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Engineering Experiment Station

Columbia, Missouri

THEORY OF THE ADIABATIC BUBBLE

RALPH L. SCORAH • Professor of Mechanical Engineering

Reprinted From Proceedings of the Midwest Conference on Fluid Dynamics, 1950

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THEORY OF THE ADIABATIC BUBBLE

Ralph Scorah
University of Missouri

Experiment

The film coefficient of heat transfer from a hot metal surface to a boiling liquid was estimated by Farber and Scorah[1] from experiments with an electrically heated wire submerged in the liquid. The heat-flow rate was given by the consumption of electric power. The temperature drop through the film was taken as the difference between the surface temperature of the wire and the mean temperature of the liquid. The surface temperature of the wire was estimated by a small thermocouple. The graph of film coefficient as a function of temperature drop through the film is called the boiling curve. The data plotted in Fig. 1 were obtained from 6 different test wires made of Chromel C alloy, 0.040 inches in diameter by 6 inches long, operated in a horizontal position under atmospheric pressure plus 20 inches of water.

Visual Observations

From visual observations of the boiling process, it was possible to identify at least six different variations corresponding to different regions along the boiling curve. The transition from one type into another, though gradual, is represented by lines in Fig. 2. The different types of boiling are described as follows:

I. For ΔT values from 0 up to about 4°F, steam was produced by evaporation at the liquid-vapor interface. The heat transfer from the metal surface to the liquid took place by conduction and single-phase convection, which maintained an upward flow of superheated liquid.

II. Ebullition began at a ΔT value of about 4°F. For values of ΔT from 4 to about 11°F, many small spheroidal bubbles would leave the metal surface, combine to form larger bubbles, which condensed in superheated liquid before reaching the liquid-vapor interface. The boiling was nucleate in the sense that the bubbles originated at favored spots on the metal surface.

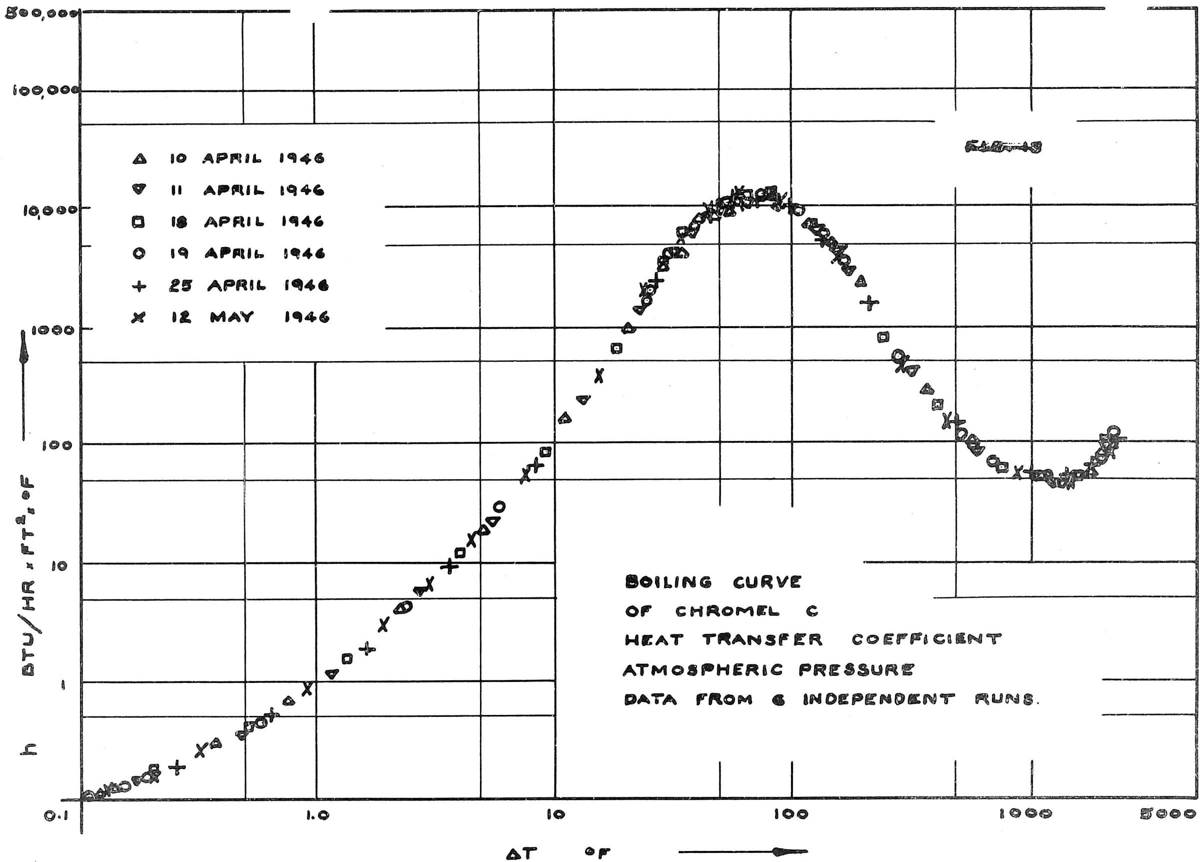
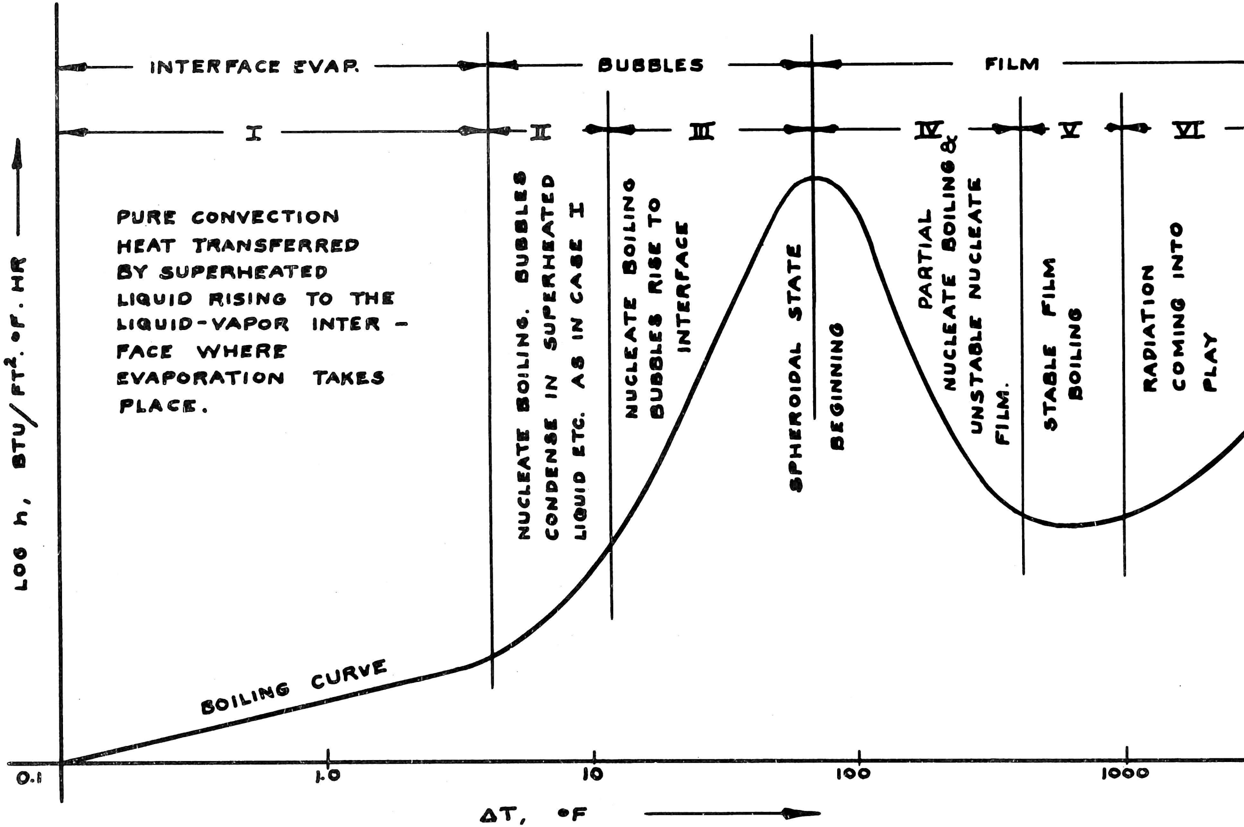

10 APRIL 1946
11 APRIL 1946
18 APRIL 1946
19 APRIL 1946
25 APRIL 1946
12 MAY 1946
BOILING CURVE
OF CHROMEL C
HEAT TRANSFER COEFFICIENT
ATMOSPHERIC PRESSURE
DATA FROM 6 INDEPENDENT RUNS.
h BTU/HR x FT², °F
ΔT °F
500,000
100,000
10,000
1000
100
10
1
0.1
1.0
10
100
1000
5000

Fig. 1



INTERFACE EVAP.
BUBBLES
FILM
I
II
III
IV
V
VI
PURE CONVECTION HEAT TRANSFERRED BY SUPERHEATED LIQUID RISING TO THE LIQUID-VAPOR INTER-FACE WHERE EVAPORATION TAKES PLACE.
NUCLEATE BOILING. BUBBLES CONDENSE IN SUPERHEATED LIQUID ETC. AS IN CASE II
NUCLEATE BOILING BUBBLES RISE TO INTERFACE
SPHEROIDAL STATE BEGINNING
PARTIAL NUCLEATE BOILING & UNSTABLE NUCLEATE FILM.
STABLE FILM BOILING
RADIATION COMING INTO PLAY
BOILING CURVE
LOG h, BTU/FT². °F. HR
0.1
1.0
10
100
1000
ΔT, °F

Fig. 2

III. For values of ΔT from 11 to about 65°F, nucleate boiling was observed. Larger and more numerous bubbles were generated, and they were able to transport steam to the liquid-vapor interface. Whether these bubbles increased or decreased in size could not be observed since several bubbles would almost invariably combine before reaching the interface.

IV. For values of ΔT from 65 to 400°F, an unstable steam film formed around the wire, and large bubbles orıginated at the outer upper surface of this film. This steam film was not mechanically stable, and under the action of the circulation currents the film appeared to collapse and reform rapidly. The presence of this steam film provided additional resistance to heat transfer, and reduced the value of the heat-transfer coefficient.

V. For values of ΔT from 400 to 1000°F, the steam film around the wire was stable in the sense that it did not collapse and reform repeatedly. The shape of the outer surface of the steam film varied continuously under the action of the circulation currents and the rapid discharge of steam bubbles.

VI. For values of ΔT above 1000°F, the influence of radiation became pronounced. In this region, the wire was observed to radiate visible light. The steam film was very stable mechanically, and the orderly discharge of bubbles suggested (1) that the frequency and location of bubble origination was controlled by factors operating at the outer surface of the steam film, and (2) that "favored spots" along the wire were without effect.

The sketches in Fig. 3 represent the phenomena observed in the different regions along the boiling curve. Photographic observations were tried with disappointing results.

Condensation of Zone – II Bubbles

The observed behavior of zone-II bubbles may be explained by considering the effect of size on their thermal stability. Neglecting the second-order effects due to gravitation, the action of surface tension is to increase the pressure of the steam within the bubble above that of the surrounding liquid, in accordance with the following equation:

$$p_v = p_l + \frac{4\sigma}{d},$$

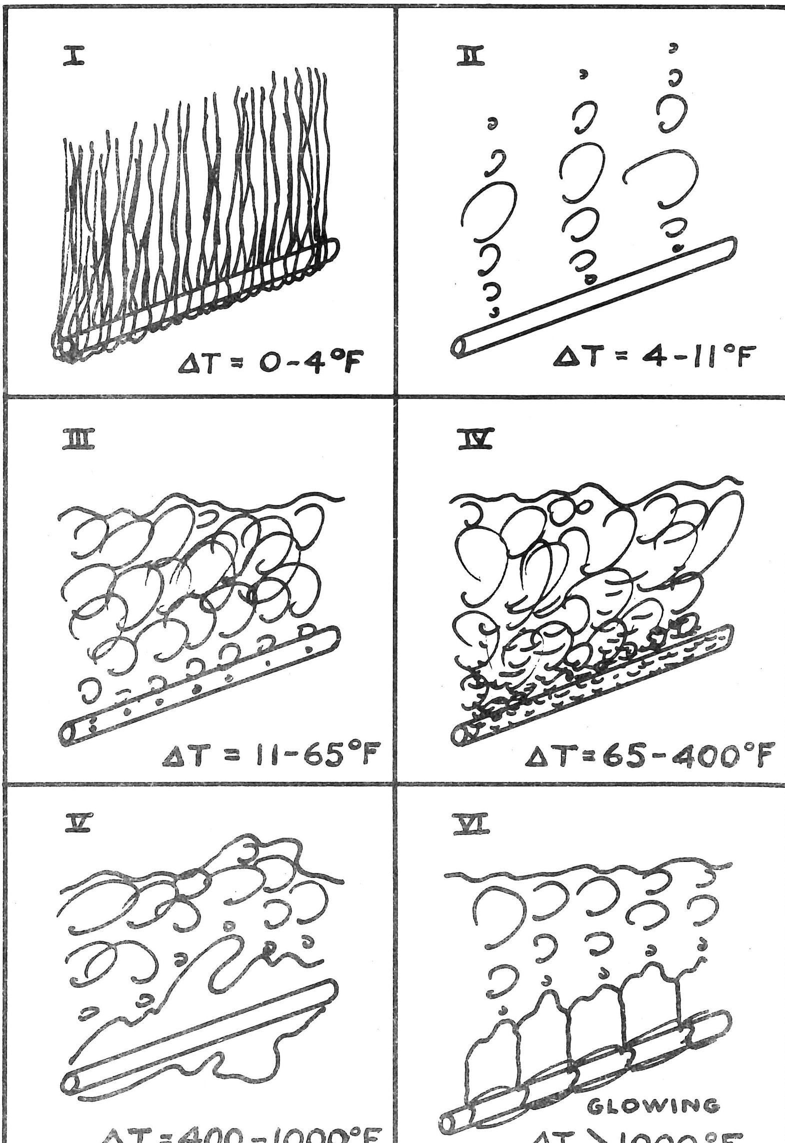


Fig. 3. Typical Boiling for the Different Sections

where p_v = pressure of the vapor within the bubble, psiab

p_1 = pressure of the surrounding liquid, psiab

σ = surface tension of the liquid-vapor interface, psi

d = diameter of the bubble, inches.

The diameter of the bubble is, then

$$d = \frac{4\sigma}{p_v - p_1}$$

and the surface tension is estimated from the following relation:

$$\sigma \doteq 0.470 \times 10^{-3} - 0.634 \times 10^{-6} t,$$

where t is the temperature of the water in °F.

Now consider zone-II operation with the liquid on the heating surface under a pressure of 1 atmosphere and a superheat of 4°F. Vapor is formed at favored spots on the heating surface, swept-up into a bubble, and launched into the surrounding superheated liquid. Due to the action of surface tension, the steam within the bubble is compressed to some pressure above 1 atmosphere. To simplify the argument, consider the bubble filled with saturated steam at a temperature corresponding to the pressure within the bubble. For a given bubble temperature, the pressure can be interpolated from the steam tables, and the diameter of the bubble computed. For the above conditions, the following results apply:

Bubble Temperature °F	Bubble Diameter Inches
220	.000535
218	.000725
216	.001106
214	.002250
212	∞

These data are shown graphically in Fig. 4.

With 4°F of liquid superheat, the water surrounding the bubble operates at 216°F. Bubbles smaller than 0.001106 inches in diameter have temperatures above 216°F, and consequently, transfer heat to the colder, surrounding liquid. As a consequence of this heat loss, condensation takes place at the vapor-liquid interface of the bubble, and the bubble volume and diameter decrease accordingly. With

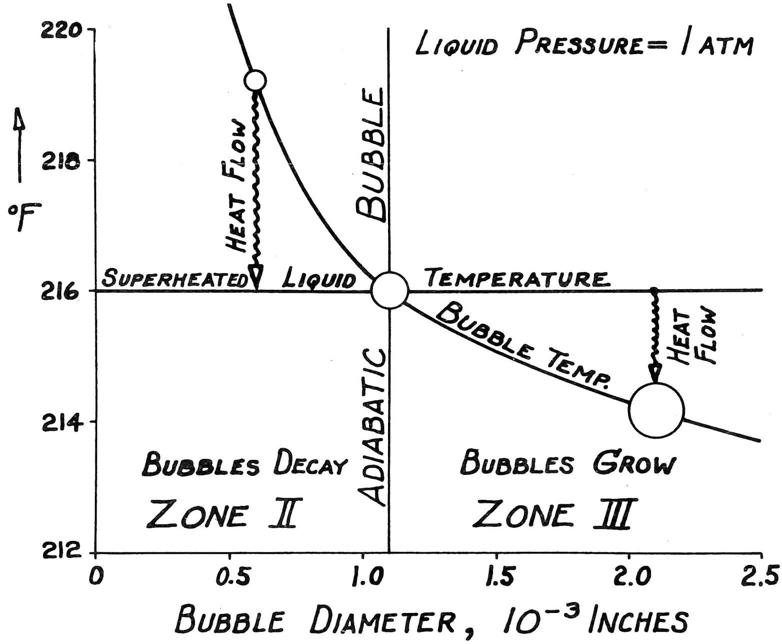


Fig. 4

diminishing bubble diameters, both the saturation pressure and temperature increase within the bubble. The result is a greater temperature difference between the remaining bubble vapor and the surrounding liquid, and a correspondingly greater rate of heat loss. This condensation process continues until the bubble vanishes, as observed in zone II.

Growth of Zone – III Bubbles

On the other hand, bubbles larger than 0.001106 inches in diameter have temperatures below 216°F, and the flow of heat is from the warmer liquid to the colder bubbles. This transfer of heat to the bubble causes evaporation at the liquid-vapor interface, and the bubble volume and diameter increase. This evaporation process at the bubble interface continues so long as there is sufficient liquid superheat to maintain the liquid temperature above the vapor temperature of the bubble, as observed in zone III.

The Adiabatic Bubble

A bubble 0.001106 inches in diameter floating in water at 216°F and 1 atmosphere pressure has the same temperature as the surrounding water. There is no heat transfer, and in this sense, the bubble exists in an adiabatic state. The adiabatic bubble acquires an interesting significance for it marks the boundary between zone II and zone III on the boiling curve. The effect of liquid pressure and superheat on the size of the adiabatic bubble is shown in Fig. 5.

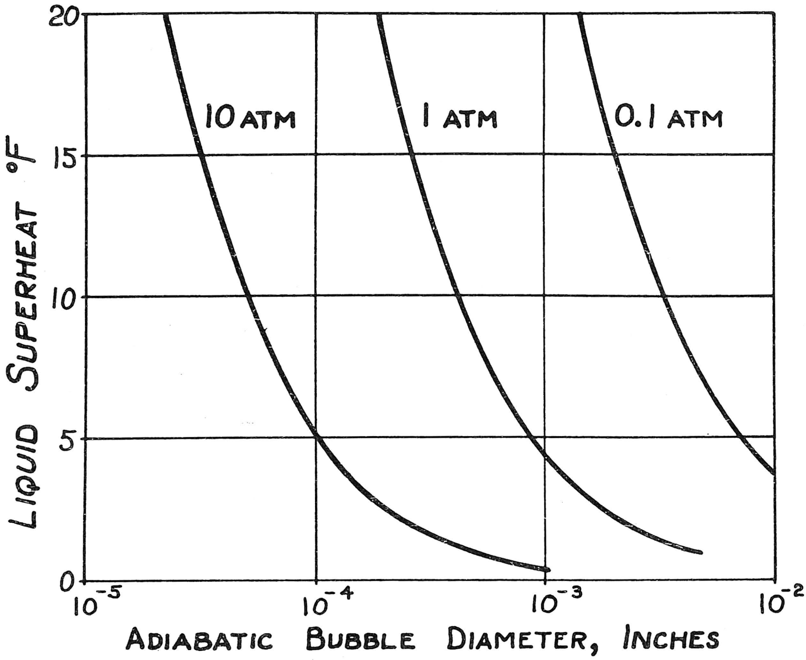


Fig. 5

REFERENCE

1. A.S.M.E. Trans. *70,* 369 (1948).

PUBLICATIONS OF THE ENGINEERING REPRINT SERIES

Reprint No.

*1. *1. Response of Circuits to Steady-State Pulses, by D. L. Waidelich, Professor of Electrical Engineering. Reprinted from the Proceedings of the I. R. E., Vol. 37, No. 12, December 1949.

*1. *2. Heat Transfer to Water Boiling Under Pressure, by E. A. Farber, Graduate Student, now Assistant Professor of Mechanical Engineering University of Wisconsin, and R. L. Scorah, Professor of Mechanical Engineering. Reprinted from The Transactions of The A. S. M. E., May 1948.

*3. Steady-State Waves on Transmission Lines by D. L. Waidelich, Professor of Electrical Engineering, (1950).

4. Theory of the Adiabatic Bubble, by Ralph Scorah. Reprinted from the Proceedings of the Midwestern Conference on Fluid Dynamics, J. W. Edwards, Ann Arbor, 1951.

*Out of Print