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EXPERIMENTS ON THE BUOYANT PLUME ABOVE A HEATED HORIZONTAL WIRE

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Abstract—The free-convection temperature field within a buoyant plume rising from a heated horizontal wire was explored experimentally. Laminar flow measurements were facilitated by use of an isolating enclosure. The laminar plume exhibited a slow, regular swaying motion. The quantitative dependence of the laminar temperature field on the heating rate and on the elevation above the wire, as deduced from the experimental data, was found to be in excellent accord with the analytical predictions for a plume induced by a line heat source. Measured temperature profiles at a range of elevations and heating rates also agreed well with laminar theory. Turbulent bursts occurred at higher elevations above the wire and at higher heating rates, thus signalling the onset of transition. The frequency of the bursts increased with increases in elevation and heating rate. The onset of transition, as indicated by the initial appearance of the turbulent bursts, occurred at a modified Grashof number of 5×10^8. Essentially fully-turbulent conditions prevailed when the modified Grashof number was 5×10^9.

NOMENCLATURE

c_p,	specific heat, constant pressure;
Gr^*,	modified Grashof number, $g\beta Q x^3/\rho c_p \nu^3$;
g,	acceleration of gravity;
h,	temperature similarity variable, equation (1);
Q,	rate of heat input per unit length of wire;
T,	temperature;
T_∞,	ambient temperature;
$T_{\mathrm{C\!\!\!L}}$,	centerline temperature ($y = 0$);
x,	elevation relative to a line heat source;
x',	elevation relative to the center of the heated wire;
y,	transverse coordinate;
β,	coefficient of thermal expansion;
ν,	kinematic viscosity;
ξ,	similarity variable, equation (2);
ρ,	density;
Φ, Ω,	property groupings, equation (3).

INTRODUCTION

BUOYANT plumes induced by temperature differences between a fluid mass and its surroundings are encountered in engineering and in other areas of applied science, e.g. meteorology. The specific situation of interest here is the buoyant plume that develops above a horizontal line source of heat such as a fine electrically-heated wire. Experiments are performed which provide information on the details of the laminar temperature field, on the transition to turbulence and the shape of the turbulent temperature field, and on other aspects of the free-convection motion. In the latter category is discussed the general tendency of the plume to execute a slow, oscillatory motion, and the special arrangements required to produce a physical system which effectively models the analytical formulation of the laminar plume. The characteristics of observed turbulent bursts are also described. The measurements are performed for a wide range of heating rates and elevations above the heated wire. Comparisons are made with the results of laminar theory whenever possible.

The analysis of the laminar plume above a horizontal line source of heat has evoked the interest of many investigators in various parts of the world. The problem appears to have been first treated by Zeldovich [1] using dimensional arguments. The fact that the laminar buoyant plume possesses a similarity solution was established by Schuh in 1948 [2]. Since that time, several authors have worked with the similarity form of the governing equations [3–6]. Among the foregoing, the paper by Fujii [6] provides the most complete numerical information and will therefore be employed for purposes of comparison here.

As far as experiments on the laminar plume are concerned, the only other investigation appears to have been carried out contemporaneously (and independently) of the present study, the paper [7] having appeared in print after the completion of the present manuscript. The emphasis and range of the results reported in reference [7] are distinctly different from those reported here. For instance, in the reference, only a single heating rate was employed, measurements were made only relatively near the heated wire, and no observations of turbulence phenomena or flow oscillations are mentioned. The information presented in reference [7] and that reported here contribute in different ways to the understanding of the problem.

The fully turbulent plume above a line source has been investigated both analytically and experimentally by Lee and Emmons [8]; this reference also cites pertinent earlier work. Although not of direct pertinence here, mention may be made of measurements of the turbulent plume above a heated point source by Schmidt [9] and by Yih [10]; an analysis of the laminar plume above a point source is included in the aforementioned papers by Fujii and by Yih.

DESIGN CONSIDERATIONS, APPARATUS, AND INSTRUMENTATION

Design aspects

Prior experience suggests that external free convection flows are readily affected by fluid motions and temperature fluctuations in the surroundings. Therefore, a laboratory room was sought which was isolated, windowless, and free of drafts from other sources. For this purpose, there were available several test cells that had been initially designed as environmental-control chambers; these rooms had thick, thermally insulated walls and pressure-tight doors. Such rooms would have to be classified as ideal for the present purpose.

A preliminary apparatus including a heated horizontal wire and a thermocouple probe was employed to sense the steadiness of the plume rising above the wire. It was found that no matter in which of the cells the tests were performed, the measured temperatures varied appreciably with time. Subsequent visualization of the flow field with a Schlieren system revealed that the plume was swaying to and fro in a plane perpendicular to the axis of the wire. It was concluded that even in the near-ideal test cells available, there were sufficient air currents to affect the plume. On this basis, it was deemed advisable to surround the heated wire with an isolation enclosure, and this feature was incorporated into the final design. In addition, the preliminary experiments indicated that the plume was affected by the presence of personnel in the test cell; consequently, the final design included the capability of remote control of the traversing apparatus from outside the test cell.

Test apparatus and instrumentation

The heated horizontal wire employed to create the buoyant plume was 0·040 in. in diameter and had an overall length of 34 in, through any segment of which an electric current could be passed. The electrical resistance, measured as 0·5406 Ω/ft, is essentially independent of temperature.† Auxiliary tests revealed that the most stable plumes were created when the heated length was 10 in or

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† The computed increase in electrical resistance is 0·1 per cent over a span of 400 degF.

less; consequently, power terminals were attached to a centrally located 10-in span. With a view toward reducing the radiant transfer from the wire to a negligible level, an electroplated gold film of thickness 2×10^{-5} in was applied.† The application of this coating reduced the electrical resistance by 1·3 per cent. The wire was supported by a framework that provides adjustments for horizontal leveling and for tensing the wire to preclude sag.

An isolation enclosure was constructed to minimize the effects of test-cell air currents. The final configuration of the enclosure, which evolved from various earlier arrangements, is as follows: In overall shape, the enclosure is a rectangular box 44-in high with 32 × 24-in horizontal dimensions, the 32-in length being parallel to the heated wire. The wire itself is situated 12 in from the bottom of the enclosure and is otherwise centrally located. Each of the large side walls (parallel to the vertical plane containing the wire) consists of a tightly-stretched, finely woven brass screen (porosity = 47 per cent); the lower eight inches of these walls are of plywood. The smaller side walls (perpendicular to the vertical plane containing the wire) were of plywood and glass, the latter material being used to facilitate visual observation. The top of the enclosure consists of the aforementioned brass screening, while the bottom is of plywood into which is cut a centrally-positioned, screen-covered opening 7 in × 19 in. The isolation enclosure is supported by the same framework that supports the heated wire. Photographs of the enclosure are presented in reference [11].

The temperature field within the heated plume was measured by a specially designed thermocouple probe. The probe body is in the shape of a two-tined fork fabricated from stainless steel, the distance between the tines being two inches. The thermocouple, fabricated from 0·001-in chromel and constantan wire, is suspended between the tips of the tines. The junction is formed at the center of the two-inch span by lap soldering the two materials.

Inasmuch as this investigation is ultimately concerned with the temperature distribution in the plume relative to ambient, it is both more accurate and more convenient to measure temperature differences (relative to ambient) directly. To this end, the cold junction was established in the ambient fluid within the isolation enclosure. Indeed, the cold junction was physically coupled to the probe so as to be situated at the same vertical height as the thermocouple itself. The thermocouple probe was calibrated both before and after the test runs; no change in the calibration was detected. The calibration is believed to be accurate to at least 0·1 degF.

Inasmuch as the thermocouple probe may, in principle, exchange radiant energy with the heated wire, an auxiliary experiment was performed to determine whether this might affect the temperature measurements. To this end, the probe was positioned at various stations *below* the heated wire. Under this condition, convective transport is negligible and the departure of the thermocouple temperature from ambient is a measure of the radiation effect. The results of these auxiliary experiments indicated that the radiative transfer had a completely negligible effect on the measurements.

A traversing mechanism was designed and constructed which provides for carefully controlled horizontal travel of the thermocouple probe to within 0·001 in. A remote-control extension was incorporated into the traversing mechanism so that personnel could remain outside the test cell during the period when data were collected. The vertical position of the probe was adjusted manually prior to the initiation of a traverse. The vertical distance of the probe above the heated wire was read by a Gaertner cathetometer capable of detecting heights to within 0·005 cm (0·002 in) in 100 cm.

Thermocouples were also employed to

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† Calculations, based on an emittance of 0·02 for gold plate, showed that for the extreme heating rates of investigation, the radiant loss was $\frac{1}{2}$ per cent of the total heat input.

measure the temperature of the heated wire† and of the ambient air within the isolation enclosure. For the former measurement, 40-gage (0·003-in diameter) iron–constantan wire was spot welded to the heated wire. The ambient temperature, needed for both the evaluation of fluid properties and probe calibration, was detected by a shielded 30-gage copper–constantan thermocouple. Both of the aforementioned thermocouples were calibrated prior to use.

The output of the thermocouple probe was sensed simultaneously by two high-precision electronic potentiometers. The special capabilities of these instruments facilitated the determination of different characteristics of the temperature field. One of these instruments is a Brown Electronik self-balancing, indicating millivoltmeter. The second is a Dymec integrating digital millivoltmeter (analog-to-digital converter), which provides both a visual display and a digital output on paper tape. When these instruments were employed simultaneously, the Brown provided a continuous indication of the instantaneous temperature and the Dymec gave the average temperature over some pre-selected time interval. Both potentiometers are accurate to ± 2 mV ($\pm 0{\cdot}07$ degF for the thermocouple probe). The temperature of the heated wire and the ambient air were also measured by the Dymec instrument.

Power was supplied to the heated wire by three 12-V aircraft-type storage batteries connected in parallel. The current was controlled by two slide-wire rheostats, one of which was employed for coarse adjustment and the second for fine adjustment. The current flow was as detected by measuring the voltage drop across a precision shunt. The voltage drop was monitored continuously by a second Brown Electronik indicating potentiometer. To compensate for battery discharge, rheostat adjustments were made periodically to maintain the power setting within 0·1 per cent of a preselected value; typically such adjustments were made about once an hour during continuous operation.

QUALITATIVE OBSERVATIONS AND MEASUREMENT TECHNIQUE

Although the use of an isolation enclosure appreciably reduced the swaying motion of the plume, some sway continued to persist. In view of the almost ideal test conditions that were established, it is felt that such motions are properly regarded as a characteristic of free-convection plumes.

As will be documented later, the flow was fully laminar for all operating conditions at elevations up to 6 in above the wire; at higher elevations, laminar flow was found to exist at the lower heating rates. For the laminar regime, the temperature, sensed at a fixed point in space by the thermocouple probe, executed a slow regular oscillation with a period on the order of a minute. This temperature oscillation is due to the slow swaying of the plume. The Brown self-balancing potentiometer was able to follow and to display such temperature measurements without difficulty.

At higher heating rates and/or higher elevations, the flow was no longer fully laminar. Periodically, the passage of a turbulent spot (or burst) would give rise to an exceedingly rapid change in the temperature sensed by the thermocouple probe, following which the laminar regime was re-established.† Not unexpectedly, the first appearance of bursts at any elevation and heating rate occurred at a transverse location corresponding to the neighborhood of the maximum temperature gradient, which, according to the available numerical solutions, is near the inflection point of the velocity profile. At higher heating rates and higher elevations, the frequency of the turbulent bursts increased, such that for some operating conditions, the flow was primarily turbulent.

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† The change of electrical resistance with temperature is so small that the wire cannot be used as a resistance thermometer.

† This is similar to the behavior described by Emmons and Bryson [12] and by Schubauer and Klebanoff [13] for transition to turbulence in a forced-convection flow.

With the foregoing as background, consideration will now be given to the quantitative measurements that were performed. For the laminar case, envision the thermocouple probe to be positioned at some given elevation above the heated wire, transversely located so that the thermocouple junction is in the same vertical plane as the wire (i.e. the symmetry plane for a stationary plume). It can be reasoned that as the plume sways, the maximum temperature recorded by the probe corresponds to the centerline temperature of a stationary laminar plume. Furthermore, this interpretation continues to apply even when intermittent turbulent bursts occur. Thus, by observing the recurring temperature maximum sensed by the probe, quantitative information was obtained about the dependence of the centerline temperature as a function of heat input. Furthermore, by performing such measurements at various elevations, the dependence of the temperature level on the height was explored.

As a matter of fact, owing to the flatness of the temperature profile in the neighborhood of the centerline, the temperature oscillation induced by the sway was always small. Indeed, at any given heating rate, the maximum and the average temperatures recorded at the centerline did not differ by more than 3 per cent under laminar and partially turbulent conditions.

At transverse positions off the centerline, it was reasoned that a more realistic picture of the temperature profile is given by long-time averages. This measurement procedure was followed both for fully laminar, transition, and predominantly turbulent flow conditions.

The temperature field was investigated at nominal elevations of $\frac{1}{4}$, $\frac{1}{2}$, 1, 3, 6, 8, 10, and 15 in above the center of the heated wire. At each height, the centerline temperature was determined for each of 12 different heating rates, ranging from 0·26 to 5·1 W/ft of wire length. Furthermore, full temperature profiles at each height were measured at 3 heating rates ranging from 0·54 to 5·2 W/ft.

RESULTS AND DISCUSSION

In presenting results for the laminar plume, it is convenient to phrase the experimental findings in terms of the variables that arise in the analysis of the horizontal line source [6]. The analytically determined temperature profiles are expressed in the similarity form $h = h(\xi)$ as follows

$$(T - T_\infty)\,\Phi\, x^{\frac{3}{5}}\, Q^{-\frac{4}{5}} = h(\xi) \qquad (1)$$

where ξ is the similarity variable

$$\xi = \Omega\, Q^{\frac{1}{5}}\, x^{-\frac{2}{5}}\, y \qquad (2)$$

and Φ and Ω are property groups

$$\Phi = (g\beta\nu^2\rho^4 c_p^4)^{\frac{1}{5}}, \qquad \Omega = (g\beta/\rho c_p \nu^3)^{\frac{1}{5}}. \qquad (3)$$

The temperature at any point x, y within the plume is T, where x and y respectively denote the vertical and horizontal coordinates measured with respect to the line source as origin. The rate of heat transfer from a unit length of the line source is Q.

Centerline temperature results

Consideration is first given to the experimental results for the temperature at the plume centerline ($y = 0$) as a function of the heating rate Q and the vertical elevation x. As discussed in the previous section, plume centerline data for a given elevation and heating rate were collected by observing the maximum temperature sensed by the thermocouple probe positioned at $y = 0$. These data should correspond to the centerline temperature of a symmetric, stationary *laminar* plume. For this reason, the subscript ℄ is affixed.

Guided by analysis, the measured centerline temperatures at a given elevation are plotted as a function of $Q^{\frac{4}{5}}$. This information is given in Fig. 1. To facilitate a concise presentation, the ratio $[(T_{\text{℄}} - T_\infty)\,\Phi]/[(T_{\text{℄}} - T_\infty)\,\Phi]_{\max}$ is plotted as a function of $(Q/Q_{\max})^{\frac{4}{5}}$ at each elevation, where the subscript max corresponds to the maximum heating rate at the given elevation. The values of $(T_{\text{℄}} - T_\infty)_{\max}$ and $Q_{\max}$ are listed in Table 1. The property grouping Φ has been evaluated at a

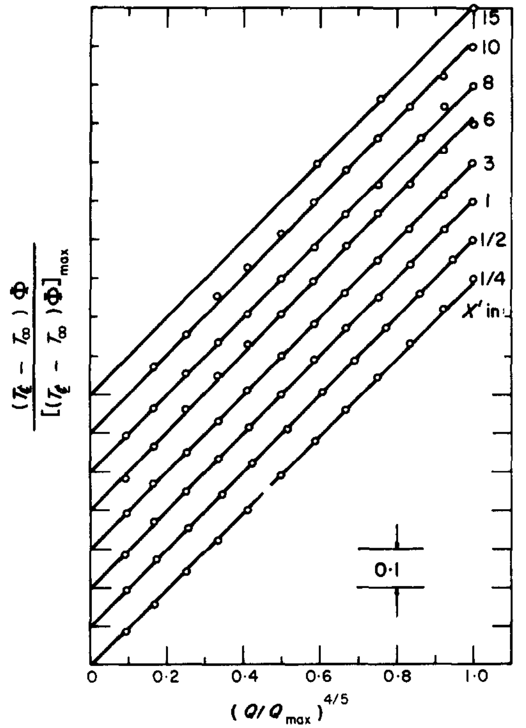

FIG. 1. Variation of laminar centerline temperature with heating rate.

Table 1. *$(T_{℄} - T_\infty)$ at maximum power levels of Fig.* 1

x' (in)	Q W/ft	$(T_{℄} - T_\infty)$ (degF)
0·258	5·06	57·5
0·491	4·87	38·8
0·993	5·06	27·3
2·971	5·06	14·8
5·963	5·06	9·7
7·945	5·06	8·4
9·906	5·06	7·2
14·926	4·05	4·7

reference temperature.† The curves are parameterized by the elevation measured from the centerline of the heated wire. Owing to the finite size of the heated wire, the aforementioned elevation may not necessarily coincide with the vertical distance x appropriate to a line source. To emphasize this distinction, the symbol x' is employed to designate elevations measured from the wire centerline. The x' values indicated on the figure are nominal, while the actual x' are listed in Table 1.

The experimental data at a given elevation have been fitted with a least squares straight line passing through the point $(T_{℄} - T_\infty = 0$, $Q = 0$. Thus, the intersection of each line with the ordinate axis establishes the zero ordinate value for that line.

Inspection of the figure reveals that for laminar conditions, $(T_{℄} - T_\infty)\Phi$ varies linearly with $Q^{\frac{4}{5}}$ at all elevations. This is in accordance with predictions of analysis, e.g. equation (1). However, this is not to imply that the flow is fully laminar at all the elevations investigated. Indeed, as will be discussed later, the flow at $x' = 15$ in is laminar for only a small fraction of any given period of time. What is demonstrated by Fig. 1 is that when the flow is laminar, the centerline temperature follows the relation

$$(T_{℄} - T_\infty)\Phi \sim Q^{\frac{4}{5}} \tag{4}$$

at any given elevation. It is especially interesting to observe that the swaying of the plume does not affect the laminar centerline temperature of the plume, at least as far as its Q-dependence is concerned.

Next, consideration is given to the x-dependence of the plume centerline temperature. To this end, the slopes of the least-squares straight lines of Fig. 1 are evaluated and rephrased into the grouping

$$\left[\frac{Q^{\frac{4}{5}}}{\Phi(T_{℄} - T_\infty)}\right]^{\frac{5}{3}}.$$

This quantity is plotted in Fig. 2 as a function of the measured elevation x'. According to laminar theory, i.e. equation (1)

$$\left[\frac{Q^{\frac{4}{5}}}{\Phi(T_{℄} - T_\infty)}\right]^{\frac{5}{3}} = [h(0)]^{-\frac{5}{3}}\,x. \tag{5}$$

A least-squares straight line, fitted through the plotted points from $x' = 0·491$ to $x' = 5·963$ in, is shown in the figure. The point at $x' = 0·258$ in was omitted from the curve fitting owing to the

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† In accordance with reference [14], $\beta = 1/T_\infty$ and all other properties are evaluated at $T_{℄} - 0·38\,(T_{℄} - T_\infty)$.

possibility that the flow at this position might be affected by the finite size of the wire. In addition, the points above $x' = 5{\cdot}963$ in were not included in the fitting because of possible effects of turbulent bursts at higher heating rates. Inspection of the figure indicates that the fitted line is a logical representation of all the data.

Careful study of Fig. 2 reveals that the abscissa intercept of the straight line does not coincide with $x' = 0$. This is entirely expected, inasmuch as the finite-size wire, with its attendant near wake, may well produce a plume different from that of a line source situated at the wire centerline. The intercept of the straight line with the abscissa axis in Fig. 2 provides the virtual location of a line source of heat that induces a plume similar to that from the finite-size wire used in the experiments. From the equation of the fitted line, one finds that the virtual location of the line source is 0·083 in below the center of the heated wire; thus,

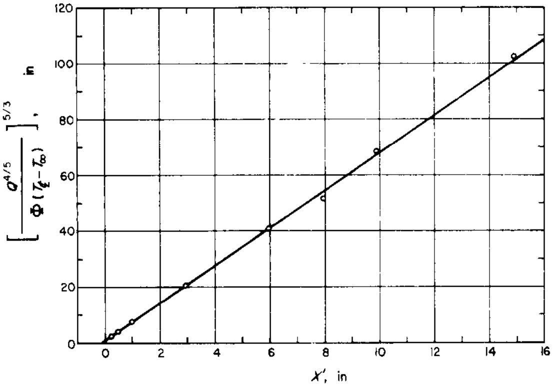

FIG. 2. Variation of laminar centerline temperature with elevation above heated wire.

$$x = x' + 0{\cdot}083. \qquad (6)$$

In conjunction with equation (5), a value of $h(0)$ can be evaluated from the slope of the line appearing in Fig. 2. This gives $h(0) = 0{\cdot}317$, which is 15 per cent below the value of 0·373 of laminar theory for $Pr = 0{\cdot}7$ (air). This departure between laminar experiment and laminar theory is the only such disparity encountered during these tests. Various aspects of the experimental procedure were checked, but no errors were detected. As already mentioned, direct radiative transfer from the heated wire to the thermocouple probe was found to have a negligible effect on the temperature measurements. Furthermore, it was demonstrated by computation that both radiative and conductive heat losses from the heated wire were very small compared with convective transfer. This finding is consistent with the uniformly good correlation of the temperature data with the heat flux as shown in Fig. 1.

With the effective elevation thus established by equation (6), one may return to equation (5) and compute $h(0)$ values corresponding to each one of the data points plotted in Fig. 2. These results are shown in Table 2. It is seen that the separate $h(0)$ are very close to the aforementioned value of 0·317 that corresponds to the least-squares line. The 3 per cent deviation at $x' = 0{\cdot}258$ in may well be due to the effects of the finite-size wire and its near wake.

Table 2. $h(0)$ values at various elevations

x' (in)	$h(0)$
0·258	0·327
0·491	0·317
0·993	0·316
2·971	0·318
5·963	0·317
7·945	0·328
9·906	0·315
14·926	0·316

Before leaving this section, it is revealing to compare the laminar centerline temperature with the timewise-average centerline temperature. When laminar flow conditions prevail, but the plume sways, the average should be slightly less than the maximum. On the other hand, when there are frequent turbulent bursts, the average should be appreciably less than the maximum. The measured results indicate that for all elevations up to and including $x' = 10$ in, the timewise average temperature at any Q was within 3 per cent of the maximum temperature measured at that same Q. However, at $x' = 15$ in, the situation was quite different; for instance, for $Q = 4{\cdot}06$ W/ft, the timewise average temperature was 68 per cent of the corresponding laminar centerline value.

Temperature profiles

The temperature profiles presented here are constructed from time-wise averages of the output of the thermocouple probe. At each fixed probe position, the signal from the probe was integrated over time intervals of 300 s and longer, with periodic checks at shorter time intervals to establish the validity of the average. The results thus obtained are denoted by $\overline{T - T_\infty}$, the bar referring to a time average. At each elevation x' and each heat input Q, the measured temperature profile was normalized by the corresponding $\overline{T_{℄} - T_\infty}$. This ratio was then plotted as a function of the similarity variable ξ defined by equation (2).

The dimensionless temperature profiles are presented in Figs. 3 and 4, which pertain respectively to the lower elevations and to the higher elevations above the wire. Each figure contains profile results for four elevations, and at each elevation, data for three different heating rates are delineated by different symbols. The solid curves represent the predictions of laminar theory. Inasmuch as a temperature profile tabulation was not given in reference [6], a numerical solution of the governing equations was performed as part of this investigation in order to secure an accurate representation. The ordinate intercept of each curve is unity.

Inspection of Fig. 3 reveals that the measured temperature profiles are in excellent agreement with the predictions of laminar theory. Among the different heating rates, the greatest deviations occur at the lowest Q value; this is attributed to the fact that the temperature differences are smaller at smaller Q, thereby diminishing the precision of the data. Particular attention may

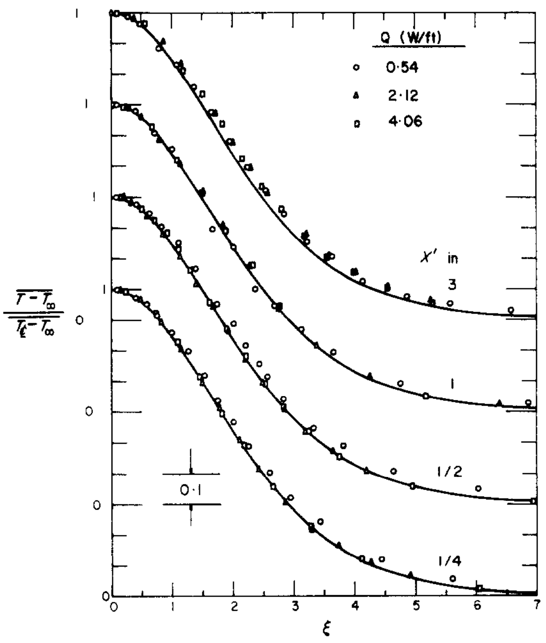

FIG. 3. Temperature profiles, $x' = \frac{1}{4}$–3 in.

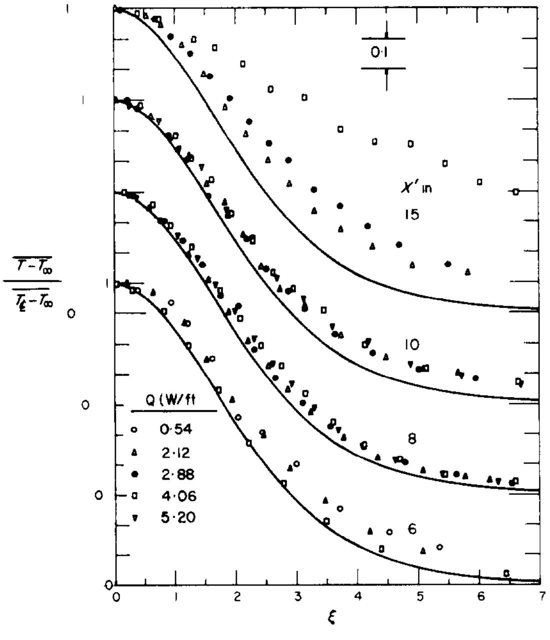

FIG. 4. Temperature profiles, $x' = 6$–15 in.

be directed to the results in Fig. 3 for $x' = \frac{1}{4}$ in. At this elevation, all data points would be shifted to the right by 12 per cent if x' were used directly in the similarity variable instead of x as given by equation (6). The good agreement evidenced in the figure supports the concept of an equivalent line source whose location is displaced from the heated wire.

Next, turning to Fig. 4, which corresponds to greater elevations, an overall inspection indicates a departure of the experimental data from laminar theory. Turbulent bursts were observed both at the 8- and 10-in elevations at the higher heating rates. At the 15-in elevation, the turbulent bursts occurred with greater frequency. Indeed, at the highest heating rate, the flow was predominantly turbulent; this is evidenced in the figure by the significant thickening of the plume relative to that for laminar conditions. From the analysis of Lee and Emmons [8], the predicted shape of a fully turbulent temperature field can be shown to be

$$T - T_\infty = c_1 \left(\frac{Q^2}{g\beta c_p^2 \rho^2}\right)^{\frac{1}{3}} x^{-1} \exp\left[-c_2 y^2/x^2\right]. \tag{7}$$

Inasmuch as only one of the presently measured temperature profiles approached the fully turbulent condition, it is not possible to investigate the validity of equation (7).

Plume oscillations, transition, turbulence

The nature of the temperature variations induced at a fixed point in space by the swaying of the plume is illustrated in Fig. 5. The figure shows the temperature–time history at two points, both having an elevation $x' = \frac{1}{2}$ in. One point is slightly displaced from the centerline, while the second corresponds to $(T - T_\infty)/(T_{\text{℄}} - T_\infty) \approx 0{\cdot}5$, which is near the location of the maximum temperature gradient. The upper graph is for a heating rate $Q = 4{\cdot}06$ W/ft, while the lower graph is for $Q = 0{\cdot}54$ W/ft.

From an inspection of the figure, it is evident that the swaying of the plume has little effect on the measured temperature in the neighbourhood of the geometrical centerline of the plume. A different state of affairs exists away from the centerline. Considering the off-centerline results, two characteristics are observable. First, the flow is not turbulent, since the traces are smooth, regular and very nearly cyclic. Second, the oscillation is more pronounced at higher heating rates. The characteristics exemplified by Fig. 5 are typical of all the measurements made under laminar flow conditions.

Measurements such as those illustrated in Fig. 5 could not be performed for partially turbulent and fully turbulent conditions because the available instrumentation did not possess

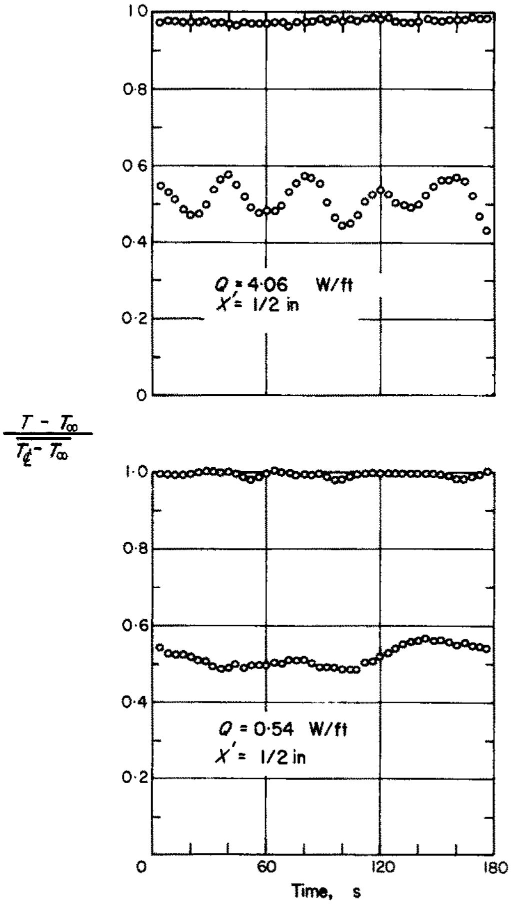

FIG. 5. Representative temperature-time data for laminar conditions.

the requisite rapid response characteristics. However, the amplitudes of the temperature fluctuations associated with the turbulent bursts were recorded. In general, these amplitudes were much larger than those of the temperature fluctuations in the laminar regime.

On the basis of observations of the output of the thermocouple probe, a criterion can be stated for the onset of transition, which is defined here as the first appearance of turbulent bursts. By employing a modified Grashof number

$$Gr^* = g\beta Q x^3 / \rho c_p \nu^3 \qquad (8)$$

that arises naturally from dimensional considerations, the experimentally determined transition point is $Gr^* = 5 \times 10^8$. In addition, on the basis of the observed probe output and from Fig. 4 (uppermost curve for $x' = 15$ in), the fully turbulent state may be characterized by $Gr^* \geqslant 5 \times 10^9$.

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Résumé—Le champ de température de convection naturelle à l'intérieur d'un panache s'élevant d'un fil horizontal chauffé a été exploré expérimentalement. Les mesures d'écoulement laminaire ont été facilitées en employant une enceinte isolante. Le panache laminaire présentait un mouvement lent, avec des oscillations régulières. On a trouvé que la dépendance quantitative du champ laminaire de températures en fonction du taux de chauffage et de la hauteur au-dessus du fil, déduite des données expérimentales, était en excellent accord avec les prévisions théoriques pour un panache produit par une source de chaleur linéaire. Des explosions de turbulence se produisaient à des hauteurs plus importantes au-dessus du fil et pour des taux de chauffages plus élevés, signalant ainsi le début de la transition. La fréquence des explosions augmentait lorsque la hauteur et le taux de chauffage croissaient. Le début de la transition, indiqué par l'apparition des explosions de turbulence, se produisait à un nombre de Grashof modifié de 5×10^8. Des conditions entièrement turbulentes prédominaient lorsque le nombre de Grashof modifié était égal à 5×10^9.

Zusammenfassung—Für freie Konvektion wurde die Temperaturverteilung in einem Auftriebsfeld über einem beheizten waagerechten Draht experimentell untersucht. Die Messungen der Laminarströmung wurden erleichtert durch Benützung einer isolierenden Kammer. Das laminare Strömungsfeld wies eine langsame, regelmässig schwingende Bewegung auf. Die aus den Versuchswerten abgeleitete quantitative Abhängigkeit des laminaren Temperaturfeldes vom Wärmestrom und der Höhe über dem Draht zeigte sehr gute Übereinstimmung mit analytischen Bestimmungen für ein Feld, das von einer linienförmigen Wärmequelle ausgeht. Die über einen Bereich verschiedener Höhen und Wärmeströme gemessenen Temperaturprofile stimmten ebenfalls gut mit der laminaren Theorie überein. Turbulenter Zerfall erfolgte in grösseren Höhen über dem Draht und bei grösseren Wärmeströmen und kennzeichnet den Beginn eines Überganges. Die Zerfallfrequenz nahm zu mit grösseren Höhen und Wärmeströmen. Der Beginn des Überganges, der durch Auftreten eines turbulenten Zerfalls erkennbar wird, erfolgte bei einer modifizierten Grashofzahl von 5×10^8. Nahezu voll ausgebildete turbulente Zustände herrschten bei einer Grashofzahlf von 5×10^9.

Аннотация—Проведено экспериментальное исследование свободно-конвективного температурного поля над нагретой горизонтальной проволокой. Использование изолирующей камеры облегчило измерение ламинарного течения. Найдено, что количественная зависимость ламинарного температурного поля от скорости нагрева и высоты над проволокой, как выведено из экспериментальных данных, прекрасно согласуется с теоретическими расчетами для области нагретого воздуха, всплывающего над линейным источником тепла. Измеренные температурные профили для различных высот и скоростей нагрева также хорошо согласуются с ламинарной теорией. На большой высоте над проволокой и при больших скоростях нагрева появлялись турбулентные вспышки, сигнализирующие начало перехода. Частота вспышек возрастала с увеличением высоты и скорости нагрева. Начало перехода имело место при модифицированном числе Грасгофа 5×10^8. Полностью турбулентный режим превалировал при значении модифицированного критерия Грасгофа, равном 5×10^9.