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SURFACE TEMPERATURE FLUCTUATIONS DURING STEADY STATE BOILING

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Abstract—Surface temperature fluctuations during steady state boiling from a tube have been measured with a fast response thermocouple and the results of these measurements are reported. In particular, the characteristics of extremely rapid temperature drops (up to 30°F/ms) which occurred for short periods of time (1–5 ms) are reported. These rapid temperature drops accounted for up to 33 per cent of the energy removed from the tube at the thermocouple position.

NOMENCLATURE

A, area;
a, thermocouple transfer function constant;
c, thermocouple transfer function constant;
c_p, specific heat;
E, energy removed from test element;
$G(s)$, thermocouple transfer function;
$\dot{q}''$, heat flux;
t, temperature,
$T(s)$, Laplace transformed temperature.

Greek symbols
γ, per cent of energy removed by rapid temperature drops;
Δ, difference;
θ, time;
ρ, density;
τ, tube wall thickness.

Subscripts
drops, rapid temperature drops;
i, ith rapid temperature drop;
max, see Fig. 4;
min, see Fig. 4;
ss, steady state;
t, tube;
tc, thermocouple;
total, calculated for total test time;
w, tube wall.

INTRODUCTION

In attempts to understand the mechanisms which are responsible for the high heat-transfer rates obtained at low temperature differences during boiling, several investigators have measured the temperature fluctuations on or near boiling surfaces. Moore and Mesler [1], who measured surface temperature fluctuations during boiling with a unique fast response thermocouple, reported that the surface temperature occasionally dropped up to 30°F in about 2 ms. The authors concluded that these temperature drops were caused by evaporation of liquid at the thermocouple position. Attempts to correlate the thermocouple traces with motion pictures of bubble behaviour at the thermocouple position were unsuccessful because the thermocouple position was obscured by bubbles at heat fluxes high enough to cause the temperature drops. This difficulty was overcome by Hendricks and Sharp [2], who correlated high speed films of bubbles moving over a small thermocouple welded to the underside of a thin

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(0·001 in.) nichrome heater with the thermocouple temperature. These experiments measured temperature drops comparable to those reported by Moor and Mesler. They found that the temperature drops started when a bubble passed over the thermocouple position and ended before the bubbles collapsed. The results indicated that a "micro-layer" of liquid was being evaporated under the bubble. This conclusion was substantiated by Cooper and Lloyd [3], who used essentially the same techniques to measure the evaporation rate of this micro-layer. Hsu and Schmidt [5] also measured surface temperature fluctuations during boiling by pressing a thermocouple against a heated surface from the liquid side. This arrangement precluded any bubble growth at the thermocouple position and consequently temperature drops such as those observed by Moore and Mesler were not observed. While these investigations have established the existence and the cause of the rapid temperature drops, the present study has determined the average characteristics of a large number of these temperature drops for a limited range of experimental conditions. Also determined were the general characteristics of the surface temperature variations during steady state boiling.

EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were performed with a 0·375 in. o.d., 2 in. long, 1·75 mil wall thickness, stainless steel tube as the test element. The test element, electrically heated by a 12 V wet cell in series with a variable resistor, was mounted horizontally in demineralized, deareated water at atmospheric pressure, subcooled approximately 3°F, flowing vertically upward past the outer test element surface at a velocity of approximately 3·3 fps (blockage corrected). The inside surface of the test element was in contact with stationary air. The test section in which the element was mounted was a 1·2 by 8 in. rectangular section 32 in. long. All tests were performed in a heat transfer loop described previously [6, 7].

Surface temperature fluctuations were measured with a fast response thermocouple welded to the inside wall of the test element. The thermocouple (Fig. 1), made from one mil diameter chromel–constantan wires, was located on the downstream portion of the test element (at the 160° position) for all tests. The thermocouple output was amplified and recorded on an oscillograph record by means of a light beam galvanometer. Before being used the thermocouple was calibrated for its transient response using the Laplace transform technique [8, 9]. The thermocouple transfer function

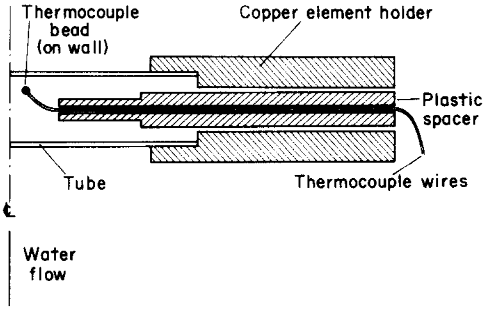

FIG. 1. Thermocouple placement in test element (thermocouple is at 160° position).

$$G(s) = \frac{T_{tc}(s)}{T_w(s)} = \frac{a}{s + c} \qquad (1)$$

evaluated from the average results of six calibration tests had a time constant ($1/c = 1/a$) of of 2·3 ms. The thermocouple was calibrated for its d.c. drop using the current reversal technique.

These tests were run in conjunction with a series of transient boiling tests [7, 10] using the following procedure. The test element was placed in the water and the desired water conditions were obtained. Next, the test element power (obtained from a direct current motor generator for this aging process only) was increased very slowly over a period of approximately 4 hours to a level at which uniform, dense nucleation of bubbles occurred over the entire test element surface. The test element power was left at this setting for approximately

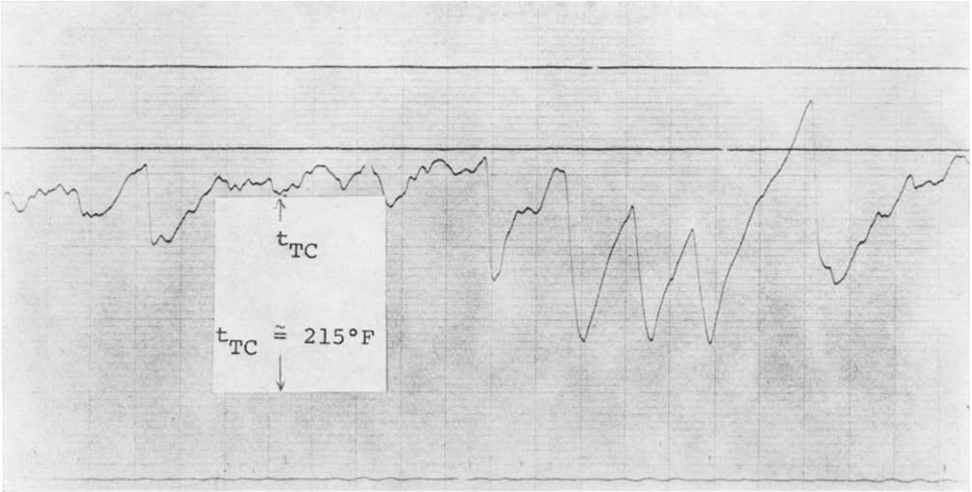

FIG. 2a. Test 16.

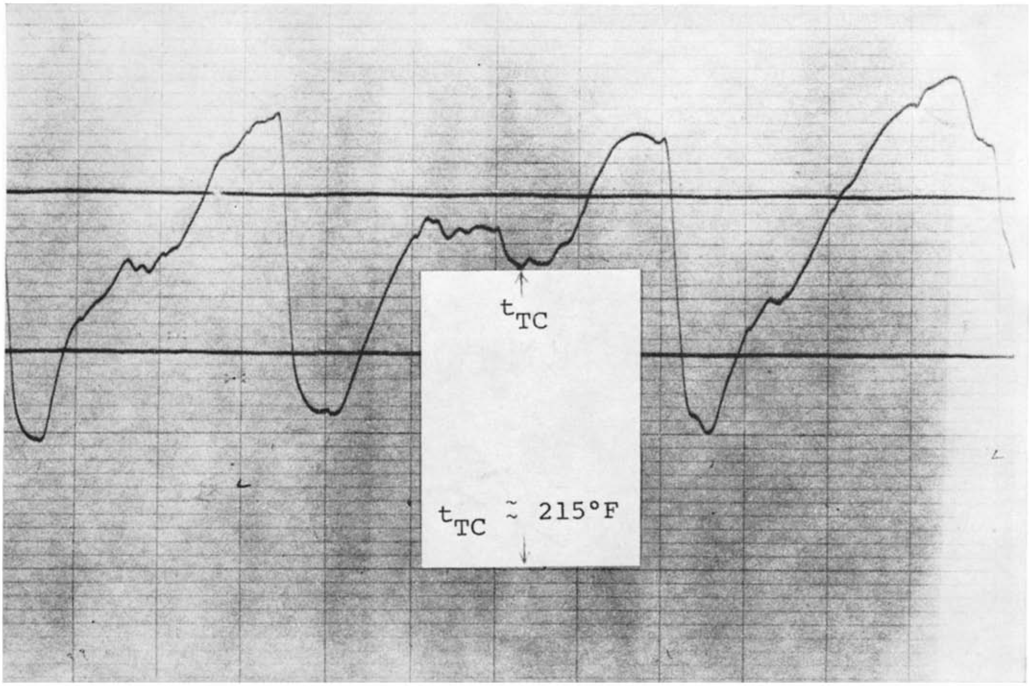

FIG. 2b. Test 9. (Photograph enlarged to illustrate rapid temperature drop.)

FIG. 2. Photographs of oscillograph records of thermocouple temperature fluctuations.
Vertical scale 1·6 F/div Horizontal scale 10 ms/div

one hour to age the test element surface. The test element power was then decreased to zero, the test element allowed to reach equilibrium with the water, and tests run by applying steps in power to the test element (with the wet cell as the power source) and recording the resultant transient and steady state temperature variations. Steady state conditions were reached within 100 ms for all tests [7, 10]. The subsequent steady state boiling lasted from 1 to 4 s for each test. After each test to a given heat flux value, the test element power was decreased to zero, the element was allowed to reach equilibrium with the water over a period of from 10 to 20 min, and then another test run. Using this procedure, tests to six different heat flux values were run with approximately four individual tests run at each heat flux value.

RESULTS

The experiments resulted in oscillograph records of the thermocouple temperature as a function of time (Fig. 2). As seen from this figure, very rapid temperature drops occurred during the runs—sometimes a series of drops occurring in sequence over a considerable portion of the run. Because of the importance of these rapid temperature drops and the significant difference in thermocouple temperature characteristics between the regions where these drops occurred (temperature drop regions) and where they did not (non-temperature drop regions), the experimental results are presented independently for each of these regions as well as for the entire test.

Referring to Fig. 3, which is a schematic diagram of the temperature variation during a test, the first results to be presented are the average temperatures of the tests. For each test this temperature was obtained by separating the oscillograph record of the test into many smaller regions (I, II; A, B ...), determining the average temperature of each of these regions by planimetry, and calculating the time weighted average temperature of all of these regions. This procedure also allowed the time averaged temperature of the non-temperature drop regions (I, II, ...) to be determined as well as the time averaged

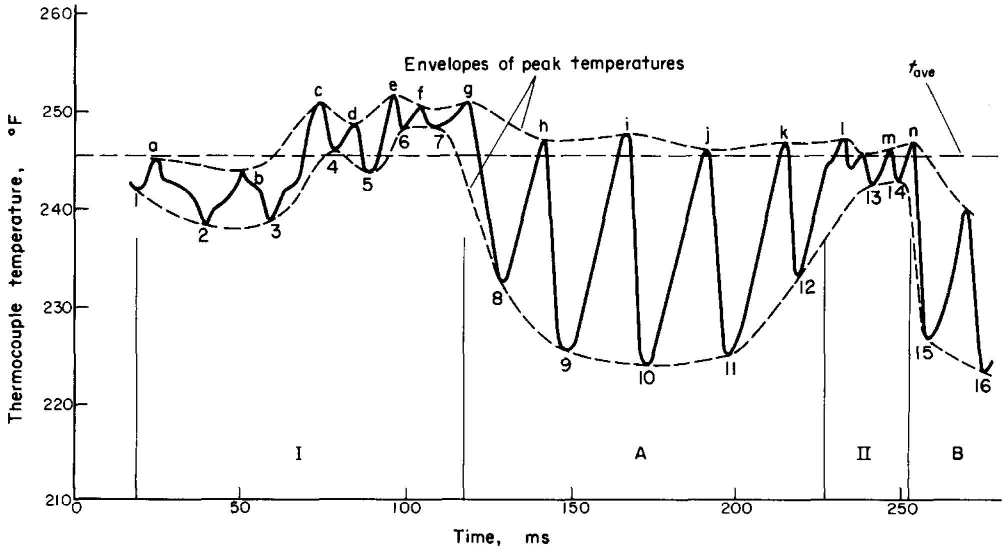

FIG. 3. Schematic drawing of thermocouple temperature fluctuations.

temperature of the temperature drop regions (A, B, ...). These average temperatures are discussed in section 1 below.

Next, the characteristics of the temperature fluctuations about the average temperature of all tests to the same heat flux were determined from the envelope of peak temperatures for the tests (Fig. 3)—c, d, e, f, g, h, i, j, k, l, m, n are positive fluctuations while 1, 2, 3, 5, 8, 9, 10, 11, 12, 13, 14, 15, 16 are negative fluctuations. All fluctuations less than 2°F have been neglected—a step taken so that attention could be focused on the more important larger amplitude fluctuations. For these calculations, fluctuations less than 2°F were recorded in the data taking procedure and eliminated from the calculations in the data reduction process. These results are presented in section 2.

The characteristics of the rapid temperature drops (such as those in regions A and B) have been determined separately and are discussed in detail in section 3.

The steady state peak heat flux for these test element characteristics and fluid conditions is $3{\cdot}37 \times 10^5$ Btu/ft^2 h [7].

1. *Steady state average temperatures*

The average temperature for each of the tests, as well as for the temperature drop and the non-temperature drop regions within each test, are presented in Table 1. The beginning of each temperature drop region was easily determined by the inception of a rapid temperature drop. The end of each temperature drop region was determined by observing a period of approximately 0·01 s at the end of the last temperature drop where no steady temperature rise occurred —the start of this 0·01 s period was chosen as the end of the temperature drop region (see Fig. 4). The periods of time over which the measurements took place are also presented in Table 1 as are the maximum and minimum thermocouple temperatures recorded during each test—the latter to indicate the range of thermocouple temperatures measured.

2. *Temperature fluctuations*

The characteristics of the temperature fluctuations about the average temperature of all tests to the same heat flux in terms of the average magnitude of the fluctuations, the standard deviation thereof, and the frequency of the fluctuations are presented in Table 2. To obtain a finer picture of the characteristics of these fluctuations, a frequency distribution of the fluctuation magnitude was calculated. These results are presented in Table 3 in terms of the frequency of fluctuations in any 2°F interval.

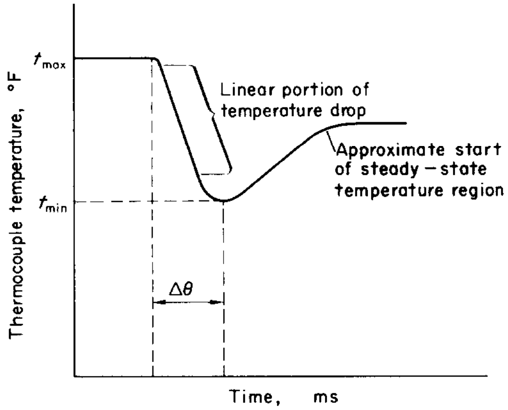

FIG. 4. Schematic drawing of a rapid temperature drop.

3. *Rapid temperature drop characteristics*

Photographs of oscillograph records showing several of the rapid temperature drops are shown in Fig. 2 while Fig. 4 is a sketch of an idealized temperature drop. The rapid temperature drops consisted of an approximately linear temperature decrease starting from t_{max} and accounting for the majority of the temperature drop, followed by a further decrease in the thermocouple temperature at a decreasing rate, until the minimum thermocouple temperature (t_{min}) was reached. The temperature then increased in an approximately linear manner at a much lower

Table 1. Steady state average temperatures

Test no.	Heat flux (10^5Btu/ft^{2}h)	T_{sat} (°F)	Average temperature (°F)			Peak temperatures (°F)		Measurement period (s)		Total
			Region *T* drop	Region non *T* drop	Total	max	min	Region *T* drop	Region non *T* drop	
					Individual tests					
1	0·64	218·0	—	234·9	234·9	242·6	228·1	—	0·61	0·61
2	0·64	218·0	—	237·8	237·8	249·1	226·8	—	1·74	1·74
3	0·64	217·9	—	235·8	235·8	247·6	225·4	—	2·45	2·45
4	0·64	217·3	—	236·0	236·0	247·3	224·3	—	1·54	1·54
5	1·02	217·6	—	251·8	251·8	267·1	237·5	—	0·42	0·42
6	1·02	217·1	—	240·5	240·5	252·6	231·2	—	2·70	2·70
7	1·02	217·0	—	241·7	241·7	253·8	232·0	—	1·41	1·41
8	1·02	217·0	—	240·4	240·4	253·9	230·9	—	1·92	1·92
9	1·66	217·1	248·0	257·3	252·1	274·7	222·5	0·45	1·36	1·81
10	1·66	217·1	246·8	254·7	250·8	275·6	221·5	1·25	1·30	2·55
11	1·95	216·7	249·6	261·0	259·2	279·1	230·0	0·13	0·76	0·89
12	1·95	216·7	254·3	262·3	260·3	279·1	229·6	0·41	1·20	1·61
13	1·95	216·7	254·9	260·1	259·0	275·1	227·2	0·45	1·83	2·28
14	1·95	216·7	253·0	260·3	258·0	277·1	228·5	0·74	1·66	2·40
15	2·20	216·5	258·2	264·9	262·9	280·5	233·4	0·30	0·69	0·99
16	2·20	216·4	255·0	265·4	262·1	283·9	230·2	0·73	1·56	2·29
17	2·20	216·4	253·6	262·7	259·9	279·1	226·1	0·83	1·89	2·72
18	2·20	216·4	257·6	264·8	262·0	277·8	232·0	0·55	0·86	1·41
19	2·47	216·1	257·5	267·2	262·7	278·1	230·1	0·34	0·38	0·72
20	2·47	216·1	257·9	266·7	262·7	277·6	231·1	0·69	0·80	1·49
21	2·47	216·1	258·7	267·1	264·7	283·8	228·3	1·01	2·56	3·57
22	2·47	216·1	259·0	267·5	264·7	282·7	230·6	0·83	1·67	2·50
					Average results					
1–4	0·64	217·8	—	236·3	236·3	249·1	224·3	—	6·34	6·34
5–8	1·02	217·1	—	241·5	241·5	267·1	230·9	—	6·45	6·45
9–10	1·66	217·1	247·1	255·3	251·1	275·6	221·5	1·70	1·66	3·36
11–14	1·95	216·7	253·5	260·8	259·0	279·1	227·2	1·73	5·45	7·18
15–18	2·20	216·4	255·5	264·2	261·1	283·9	226·1	2·41	5·00	7·41
19–22	2·47	216·1	258·5	267·2	264·2	283·8	228·3	2·87	5·41	8·28

Table 2. Temperature fluctuation characteristics

Tests	Positive fluctuations Magnitude (°F)	Positive fluctuations Standard deviation (°F)	Positive fluctuations Frequency (cps)	Negative fluctuations Magnitude (°F)	Negative fluctuations Standard deviation (°F)	Negative fluctuations Frequency (cps)
1–4	5·7	2·1	29·2	5·0	2·1	47·5
5–8	7·0	3·9	24·8	5·5	2·1	44·6
9–10	9·3	5·0	49·4	13·3	8·4	41·1
11–14	6·8	3·5	51·4	8·8	7·4	42·6
15–18	7·7	3·7	56·0	11·2	8·1	42·8
19–22	7·4	3·4	65·6	11·2	8·5	48·8

rate than it had decreased until an approximately steady state temperature was reached or else another drop occurred.

For each of the tests analyzed, the parameters t_{max}, t_{min}, $\Delta\theta$, and the slope of the linear portion of the temperature drop curve were recorded for each drop during the test. No difficulty was encountered in determining when a drop occurred because of the rapid temperature drop rate compared to the regions of the record where no drops were occurring.

The average characteristics of the rapid temperature drops for each of the tests in which drops were recorded and the average results for all tests at the same heat flux value are presented in Table 4 in terms of the number of temperature drops recorded, the average temperature at the beginning of the rapid temperature drops (t_{max}), the average temperature at the lowest portion of the temperature drops (t_{min}), the average temperature drop ($t_{max} - t_{min}$), the average length of the temperature drops ($\Delta\theta$), the rate of decrease of thermocouple temperature for both the linear portion of the temperature drops and for the complete drop ($\Delta t/\Delta\theta$), the frequency with which drops occurred during the test (number of temperature drops/length of test) and during the time they were occurring (number of temperature drops/length of temperature drop regions), the per cent of time the temperature drops occurred during the runs ($n\Delta\theta/\theta_{TEST}$), and the fraction of energy removed by the temperature drops during each test (γ).

DISCUSSION

1. *Steady state average temperature*

The steady state boiling curve determined from the experimental results of Table 1 compares well with the results of Vliet [11]. This point is discussed further in [7]. Also, as shown in Table 1, the amount of scatter in the data between tests at the same heat flux setting is small. It can also be seen that the average thermocouple temperature during the temperature drop regions is considerably less than the average temperature during the non-temperature drop regions, illustrating that the "average" temperature can vary considerably depending on the type of region in which the temperature is measured.

2. *Temperature fluctuations*

The range of temperatures measured is indicated by the peak temperatures of Table 1. The maximum temperature recorded by the thermocouple during each test is approximately 20°F higher than the average temperature of the test at all heat fluxes investigated. On the other hand, the minimum thermocouple temperature recorded remains close to 225°F for all tests. The tube temperature corresponding to this thermocouple temperature is probably the fluid saturation temperature (approximately 217°F). The difference between the tube and thermocouple temperatures is due to the fact that these minimum temperatures occurred at the end of the rapid temperature drops and thus the thermocouple temperature lagged the tube temperature (see the next section for further discussion of this point). The maximum temperatures, however, occurred at the end of slowly increasing temperature rises which could be followed easily by the thermocouple and thus these thermocouple temperatures correspond closely to the tube temperatures.

Within this range the thermocouple temperature varied considerably. Looking at all fluctuations greater than 2°F, the results presented in Table 2 indicated that the average fluctuations from 5 to 14°F in magnitude and occur at frequencies ranging from 25 to 65 fluctuations per s. The fluctuations presented in Table 2 are probably caused by bubble growth adjacent to the thermocouple and turbulence induced in the liquid by the vapor and bulk liquid motion. The magnitude of these temperature oscillations are comparable to the magnitudes of the oscillations reported by Hsu and Schmidt [5].

The results also show that the average frequency at which positive fluctuations occur increases as the heat flux increases, while the

Table 3. Frequency distribution of temperature fluctuations

Temperature interval (°F)	Tests 1–4	5–8	9–10	11–14	15–18	19–22
	Frequency of positive fluctuations (cps)					
2–4	10·6	9·1	8·0	13·0	9·6	11·4
4–6	9·6	5·0	8·6	12·7	11·7	13·2
6–8	5·8	3·2	8·3	10·0	11·2	17·3
8–10	1·3	2·2	4·5	6·7	9·4	11·6
10–12	1·6	1·9	4·5	4·4	6·5	5·2
12–14	0·3	0·6	5·6	1·7	3·8	3·4
14–16	0	0·8	4·8	1·1	1·9	2·2
16–18	0	0·5	2·1	1·0	1·2	1·1
18–20	0	0·2	1·8	0·6	0·3	0·4
	Frequency of negative fluctuations (cps)					
2–4	17·4	13·2	6·5	13·0	10·7	11·6
4–6	15·1	14·1	6·0	8·8	8·4	7·2
6–8	10·2	10·8	3·6	5·6	4·8	5·4
8–10	3·9	5·1	2·4	3·3	3·1	2·5
10–12	0·5	1·1	1·8	1·8	1·8	4·5
12–14	0·3	0	2·1	1·5	1·5	2·0
14–16	0	0·3	2·7	1·7	1·2	3·1
16–18	0	0	2·1	0·7	2·6	1·8
18–20	0	0	2·1	1·1	1·8	1·7

Table 4. Average temperature drop characteristics

Test	Number of drops n	$t_{\max}$ (°F)	$t_{\min}$ (°F)	Δt (°F)	$\Delta\theta$ (ms)	Slopes		Frequencies		Percent of time drops occur	γ (%)
						Linear (°F/ms)	Average (°F/ms)	Total (cps)	T drop region (cps)		
9	16	262·3	231·8	30·5	5·2	21·8	6·3	36·6	10·0	10·0	26·6
10	63	259·1	233·0	26·1	3·5	29·4	8·1	24·7	50·4	8·8	28·5
11	8	263·4	239·4	24·0	2·8	19·9	8·6	9·0	61·5	2·4	8·9
12	22	264·6	240·0	24·6	3·6	21·0	7·5	13·7	53·6	4·8	15·3
13	24	264·8	242·9	21·9	2·8	23·0	8·5	10·5	53·5	2·7	10·3
14	36	265·2	239·6	25·6	3·3	26·0	8·4	15·0	48·6	4·6	15·4
15	13	269·2	241·1	28·1	3·7	25·3	8·5	13·1	43·3	4·7	14·3
16	45	267·1	244·1	23·0	3·0	23·5	7·9	19·7	61·7	6·0	20·3
17	48	265·8	242·6	23·2	2·6	25·6	9·9	17·6	57·8	4·2	15·9
18	25	269·9	245·2	24·7	2·9	31·1	10·2	17·7	45·5	4·9	17·8
19	20	269·0	245·8	23·2	3·0	25·2	9·3	24·1	58·9	7·8	25·5
20	55	268·0	247·2	20·8	2·4	25·7	10·0	36·9	79·7	8·8	33·6
21	56	268·3	246·5	21·8	3·0	23·0	8·3	15·7	55·5	4·4	14·3
22	45	271·3	247·2	24·1	3·0	22·4	9·1	18·0	54·3	5·2	17·4
9–10	79	259·7	232·8	26·9	3·9	23·9	7·7	23·5	46·5	9·0	28·0
11–14	90	264·8	240·6	24·2	3·2	23·4	8·2	12·5	52·0	3·7	12·9
15–18	131	267·7	243·4	24·3	2·9	25·9	9·1	17·7	54·4	5·0	17·5
19–22	176	269·0	246·8	22·2	2·8	23·9	9·2	21·0	61·3	5·7	19·5

average frequency of negative fluctuations remains approximately constant. The positive fluctuation behavior is as expected, whereas the negative fluctive fluctuation behaviour is difficult to explain. For both positive and negative fluctuations, the average magnitude of the fluctuations increases as the heat flux increases, the effect being more pronounced for the negative fluctuations due to the onset of the rapid temperature drops.

3. *Rapid temperature drops*

Before discussing these results, the relation of the tube and thermocouple temperatures will be discussed.

It should be emphasized that the results presented in Table 4 are for the temperature drops recorded by the thermocouple and not the temperature drops experienced by the tube wall. Because of the rapid rate at which the wall temperature dropped, the thermocouple temperature necessarily lagged behind the tube wall temperature. Thus, before applying these results to the tube, the thermocouple transfer function must be applied to the thermocouple temperature to convert it into the tube wall temperature. Because of the large number of temperature drops involved in these tests and the substantial effort required for data conversion, only two thermocouple temperature drops were converted to wall temperature drops. The conversions were obtained by fitting the experimental thermocouple temperatures to a polynomial in a least squares manner and applying the thermocouple transfer function to obtain the corresponding tube temperatures. The results show (Fig. 5) that the temperature drop experienced by the thermocouple is considerably less than the temperature drop experienced by the tube.

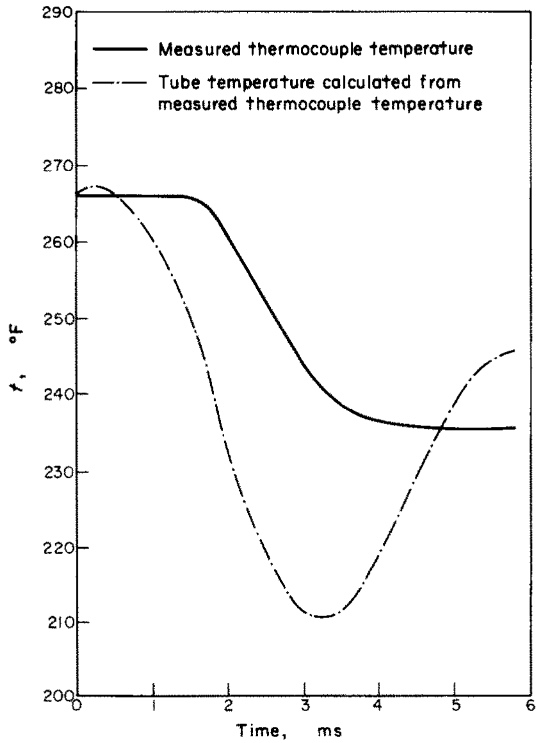

FIG. 5. Thermocouple and tube temperature drops.

It should be noted in Fig. 5 that the calculated tube temperature decreases below the fluid temperature and the fluid saturation temperature. Physically this is impossible and the discrepancy is due to experimental errors in the determination of the thermocouple temperature and to limitations in the procedure used to calculate the tube temperature. That is, if a larger number of experimental points had been used, the error could have been reduced. However, the results of Fig. 5 are used only qualitatively to show the trend of the tube temperature during a rapid temperature drop and the accuracy obtained is sufficient. That is, the significant fact shown by this figure is that the tube temperature approaches the fluid saturation temperature as a minimum value.

The present experiments give no information as to what mechanism causes the rapid temperature drops. For these arguments the papers of Hendricks and Sharp [2] and Cooper and Lloyd [3] must be consulted. The temperature rise following each rapid temperature drop occurs during transient conduction to liquid in most cases. This conclusion is drawn from the observed rate of thermocouple temperature increase following the temperature drops. To determine whether these temperature rises accompanied transient conduction to liquid or whether the tube was insulated by vapor, the rate of increase of thermocouple temperature was measured following ten typical temperature drops during test 20. The average value of the rate of increase of temperature was 4·85°F/ms which is considerably less than the value expected if the tube had been completely insulated (8·6°F/ms). This indicates that the rising portion of the thermocouple temperature curve following a rapid temperature drop is associated with transient conduction (or convection) to the liquid. This conclusion is strengthened by the fact that several rapid temperature drops originated during the rising portion of these curves, indicating that bubbles were forming and, therefore, that liquid was present on the tube surface. Some of the rising portions of the temperature curves have increase rates comparable with the rates expected for a fully insulated tube. For these cases the vapor does not leave the thermocouple position immediately, but remains on the tube, insulating the tube above the thermocouple position.

Now, consider the average experimental results presented in Table 4 for all tests at the same heat flux. As the heat flux increases:

(1) the frequency of the temperature drops during the tests increases (tests 9 and 10 are exceptions to this trend reflecting the local nature of the temperature measurements),

(2) the frequency of the temperature drops during the temperature drop region increases,

(3) $t_{\max}$ increases,

(4) $t_{\min}$ increases,

(5) the thermocouple temperature drop decreases,

(6) the temperature drop interval ($\Delta\theta$) decreases,

(7) the linear rate of decrease of thermocouple temperature remains approximately constant, and

(8) the average rate of decrease of thermocouple temperature increases slightly.

Results (1) and (2) are expected due to the increased frequency of bubble formation at higher heat fluxes. The increase in $t_{\max}$ can be explained by the increase in the average wall temperature which makes higher temperature–liquid available for bubbles to form in. Results (4)–(8) are somewhat artificial since they represent the thermocouple temperature and not the tube temperature. If, as discussed previously, $t_{\min}$ of the tube after each drop is the fluid saturation temperature, then the following observations concerning the tube temperature can be made

(4′) $t_{\min}$ remains constant,

(5′) the average tube temperature drop increases, and

(8′) the average rate of decrease of the tube temperature increases significantly.

These observations indicate that as the heat flux increases the rapid temperature drops become more intense (higher frequency, larger magnitude and higher heat transfer rates) and, therefore, play a more important role in the boiling heat transfer process.

To investigate this point further, the present experiments can be used to determine the contribution of these rapid temperature drops to the overall heat transfer from the tube at the thermocouple position. In this respect, the question of most interest is what percentage of the total energy removed from the test element at the thermocouple position during a given time interval is removed during these rapid temperature drops. Using the nomenclature of Fig. 4, an energy balance on the tube gives, for the energy removed from the tube at the thermocouple position during any one temperature drop,

$$E_i = \dot{q}''_{ss} A_{tc} \Delta\theta_i - (\rho c_p \tau)_t \times A_{tc} (t_{\max\, i} - t_{sat}). \qquad (2)$$

This expression assumes: (1) that the mass of the thermocouple which undergoes any significant temperature change because of the temperature drop is negligible—an assumption which gives a conservative estimate in the end result, (2) that there is no conduction to or from the surrounding metal during the temperature drop—a reasonable estimate since the surrounding metal is probably undergoing the same temperature transient as the tube at the thermocouple position, and (3) that initially the tube is at the thermocouple temperature while in the final state it is at the fluid saturation temperature. For any given steady state test of length θ, the total energy removed from the tube at the thermocouple position is $\dot{q}''_{ss} A_{tc} \theta$, while the total energy removed during the rapid temperature drop is

$$E_{\text{drops}} = \dot{q}''_{ss} A_{tc} n \Delta\theta - (\rho c_p \tau)_t A_{tc} n (t_{\max} - t_{\text{sat}}). \quad (3)$$

The fraction of the energy removed from the thermocouple position by these temperature drops during the time θ is given by

$$\gamma = \frac{E_{\text{drops}}}{E_{\text{total}}} \times 100\% \quad (4)$$

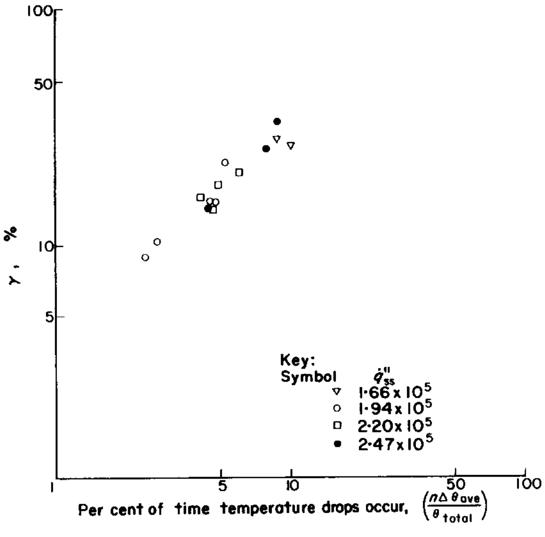

FIG. 6. Energy removed by rapid temperature drops.

or

$$\gamma = \left[\frac{n\Delta\theta}{\theta} - \frac{(\rho c_p \tau)_t n (t_{\max} - t_{\text{sat}})}{\dot{q}''_{ss} \theta}\right] \times 100\% \quad (5)$$

with n, $\Delta\theta$ and $t_{\max}$ presented in Table 4, θ, $\dot{q}''_{ss}$ and t_{sat} presented in Table 1, and ρ, c_p and τ being known tube properties.

Using these values, γ has been calculated and plotted in Fig. 6 (see Table 4 also) vs. the per cent of time the drops occur at the thermocouple position. The results show some scatter because of the local nature of the temperature measurements, but the trend towards an increased fraction of the energy being removed by the temperature drops at higher percentages is clearly visible.

To obtain the total fraction of the energy removed by these temperature drops for the entire tube, rather than just the thermocouple position, it would be necessary to account for the evaporation around the entire tube, which involves knowing both the spatial and temporal distribution of evaporating liquid on the tube surface. It is reported in [12] that near the peak heat flux for distilled water boiling from a horizontal surface, about 40 per cent of the surface is covered with vapor at any one time. This would indicate that a considerable portion of the energy removed from the surface is removed by evaporation of liquid for this condition.

It appears from the results presented in Table 4 that γ depends on both heat flux level and on frequency of drop formation (which is itself somewhat dependent on heat flux). The present experiments were not extensive enough to separate out these effects. However, the data correlates well when presented as in Fig. 6.

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FLUCTUATIONS DE LA TEMPÉRATURE DE SURFACE PENDANT L'ÉBULLITION EN RÉGIME PERMANENT

Résumé— Les fluctuations de la température de surface pendant l'ébullition en régime permanent á partir d'un tube ont été mesurées avec un thermocouple à réponse rapide et les résultats de ces mesures sont décrits. En particulier, les caractéristiques de chutes de température extrêment rapides (allant jusqu'à 16,7 °C/ms) qui se produisent pendant de courtes périodes de temps (1 à 5 ms) sont signalées. Ces chutes rapides de température rendent compte jusqu'à 33 pour cent de l'énergie enlevée du tube à l'endroit du thermocouple.

SCHWANKUNGEN DER OBERFLÄCHENTEMPERATUR BEI STABILEM SIEDEN

Zusammenfassung—Es wurden Schwankungen der Oberflächentemperatur bei stabilem Sieden an einem Rohr mit einem schnell reagierenden Thermoelement gemessen und über die Messergebnisse wird berichtet. Im Besonderen werden die Charakteristiken von extrem schnellen Temperaturabfällen (bis zu 17°C/ms) mitgeteilt, die für kurze Zeiträume auftraten (1 bis 5 ms). Diese schnellen Temperaturänderungen waren dafür verantwortlich, dass vom Rohr, am Ort der Thermoelementlötstelle bis zu 33 Prozent der Energie abgeführt wurde.

ИЗМЕНЕНИЯ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ ПРИ СТАЦИОНАРНОМ КИПЕНИИ

Аннотация—С помощью малоинерционной термопары измерены изменения температуры поверхности при стационарном кипении в трубе и представлены результаты этих измерений. В частности, даны характеристики исключительно быстрых перепадов температуры (до 30°F/ms), происходящих в короткие промежутки времени (от 1 до 5 ms). Такие перепады температуры соответствуют колебаниям теплового потока, доходящим до 33% от среднего теплового потока через стенку трубы в месте расположения термопары.