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Development of stratification in a cylindrical enclosure

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Abstract—This paper describes temperature measurements and flow visualization in a piston–cylinder enclosure where a temperature difference is suddenly established between the enclosure and the gas contained in it. The data provides experimental support for the existence of internal waves and reveals several time constants that characterize the process.

DESCRIPTION OF THE EXPERIMENT

A 2.0 LITER gas volume contained by a piston–cylinder enclosure is filled with nitrogen gas [1, 2]. A temperature difference between the gas and the enclosure wall is rapidly established by suddenly compressing the gas with the piston. The compression is then maintained by holding the piston stationary, and the system is observed to come to thermal equilibrium by natural convection. With this method, the large thermal inertia of the enclosure is an advantage rather than a drawback. It permits the wall temperature to remain nearly constant (within 5%), and does not limit the rate of establishment of the initial wall-to-gas temperature difference.

The stroke is set to give a volume reduction of 25% and an aspect ratio of $L/D = 1.0$ for the enclosure with final pressures ranging up to 100 atm. The piston is driven hydraulically, and the stroke is accurately repeatable with compression times of 1 s or less as limited by the hydraulic drive system. The stroke axis is vertical with the piston at the bottom as illustrated in Fig. 1.

Seven 0.0013 cm copper–constantan thermocouples (TCs) are located within the gas volume as shown. The TC outputs are recorded on a Nicolet 4-channel digital oscilloscope. Each run required two identical compression strokes: TCs 1–3 and 7 on the first stroke, and TCs 4–7 on the second stroke (TC 7 repeated for comparison). The results for a typical set of data are shown in Fig. 2. The outputs of all seven thermocouples rise simultaneously during the piston stroke (approx. 0.5 s) as the gas experiences an adiabatic compression. The zero reference for time is set at the end of the compression stroke.

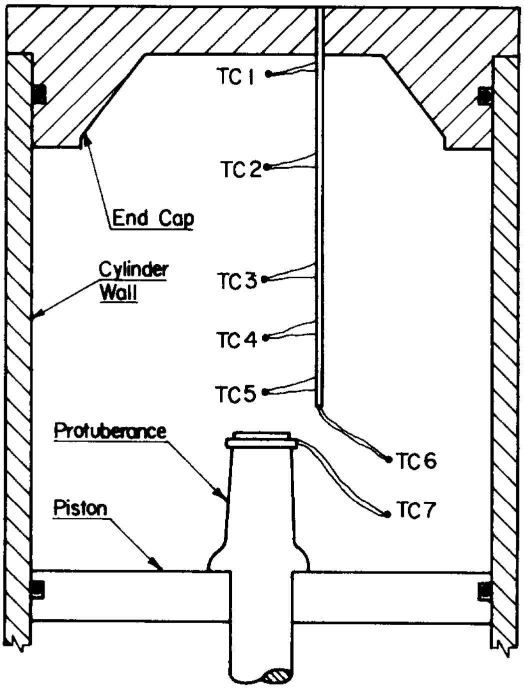

FIG. 1. Schematic cross-sectional view of the piston–cylinder enclosure. The heights of each TC as measured from the piston are 1.5, 3.0, 4.5, 6.0, 7.5, 10.5, and 13.0 cm.

DISCUSSION OF RESULTS

Wave motion is evident for TCs 4–7, and a nominal value of 3 Hz for the Brunt–Väisälä frequency (the 'buoyancy frequency' [3]) is close to what is observed. It is clear that we are observing the sloshing of internal waves, and the waves are highly damped for TC 6, because it is located level with the top of the piston protuberance which acts as a shelf on which 'wave breaking' can occur. These waves are produced by the downflow from the cool boundary layer which forms on the cylinder walls. Such waves have been reported by a number of investigators in connection with

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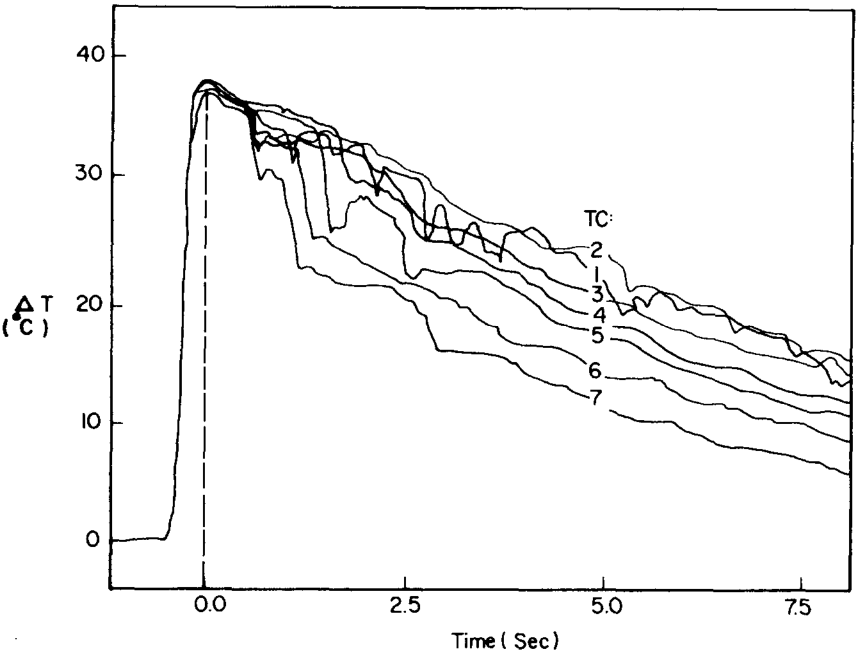

FIG. 2. Gas temperature history.

numerical solutions for transient natural convection in enclosures [4–7]. Ivey [8] has observed oscillations in transient natural convection experiments in a rectangular cavity which he associates with hydraulic jumps.

Starting at the bottom (at TC 7), each thermocouple experiences a sudden drop in temperature as the cylinder fills up with cool gas delivered by the downflowing boundary layer. This drop is largest for TC 7, and becomes progressively less as the cold front advances up through the cylinder. This suggests that the front is not maintained, but that mixing is occurring. Molecular diffusion is not 'fast enough', and it is suspected that turbulent mixing arises from internal wave breaking [9]. That is, the fundamental 3 Hz waves are broken up and randomized.

A most interesting feature is the almost constant difference in temperature between TC 2 and TC 7. This stratification temperature 'band' remains almost constant at about 10°C even though the gas temperature has dropped from about 65 to 37°C in 7.5 s. This feature has also been observed in experiments where the piston is cycled sinusoidally with the stratification temperature difference remaining constant and exceeding the bulk mean gas temperature variation during the cycle [1, 2]. It appears that a kind of 'quasi-steady state' has been attained after the damping of the internal waves and the passage of the cold front.

Siegel [10] showed (in his integral boundary layer solution using the method of characteristics) that the boundary layer 'conduction regime' should end in about 1.1 s for our case, and a quasi-steady state should occur after 2.7 s [11]. This appears consistent with the formation of the constant stratification band mentioned above. At least four important time constants are observable in Fig. 2: (1) reciprocal of the internal wave frequency (about 0.3 s), (2) internal wave damping time (about 2 s), (3) the time required for the cold front to advance from bottom to top (about 2 s), and (4) the time constant for cooling the entire enclosure (about 8 s). Since these are all somewhat independent, it implies the possibility of many different regimes for the transient process as has been suggested by Patterson and Imberger [5].

The temperature traces typically show turbulence which dies out as the gas cools. The Rayleigh number is of the order of 10^{10} at time zero for this test. Its value decreases during the test varying linearly with the gas-to-wall temperature difference.

Thermocouple 1 always indicates a temperature lower than TC 2, which is opposite to the usual order. This is believed to result from the unstable inversion to be found at the top of the cylinder. The top of the cylinder is cold with respect to the gas, and so one would expect plume or Benard cell formation near the top which would enhance convection there.

One might ask how it is that the temperatures of TCs 3 and 4 are decreasing even before they are engulfed by the cold front. Should they not remain at constant temperature since they are far removed from plumes, wall boundary layers, and the rising cold front? Note that there is a definite change in slope of the curves after the arrival of the cold front (most easily seen in TC 4). The cold front arrives at TC 4 in about 1.6 s. The drop in temperature from time zero till 1.6 s is simply a consequence of the adiabatic expansion experienced by the interior gas. The cooling that is occurring in the wall boundary layers reduces the volume of the gas which passes through the bound-

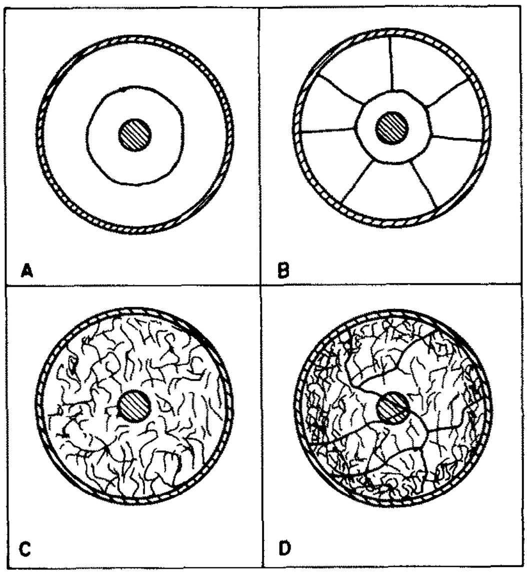

FIG. 3. Flow visualization through the end-cap window.

ary layers. Hence, the interior gas has a greater volume available to it, and so experiences an adiabatic expansion. The initial slope of TC 4 is consistent with such an expansion. This effect would not be observed in a liquid system or a gas system that was vented to maintain constant pressure.

Turning now to a more qualitative description of the flow, we consider some observations made by looking through a glass window which replaced the end-cap (and for these tests we operated at pressures of 10 atm or less). By projecting a light beam through the window, it was possible to observe motions much in the same way as one sees 'heat waves' rise from a hot radiator, except that at 10 atm the 'heat waves' are more easily seen. Of course, the interpretation is somewhat speculative, since it is not always clear what is being seen, and whether it is at the top, middle or bottom of the cylinder.

During the first stage of the compression (while the piston is in motion), a circular 'wave' converges rapidly from the wall toward the center (Fig. 3(a)). Radially orientated lines then appear between the walls and the circular wave (Fig. 3(b)), and these features break down into a turbulent motion shortly thereafter (Fig. 3(c)). This all occurs during the half second of the compression stroke. Subsequently, a quasi-steady picture emerges showing turbulent motions (most intense near the walls), and a pattern of heavy lines moving slowly around, independently from the turbulence (Fig. 3(d)).

The converging circular 'wave' could be an internal wave front as mentioned above. Or, it might involve the rollup vortex from the piston motion [12, 13] which is now pushed radially inward by the downward boundary layer flow. The radial lines suggest the formation of convective cells which resemble in appearance the cells observed by Bejan [14] when filling a glass with dark Bavarian beer. Or, these could have resulted from azimuthal sloshing modes. These features would not show up in the temperature traces (Fig. 2), since all TCs are at the same temperature during the compression stroke. The 'heavy lines' (Fig. 3(d)) which appear after the end of the piston stroke may be internal waves which can be identified with the 3 Hz oscillations seen in Fig. 2.

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DEVELOPPEMENT DE LA STRATIFICATION DANS UNE ENCEINTE CYLINDRIQUE

Résumé—On décrit des mesures de température et des visualisations d'écoulement dans une enceinte piston-cylindre où une différence de température est brutalement réalisée entre la paroi et le gaz à l'intérieur. Les résultats donnent un support expérimental à l'existence d'ondes internes et elles révèlent plusieurs constantes de temps qui caractérisent le mécanisme.

ENTWICKLUNG EINER SCHICHTUNG IN EINEM ZYLINDRISCHEN GEFÄSS

Zusammenfassung—In diesem Beitrag wird die Temperaturmessung und die Sichtbarmachung der Gasströmung in einem Kolben-Zylinder-Gefäß beschrieben, in dem zwischen Wand und Gas plötzlich eine Temperaturdifferenz aufgebracht wird. Die Daten liefern eine experimentelle Unterstützung für die Existenz von internen Wellen und enthüllen einige Zeitkonstanten, die den Prozeß charakterisieren.

РАЗВИТИЕ СТРАТИФИКАЦИИ В ЦИЛИНДРИЧЕСКОЙ ПОЛОСТИ

Аннотация—Дано описание температурных измерений и визуализации течения в поршневой цилиндрической полости при внезапном возникновении перепада температур между полостью и содержащимся в ней газом. Экспериментальные данные подтверждают существование внутренних волн и нескольких характерных времён.