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Characteristics of Flat-Seated Valves with Broader Seat-Face*

(8th Report, Experimental Research on Disc Valve)

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This paper presents the results of experiments on flat-seated valves with broader seat-face, discharging water into the air under a constant head of about 194 cm. Five valves were used in all, of which the first four had diameter d smaller than seat-face diameter d_1 and the last one had d equal to d_1 .

When the lift of the valves with $d < d_1$ is gradually increased, the steam flowing out separates partially from the seat-face at a certain valve-lift, and then separates completely from the seat-face at a higher lift and becomes free jet. When the valve is closing the free jet finally clings to the seat-face at a very small valve-lift. These are represented by three special points on the characteristic curve of each valve. In case of the valve with $d = d_1$, there are one separating and one clinging point on the curve, just as the valves with $d > d_1$ on which the authors have already reported.

They try to give some explanations for these phenomena hereunder.

1. Introduction

In the experiments on flat-seated disc valves hitherto reported⁽¹⁾ by the authors the diameter d of the valve was larger than or equal to the external diameter d_1 of valve seat-face, except in a few cases where d/d_1 was slightly smaller than unity.

A series of experiments was performed, in the Hydraulic Laboratory of Waseda University, on broader-seated valves with $d \leq d_1$ in the year 1955, along with the experiments on the narrow-seated ones described in the fourth Report. The results obtained were very complicated and of quite unexpected nature. In this paper an explanation of these phenomena is given as far as it is possible by the present knowledge.

Experimental apparatus and method of measurement were quite the same as those described in the fourth Report. The water was discharged through the valves into the air under a nearly constant head of about two meters. The angle θ

of issuing jet was measured only in a few cases.

Beside d and d_1 mentioned above the authors denote by d_0 valve-port diameter, hence $a_0 = (\pi/4)d_0^2$ port area, Q discharge through valve per unit time, P lifting force, g acceleration of gravity, γ specific weight of water.

Let h_I be the statical head (read from the valve seat-face) measured at a manometer hole I made on the wall of valve-chamber entrance and $v_I^2/2g$ be the velocity head in the same place, v_I being mean velocity of flow.

Then the total head H_I in this place is

$$H_I = h_I + v_I^2/2g \dots\dots\dots (1)$$

In the case of discharge in the air the authors take H_I as effective head as they have done before. Using this H_I the non-dimensional discharge is defined as

$$q = Q/a_0\sqrt{2gH_I} \dots\dots\dots (2)$$

also non-dimensional lifting force as

$$p = P/a_0\gamma H_I \dots\dots\dots (3)$$

When discharge coefficient c for a valve lifted by l is expressed as

$$c = Q/\pi d_0 l \sqrt{2gH_I} \dots\dots\dots (4)$$

we have the following relation from Eqs. (2) and

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(4)

$$q = cAl/d_0 \dots\dots\dots (5)$$

where l/d_0 is opening ratio of the valve.

For fundamental study of valve characteristics the total head H_0 determined at port-end should be adopted as effective head as was done in the fourth and seventh Reports. In this paper, however we treat principally the case where the opening ratio is smaller. In such a case it makes little difference on the values of p and q whether H_I or H_0 is used in computation. Hence for the sake of simplicity we use H_I as effective head in this paper and write H for H_I .

2. The valves tested

Both valves and valve-seats are made of brass. As shown in Fig. 1 the port diameter d_0 is 25 mm throughout the experiments, while there are two types of seat-face used; types A and B. In A-type the seat-face is flat and its external diameter d_1 is 39 mm. In B-type the seat-face is inclined and lowered at the outer edge, in one case by $t=0.5$ mm and in the other by $t=1.0$ mm. Hence in A-type t is zero.

Five kinds of valve were used in combination with the seats as shown in Fig. 1. Their diametral relations are given in Table 1. In the case of the flat seat ($t=0$) the diametral ratio d/d_0 is equal to the diametral ratio k of contact face, while in the case of $t>0$, $k=1$. Hence if we define lap-face

Fig. 1 Valve tested

Table 1 Dimensions of the valves tested

	Valve	t mm	d mm	d/d_0	k
A	e'	0	28.0	1.120	1.120
	f'	0	30.2	1.208	1.208
	g'	0	32.8	1.312	1.312
	h'	0	35.9	1.436	1.436
	i'	0	38.8	1.552	1.552
B	g''	0.5	32.8	1.312	1.0
	i''	0.5	38.8	1.552	1.0
	g'''	1.0	32.8	1.312	1.0
	i'''	1.0	38.8	1.552	1.0

Diameter of valve-port $d_0=25$ mm,
diameter of seat-face $d_1=39$ mm,
 $k=d/d_0$ when $t=0$,
 $k=d_0/d_0=1$ when $t>0$.

ratio as $r=(d-d_0)/2d_0$ we have for $t=0$, $r=(k-1)/2$, and for $t>0$, $r=0$.

3. Results of experiments

3.1 The experiments with A-type valve-seat ($t=0$)

In this case, the seat-face being broader, the stream adheres firmly to the seat-face and separates from the seat just only when the valve is opened sufficiently wide. The free jet issuing through the valve takes the same values of p , q and c as those obtained in the corresponding case in the fourth Report. Accordingly, in illustrating the characteristic curves for the valves $e' \sim i'$ in Figs. 2~6, the part of opening ratio larger than 0.16 is omitted. For the opening ratio $l/d_0 \leq 0.16$ non-dimensional discharge q is of smaller value, which enables us to use H_I as effective head instead of H_0 as stated in 1. When $l/d_0=0$ the authors got in their experiments $H_I=194.0 \pm 0.1$ cm, while when $l/d_0=0.16$, $H_I=193.7 \pm 0.1$ cm.

3.2 Experiments with valve-seat of B-type ($t>0$)

The valves g' ($d=32.8$ mm) and i' ($d=38.8$ mm) were tested in combination with the seat with $t=0.5$ and 1.0 mm. Their p - and c -curves computed from the experimental results are illustrated in Figs. 7 and 8. For the sake of comparison are added in Fig. 7 p - and c -curves for $t=0$ taken from Fig. 4, and in Fig. 8 those for $t=0$ taken from Fig.

Fig. 2 Valve e' , $d=28.0$ mm, ($t=0$)

6. We see in both figures that there is no separation point on p - and c -curves for $t=1.0$. This is due to the fact that as soon as the valve opens the stream separates completely from the seat-face.

In the case of $t=0.5$ mm the jet separates from the seat in earlier stage than in the case of $t=0$ and is apt to give rise to small vibration with higher frequency.

Fig. 3 Valve f' , $d=30.2$ mm, ($t=0$)

Fig. 4 Valve g' , $d=32.8$ mm, ($t=0$)

4. Considerations on the experimental results

4.1 Singular points on characteristic curves for valves with broader seat-face

At the present stage the authors' experimental

Fig. 5 Valve h' , $d=35.9$ mm, ($t=0$)

Fig. 6 Valve i' , $d=38.8$ mm, ($t=0$)

data for B-type seat ($t > 0$) are not sufficient to make consideration on them. So we are going to treat chiefly the cases of A-type seat ($t = 0$).

If we gradually open a flat-seated valve, in which $d \geq d_1$, the stream separates from the seat face at a certain valve lift l and becomes a free

jet, as reported in the authors' previous papers. This is named the first singular (or transition) point on characteristic curve and denoted by $(l/d_0)_1$. When the valve is closed gradually down from larger opening the free jet comes to adhere to the seat-face at a very small opening and fills up completely the narrow passage. The authors call this the second singular point and denote it by $(l/d_0)_2$. This singular point was seen in Fig. 9 of the fourth Report. Still more distinctly it appears in the characteristic curves for the valves described in this paper. This phenomenon occurs only in the case of discharging water in the air.

In the valves $e' \sim h'$, in which $d < d_1$, we have, as shown in Figs. 2~5, the third singular point denoted by $(l/d_0)_3$. In these valves the stream separates partially from the seat face at $(l/d_0)_1$ and separates completely at $(l/d_0)_3$. Fig. 9 is a

Fig. 7 Valve $d=32.8$ mm
 g'' for $t=0.5$ mm
 g''' for $t=1.0$ mm

Fig. 8 Valve $d=38.8$ mm
 g'' for $t=0.5$ mm
 g''' for $t=1.0$ mm

Fig. 9 Three singular points for a valve in which $d < d_1$ and $t = 0$

Fig. 10 Supposed features of stream through valve-seat

sketch of typical curve of non-dimensional lifting force p for these valves. On the other hand, in the case of valve i' , where $d=d_1$, the two singular points $(l/d_0)_1$ and $(l/d_0)_3$ coincide in the same way

Fig. 11 p -curves for five valves $e' \sim i'$, in which $d_1=39$ mm and $t=0$, being opened

as the valves with $d \geq d_1$ described in the previous reports.

4.2 The singular points $(l/d_0)_1$ and $(l/d_0)_3$

Fig. 10 shows supposed features of the stream flowing out through the valve seat at several stages of opening ratio.

(a) When valve opening is very small the stream fills up the narrow passage, owing to the lower value of Reynolds number.

(b) If the valve opening increases a little a local separation takes place at the inlet corner of passage, due to the inertia of stream. Until the top of the locally separated space reaches the outer edge of the valve, marked b , the pressure on the seat-face drops and accordingly the lifting force p decreases continuously.

(c) At the instant when the top of separated space overruns the point b the stream separates on the greater part of the seat-face. This corresponds to the first singular point $(l/d_0)_1$.

(d) The issuing stream, adhering to the

Table 2 Singular points on characteristic curves for broad-faced disc valves

Valve name	e'	f'	g'	h'	i'
Valve diameter d mm	28.0	30.2	32.8	35.9	38.8
Singular points	(1), $(l/d_0)_1$	0.016	0.023	0.040	0.042
	(2), $(l/d_0)_2$	0.006~0.009			
	(3), $(l/d_0)_3$	0.096	0.110	0.099	0.080

Table 3 Relations of diametral ratio of contact face, k , singular point $(l/d_0)_1$ and $p_{\min}$ for minimum of non-dimensional force, and non-dimensional force p' when valve is closed
 $k=d/d_0$ in case of $d \leq d_1$
 $=d_1/d_0$ in case of $d > d_1$

Valve chamber type	Valve name	diameter, inches, mm			$k=d/d_0$ (d_1/d_0)	Lap ratio r	$(l/d_0)_1$	$p_{\min}$	p'	H meter	Report No.
		valve port d_0	seat face d_1	valve d							
Vertical cylindrical	No.2	2 1/2"	3"	3"	1.20	0.10	0.018	0.83	1.43	1.37	1
	No.6	1 1/4"	1 1/2"	1 1/2"	1.20	0.10	0.020	0.83	1.45	1.48	2
	No.9	1 1/4"	1 3/4"	1 3/4"	1.40	0.20	0.040	0.47	1.47	1.48	3
Angle-valve type	c1	30	34.2	30.1	1.003	0	—	—	1.09	—	—
	c2	30	34.2	32.9	1.097	0.05	0.018	0.95	1.14	1.80	5 & 6
	c3~c5	30	34.2	36 or larger	1.140	0.07	0.020	0.85	1.16	—	—
Discharge in the air	k smaller	a	30.05	34.2	30.2	1.005	0	—	1.02	—	—
		b	30.05	34.2	32.8	1.092	0.046	—	1.09	—	—
		c, d	30.05	34.2	35.9 or larger	1.140	0.070	0.025	0.80	1.15	1.94
		e	25	28	28.0	1.120	0.060	0.020	0.92	1.14	—
		$f \sim i$	25	28	30.2 or larger	1.120	0.060	0.018	0.85	1.11	—
	k larger	e'	25	39	28.0	1.120	0.060	0.016	0.91	1.12	—
		f'	25	39	30.2	1.208	0.104	0.025	0.78	1.19	—
		g'	25	39	32.8	1.312	0.156	0.035	0.60	1.20	1.94
		h'	25	39	35.9	1.436	0.218	0.042	0.43	1.33	—
		i'	25	39	38.8	1.552	0.276	0.048	0.32	1.58	8

Note (1) In case of vertical cylinder type chamber we take average values of p' for larger chamber diameter D ,
 (2) Effective head H is the mean values of H for opening ratio $l/d_0 < (l/d_0)_1$.

outer-edge of the seat-face, forms a beautiful water-membrane just like a fully opened umbrella. In this state the pressure under the membrane is a little lower than the atmospheric pressure due to the effect of surface tension. Hence in this period the curve of lifting force p lies at a middle height as shown in Fig. 9.

(e) As the valve lifts higher and attains opening ratio $(l/d_0)_3$ the water-membrane tears down and the stream separates completely from the seat-face, forming a free jet.

In Fig. 11 are illustrated all of the p -curves for five valves $e' \sim i'$ together, in which $t=0$, up to the point where l/d_0 is a little higher than $(l/d_0)_1$. We see in Figs. 5 and 11 that an abrupt change in p -curves for valve h' occurs at $l/d_0=0.52$, while a minimum value p_m takes place at $l/d_0=0.42$. We take this value as $(l/d_0)_1$ for this valve. Also in valves e' (Fig. 2) and f' (Fig. 3) l/d_0 for the minimum value p_m in each curve is taken as $(l/d_0)_1$. The values of $(l/d_0)_1$ for the singular points, defined as above in the case of five valves $e' \sim i'$, where $t=0$, are given in Table 2, in which port diameter $d_0=25$ mm and external diameter of seat-face $d_1=39$ mm.

The values of p_m and $(l/d_0)_1$ for these valves are given in Table 3 together with those for all the valves tested and reported hitherto by the

authors. From this table two curves for p_m and $(l/d_0)_1$ are plotted against diametral ratio of contact face, $k=d/d_0$ or d_1/d_0 and illustrated in Fig. 12. In this figure we see that the points marked $\bullet$ for four valves $e' \sim h'$, where $d < d_1$, come on or near either of the two smooth curves with the points marked $\circ$ for the rest of the valves.

In Table 2 are given also the values of the second singular point $(l/d_0)_2$ and the third singular point $(l/d_0)_3$. As seen from this table the values of the third singular point $(l/d_0)_3$ depend on the values of $(d_1-d)/(d-d_0)$. In the valve h' $(d_1-d)/(d-d_0)$ is smaller and the action of surface tension on the water membrane seems to be weak.

E. Schrenk⁽²⁾ obtained for $(l/d_0)_3$ much larger values than those in the authors' experiments. The difference may be attributed to the fact that his experiments were carried out by discharging water in a water vessel through valves with larger dimension.

4.3 The second singular point $(l/d_0)_2$

This singular point can be seen only in the case of the valve discharging water into the air and is the lowest limit of l/d_0 for separation phenomena. In Fig. 13 we illustrate p - and q -curves enlarged for the valves g' ($d=32.8$ mm) and i' ($d=38.8$ mm), taken from Figs. 4 and 6. In both valves the second singular points appear at $(l/d_0)_2=0.008$ or thereabouts. These phenomena are:

Fig. 12 Singular points $(l/d_0)_1$ and minimum value p_m for flat-seated disc valve, $\bullet$ for valves $e' \sim h'$ where $d < d_1$, $\circ$ for the rest of valves

(a) g' , $d=32.8$, ($t=0$) (b) i' , $d=38.8$, ($t=0$)
Fig. 13 Singular points $(l/d_0)_2$ on p - and q -curves

caused by the nature of water adhering to metal surface, so that a quantitative explanation of it can not be given.

4.4 Flat-seated valve considered as divergent nozzle

A flat-seated disc valve is analogous to a short divergent nozzle fitted on the side of a tank, in that water flows through the diverging passage. In the latter there may exist two kinds of separation of stream. One takes place locally behind the inlet corner due to the inertia of flow and the other occurs at some point in the diverging passage due to a pressure rise along the boundary layer on the wall.

When a valve-seat passage is represented as a divergent nozzle with cone angle 2θ as shown in append-Fig. 3 in the appendix, we have relations given there by Eqs. (8') and (9') for θ and length ratio of the nozzle. This shows that for a given valve the area ratio of valve-seat passage is constant, being equal to k , while the angle θ becomes smaller as the opening ratio m decreases. When this idea is applied to the authors' experimental results the following conclusion might be drawn. The valves, when opened by $(l/d_0)_1$ correspond to nozzles so small in diverging angle and so short in length, that there can be no separation due to divergency.

It was on this supposition that the authors took into consideration only the local separation occurring behind the inlet corner as is shown Fig. 10. However, as already pointed out in 4.2, the opening ratio where an abrupt change in p -curve for valve h' occurs is larger than that for p_m , the minimum value of p (Fig. 11). This implies that there are more things to be considered in the problem of separation phenomena.

In the experiments of valves No. 2 and No. 3 described in the first Report the authors measured pressure head at several points on the valve-and seat-face. If we apply the same method to these broader-seated valves it may be one step forward to the solution of the problem.

Fig. 14 Simplified mode of pressure distribution on seat face

T. Uzawa⁽³⁾ recently wrote a paper on the theory for lifting force on a flat-seated valve in which a new hypothesis as to the cause of separation was introduced.

4.5 Lifting force when $l/d_0=0$

We get for $l/d_0=0$ a lifting force P' , accordingly a non-dimensional lifting force p' as follows, the nomenclatures being the same as already used,

(1) from the theory of viscous flow through a narrow passage (see the appendix)

$$p' = P'/a_0 \gamma H = (k^2 - 1)/2 \log_e k \dots \dots \dots (6)$$

(2) by integration, assuming a linear distribution of pressure on the seat face, as shown in Fig. 14,

$$p' = P'/a_0 \gamma H = (1 + k + k^2)/3 \dots \dots \dots (7)$$

(3) by multiplying the contact area by mean pressure

$$p' = P'/a_0 \gamma H = (1 + k^2)/2 \dots \dots \dots (8)$$

the authors plotted against the diametral ratio k the actual values of non-dimensional lifting force p' obtained from their experimental results hitherto reported (Table 3) and compared them with those computed by Eqs. (6), (7) and (8) as shown in Fig. 15.

In this figure the point for $k=1.005$ should be omitted, since this is for the case when there is no lap of face. The line $p'=k^2$ is for the case of seat face in a bad condition as illustrated in Fig. 16. The two points on this line correspond to those for the valves No. 2 and No. 6, in which $k=1.2$ as given in Table 3. The authors are unable

Observed values
 ○ vertical cylinder type chamber
 ● angle-valve type chamber
 ⊙ discharge in the air, when k is smaller
 ⊗ discharge in the air, when k is larger
 Fig. 15 Non-dimensional lifting force p' for $l/d_0=0$ plotted against diametral ratio of contact face, k

at present to find a reasonable explanation of such results. Except these three cases the experiment gave fairly good results as shown in the figure.

Fig. 16

From the figure we see that if the diametral ratio k is not too large, Eq. (8), the simplest of the three, may be used without any appreciable error.

Appendix

(1) Append-Fig. 1 shows flat-seated disc valves with diametral ratio of contact face, $k=r_2/r_1$. We consider now a case when the contact faces are precisely finished and the valve is set exactly on the seat. When the spaces S are very small compared with the contact length r_2-r_1 , we may neglect the term of velocity head in viscous-flow resistance. Thus the pressure head h at an arbitrary radius r is expressed as

$$h = H - \frac{6\nu Q}{\pi g s^3} \log_e \frac{r}{r_1} \quad (1')$$

where H is effective head, Q discharge, ν kinematic coefficient of viscosity and g acceleration of gravity.

At the exit end of the passage we have $h=0$, hence from Eq. (1') we have

$$H = (6\nu Q / \pi g s^3) \log_e k, \quad k = r_2/r_1 \quad (2')$$

From Eqs. (1') and (2') we have for the case when $s=0$

$$h = H [1 - \log_e (r/r_1) / \log_e k] \quad (3')$$

Then the lifting force P' for $s=0$ is

$$P' = \pi r_1^2 \gamma H + \int_{r_1}^{r_2} \gamma h 2\pi r dr \\ = \pi r_1^2 \gamma H (k^2 - 1) / 2 \log_e k \quad (4')$$

$$\therefore p' = \frac{P'}{\pi r_1^2 \gamma H} = \frac{k^2 - 1}{2 \log_e k} \quad (5')$$

At present we are performing experiments in which the effective head H is varied stepwise from 9 to 194 cm. The measured values of P' agree fairly well with those computed by Eq. (4').

Append-Fig. 2 shows the pressure head distribution on the seat face for the case of $r_2/r_1=2$ when $s=0$ as an example.

If we rewrite Eq. (2') as

$$Q = (\pi g H / 6\nu \log_e k) s^3 \quad (6')$$

we have for discharge coefficient c at $s=0$

$$c = Q / 2\pi r_1 s \sqrt{2gH} \propto s^2 \\ = 0 \quad (7')$$

On the other hand, as to the discharge for very small opening ratio, the authors have found that the problem is far more complicated.

(2) A valve-seat passage shown in append-Fig. 1 is represented as a divergent nozzle as in

Append-Fig. 1

Case of $r_2/r_1=2$ Append-Fig. 2 Pressure head distribution on the seat face when $l/d_0=0$

Append-Fig. 3 A divergent nozzle with the same area-ratio and length with a flat-seated valve

append-Fig. 3, in which inlet area $\pi R_1^2 = 2\pi r_1 s$, outlet area $\pi R_2^2 = 2\pi r_2 s$ and length $r_2 - r_1$. When 2θ is the cone angle we have relations as follows ;

$$\tan \theta = \frac{R_2 - R_1}{r_2 - r_1} = \frac{2\sqrt{m}}{\sqrt{k} + 1} \quad (8')$$

and

$$\text{length ratio} = \frac{r_2 - r_1}{R_1} = \frac{k - 1}{2\sqrt{m}} \quad (9')$$

in which $k = r_2/r_1$, and $m = s/2r_1$

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Discussion

K. TABUSHI: (1) When the flow separates from the valve seat, curves $p-l/d_0$, $c-l/d_0$ appear not to be affected by d_1 , t and d . In this case c is considered, neglecting losses, to be coefficient of contraction at a Fig. 10. How is the actual flow?

(2) If the corner of the valve seat is rounded up, separation may occur between a and c (Fig. 10) also. How sharp is the corner?

(3) l/d_0 is very effectual as main parameter to simplify the results. Supposing l/d at c is better as chief variable, for the pressure there is approximately constant while at a changes considerably, and it was attempted to simplify the experimental data, but the result was not as expected. To take $l/(d-d_0)$ as standard variable and shape of valve, Reynolds number, Weber number etc. as parameters seems to be another way. How is the author's opinion?

(4) The characteristic point 2 is reported not to appear when water discharges into water. Does this mean that $p-l/d$ curve has no loop then?

Author's closure

(1) We are unable to find a simple relation between the discharge—and contraction—coefficient for a flat-seated disc valve issuing water freely as a jet. Thickness δ of the jet does not much increase even for a large valve-opening l ; hence δ/l decreases as l/d_0 increases. When l/d_0 is very small, δ/l_0 in the case of non-viscous fluid takes a value a little larger than 0.6, while in actual cases

the coefficient of discharge attains a value as large as 0.9 or more, due to the effect of viscosity of fluid (see Figs. 2~6).

(2) If the inlet corner of valve seat is sufficiently rounded, any separation will not occur in the passage and the characteristic curve will take a quite different feature*. In the author's case the Right-angled inlet-corner was finished as accurately as possible. After the experiments it was confirmed by inspection that the corner had been kept in good order.

(3) In general it may be reasonable to define the discharge coefficient at the inlet of valve-seat passage.

For the case where the valve-lift is very small in broader-seated disc valve, application of viscous-flow theory, though tried by so many people, has yet offered no exact solution.

Seen from the action of surface tension on water membrane formed around the valve when the opening ratio is very small, Weber number can be introduced, as you suggest, into consideration.

(4) When water is issued under the water surface through a valve with very small opening ratio, water fills the narrow space left between the jet and seat-face and offers so much viscous resistance that the flow can not make a free jet. This is the reason why the loop of characteristic curve can not exist in this case.

* L.F. Welanetz, *J. Appl. Mech.*, Vol. 23, No. 2, (June 1956), p. 271, Fig. 2.