

An experimental investigation of the surface temperature field during evaporative convection

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Measurements of the surface temperature field are presented for a water surface undergoing evaporation. These temperature fields were measured using an infrared camera for a range of heat fluxes $q'' = 30\text{--}500\text{ W/m}^2$. Experiments were conducted for water surfaces with and without a surfactant monolayer. A statistical analysis of the data is presented which shows the effect of heat flux and surfactants on the root mean square and skewness of the field. The data reveals a linear increase in the rms with increasing heat flux, which is similar for clean and surfactant conditions. In contrast, the skewness is markedly different for the clean and surfactant-covered cases. For clean surface conditions, the skewness attains large, negative values, becoming increasingly negative as q'' increases. When the surface is covered with a surfactant monolayer, however, the skewness exhibits small, negative values which approach zero as the heat flux increases. This behavior is reflected in the pdf which is clearly asymmetric in the clean case and virtually symmetric in the surfactant case. A physical mechanism is presented to explain these results. Temporal power spectra are presented which reveal the role of heat flux and surfactants on the temporal evolution of the surface temperature field. © 2001 American Institute of Physics. [DOI: 10.1063/1.1337064]

I. INTRODUCTION

Evaporative convection is natural convection in a liquid layer which has a free surface undergoing evaporation. The hydrodynamic boundary condition at this free surface is shear-free if the surface is devoid of surfactant monolayers. If a surfactant monolayer is present, the hydrodynamic boundary condition is one of an imposed elasticity. The difference between these two boundary conditions is significant and impacts the fluid mechanics which occur near the free surface during evaporative convection, concomitantly affecting the characteristics of the surface temperature field. The change in the surface temperature field due to both surfactant contamination and heat flux is the subject of this experimental study.

An important motivation for studying evaporative convection stems from remote sensing applications. Remote sensors located on aircraft and satellite platforms possess excellent capabilities with regard to the characterization of the ocean surface. However, the ability of these sensors to penetrate the ocean surface is poor. With the exception of visible laser light imaging methods,^{1,2} an ability to obtain subsurface information from remote platforms is lacking, restricting the remote location of navigational hazards, mines and submarines.

Submerged objects located near the water surface affect the fluid dynamics at the free surface, and thereby alter the surface temperature field.³ Therefore it is possible, in principle, to intuit the existence and location of near surface

objects from surface information alone. Such an ability, however, requires an understanding of how the physical processes which naturally occur near the air/water interface affect the surface temperature field. Such an understanding is currently lacking. Evaporative convection and the effect of surfactants and heat flux on the surface temperature field are important examples of these naturally occurring processes and were chosen for experimental investigation in this work.

An excellent survey of the early studies of evaporative convection, along with a discussion of the history of the topic and its place in the overall understanding of natural convection, can be found in the review of Berg *et al.*⁴ As noted in this reference, much of the early experimental work is due to Bénard (e.g., Bénard⁵) who employed optical methods to measure the surface deformation field, and simple flow visualizations to understand the basic fluid mechanics. These studies and the recent work which has followed the general lines of Bénard's initial investigations (e.g., Spangenberg and Rowland⁶) focus on the laminar, cellular structures which are observed in the low heat flux regime of evaporative convection. Measurements of the surface temperature were not obtained by these researchers.

A less phenomenological approach to the study of evaporative convection has been pursued by investigators seeking to understand the relationship between the evaporation or heat transfer rate, and the air flow above the water surface. Examples of such investigations can be found in the work of Sharpley and Boelter⁷ and Boelter *et al.*⁸ who relate

the Nusselt number to the Rayleigh number of the air residing above the water surface. Sparrow and co-workers performed extensive studies of this nature, relating the evaporation rate (using the Sherwood number), to both the Rayleigh number for quiescent air,^{9–11} as well as the Reynolds number for forced convection,^{12–14} for several geometric configurations. While the bulk water temperature is recorded in studies of this type, measurements of the surface temperature field are not obtained.

The current investigation concerns the effect that surfactant monolayers and heat flux have on the surface temperature field, and the statistics and spectra which characterize it. It is noted that many surfactants affect the temperature field by suppressing evaporation.^{15–19} Our interest lies in the hydrodynamic damping that surfactant monolayers impose, and the concomitant effects that this hydrodynamic damping has on the surface temperature field. Therefore, we will only be considering a surfactant monolayer which does not impede evaporation in this work.

The hydrodynamic damping effect of surfactant monolayers on heat transfer during evaporative convection was perhaps first realized by Navon and Fenn^{20,21} who found that the presence of an evaporation-impeding surfactant reduced the heat flux by an amount larger than that which could be attributed to evaporation suppression alone. They attributed this difference to the damping of fluid motion in the water by the surfactant monolayer. This effect of hydrodynamic damping on the temperature field was subsequently demonstrated in the investigations of Jarvis and of Katsaros. Jarvis²² demonstrated that monolayers of oleic acid, which do not impede evaporation,²³ can affect the average and fluctuating components of temperature time traces obtained at a point on an evaporating water surface. Katsaros and Garrett²⁴ performed experiments similar to those of Jarvis, but in a larger volume of water and found that the presence of an oleyl alcohol monolayer significantly modulated the temperature time traces obtained at the water surface.

The aforementioned researchers measured surface temperature using thermistors and thermocouples. Much of the fluid dynamics affecting the surface temperature field during evaporative convection occurs close the air/water interface where the inherently intrusive nature of such surface temperature probes is undesirable. McAlister and McLeish²⁵ circumvented this problem by obtaining remote temperature measurements using an infrared radiometer. In a laboratory water facility they employed a two-wavelength radiometer to obtain nonintrusive temperature measurements at a point. These measurements showed changes in heat flux due to differences in the air and water flow conditions, and due to the presence of a surfactant slick, demonstrating the utility of remote temperature measurements in the study of evaporative convection.

While point measurements of surface temperature are useful in elucidating the temporal behavior of evaporative convection, a connection to remotely sensed imagery requires experiments which measure the surface temperature field. Such measurements were obtained by Volino and Smith²⁶ who simultaneously recorded the surface temperature field and subsurface velocity field using infrared imag-

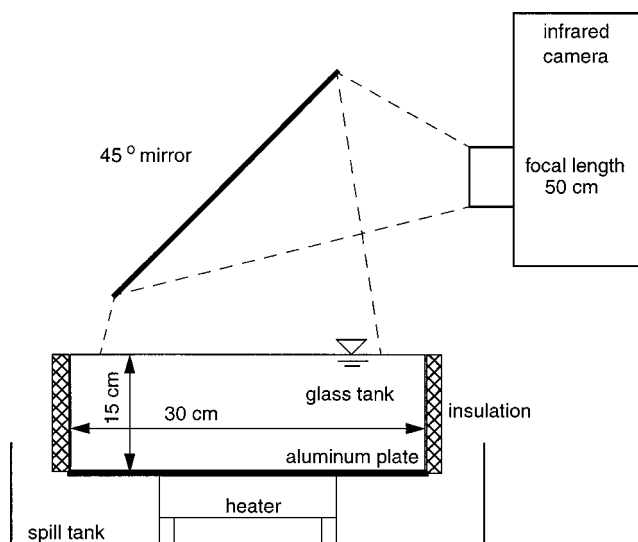


FIG. 1. Schematic illustration of the experimental setup used to obtain temperature fields from the surface of a body of water during evaporation.

ing and particle image velocimetry (PIV), respectively. This study revealed the degree to which the surface temperature field is correlated to the hydrodynamics beneath, for the experimental configuration which was investigated. Saylor *et al.*²⁷ utilized infrared imagery to obtain the surface temperature field during evaporative convection in an environment where both heat flux and surfactant concentration were carefully controlled, showing that the spatial structure of the surface temperature field was significantly affected by heat flux and by the presence or absence of a surfactant monolayer. Only two heat fluxes were investigated in this work, however, preventing an understanding of the functional relationship between such statistical quantities as the rms and skewness, and heat flux. In the work presented here, the work of Saylor *et al.*²⁷ is extended to (i) determine the relationship of the skewness and rms to heat flux and surfactant concentration, and (ii) ascertain how the frequency spectra of the surface temperature field vary with heat flux and surfactant concentration.

II. EXPERIMENTAL METHOD

A. Setup

The experimental facility used in these experiments is illustrated in Fig. 1, which shows the tank and the optical setup used to acquire the temperature fields presented in the following section. The tank was made of glass and sealed using an RTV sealant, which was allowed to cure for several days before being used in the experiments. The tank was square, 30 cm on a side and 15 cm deep, and was insulated on four sides to reduce heat loss. The heat fluxes reported in Sec. III are corrected for heat loss through the walls, and represent the flux through the water surface only.

Infrared images of the water surface were obtained using a Raytheon-Amber AE4256 IR camera having a 256×254 InSb array. The camera is liquid nitrogen cooled and exhibits a noise level equivalent to approximately 25 mK in measured temperature. The water surface was imaged through a 45°

bounce mirror, and the imaged region was approximately 16 cm on a side. Appropriate calibrations were performed to permit conversion of the IR imagery into surface temperature fields. Spatial calibrations were also performed to allow computation of the physical dimensions of structures observed in the fields.

Deionized water was used in all experiments and for all cleaning procedures conducted prior to the experiments. The deionized water was obtained from a Milli-Q UV Plus deionization system consisting of a single distillation unit, followed by a millipore filter and an ultraviolet filter. Care was taken to avoid contamination by indigenous surfactants in all portions of the experimental procedure. The deionized water was stored in nalgene carboys which were tapped from the bottom to avoid contamination by surfactants which migrate to the surface. Water was transferred from the carboys to the glass tank using teflon tubing and valves, minimizing any surfactant contamination from the piping. Prior to an experiment, the tank was overflowed into a spill tank as shown in Fig. 1. This process removed surfactants on the surface. Nitrogen bubble sparging, using a clean glass frit, was also employed prior to the beginning of each experiment, to draw any dissolved surfactants from the water bulk to the water surface where they were subsequently removed in the overflow. Finally, a glass rod which was cleaned with methanol and deionized water, was used to swipe the water surface prior to each experiment, to remove any remaining surfactant monolayers.

In the results which follow, two cases are considered: (i) a clean case, and (ii) a surfactant-covered case. For the clean cases, the aforementioned cleaning procedure was performed and then the experiments were initiated. For the surfactant case, the cleaning procedure was followed by deposition of a monolayer of oleyl alcohol. Oleyl alcohol was chosen because it does not impede evaporation,²⁴ and because its elasticity properties are similar to those of monolayers found on the surface of typical ocean waters.²⁸ A monolayer of oleyl alcohol was deposited by spreading a stock solution of oleyl alcohol and HPLC grade heptane. The solution quickly spread over the water surface,²⁹ and upon evaporation of the heptane, left a monolayer of oleyl alcohol having a surface concentration of $c = 0.11 \mu\text{g}/\text{cm}^2$. Oleyl alcohol is insoluble in water, and hence its concentration on the water surface was constant throughout the experiment.

Simple evaporation of the water into the quiescent laboratory air did not provide a sufficient range in heat flux q'' . To increase the range in q'' , the bulk water temperature was elevated to different temperatures prior to initiation of the experiment. This was achieved using the heater indicated in Fig. 1. An aluminum plate was located between the heater and the glass tank floor to act as a heat spreader and to prevent fracture of the glass. After the water achieved the desired temperature, a waiting period was imposed to allow the heater plate to cool before experiments were initiated. A thermocouple was inserted into the air space between the aluminum plate and the glass floor, and data acquisition was not initiated until this temperature dropped to the bulk water temperature. In this way, the possibility of convective motions originating from a warm tank floor was eliminated.

The heat flux was measured using calorimetry. The bulk water temperature was measured using a mercury in glass thermometer, having a resolution of 0.1°C , and the rate of temperature drop, dT_b/dt , along with the surface area of the water, was used to compute the heat flux from the water surface. Heat transfer through the tank walls and floor was measured during a separate set of experiments, and these values were used to correct the values of heat flux reported here.

Further details concerning the experimental setup, instrumentation and procedure can be found in Saylor *et al.*²⁷

B. Data processing

One of the main results presented in the following section concerns the skewness of the surface temperature field. This quantity, the second moment of the pdf, is very sensitive to even a small number of spurious values in the data. Accordingly, care was taken to locate and eliminate erroneous values from the IR data prior to computing statistics. To facilitate this discussion of data processing, a schematic representation of the data accumulated in each experiment is presented in Fig. 2. Temperature fields were acquired sequentially, resolving both the spatial structure of the temperature field, and the temporal evolution of that field. By stacking each field on top of the next, as indicated in the figure, the data is represented as a cube, where the third dimension of the data cube is time. Structured in this way, each pixel can be represented as a time trace. A single point in the three-dimensional data cube is referred to as a "data point." For the experiments reported here, the time traces were 238 data points long, which is the "depth" of the data cube. The Δt between frames varied from 0.25 to 0.75 s, depending on the experiment, resulting in sequences lasting from ~ 60 to 180 s.

The main contributor to erroneous skewness values was malfunctioning pixels in the IR array which typically gave values which were very high or very low, some or all of the time. While the total number of data points that gave spurious values was small, they still affected the skewness values and therefore had to be addressed. The camera had a 12-bit dynamic range giving values ranging from 0 to 4095. Data points in the data cube having a value of 0, 1, 4094 or 4095 were designated as erroneous and were flagged. The camera offset and gain were adjusted to insure that the maximum and minimum temperatures observed did not correspond to these four intensities. After flagging all of the erroneous data points, each time trace was then scanned, and traces containing more than 40 flags were discarded. Flagged data points which resided in the remaining time traces (those with < 40 flags) were set to a value of zero. The average temperature was subtracted from the data cube in subsequent steps (see below), hence setting a point to zero is equivalent to setting it to the average value.

In addition to pixels that gave a consistently low or high value, a small number of pixels gave an almost unchanging and arbitrary value, regardless of the scene viewed. These malfunctioning pixels were identified by rescanning the remaining time traces and locating those traces where the val-

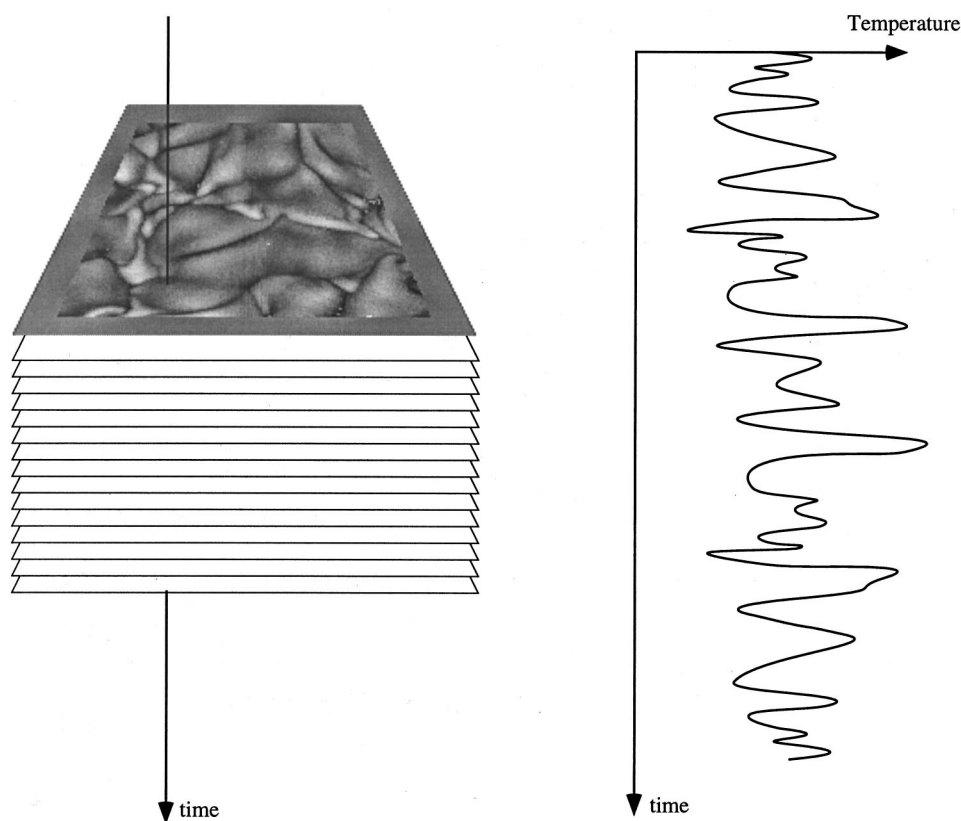


FIG. 2. Illustration of the data cube created by sequentially acquired temperature fields. Each pixel can be represented as a time trace.

ues did not change for 40 consecutive points. Such time traces were also discarded.

The choice of discarding time traces containing 40 flagged data points or 40 consecutive unchanging data points was somewhat arbitrary. To test the sensitivity to this number, it was varied between 10 and 150 without a significant change in the computed statistics. This insensitivity indicates that, with few exceptions, a time trace had data points which were either entirely erroneous, or entirely valid.

The total number of flagged data points in a typical experiment was less than 0.01% of the total number of data points in the data cube ($> 11 \times 10^6$). The greatest number of flagged data points in any experiment reported here was 0.33%. The maximum number of time-traces discarded in any of the experiments was 28, out of 46 633 time traces/cube (0.06%). In a typical experiment, less than five time traces were discarded from the data cube. Hence, in terms of data points or time traces, a very small fraction of the available data was discarded for any given experiment.

After identifying and removing bad time traces and data points, the remainder of the data cube was converted to temperature. An average temperature was then computed for each frame in the cube and this value was subsequently subtracted from each frame. Because the water in the tank was cooling, the average frame temperature decreased slightly from frame-to-frame. While this change was small and did not affect the computed spectra, mean, or rms, it did affect the skewness. By subtracting the frame average, error due to tank cooling was eliminated.

After the frame-average subtraction, the time trace average was computed for each trace in the data cube and then

subtracted. In a strict sense this step was unnecessary, since the average temperature should have been eliminated by the frame average subtraction described above. The procedure was employed, nevertheless, to reduce possible errors which would be introduced should one or two bad time traces remain in spite of the steps taken to eliminate them. Should such bad time traces remain, they would not necessarily have a zero dc bias, and would therefore have a significant effect on the computed statistics. By subtracting the time trace averages, any remaining bad traces are not eliminated, but their dc bias is eliminated, and their effect on the computations of the statistics is greatly reduced.

The final step in the data processing was a spatial Fourier processing of each frame, wherein the three lowest wave numbers in the spectrum were eliminated. During the IR camera calibration,²⁷ pixel gains were set to insure a uniform response across the array. Small imperfections in this calibration procedure resulted in a slight low spatial frequency variation in the imagery. The spatial Fourier filtering removed this error. The merit of this final step, and the rationale for choosing the three lowest wave numbers in the filtering, is presented in Saylor *et al.*²⁷

III. RESULTS

Temperature fields obtained from sample experiments are presented in Fig. 3. These are fields obtained from eight representative experiments taken from a total of 26 experiments reported here. The fields used in generating Fig. 3 are the actual temperature fields processed in the manner described in Sec. II B. In order to present the fields in a single

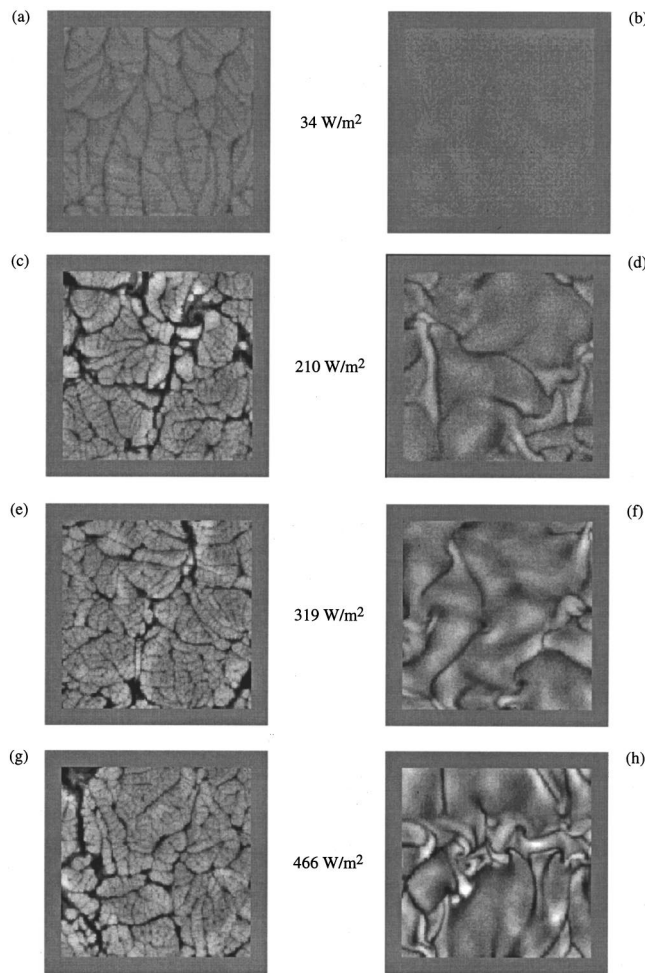


FIG. 3. Sample temperature fields obtained from eight different experiments. The left-hand member of each pair was obtained under clean conditions and the right-hand member under surfactant-covered conditions. Each pair of images was obtained at essentially the same heat flux. The average heat flux is indicated between each member of the image pair. The actual heat fluxes were (a) 36 W/m², (b) 31 W/m², (c) 219 W/m², (d) 201 W/m², (e) 319 W/m², (f) 318 W/m², (g) 466 W/m², (h) 466 W/m².

figure, the contrast for each field was adjusted so that all of the fields could be presented using a single gray scale palette. The max-min temperature range was on the order of 1 K for all of the fields in the figure, and varied from 0.6 K to 2.6 K, increasing as the heat flux increased. The temperature fields are presented in pairs, with the left-hand member of each pair corresponding to an experiment conducted under clean conditions and the right-hand field corresponding to an experiment conducted under surfactant-covered conditions. The effect of the surfactant monolayer on the structure of the temperature field is readily apparent: the monolayer elimi-

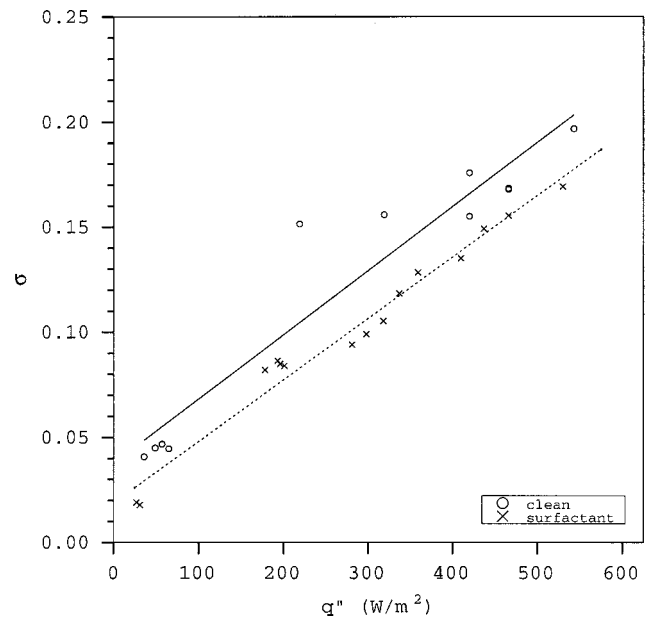


FIG. 4. Plot of the root mean square (rms) of the entire data cube associated with each experiment, as a function of heat flux. Data are grouped into clean and surfactant-covered conditions. The solid and dotted lines are linear fits to the clean and surfactant data, respectively. These fits are presented in Table I.

nates the small scale structures which are present in the clean field. The effect of the monolayer on the spatial structure can be characterized by the spatial Fourier spectrum which is presented in Saylor *et al.*²⁷ and is not discussed herein.

An increase in the small scale structure can also be observed as the heat flux is increased. The heat flux increases while traveling vertically downward in either column of images presented in Fig. 3, and an increase in small scale structure for both the clean and surfactant cases is evident. The temperature fields presented in Figs. 3(a) and 3(b) are for a very low heat flux, where the turbulence is most likely not fully developed. This accounts for the qualitative difference in appearance between these two fields and the others presented in Fig. 3.

The presence of the monolayer also affects the statistical characteristics of the temperature field, which are now presented. In Fig. 4 the root mean square (rms) of the data cube for each experiment is plotted against the heat flux for that experiment. This plot reveals a linear increase of rms σ with q'' for both the clean and surfactant cases. The rms for the clean case is slightly higher than for the surfactant case. The linear fits used for the two cases are presented in Table I, and reveal that the y-offset between the two fits is less than 0.02 K, and the slopes differ by less than 5%, revealing a similar-

TABLE I. Linear fits to the rms and skewness data presented in Figs. 4 and 5.

Case	Linear fit	Rms deviation from the linear fit (K)
σ , clean (Fig. 4)	$\sigma = 3.05 \times 10^{-4}(q'') + 0.0376$	1.98×10^{-2}
σ , surfactant (Fig. 4)	$\sigma = 2.92 \times 10^{-4}(q'') + 0.0188$	7.46×10^{-3}
γ , clean (Fig. 5)	$\gamma = -1.06 \times 10^{-3}(q'') - 0.8568$	0.148
γ , surfactant (Fig. 5)	$\gamma = 2.11 \times 10^{-4}(q'') - 0.3307$	6.90×10^{-2}

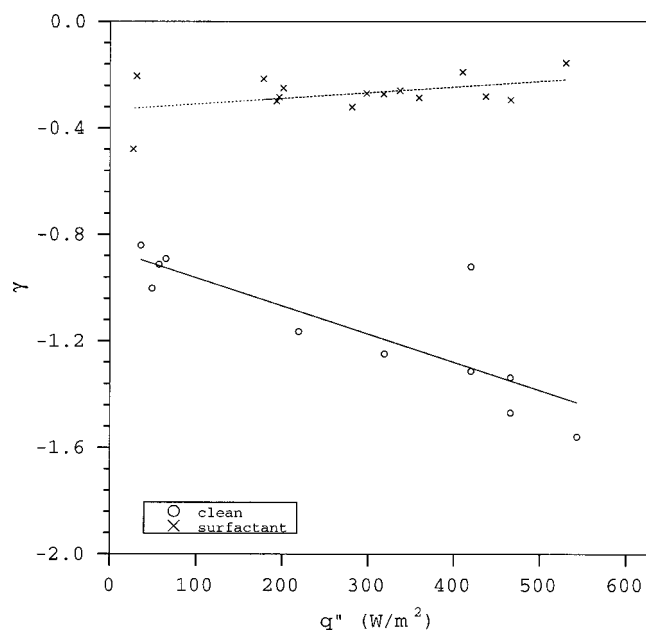


FIG. 5. Plot of the skewness of the entire data cube associated with each experiment, as a function of heat flux. The solid and dotted lines are linear fits to the clean and surfactant data, respectively. These fits are presented in Table I.

ity between the clean and surfactant cases, which is somewhat surprising in light of the structural differences which are apparent in Fig. 3. This point is further elucidated by the rms deviation from the linear fits, also presented in Table I. The largest deviation of the experimental data from the linear fits for σ is 1.98×10^{-2} , indicating that the scatter in the data is comparable to the y -offset between the two linear fits. This again suggests that the σ versus q'' behavior is essentially the same for the clean and surfactant cases.

The skewness γ , defined as

$$\gamma = \frac{\overline{(T - T_a)^3}}{\sigma^3}, \quad (1)$$

where T_a is the average surface temperature, is plotted in Fig. 5. In contrast to the σ plot, the γ vs q'' behavior is significantly different for the clean and surfactant cases. In both cases, γ is negative for the entire range of heat flux considered. However for the clean case γ becomes increasingly negative as the heat flux increases, having a slope of -1.06×10^{-3} , as indicated in Table I. For the surfactant case, the slope is 5 times smaller in magnitude (2.11×10^{-4}), and is positive in sign, indicating a very slow increase with heat flux. As Fig. 5 reveals, the data are well described by a linear fit, and the difference between the two fits is clearly larger than the scatter in the data.

For both γ and σ , the scatter of the data about the linear fits is larger for the clean case than for the surfactant case. We suspect that this is most likely due to the difficulty in maintaining surface cleanliness during the clean runs.

Further insight into the statistical characteristics of the surface temperature field can be obtained from the probability density functions (pdfs) themselves. These are presented in Fig. 6 for the clean case and Fig. 7 for the surfactant case.

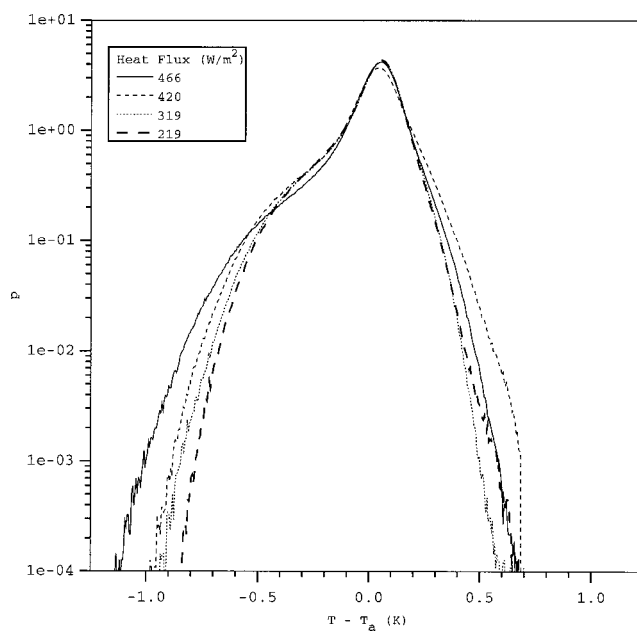


FIG. 6. The probability density function (pdf) for several of the experiments conducted under clean conditions. Each pdf is obtained using the entire data cube for that experiment.

For clarity, only a representative sample of the pdfs are presented in each figure. Each pdf presented in these figures is obtained using the entire data cube for an experiment, processed in the manner described in Sec. II. Hence, these pdfs are for the deviation of the surface temperature from the average temperature.

The width of the pdfs increase with q'' , for both cases, as is expected from the linear increase in σ with q'' illustrated in Fig. 4. For the clean case, there is an obvious asymmetry in the pdf, which is reflected in the more negative γ values

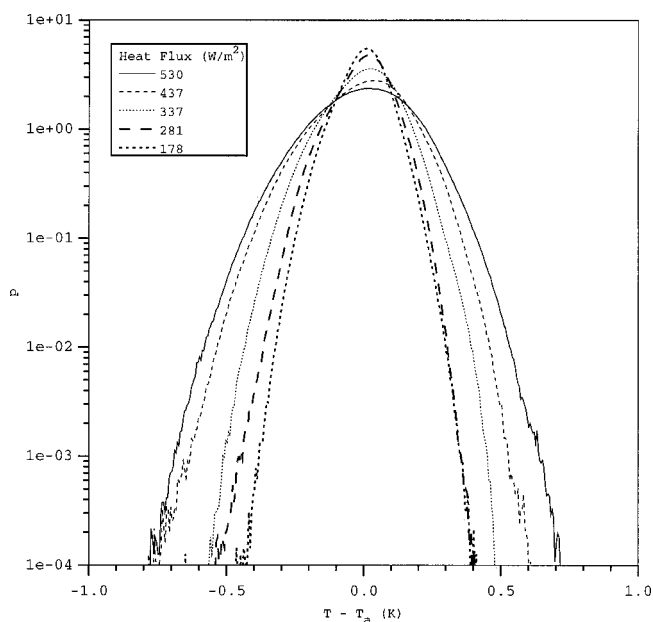


FIG. 7. The probability density function (pdf) for several of the experiments conducted under surfactant-covered conditions. Each pdf is obtained using the entire data cube for that experiment.

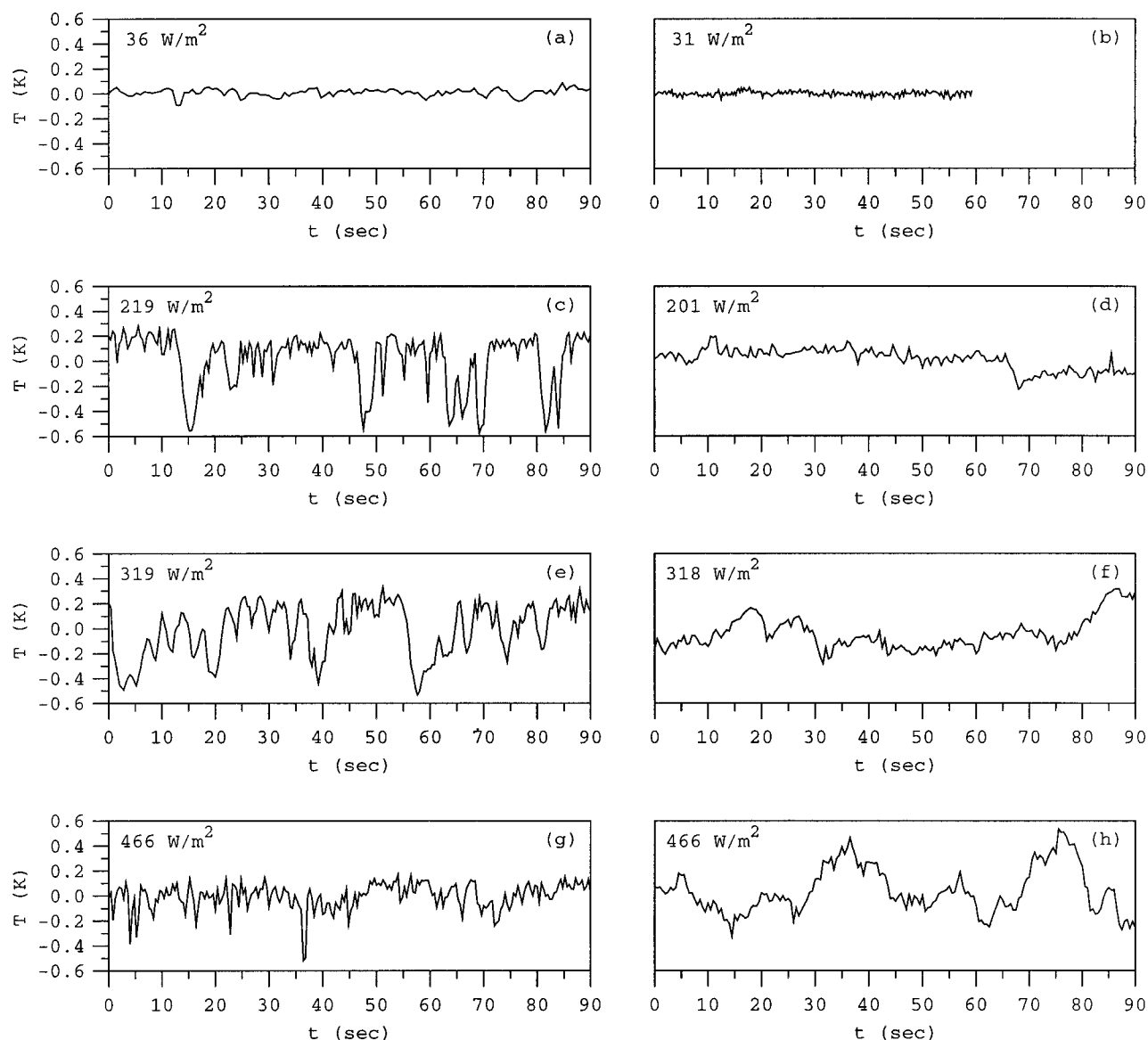


FIG. 8. Sample time traces obtained from the center pixel of each of the temperature fields presented in Fig. 3. Temperature is plotted for the first 90 s of the experiment.

which exist for the clean case (Fig. 5). This asymmetry is especially visible in the left wing of the pdf in Fig. 6, which extends as far as -1.0 K from the average, while the right wing does not exceed 0.75 K. For the surfactant case, the pdfs are relatively symmetric, in accordance with the small values of γ presented in Fig. 5. A physical mechanism which explains the asymmetry of the pdfs and the γ vs q'' behavior is presented in Sec. IV.

As illustrated in Fig. 2, each pixel in the data cube can be represented as a time trace, revealing the temporal evolution of the temperature field at each point. Examples of such time traces are presented in Fig. 8, where the temperature at the center pixel of each temperature field presented in Fig. 3 is plotted as a function of time. These time traces reveal a damping of the temperature fluctuations upon addition of a surfactant monolayer (at constant heat flux). It is also evident, at least between the two lowest heat fluxes, that in-

creasing the heat flux increases the degree of high frequency structure in the time trace.

The effect of heat flux and the presence of a monolayer on the frequency spectra is presented in Figs. 9–11. The power spectra for several representative experiments, obtained under clean conditions, are presented in Fig. 9, and power spectra for the surfactant case are presented in Fig. 10. These spectra were obtained by computing a spectrum for each time trace in the data cube, and then performing an ensemble average over all traces. The sensitivity of the power spectra to heat flux is much weaker for the clean case than for the surfactant case. In Fig. 9, there is a slight trend toward increasing energy with increasing heat flux at high frequencies. However, for virtually all frequencies, a very significant increase in energy is observed with increasing heat flux for the surfactant case displayed in Fig. 10.

The effect of surfactants on the spectra is isolated in Fig.

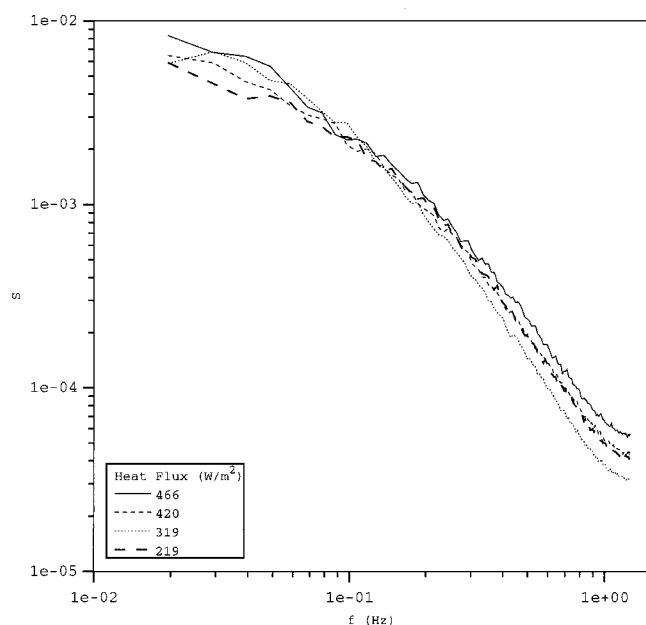


FIG. 9. Frequency spectra for several of the experiments conducted under clean conditions.

11, where two heat fluxes, one low and one high, are selected, and the spectrum is presented for the case of clean and surfactant-covered surface conditions for each heat flux. This plot reveals that the presence of the surfactant monolayer reduces the energy by a significant amount, in excess of a factor of 3. This reduction is seen to occur at all frequencies measured.

IV. DISCUSSION

A theory which predicts the σ and γ vs q'' behavior does not exist for evaporative convection. Therefore, a direct com-

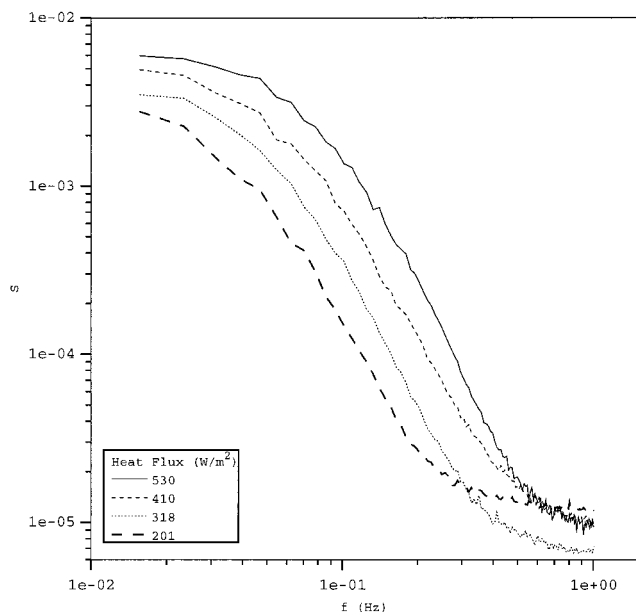


FIG. 10. Frequency spectra for several of the experiments conducted under surfactant-covered conditions.

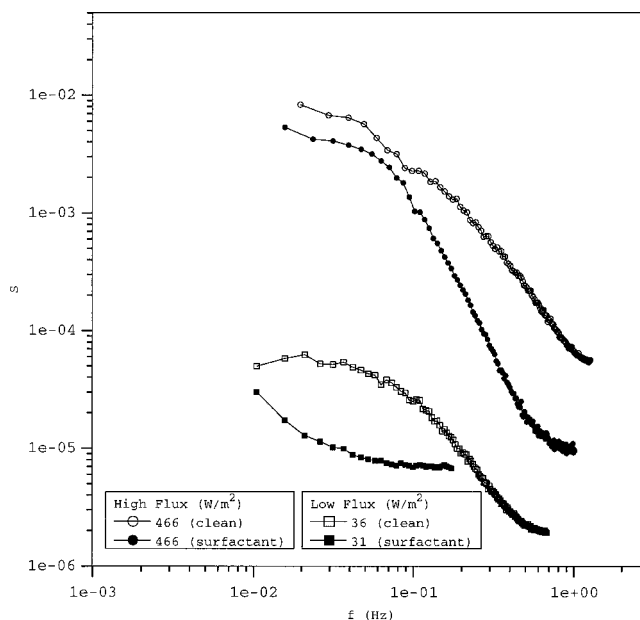


FIG. 11. Comparison of frequency spectra obtained under clean and surfactant-covered conditions. Comparison is made at a low and a high heat flux.

parison of the current results with theoretical predictions corresponding to the precise configuration considered here is not possible. However, a significant body of literature exists for natural convection heated from below with an insulated upper boundary.^{30–35} These investigations, which we refer to as “heated floor” studies, provide predictions for σ (but not γ) vs q'' . These predictions are now compared with the present experimental results.

Heated floor experiments are similar to the present configuration in that the thermal boundary conditions are analogous to those employed here. That is, for evaporative convection there is an insulated *lower* boundary, and a cooled *upper* boundary while in heated floor studies the lower boundary is heated and the upper boundary is insulated. Hence, our configuration can be thought to be analogous to the heated floor case if the whole configuration is simply flipped over. The one flaw in this analogy is that the heated floor has a no-slip boundary condition, while the analogous boundary in evaporative convection (the cooled boundary) has a boundary condition which is either shear-free (for the clean surface) or elastic (for the surfactant-covered surface). The work of Handler *et al.*³⁶ shows that even extremely small quantities of surfactant can create a boundary condition which is insignificantly different from a no-slip boundary condition. This suggests that predictions developed for a heated floor may serve adequately to describe the results presented here for evaporative convection, at least for the surfactant-covered case. This postulate is now explored.

The scales relevant to this problem are presented in the work of Townsend.³⁰ A more recent investigation due to Adrian *et al.*³² presents an excellent summary of the research in this field, and their treatment is followed below. The scaling of σ typically takes the form

$$\sigma = \theta_0 f(z), \quad (2)$$

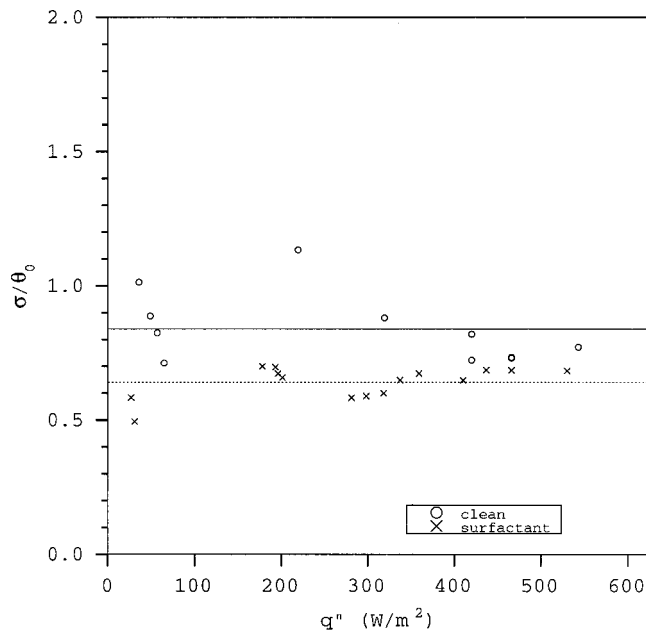


FIG. 12. Plot of the rms σ presented in Fig. 4, scaled to the conduction scale, θ_0 . The solid line is $\sigma/\theta_0=0.839$ and the dotted line is $\sigma/\theta_0=0.640$.

where θ_0 accounts for the variation of σ with heat flux, and $f(z)$ accounts for its variation with distance from the surface, z . In the case of a heated floor, Townsend³⁰ finds

$$f(z) = z/z_0, \quad (3)$$

where z_0 is the thickness of the conduction layer,

$$z_0 = \alpha/w_0, \quad (4)$$

α is the thermal diffusivity, and w_0 is defined below. This form of $f(z)$ forces σ to zero near the heated wall, which is not the case for evaporative convection. This difference between the heated floor and evaporative convection cases is not surprising, since the boundary conditions are different. To accommodate this difference, we ignore the spatial portion of the scaling in Eq. (2) and focus on the degree to which scaling σ by θ_0 renders σ insensitive to q'' ; that is, we ask the question, "Is σ/θ_0 a constant for evaporative convection, as is the case in heated floor studies?"

Following Adrian *et al.*,³² the scaling temperature, θ_0 , is defined as

$$\theta_0 = Q_0/w_0, \quad (5)$$

where

$$Q_0 = q''/\rho c_p, \quad (6)$$

$$w_0 = (\beta g Q_0 \alpha)^{1/4} \quad (7)$$

[H_0 is used instead of q'' in Adrian *et al.*³² in Eq. (6)]. β is the thermal coefficient of expansion, ρ is the fluid density, c_p is the specific heat, and g is the acceleration due to gravity. The scaling variable θ_0 presented in Eq. (5) is valid for the conduction region, $z < z_0$ which is the region near the heated wall where conduction dominates the heat transfer process.

Figure 12 presents the data of Fig. 4, scaled to θ_0 . The solid and dotted horizontal lines are the average for the clean

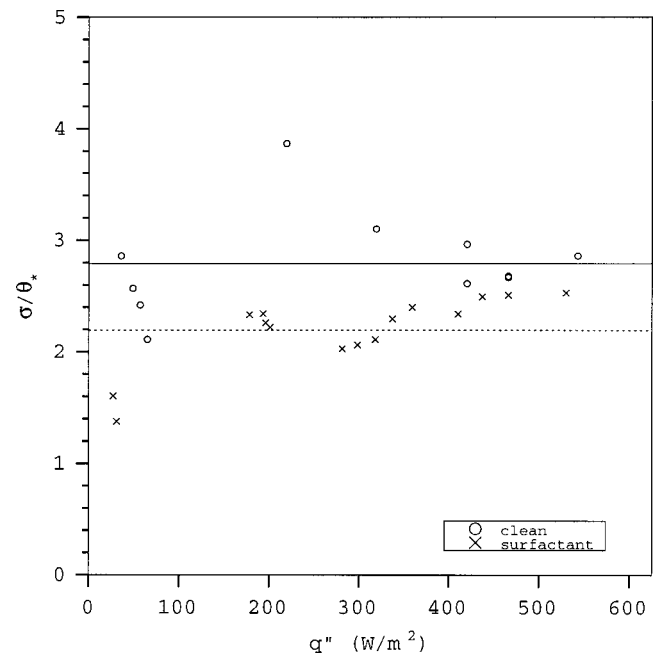


FIG. 13. Plot of σ from Fig. 4, scaled to the convection scale, θ_* . The solid line is $\sigma/\theta_*=2.79$ and the dotted line is $\sigma/\theta_*=2.19$.

and surfactant data, 0.839 and 0.640, respectively. The scaling works well for the surfactant case, where the data are relatively constant over the range of heat flux considered. Surprisingly, the clean data is also well scaled by θ_0 . There is more scatter about the mean than for the surfactant case, but this is observed to be true for the raw data as well (Fig. 4 and Table I).

The scaling described above is valid only for the conduction region near the cooled surface. It can be argued that for clean surface conditions where there is no hydrodynamic damping due to a surfactant monolayer or solid wall, the conduction scales may not be appropriate and that, instead, the convective scale θ_* which is employed away from the wall in the natural convection paradigm, may be more relevant. Again, following the treatment due to Adrian *et al.*,³² θ_* is defined as

$$\theta_* = Q_0/w_*, \quad (8)$$

where

$$w_* = (\beta g Q_0 z_*)^{1/3}, \quad (9)$$

and z_* is the tank depth. The σ vs q'' data scaled to θ_* is presented in Fig. 13. The solid and dotted lines are the average values for the scaled clean and surfactant data, 2.79 and 2.19, respectively. The values of σ/θ_* are larger than the values of σ/θ_0 presented in Fig. 12. The rms deviation of the data from the average is presented in Table II, as a fraction of the data average. This table reveals no significant change in the scatter for the two different scalings, and it seems that θ_0 and θ_* scale the data equally well.

Predictions of γ vs q'' were not found in the literature. While the γ results cannot, therefore, demonstrate the utility of any existing theory, the behavior of γ does provide in-

TABLE II. Rms of data presented in Figs. 12 and 13, scaled to data average.

Case	rms/avg
σ/θ_0 , clean (Fig. 12)	0.504
σ/θ_0 , surfactant (Fig. 12)	0.339
σ/θ_* , clean (Fig. 13)	0.509
σ/θ_* , surfactant (Fig. 13)	0.557

sight into the hydrodynamics of evaporative convection. In our earlier work,²⁷ we explain the difference between the symmetry of the pdf for the clean and surfactant cases using the difference between the average surface temperature and the bulk temperature. This idea is now expanded upon to explain the present results.

The surface temperature T is constrained to values lower than the bulk water temperature T_b . Evaporation is a cooling process, and therefore T cannot exceed T_b . This upper bound in temperature permits large, infrequent excursions *below* the average surface temperature T_a , but proscribes large excursions *above* T_a . Hence, if the pdf is asymmetric, it is skewed to the left, giving $\gamma < 0$.

The degree to which this restriction on T affects the pdf is determined by T_a . If the average surface temperature is relatively close to T_b , then the pdf will be highly skewed because the liquid at the surface cannot deviate significantly from the average in the positive direction, while deviations in the negative direction are unrestricted. On the other hand, if T_a is significantly smaller than T_b , then relatively large excursions in T can occur, even to the right, since the average temperature is very different from the bulk temperature, permitting a symmetric pdf. Hence, conditions which favor a small value for the magnitude of $T_a - T_b$ result in a more skewed pdf, and conditions which result in a larger value for the magnitude of $T_a - T_b$ favor a symmetric pdf.

As revealed by Eq. (1), σ also plays a role in the value of γ . Hence, the way in which σ varies with $T_a - T_b$ is important. This is especially true in this discussion because as σ increases, the effective width of the pdf grows, making the importance of the upper bound on temperature more important and making the skewness more negative. However, as noted earlier, σ increases linearly with q'' in a fashion which is essentially identical for the clean and surfactant cases. Thus, any difference in the γ vs q'' behavior for these two cases cannot be attributable to how the width of the pdf is growing with heat flux.

Figure 14 is a plot of $T_a - T_b$ vs q'' for data obtained under clean and surfactant conditions. As the plot reveals, $T_a - T_b$ is close to a value of ~ -1.0 when q'' is small, for both the clean and surfactant cases. As q'' is increased, $T_a - T_b$ approaches zero, for the clean case. This agrees with the skewness trends for the clean case (Fig. 5), where the skewness becomes increasingly negative with q'' . For the surfactant case, on the other hand, Fig. 14 shows that $T_a - T_b$ becomes more negative as q'' increases. This indicates that as q'' increases, the pdf can become more symmetric. While γ is relatively insensitive to q'' for the surfactant case, in Fig. 5 the weak trend it does exhibit is $\gamma \rightarrow 0$; i.e., toward symmetry. It is noted that while $T_a - T_b$ can attain an arbitrarily

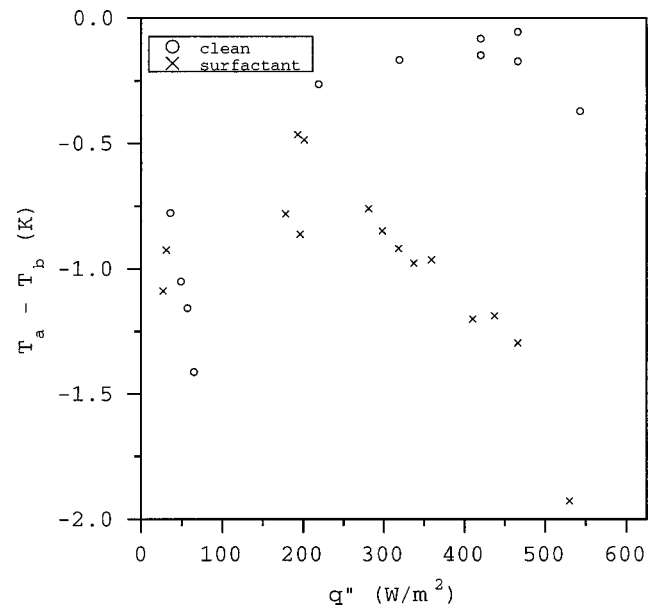


FIG. 14. Plot of the difference between the bulk temperature and the average surface temperature, vs heat flux, for each of the experiments.

large, negative value, the pdf itself can only reach a certain level of symmetry. That is, once γ is essentially zero, further decreases in $T_a - T_b$ can have no further effect on the symmetry of the pdf. This is exemplified in Fig. 14, where, for the surfactant case, $T_a - T_b$ decreases almost linearly with heat flux at large heat fluxes, yet the values of γ in Fig. 5 are not changing rapidly. At these high fluxes, the pdf is very symmetric, γ is almost zero, and further increases of $T_a - T_b$ result in no change.

One of the motivations for this work was the development of the groundwork for obtaining a remote sensing method for locating submerged objects. In Sec. I it was noted that development of such a method would first require an understanding of how naturally occurring phenomena, such as variations in surfactant concentration and heat flux, affect the surface temperature field. The work presented here represents a solid step in this direction. Moreover, the statistical results are intriguing in this regard and suggest some avenues for future research. The results reveal that γ is insensitive to heat flux when surfactants are present. It is frequently argued that the ocean surface is, except for rare occasions and locations, always covered with surfactant monolayers.^{37,38} If this is indeed the case, then the insensitivity of γ to q'' makes γ a candidate parameter for the remote detection of submerged obstacles, such as mines. Since γ will not vary from image to image as a result of heat flux variations (which are bound to occur), any deviation of γ from its typical background value may suggest the presence of a submerged object.

Obviously the situation investigated here is idealized; waves and wind were absent, and both of these can be expected to significantly affect the temperature field. For example, Jessup and co-workers have documented modulations of the surface temperature due to breaking waves,³⁹ microscale breakers,⁴⁰ and swell waves.^{41,42} Nevertheless, the results presented here for evaporative convection alone suggest the possible utility of using γ to detect submerged objects; at

the very least, it may be useful for low wind conditions.

While the insensitivity of γ to q'' points toward its possible use in detecting underwater objects, the linear relationship between σ and q'' suggest its possible use in measuring heat flux. Because the degree of surfactant contamination does not affect the measurement, and because of the high degree of linearity in the σ vs q'' data, σ could be a robust measure of heat flux. The lack of waves or wind precludes extrapolation of these results to oceanic conditions. However, it should be noted that similar results have been obtained over wavy water surfaces where heat flux is related to rms temperature fluctuations using the surface renewal model.⁴³ These results are intriguing and suggest that pursuing this line of thought in the evaluation of field data may prove fruitful.

V. CONCLUSION

Measurements of the surface temperature field were presented for the case of evaporative convection under both clean and surfactant-covered conditions. The rms and skewness were plotted as a function of heat flux for both cases, showing a linear increase in rms with heat flux for both conditions. The skewness shows intriguing results, demonstrating a very weak dependence on heat flux in the presence of a surfactant monolayer, but exhibiting a linear decrease in skewness with heat flux, for the clean condition. This behavior is reflected in the pdfs which are asymmetric for the clean case and approximately symmetric for the surfactant case. This behavior is explained as being the result of differences in the average bulk/surface temperature difference for the two cases. Frequency spectra of the surface temperature were also presented, illustrating greater energy at virtually all frequencies for the clean case, when compared with the surfactant case, at constant heat flux. Finally, the possible utility of rms and skewness in the remote sensing of heat flux and submerged objects is noted.

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