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THERMALS, PUFFS AND MASS SOURCES III - LABORATORY STUDIES

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ABSTRACT

Experimental studies have been carried out on line thermals, both free and adjacent to walls. Comparison with previous experimental studies has shown that the similarity constants vary greatly depending on the source conditions. The flows were seen to develop in a highly three-dimensional manner characterized by the growth and merging of convective cells due to hydrostatic instability which exists at all stages of the motion of the thermal. The cells grow and merge in a self-similar manner so that at no stage do they form a two-dimensional flow, but the spatial period of cells along the axis grows with the scale of the cells. Thus assumptions of self-similarity are seen to be applicable to individual realizations, but similarity assumptions in which universal constants are applied to predict all such flows are shown to be inappropriate due to the sensitivity of the flow patterns to the initial conditions.

INTRODUCTION

Thermals form when isolated volumes of fluid are released from rest in an environment of different density. In laboratory situations the method of release determines the initial conditions of the thermal. In reality thermals are never released instantaneously from rest but are formed either from a source of buoyant material which acts for a short time (such as a mid-air explosion), or from the accumulation of buoyancy leading to instability (such as air heated from beneath by terrain). Where there is net momentum associated with the source (such as a ground based explosion which results in net upward momentum) the flow is termed a forced thermal. The extreme case where there is release of a finite volume of fluid with momentum but zero buoyancy is referred to as a puff. In this paper we shall restrict ourselves to discussion of thermals formed in a laboratory when buoyant fluid is released at rest from a two-dimensional source.

Dimensional arguments coupled with a knowledge of the geometry of the source, and therefore an assumption of the geometry of the resultant flow, can be used to derive similarity laws for the behaviour of the thermal. For a two-dimensional (line) thermal these are:

$$z_v = nr$$

and

$$z_v^{3/2} = C\left(\frac{\Delta\rho}{\rho}gA_o\right)^{1/2} t,$$

where
z_v = distance from the virtual origin,
A_o = cross sectional area of the thermal,
$\Delta\rho$ = density difference between thermal and environment, and
ρ = ambient density.

In previous experimental studies the constants C and n in the above equations have been determined for thermals released in a variety of different manners. Richards (1963) used an overturning semi-circular cylinder (trough) to generate line thermals which he then studied with the aid of either dye or tracer particles to determine shape evolution and streamlines, respectively. All results were obtained by viewing the flow along its axis and a streamline pattern similar to that of a line vortex pair was observed. There was considerable variability in the derived constants n and C between realizations, with $1.05 < C < 3.33$ and $1.49 < n < 3.08$. Tsang (1971) was critical of the large variation in the 'constants' reported by Richards and employed a novel release mechanism in which a horizontal cylinder was withdrawn axially so that the direction and speed of withdrawal would affect only the axial uniformity of the resultant flow (which he assumed) rather than the symmetry in cross-sections. Despite his best efforts, Tsang still saw considerble variation in the values of his derived constants, with $1.7 < C < 2.3$ and $3.1 < n < 3.7$.

EXPERIMENTAL ARRANGEMENT

In the present study both free line thermals and line thermals moving against walls are under investigation. Some effort was put into the design of the release mechanisms in an attempt to produce repeatable source conditions and to reduce to a minimum, in the case of the free line thermal, asymmetries from the source. Only two values of relative density (1.03 and 1.05) were used, and this range may be extended in future. The arrangements for the wall and free line thermals were as illustrated schematically in Figures 1 and 2. For the wall thermal a quarter-circular channel is allowed to pivot about an axis through its centre of radius and is held against the wall against the force of a spring. On release the action of the spring combined with a damping mechanism opens the channel in a reproducible manner. For the free line thermal the ideal situation would be two quarter-circular channels with an edge seal between. This situation is difficult to achieve, however, and two concentric semi-circular channels were used, which were rotated in opposite directions so that the fluid was released symmetrically. These were actuated by means of

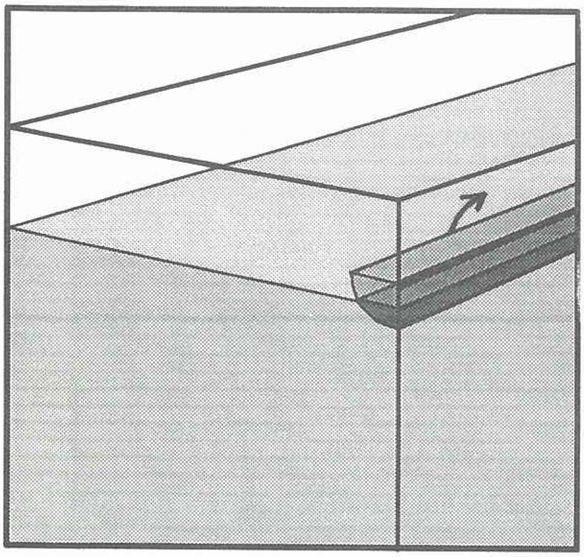

Figure 1: Schematic diagram of release mechanism for wall thermal

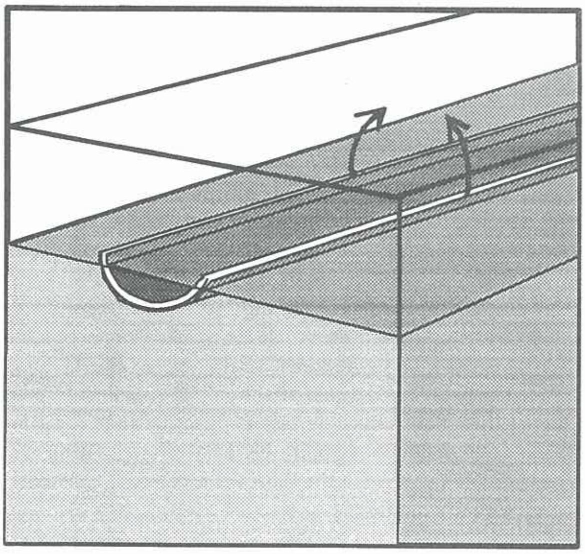

Figure 2: Schematic diagram of release mechanism for free thermal

an electric motor which produced a constant turning rate and was highly reproducible, and certainly better than turning by hand!

The experiments were filmed from two orthogonal directions to provide a record of each run on videotape for later analysis. For the purposes of the present paper, results from the analysis of images viewed along the axis of the thermal will be presented, although mention will be made of the appearance of the flow when viewed from the direction orthogonal to the thermal axis and direction of propogation.

Images from the videotape record were digitized with an Imaging Technology Series 151 image processing module and the image of the thermal extracted by subtracting an image of the tank immediately before release from each successive image. Thus the only non-zero pixels were those which had changed in intensity (i.e. the thermal). The image was then thresholded to remove minor variations in illumination and the outline of the thermal established. The parameters such as thermal area, position, width and height could be calculated. The centre of the thermal was deemed to be at the centroid of the image and the radius was taken as the radius of the equivalent circle (a circle with the same area as the thermal).

OBSERVATIONS

The most significant observation was that when the flows were viewed from the side it became very clear that the assumption of two-dimensional flow is a very poor one. Indeed the flow was highly three-dimensional in character with the flow development being governed by cell growth and merging. At no stage do the cells merge into a line but remain distinct with the number of cells per unit length along the axis reducing as the cells grow and merge. Figure 3 shows the development of the outlines of the flow viewed both along the axis and at right angles. This may be compared with the cell development predicted by the large eddy simulation model shown in Figure 4. It is seen that an inherent feature of the flow is the formation and development of three dimensional structures and the way in which these structures interact determines the validity of the two-dimensional similarity assumptions. If the structures were to grow independantly of each other then the similarity laws based on two-dimensional assumptions would be invalid. However, the distinction between the similarity law derived for a spherical thermal and that for a line thermal lies in the relationship between volume of fluid entrained and the lengthscale of the flow (in this case, the radius of the thermal when viewed along the axis). The only other differences are in the constants in the resultant equations. Consider the thermal volume as defined by the observed profile when viewed in cross-section projected along the axis, which is the two dimensional assumption. Now if the cells grow in self-similar manner, so that the shape viewed from the side increases in scale but retains the same character, and the number of cells per unit length reduces accordingly, then the fraction of ambient, as yet unentrained, fluid within the thermal volume will be a constant. In this case the increase in lengthscale will be proportional to the square root of the entrained volume, and the assumptions involved in deriving the two-dimensional similarity law will remain valid. The alternative to this is that the cells grow in size and finally merge together, in which case the flow would begin in a three dimensional manner, with each cell following the similarity laws for a spherical thermal. After merging the flow would become truly two dimensional with no dominant spacial correlations in the axial direction, and the flow would follow similarity behaviour. The side view outlines of Figure 3 show that this is not the case, so that whilst the flow is self-similar and follows the general two-dimensional similarity behaviour, it is still a highly three dimensional flow. Had the flow been fully two-dimensional, we would have expected numerical constants in the similarity relations which would then apply to all line thermals regardless of the source conditions. We see, however, that the flow appears to retain its axial shape and therefore it may be inferred that characteristics of the flow at release will govern the behaviour of the thermal throughout its life. From this argument we expect the constants in the similarity relations to be constant for any given set of source conditions, but to differ between thermals released in different manners, as the source differences persist throughout each realization.

Free Line Thermal				
Run	ρ	$A_o g\Delta\rho/\rho$	n	C
2	1.030000	158.9218	1.641678	0.9171661
4	1.030000	158.9218	1.586630	0.8839727
5	1.050000	264.8698	1.537417	0.8965668
6	1.050000	264.8698	1.539298	0.9316515
Line Wall Thermal				
Run	ρ	$A_o g\Delta\rho/\rho$	n	C
8	1.030000	144.8837	1.729031	0.9033376
9	1.030000	144.8837	1.722683	1.015892
10	1.030000	144.8837	1.802439	0.9913914
11	1.050000	241.4729	1.677734	0.9588718
12	1.050000	241.4729	1.671259	0.9651617

Table 1: Summary of Experiments; units of length are cm, density is relative to water. Runs 1, 3, and 7 have been excluded due to irregularities which require less sparse data to resolve

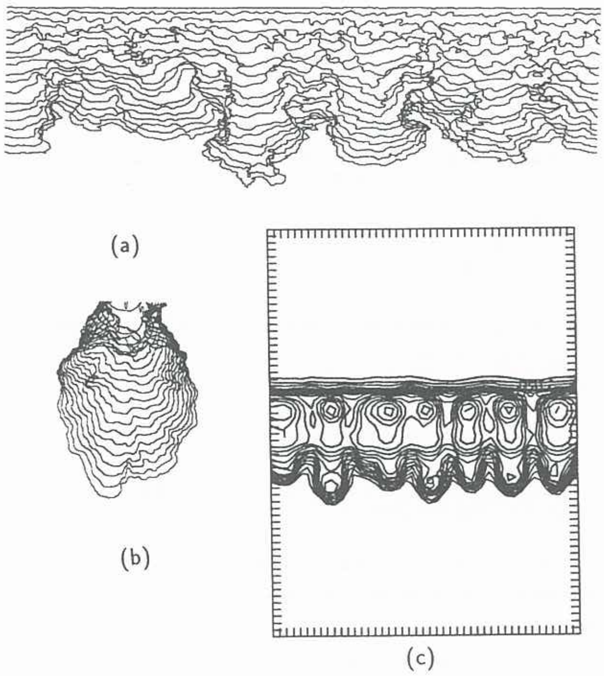

Figure 3: (a) Successive side views of the leading edge development; (b) axial views of leading edge development; (c) side view of temperature field from LES calculations.

RESULTS AND DISCUSSION

The results for the present experiments are summarized in Table 1.

Figures 4 and 5 show graphs of distance from virtual origin (calculated for each thermal individually) against thermal radius for free and wall line thermals, respectively. The distance from the virtual origin is taken as the distance of the leading edge of the equivalent circle, and the radius is that of the equivalent circle. These graphs give values for the constant n in the relation $z = nr$ as $1.5 < n < 1.64$ for the free thermal and $1.67 < n < 1.8$ for the wall thermal. Figures 5 and 6 demonstrate the second similarity relationship $z_v^{3/2} = C\left(\frac{\Delta\rho}{\rho} g A_o\right)^{1/2} t$ where C corresponds with the slope of a fitted straight line to the experimental points. The values of C lie in the range $0.88 < C < 0.93$ for the free thermal and $0.9 < C < 1.01$ for the wall thermal. Although there are too few realizations for the narrowness of these ranges to be of statistical significance, it may be inferred from the graphs that the free thermal appears to be fairly reproducible with little scatter in the data whilst slightly more scatter (*between realizations*) is evident in the case of the wall thermal. This is consistent with the scatter in C found by other workers (Richards 1963, Tsang 1971). In the present experiment, the wall thermal release mechanism results in an initial acceleration phase of the channel motion about its axis which depends on several variables that may differ between realizations. The free thermal release mechanism also involves an initial acceleration phase for the channels, but the thermal is not released until the channels are half way through their rotations. Thus the channels are rotating with constant,

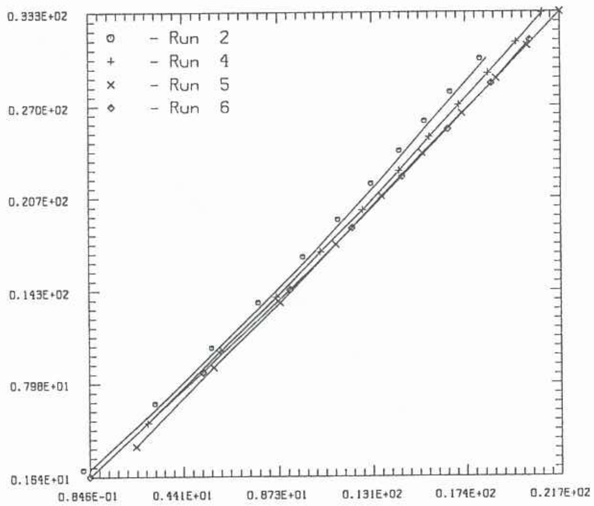

Figure 4: Graph of distance from virtual origin against radius of equivalent circle for free thermal.

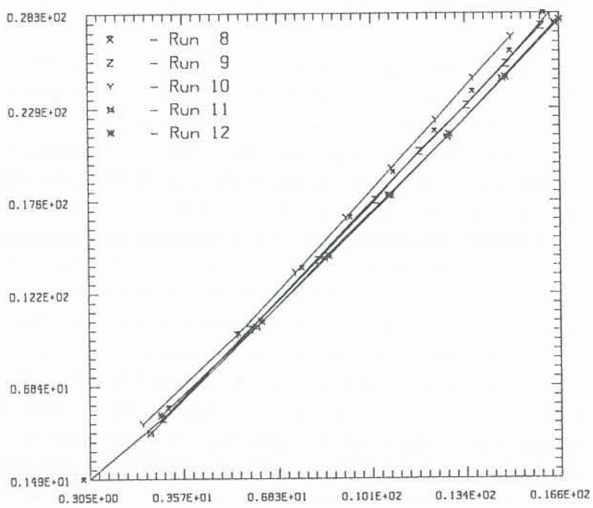

Figure 5: Graph of distance from virtual origin against radius of equivalent circle for wall thermal.

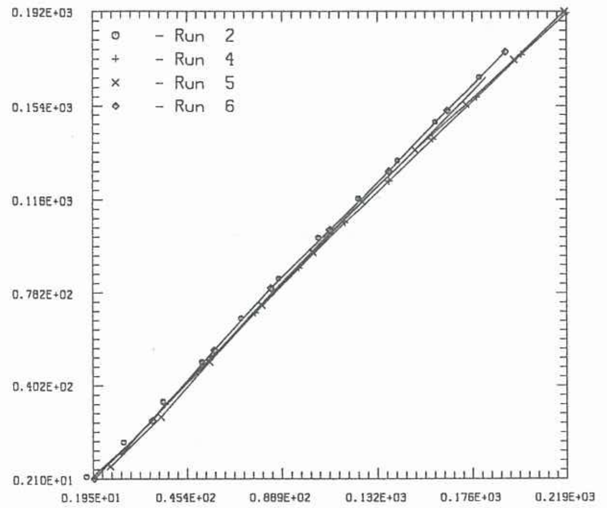

Figure 6: Graph of $z_v^{3/2}$ against $B_o^{1/2}t$ for free thermal, where $B_o = A_o g \Delta\rho/\rho$.

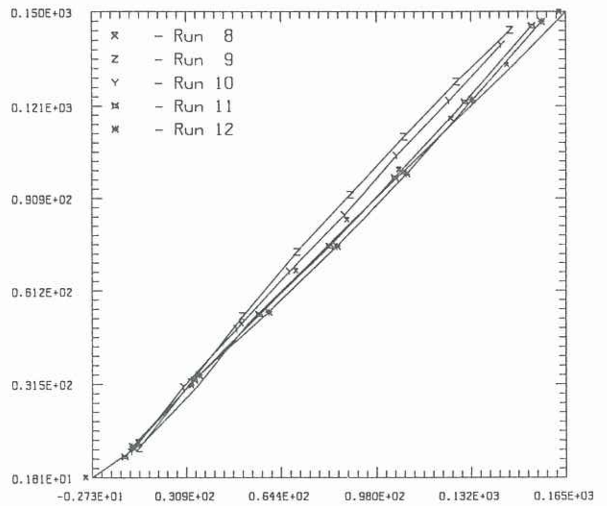

Figure 7: Graph of $z_v^{3/2}$ against $B_o^{1/2}t$ for wall thermal.

and reproducible, angular velocities during the thermal release. The the values of C measured here $(0.88 \rightarrow 1.01)$ and those reported by Richards $(1.05 \rightarrow 3.33)$ and Tsang $(1.49 \rightarrow 3.08)$ are different both in range and value. This is not necessarily a reflection on the quality of any of the experiments, but suggests strongly that there are no universal constants for this type of flow, the constants C and n depending on the initial conditions in a manner which is unlikely to be predictable. The situation contrasts with the success of similarity assumptions in other flows, such as the negatively buoyant jet (Turner 1966). The negatively buoyant jet has buoyancy force acting against the initial momentum causing deceleration and a finite penetration depth. In that case, the relationship between the buoyancy and momentum at source and the penetration depth involves a constant which is universal; and dimensional arguments work very well to produce a universal constant which may be used to give accurate predictions of penetration depth for any jet. The negatively buoyant jet differs in that the buoyancy is stabilizing whilst with the thermal it is destabilizing. The hydrostatic instability, which affects the behaviour of the thermal, exists throughout its life. At no stage is the thermal in a stable state and this results in both the three-dimensional character of the flow and a sensitivity to initial conditions. The value of the constant C for the free line thermal derived from the present experiment may be a universal constant for the present experimental arrangement (although even this is in doubt), but it clearly cannot be used to describe the behaviour of thermals released by the apparatus used by either Richards or Tsang.

We have seen that the behaviour of line thermals may be regarded as self-similar, in so far as observed behaviour at one stage of their evolution may be used to predict behaviour at a later stage, but that the application of similarity laws to predict the behaviour of all flows of the same geometry is destined to failure due to the lack of universality in the constants.

REFERENCES

Richards J.M.
Experiments on the motion of isolated cylindrical thermals through unstratified surroundings. *Int. J. Air Wat. Poll.*, 7:17, 1963.

Tsang G.
Laboratory study of line thermals. *Atmos. Environ.*, 5:445, 1971.

Turner J.S.
Jets and plumes with negative or reversing buoyancy. *J. Fluid Mech.* , 4:779, 1966.

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