An Experimental Study of Baroclinic Flows in an Open Cylinder

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Abstract

Baroclinic flows in an open cylinder with rim heating and center cooling are studied by laboratory experiments. The experiments have been carried out at room temperature, kept as close as possible to the rim temperature, without any additional heating such as the internal heating due to incandescent lights employed by Spence and Fultz (1977).

Visual observations and temperature measurements of the top-surface have shown that axisymmetric time-independent flows, steady waves and regular periodic vacillations occur, in addition to irregular wavy flows. A régime diagram for these flows is presented with the fluid depth as ordinate and the angular speed as abscissa. Flow characteristics revealed by the temperature measurements are also described.

1. Introduction

Laboratory experiments of baroclinic waves have contributed to a large extent to our knowledge of the general circulation of the atmosphere. In the experiments, most of the investigators have adopted annular containers [originated by Hide (1953)] rather than open cylindrical containers [originated by Fultz (1951)]. This is due to the fact that open-cylinder experiments did not easily produce stable and reproducible results, though the cylindrical configuration bears a closer resemblance to the geometry of the atmosphere than the annular configuration.

Spence and Fultz (1977), however, reinvestigated baroclinic flows in the cylindrical configuration (see Fultz et al., 1959) using a new apparatus improved in the control of external conditions and in instrumentation, and obtained completely axisymmetric flows, steady waves, periodic vacillation states and a régime diagram comparable to those obtained in annulus experiments [see Hide (1958); Hide and Mason (1975)]. They stressed in their paper that the internal heating due to incandescent lights plays an important role in the production of stable and reproducible results.

Nevertheless, without any additional internal heating, we have obtained axisymmetric flows, steady waves and vacillations in an open cylindrical container with rim heating and center cooling similar to theirs. Our experiments were carried out by keeping the room temperature as close as possible to the rim temperature; therefore, the essential role of the internal heating employed by them can be regarded as making the main body of the working fluid statically stable.

This experimental study is confined to visual observations and temperature measurements of the top-surface, because flow fields tended to be seriously modified by probes when they were inserted into the working fluid. Internal structures and energetics of flows will be revealed by numerical study, which is the subject of a subsequent study.

2. Experimental apparatus and techniques

The main parts of the experimental apparatus are shown in Fig. 1 schematically. A brass cap A for center cooling and a brass cylinder B for rim heating are embedded concentrically in a polyvinyl chloride base C 3.0 cm thick and 46.0 cm in diameter. The outer radius of A with a thickness of 0.20 cm, is 4.468 cm. The inner radius of B with a thickness of 0.20 cm and a height of 14.5 cm, is 9.663 cm. The outer cylinder D and a cold water container E are made of polyvinyl chloride; their inner radii are 19.7 cm and 29.7 cm, respectively. The base of the convection chamber, C, is held by three columns at a height of 5.0 cm from the bottom of E. The temperature of the cap A was maintained at $T_a = 23.00 \pm 0.02^\circ C$ by cold circulating water, while the temperature of the cylindrical wall B was maintained at $T_b = 27.00 \pm 0.02^\circ C$ by warm circulating water. The flow rate and speed at the outlet of each circulating water system were estimated at 130 cm$^3$/s and 100 cm/s, respectively. The open cylindrical space was filled with water as a working fluid W to a depth $d$ of 1.5–5.0 cm. Above the upper surface of the working fluid was fixed a transparent
acrylic lid F of 1.5 cm thickness, which reduced the effects of evaporation and wind stress on the working fluid. The room temperature was maintained at 27.0 ± 0.5°C and the depth of the water for rim heating was set at 10 cm. Thereby the temperature of the air overlying the working fluid was made very close to $T_b$. The main body of the working fluid was, as a result, kept statically stable without any additional heating. The container E was mounted on a turntable G which rotated counterclockwise about a vertical axis. The angular speed $\Omega$ of the turntable was variable from 0 to 2.6 rad/s and controlled within an accuracy of ±0.001 rad/s.

Use was made of two needle-shaped thermistor probes TT suspended from the lid to detect surface temperature variations. Each probe consisted of a bead thermistor 0.8 mm in diameter, which was set at the tip of a stainless tube 1.3 mm in diameter. The tips were located at $(r, \theta, z) = (4.5 \text{ cm}, 0^\circ, d)$ and $(9.0 \text{ cm}, 180^\circ, d)$, being in contact with the top-surface, where $r$, $\theta$ and $z$ are the radial distance from the axis of rotation, the azimuthal angle and the height from the bottom of the working fluid, respectively.

Flow patterns were visualized by aluminum powder scattered on the free top surface. When taking photographs, apart from visual observations, we made the following arrangements beforehand: first, the lid with thermistor probes was removed; secondly, a small amount of India ink (about 0.2 cm$^3$) and a surface-active agent (about 0.05 cm$^3$) were added to the working fluid with stirring; lastly, another lid with no obstacles was fixed on the open cylinder. A camera was mounted on the axis of rotation 0.7 m above the top-surface; fluorescent lamps were used for the light source.

3. Experimental results

3.1 Top-surface flow patterns

Examples of top-surface flow patterns showing different flow types are given in Figs. 2–5. The fluid depth was 3.0 cm, with the exception of 4.0 cm in the case of vacillation (Fig. 4); the exposure time was 3 seconds for all top-surface streak photographs.

Figure 2 shows an axisymmetric time-independent flow observed at $\Omega = 0.199$ rad/s. The flow direction is counterclockwise and the maximum zonal velocity, being about 3 mm/s, is located near the mid radius. Steady wave flows of wavenumber $M = 2$ observed at $\Omega = 0.240$ rad/s and 0.270 rad/s are shown in Fig. 3. The elliptical stream with the maximum speed estimated at 3.0–3.5 mm/s, is blunt at a low angular speed (Fig. 3a) but it becomes sharp at a high angular speed (Fig. 3b). The whole flow pattern drifts counterclockwise with a steady speed; the time required for a complete revolution of the flow pattern relative to the rotating cylinder is about 5 minutes. Figure 4 shows the extreme stages of periodic vacillation observed at $\Omega = 0.348$ rad/s for $d = 4.0$ cm. The flow pattern vacillates regularly between a circular stage (Fig. 4a) and a fully developed elliptical stage (Fig. 4b). The times required for the waves to amplify (Fig. 4a to 4b) and to decay (Fig. 4b to 4a) are about 13.5 and 8.5 minutes, respectively. Careful examinations of streak photographs indicated that the center of the regular flows described above coincides with the axis of rotation; this was confirmed by temperature measurements made for Sections 3.2 and 3.3.

Figure 5 presents examples of irregular wavy
flows, which are accompanied by a continuous or a few discontinuous meandering streams near the rim. Figure 5a shows the flow observed at $\Omega = 0.362$ rad/s. The center of this flow drifted around the axis of rotation and the flow pattern of wavenumber 2 fluctuated irregularly. The flow at $\Omega = 0.500$ rad/s behaved almost identically with the above flow but developed from time to time double cyclonic eddies as shown in Fig. 5b. The higher the angular speed, the more irregular the wavy flows became. Thus the identification of the dominant wavenumber tended to be difficult but we observed that clear flow patterns, such as Figs. 5c and 5d, appeared at intervals of 20 to 40 minutes and persisted for several minutes.

3.2 Régime diagram

Figure 6 shows the positions of the various flow régimes in a diagram with fluid depth $d$ as ordinate...
and angular speed $\Omega$ as abscissa. The number in the figure denotes the dominant wavenumber $M$. Notations $A$, $S$, $V$ and $Ir$ denote axisymmetric (time-independent) flow, steady wave flow, (regular periodic) vacillation and irregular (wavy) flow, respectively. This régime diagram was made with the aid of temperature traces from the probes located on the top-surface under visual observations. The experiments were carried out by varying the angular speed $S$ stepwise for each fluid depth $d$ under the fixed temperature difference $\Delta T \equiv T_b - T_a = 4.0$ K. The increment or decrement of $\Omega$ in regular flow régimes was usually 0.01–0.02 rad/s but about 0.005 rad/s near transition points between the axisymmetric flow and the steady wave flow. Typical experiments to determine the final stable states were run for more than 3 hours, though most of flows became stable in about 1 hour.

The top-surface temperature measurements have revealed the following.

(1) The radial temperature gradient of the axisymmetric flows increases with $\Omega$.

(2) For $d \geq 2.5$ cm, the axisymmetric flow transits...
to the steady wave flow of $M = 1$ as $\Omega$ is increased. With more increase of $\Omega$, the flow of $M = 2$ appears and grows to overcome the flow of $M = 1$; that is, there exists a narrow regime, denoted by $1&2$, where two waves of $M = 1$ and 2 coexist. Although a similar régime was also found by Spence and Fultz (1977), a more detailed study is required to reveal the characteristics of these two waves. On the other hand, for $d = 1.5$ cm, the axisymmetric flow transits to the steady wave flow of $M = 2$ directly as $\Omega$ is increased.

(3) The temperature amplitude of steady waves of $M = 2$ increases with $\Omega$.

(4) Vacillation occurs for $d \geq 3.0$ cm and its régime is located between the steady wave régime and the irregular flow régime. The decayed stage (Fig. 4a) and the grown-up stage (Fig. 4b) of the vacillating flow almost coincide with the minimum and maximum stages of the envelope of the temperature trace as shown in Fig. 7, respectively. The variation of the envelope is small near the transition region from the vacillation ($2V$) régime to the steady wave ($2S$) régime and becomes large with increasing $\Omega$. This tendency is similar to that of “tilted-trough” vacillations [intensified with increasing $\Omega$ (Tamaki and Ukaji, 1993)] rather than “amplitude” vacillations [intensified with decreasing $\Omega$ (Fowlis and Pfeffer, 1969; Tamaki and Ukaji, 1985)] observed in annulus experiments, though the flow patterns (Fig. 4) resemble those of “amplitude” vacillations.

(5) We defined a flow accompanying quasi-periodic or irregular oscillations on the temperature trace as an irregular flow. Quasi-periodic flows appear for relatively low angular speeds in the irregular flow régime, where we can still discern a dominant wavenumber ($M = 2$) for $d \leq 3.0$ cm, or vacillating behavior for $d > 3.0$ cm, in fluctuating flows.

(6) There is no hysteresis on régime transitions; this is a great contrast to the result of Spence and Fultz (1977).

3.3 Periods of wave drift and vacillation

Both periods of the wave drift and the vacillation were determined by the use of temperature traces, where the drift period was defined as the mean time required for a complete revolution of the flow pattern relative to the rotating cylinder.

Figure 8a shows the dependence of the drift period $\tau_d$ of the steady and vacillating waves of $M = 2$ on the angular speed $\Omega$ and the fluid depth $d$. The drift period increases with increasing $\Omega$ for each depth and decreases with increasing $d$ against the same $\Omega$. However, as shown in Fig. 8b, they tend to fall on a curve provided they are plotted by using $Q/d$ as abscissa. Roughly speaking, $\tau_d$ increases linearly with $\Omega/d$ so that we can interpret that the waves are drifted by the thermal wind. The dependence of vacillation period $\tau_v$ on the angular speed and the fluid depth is shown in Fig. 9. The vacillation period decreases with increasing $\Omega$ for each depth and increases with $d$ against the same $\Omega$; there is a tendency for this period to decrease with increasing $Q/d$.

The ratio $\tau_v/\tau_d$ decreases with increasing $\Omega$ for each fluid depth. However, this ratio near the transition point from the vacillation régime to the irregular régime is almost constant, namely $\tau_v/\tau_d = 3.0 \pm 0.1$, regardless of the fluid depth. On the other hand, near the transition point from the vacillation régime to the steady wave régime, we obtain the relation $\tau_v/\tau_d = 3-9$ according to $d = 3.0-5.0$ cm. We note here that this value is remarkably large in comparison with that observed in annulus experiments: $\tau_v/\tau_d = 0.2-0.3$ in tilted-trough vacillation (e.g. Hide, 1958; Tamaki and Ukaji, 1993) and $\tau_v/\tau_d = 0.7-1.4$ in amplitude vacillation (e.g.
Tamaki and Ukaji, 1985). Such a large value is also seen in the results by Spence and Fultz (1977); we can estimate $\tau_v/\tau_d = 6-8$ from their Table 6.

4. Summary

We have showed that regular baroclinic flows occur in the open rotating cylinder with rim heating and center cooling without any additional heating. Our experiments were carried out by keeping the room temperature as close as possible to the rim temperature so as to make the main body of the working fluid statically stable.

The main results are summarized as follows.

1. Axisymmetric flows, steady waves and vacillations have been obtained, in addition to irregular wavy flows.

2. The régime diagram for these flows has been illustrated with the fluid depth $d$ as ordinate and the angular speed $\Omega$ as abscissa.
(3) Transitions between flow régimes occur without hysteresis.

(4) The drift period $T_d$ of the steady waves increases in proportion to $\Omega/d$ so that the wave drift is attributable to the thermal wind.

(5) The vacillation régime is located between the steady wave and the irregular wavy flow régimes for the fluid depth of $d \geq 3.0 \text{ cm}$. The vacillation period $\tau_v$ tends to decrease with increasing $\Omega/d$.

(6) The ratio $\tau_v/\tau_d$ tends to decrease with increasing $\Omega$ for each fluid depth. However, the ratio near the transition point from the vacillation to the irregular wavy flow is almost constant, being $\tau_v/\tau_d = 3.0 \pm 0.1$, regardless of the fluid depth.

(7) The relation $\tau_v/\tau_d = 3-9$ is obtained from the overall régime of the vacillation; this value is remarkably large in comparison with that of annulus experiments.

**References**


オープン・シリンダー型の回転水槽中に生じる傾圧流

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オープン・シリンダー型の回転水槽中に生じる傾圧流のふるまいを室内実験で調べた。Spence and Fultz (1977) とは異なり、補助的な熱源を用いず実験を行なったが、不規則な流れのみならず規則的で再現性のある流れ、すなわち、軸対称流、定常な傾圧波動およびパシレーションを得ることができた。これら4タイプの表面流のパターンと流れの領域図が示されている。また、ドリフト周期とパシレーション周期についても調べられている。