplifier and splitter in case of flow divided by splitter (I: adjacent wall of amplifier of attachment side, II: adjacent wall of splitter of attachment side, III: adjacent wall of amplifier of non-attachment side, IV: adjacent wall of splitter of non-attachment side)

$(p - p_{s'}) / (\rho v_s^2 / 2)$ = non-dimensional pressure
 p = pressure

$p_{s'}$ = pressure at S'

ρ = density

v_s = mean flow velocity in main nozzle

Re = Reynolds number = $v_s w_s / \nu$

ν = kinematic viscosity

q_1 = output volume flow ratio of attachment side = Q_1 / Q_s

Q_1 = output volume flow rate of attachment side

Q_s = main volume flow rate

t = water temperature

The co-ordinates are defined along the adjacent walls of the amplifier with origins of 0 and 0' in Fig. 2. It is found from the figure that the pressure distri-

bution of the attachment side has a maximum near the point $4w_s$ and a minimum near the point $7w_s$ and increases abruptly from the vicinity of the point $7w_s$ to that of the point $12w_s$ and that the pressure distribution of the non-attachment side has a minimum near the point $8w_s$ and a maximum near the point $12w_s$.

Fig. 4 shows the case of Fig. 3 with the streak marks on the upper cover of the amplifier observed by the oil film method. It is found from the figure that the flow attaches to the adjacent wall of the amplifier near the exit of the main nozzle and continues downstream along the wall and that a part of the attached flow reverses toward the upstream region of the non-attachment side.

The flow condition in the amplifier in the case of the flow divided by the splitter is presumed by these experimental results as follows: The main flow attaches to one of the adjacent walls of the amplifier near the point $4w_s$ due to the Coanda effect and the attached flow continues downstream along the wall. The flow is influenced by the load and begins to incline toward the inner part of the conduit from the vicinity of the point $7w_s$. The output flow of the attachment side increases in its width and behaves like a flow in a diffuser. The output flow of the non-attachment side and a reversed flow toward the upstream region of the non-attachment side impinge on the adjacent wall of the amplifier of the non-attachment side near the point of the splitter and continue downstream and upstream, respectively. The flow is not uniform in the inlet region of output ports of attachment and non-attachment sides.

Fig. 5 shows the non-dimensional pressure distributions on the adjacent walls of the amplifier and splitter in the case of the flow joined with a reversed flow from the output port of the non-attachment side. It is found from the figure that the pressure distribution of the attachment side has a maximum near the point $4w_s$ and a minimum near the point $13w_s$. The pressure distribution of the non-attachment side is approximately uniform throughout the region.

Fig. 6 shows the case of Fig. 5 with the streak marks on the upper cover of the amplifier observed by the oil film method. It is found from the figure that the flow attaches to the adjacent wall of the amplifier near the exit of the main nozzle and continues along the wall.

The flow condition in the amplifier in the case of the flow joined with a reversed flow from the output port of the non-attachment side is presumed by these experimental results as follows: The main flow attaches to one of the adjacent walls of the amplifier near the point $4w_s$ due to the Coanda effect and the attached flow continues downstream along the wall. The attached flow joins with a reversed flow from the output port of the non-attachment

Fig. 4 Streak marks in case of Fig. 3
($Re = 27400$)

Fig. 5 Non-dimensional pressure distributions on adjacent walls of amplifier and splitter in case of flow joined with a reversed flow from output port of non-attachment side (see symbols in Fig. 3)

Fig. 6 Streak marks in case of Fig. 5
($Re = 32000$)

side near the point of the splitter. The flow is not uniform in the inlet region of the output port of the attachment side.

Fig. 7 compares the above-mentioned pressure distributions near the attachment point on the adjacent walls of the amplifier. It is found from the figure that

Fig. 7 Pressure distribution near attachment point on adjacent wall of amplifier (solid and a dot-dash lines show results of Figs. 3 and 5, respectively)

the pressure distributions of attachment and non-attachment sides between the exit of the main nozzle and the attachment point do not depend on the load.

Fig. 8 shows the components of the flow velocity profile in the directions of X and Y at points $4w_s$ and $7w_s$, u and v, respectively. Calculated values* of the components at the point $7w_s$ obtained by the results of Schwarz and Cosart⁽³⁴⁾ and Myers⁽³⁵⁾ are also plotted in the figure (see marks x in Fig. 8). It is found from the figure that the flow velocity profile at the point $4w_s$ and that of the attached flow at the point $7w_s$ do not depend on the load. The flow velocity profile of a reversed flow toward the upstream region of the non-attachment side at the point $7w_s$ depends on the flow pattern; that is, its profile in the case of the flow divided by the splitter is linear with a maximum near the adjacent wall of the amplifier of the non-attachment side and zero near the center of the conduit and that in the case of the flow joined with a reversed flow from the output port of the non-attachment side is approximately uniform.

It is recognized from these experimental results that the flow condition in the upstream region from the attachment point does not depend on the load, that the flow velocity profile of the attached flow which continues downstream over certain distances from the attachment point does not depend on the load, and that the flow velocity

* Calculated values, which are those at points $0.14w_s$ and $0.26w_s$ downstream from points M_1 and M_2 in the X direction, respectively, are considered to correspond to the flow velocity at points M_1 and M_2 approximately (see Appendices (1) and (2)).

(a) Flow velocity component in X direction, u

(b) Flow velocity component in Y direction, v

$4w_s$	Re	t °C	q_1
○	32800	19.8	0.68
□	22000	19.8	0.65
●	28100	14.0	1.59
■	19000	14.3	1.58

$7w_s$	Re	t °C	q_1
○	27000	13.0	0.68
□	19800	14.0	0.65
●	26500	11.5	1.58
■	17800	11.5	1.55

Fig. 8 Flow velocity profile at points $4w_s$ and $7w_s$ (marks x are calculated values by results of Schwarz and Cosart)

profile of a reversed flow toward the upstream region of the non-attachment side depends on the flow pattern over certain distances downstream from the attachment point.

4. Theoretical considerations

4.1 Case of flow divided by splitter

Fig. 9 shows the proposed flow model in the amplifier in the case of the flow divided by the splitter. Two types of the flow region are macroscopically distinguished in the amplifier. The attached flow region does not depend on the load and is mainly dominated by the Coanda effect. The divided or joined flow region depends strongly on the load and is analyzed in this section. Referring to the control surface $\overline{1,2,3,4,6,7,8,9,10,11,1}$ in the figure, the output volume flow rate of the attachment side Q_1 enters the control surface across $\overline{1,2}$ and leaves it across $\overline{10,11}$. The output volume flow rate of the non-attachment side Q_2 enters the control surface across $\overline{2,3}$ and leaves it across $\overline{9,10}$. A part of the attached flow Q_R enters the control surface across $\overline{3,4}$ and leaves it across $\overline{4,6}$. The streamline $\overline{2,10}$ is a divided streamline between Q_1 and Q_2 and the streamline $\overline{3,8}$ is one between Q_2 and Q_R . The main assumptions made in this flow model are as follows: The flow velocity profile across $\overline{1,4}$ does not depend on the load. The flow velocity profile across $\overline{4,6}$ is dominated by the flow pattern and does not depend on the load within the same flow pattern. The pressure acting on $\overline{9,10}$ and $\overline{10,11}$ depends on the load. The analysis in this paper deals with fluid per unit height.

Assuming the flow velocity profile across $\overline{1,4}$ and $\overline{4,6}$ to be linear yields

$$u(1,4) = u_m \{1 - y_1 / l(1,4)\} \quad (1)$$

$$u(4,6) = u_m \{1 - y_2 / l(4,6)\} \quad (2)$$

where

$u(1,4)$ = flow velocity profile across $\overline{1,4}$

$u(4,6)$ = flow velocity profile across $\overline{4,6}$

u_m = flow velocity at point 1

u_m = flow velocity at point 6

$l(1,4)$ = distance between points 1 and 4

$l(4,6)$ = distance between points 4 and 6

y_1 and y_2 = distance in inner direction perpendicular to adjacent walls with origins of points 1 and 6, respectively

Assuming that the flow begins from origin 0 and using the results by Myers⁽³⁵⁾ yield u_m . $l(1,4)$, $l(4,6)$ and u_m are obtained by the continuity of flow;

$$\int_0^{l(1,4)} u(1,4) dy_1 = \int_0^\infty u dy \quad (3)$$

$$\int_0^{l(1,4)} u(1,4) dy_1 = Q_s + \int_0^{l(4,6)} u(4,6) dy_2 \quad (4)$$

and the geometrical relations;

Fig. 9 Flow model in amplifier in case of flow divided by splitter

$$l(4,6) = \{l(1,7) - l(1,4)\} \cos \theta \quad (5)$$

$$l(1,7) = (2D + w_s) \cos \theta + \{l(0,1) + (2D + w_s) \sin \theta\} \tan \theta \quad (6)$$

where

$l(1,7)$ = distance between points 1 and 7

$l(0,1)$ = distance between points 0 and 1

θ = wall angle

D = offset

The seventh-root law is applied in the vicinity of the wall and the result by Schwarz and Cosart⁽³⁴⁾ is applied at a distance from the wall to the velocity profile across $\overline{1,4}$ u. Therefore, the volume flow rate across $\overline{1,4}$ $Q(1,4)$ and its momentum $J(1,4)$ and the volume flow rate across $\overline{4,6}$ $Q(4,6)$ and its momentum $J(4,6)$ are expressed as follows:

$$Q(1,4) = l(1,4) u_m / 2 \quad (7)$$

$$J(1,4) = \rho l(1,4) u_m^2 / 3 \quad (8)$$

$$Q(4,6) = l(4,6) u_m / 2 \quad (9)$$

$$J(4,6) = \rho l(4,6) u_m^2 / 3 \quad (10)$$

Considering the control surface $\overline{1,2,10,11,1}$ concerning the energy of the output volume flow rate of the attachment side Q_1 , application of Bernoulli's equation with loss due to enlargement to points 1 and x_1 yields

$$\rho U(1,2)^2 / 2 + p_B = \rho U_{x1}^2 / 2 + p_{x1} + \rho \phi \{U(1,2) - U_{x1}\}^2 / 2 \quad (11)$$

where

x_1 = distance along adjacent wall of amplifier with origin of point 1

$U(1,2)$ = mean flow velocity across $\overline{1,2}$ = $Q_1 / l(1,2)$

$l(1,2)$ = distance between points 1 and 2

U_{x1} = mean flow velocity at point x_1 = Q_1 / y_{1*}

y_{1*} = flow width at point x_1

p_B = pressure acting on $\overline{1,2}$

p_{x1} = pressure at point x_1
 ϕ = loss coefficient due to enlargement
 Eq. (1) and the relation

$$Q_1 = \int_0^{1(1,2)} u(1,4) dy_1 \quad \dots\dots\dots (12)$$

yield

$$1(1,2) = 1(1,4) \{1 - \sqrt{1 - q_1/a}\} \quad \dots\dots\dots (13)$$

where

$$a = Q(1,4)/Q_s$$

Assuming the divided streamline $\overline{2,10}$ between Q_1 and Q_2 to be expressed by conic sections yields

$$\{x_1/1(1,11)\}^2 + \{1(1,5) - y_{1*}\}^2 / \{1(1,5) - 1(1,2)\}^2 = 1 \quad \dots\dots\dots (14)$$

where

$1(1,11)$ = distance between points 1 and 11

$1(1,5)$ = distance between points 1 and 5

= width of output port

Substituting Eq. (13) into Eq. (14) yields

$$y_{1*} = 1(1,5) [1 - \{1 - b(1 - \sqrt{1 - q_1/a})\} \sqrt{1 - x_1^2}] \quad \dots\dots\dots (15)$$

where

$$b = 1(1,4)/1(1,5)$$

$$x_{1*} = x_1/1(1,11)$$

Therefore p_{x1} is obtained by Eqs. (11), (13) and (15) and the integration of p_{x1} from points 1 to 11 yields the force acting on 1, 11 F_1 ; that is,

$$F_1 = \int_0^{1(1,11)} p_{x1} dx_1 \\ = \rho u_m^2 A_0 [1(1,11) q_1^2/2 + 1(1,11) p_B] \quad \dots\dots (16)$$

where

$$A_0 = A_1 \pi/2 + A_2 (\text{Arcsin } c + \pi/2) / \sqrt{1 - c^2}$$

$$+ A_3 \{c + (\text{Arcsin } c + \pi/2) / \sqrt{1 - c^2}\}$$

$$/ (c^2 - 1) + A_4 (c - \pi/2)$$

$$c = 1 - b(1 - \sqrt{1 - q_1/a})$$

$$A_1 = (b/a)^2 \{\phi(2c - 3) + 1\} / \{4c(1 - c)^2\}$$

$$A_2 = (b/a)^2 \{\phi(3 - c) + (1 - c)\} / \{4c(1 - c)\}$$

$$A_3 = (b/a)^2 (1 + \phi) / (4c)$$

$$A_4 = (b/a)^2 (1 - \phi) / \{4c(1 - c)^2\}$$

The energy relations of flow in the load conduits* are given by

$$p_1 + \rho U_1^2/2 = \zeta_1 \rho U_1^2/2 \quad \dots\dots\dots (17)$$

$$p_2 + \rho U_2^2/2 = \zeta_2 \rho U_2^2/2 \quad \dots\dots\dots (18)$$

where

p_1 and p_2 = pressure acting on $\overline{10,11}$ and $\overline{9,10}$, respectively

U_1 = mean flow velocity across $\overline{10,11}$ = $Q_1/1(10,11)$

$1(10,11)$ = distance between points 10 and 11

U_2 = mean flow velocity across $\overline{9,10}$ = $Q_2/1(9,10)$

$1(9,10)$ = distance between points 9 and 10

$1(10,11) = 1(9,10) = 1(1,5)$

ζ_1 and ζ_2 = loss coefficients in load conduits of attachment and non-attachment sides, respectively

The pressure is measured above or below that in the tank as a base. Using the continuity of flow $Q_s = Q_1 + Q_2$, Eqs. (17) and (18) reduce to

$$p_1 = \rho (\zeta_1 - 1) u_m^2 (b/a)^2 q_1^2/8 \quad \dots\dots\dots (19)$$

$$p_2 = \rho (\zeta_2 - 1) u_m^2 (b/a)^2 (1 - q_1)^2/8 \quad \dots\dots (20)$$

Substituting Eqs. (13) and (19) into Eq. (11) yields

$$p_B = \rho D_0 u_m^2 q_1^2/2 \quad \dots\dots\dots (21)$$

where

$$D_0 = (b/a)^2 \{(\phi + \zeta_1) - (1 - \phi)/(1 - c)^2 - 2\phi/(1 - c)\}/4$$

Assuming that the pressure acting on $\overline{1,2,3,4,6}$ is equal to p_B and neglecting the shearing forces acting on the control surface, equations of momentum in the directions of X and Y are expressed as follows:

$$\{J_1 + J_2 - J(1,4) - J(4,6)\} = \{1(1,4) + 1(4,6)\} p_B - 1(1,5) (p_1 + p_2) + (F_1 + F_2) \tan \theta \quad \dots\dots (22)$$

$$\{-J_1 + J_2 + J(1,4) - J(4,6)\} = \{-1(1,4) + 1(4,6)\} p_B + 1(1,5) (p_1 - p_2) + (F_1 - F_2) (1/\tan \theta) \quad \dots\dots\dots (23)$$

where

J_1 = flow momentum across $\overline{10,11}$ = $\rho 1(10,11) U_1^2$

J_2 = flow momentum across $\overline{9,10}$ = $\rho 1(9,10) U_2^2$

F_2 = force acting on $\overline{6,9}$

Substituting Eqs. (19), (20) and (21) into Eqs. (22) and (23), respectively, and combining Eqs. (22) and (23) by eliminating F_2 , q_1 with any ζ_1 and ζ_2 in the load conduits in the case of the flow divided by the splitter is given by

$$(-A_0 E_1 - D_0 E_2 + E_4 + E_5) q_1^2 - 2E_5 q_1 - E_3 + E_5 = 0 \quad \dots\dots\dots (24)$$

where

$$E_1 = 1(1,11)/1(1,5)$$

$$E_2 = E_1 + b T_1 + 1(4,6) T_2/1(1,5)$$

$$E_3 = 2b T_1/3 + 2(u_m/u_m)^2 1(4,6) T_2/\{31(1,5)\}$$

$$E_4 = (\zeta_1 + 1) (b/a)^2 T_1/4$$

$$E_5 = (\zeta_2 + 1) (b/a)^2 T_2/4$$

$$T_1 = (1 - \tan^2 \theta)/(2 \tan \theta), T_2 = (1 + \tan^2 \theta)/(2 \tan \theta)$$

* The load conduit includes the output port from the point of the splitter to O_1 or O_2 .

4.2 Case of flow joined with a reversed flow from output port of non-attachment side

Fig. 10 shows the proposed flow model in the amplifier in the case of the flow joined with a reversed flow from the output port of the non-attachment side. The flow regions, control volume and main assumptions made in this flow model are the same as those in section 4.1. Referring to the control surface, the attached flow enters the control surface across 1,4 and a reversed flow toward the upstream region of the non-attachment side leaves it across 4,6. The output volume flow rate of the non-attachment side Q_2 enters the control volume across 9,10 and that of the attachment side Q_1 leaves it across 10,11.

Assuming the velocity profile across 1,4 to be linear, $u(1,4)$, $l(1,4)$ and $l(4,6)$ are obtained by Eqs. (1), (3), (5) and (6). Assuming the velocity profile across 4,6 to be uniform yields

$$u(4,6) = u_{m1} \quad \dots\dots\dots (25)$$

where

u_{m1} = flow velocity profile across 4,6
Therefore, the volume flow rate across 1,4 $Q(1,4)$ and its momentum $J(1,4)$ are expressed by Eqs. (7) and (8), respectively, and the volume flow rate across 4,6 $Q(4,6)$ and its momentum $J(4,6)$ become

$$Q(4,6) = l(4,6)u_{m1} \quad \dots\dots\dots (26)$$

$$J(4,6) = \rho l(4,6)u_{m1}^2 \quad \dots\dots\dots (27)$$

Substituting Eq. (9) into Eq. (26) yields

$$u_{m1} = u_m/2 \quad \dots\dots\dots (28)$$

The energy relations of flow in the load conduits are given by

$$p_1 + \rho U_1^2/2 = \zeta_1 \rho U_1^2/2 \quad \dots\dots\dots (29)$$

$$p_2 + \rho U_2^2(1+\zeta_2)/2 = 0 \quad \dots\dots\dots (30)$$

The pressure is measured above or below that in the tank as a base. Using the continuity of flow $Q_1 = Q_s + Q_2$, Eqs. (29) and (30) reduce to

$$p_1 = \rho(\zeta_1 - 1)u_m^2(b/a)^2q_1^2/8 \quad \dots\dots\dots (31)$$

$$p_2 = -\rho(\zeta_2 + 1)u_m^2(b/a)^2(q_1 - 1)^2/8 \quad \dots\dots\dots (32)$$

Assuming that the pressure acting on 11,1,4,6,7,9 is equal to p_B and neglecting the shearing forces acting on the control surface, equations of momentum in the directions of X and Y are expressed as follows:

$$\begin{aligned} \{J_1 + J_2 - J(1,4) - J(4,6)\} = & \{l(1,4) + l(4,6) \\ & + \{l(1,11) + l(6,9)\}\tan\theta\}p_B - l(1,5)(p_1 - p_2) \end{aligned} \quad \dots\dots\dots (33)$$

Fig. 10 Flow model in amplifier in case of flow joined with a reversed flow from output port of non-attachment side

$$\begin{aligned} & \{-J_1 + J_2 + J(1,4) - J(4,6)\} \\ & = \{[-l(1,4) + l(4,6)] + \{l(1,11) \\ & \quad - l(6,9)\}(\tan\theta)\}p_B + l(1,5)(p_1 - p_2) \end{aligned} \quad \dots\dots\dots (34)$$

where

$l(6,9)$ = distance between points 6 and 9
Substituting Eqs. (31) and (32) into Eqs. (33) and (34) and eliminating p_B , q_1 with any ζ_1 and ζ_2 in the load conduits in the case of the flow joined with a reversed flow from the output port of the non-attachment side is given by

$$\begin{aligned} & (b/a)^2\{(\zeta_1 + 1)/2 - G_0(\zeta_2 - 1)/2\}q_1^2/2 \\ & + (b/a)^2G_0(\zeta_2 - 1)q_1/2 - \{(b/a)^2G_0(\zeta_2 - 1)/4 \\ & + 2b/3 + 2(u_{m1}/u_m)^2G_0l(4,6)/l(1,5)\} = 0 \end{aligned} \quad \dots\dots\dots (35)$$

where

$$\begin{aligned} G_0 &= (G_1 - G_2)/(G_1 + G_2) \\ G_1 &= \{-l(1,4)/l(1,5) + l(4,6)/l(1,5)\} \\ & \quad + \{l(1,11)/l(1,5) - l(6,9)/l(1,5)\}/\tan\theta \\ G_2 &= \{l(1,4)/l(1,5) + l(4,6)/l(1,5)\} \\ & \quad + \{l(1,11)/l(1,5) + l(6,9)/l(1,5)\}\tan\theta \end{aligned}$$

5. Comparison of numerical results with experimental data

Applying the configuration and dimensions of the amplifier used in the experiment to the proposed flow models, the calculation was performed under the following conditions: The point $7w_s$ is selected for the point 1 in the control surface with reference to the experimental results and the value of ϕ is so selected that ζ_1 and ζ_2 obtained from two flow models for $q_1 = 1$ agree respectively. Calculating

the value of ϕ for $\zeta_1 = \zeta_2$ yields $\phi = 0.095$. Considering that the loss coefficient due to enlargement in the case of the conventional conical diffuser is in the range of 0.1 to 1.2, the value of ϕ obtained are considered to be an appropriate one. The Newton method is applied to solve Eq. (24) in the case of the flow divided by the splitter.

Fig. 11 shows the numerical results of q_1 in the wide range of ζ_1 and ζ_2 and the experimental data with water and mineral oil* as the working fluid. It is found from the figure that the theoretical calculation on the characteristics agrees fairly well with the experimental data regardless of the many assumptions and that the flow pattern in the amplifier depends only on the load condition of the attachment side regardless of the load condition of the non-attachment side. The experiments performed in this study yield the flow divided by the splitter for $\zeta_1 \geq 4.2$ and the flow joined with a reversed flow from the output port of the non-attachment side for $\zeta_1 \leq 4.2$. For $\zeta_1 = \zeta_2$, q_1 approaches 0.5 as ζ_1 is increased (see dashed line in Fig. 11).

6. Conclusions

In this paper, the flow patterns were observed in detail in cases of the flow divided by the splitter and the flow joined with a reversed flow from the output port of the non-attachment side. As a result of experiments, it was clarified that:

- (1) The flow condition in the upstream region from the attachment point does not depend on the load.
- (2) The flow velocity profile of the attached flow which continues downstream over certain distances from the attachment point does not depend on the load.
- (3) The flow velocity profile of a reversed flow toward the upstream region of the non-attachment side depends on the flow pattern over certain distances downstream from the attachment point; that is, the profile in the case of the flow divided by the splitter is linear with a maximum near the adjacent wall of the non-attachment side and zero near the center of the conduit and that in the case of the flow joined with a reversed flow from the output port of the non-attachment side is approximately uniform.

The flow models in the amplifier were proposed by referring to these experimental phenomena and the effect of load on the characteristics of the amplifier was theoretically investigated. The theoretical calculation on the characteristics agreed fairly well with experimental data.

* The experimental data with mineral oil as the working fluid were obtained by using the amplifier geometrically similar to that in chapter 2 in this paper with the width of the main nozzle 1 mm (30) (31).

Experimental data

symbol	ζ_1	ζ_2	t °C	Re	q_1	fluid
●	14.2	14.2	13.0	27000	0.68	water
○	0.69	0.69	11.5	26500	1.58	water
■	30.3	30.3	40.0	4000	0.57	oil
□	30.3	6.49	60.0	4000	0.44	oil
▲	30.3	2.96	60.0	4000	0.40	oil
△	6.49	6.49	40.0	4000	0.87	oil
◆	6.49	2.96	60.0	4000	0.89	oil
◇	2.96	2.96	40.0	4000	1.17	oil

Fig. 11 Effects of ζ_1 and ζ_2 on q_1
($u_m/v_s = 1.00$, $u_m/v_s = 0.541$,
 $a = 1.449$, $b = 0.941$, $Re = 20000$.
The loss coefficient is the sum of the loss coefficient in the conduit between 01 or 02 and T and that in the conduit between the point of the splitter and 01 or 02. The former was obtained by measuring the volume flow rate and pressure difference and the latter was obtained by applying the Blasius formula of the friction coefficient of smooth pipes of circular cross section to the conduit with rectangular cross section. For the calculation of the friction coefficient, Reynolds number based on the hydraulic diameter $Re = 20000$ for water and $Re = 4000$ for mineral oil were used.)

As a result of calculations, it was clarified that:

- (4) The flow pattern in the amplifier depends only on the load condition of the attachment side regardless of the load condition of the non-attachment side (The experiments performed in this study yield the flow divided by the splitter for $\zeta_1 \geq 4.2$ and the flow joined with a reversed flow from the output port of the non-attachment side for $\zeta_1 \leq 4.2$).

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Appendices

(1) The results obtained by Myers are expressed as follows:

$$u_m/v_s = t_m = 1/\sqrt{0.0544(x/w_s - 7) + 1}$$

$$\delta_2/w_s = (1.33\text{Re}^{0.2} - 2.05 + 1.76rt_m)/(t_m^2\text{Re}^{0.2})$$

$$r = (0.523t_m^{10} + 0.477t_m^{-1})^{0.8}$$

where

u_m = maximum flow velocity of wall jet

δ_2 = distance between point with flow velocity of $u_m/2$ in outer layer and wall

x = distance from exit of main nozzle

(2) The seventh-root law and the results obtained by Schwarz and Cosart are expressed as follows:

$$u/u_m = (\eta/0.14)^{1/7}, \quad 0 < \eta < 0.14$$

$$u/u_m = \text{sech}^2(\eta - 0.14), \quad 0.14 < \eta < \infty$$

where

$\eta = y/\delta_2$

y = distance in inner direction perpendicular to wall

$y = \delta_m = 0.14\delta_2$ with $u = u_m$

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