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Observations and other characteristics of thermals

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Experiments have been performed to explore the qualitative and quantitative characteristics of thermals which ascend through the fluid environment above a heated horizontal surface. With water as the participating fluid, an electrochemical technique was employed which made the flow field visible and facilitated the direct observation of thermals. Measurements were also made of the fluid temperature above an active site of thermal generation.

As seen in flow field photographs, a thermal has a mushroom-like appearance, with a blunted nearly hemispherical cap. At a given heating rate, thermals are generated at fixed sites which are spaced more or less regularly along the span of the heated surface. At these sites, the generation of thermals is periodic in time, thereby validating a prediction of Howard. Both the spatial frequency of the sites and the rate of thermal production increase with increases in heating rate. The break-up Rayleigh number of the conduction layer is shown to be a constant (within the uncertainties of the experiment), which is in accord with Howard's phenomenological model.

Introduction

Thermals are masses of relatively hot fluid which ascend through the environment above a heated horizontal surface. The generation of thermals is thought to be the result of an instability in the conduction layer adjacent to the heated surface. Thermals are believed to play an important role in certain thermal convection phenomena (Townsend 1959; Howard 1966, p. 1109).

The extensive temperature field measurements of Townsend (1959), performed in air above a heated horizontal plate†, provide a clear documentation of the existence of thermals. A phenomenological theory which explains the generation of thermals has been formulated by Howard (1966). According to this model, thermals are produced by a periodic process, each period of which consists of a conductive phase followed by a break-off and mixing phase. At the beginning of the conductive phase, the fluid adjacent to the plate is envisioned as having a uniform temperature which is different from that of the plate. As a result, a temperature front moves away from the plate into the fluid. When the thickness of the conduction layer contained between the moving front and the plate surface is such that the corresponding Rayleigh number exceeds a critical value, the layer becomes unstable and breaks up, thereby producing a thermal. The mixing and agitation associated with the break-up of the conduction layer

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† The heated plate constituted the floor of an open-topped box.

restores the fluid adjacent to the plate to a uniform temperature, and the entire process begins again.

In addition to providing a physical picture of the process by which thermals are generated, Howard's model yields quantitative predictions for the temperature field, the Nusselt number and the duration of the conductive phase. These predictions are based on the postulate that the break-off phase is much shorter than the conductive phase.

The present experiments were undertaken to provide additional qualitative and quantitative information on the nature of thermals. The experiments were performed utilizing electrically heated horizontal copper surfaces situated in a water environment. In the first part of the investigation, an electrochemical technique was employed which facilitated direct visual observation of thermals. The flow visualization technique is one in which the fluid motions are made visible by local changes in colour of the fluid itself, the colour changes resulting from changes in pH. Photographs of the flow field thus revealed constitute a clear record of the existence and nature of thermals.

In the second part of the research, measurements were made of the time history of the fluid temperature above a site at which thermals were being generated. Strip chart recordings of the output of the temperature sensor revealed that the generation of thermals is periodic, as predicted by the model of Howard. The measured periods were shown to be correlatable in terms of a Rayleigh number suggested by Howard.

Experimental apparatus

The environment in which the experiments were performed was a glass-walled tank filled with water. Minute amounts of other constituents, added to the water to facilitate the electrochemical flow visualization, will be discussed later. The tank dimensions were 58 × 30 × 40 cm, length by width by height.

The test surfaces utilized in the experiments were fabricated from 0·5 cm thick copper plate. Two surfaces were employed, one of square planform (8·9 cm side) and the second of circular planform (8·7 cm diameter). Each of the plates was mounted in a plastic holder, such that the test surface was, in effect, the top of a table having solid vertical side walls. The side walls were thin plexiglass sheets (thickness 0·5 mm) cemented to the edges of the copper plate. As a result of this mounting arrangement, the test surfaces were positioned about 8 cm above the floor of the tank. Typically, the height of the water above the test surface was about 30 cm, which is susbtantially greater than the conduction layer thicknesses of 0·1–0·2 cm encountered in these experiments. At any given time, only one of the test plates was situated within the tank.

The test plates were heated electrically by means of resistance wire cemented to the downward-facing surface, the rate of heating (and, hence, the surface temperature) being adjustable. The temperature of the plate was measured by a calibrated copper-constantan thermocouple cemented into a hole drilled through an edge and parallel to the surface.

Measurement of the bulk temperature of the water environment was accomplished by a laboratory-grade thermometer whose bulb was positioned at the same height as the test surface, but displaced horizontally from the edge of the plate by approximately 5 cm. The fluid temperature above a site at which thermals were being generated was sensed by a copper-constantan thermocouple (wire diameter = 0·25 mm), whose output was recorded by a Speedomax strip chart recorder. This instrument provided a time history of the temperature variations induced by the passage of a succession of thermals. The thermocouple junction was situated approximately 8 mm above the surface of the heated plate, this distance being substantially greater than the thickness of the conduction layer. The positioning of the thermocouple so that it was situated above an active site was facilitated by the flow visualization afforded by the electrochemical technique. However, the electrochemical potential was always deactivated during periods of thermocouple data acquisition.

The flow visualization technique is an adaptation of that described by Baker (1966) and makes use of thymol blue, a pH indicator. Thymol blue is either blue or yellow-orange in colour depending upon whether the pH of the solution is greater or less than 8. An amount of thymol blue approximately 0·01 per cent by weight is added to the water and the solution is titrated to the end-point with sodium hydroxide. Then, by drop-by-drop addition of hydrochloric acid, the solution is made yellow-orange in colour. When a small d.c. voltage ($\sim$ 10–20 volts) from a dry-cell source is impressed between a pair of electrodes situated within such a fluid, H^+ ions are removed from solution at the negative electrode. As a result, there is an increase of pH of the fluid at the negative electrode, with a corresponding change in colour from yellow-orange to blue. The thus-created 'dye' is neutrally buoyant and faithfully follows the motion of the fluid.

In the present experiments, the test surface itself served as the negative electrode, while the positive electrode was a large copper sheet situated adjacent to the wall of the tank, well removed from the test plate.

The flow patterns were recorded photographically by a camera situated at the same height as the heated surface. The camera looked through the glass side wall of the tank along a line of sight parallel to the test surface. Although visual observations were made both for the circular and the square planforms, flow patterns were photographed only for the square planform since it facilitated a sharper focus. The pictures were taken at an exposure of $\frac{1}{25}$ sec on Tri-X film, with lighting provided by a diffuse fluorescent source. Prints were made on F6 contrast grade paper.

Auxiliary visual observations were also made by employing a shadowgraph system, the light source being a carbon arc.

Observations and results

Direct visual observation of thermals

Insight into the qualitative nature of thermals is afforded by observation of flow patterns made visible by the electrochemical technique. A pair of representative photographs of the flow field is presented in figure 1, plate 1. The thermals displayed therein were generated along a line that is more or less parallel to the edge of the heated surface. The photographs correspond to different heating rates, with that for the upper photograph being greater.

As is seen from the figure, thermals are rising columns of fluid which are spaced more or less regularly along the span of the heated surface. As a thermal rises through the relatively quiescent fluid environment, its leading edge is blunted and folded back, producing a nearly hemispherical cap and giving a mushroom-like appearance to the thermal as a whole. Once they are established for a given heating rate, the sites at which thermals are generated appear to be fixed. That is, successive generations of thermals are produced at the same fixed sites. This characteristic is illustrated in the upper photograph of figure 1, where three generations of thermals are in evidence.

The heating rate has a decisive influence on the generation of thermals. As is seen by comparing the upper and lower photographs of figure 1, both the spatial frequency of the sites and the temporal frequency of generation increase with increases in the rate of heating.

The foregoing observations, based on the electrochemical flow visualization technique, were qualitatively confirmed by observations of the flow field with a shadowgraph system. This confirmation, as well as later measurements, rules out the possibility that the electrochemical reaction itself is somehow responsible for the observed phenomena.

Periodicity and frequency of thermal generation

Temporal characteristics of the process of thermal generation can be evaluated from measurements of the fluid temperature above an active site. Representative segments of strip chart recordings of such temperature measurements are reproduced in figure 2. The recording in the upper part of the figure corresponds to a substantially higher heating rate than that for the recording in the lower part of the figure. The temperatures of the surface and of the bulk fluid are respectively denoted by T_s and T_∞. The temperature differences $T_s - T_\infty$ corresponding to figure 2 are stated in the caption.†

The features of figure 2 that are particularly worthy of note are the essentially periodic form of the temperature signal and its more or less constant amplitude. The first of these attributes indicates that the process by which thermals are generated is a periodic one, a finding which is in accord with the phenomenological model of Howard. The periods τ corresponding to the traces shown in figure 2 are indicated in the caption. The fact that the temperature oscillations are of nearly constant amplitude indicates that the site at which the thermals are being generated is essentially fixed.

The minimums in the strip chart trace may be associated with the bulk fluid temperature T_∞. Deviations from T_∞ are induced by the passage of a thermal. The extent of the time during which the measured fluid temperature deviates from T_∞ depends on the height of the buoyant element. There surely must be a connexion between the height of the buoyant element and the duration of the break-up of the conduction layer, but, to the knowledge of the authors, this

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† For figure 2(*a*), $T_s = 43{\cdot}1$ °C and $T_\infty = 23{\cdot}6$ °C, while for figure 2(*b*), $T_s = 32{\cdot}2$ °C and $T_\infty = 21{\cdot}2$ °C.

relationship has yet to be established. In this light, the fact that the fluid temperature exceeds T_∞ during a substantial fraction of a period cannot be taken as a definite indication that the breakup phase occupies a similarly substantial fraction of a cycle in the history of the conduction layer. Therefore, although figure 2 does not lend definite support to Howard's postulate that the breakup phase is short compared with the conductive phase, it does not present conclusive evidence to the contrary.

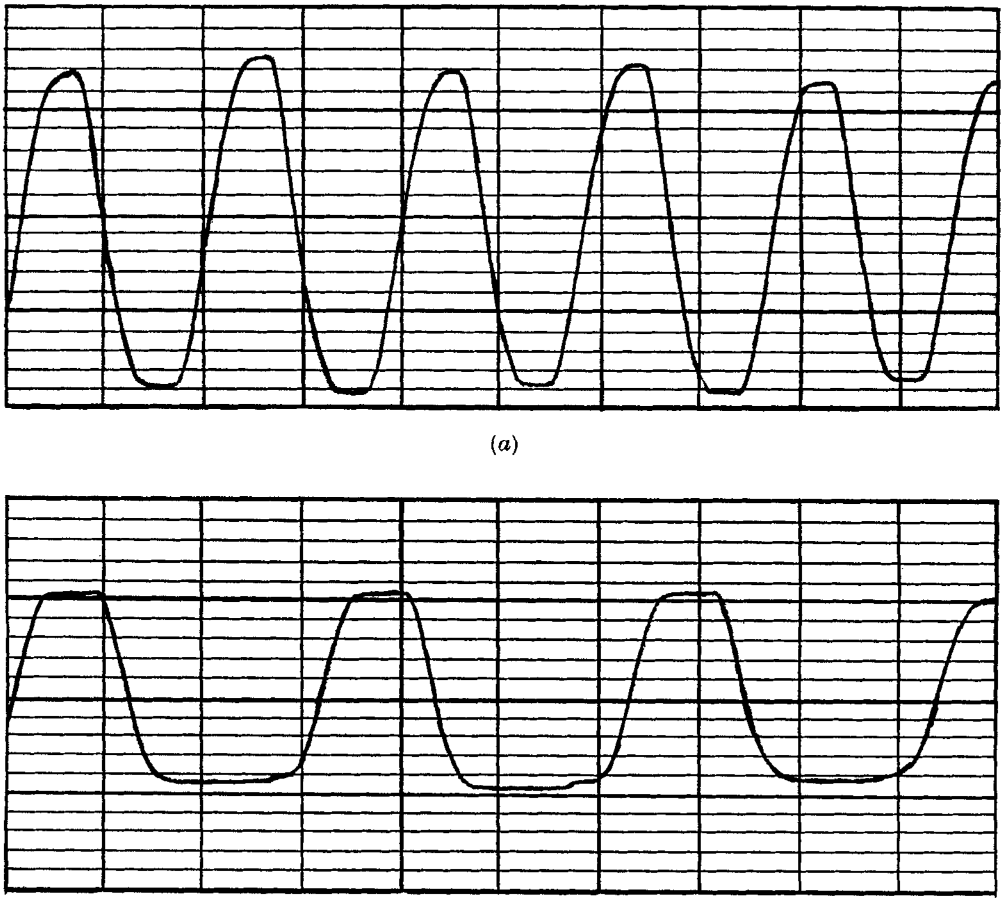

FIGURE 2. Representative strip chart recordings of fluid temperature measurements above an active site. (*a*) $T_s - T_\infty = 19{\cdot}5$ °C, $\tau = 2{\cdot}09$ sec. (*b*) $T_s - T_\infty = 11$ °C, $\tau = 3{\cdot}67$ sec.

Closer inspection of figure 2 reveals small departures from strict periodicity and constant amplitude. These departures are due to the tendency of buoyant plumes to meander. The influence of these meanderings on the temperature signal is exaggerated when the sensing thermocouple is not well centred with respect to the hemispherical leading edge of the thermal.

The periods of cyclic temperature variations such as those of figure 2 have been determined for a range of operating conditions. This information is brought together in figure 3, wherein the period τ and the temperature difference $T_s - T_\infty$ are plotted on the co-ordinate axes and T_∞ is used to parameterize the data. Dashed lines have been faired to tie together data points corresponding to a common T_∞ value.

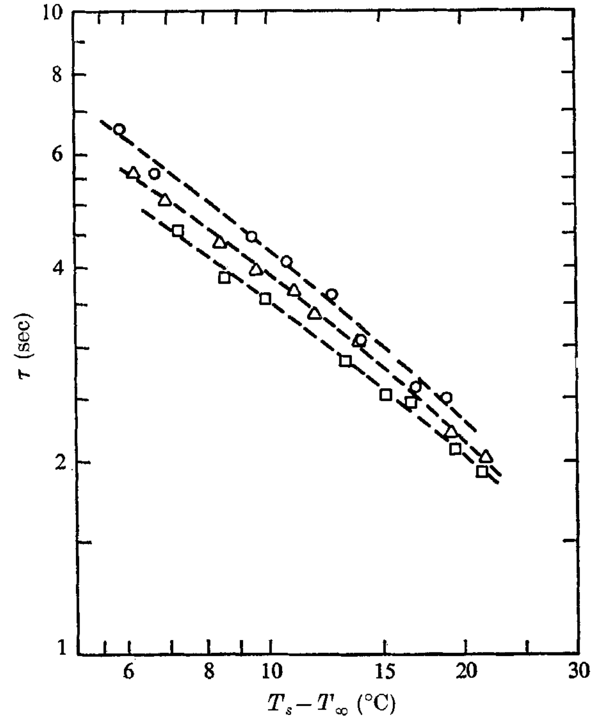

FIGURE 3. Periods of cyclic temperature variations. T_∞(°C): ○, ~ 17; △, ~ 21; □, ~ 24.

The data presented in figure 3 indicate that the period τ decreases markedly as the temperature potential $T_s - T_\infty$ increases. That is, the rate of generation of thermals increases as the heating rate increases.

It is appropriate to employ the data of figure 3 to examine certain aspects of the phenomenological model proposed by Howard. He postulates that when the Rayleigh number R_δ (based on the instantaneous thickness δ of the conduction layer) reaches a critical value, the layer will break up and a thermal will be produced. The Rayleigh number thus defined is representable as

$$R_\delta = \frac{g\beta(T_s - T_\infty)\,\delta^3}{\alpha\nu}, \tag{1}$$

in which g is the acceleration of gravity, β the coefficient of thermal expansion, α the thermal diffusivity, and ν the kinematic viscosity. In Howard's analysis, δ was taken as $\sqrt{(\pi\alpha t_*)}$, where t_* is the duration of the conductive phase. This definition yields $(T - T_s)/(T_\infty - T_s) \simeq 0{\cdot}79$ at the edge of the conduction layer. The present authors have chosen to evaluate δ from

$$\delta = 2{\cdot}77\sqrt{(\alpha t_*)}, \tag{2}$$

which corresponds to $(T - T_s)/(T_\infty - T_s) = 0{\cdot}95$ at the edge of the conduction layer.

The experiments reported herein have provided information on the period τ of a cycle which includes both the conductive and break-up phases. At present, there appears to be no rational basis for deducing t_* from τ. To proceed with an estimate of R_δ, equation (2) has been numerically evaluated by employing the experimentally determined values of τ in lieu of t_* (the thus-evaluated δ values ranged from 0·095 to 0·17 cm). Since $\tau > t_*$ and $R_\delta \sim t_*^{\frac{3}{2}}$, such a procedure will overestimate R_δ.

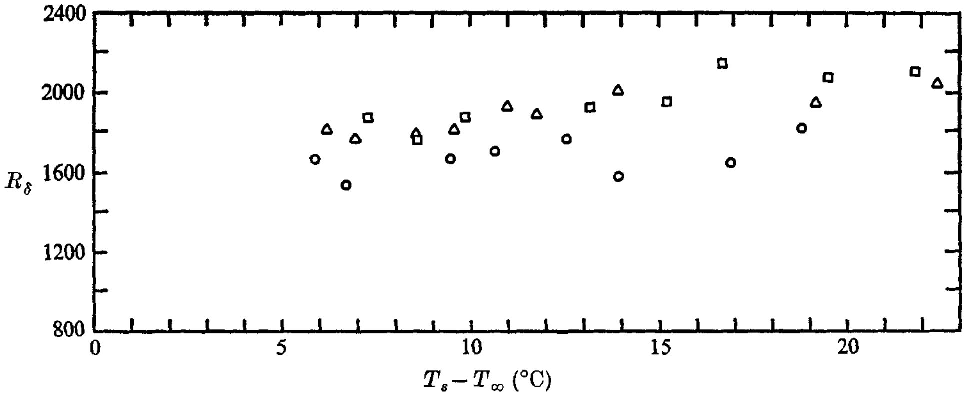

FIGURE 4. Rayleigh numbers based on the thickness of the conduction layer. T_∞ (°C): ○, ~ 17; △, ~ 21; □, ~ 24.

Values of R_δ have been calculated as described in the preceeding paragraphs, the fluid properties being evaluated at a mean temperature $\frac{1}{2}(T_s + T_\infty)$. The results of these calculations are shown in figure 4 where R_δ is plotted against the temperature difference $T_s - T_\infty$. Although there is some spread among the plotted points, the extent of the spread is remarkably small, considering the nature of the experiment itself as well as the use of τ instead of t_* and the uncertainty in the appropriate temperature for the fluid properties. The mean Rayleigh number of figure 4 is about 1800.

To strictly validate Howard's theory, it would be necessary that the experimentally determined Rayleigh numbers all have the same value. Within the level of uncertainty of the experiment and the evaluation of the Rayleigh number, the data appear to support this aspect of Howard's model. This finding is especially interesting inasmuch as Howard's model does not include the existence of preferential sites above which plumes are generated sequentially.

It is also of interest to compare the experimental values of R_δ with the theoretical value of 1100 for the onset of instability in a fluid layer with a linear temperature distribution and a free surface. To bring the mean value of the experiments into congruence with that of theory, it would be necessary that $t_* \sim 0{\cdot}7\tau$, which is by no means unreasonable.

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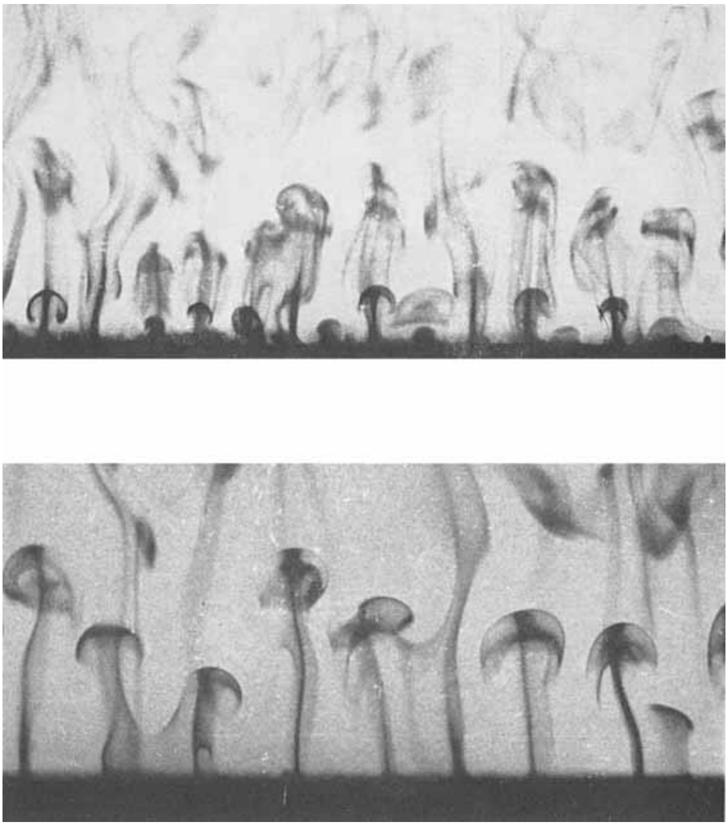

FIGURE 1. Photographs of thermals rising from a heated horizontal surface.