An Experimental Study on Vortex Breakdown in Straight and Divergent Pipes

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(Received May 30, 1974)

1. Introduction

An abrupt change in the structure of a swirling flow has been observed to occur in flow fields of delta wings at large incidences and axisymmetric pipe flows with a swirl component. This abrupt change, which is called the vortex breakdown, has a lot of peculiar features among which an expansion of the core, stagnation and reversal of the flow, and changes in the velocity and pressure profiles are typical examples. The vortex breakdown is important for flight performance of delta type planes. In fact, its occurrence over wings has a bad influence on wing characteristics. The significance of the vortex breakdown in wider classes of fluid machines is also worth noting.

Since Peckham & Atkinson, Elle and Lambourne & Bryer drew attention to its occurrence over wings, the phenomenon has been studied both experimentally and theoretically. While the spiral type of breakdown is commonly seen over wings, Harvey[1)] observed the axisymmetric type of breakdown, with a characteristic bubble, in a straight pipe. In addition, Sarpkaya[2),3)] found out very recently the triangular sheet type of breakdown in a divergent pipe. It has been shown that the type and the position of breakdown depend upon the particular combination of the Reynolds and circulation numbers.

On the other hand, theoretical explanations of the breakdown have been in dispute[4)]. They may be divided into three categories as follows;

(i) The breakdown is caused by a kind of hydrodynamic instability (Ludwieg).

(ii) The breakdown is a phenomenon like the boundary layer separation (Hall[5),6)]).

(iii) The breakdown is a finite transition between two steady states of axisymmetric swirling flow, analogous to the hydraulic jump in open channel flows (Benjamin [7),8),9)]).

In spite of these interesting studies, however, it seems that our understanding

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of the vortex breakdown still remains only incomplete. The aim of the present report is to describe the first phase of authors' related study now in progress. Main results are visual observations and position measurements of the breakdown generated in water flows through a straight and two kinds of divergent pipes at various values of the Reynolds number and the swirl parameter.

Notation

d_1, d_2	;	inner diameter of the test pipe
h	;	total head of the water reservoir
Q	;	flow rate
$Re=d_1 \cdot \bar{v}_z/\nu$	;	Reynolds number
(r, θ, z)	;	cylindrical coordinates
$\bar{v}_z=4Q/\pi \cdot d_1^2$	;	mean axial velocity
α	;	angle of divergence of the test pipe
β	;	tip angle of the guide vanes
ϑ	;	set angle of the guide vanes
ν	;	kinematic viscosity of the water

2. Apparatus

As is shown in Fig. 1, the experimental apparatus is essentially composed of a water reservoir, a swirl generator and a horizontal test pipe. The reservoir is about 75cm long, 55cm wide and 65cm high, and the test pipe is made of transparent acrylic resin for visualization. The water supplied from the inlet pipe 1, flows into the swirl generator through two gauze screens 2. Any amounts of a swirl is imparted to the water by adjusting the set angle ϑ of six-

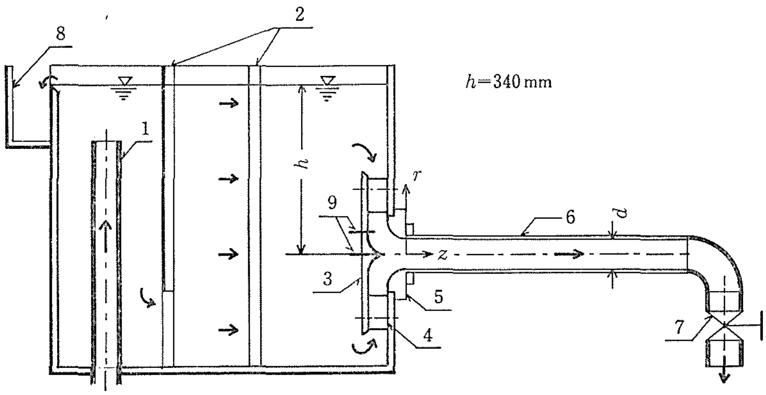


Fig. 1 Experimental apparatus (not to scale)

teen guide vanes 4 placed symmetrically within the swirl generator. The water from the swirl generator is conveyed smoothly through a gap between an entrance piece (center-body) 3 and a bell-mouth into the test pipe 6, where the vortex breakdown is generated*. The total head h is kept constant by a simple over-flow system 8. For the purpose of observing flow patterns and measuring the position of the breakdown, two dye injection tubes 9 are attached to the center-body**.

The flow rate through the test pipe is regulated by the sluice valve 7, and is measured by a measuring cup. A part of the guide vane geometry is sketched in Fig. 2. Each of the sixteen two-dimensional guide vanes used is 60mm in the chord length, 18mm in the maximum thickness and 30mm high. The vane angle ϑ is measured from the radial position as is shown in Fig. 2, so that the amount of swirl imparted to the water increases with ϑ. Since the tip angle β is 22.5 (=360/16) degrees, the width b between neighboring vanes remains uniform in the flow direction regardless of the value of ϑ. Shapes and dimensions of the three kinds of test pipe are shown in Fig. 3.

In the followings, the flow rate is denoted by Q, and the mean axial velocity at the entry of the test pipe by $\bar{v}_z=4Q/\pi d_1^2$, where d_1 is the inner diameter of the pipe at the inlet section.

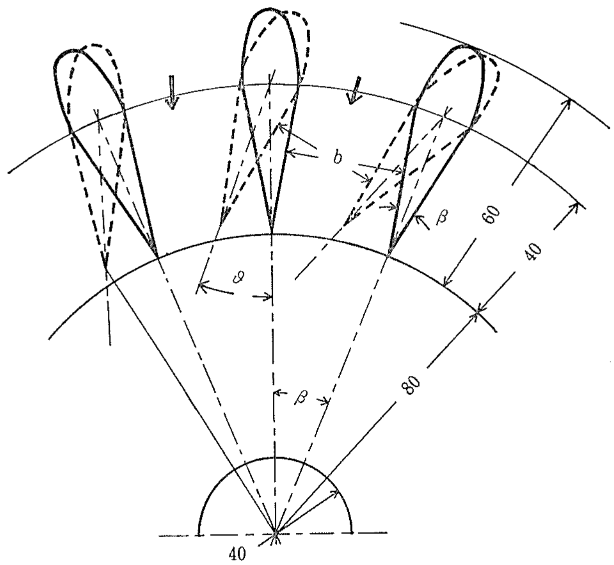
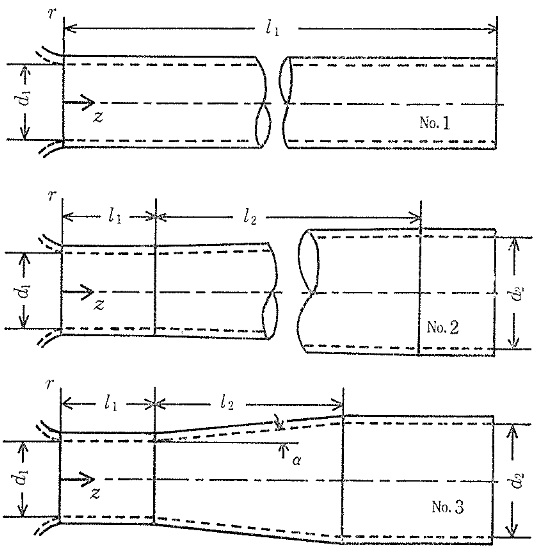


Fig. 2 Vane geometry (figures are in mm).

* This figure shows the straight pipe case.

** The tubes are about 1mm in diameter. They are located at the axis and at about 5 cm above the axis of the test pipe, respectively.



	$d_1$mm	$d_2$mm	$l_1$mm	$l_2$mm	$\tan \alpha = \frac{d_2 - d_1}{l_2}$	α^0
test pipe No. 1	40	40	1400	—	0.00	0.00
test pipe No. 2	40	60	50	500	0.02	1.15
test pipe No. 3	40	60	50	100	0.10	5.73

Fig. 3 Shapes and dimensions of the test pipes.

3. Experimental results

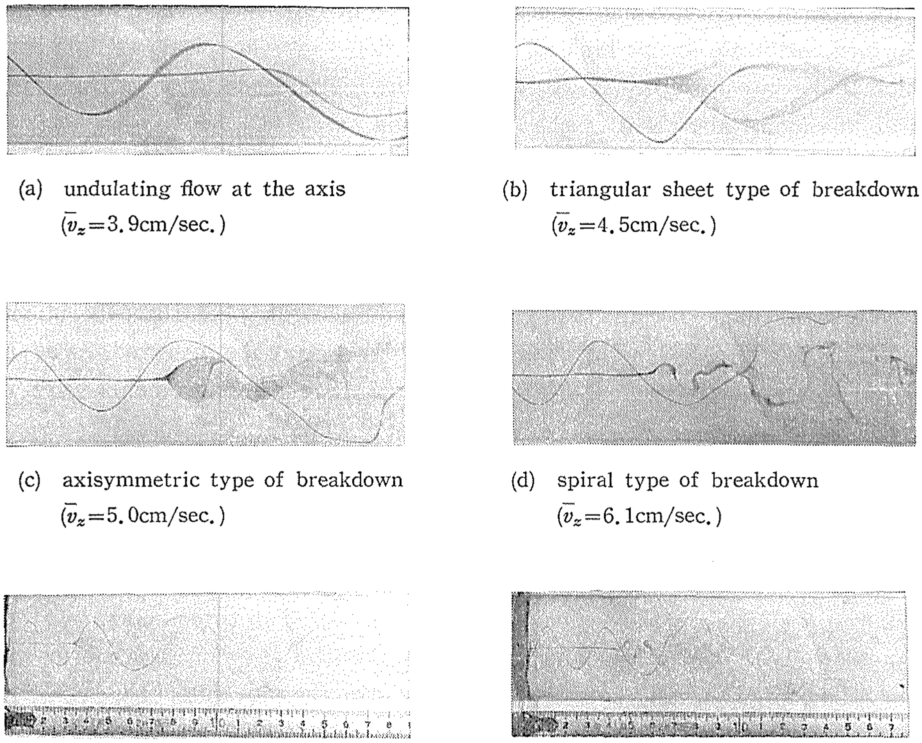
Flow observation

Observations show that the nature of the breakdown and the position of stagnation are strongly influenced by the flow rate Q, the angle α of divergence of the test pipe as well as the set angle ϑ of the guide vanes. Several series of experiments were made by changing the flow rate through the test pipe, with ϑ being fixed in each series. The values of ϑ in these experiments ranged from 35° to 50° by every five degrees. For illustration, however, all the pictures shown below are particularly concerned with the case of $\vartheta = 45°$ which was typical of the present observations.

(a) The straight pipe case (test pipe No. 1, $\tan \alpha = 0$).

When the mean axial velocity $\bar{v}_z$ was increased from 0, the dye filament on the axis gradually began to undulate like Fig. 4 (a). At this stage, there appeared no distinct stagnation point on the axis.

If $\bar{v}_z$ was increased a little more, the flow near the axis was decelerated



(a) undulating flow at the axis
($\bar{v}_z$=3.9cm/sec.)

(b) triangular sheet type of breakdown
($\bar{v}_z$=4.5cm/sec.)

(c) axisymmetric type of breakdown
($\bar{v}_z$=5.0cm/sec.)

(d) spiral type of breakdown
($\bar{v}_z$=6.1cm/sec.)

(e) moving type of breakdown
(axisymmetric form)
($\bar{v}_z$=12.7cm/sec.)

(f) moving type of breakdown
(spiral form)
($\bar{v}_z$=12.7cm/sec.)

Fig. 4 Various types of breakdown in the straight pipe ($\vartheta = 45°$). The off-axis dye filament upstream of the breakdown gyrates in a regular way, but it breaks into irregular form at the position of the breakdown. The pictures are taken with an exposure of 1/60 sec.. Note that the apparent scale of phenomenon in the radial direction is about 30% greater than the actual one because of the refraction effect of water.

rapidly and the filament expanded into a slightly curved triangular sheet, filling the entire test pipe downstream. This type of breakdown is referred to as the triangular sheet vortex breakdown (Fig. 4 (b))*.

For larger $\bar{v}_z$, the axisymmetric type of vortex breakdown like Fig. 4 (c) was observed. The axial filament spread symmetrically from the stagnation point to form a closed "bubble". The flow downstream of the bubble was likely to be similar to that upstream of the breakdown, and then became turbulent.

When $\bar{v}_z$ was increased from the stage just mentioned, the spiral type of

* This type is called the double helix breakdown by Sarpkaya[2),3)].

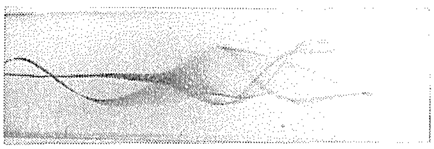
vortex breakdown was found to occur as shown in Fig. 4 (d). The axial filament deformed, with an abrupt kink at the stagnation, into a spiral configuration, which broke into turbulence after a few turns. The sence of rotation of the spiral was identical to that of the off-axis fluid particles.

In the next stage, the position of the stagnation was no more stationary but moved to and fro along the axis. During the upstream movement, the brokendown filament was of an axisymmetric form (Fig. 4 (e)). During the downstream movement, on the other hand, it was of a spiral form (Fig. 4 (f)) or an axisymmetric form or an intermediate form according as the experimental conditions (see Fig. 7–9). This type of breakdown may be referred to as the moving vortex breakdown. It should be noted that the movements were not strictly periodic.

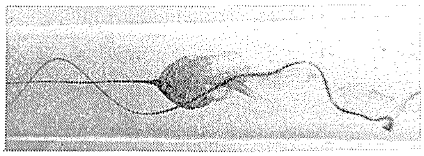
When $\bar{v}_z$ was increased still more, the flow near the axis became turbulent, and the breakdown could not be observed.

(b) The divergent pipe cases (test pipes No. 2, No. 3).

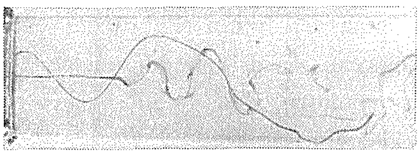
Typical appearances of the breakdown in the pipe of smaller divergence No. 2 ($\tan \alpha = 0.02$) are shown in Fig. 5 (a), (b), (c). The three types, viz. the triangular sheet, the spiral and the axisymmetric types of breakdown were observed in an essentially similar way to the straight pipe case.



(a) triangular sheet type of breakdown ($\bar{v}_z = 3.5$ cm/sec.)

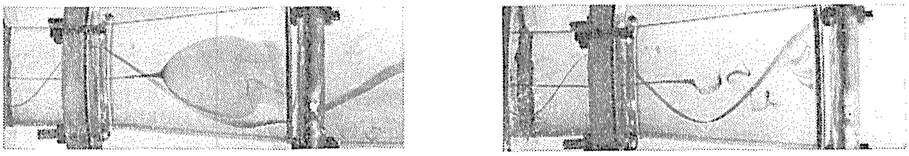


(b) axisymmetric type of breakdown ($\bar{v}_z = 4.0$ cm/sec.)



(c) spiral type of breakdown ($\bar{v}_z = 5.0$ cm/sec.)

Fig. 5 Three typical types of breakdown in the divergent pipe No. 2 ($\tan \alpha = 0.02$). $\vartheta = 45°$.



(a) axisymmetric type of breakdown ($\bar{v}_z = 2.8$cm/sec.) (b) spiral type of breakdown ($\bar{v}_z = 3.1$cm/sec.)

Fig. 6 Two typical types of breakdown in the divergent pipe No. 3 ($\tan\,\alpha = 0.1$). $\vartheta = 45°$.

In the pipe of larger divergence No. 3 ($\tan\,\alpha = 0.1$), the spiral and the axisymmetric breakdowns were observed (Fig. 6 (a), (b)). In contrast with the foregoing cases, the scale of the axisymmetric bubble was considerably greater and the triangular sheet breakdown could not be observed.

The moving breakdown was also observed in the divergent pipe cases, but it became less and less remarkable as the angle α of divergence was increased.

Position measurements

Results of quantitative position measurements are shown in Figs. 7, 8, 9.

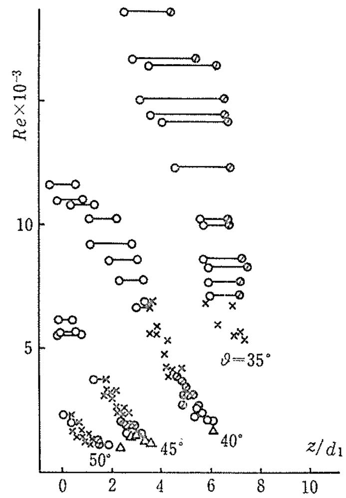


Fig. 7 The type and position of vortex breakdown vs. the Reynolds number Re and the set angle ϑ of the guide vanes. This is the results in the straight pipe No. 1. ○, axisymmetric type of breakdown; ×, spiral type of breakdown; △, triangular sheet type of breakdown; ⊘, intermediate type of spiral and axisymmetric types; ○—×, ○—⊘, ○—○, moving type of breakdown.

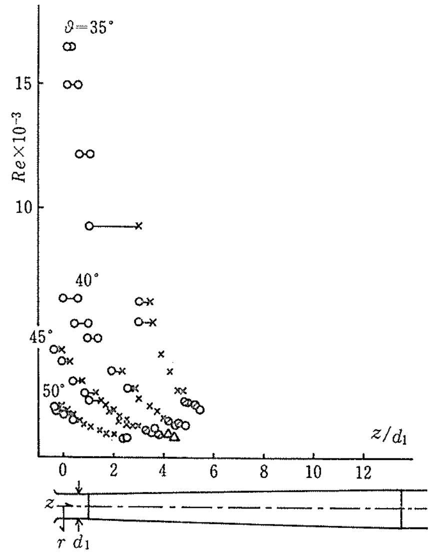


Fig. 8 The type and position of vortex breakdown vs. the Reynolds number Re and the set angle ϑ of the guide vanes. This is the results in the divergent pipe No. 2 ($\tan\,\alpha = 0.02$). Symbols are the same as in Fig. 7.

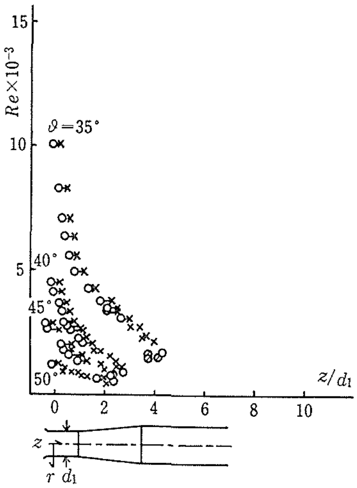


Fig. 9 The type and position of vortex breakdown vs. the Reynolds number Re and the set angle ϑ of the guide vanes. This is the results in the divergent pipe No. 3 ($\tan\alpha=0.1$). Symbols are the same as in Fig. 7.

They are briefly summarized as follows;

(a) Types of the stationary vortex breakdown phenomena in straight and divergent pipes can be classified into the triangular sheet, the spiral and the axisymmetric ones. The type and the position of the breakdown depend upon the axial Reynolds number $Re=\bar{v}_z \cdot d_1/\nu$, the set angle ϑ of the guide vanes as well as the angle α of divergence of the test pipe.

(b) The transition between different types takes place continuously rather than abruptly. However, the order of successive types differs from that of the results by Sarpkaya[2),3)].

(c) The moving type of breakdown which has not been described by Sarpkaya[2),3)] is observed for higher values of Re. It is not clear at present whether this is of universal character or this is caused by certain specific disturbances inherent in the experimental apparatus.

(d) In general the position of breakdown shifts upstream with increases of Re, ϑ and α. The range where the breakdown is observed has a tendency to decrease with increasing ϑ and α.

(e) The triangular sheet breakdown appears in the lowest Reynolds number range, and this type is observed in straight and slightly divergent pipes only.

4. Concluding remarks and acknowlegement

Observations and measurements of the type and position of breakdown were made in straight and two divergent pipes. As is seen from the illustrating pictures (Figs. 4, 5, 6) the phenomenon has a large variety of appearances depending upon the experimental conditions such as the Reynolds number, the angle α of divergence of the test pipe and the set angle ϑ of the guide vanes. Since ϑ relates to a swirl ratio, where the breakdown is generated, and α relates to the degree of divergence of the streamlines as well as to the wall pressure gradient in the test pipe, it appears that in effect the type and position of breakdown depend upon the swirl ratio, the wall pressure gradient, the degree of divergence of the streamlines and the Reynolds number. In the present experiment, however, the Reynolds number could not be varied without changing the swirl ratio. The next step is thus to measure the velocity and pressure profiles before and after the breakdown in oder to separate the effects of these parameters in a proper way. Unfortunately, it is not an easy task to carry out these measurements by conventional method of inserting a test probe into the flow field, because the breakdown is found to be highly sensitive even to very small disturbances. This kind of difficulty might be minimized by introducing some optical measurements which are now being planned.

The authors wish to express their hearty thanks to Professor Michio OHJI for his interest and guidance in this study. Thanks are also due to Messrs. Y. YAMANE and T. IKEDA who were so helpful in the experimental work.

References

1) J. K. Harvey, "Some observations of the vortex breakdown phenomenon" *J. Fluid Mech.*, Vol. **14** (1962), 585–592.

2) T. Sarpkaya, "On stationary and travelling vortex breakdowns" *J. Fluid Mech.*, Vol. **45** (1971), 545–559.

3) T. Sarpkaya, "Vortex breakdown in swirling conical flows" *J. AIAA*, Vol. **9**, No. **9** (1972), 1792–1799.

4) M. G. Hall, "Vortex breakdown" *Ann. Rev. Fluid Mech.*, Vol. **4** (1972), 195–218.

5) M. G. Hall, "A numerical method for solving the equations for a vortex core" *Aero. Res. Counc. R & M* **3465** (1965), 29.

6) M. G. Hall, "A new approach to vortex breakdown" *Proc. Heat Transfer Fluid Mech. Inst.*, (1967), 319–340.

7) T. B. Benjamin, "Theory of the vortex breakdown phenomenon" *J. Fluid Mech.*, Vol. **14** (1962), 593–629.

8) T. B. Benjamin, "Significance of the vortex breakdown phenomenon" *J. Basic. Engng.*, *Trans. ASME.*, *Ser.* **D** Vol. **85** (1965), 518–524.

9) T. B. Benjamin, "Some developments in the theory of vortex breakdown" *J. Fluid Mech.*, Vol. **28** (1967), 65–84.