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OBSERVATION OF TAYLOR INSTABILITY IN GASES

by

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OBSERVATIONS OF TAYLOR INSTABILITY IN GASES

In 1950 Sir Geoffrey Taylor[1] published a Taylor theoretical treatment of the instability of an interface between two fluids when it is accelerated in a direction perpendicular to itself. A good example of this instability can be observed by quickly inverting a glass full of water. Gravitational acceleration is now directed from the lighter fluid, air, to the heavier fluid, water. Under these conditions the interface between the fluids is unstable and the water falls out. Equations 1 and 2 summarize Taylor's results for the rate of growth of amplitude of an infinitesimal, two dimensional, sinusoidal disturbance on the surface.

$$\eta = \eta_0 \cosh \alpha t \qquad (1)$$

$$\alpha = \left(\frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} \, k g \right)^{1/2} \qquad (2)$$

where ρ_1 and ρ_2 are the densities of the fluids, k is the wave number of the disturbance and g is the acceleration. Note that the rate of growth increases without limit as the wavelength decreases.

A little later in 1950 Lewis[2] published experimental results which in general verified the theoretical predictions and also demonstrated an asymmetrical development of the instability in the later stages of its growth. Lewis used compressed air to accelerate a 2 1/2" x 1/2" column of liquid which was from 3/8" to 20" long. He was able to get accelerations

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[1] Proc. Roy. Soc. A201, 192, (1950)

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[2] Lewis, Proc. Roy. Soc. A202, 81, (1950)

as high as 140 g in this way. Figure 1 taken from the Lewis paper shows the acceleration of a water-air interface. The asymmetrical development of the instability is quite clear.

These two contributions are all that have been published on this interesting subject. The effects of surface tension and viscosity have been treated in a unpublished report by Pennington[3]. As would be expected, taking these two fluid properties into consideration reduces the rate of growth of short wavelength instability. In fact, there is a maximum rate of growth for a finite wave number. Equation 3 gives the transcendental equation relating α and k when surface tension and viscosity are considered:

$$\left[(\rho_1-\rho_2)g k + T k^3 + (\rho_1+\rho_2)\alpha^2\right]\left\{\frac{1}{\mu_1 k+\sqrt{\mu_2^2 k^2+\mu_2\rho_2\alpha}} + \frac{1}{\mu_2 k+\sqrt{\mu_1^2 k+\mu_1\rho_1\alpha}}\right\} + 4\alpha k = 0 \qquad (3)$$

The authors were curious as to what the appearance of Taylor instability would be in an all gaseous system. This curiosity lead to the present investigation.

In order to investigate Taylor instability in a gaseous system, it is first necessary to set up an interface between two gases. Since there are no immiscible gases, this is not an easy problem. Ideally one would like to remove a membrane from between two gases instantaneously without disturbing the gases in any way. This, too, is difficult. Actually

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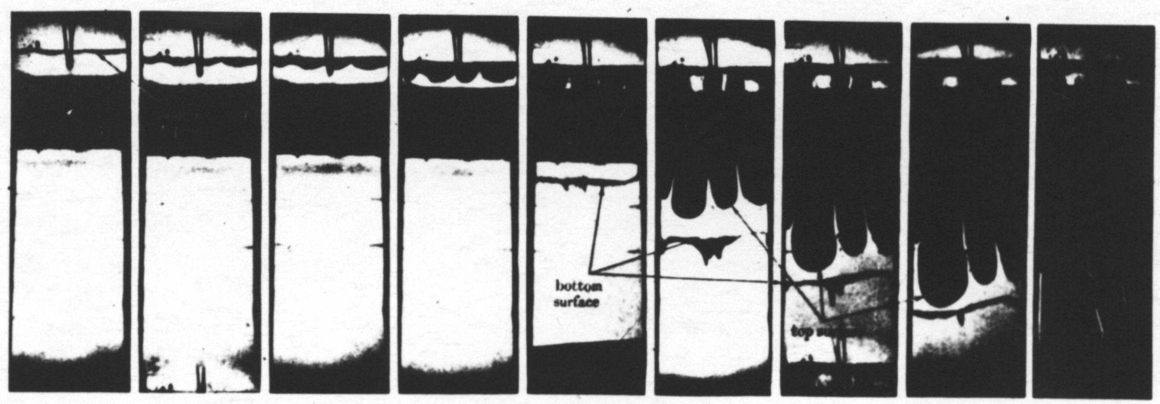
[3]Pennington, Princeton University Report, Effects of Surface Tension and Viscosity on Taylor Instability, January 28, 1952.



photograph number	0	1	2	3	4	5	6	7	8
time (msec.)		3·39	5·95	8·98	19·25	26·88	31·02	33·35	37·20

FIGURE 5. Acceleration of water; film 2. Depth of water 1·14 in.; initial acceleration = 20·7*g*.

(Facing p. [illegible])

the membrane should be removed quickly to minimize diffusive mixing of the gases but not quickly enough to cause turbulent mixing. The problem of producing this interface was the most difficult part of this investigation.

The attack employed was briefly as follows: a glass sided cell was constructed which was roughly 8" high by 4" wide by from 1" to 3" deep. A membrane of some type was stretched across the center of the cell thus making two smaller cells each 4" square. Gases of interest were introduced usually with the heavy gas on the bottom to prevent gravitational instability. The behavior of the interface after the membrane was removed was observed by means of a schlieren optical system using 8" f8.0 parabolic mirrors off axis as primary optical elements. Photographs could be taken with either a modified 4 x 5 plate camera or with an Eastman high speed 16 mm. movie camera. The light source used was an AH6 high pressure mercury arc, operated by direct current supplied from a bridge rectifier driven by the same high reactance transformer ordinarily used for AC operation of the lamp. Usually experimental conditions were varied until as smooth and well defined an interface as possible was obtained.

One method tried made use of a soap film. The film made from a solution described by Bragg and Nye[4] was stretched across a plate glass cell 8" x 4" x 1" deep. The only practical way to fill one chamber of the cell with a gas heavier or lighter than air was by flushing since the

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[4]Bragg and Nye, Proc. Roy. Soc. A190, p. 474 (1947)

cell could not be evacuated with the film in place. A spark was used to break the film at the desired time. This system was tested by placing a heavy gas below air in the cell so that no Taylor instability could develop. Then it was found that the soap film broke too fast causing considerable short wavelength turbulence.

The most encouraging results to date have been obtained by actually pulling a thin metal or plastic film from between two gases. In most of this work two 4" x 4" x 1" cells were used which were separated by the slide. Several pulling mechanisms have been investigated. The very early work was done by pulling the slide out with a stretched screen door spring. This simple system might have been satisfactory if a good lubricant could have been found for the slide. Many oils and greases were tried but all were unsatisfactory; however, the best of these was Dow Corning high vacuum silicone stopcock grease. Much later it was found that flake graphite liberally applied to thin neoprene sheet cemented to the cells made an excellent lubricant for the slide but this system had the disadvantage of not being vacuum tight.

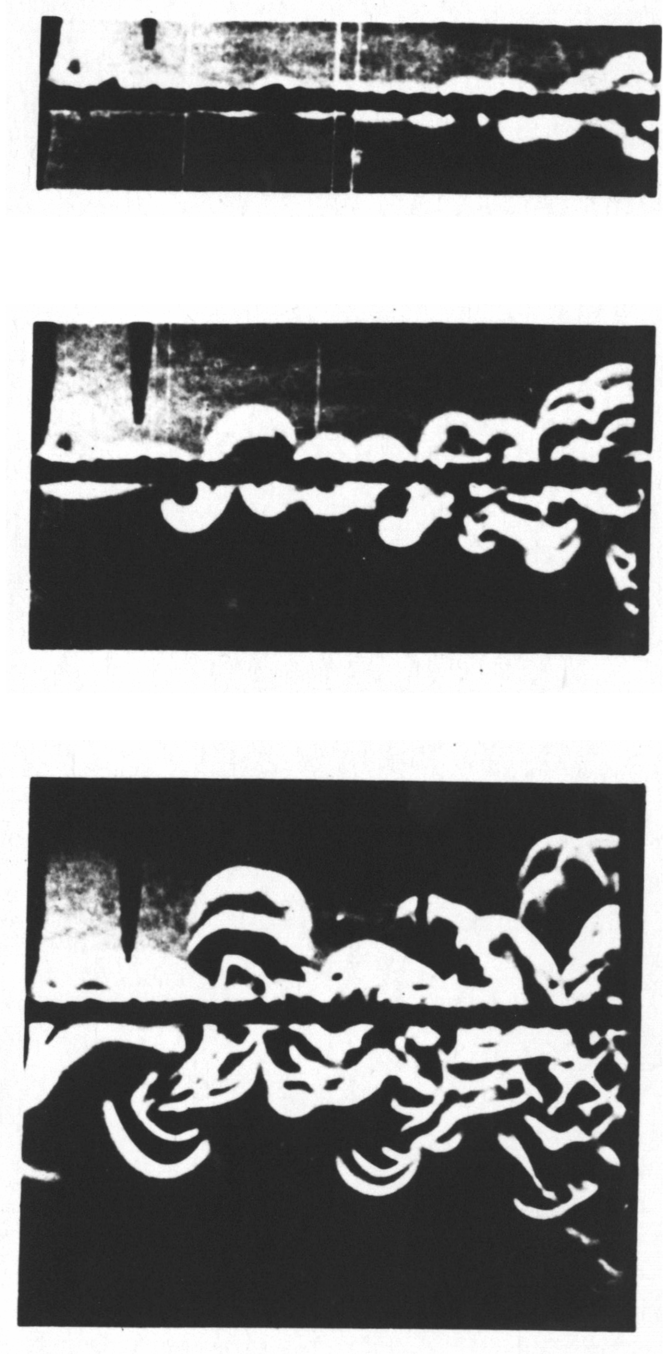
Since the screen door spring exerted a relatively small pull on the slide, changes in friction between the cells and slide produced unpredictable variations in slide pulling velocity—and therefore an uncontrolled interface. These changes were caused by inevitable variations in the thickness of the grease layers. An attempt was made to overcome this deficiency by yanking the slide out by means of a 75 pound pendulum swung from the ceiling. This attempt was unsuccessful because the impulsive shock transmitted to the apparatus at the start of the pull produced vibration in the sensitive schlieren system.

The limitations of the two early pulling mechanisms were overcome by the use of a system consisting of a piston operated by compressed air backed up by a water dashpot to regulate the slide velocity. With a piston 1 1/4" in diameter pushed by air at from 40 to 80 pounds per square inch pressure, it was found that the slide was removed smoothly, reproducibly, and with constant velocity.

A satisfactory material for the slide was found to be 7 mil spring steel sheet. A 4" wide slide made of this material could be pulled from a cell 1" wide at a velocity of 30" per second without producing turbulence.

Taylor instability could now be investigated by simply placing the heavy gas above the lighter one, pulling the slide, and photography the results with a high speed motion picture camera.

The SF_6-air system was investigated. Figure 2 presents three views of the instability and Figure 3 shows the results of measurements of instability amplitude as a function of time. Note that during the initial phases an exponential growth is observed as expected. Note also that during the late stages the amplitude of the heavy fluid "Spikes" increases roughly as $t^{1.5}$. Professor Carrier of Harvard University has suggested that one should expect a modified free fall growth where the acceleration is reduced by the factor $\frac{\rho_1 - \rho_2}{\rho_1}$. This prediction was not verified. Figure 4 shows



2-1
Time = 0

2-2
Time = 60 msec.

2-3
Time = 130 msec.

Fig. 2 Taylor Instability in Sulfur Hexafluoride and Air

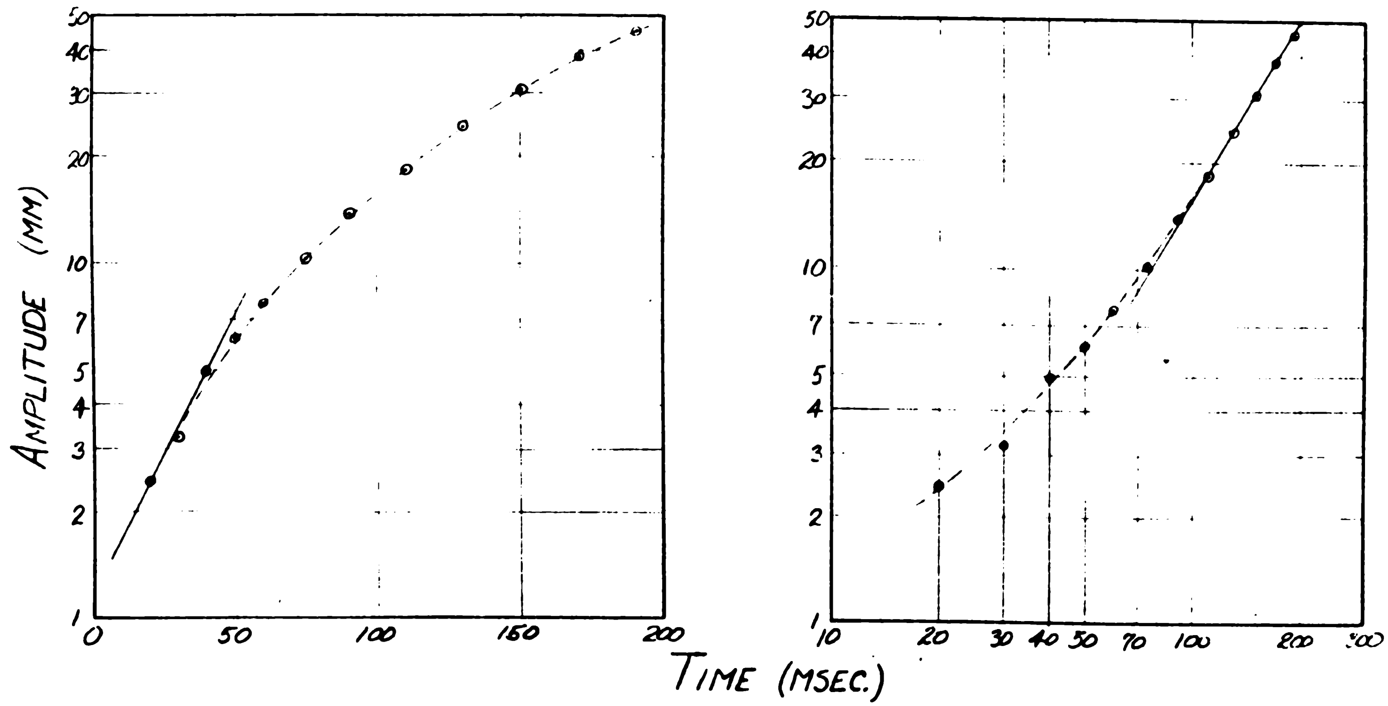

AMPLITUDE (MM)
TIME (MSEC.)
50
40
30
20
10
7
5
4
3
2
1
0
50
100
150
200
10
20
30
40
50
70
100
200
300

FIG. 3

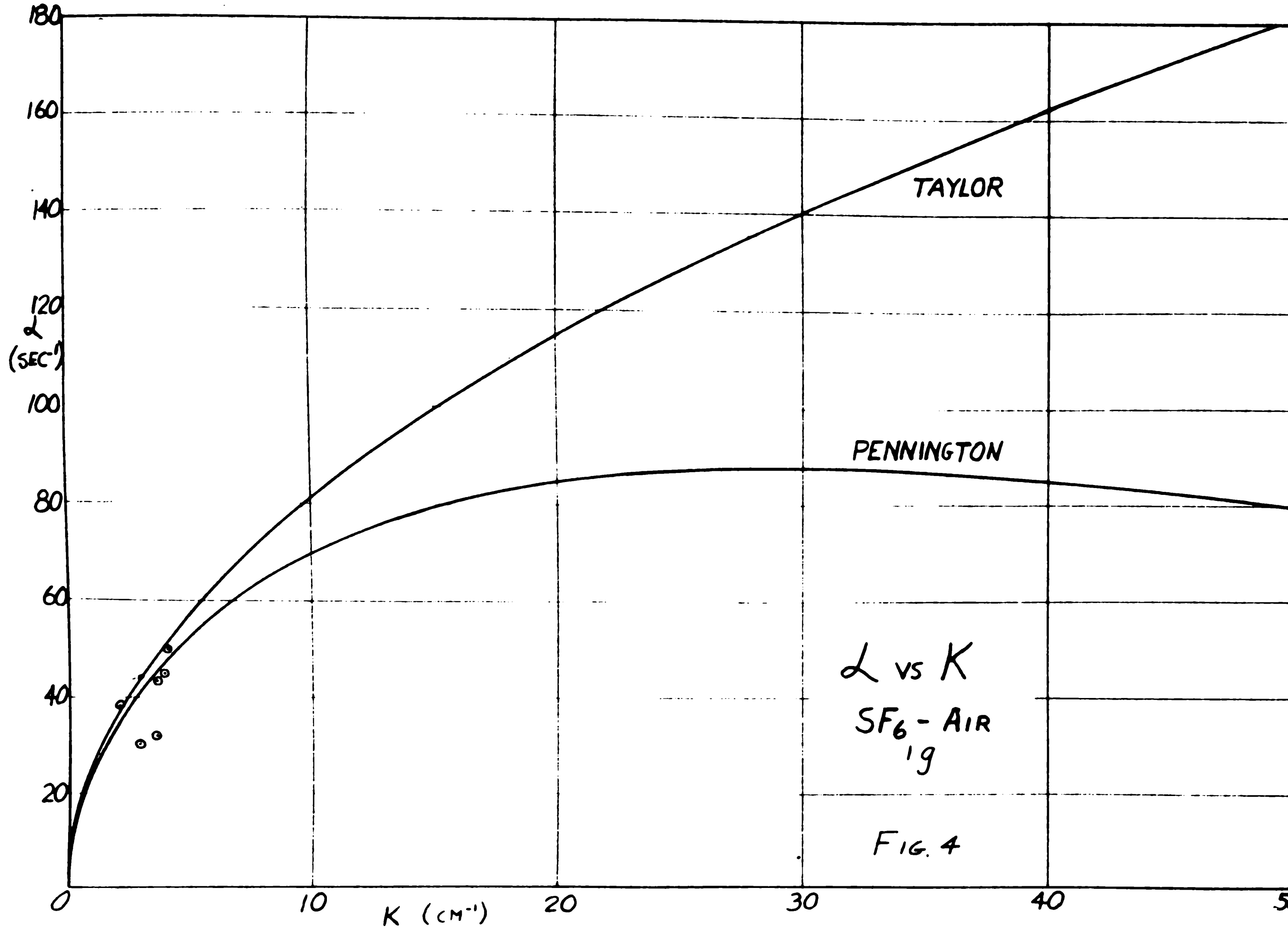

180
160
140
120
100
80
60
40
20
α (SEC^{-1})
0
10
20
30
40
50
K (CM^{-1})
TAYLOR
PENNINGTON
α vs K
SF_6 - AIR
1g

FIG. 4

the predictions of the Pennington and Taylor theories together with experimental results. It is difficult to decide what should be measured as the characteristic wavelength of the instability, presumably because of diffusion effects. The figures quoted correspond approximately to twice the diameter of the roughly spherical "spikes". Quite possibly a more realistic number would be one half of this value.

As yet there is no quantitative explanation for the type of Taylor instability observed in these experiments. In particular it is not clear why asymmetries do not develop. It is firmly believed that the results are not caused by the finite size of the cells because exactly similar results were obtained in a cell 16" x 4" x 3". Also interface turbulence may be ruled out because the later stages of instability are similar whether the interface is initially turbulent or not. In fact, a large part of the effort expended in investigating interface production resulted from attempts to produce "classical" instability. The efforts were just not successful. No doubt the observed symmetry arises, at least in part, from the inability of the spikes to grow without curling up. One fact which must be important in causing the curling and mushrooming observed is Helmhotz instability—the instability of an interface between fluids in relative motion. As mentioned above, there is as yet no comprehensive theory of large amplitude Taylor instability with which to compare these results.