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**TWO-PHASE FLOW AND
HEAT TRANSFER
IN MULTIROD GEOMETRIES:
A STUDY OF THE
LIQUID FILM IN ADIABATIC
AIR-WATER FLOW
WITH AND WITHOUT OBSTACLES**

B.S. SHIRALKAR

U.S. ATOMIC ENERGY COMMISSION
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PROJECT AGREEMENT 44

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B. S. Shiralkar

Approved:

E. Janssen
Project Engineer

Approved:

F. A. Schraub
Manager, Core Development

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ABSTRACT

An experimental study was made of a water film in a rectangular channel in air-water flow, in which two-phase parameters such as the film thickness and wall shear stress were measured. A photographic and quantitative study was also conducted on the phenomenon of film disruption due to various shapes of obstacles to simulate grid spacer contacts in multirod geometries. A simplified analysis of this phenomenon has been made in terms of the momenta of the air and water streams.

1. INTRODUCTION

In both adiabatic and diabatic annular two-phase flow, a liquid film covers the conduit walls, with the vapor phase flowing in the central core region. This is a highly idealized description of the flow regime, which generally has entrained liquid droplets in the core and substantial void content in the "liquid" film. Moreover, the liquid film thickness cannot generally be uniquely defined because of the presence of large amplitude waves and vapor in the film. Nevertheless, the idea of an average liquid film thickness is attractive from the view point of modeling, and a number of studies both experimental and theoretical, have been made to establish a relationship between the film thickness and the film flow rate.^{1,2,3}

In the present study, carried out with air and water under adiabatic conditions, the shear stress and film thickness were measured, and the film flow rate was taken to be equal to the amount of liquid introduced (negligible entrainment occurred). The validity of some previous models for the film thickness could then be examined.

One of the major objectives of the present study was to examine the behavior of the liquid film in the presence of obstacles. This simulates the effects of grid spacer type contacts in complex multirod geometries on the liquid film, and hence on the critical heat flux. Disruption of the liquid film on a heated surface due to local spacer contacts can produce dry patches and hence premature CHF.

Results of the study, which includes the development of a simple analytical model in addition to the air-water tests, are reported in the following pages.

2. EXPERIMENTAL APPARATUS

The experimental study was conducted in a plexiglass air-water channel shown in Figure 1. This is a modified and rebuilt version of the air-water channel originally constructed under P.A. 44.⁴

A schematic drawing of the setup is shown in Figure 2. Air is supplied from a blower (3 hp, 1120 cu ft/min at 10 inches SP) and passes through an entrance section which includes several wire mesh screens and a honeycomb for flow straightening, and a venturi. Average air velocities of up to 120 ft/sec can be obtained with the blower. A two-dimensional air velocity profile was obtained in the test section, which is a rectangular channel 6 inches wide X 1 inch high (the height is hereinafter referred to as the gap) and 5 feet long. The bottom surface of the channel consists of a ground-glass plate, and the other three sides are made of clear plexiglass to allow visual observation. The ground-glass plate is used to ensure uniform wetting. The channel gap can be reduced to 1/2 inch over a 20-inch length by attaching a piece with a streamlined leading edge to the underside of the top plate.

Water is introduced as a film between a projecting tip and the ground-glass bottom plate. The nominal entry gap is 1/16 inch; however, the film thickness is governed by the air flow rate. Water is recycled by a small centrifugal pump from the drain tank and through a commercial water softener (not shown in the schematic) and a rotameter. One of two rotameters in parallel was used, depending on the flow rate.

In addition to the water flow rate which is measured by the rotameter, the air flow rate is monitored with the venturi in conjunction with a 4-inch inclined manometer. Merriam blue manometer oil (S.G. 1.75) and red oil (S.G. 0.827) were used in the tests. Other instrumentation included a pitot tube and hot wire which could be traversed to measure air and water velocity profiles, and an electrical contact probe and a conductivity cell to measure film thickness. The pressure drop across 3-1/2 feet of the test section was measured with the inclined manometer. An attempt was made to calculate the wall shear stress from pressure drop measurements, but this approach was given up in favor of direct measurement with a flush heat-meter type shear probe. Details of the various instruments are given in the relevant sections describing these measurements.

Figure 1. Overall View of Experimental Setup

Figure 2. Schematic of Air-Water Table

Various obstacles, which consisted of cylindrical and rectangular steel objects were used in the film disruption study. These were held in place on the floor of the test channel with a magnet. A photographic study was made of the flow in the vicinity of some of these objects. Strobe illumination (1/1000 sec) was used for the photographs.

3. PRELIMINARY TESTS AND OBSERVATIONS

Preliminary tests were conducted to establish the two-dimensionality of the air velocity profile. The profile was measured at five different positions, as shown in Figure 3. Both a pitot tube and a straight hot wire probe were used. The hot wire (0.040 inch long X 0.00015 inch diameter), with a DISA 55 DO1 anemometer, was calibrated with reference to the pitot tube. The air velocity at the midpoint of the traverse (zero water flow) was found to agree within 1% at the five probe station. At the air Reynolds numbers used, the flow was turbulent and exhibited a typical turbulent velocity profile, as shown in Figure 4.

Some single-phase and two-phase pressure drop measurements were made, using two pressure taps located in the top plate 42 inches apart.

The single-phase data are plotted in Figure 5, showing

$$\Delta p \sim V_a^{1.75}$$

or

$$\Delta p \sim \frac{C V_a^2}{Re^{0.25}}$$

where the friction factor f can be represented by $C/Re^{0.25}$ in this range of Reynolds numbers.

Figure 3. Traversing Stations for Hot Wire and Pitot Probes

Figure 4. Typical Velocity Profile for Air Flow

Figure 5. Pressure Drop Measurement for Air Flow

The friction factor is comparable to the "smooth" tube friction factor at equivalent Reynolds numbers based on the equivalent diameter (4A/P) concept. These measurements were used in calculating the single-phase shear stress and the two-phase multiplier for shear stress. Visual observation of the liquid film indicated fairly uniform wetting. Due to the shear of the high-velocity air, the film thinned down noticeably immediately on entering the test channel, but appeared fairly uniform over the rest of the channel. Since all measurements were made more than 3 feet from the liquid entrance section, entrance effects were neglected.

As the liquid flow rate was reduced, dry patches appeared in the film, starting near the entrance where the shearing action was the greatest, and propagating downstream. This critical flow rate of water was of the order of 0.05 gpm, corresponding to 50 lb/h-ft at high air velocities, and was lower at low air velocities. This was considered satisfactory and compares favorably with the values of film flow rate at breakup calculated by Hartley and Murgatroyd.⁵

At low air and liquid flow rates, ripples appeared on the surface which rapidly formed two-dimensional waves. On increasing the air or liquid flow rates, the water surface became "pebbled." At still higher air flow rates, roll waves formed on the liquid surface. These observations are in agreement with those of Hanratty and Engen.⁶

4. FILM THICKNESS MEASUREMENTS

The film thickness was measured by using a conductivity cell and an electrical contact cell. Agreement between the two instruments was very good.

The conductivity cell (shown in Figure 6) consists of two stainless steel pins (0.030 inch in diameter) which pass through the glass plate and are flush with the top surface. This forms one arm of a two-arm resistance bridge. The other arm is the resistance across the contacts of a reference cell. The reference cell (Figure 6) consists of a plexiglass cylinder with a plunger that can be moved in or out with a fine screw thread. The gap between the plunger and the bottom surface of the cylinder, which has two flush stainless steel pins identical to the pins in the glass plate, is measured with a dial gage. The water inlet and outlet are located at the bottom of the cylinder. The reference cell is placed in the main flow loop and serves to compensate for any day-to-day changes in the conductivity of the water. A servo amplifier drives a helipot which varies the potential across the two resistances to achieve a null. A reading corresponding to the helipot position appears on an indicator. The circuit diagram for the device, originally built for film thickness measurements in steam-water under P.A. 44⁷ is shown in Figure 7. A calibration chart for the conductivity cell giving indicator reading versus film thickness for a 15-mil gap in the reference cell is shown in Figure 8.

An electrical contact probe was also used as a check on the film thickness. This is merely a pointed steel needle which was traversed vertically within the channel gap. Electrical resistance was measured between the needle and another electrode situated in the water. The resistance approaches infinity when the probe is located in air and a finite smaller value when it is in water. This device was of greatest use for thin films without a markedly wavy surface. When waves of significant amplitude existed on the liquid interface, the position corresponding to 50% liquid and 50% air was taken as the mean film thickness.

Listed in Table 1 are the film thicknesses measured by both methods for varying air and water flow rates in the channel.

5. SHEAR STRESS

Relatively few efforts have been made to measure the shear stress in two-phase flow; e.g., Reference 8. Generally, the shear stress is calculated from pressure drop measurements. In an experiment such as the present one, where one wall is near a two-phase interface and the other is in contact with air alone, the shear stress may be estimated approximately as follows:

Referring to Figure 9,

$$\frac{\Delta P}{\Delta Z} \cdot a \cdot W_c = \tau_{air} \cdot W_c$$

$$\frac{\Delta P}{\Delta Z} \cdot b \cdot W_c = \tau_i \cdot W_c$$

Figure 6. Conductivity Cell

Figure 8. Conductivity Cell Calibration Curve

Table 1
FILM FLOW RATE VERSUS FILM THICKNESS

Mean Air Velocity (ft/sec)	Film Flow Rate		Film Thickness δ (mils)		Mean
	(gpm)	Γ (lb/ft-h)	1*	2*	
56.5	0.05	50	10.00	10.00	10.00
	0.10	100	13.25	13.75	13.50
	0.15	150	16.50	16.50	16.50
	0.20	200	18.25	17.75	18.00
	0.30	300	19.00	20.00	19.50
	0.40	400	19.50	20.50	20.00
	0.50	500	21.00	21.50	21.25
71.5	0.09	90	11.50	11.50	11.50
	0.20	200	13.75	14.25	14.00
	0.30	300	14.50	14.50	14.50
	0.40	400	15.00	15.00	15.00
	0.50	500	15.00	16.00	15.50
79.5	0.05	50	7.50	7.50	7.50
	0.10	100	10.75	10.50	10.62
	0.20	200	12.00	12.00	12.00
	0.30	300	12.50	12.50	12.50
	0.40	400	12.80	12.75	12.77
	0.50	500	13.25	13.75	13.50
86.5	0.05	50	6.50	6.50	6.50
	0.08	80	7.50	7.50	7.50
	0.15	150	9.60	9.50	9.55
	0.25	250	10.10	10.00	10.05
	0.50	500	10.50	11.50	11.00
100.0	0.05	50	6.00	6.00	6.00
	0.10	100	7.80	7.75	7.77
	0.15	150	8.25	8.75	8.50
	0.20	200	8.50	8.75	8.62
	0.30	300	9.00	9.75	9.35
	0.40	400	9.50	10.00	9.75

1* Corresponds to measurements made with conductivity cell

2* Corresponds to measurements made with resistance probe

Figure 9. Shear Stress Calculation

where a and b are distances from the plane of zero shear stress to the upper wall and to the liquid interface, respectively, and W_c is the width of the channel. The liquid film thickness is small relative to channel height. Therefore,

$$\tau_i \cong \tau_w = \frac{\Delta P}{\Delta Z} \cdot b.$$

This method has the disadvantages that: (1) it does not account for any acceleration in the liquid film due to the air flow, i.e., it assumes a steady-state film; and (2) the distance " b " is difficult to determine accurately for a flat turbulent velocity profile.

It was decided to use a flush shear probe for direct measurement of the wall shear stress. The probe used was made by DISA Electronics (Model No. 55-A93). The sensor is a nickel film deposited by sputtering on the end of a quartz rod. A protective quartz coating of 0.00008 inch is applied to the sensor and conductor pads for use in a conductive medium like water. The rod with the sensor is centrally located in the cylindrical probe body which is equipped with a connector. The probe, with its main dimensions, is shown in Figure 10. The length of the film is 0.018 inch and the width is 0.006 inch. The temperature coefficient of resistance is 0.14% per °F.

The probe was mounted in the bottom glass plate so that it was flush with the top surface of the plate, and was oriented so that the length of the film was normal to the direction of the flow. The probe was connected to the 55-DO1 constant-temperature anemometer and was operated at a constant temperature about 30°F higher than the water temperature.

The theory of operation of the shear probe can be understood by considering the boundary layer problem associated with flow over a heated wall (Leveque Problem, Appendix A). The bridge voltage of the anemometer, E , required to maintain the sensor at a temperature T_0 in a flowing fluid at a temperature of T_∞ (see Figure 11) can be expressed as

$$E^2 = A + B\tau_w^{1/3},$$

where τ_w is the wall shear stress and A and B are constants for given values of T_0 and T_∞ .

DISA PROBE 55 A93 FOR CONDUCTING FLUIDS

TECHNICAL DATA

FILM MATERIAL	NICKEL
FILM SIZE	0.018 in. X 0.006 in.
QUARTZ LAYER	8×10^{-5} in.
TEMP. COEFF. OF RESISTANCE	0.14% per $^{\circ}\text{F}$
UPPER FREQUENCY LIMIT IN WATER	30 khz

Figure 10. Shear Probe

Figure 11. Flow Description and Coordinate System for Flush Probe

A is proportional to the power required to maintain the film at T_0 without any flow, because of natural convection, and B is proportional to

$$\frac{k (T_0 - T_\infty) w^{2/3}}{[\alpha\mu]^{1/3}}$$

where

- k = thermal conductivity of fluid,
- w = width of sensor film,
- α = thermal diffusivity of fluid, and
- μ = viscosity of fluid.

A and B are determined experimentally by calibration in the particular fluid being used at the overheat ratio to be employed during the tests.

To calibrate the probe, a plexiglass block with a gap of 0.030 inch (Figure 12) was used. Water was pumped through the gap, and the pressure drop across 9 inches along the length was measured. The calibration points are listed in Table 2. Three different overheat ratios were used with the probe, and the results were found to be very sensitive to the probe temperature. The shear stress measurements agreed very well with calculated values. The calibrations are plotted as $\tau^{1/3}$ versus E^2 in Figure 13, and show the expected linear trend.

This calibration was used for two-phase flow shear stress measurements. This is valid when the thermal boundary layer thickness at the downstream end of the probe film is small compared with both the liquid film thickness and the half gap (0.015 inch) of the calibration piece. Since the nickel film was 0.006 inch wide, the thermal boundary layer thickness is of the order of 0.0001 inch at the downstream end of the element, and the assumption of an "infinite" fluid stream is valid.

The shear stress was measured for a variety of two-phase flow conditions, and some of the data are listed in Table 3. The quality, and the shear stress with air only, are also tabulated. The latter were used to calculate the two-phase shear stress multiplier ϕ_{gt}^2 defined as $\tau/\tau_{\text{air alone}}$.

Figure 12. Shear Probe Calibration Piece

The multiplier is plotted in Figures 14 and 15 versus the quality, and shows a mild velocity effect at the higher air flow velocities. The reproducibility of the data (checked on different days) corresponds to a maximum of ± 0.1 in the multiplier. The velocity effect is very pronounced at low air flow rates because of the presence of two-dimensional waves on the liquid surface at low water film flow rates. This results in high shear stress at qualities close to 1.0. The envelope of the curves for the higher air velocities is shown in Figure 16. It is difficult to compare this data for high qualities with the Lockhart-Martinelli multiplier since only extrapolated curves are available in this range. Moreover, unless the liquid is specially introduced as a film as in this experiment, dispersed fog flow would be expected at equivalent qualities.

Table 2
SHEAR PROBE CALIBRATION

1 Cold Resistance = 8.19Ω
Overheat = 0.40Ω

gpm	$\tau(\text{lb}_f/\text{ft}^2)$	$\tau^{1/3}$	Voltage, E	E^2
0.132	0.0162	0.254	4.60	21.19
0.232	0.0262	0.298	4.89	23.94
0.32	0.0345	0.326	5.04	25.40
0.49	0.050	0.368	5.375	28.89
0.60	0.0585	0.387	5.54	30.69
0.80	0.074	0.420	5.75	33.06
1.00	0.0895	0.448	5.87	34.41
1.20	0.107	0.475	6.00	36.00
1.50	0.130	0.507	6.12	37.44

2 Cold Resistance = 8.23Ω
Overheat = 0.45Ω

0.13	0.016	0.251	4.84	23.43
0.29	0.0317	0.316	5.33	28.41
0.50	0.050	0.369	5.69	32.38
0.80	0.074	0.420	5.995	35.94
1.00	0.0895	0.448	6.16	37.95
1.50	0.130	0.507	6.48	41.99

3 Cold Resistance = 8.19Ω
Overheat = 0.50Ω

0.136	0.0167	0.256	5.06	25.60
0.299	0.0325	0.220	5.47	30.0
0.50	0.050	0.369	6.88	34.64
0.80	0.074	0.420	6.24	38.94
1.00	0.0895	0.448	6.42	41.09
1.00	0.130	0.557	6.76	45.70

-1/-

Figure 13. Shear Probe Calibration Curves

Table 3
TWO-PHASE SHEAR STRESS MEASUREMENT

Water Flow (gpm)	Air Flow		(1 - x)	τ (lb/ft ²)	Shear Stress τ_{AO} (lb/ft ²)	ϕ_{gt}^2
	inches	ft/sec				
0.05	2.18	81.5	0.027	0.054		1.42
0.075	2.20	81.5	0.040	0.073	0.0380	1.92
0.105	2.18	81.5	0.055	0.077		2.03
0.175	2.18	81.5	0.088	0.080		2.10
0.255	2.18	81.5	0.124	0.0855		2.25
0.335	2.14	81.2	0.157	0.096		2.55
0.485	2.12	81.0	0.213	0.112	0.0377	2.97
0.720	2.09	80.5	0.287	0.118		3.13
0.98	2.06	80.0	0.356	0.124		3.29
0.055	3.00	96.0	0.025	0.065		1.30
0.06	2.99	95.8	0.027	0.078	0.050	1.56
0.065	3.02	96.2	0.030	0.0807		1.61
0.11	2.99	95.8	0.049	0.089		1.78
0.125	2.98	95.6	0.056	0.098		2.00
0.205	2.96	95.0	0.089	0.105	0.0490	2.14
0.335	2.91	94.5	0.138	0.115		2.35
0.50	2.87	94.0	0.193	0.131		2.67
0.72	2.81	93.0	0.237	0.144	0.0470	2.94
0.99	2.76	92.0	0.327	0.154		3.27
0.05	0.86	51.5	0.042	0.034		2.02
0.11	0.86	51.5	0.089	0.038		2.26
0.21	0.86	51.5	0.157	0.040	0.0168	2.38
0.34	0.85	51	0.231	0.041		2.44
0.495	0.85	51	0.309	0.047		2.79
0.73	0.85	51	0.392	0.056		3.33
1.00	0.84	50.5	0.469	0.057		3.39
0.04	0.44	36.5	0.048	0.021		2.27
0.095	0.44	36.5	0.106	0.022	0.00926	2.38
0.215	0.43	36	0.212	0.023		2.48

Table 3 (continued)

Water Flow (gpm)	Air Flow		$(1 - x)$	τ (lb/ft ²)	Shear Stress	ϕ_{gt}^2
	inches	ft/sec			τ_{AO} (lb/ft ²)	
0.345	0.43	36	0.302	0.026	0.00926	2.80
0.505	0.43	36	0.387	0.031		3.35
0.74	0.43	36	0.481	0.035		3.78
1.00	0.43	36	0.556	0.033		3.56
0.04	0.21	22.5	0.074	0.0116		2.90
0.11	0.21	22.5	0.180	0.0122		3.05
0.225	0.21	22.5	0.319	0.0130	0.0040	3.25
0.32	0.21	22.5	0.391	0.0124		3.10
0.47	0.21	22.5	0.485	0.0141		3.52
0.70	0.21	22.5	0.584	0.0169		4.22
1.00	0.21	22.5	0.667	0.0171		4.27
0.06	3.90	109.5	0.024	0.095	0.0635	1.49
0.105	3.88	109.0	0.042	0.130		2.05
0.185	3.85	108.5	0.071	0.141	0.060	2.22
0.335	3.78	107.5	0.123	0.147		2.45
0.49	3.68	106	0.172	0.164		2.73
0.72	3.56	104.5	0.237	0.167	0.0560	2.98
1.00	3.48	103	0.309	0.171		3.05
0.045	1.36	65	0.030	0.037		1.46
0.085	1.36	65	0.056	0.049		1.94
0.185	1.34	64.5	0.115	0.056	0.0253	2.21
0.325	1.34	64.5	0.185	0.058		2.29
0.505	1.34	64.5	0.261	0.072		2.84
0.73	1.32	64	0.338	0.081		3.25
1.00	1.33	64	0.411	0.090		3.56

Figure 14. Shear Stress Multiplier versus Flow Quality

Figure 15. Shear Stress Multiplier versus Flow Quality

Figure 16. Shear Stress Multiplier versus Flow Quality

6. FILM FLOW RATE VERSUS FILM THICKNESS

Film flow is generally correlated versus the film thickness in terms of the nondimensionalized parameters,

$$G_f^+ = \frac{\Gamma}{\mu} \text{ and } \delta^+ = \frac{\delta \sqrt{\tau/\rho}}{\nu},$$

where

Γ = film flow rate per unit width,

μ = liquid viscosity,

δ = film thickness,

τ = shear stress,

ρ = density of liquid, and

ν = kinematic viscosity of the liquid.

Listed in Table 4 are the nondimensional film thickness and film flow rates for various flow conditions. Here all the liquid introduced into the channel is assumed to be in the film. This assumption is only valid at small values of the liquid flow rate when the entrainment is negligible. The data are plotted in Figure 17. It can be seen that the parameters correlate the trend in the data, but do not account for the velocity effect. The scatter in the data is less than that seen by other investigators,⁴ possibly because the measured value of shear stress was used in nondimensionalizing the film thickness.

7. VISUAL STUDY OF FLOW WITH OBSTACLES

The obstacles shown in Figure 18 were used for a study of their effects on the liquid film. They were tested in the rectangular channel with both a 1-inch and a 1/2-inch gap. The testing included a photographic study of some of these objects; viz., the 1/2-inch diameter cylinders and the 1/4-inch rectangular blocks, the former in the 1-inch gap and the latter in the 1/2-inch gap.

The air and liquid flow rates were first set so that the liquid film covered the floor of the channel. Then, as the liquid film flow was reduced, dry patches were observed near the obstacles. Typically, these patches occurred in front of the 1-inch-high cylinder and the rectangular pieces, as shown in Figure 19(a) (TYPE I). Sometimes the dry patch occurred behind the object, particularly for the short cylinder [Figure 19(b), TYPE II].

Typical photographs of the long cylindrical obstacle are shown in Figures 20 through 28. These photographs were taken with strobe light illumination and an exposure time of 1/1000 sec.

Figures 20 through 22 show the effect of lowering the water flow rate at an air velocity of 47 ft/sec. At a water flow rate of 155 lb/ft-h, a small dry patch appears in front of the cylinder. Dry patches appear bright due to light reflecting from the exposed ground-glass surface. When the film flow rate is reduced to 100 lb/ft-h, the dry patch becomes larger and extends for an appreciable distance in front of the cylinder. Figures 23 through 28 show the same behavior developed at a higher air velocity of 78 ft/sec as the liquid flow is reduced. Note the thinning of the liquid film in front of the cylinder, followed by the appearance and enlargement of the dry patches. Shown in Figures 27 and 28 is the development of the dry patch at a still higher air velocity (110 ft/sec). The interface is generally wavy and substantial entrainment occurs downstream at the higher air velocities.

Phenomenologically, the appearance of a dry patch in front of certain obstacles is related to a balance between the inertia of the liquid film and the pressure increase due to stagnation of the air stream. This mechanism, which will be discussed in more detail later, appears to be related to the occurrence of diabatic film dryout (CHF), observed upstream of grid-type spacers.

As mentioned earlier, a dry patch appears preferentially behind the short cylinder. This has the shape of a long, narrow strip, which cannot be readily rewetted by increasing the water flow. Figure 29 shows an overall view of this phenomenon and indicates the length of the dry region. Figures 30 and 31 exhibit the thinning of the film and formation of the dry strip. Figure 32 is taken at a higher air flow rate (78 ft/sec).

The mechanism of this dryout behind the object appears to be caused by the air vortex due to air flow over the "step," combined with the slow-moving "wake" flow in the liquid. The air vortex due to flow around the object seems to be weaker in this region. A closeup of the flow, Figure 33 brings out some of the details of the flow.

Table 4
 NONDIMENSIONAL FILM THICKNESS VERSUS FILM FLOW RATE

V	gpm	Γ lbs/ft-h	δ (mils)	$(1-x)$	ϕ_{gt}^2	τ_{air} (lb/ft ²)	τ lb/ft ²	δ^+	G_f^+
55.5	0.05	50	10.0	0.039	1.81	0.0192	0.035	13.2	22.9
	0.10	100	13.5	0.075	2.02		0.039	18.8	45.8
	0.15	150	16.5	0.108	2.18		0.042	23.9	68.8
	0.20	200	18.0	0.140	2.29		0.044	26.7	91.7
	0.30	300	19.5	0.196	2.40		0.046	29.5	137.6
	0.40	400	20.0	0.245	2.50		0.048	31.0	183.5
	0.50	500	21.25	0.289	2.63		0.050	33.6	229.4
71.5	0.09	90	11.5	0.054	1.89	0.03	0.057	19.4	41.3
	0.20	200	14.0	0.112	2.25		0.0675	25.7	91.7
	0.30	300	14.5	0.159	2.45		0.0735	27.8	137.6
	0.40	400	15.0	0.201	2.61		0.078	29.6	183.5
	0.50	500	15.5	0.239	2.75		0.0825	31.4	229.4
79.5	0.05	50	7.5	0.027	1.66	0.0363	0.060	13.0	22.9
	0.10	100	10.6	0.054	1.89		0.069	19.6	45.8
	0.20	200	12.0	0.102	2.24		0.081	24.1	91.7
	0.30	300	12.5	0.145	2.46		0.089	26.3	137.6
	0.40	400	12.8	0.185	2.61		0.095	27.9	183.5
	0.50	500	13.6	0.221	2.75		0.099	30.2	229.4
86.5	0.05	50	6.5	0.025	1.57	0.042	0.066	11.8	22.9
	0.08	80	7.5	0.040	1.75		0.0735	14.4	36.7
	0.15	150	9.5	0.072	1.92		0.081	19.1	68.8
	0.25	250	10.1	0.115	2.32		0.097	22.2	114.7
	0.50	500	11.0	0.206	2.70		0.113	26.1	229.4
100	0.05	50	6.0	0.022	1.58	0.053	0.084	12.3	22.9
	0.10	100	7.8	0.043	1.90		0.101	17.5	45.8
	0.15	150	8.5	0.063	2.13		0.113	20.2	68.8
	0.20	200	8.8	0.083	2.30		0.122	21.7	91.7
	0.30	300	9.0	0.119	2.53		0.134	23.3	137.6
	0.40	400	9.5	0.153	2.68		0.142	25.3	183.5

Figure 17. Film Flow Rate versus Film Thickness

CYLINDERS

RECTANGULAR OBJECTS

Figure 18. Obstacles for Film Disruption Study

(a)
TYPE I

(b)
TYPE II

LOCATION OF DRY PATCH

Figure 19. Location of Dry Patch

Figure 20. Long Cylinder— $V_a = 47$ ft/sec, $\Gamma = 210$ lb/ft-h

Figure 21. Long Cylinder— $V_a = 47$ ft/sec, $\Gamma = 155$ lb/ft-h

Figure 22. Long Cylinder— $V_a = 47$ ft/sec, $\Gamma = 100$ lb/ft-h

Figure 23. Long Cylinder— $V_a = 78$ ft/sec, $\Gamma = 270$ lb/ft-h

Figure 24. Long Cylinder— $V_a = 78$ ft/sec, $\Gamma = 170$ lb/ft-h

Figure 25. Long Cylinder— $V_a = 78$ ft/sec, $\Gamma = 135$ lb/ft-h

Figure 26. Long Cylinder— $V_a = 78$ ft/sec, $\Gamma = 100$ lb/ft-h

Figure 27. Long Cylinder— $V_a = 110$ ft/sec, $\Gamma = 200$ lb/ft-h

Figure 28. Long Cylinder— $V_a = 110$ ft/sec, $\Gamma = 130$ lb/ft-h

*Figure 29. Overall View of Dry Patch Behind Short Cylinder
(1/4 in. high) $V_a = 96$ ft/sec, $\Gamma = 100$ lb/ft-h*

Figure 30. Short Cylinder— $V_a = 47$ ft/sec, $\Gamma = 185$ lb/ft-h

Figure 31. Short Cylinder— $V_a = 47$ ft/sec, $\Gamma = 80$ lb/ft-h

Figure 32. Short Cylinder— $V_a = 78$ ft/sec, $\Gamma = 145$ lb/ft-h

*Figure 33. Short Cylinder, Closeup of Downstream Flow,
 $V_a = 78$ ft/sec, $\Gamma = 130$ lb/ft-h*

The rectangular objects were tested with the channel gap reduced to 1/2 inch. Dry patches were found to occur both behind and in front of these obstacles. However, except at the highest air velocities tried, the dry patches appeared ahead of the objects first, as the film flow rate was reduced. Shape A was found to cause less thinning of the liquid film immediately in front of it, and dryout occurred at fairly low water flow rates, as shown in Figures 34 through 36, for an air velocity of 105 ft/sec. The lower air velocity of 47 ft/sec is shown in Figure 37. Figures 38 through 40 show the unwetted regions in front of shape B, at film flow rates comparable with and higher than those in Figures 34 through 37.

Figure 34. Rectangular Object (Shape A), $V_a = 105$ ft/sec, $\Gamma = 200$ lb/ft-h

Figure 35. Rectangular Object (Shape A), $V_a = 105$ ft/sec, $\Gamma = 100$ lb/ft-h

Figure 36. Rectangular Object (Shape A), $V_a = 105$ ft/sec, $\Gamma = 70$ lb/ft-h

Figure 37. Rectangular Object (Shape A), $V_a = 47$ ft/sec, $\Gamma = 130$ lb/ft-h

Figure 38. Rectangular Object (Shape B), $V_a = 32$ ft/sec, $\Gamma = 190$ lb/ft-h

Figure 39. Rectangular Object (Shape B), $V_a = 32$ ft/sec, $\Gamma = 150$ lb/ft-h

Figure 40. Rectangular Object (Shape B), $V_a = 120$ ft/sec, $\Gamma = 150$ lb/ft-h

8. CRITICAL FILM FLOW RATE

In annular flow, the critical heat flux is hypothesized to occur when the film flow rate on the heated surface approaches a small value, close to zero. In the presence of the obstacles examined in the previous section, it is obvious that dryout will occur because of the hydrodynamics of the flow at finite values of the film flow rate. To examine quantitatively the influence of these different objects, it was decided to plot this critical film flow rate at which dry patches first occur versus the air velocity for each object. It can be seen that the higher the film flow rate at dryout the lower is the quality, and consequently the poorer is the performance of the component from the point of view of CHF. However, it was found to be very difficult to determine exactly when a dry spot first forms in front of an object, since the film successively passes through the stages of thinning, partial dewetting and rewetting, leading to formation of a small dry spot which further enlarges as the film flow rate is reduced. The observed rewetting process is caused by waves in the liquid, which were generally present except at very low liquid flow rates.

As a basis for comparison, the critical flow rate was defined to be that which causes a dry spot 1/8 inch long in front of the object. It should be noted that this arbitrarily defined dry spot does not necessarily correspond to CHF under diabatic conditions. Due to evaporation, CHF will probably occur earlier; i.e., at a higher film flow rate. During the tests, the objects were positioned with their leading edges exactly 1/8 inch downstream of a conductivity cell electrode, so that the conductivity cell could be used to set the water flow rate at the value for which the dry spot reached the electrode. In contrast, when dryout occurred behind an object, the phenomenon was quite sudden and a sizeable patch appeared with a small decrease in film flow rate.

Cylindrical and rectangular objects, as shown in Figure 18, were evaluated in terms of the critical film flow rate. To examine the effects of changing the object and gap size, the following combinations were tried:

- a. Long, 1/2-inch-diameter cylinders in 1-inch and 1/2-inch gaps.
- b. Short, 1/2-inch-diameter X 1/4-inch-high cylinder in 1-inch and 1/2-inch gaps.
- c. Long, 1/4-inch-diameter cylinder in 1-inch gap.
- d. 1/4-inch-high rectangular objects in 1-inch and 1/2-inch gaps.
- e. 1/8-inch-high rectangular objects in 1-inch and 1/2-inch gaps.

Some of the critical film flow rate plots are shown on the following pages. Figure 41 is a plot of the critical film flow rate for two 1/2-inch-diameter cylinders, one spanning a 1-inch gap and the second one spanning a 1/2-inch gap. The region above the line represents a completely wetted region, whereas at liquid flow rates below the line, dry patches exist. Two plots have been made for each object. One is where, starting from the completely wetted condition, the film flow rate is continuously decreased at a set value of air velocity until a dry patch appears. The other plot is where, starting from the existence of a dry patch, the film flow rate is continuously increased until the dry patch disappears. At low air flow rates there is a wide difference in these plots due to the relative importance of surface tension. At higher air velocities, the curves approach each other. This phenomenon has been seen for all the objects tested. A critical Weber number can be defined as

$$\frac{(\rho V^2)_{\text{air}} \delta}{g_c \sigma}$$

at which the surface tension effects are no longer important. This has been found to be of the order of 2 to 3. Note that the performance of the two cylinders is very similar, and also that at higher air velocities the critical film flow rate is independent of the air velocity.

The data in Figure 42 are for a 1/4-inch-diameter cylinder and show that the critical flow rate is smaller (approximately half) than that for a 1/2-inch-diameter cylinder. Figure 43 illustrates the situation for a 1/2-inch X 1/4-inch-high cylinder in a 1-inch gap. Here dryout occurs first behind the cylinder and then ahead of the cylinder at much lower flow rates.

For the 1/2-inch-diameter 1/4-inch-high cylinder in a 1/2-inch gap, dryout occurs behind and ahead of the cylinder at similar flow rates, as shown in Figure 44. For dryout behind the cylinder, the critical film flow rate was found to be a function of the air velocity.

Shown in Figure 45 is a comparison between the two rectangular shapes C and D shown in the insets in a 1/2-inch gap. The results for the two shapes are very similar. Dryout occurs first upstream of the objects, and occurs downstream at a much lower film flow rate. Figure 46 shows that shape A performs substantially better than shape B; i.e., causes dryout at a lower film flow rate. Again, dryout is preferentially in front of the objects.

Two blocks of shape B, but with different heights, were tried out in the 1-inch gap. The results, given in Figure 47, show that the thinner block improves wetting in front of the obstacle, but aggravates the situation downstream.

Figure 48 is a composite of some of the results presented above, showing only the curves made for decreasing film flow rate, since this is normally the situation of interest. Some of the conclusions that can be drawn from this figure are:

- Certain shapes are noticeably worse than others with respect to film disruption. Shape B caused the most film disruption.
- Performance of the obstructions appears to be a function of the ratio of the height of the object to the gap size; e.g., 1/2-inch-high cylinder in a 1/2-inch gap is equivalent to the 1-inch-high cylinder spanning 1-inch gap. Also, the 1/8-inch-high rectangular block in a 1/2-inch gap was found to behave similarly to a 1/4-inch block in a 1-inch gap. However, this scaling may not extend to a very narrow gap where the film thickness is comparable with the obstacle size.
- When dryout occurs in front of the obstacle, the situation is improved by reducing the height of the obstacle with respect to the gap. For dryout behind the object, this trend is not clear. From the evidence available, there appears to be a particular height where the film disruption is maximum behind an object. When the width of the obstacle is reduced—e.g., 1/4-inch-diameter cylinder compared with the 1/2-inch-diameter cylinder—the severity of dry patch is reduced. The ratio of the size of the dry spot to the width of the object was found to be about the same for equivalent flow conditions.

Figure 41. Critical Film Flow Rate versus Air Velocity—Long Circular Cylinder (1/2 in. diameter)

Figure 42. Critical Film Flow Rate versus Air Velocity—Long Circular Cylinder (1/4 in. diameter)

Figure 43. Critical Film Flow Rate versus Air Velocity—Short Cylinder (1/2 in. diameter X 1/4 in. high) in a 1-inch Gap

Figure 44. Critical Film Flow Rate versus Air Velocity—Short Cylinder (1/2 in. diameter X 1/4 in. high) in a 1/2-inch Gap

Figure 45. Critical Film Flow Rate versus Air Velocity—Rectangular Block (Shapes C and D) in 1/2-inch Gap

Figure 46. Critical Film Flow Rate versus Air Velocity—Rectangular Block (Shapes A and B) in 1/2-inch Gap

Figure 47. Critical Film Flow Rate versus Air Velocity—Rectangular Blocks (Shapes B and B_1) in 1-inch Gap

Figure 48: Comparison of Critical Film Flow Rates for Various Objects

9. SIMPLIFIED ANALYSIS OF DRYOUT

The conditions under which a thin liquid film, flowing concurrently with a higher velocity air stream, will tend to completely wet the surface were first investigated by Hartley and Murgatroyd.⁵ They suggested a criterion based on a force balance at the upstream stagnation point of a dry patch and considered the stability of such a dry patch. Figure 49 is taken from their paper and shows the forces acting on the dry patch; viz., the dynamic pressure of the liquid and the surface tension force.

In terms of these forces, the criterion for neutral stability of point G is

$$\sigma (1 - \cos \theta) = \frac{1}{2} \rho_L \int_0^\delta V_L(y)^2 dy,$$

where

σ = surface tension,

θ = contact angle,

$V_L(y)$ = local velocity in liquid, and

δ = film thickness.

Later, in order to explain the experiments of Hewitt and Lacey,⁹ two other forces were introduced by Murgatroyd¹⁰—a form force due to the change in static pressure around the front G, and a shear force due to the out-of-balance stress between the interfacial shear τ_i , which is assumed to change very little toward the stagnation point, and the wall shear τ_o which decreases as the film stagnates.

The force balance was then written as

$$\sigma (1 - \cos \theta) = \frac{1}{2} \rho_L \int_0^\delta V_L(y)^2 dy + (K_1 + K_2) \tau_i \delta,$$

where K_1 and K_2 are factors which account for the shear and form forces.

Zuber and Staub¹¹ modified the Hartley-Murgatroyd criterion for the diabatic case by including two other terms; one, due to thermocapillarity and the other due to "vapor thrust". The modified criterion was stated as:

$$\sigma (1 - \cos \theta) + \rho_V \left[\frac{q''}{\rho_V h_{fg}} \right]^2 \left(\frac{\rho_L - \rho_V}{\rho_L} \right) \delta \cos^2 \theta + \frac{d\sigma}{dT} \frac{q''}{k} \delta \cos \theta = \frac{1}{2} \rho_L \int_0^\delta V_L(y)^2 dy.$$

In a recent paper,¹² Thompson and Murgatroyd concluded, on the basis of diabatic steam-water tests, that the terms of greatest importance are the dynamic pressure of the liquid and the surface tension force. The interfacial shear and thermocapillarity forces were an order of magnitude smaller and the vapor thrust and drag forces were several orders of magnitude smaller.

Applying a similar type of analysis to the case where obstacles are present, the pressure rise in front of the obstacle has to be included in the force balance, which becomes (omitting the diabatic terms):

$$\delta \cdot \Delta P_{air} + \sigma (1 - \cos \theta) = \delta K \tau_{fg} + \frac{1}{3} \rho_L \bar{V}_L^2 \delta,$$

where $\Delta P_{air} = P_{air} - P_{air_\infty}$ and a linear velocity profile has been assumed in the liquid film.

Figure 49. Dry Patch Formation in a Liquid Film

It should be noted that surface waves, which were observed, particularly at the higher liquid and air flow rates, are not accounted for in this formulation. The kinetic energy of the waves is large compared with that of the film, and leads to a dewetting and rewetting phenomenon. Order-of-magnitude considerations show that

$$\begin{aligned}\Delta P_{\text{air}} &\sim 0 \left[\frac{\rho_a V_a^2}{2g_c} \right] \\ K_{\tau_{fg}} &\sim 0 \left[50 \times f \times \frac{\rho_a V_a^2}{2g_c} \right] - [\text{Ref. 10}] \\ &\sim 0 \left[0.2 \frac{\rho_a V_a^2}{2g_c} \right]\end{aligned}$$

The evaluation of the surface tension force is very sensitive to the contact angle. Estimates of contact angle for water drops in air range from 49 to 78 degrees depending on the nature of the surface. Surface tension forces are probably of importance mainly at low air flow rates. This partly explains the hysteresis seen in dryout and wetting liquid flow rates at low air velocities. The significance of the surface tension forces can be evaluated in terms of a Weber number, $\rho V^2 \delta / \sigma$.

The increase in air pressure in front of simple objects can be found from potential theory; e.g., for an infinite cylinder,

$$\left| \Delta P_{\text{air}} \right|_x = \frac{\rho_a V_{\infty}^2}{2g_c} \left[\frac{2R^2}{x^2} - \frac{R^4}{x^4} \right]$$

where

V_{∞} = upstream air velocity,

R = radius of cylinder, and

x = distance from center of cylinder.

For a hemispherical object (which approximates a short cylinder),

$$\left| \Delta P_{\text{air}} \right|_x = \frac{\rho_a V_{\infty}^2}{2g_c} \left[\frac{2R^3}{x^3} - \frac{R^6}{x^6} \right]$$

To calculate the kinetic energy of the liquid film, the liquid film flow rate and the average film thickness must be known. The film thickness was obtained from Table 1 for various conditions.

As an example, consider the experimental dryout in front of the long cylinder (1/2-inch diameter) which was defined as a dry patch of length 1/8 inch. Here,

$$\begin{aligned}
 V_{\infty} &= 100 \text{ fps,} \\
 \Gamma &= 150 \text{ lb/h-ft,} \\
 \delta &= 8.5 \times 10^{-3} \text{ inches,} \\
 x &= 3/8 \text{ inch,}
 \end{aligned}$$

$$\begin{aligned}
 \left| \Delta P_{\text{air}} \right|_{3/8 \text{ inch}} &= \frac{\rho_a V_{\infty}^2}{2g_c} \left[2 \left(\frac{1/4}{3/8} \right)^2 - \left(\frac{1/4}{3/8} \right)^4 \right] \\
 &= \frac{28}{81} \frac{\rho_a V_{\infty}^2}{g_c}
 \end{aligned}$$

$$\therefore \delta \cdot \Delta P_{\text{air}} = \frac{28}{81} \times \frac{0.071 \times (100)^2}{32.2} \times \frac{0.0085}{12} = 5.39 \times 10^{-3} \text{ lb/ft.}$$

Surface Tension Force ($\theta = 64^\circ$)

$$\sigma (1 - \cos \theta) = 0.005 \times 0.4 = 2.0 \times 10^{-3} \text{ lb/ft}$$

$$\text{Liquid K.E.} = \frac{1}{3} \frac{\rho_L \bar{V}_L^2 \delta}{g_c}$$

$$= \frac{1}{3} \frac{1^3}{\rho_L \delta g_c}$$

$$= \frac{1}{3} \times \frac{(150)^2}{62.3 \times 0.0085/12 \times 32.2 \times (3600)^2} = 4.04 \times 10^{-4} \text{ lb/ft}$$

$$\text{Form Force} = K \tau_{fg} \delta = 1.50 \times 10^{-3} \text{ lb/ft.}$$

It is apparent that the liquid kinetic energy is an order of magnitude too small to prevent stagnation of the film. For neutral equilibrium, $\Gamma = 500 \text{ lb/h-ft}$, which is three times the measured value. This corresponds to the incipience of the dry patch in the absence of surface waves. In practice, this probably corresponds to the beginning of the partially wetted region.

It appears, therefore, that the kinetic energies of the air stream and the liquid waves are the governing factors. Since the wave velocity and the kinetic energy depend on the air and water densities and velocities, the ratio of the average momenta of the air and water is a possible parameter for correlating critical film flow values, particularly at high air flow rates:

$$\begin{aligned}
 M &= \frac{(\rho \bar{V}^2)_{\text{air}}}{(\rho \bar{V}^2)_{\text{water}}} \\
 &= \frac{\rho_L \rho_a \bar{V}_a^2 \delta^2}{\Gamma^2}
 \end{aligned}$$

Shown in Table 5 are the values of M for dryout in front of the long cylinder. M increases at low air velocities but remains constant in the neighborhood of 13 at higher air velocities. Similar behavior is seen in front of other obstacles with different critical values of M .

An *a priori* evaluation of the influence of the obstacle shape can be made from an estimate of upstream pressure rise produced by the object from potential theory. The greater the pressure rise, the larger is the critical film flow rate to prevent stagnation.

Table 5
CRITICAL MOMENTUM RATIO
(Long Cylinder)

V_{crit} (ft/sec)	Γ_{crit} (lb/ft-h)	$\delta \times 10^3$ (inches)	M
30	120	13.5	4.53
50	150	17.0	12.80
60	150	15.0	14.30
80	150	11.0	14.10
100	150	8.5	12.80

9.1 DRYOUT BEHIND OBJECTS

This is a more complex phenomenon involving the interaction between the slow-moving wake flow in the film and the air flow. This occurs generally when there is less blockage to the air stream and less of an increase in air pressure upstream of the object. Some work has been done by several researchers¹³ on the phenomenon of air flow over bluff obstacles. The pressure field increases in the axial direction starting at a point near the center of the trailing vortex. This slight adverse pressure is sufficient to cause stagnation in the film in this region. Here also the liquid and air momenta appear to be the important parameters, but the film thickness and velocity in the wake region are not known. The larger the drag coefficient C_D of the object, the worse its performance is likely to be, since this implies a greater reduction in the liquid momentum.

9.2 IMPLICATIONS FOR DIABATIC FLOW

With heat addition, some other forces come into play,¹¹ but none of these is estimated to be very significant.¹² The main difference according to Thompson and Murgatroyd¹² is that thermal instabilities affect the film, due to nucleation bubbles clinging to the floor of the channel.

It is expected that the relative performances of various obstacles will be similar in air/water and steam/water flows. The critical momentum ratio M could be used for steam/water flow (if the liquid vapor interface characteristics are similar) to get an order-of-magnitude estimate of the critical film flow rate. This can further be translated into a penalty in the critical quality; i.e., dryout occurs at a lower quality.

Another possible effect is upstream propagation of the dry patch due to thermal conduction. However, an analysis showed (Appendix B) that this will not lead to large upstream enlargement of the dry patch. This implies that significant damage could occur in the heater surface if temperature detectors are not located in the immediate vicinity of the dryout region.

10. CONCLUSION

Liquid film thickness and flow rate measurements indicate that the normal manner of correlating these variables in terms of G_f^+ and δ^+ is useful, but does not take into account some velocity dependence in the data. The flush shear probe proved to be a useful and direct means of measuring the shear stress. Perhaps this method can be used more extensively in two-phase flow studies, where there is a liquid film on the wall.

In the presence of obstacles, two main types of dry patch formation were obtained. The first type, involving upstream dryout, can be satisfactorily explained in terms of stagnation of the liquid film. The kinetic energy of the waves in the liquid and the pressure rise in the air stream are the dominating factors in the phenomenon. The ratio of the momenta of the air and liquid appears to be a promising parameter for correlating the incipience of dry patches.

Dry patches of the second type, which occur due to stagnation of the wake flow behind obstacles, are dependent on the strength of the air vortex (a function of the air velocity) and the liquid momentum in that region.

The general trends in the behavior of the obstacles are expected to be similar in diabatic flow. The experimental channel is a useful tool in obtaining qualitative information about their performance.

APPENDIX A

PRINCIPLE OF OPERATION OF FLUSH SHEAR PROBE

With reference to Figure 11, consider the shear flow over a flat plate, with the wall maintained at temperature $T = T_0$ beyond $x = 0$.

Assuming a fully developed linear velocity profile; i.e.,

$$u(x, y) = \beta y \quad (\text{A-1})$$

$$v(x, y) = 0 \quad (\text{A-2})$$

the equations of continuity and momentum for an incompressible fluid,

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} = 0 \quad (\text{A-3})$$

$$u \frac{\delta u}{\delta x} + v \frac{\delta u}{\delta y} = \nu \frac{\delta^2 u}{\delta y^2} \quad (\text{A-4})$$

are automatically satisfied. Note: $\frac{\delta}{\delta x}$ denotes partial derivative with respect to x .

Energy Equation

$$u \frac{\delta T}{\delta x} + v \frac{\delta T}{\delta y} = \alpha \frac{\delta^2 T}{\delta y^2} \quad (\text{A-5})$$

$$\left(\text{where } \alpha = \text{thermal diffusivity} = \frac{k}{\rho c_p} \right)$$

has to be solved for the boundary conditions:

$$T(x, 0) = T_0 \quad (\text{A-6})$$

$$T(0, y) = T_\infty \quad (\text{A-7})$$

$$T(x, \infty) = T_\infty \quad (\text{A-8})$$

Introducing the expression for $u(x, y)$ into the energy Equation (A-5),

$$\beta y \frac{\delta T}{\delta x} = \alpha \frac{\delta^2 T}{\delta y^2} \quad (\text{A-9})$$

Defining

$$\Theta \triangleq \frac{T(x, y) - T_0}{T_\infty - T_0}$$

$$\beta y \frac{\delta \Theta}{\delta x} = \alpha \frac{\delta^2 \Theta}{\delta y^2} \quad (\text{A-10})$$

with the boundary conditions,

$$\Theta(x, 0) = 0 \quad (\text{A-11})$$

$$\Theta(0, y) = 1 \quad (\text{A-12})$$

$$\Theta(x, \infty) = 1 \quad (\text{A-13})$$

With a similarity transformation,

$$\eta \equiv \frac{Ay}{x^n} \quad (\text{A-14})$$

$$\Theta = F(\eta) \quad (\text{A-15})$$

$$\frac{\delta \Theta}{\delta x} = F' \frac{\delta \eta}{\delta x} = F' \left[\frac{-n Ay}{x^{n+1}} \right] \quad (\text{A-16})$$

$$\frac{\delta^2 \Theta}{\delta y^2} = F'' \cdot \frac{A^2}{x^{2n}} \quad (\text{A-17})$$

Substituting Equations (A-16) and (A-17) into Equation (A-10),

$$-\rho y \cdot \frac{n Ay}{x^{n+1}} F'(\eta) = \alpha \frac{A^2}{x^{2n}} F''(\eta). \quad (\text{A-18})$$

Substituting for y from Equation (A-14),

$$\frac{n\beta}{\alpha A^3} x^{3n-1} \eta^2 F'(\eta) + F''(\eta) = 0. \quad (\text{A-19})$$

$$\text{For } n = 1/3, \quad A^3 = \frac{1}{3} \frac{\beta}{\alpha}. \quad (\text{A-20})$$

Equation (A-19) reduces to

$$F''(\eta) + \eta^2 F'(\eta) = 0, \quad (\text{A-21})$$

the boundary conditions (B.C.) for Equation (A-20) are now

$$F(0) = 0 \quad (\text{A-22})$$

$$F(\infty) = 1. \quad (\text{A-23})$$

Defining

$$P(\eta) = F'(\eta)$$

$$\frac{dP}{d\eta} + \eta^2 P = 0$$

$$\therefore P = C_1 e^{-\frac{1}{3}\eta^3}$$

Integrating again,

$$F(\eta) = \int_0^\eta C_1 e^{-\frac{\sigma^3}{3}} d\sigma + C_2$$

To satisfy B.C. [Equation (A-22)], $C_2 = 0$,

$$F(\eta) = \int_0^{\eta} C_1 e^{-\frac{\sigma^3}{3}} d\sigma.$$

From Equation (A-23),

$$F(\infty) = 1.0,$$

$$\therefore C_1 = \frac{1}{\int_0^{\infty} e^{-\frac{\sigma^3}{3}} d\sigma} = \frac{3^{2/3}}{\Gamma(1/3)},$$

where Γ is the complete gamma function.

Substituting

$$t = \frac{\sigma^3}{3}$$

$$dt = \sigma^2 d\sigma$$

$$F(\eta) = \frac{C_1}{3^{2/3}} \int_0^{\eta^3/3} t^{-2/3} e^{-t} dt. \quad (\text{A-24})$$

The integrand is an incomplete gamma function of the form:

$$\gamma(\eta, z) = \int_0^z e^{-t} t^{n-1} dt,$$

$$\therefore F(\eta) = \frac{\gamma[1/3, \eta^{3/3}]}{\Gamma(1/3)}. \quad (\text{A-25})$$

This solves the problem of the temperature distribution in the boundary layer for $x > 0$.

To apply this to the problem of measurement of the shear stress:

$$\begin{aligned} q''(x, 0) &= -k \left. \frac{\delta T}{\delta y} \right|_{y=0} = k (T_0 - T_{\infty}) \left. \frac{\delta \Theta}{\delta y} \right|_{y=0}, \\ &= \frac{\delta \Theta}{\delta y} F'(\eta) \frac{\delta \eta}{\delta y}, \end{aligned}$$

where, from Equations (A-14) and (A-20),

$$\eta = \frac{Ay}{x^{1/3}},$$

$$A = \left[\frac{1}{3} \frac{\beta}{\alpha} \right]^{1/3},$$

$$\frac{\delta\Theta}{\delta y} = \left[\frac{1}{3} \frac{\beta}{\alpha} \right]^{1/3} \frac{F'(\eta)}{x^{1/3}},$$

$$\text{and } q''(x,0) = k(T_0 - T_\infty) \frac{F'(0)}{\left[\frac{3\alpha x^{1/3}}{\beta} \right]} \quad (\text{A-26})$$

Since

$$\tau_w = \mu \frac{\delta u}{\delta y} = \mu\beta,$$

$$q''(x,0) = \frac{k(T_0 - T_\infty) F'(0)}{\left[\frac{3\alpha x \mu}{\tau_w} \right]^{1/3}} \quad (\text{A-27})$$

Since $(T_0 - T_\infty)$ is maintained constant, and $k, \alpha, \mu, F'(0), \tau_w$ are constant, integrating over the width of the film w ,

$$\begin{aligned} q'(w) &= \frac{k(T_0 - T_\infty) F'(0)}{\left[\frac{3\alpha \mu}{\tau_w} \right]^{1/3}} \cdot \frac{w^{2/3}}{2/3} \\ &= C_3 (T_0 - T_\infty) \tau_w^{1/3}, \end{aligned} \quad (\text{A-28})$$

where

$$C_3 = \frac{k F'(0) w^{2/3}}{[3\alpha \mu]^{1/3} \cdot 2/3}.$$

The power supplied by the anemometer,

$$I^2 R(T_0) \sim C_3 (T_0 - T_\infty) \tau_w^{1/3},$$

and the bridge voltage of the anemometer E can be related to the shear stress as,

$$E^2 = C_4 (T_0 - T_\infty) \tau_w^{1/3}. \quad (\text{A-29})$$

In practice, the anemometer supplies some power to the probe to maintain it at T_0 even with zero flow due to natural convection,

$$E^2 = A + B \tau_w^{1/3}, \quad (A-30)$$

where A and B are constants for a particular T_0 , to be determined by calibration and $B = C_4 (T_0 - T_\infty)$.

Equation (A-27), when appropriate substitutions are made, can be expressed as

$$h = \frac{q''}{\Delta T} = 0.538 k \left(\frac{\tau_w}{\mu \alpha x} \right)^{1/3} \quad (A-31)$$

from which one can obtain an "equivalent thermal boundary layer thickness" at x.

$$\delta = \frac{k}{h} = 1.86 \left(\frac{\mu \alpha x}{\tau_w} \right)^{1/3} \quad (A-32)$$

APPENDIX B

MOVEMENT OF DRYOUT POINT DUE TO THERMAL CONDUCTION

When a dry patch of appreciable size forms in the liquid film on a heater wall, a question is raised as to how far this patch will propagate due to thermal conduction. This problem is of practical interest since there may not be temperature detectors in this region, resulting in damage to the heater. A simple one-dimensional analysis was conducted to get an order-of-magnitude estimate of the propagation distance:

The liquid is assumed to form a dry patch due to stagnation and evaporation at the point i. Due to high wall temperature T_w in the dryout region, thermal conduction along the wall will cause the film dryout point to move upstream by a distance λ to the point f. (In the case of a dry patch of Type II, there will also be a downstream movement of the dry patch.) T_w denotes the local wall temperature for the heater wall, which is treated as a fin.

Solving for the final wall temperature distribution, with the substitution of $T = T_w - T_{sat}$:

$$k_w t \frac{d^2 T}{dx^2} - h T + q''' t = 0 \quad (B-1)$$

or

$$\frac{d^2 T}{dx^2} - \frac{h}{k_w t} T + \frac{q'''}{k_w} = 0 \quad (B-2)$$

where

k_w = thermal conductivity of the wall

and t = wall thickness

q''' = heat generation in the wall/volume

Denoting the regions $x > 0$ by + and $x < 0$ by -:

For $x < 0$, $h = h_1$ (heat transfer coefficient to vapor)

$$T^- = \frac{q''' t}{h_1} + C_1 e^{\sqrt{h_1/tk_w} x} \quad (B-3a)$$

For $x > 0$, $h = h_2$ (boiling heat transfer coefficient)

$$\therefore T^+ = \frac{q''' t}{h_2} + C_2 e^{-\sqrt{h_2/tk_w} x} \quad (\text{B-3b})$$

Matching Equations (B-3a) and (B-3b) at $x = 0$; i.e.,

$$T^+ \Big|_{x=0} = T^- \Big|_{x=0} \quad \text{and} \quad \frac{dT^+}{dx} \Big|_{x=0} = \frac{dT^-}{dx} \Big|_{x=0}$$

C_1 and C_2 can be solved as:

$$C_1 = \frac{-q''' t}{h_1 h_2} \frac{(h_2 - h_1)}{(1 + \sqrt{h_1/h_2})} \quad (\text{B-4})$$

$$C_2 = \frac{q''' t}{h_1 h_2} \frac{(h_2 - h_1)}{(1 + \sqrt{h_2/h_1})} \quad (\text{B-5})$$

The temperature distributions in the two regions are:

$x < 0$

$$T^- = \frac{q''' t}{h_1} - \frac{q''' t}{h_1 h_2} \frac{(h_2 - h_1)}{(1 + \sqrt{h_1/h_2})} e^{\sqrt{h_1/tk_w} x} \quad (\text{B-6})$$

$x > 0$

$$T^+ = \frac{q''' t}{h_2} + \frac{q''' t}{h_1 h_2} \frac{(h_2 - h_1)}{(1 + \sqrt{h_2/h_1})} e^{-\sqrt{h_2/tk_w} x} \quad (\text{B-7})$$

The overall temperature distribution is as shown in the following sketch:

The heat input to the liquid in the region $x > 0 = h_2 T / (\text{unit length} \times \text{unit depth})$

$$h_2 T = q'''_t + q'''_t \gamma \cdot e^{-\sqrt{h_2/tk_w} x}, \quad (\text{B-8})$$

where

$$\gamma \equiv \frac{(h_2 - h_1)}{h_1 (1 + \sqrt{h_2/h_1})} \quad (\text{B-9})$$

At $x = 0$, film flow rate/unit depth $\Gamma = 0$.

An energy balance for the liquid film leads to:

$$\begin{aligned} \frac{d\Gamma}{dx} &= \frac{\text{Heat input/area}}{h_{fg}} \\ &= \frac{h_2 T}{h_{fg}} \end{aligned} \quad (\text{B-10})$$

where

h_{fg} = latent heat of evaporation.

Substituting for $h_2 T$ from Equation (B-8),

$$\frac{d\Gamma}{dx} = \frac{q'''_t}{h_{fg}} + \frac{q'''_t}{h_{fg}} \gamma e^{-\sqrt{h_2/tk_w} x} \quad (\text{B-11})$$

Integrating with the boundary condition

$$\Gamma = 0 \text{ at } x = 0,$$

$$\Gamma = \frac{q'''_t}{h_{fg}} x + \frac{q'''_t}{h_{fg}} \gamma \sqrt{\frac{tk_w}{h_2}} \left(1 - e^{-\sqrt{h_2/tk_w} x} \right) \quad (\text{B-12})$$

The initial film distribution $\Gamma_0(x)$ before thermal conduction caused further evaporation is assumed to be linear; i.e.,

$$\Gamma_0 = (\lambda + x) \frac{q'''_t}{h_{fg}} \quad (\text{B-13})$$

For large x (i.e., reasonable distance away from dryout) the film flow rate should be unaffected by movement of the dry patch; i.e.,

$$\Gamma(\infty) \cong \Gamma_0(\infty).$$

Substituting for Γ and Γ_0 from Equations (B-12) and (B-13) for large x ,

$$\frac{q'''_t x}{h_{fg}} + \frac{q'''_t \gamma}{h_{fg}} \sqrt{\frac{tk_w}{h_2}} = (\lambda + x) \frac{q'''_t}{h_{fg}} \quad (\text{B-14})$$

or

$$\begin{aligned} \lambda &= \gamma \sqrt{tk_w/h_2} \\ &= \frac{(h_2 - h_1) \sqrt{tk_w/h_2}}{h_1 (1 + \sqrt{h_2/h_1})} \end{aligned}$$

Since h_2 is normally much larger than h_1

$$\lambda \cong \frac{h_2}{h_1} \frac{\sqrt{tk_w/h_2}}{(1 + \sqrt{h_2/h_1})}$$

For typical values of

$$h_2 = 10,000 \text{ Btu/ft}^2 \cdot \text{h} \cdot ^\circ\text{F}$$

$$h_1 = 200 \text{ Btu/ft}^2 \cdot \text{h} \cdot ^\circ\text{F}$$

$$t = 0.01 \text{ ft}$$

$$k = 10 \text{ Btu/ft} \cdot \text{h} \cdot ^\circ\text{F}$$

$$\lambda = 0.23 \text{ inch.}$$

Thus, it can be seen that enlargement of a large dry patch due to thermal conduction is relatively small.

NOMENCLATURE

a	=	Distance from plane of zero shear stress to the upper wall (Figure 9)
b	=	Distance from plane of zero shear stress to the lower wall (Figure 9)
A	=	Area
A, B	=	Constants relating shear stress to probe voltage (defined in Appendix A)
D	=	Diameter of cylindrical object
E	=	Bridge voltage of anemometer
f	=	Friction factor
g_c	=	Constant, $\frac{\text{lb}_f}{\text{lb}_m \text{ ft/sec}^2}$
G_f^+	=	Dimensionless film flow rate = $\frac{\Gamma}{\mu}$
h	=	Heat transfer coefficient from heated wall to fluid
h_{fg}	=	Latent heat of evaporation
H	=	Half height of channel
I	=	Current supplied by anemometer
k	=	Thermal conductivity of liquid
k_w	=	Thermal conductivity of wall
K_1, K_2	=	Empirical constants in Hartley's formulation
M	=	Ratio of momenta of air and liquid
p	=	Pressure
P	=	Perimeter
q'	=	Heat generation/width of probe film
q''	=	Heat flux on heater wall
q'''	=	Heat generation/volume of heater wall
R	=	Radius of cylindrical obstacle
$R(T)$	=	Resistance of probe as a function of temperature

Re	=	Reynolds number for air stream
t	=	Heater wall thickness
T	=	Temperature
T_o	=	Temperature of probe
T_∞	=	Temperature at a remote point in the air stream
$u(x, y)$	=	Local axial velocity in water film
$v(x, y)$	=	Local velocity component normal to the surface in the water film
V_a	=	Mean air velocity
V_c	=	Centerline air velocity
V_L	=	Mean liquid velocity
V_∞	=	Freestream air velocity far upstream of obstacle
w	=	Width of probe film
W_c	=	Width of channel
We	=	Weber number
x	=	Quality = air mass flow rate/total mass flow rate
y	=	Coordinate normal to channel wall
z	=	Coordinate along channel wall
α	=	Thermal diffusivity of liquid
β	=	Slope of linear velocity profile at wall
Γ	=	Film flow rate/unit width of channel
$\Gamma(z)$	=	Gamma function (Appendix A)
$\gamma(\eta, z)$	=	Incomplete gamma function (Appendix A)
δ	=	Liquid film thickness
δ^+	=	Nondimensional film thickness = $\frac{\delta \sqrt{\tau_w/\rho}}{\nu}$
ΔP	=	Pressure drop

θ	=	Contact angle
Θ	=	Nondimensional temperature (Appendix A)
μ	=	Liquid dynamic viscosity
τ_i	=	Interfacial shear stress
τ_w	=	Wall shear stress
τ_{AO}	=	Shear stress with only air at similar flow rate
ρ_a	=	Air density
ρ_L	=	Liquid density
ρ_V	=	Vapor density (diabatic situation)
ϕ_{gt}^2	=	Two-phase multiplier = $\frac{\tau_w}{\tau_{AO}}$
σ	=	Surface tension
ν	=	Kinematic viscosity of liquid
λ	=	Distance dry patch propagates due to thermal conduction (Appendix B).

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Project Engineer	E. Janssen
Subsection Manager	F. A. Schraub
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Italy
Attn: M.R. Morin

1