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Density Gradients Near a Liquid/Air Interface

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ABSTRACT

An experimental investigation of the density variations which occur in a liquid near a liquid/air interface was conducted by means of a Mach-Zehnder interferometer and a gas laser light source. The liquid used in this investigation was distilled water. Experiments were made under two conditions. The first condition was evaporation from an undisturbed interface. The second condition was evaporation in the presence of a submerged, heated copper tube. The quantities of interest were the variations in the interfacial temperature, the changes in thickness of the interfacial thermal layer, and the temperature gradient at the interface. The depth of the submerged, heated surface varied from 10.2 cm to 76.2 cm, and the temperature difference between the submerged, heated tube and the surrounding liquid bulk temperature varied from 0.0 °C to 5.0 °C. The results gave an indication of the behavior of the thin thermal liquid layer at the interface. The mechanism responsible for the changes in the thermal layer was due to a momentum disturbance at the underneath side. The small disturbances were sufficient to alter the frequency and magnitude of the changes that normally occur at an evaporating interface.

PROBLEM STATUS

This is an interim report; work in this general area is continuing.

AUTHORIZATION

NRL Problem G01-02C
AIRTASK WF-08-125-703

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DENSITY GRADIENTS NEAR A LIQUID/AIR INTERFACE

INTRODUCTION

It has been pointed out in recent articles that the behavior of the thin thermal layer which forms at the air/sea interface has a strong influence on the transport of heat, mass, and momentum across the interface. The thickness of this layer is usually no more than 5.0 mm, but it is very sensitive to changes in the surroundings on either side of the interface. To understand the transport phenomena which occur at a liquid/air interface, it is first necessary to gain a better understanding of the thermal layer.

The objective of this study was to help clarify the behavior of the interface under certain laboratory conditions. A laboratory study was made by means of an optical interferometer which used a gas laser as the light source. The coherence and intensity of the laser made the use of the interferometer very simple. The local evaporative cooling within the thermal layer changed the local index of refraction of the water. This change caused a fringe shift which indicated the thickness and density changes within the thermal layer.

The laboratory model used was admittedly not representative of an actual air/sea interface, because the effects of radiation, wind, ocean currents, salinity, etc., were not considered. In the laboratory the interface was sensitive to evaporation into the air and internal convection currents within the water. Even this simple laboratory model produced complex variations within the thermal layer. The convection currents within the water were due to self-induced convection, caused by instability induced by evaporation, for all test runs. In addition, when a submerged, heated copper tube was located beneath the interface, additional convection currents were set up due to the buoyant force around the tube.

Results are presented for submerged depths of the heated surface between 10.2 cm and 76.2 cm. The results of tests with a submerged, heated surface are compared with the results of tests with no submerged, heated surface. The results showed that the presence of a submerged, heated surface can affect the normally occurring fluctuations which are present within the interfacial layer.

LITERATURE SURVEY

The interferometer has proven to be a very useful tool in studies of heat and mass transfer in air and gases. However, as of late, attempts have been made to extend these studies into the liquid environment. Azami (1) was one of the first to use the Mach-Zehnder interferometer in a study of heat transfer in liquids. He studied the heating of an aluminum strip in water, and a fringe pattern with a large curvature near the strip was detected. The temperatures determined from the interferograms were compared with temperatures measured independently using a thermocouple and were found to be from 10 to 35% in error. His results were negated due to an incorrect assumption neglecting end effects. Also, the optical path length varied due to the buckling of his glass plates as a result of the heating. However, it was a start in extending interferometry to liquids.

Ostromunov (2) did some of the earliest work in transient experimental studies in liquids, but using a Schlieren system. Platinum wires were submerged in different liquids, and a dc current was passed through them. Temperature distributions about these wires were observed. The results were mainly qualitative, however. He found that the temperature near the wire reached a maximum and then dropped off to a steady-state value. Little correlation with theory could be provided. This is precisely the case which the interferometer improved.

McLean, et al (3), modified the work of Azami and extended it to transient studies. They showed that the interferometer was superior to thermocouples for determining temperature distributions in both air and water because the interferometer provided essentially instantaneous temperature distributions. Thermocouples generally lacked sufficient response time to react, for example, to pulsed heating. Also, the basic expressions relating fringe shifts and corresponding temperature differences were discussed. Mention was also made of necessary corrections due to end effects and refraction errors. They found that increasing the length of the surface in the water reduced end effects. Temperature distributions as a function of both time and distance from the heated surface were also plotted.

Goldstein (4) reached several basic conclusions concerning the optical methods for studying the transport phenomenon in liquids. He stated that the Mach-Zehnder interferometer was especially suited for geometries where the optical properties vary only in the direction of the light path and for systems where properties are locally constant or of known variation.

Goldstein and Eckert (5) studied both the transient and the steady-state boundary layer in air and water. For the study in the liquid environment, the fact that the index of refraction for water was a strong function of temperature restricted this work to very small temperature differences. Novotony (6) did a similar experiment using a fluid with an internal heat source. The fluid was made slightly conducting, and an electrical current was passed through it.

Spangenberg and Rowland (7) used a Schlieren system and showed that the evaporation process gave rise to a cooling at the interface which caused a cooler liquid layer to form. This layer eventually became unstable and initiated convection within the fluid. They also showed that this instability was a function of the evaporation rate. As the water temperature of the test tank was increased, more sheets of water were observed plunging downward. Another finding was that the total depth of the fluid was unimportant in this process. Using a form of the Rayleigh number as a stability index, they showed that the instability first occurred for a Rayleigh number of 1193. After the initial sheetlike plunging, they observed that the plunging continued to grow and fade and continuously changed form. When plunging occurred, the surface water continued to flow downward through the sheets and reduced the cooled surface layer to a thin film. It was also reported that only after several hours in an undisturbed condition did the circulation apparently reach a steady state. After the initial circulation, the thickness of the cooled thermal layer was less than that required to start the convective circulation. Thus, the available potential energy between the plunging sheets was less than that required initially. The cooled layer was apparently continuously drained by the plunging sheets.

Convection due to instability was treated theoretically by Roberts (8) and experimentally by Tritton and Zarraga (9) for the same experimental configuration. In this case, the experimental study came first, and the theoretical verification followed. Essentially what was studied by Tritton and Zarraga (9) was the convection of fluids between two horizontal surfaces at different temperatures. They developed a technique using polystyrene beads for visualizing flow patterns when the fluid was heated internally. The most striking discovery was the size of the large horizontal convection

patterns. The distance between rising and falling currents was typically five times the depth of the layer. Roberts (8) made a theoretical study of the convective motions in the horizontal layer cooled from above and heated internally. He found that the critical Rayleigh number for marginal stability of the layer was 2772. The remainder of the paper was devoted to studying the finite amplitude convections ensuing above this critical Rayleigh number.

Van den Driessche (10) studied properties of a viscous liquid nonuniformly heated from below. A simple model of a cylindrical dishpan filled with an incompressible fluid was used. It was found that the basic temperature profile arising due to constant generation within the fluid was parabolic. The velocity profiles, both vertical and radial, were plotted as functions of the Rayleigh number and a radiation parameter. The velocity profiles were also found to be parabolic for the vertical case, going from zero at the lower surface through a maximum and back to zero at the upper surface.

More recently Foster (11, 12) has made a theoretical and experimental investigation of the onset of convection in a layer of fluid cooled from above. The results showed that the initial behavior of the system depended on the Rayleigh and Prandtl numbers, but the system was independent of the depth of fluid after a minimum depth for a given heat transfer rate had been exceeded. He measured the surface temperature with a radiometer and noted that warmer water was brought to the surface as soon as convection commenced. The observed subsequent development of the convection cells showed more regularity than those reported by Spangenberg and Rowland (7). Foster suggested that this might be due to the fact that his test tank had a very large width-to-depth ratio, which tended to eliminate interfering edge effects.

Jakob (13) presented a submerged heating study in which water was boiled on a horizontal heating plate. He found that, beginning with the temperature of the heating surface, the water temperature dropped off considerably very near the surface, indicating a layer not mixed by convection. Perhaps the most significant result was that the heat flow had very little effect on the temperature difference between the fluid on one side of the interface and steam on the other side of the interface. For two cases, one in which the heat flux was 150 times the other, the drop at the interface was only 0.4 °C in both cases.

The actual interface temperature of the ocean was studied by Osborne (14). He conducted a heat balance around the interface of an ocean model and derived an expression for the interface temperature. This model assumed a thermal and velocity boundary layer in both the air and the water.

THEORY

The basic equation which relates the fringe shift to the change in index of refraction is

$$\Delta S = \frac{L}{\lambda}(n - n_r) , \tag{1}$$

where

L = length of test section (23.8 cm),

λ = wavelength of light (6328 Å),

n_r = reference index of refraction,

n = local index of refraction, and

ΔS = fringe shift measured relative to reference.

A relationship between the index of refraction and the density can be expressed in the form of the Lorentz-Lorentz equation for liquids:

$$\frac{1}{\rho}\frac{n^2 - 1}{n^2 + 2} = K \tag{2}$$

where K = Gladstone-Dale constant and ρ = local density. The Gladstone-Dale constant depends only on the medium and the wavelength of light. By using tabulated values of K for water and experimentally determining n from Eq. 1, Eq. 2 can be used to calculate the local density value. An equation of state can then be used to calculate the corresponding local temperature. When very small temperature differences occur in the liquid, it is possible to use the method followed by McLean et al (3), and express the temperature change directly in terms of the fringe shift. This was a valid approach in the current investigation, since the observed temperature differences across the thermal layer were approximately 0.2 °C. Following the method of McLean (3), one may assume a linear variation of the form $n = mT + b$, where m and b are constants. The fringe shift can then be written as

$$\Delta S = \frac{Lm}{\lambda}(T - T_r) . \tag{3}$$

The value of m, which is the slope of the linear variation of $n = f(T)$, was $1.19 \times 10^{-4}/°C$. The local temperature T could then be easily calculated from experimental measurements of ΔS, L, λ, and T_r. In this report the reference temperature T_r is the bulk temperature T_B. The variation of ΔS with distance from the interface was directly related to the variation of $T - T_r$ through Eq. 3, and temperature profiles within the thermal layer could be determined.

APPARATUS

The experimental apparatus is shown in Fig. 1. The gas laser and collimator, which produced a parallel, 50-mm-diameter beam, are shown on the right. In the center of the picture a water tank can be seen in which the water/air interface was produced. The tank is placed in one light path of the interferometer. The tank size was 20.3 cm in the direction of the light path and 30.5 cm normal to the light path. Tanks of different depths were used so the depth of submergence of the heated copper tube could be varied. A temperature-controlled water bath was used to control the temperature of the water which flowed through the submerged copper tube. The fringe pattern was focused on a ground-glass screen, and photographs were taken as shown in Fig. 1.

The formation of the thermal layer was easily observed with the experimental equipment. When the tank was covered for several hours until evaporation no longer occurred from the interface, the observed fringe pattern showed vertical, parallel fringes throughout the liquid. When the cover was removed, it took only a few seconds for the evaporatively cooled layer to form, and the fringe pattern appeared as shown in Fig. 2. The reference temperature T_r is the temperature of the fluid where the thick vertical fringes still appear. The thin vertical fringes in the upper half of the photograph occur in the air above the interface. The fringe shift indicates a local cooling, relative to the reference temperature, within the interface thermal layer. The effect of the submerged, heated surface on the interface is indicated in Fig. 3 through 7. The ΔT value indicates

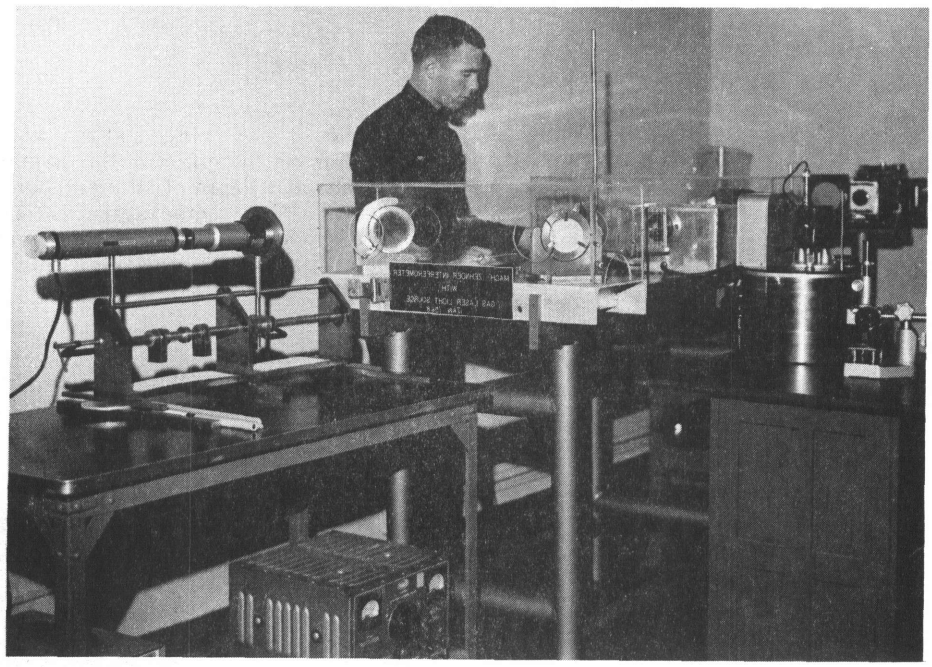


Fig. 1 - Experimental apparatus which includes a Mach-Zehnder interferometer, a He-Ne gas laser, a temperature-controlled water bath, and a tank containing the liquid air interface

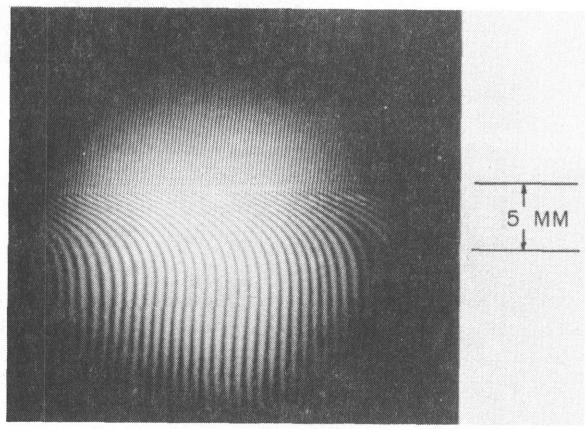


Fig. 2 - A fringe pattern showing the fringe shift within the thin, liquid thermal layer caused by cooling due to evaporation at the interface. No submerged, heated tube is present.

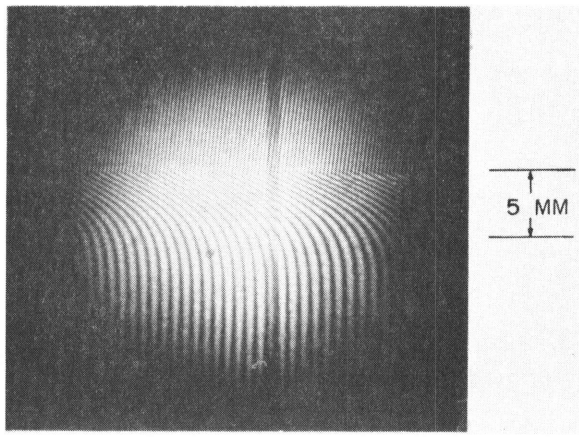


Fig. 3 - A fringe pattern at the interface showing the effect of the submerged, heated tube at a depth of 10.2 cm below the interface. The temperature difference between the tube surface and the bulk liquid is 0.05°C. The effect is small at this temperature difference.

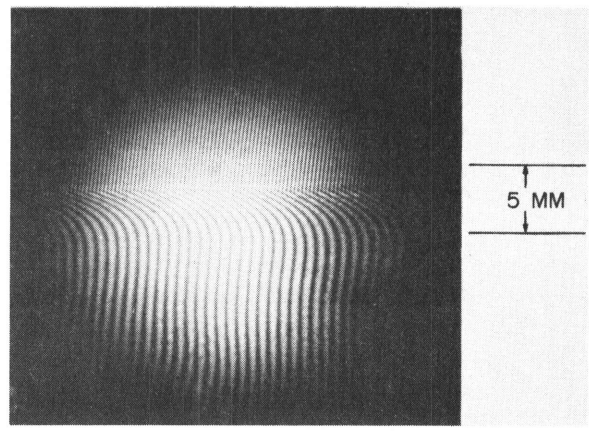


Fig. 4 - A fringe pattern at the interface showing the effect of the submerged, heated tube at a depth of 10.2 cm below the interface. The temperature difference between the tube surface and the bulk liquid is 1.50°C. A significant effect is noted, and a positive fringe shift to the right occurs in the lower half of the thermal layer.

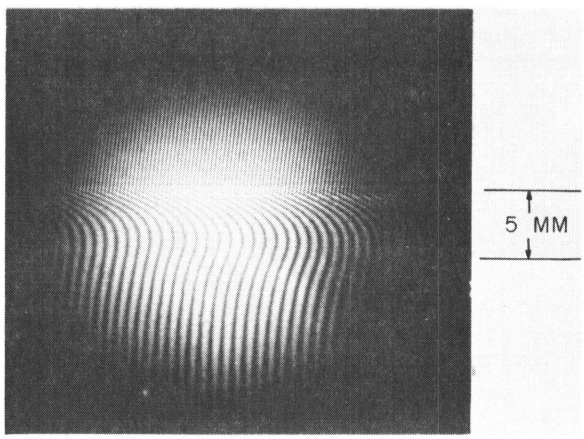


Fig. 5 - A fringe pattern at the interface showing the effect of the submerged, heated tube at a depth of 10.2 cm below the interface. The temperature difference between the tube surface and the bulk liquid is 1.75°C. The effect has been to reduce the thickness of the thermal layer at the interface.

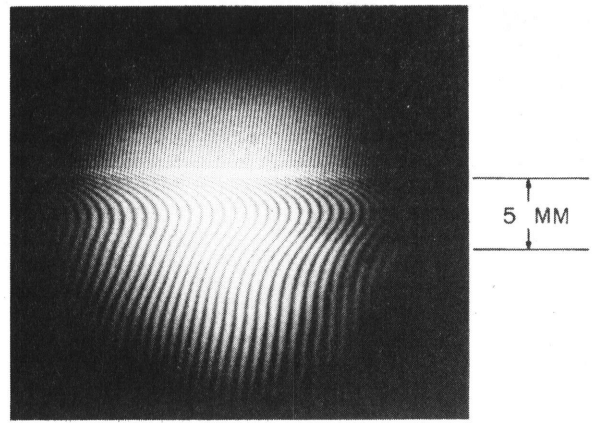


Fig. 6 - A fringe pattern at the interface showing the effect of the submerged, heated tube at a depth of 10.2 cm below the interface. The temperature difference between the tube surface and the bulk liquid is 2.25°C. The effect has caused a large positive fringe shift within the thermal layer, indicating that a maximum in the temperature profile occurs within the thermal layer.

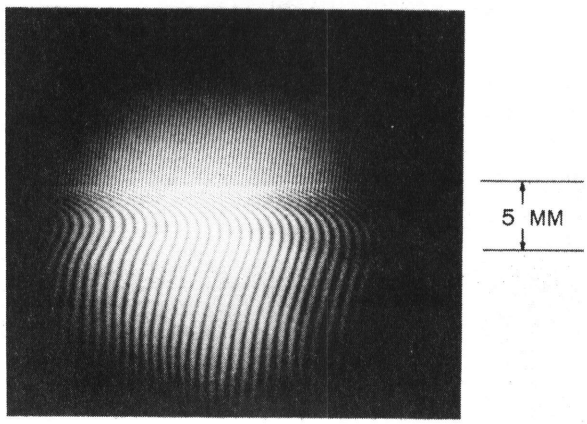


Fig. 7 - A fringe pattern at the interface showing the effect of the submerged, heated tube at a depth of 10.2 cm below the interface. The temperature difference between the tube surface and the bulk liquid is 2.50°C. The effect has again made the thermal layer thinner and reduced the positive fringe shift within the thermal layer.

the difference between the submerged-tube temperature and the surrounding-bulk temperature.

The number of fringe shifts as a function of distance from the interface was obtained from the photographs by using an optical comparator, and temperature profiles within the thermal layer were calculated from Eq. 3. Typical temperature profiles are shown in Figs. 8 and 9. The temperature gradient at the interface was graphically determined as shown. The thermal layer thickness ΔD was defined as the intersection on the abscissa by the linear extension of the temperature gradient at the interface. All three quantities ΔT, ΔD, and $\Delta T/\Delta D$ were of interest.

RESULTS

One of the motivations for this study was to investigate the effects of a submerged, heated surface on the interface thermal layer. It was therefore necessary to first know the behavior of the interface thermal layer without the presence of a submerged, heated surface. A few papers have been published on the instabilities associated with evaporation at a liquid/air interface. Some of these studies are mentioned briefly in the literature survey. These studies were mainly concerned with the onset of circulation, but a few qualitative remarks were made concerning the long-term behavior of the interface.

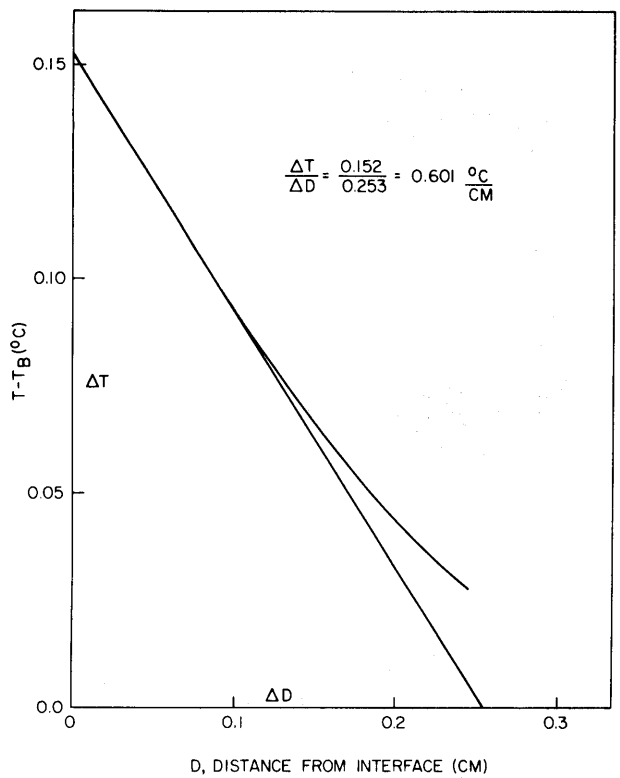


Fig. 8 - A temperature profile within the thermal layer obtained from fringe-shift measurements. The straight line represents the linear gradient at the interface. The fringe pattern indicated no positive shift to the right within the thermal layer. The temperatures of the submerged, heated tube is 1.0°C above the bulk fluid temperature.

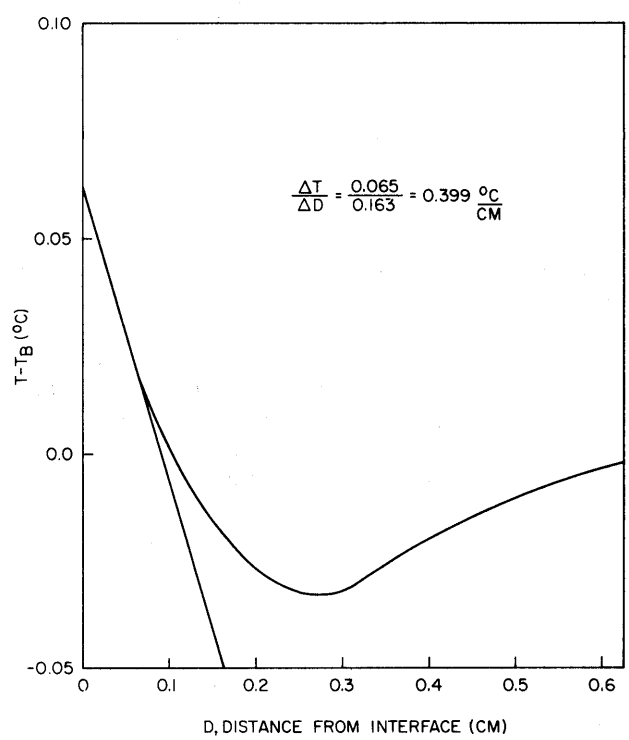


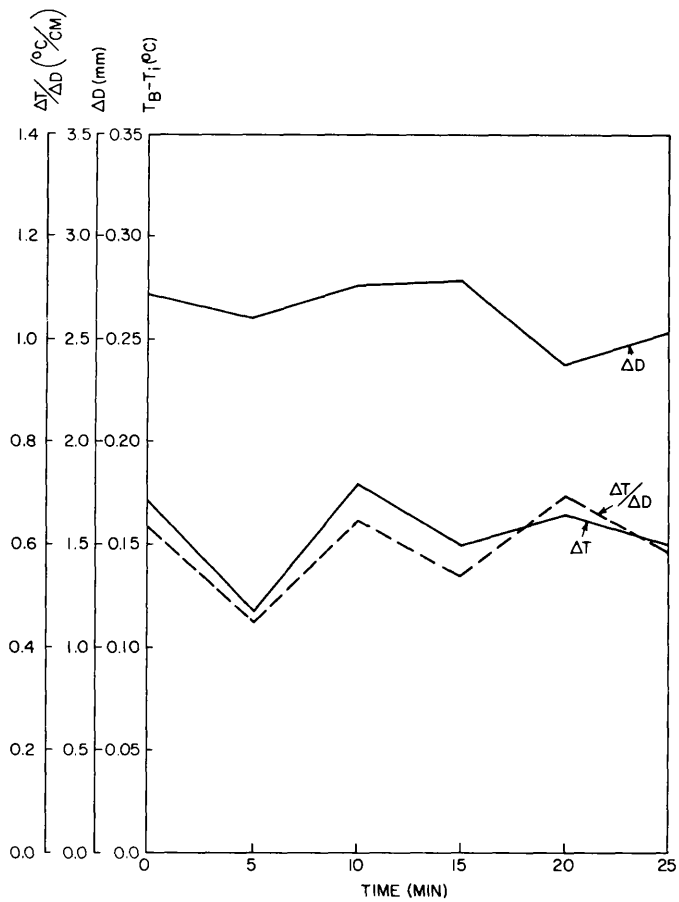
Fig. 9 - A temperature profile within the thermal layer obtained from fringe-shift measurements. The straight line represents the linear gradient at the interface. The fringe pattern indicated a positive shift to the right within the thermal layer. The temperature of the submerged, heated tube is 1.5°C above the bulk fluid temperature.

Since the current experimental technique was different from the previously reported work, it was desirable to study the interface without the presence of a submerged, heated surface by means of the Mach-Zehnder interferometer. The photographs obtained were made at time intervals of either 1.0 min or 5.0 min. The tank was uncovered and allowed to sit for 15 to 20 min before the first photograph was taken. Thus, the convective circulation induced by evaporatively cooling was well established before the first photographs were made, since the Rayleigh number was well above the critical value reported by Spangenberg and Rowland (7).

Figure 10a through 10c show typical results from photographs taken at 5.0-min intervals. The relative humidity varied between 60% and 71% for these three tests. The object was to determine the variation of the thermal layer depth ΔD with time, the temperature difference between the interface and the bulk fluid ΔT, and the gradient $\Delta T/\Delta D$. The following observations apply to the results presented in Figs. 10a through 10c. In all three cases, the variation of ΔT with time shows a decreasing trend. It should be pointed out that the straight lines which connect the data points are not meant to infer a linear variation between points but are used only to indicate the trend of the variation. This smoothing of the temperature variation as time increased is in agreement with the observations of Spangenberg and Rowland (7) and Foster (11, 12). The results reported in Fig. 10c for the highest relative humidity show signficiantly lower values of ΔT and $\Delta T/\Delta D$, which is to be expected with the lower evaporation rates. The reduction in the interfacial temperature gradient is primarily due to a reduction in ΔT rather than an increase in ΔD.

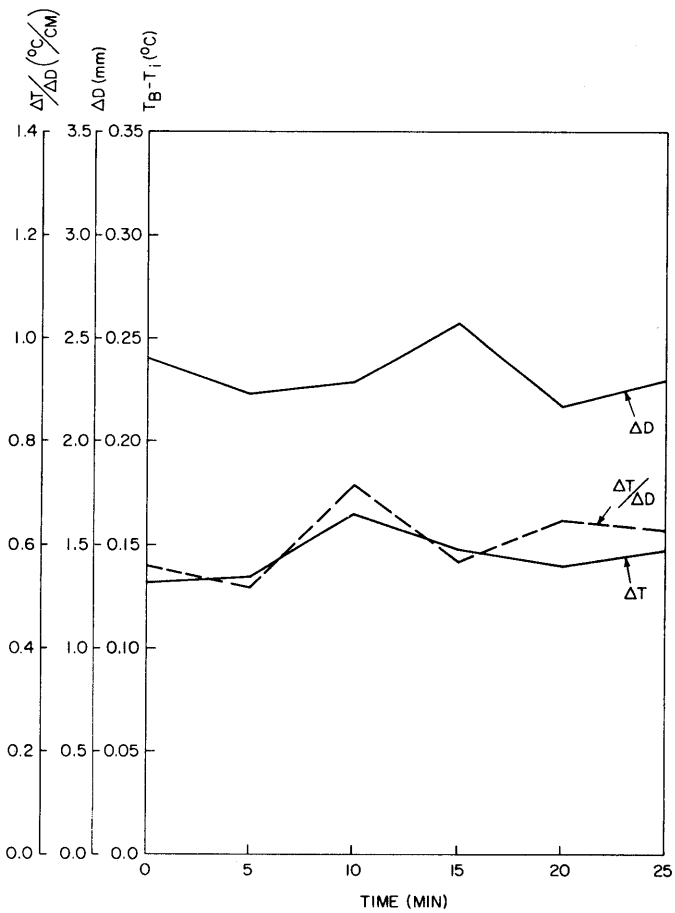
It was desirable to obtain photographs as frequently as possible, especially during the initial period when strong fluctuations occurred. Due to the photographic equipment and the polaroid film strips being used, it was not feasible to take photographs more often than at 1-min intervals. Figure 10d gives the results of a test run which was made in the same manner as those reported in Figs. 10a through 10c, except that the data were evaluated at 1-min intervals. Only the first 10 min are shown since the data tended to smooth out in the manner shown by the previous figures. Figure 10d shows that the frequency of fluctuations during the first few minutes was much greater than indicated by the previous results. In fact, it is suspected that spontaneous adjustments in the thermal layer occur within a period of a few seconds, and a continual recording system would be required to determine the actual frequency of fluctuations. A continual record was obtained by taking 16-mm movies of the process, but the variations could not be detected without magnification and accurately counting each individual frame. This was not considered feasible in the present study.

A decision was necessary before the tests on the effects of a submerged, heated surface with a wall temperature T_W were conducted. Initially it was thought that a investigation with $T_W - T_B$ held constant would be the best way to study the fluctuations of the interface thermal layer with time. However, the continual increase in T_B due to the energy input from the submerged tube required that T_W also be changed to maintain a constant $T_W - T_B$. Instead, it was decided to use a uniform heating rate for each test and observe the behavior on the interface as the value of $T_W - T_B$ increased. The heating rate was chosen such that a $T_W - T_B$ of 2.5°C could be reached in approximately 20 min, and a $T_W - T_B$ of 5.0°C could be reached in approximately 45 min. A typical set of photographs is shown in Figs. 2 through 7. These pictures were taken for a 0.635-cm-diameter tube at a submergence depth of 10.2 cm. The inversion that is obvious in Fig. 4 and Fig. 6 indicates that the maximum temperature within the fringe pattern shown occurs within the thermal layer. The water has been cooled at the interface due to evaporation and has also been cooled below by cooler water which evidently has been circulated from the interface. This inversion appeared periodically, and it could be observed to sweep across the field of view. The reference temperature was still taken as the temperature in the region of the vertical fringes in the lower part of the photograph.



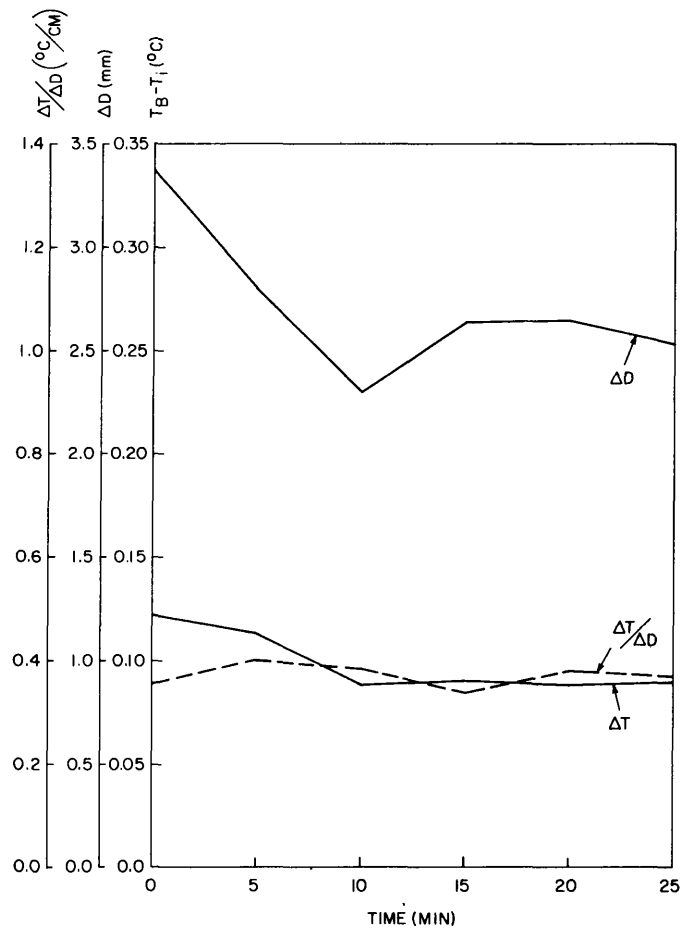
(a) Relative humidity equals 60%.
Time interval is 5 min.

Fig. 10 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to the instability caused by evaporation cooling. No submerged, heated tube is present.



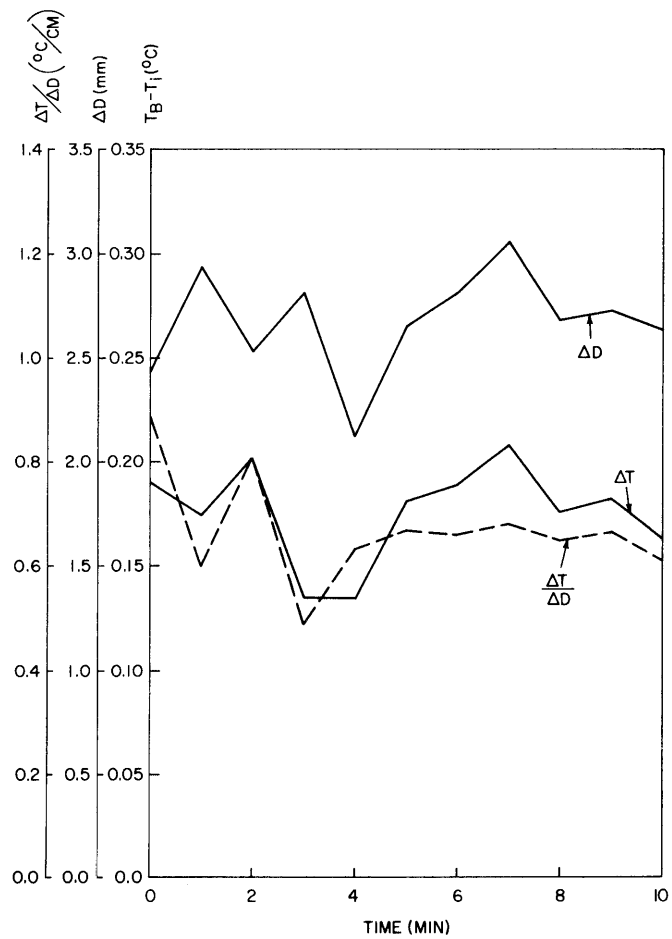
(b) Relative humidity equals 63%
Time interval is 5 min.

Fig. 10 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to the instability caused by evaporation cooling. No submerged, heated tube is present—Continued.



(c) Relative humidity equals 71%.
Time interval is 5 min.

Fig. 10 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to the instability caused by evaporation cooling. No submerged, heated tube is present—Continued.



(d) Relative humidity equals 61%.
Time interval is 1 min.

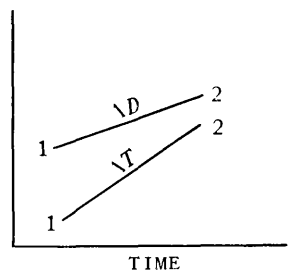
Fig. 10 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to the instability caused by evaporation cooling. No submerged, heated tube is present—Continued.

Thus, ΔT can fluctuate due to a change in the reference temperature T_B as well as in the interface temperature T_i. The reference temperature has obviously changed when inversions occur in the fringe pattern such as shown in Fig. 6. T_i can change due to evaporation and convection, but T_B would change only as a result of internal convection within the fluid.

The variation of ΔT and ΔD with time appeared to be independent of each other for tests without a submerged, heated surface as well as for tests with a submerged, heated surface. Based on the understanding gained from this study, as well as on behavior reported by other authors, an attempt was made to explain the phenomena which could cause the observed variations. The possible variations and explanations are listed below:

Case A

Increasing $T_B - T_i = \Delta T$
Increasing layer thickness = ΔD

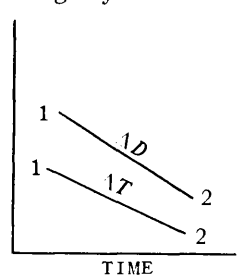


Explanation

Evaporation has cooled the interface and thickened the thermal layer. This is similar to the effect that was observed when a covered tank was suddenly uncovered and the thermal layer began to form.

Case B

Decreasing $T_B - T_i = \Delta T$
Decreasing layer thickness = ΔD

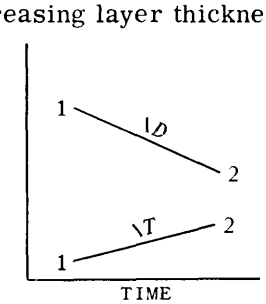


Explanation

Colder surface fluid has plunged due to the instability caused by evaporation. The plunging has carried other colder water down with it leaving warmer water at the interface and thinning the thermal layer.

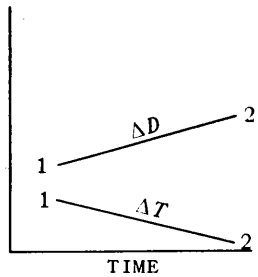
Case C

Increasing $T_B - T_i = \Delta T$
Decreasing layer thickness = ΔD



Explanation

Due to upward flow of warmer water T_r has increased, thus increasing $T_B - T_i$. Due to the presence of the interface, the flow is circulatory, changing from vertical to horizontal beneath the interface. This flow reduces the thickness of the thermal layer.

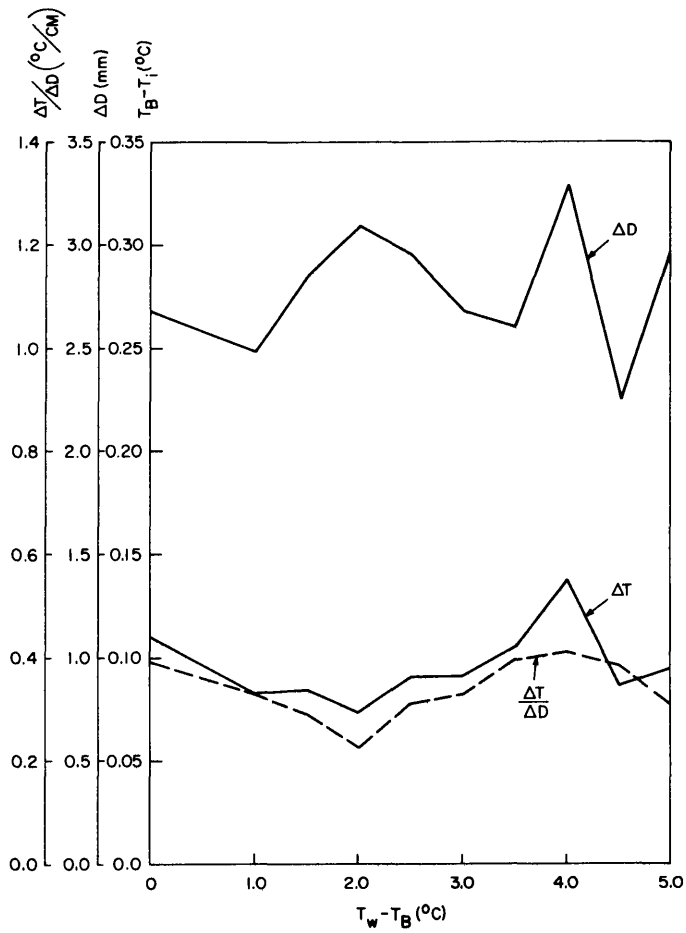
Case D	Explanation
Decreasing $T_B - T_i = \Delta T$ Increasing layer thickness = ΔD 	Cool water from adjacent plunging sites decreases T_B by thermal conduction, thus decreasing $T_B - T_i$. This also reduces the gradient within the thermal layer; thus, the thickness is increased.

Typical results for the effect of a 1.27-cm-diameter tube at a submergence depth of 76.2 cm are given in Figs. 11a and 11b. One must interpret these results with caution, since it is quite possible that the presence of the submerged surface will affect the frequency of the fluctuations within the thermal layer before it affects the magnitude of the fluctuations. As explained earlier, this effect would not be clearly seen with the present method of data acquisition. However, if one compares Figs. 11a and 11b with Fig. 10c, certain conclusions can be made. The figures present results at approximately the same relative humidity. It is obvious that the submerged surface is affecting the magnitude, and probably the frequency, of all three quantities which appear as a function of $T_W - T_B$. The fluctuations appear to become more severe as $T_W - T_B$ is increased, as would be expected.

The results of three tests made at a submergence depth of 45.7 cm are given in Figs. 12a through 12c. In all three plots the trend of ΔD is to decrease with time. This indicates that the convective momentum exchange set up by the thermal buoyant forces around the submerged, heated tube are causing additional circulation near the interface, and this in turn is producing a thinner thermal layer due to mixing near the lower boundary of the thermal layer. The fluctuations of ΔT and $\Delta T/\Delta D$ are quite pronounced for all values of $T_W - T_B$. Here again the limited frequency response of the experimental technique prohibits a detailed explanation of the behavior. However, the fluctuations of ΔT about a mean value shown in Figs. 10a and 10b amount to $\pm 0.015\,°C$ or $\pm 10\%$. The fluctuations of ΔT about a mean value in Figs. 12a through 12c amount to $\pm 0.03\,°C$ or $\pm 18\%$. Thus, it is safe to conclude that the interface temperatures are significantly altered by the presence of the submerged surface.

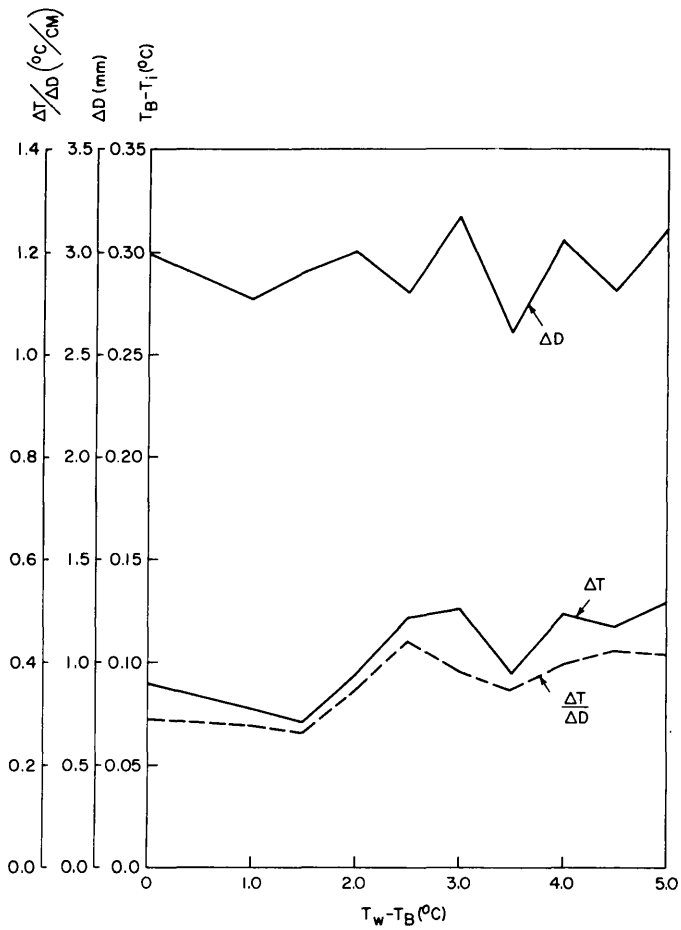
Measurements of the bulk fluid near the submerged surface and between the submerged surface and the interface were made to determine what mechanism was causing the increased variation in $T_B - T_i$ at the interface. The measurements were made with a quartz thermometer, which gave readings to 0.001 °C. Even when the surface of the tube was 4.0 °C warmer than the surrounding fluid at the same depth, it was difficult to detect a local temperature increase directly above the heated surface when the probe was placed more than 5.0 cm above the tube. During the experimentation the value of the interfacial temperature was never equal to or greater than the reference temperature of the bulk fluid.

Based on these two observations, it is suggested that the increased fluctuations in the presence of the submerged, heated surface were due to increased disturbances of the unstable interface. It is suggested that the thermal energy required to periodically decrease $T_B - T_i$ by increasing T_i came from the bulk fluid directly beneath the interface. Then the value of $T_B - T_i$ was increased again rapidly due to the accelerated evaporation which decreased T_i. The increased disturbance of the unstable interface was probably



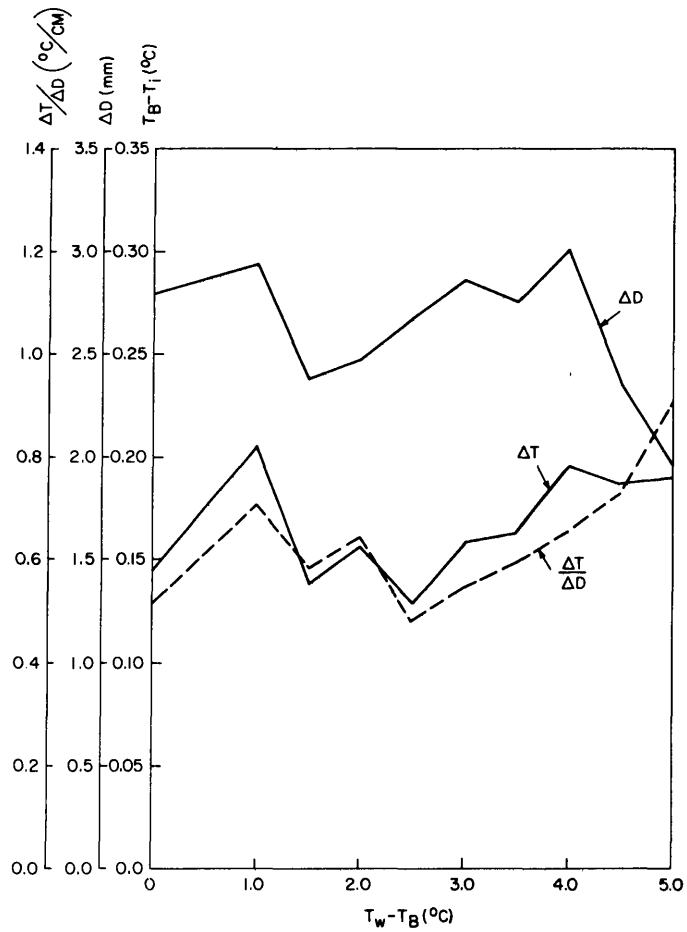
(a) Relative humidity equals 73%

Fig. 11 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 76.2 cm, and the tube diameter was 1.27 cm.



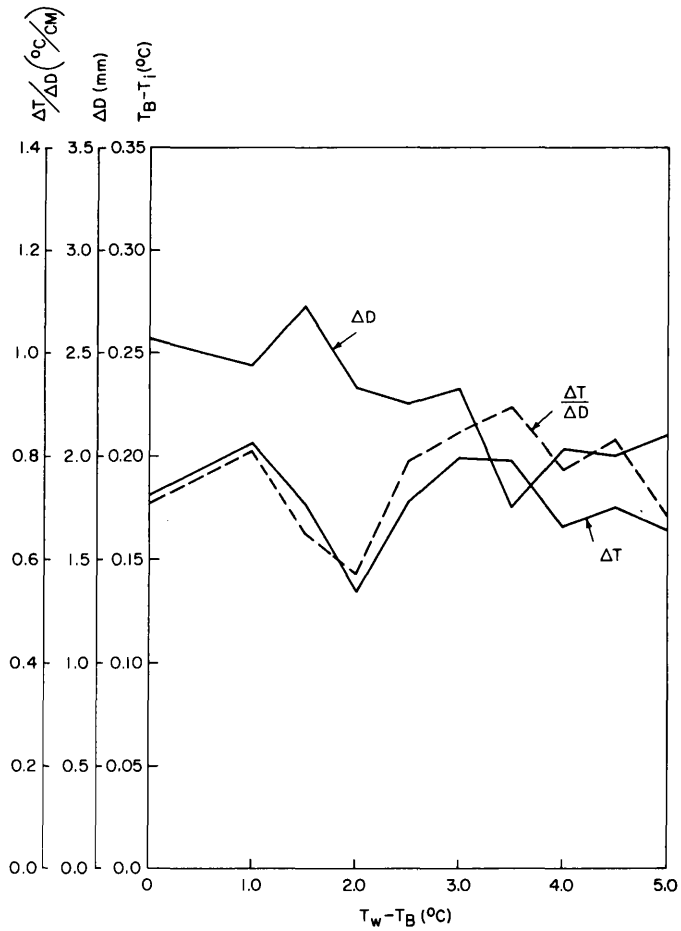
(b) Relative humidity equals 71%

Fig. 11 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 76.2 cm, and the tube diameter was 1.27 cm—Continued.



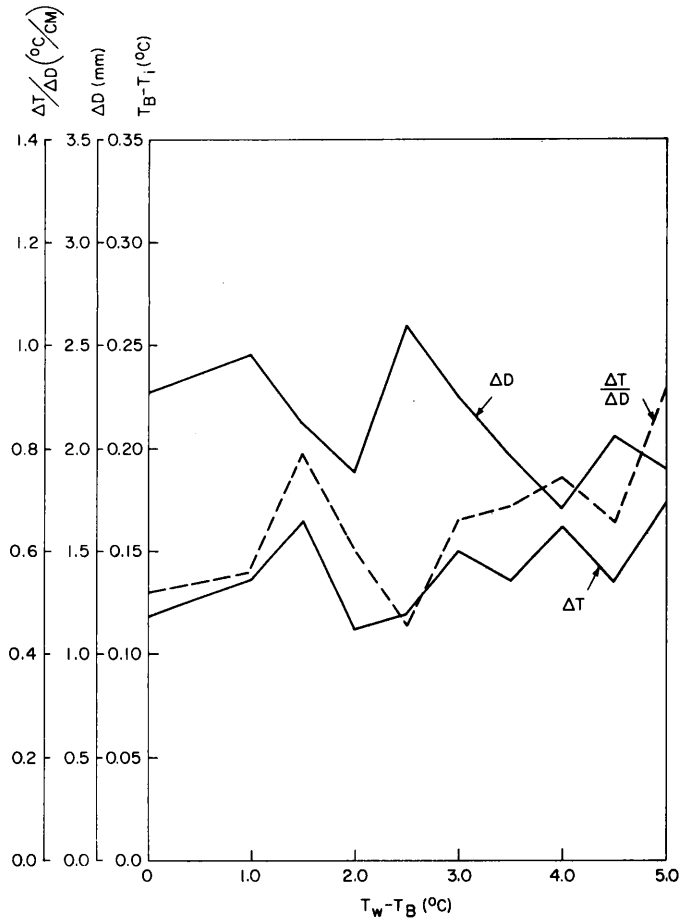
(a) Relative humidity equals 60%

Fig. 12 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged. heated tube. The surface temperature of the tube increased with time. The submergence depth was 45.7 cm, and the tube diameter was 1.27 cm. Figures 12a through 12c present data taken at different times under approximately the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases.



(b) Relative humidity equals 61%

Fig. 12 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 45.7 cm, and the tube diameter was 1.27 cm. Figures 12a through 12c present data taken at different times under approximately the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases—Continued.



(c) Relative humidity equals 61%

Fig. 12 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 45.7 cm, and the tube diameter was 1.27 cm. Figures 12a through 12c present data taken at different times under approximately the same laboratory conditions. The results show the trends of the data as T_W - T_B increases—Continued.

due to a complicated interaction between the normally induced internal convection and the free convection above the heated tube. Although the quartz thermometer measurements indicated that the buoyant-temperature driving force was quickly damped out, it was felt that the inertia effects would allow the thermally induced motion to penetrate to the interface.

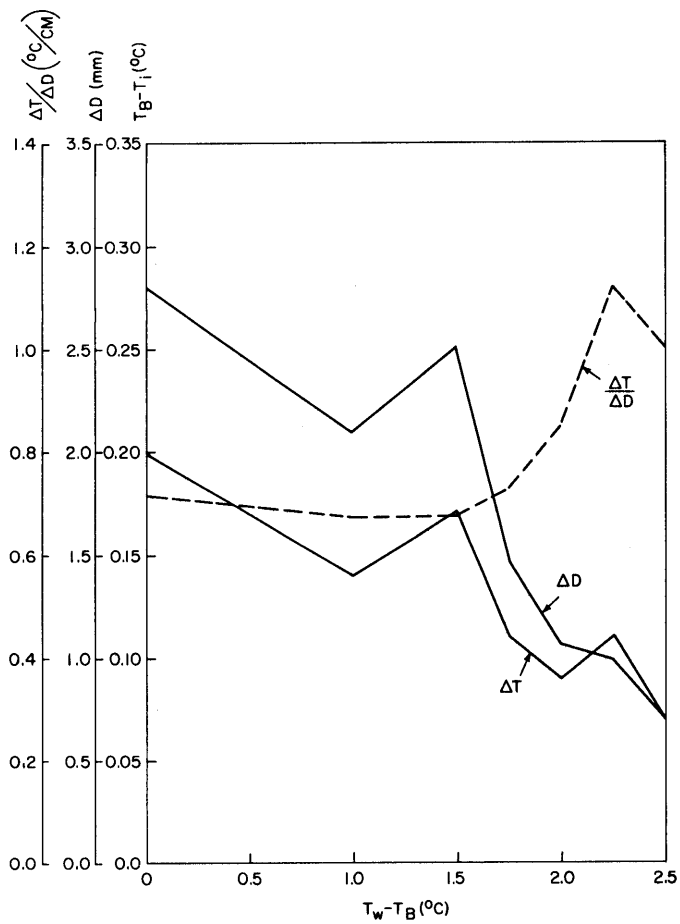
This phenomenon is analogous to the streaming observed by Spangenberg and Rowland (7) where deep penetration of the evaporatively cooled streamers occurred through the underlying layers of a thermally stable liquid. This occurred even though the temperature of the cold sheet of water was increased by thermal diffusion, and at 4.0 cm below the surface its center was only 0.04°C cooler than the undisturbed liquid. The submerged, heated surface in this study produced warm streamers flowing upward, but the same penetration mechanism should apply. Another example of penetration mentioned by Spangenberg and Rowland (7) concerned atmospheric currents originating in an unstable layer near the earth's surface and rising through the adiabatic temperature gradient to the outer boundary of the troposphere.

The final set of data, represented by Figs. 13a through 13d, were made using a submerged tube of diameter 0.635 cm at a depth of 10.2 cm. These data were taken during the winter when the relative humidity in the laboratory was much lower. Due to the low submergence depth, the value of $T_W - T_B$ could only be increased to 2.5°C. At this temperature the fringe pattern showed very irregular motion and was difficult to observe. These results clearly show a decreasing trend in ΔD caused by the convective motion near the interface. There is also an obvious decrease in $T_B - T_i$ with time. This was probably caused by the very strong convection effects which forced some of the bulk fluid to the interface, increasing T_i.

During this discussion very little reference has been made to the actual quantitative values associated with the data. It is felt that the results do give reasonably accurate values, but there were certain experimental errors which could not be evaluated. One of these errors was mentioned by Spangenberg and Rowland (7), since it affected their Schlieren results. It was caused by the surface depressions above the plunging streams which diverged the light as a negative lens. This error was considered small in the present application. The tank was designed so that a compromise between the errors due to end effects and the refraction errors of the light path through the test section was obtained. These were also considered negligible. The equations used in evaluating the results presupposed a two-dimensional density field normal to the ray path. The irregular internal convection motion undoubtedly had a three-dimensional character, especially in the bulk fluid within the tank. However, within the thermal layer the irregular motion was minimized. In fact, there was very little motion at all on the interface itself, except for the occasional plunging, the effects of which were quickly dissipated. It is expected that the two-dimensional analysis, made in a carefully designed tank to minimize the optical errors, has produced meaningful results, both quantitatively and qualitatively.

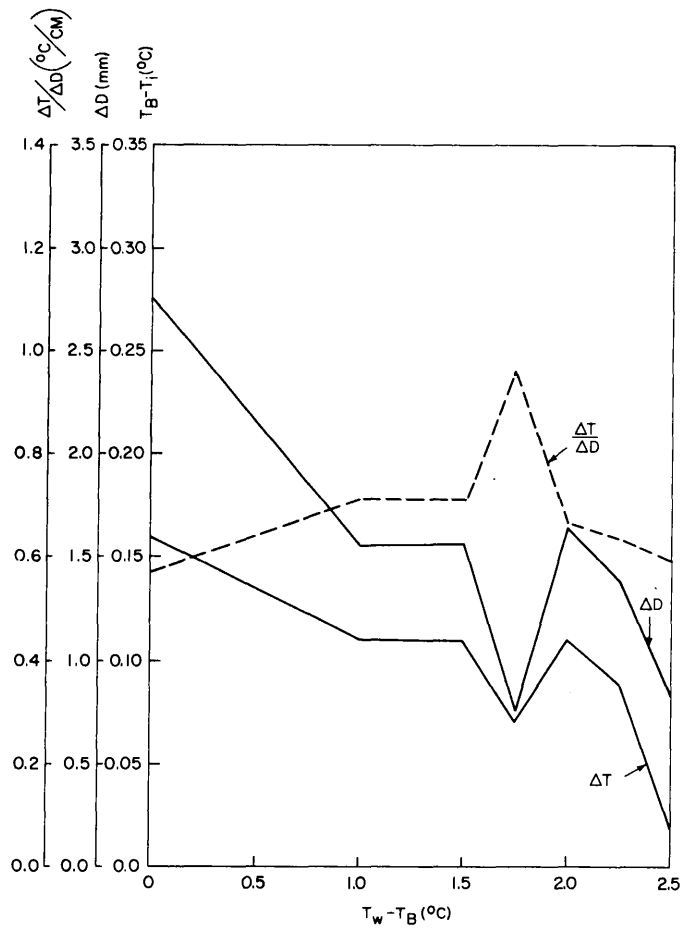
CONCLUSIONS

The use of a Mach-Zehnder interferometer proved to be a very accurate and convenient way to study the thin thermal layer at a water/air interface. The major limitation of the present system was the difficulty in the rate of data acquisition for transient situations with a low time constant. The results of this study showed the very sensitive nature of the unstable layer that forms due to evaporation from a liquid/air interface. The presence of a submerged, heated surface at temperatures of only 1.0°C to 5.0°C above the bulk fluid temperature caused evident alterations in the thermal layer behavior. This was true for all submergence depth values of the heated surface, which varied between 10.2 cm and 76.2 cm.



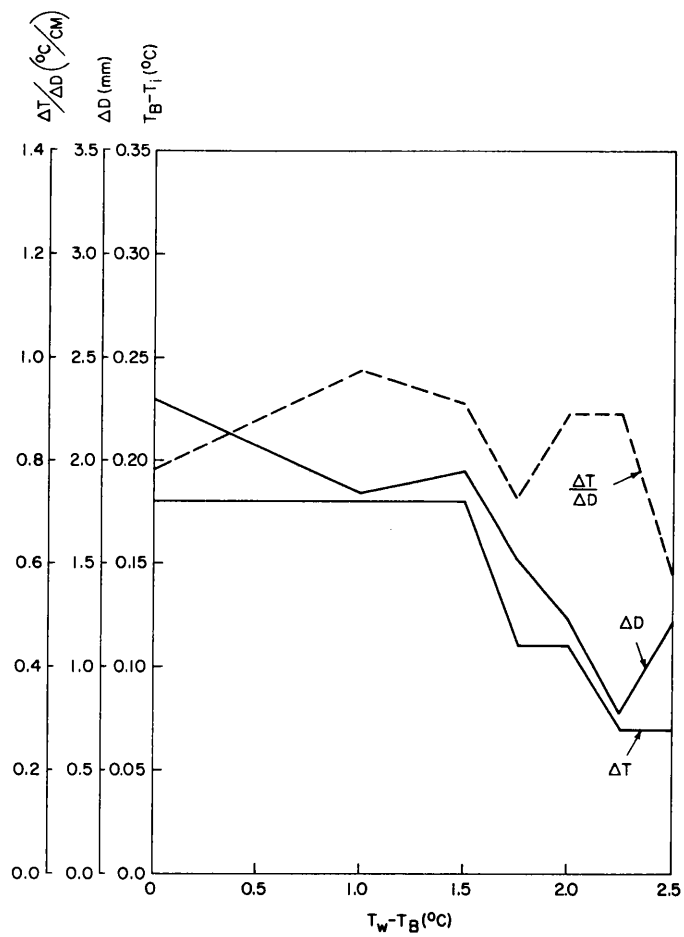
(a) Relative humidity equals 22.0%

Fig. 13 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 10.2 cm, and the tube diameter was 0.635 cm. Figures 13a through 13d present data taken at the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases.



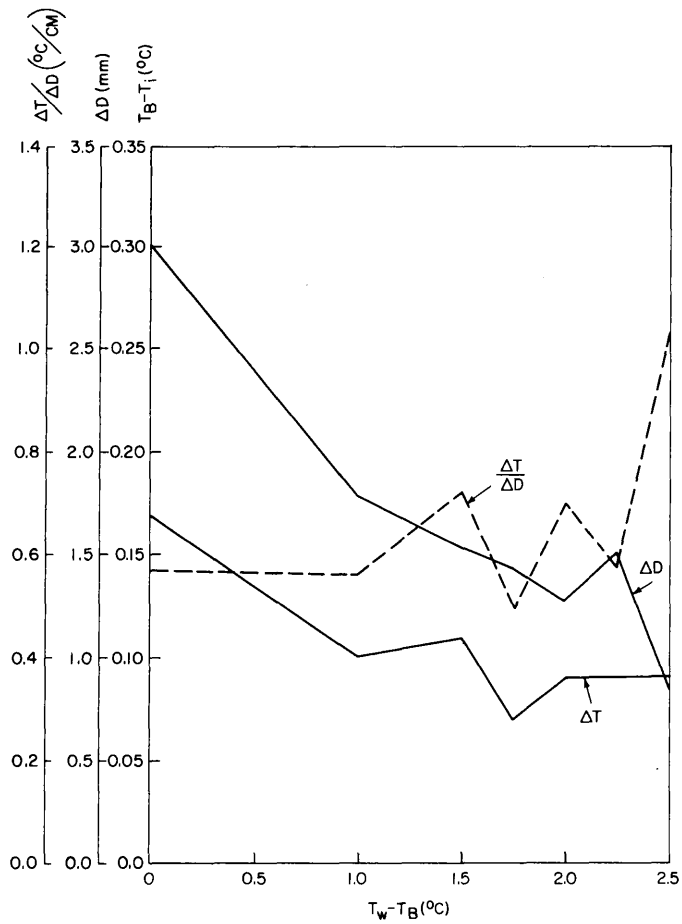
(b) Relative humidity equals 22.4%

Fig. 13 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 10.2 cm, and the tube diameter was 0.635 cm. Figures 13a through 13d present data taken at the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases—Continued.



(c) Relative humidity equals 22.4%

Fig. 13 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 10.2 cm, and the tube diameter was 0.635 cm. Figures 13a through 13d present data taken at the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases—Continued.



(d) Relative humidity equals 22.7%

Fig. 13 - Fluctuations in the interfacial temperature gradient, thermal layer thickness, and difference between interface temperature and bulk liquid temperature. Fluctuations are due to both the instability caused by evaporation cooling and a submerged, heated tube. The surface temperature of the tube increased with time. The submergence depth was 10.2 cm, and the tube diameter was 0.635 cm. Figures 13a through 13d present data taken at the same laboratory conditions. The results show the trends of the data as $T_W - T_B$ increases—Continued.

It was concluded that the mechanism responsible for the changes in the behavior of the thin, thermal layer were due to small momentum disturbances at the underneath side of the thermal layer. These small disturbances were sufficient to trigger a reaction in the unstable layer and, thus, alter the frequency and magnitude of the small temperature changes that would normally occur without the presence of a submerged, heated surface. A more detailed study of the actual frequencies involved will require a different data acquisition system which will provide a continual data output.

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13. ABSTRACT

An experimental investigation of the density variations which occur in a liquid near a liquid/air interface was conducted by means of a Mach-Zehnder interferometer and a gas laser light source. The liquid used in this investigation was distilled water. Experiments were made under two conditions. The first condition was evaporation from an undisturbed interface. The second condition was evaporation in the presence of a submerged, heated copper tube. The quantities of interest were the variations in the interfacial temperature, the changes in thickness of the interfacial thermal layer, and the temperature gradient at the interface. The depth of the submerged, heated surface varied from 10.2 cm to 76.2 cm, and the temperature difference between the submerged, heated tube and the surrounding liquid bulk temperature varied from 0.0°C to 5.0°C. The results gave an indication of the behavior of the thin thermal liquid layer at the interface. The mechanism responsible for the changes in the thermal layer was due to a momentum disturbance at the underneath side. The small disturbances were sufficient to alter the frequency and magnitude of the changes that normally occur at an evaporating interface.

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