

ME96
Boiling Heat Transfer

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1 Introduction

This experiment demonstrates the characteristics of boiling and the accompanying heat transfer processes. The term boiling describes the process in which the addition of heat to a liquid generates vapor. In most applications, the heating is from a submerged surface with a surface temperature greater than the saturation temperature at the system pressure. The vapor forms bubbles which begin growing at the heater surface and rise through the liquid after reaching a certain size. Since the flow patterns depend on the bubble formation and growth and on the variation in fluid properties with temperature, the fluid motion and heat transfer processes are coupled. Due to the coupling effects, the transport processes are difficult to model theoretically. However, the basic phenomena are well documented and are explored in the present experiment.

To illustrate the boiling process, consider a container of water heated from the lower surface. Assume that the temperature of the heater can be maintained at any desired value and that the bulk temperature of the water is lower than the saturation temperature. For these conditions, the process is termed subcooled pool boiling. This differs from saturated pool boiling in which the bulk liquid temperature is at the saturation temperature. Figure 1 from Collier (1981) presents the subcooled pool boiling curve for water at atmospheric pressure and Figure 2 depicts the flow characteristics at various stages of the boiling process.

As the temperature of the heater is increased from the initial bulk value, the liquid close to the heated surface rises and is replaced by cooler fluid. Since no vapor is formed in the heating process the heat transfer is governed by natural convection. Transport by natural convection occurs until the heater temperature is slightly greater than the boiling temperature. When the surface temperature is increased beyond the boiling point, small vapor bubbles form at points along the heater surface. On Figure 1, this temperature difference corresponds with point B' called the onset of nucleate boiling. The bubbles formed along the heater surface collapse as they move and grow into the colder subcooled liquid. The growth and collapse of the bubbles causes increased fluid motion from that found in the natural convection process. This increased motion along with the latent heat transported by the vapor bubbles yields an increase in the surface heat transfer. Therefore, the nucleate boiling region is accompanied by a substantial increase in heat transfer from that for natural convection as shown in Figure 1. Note that the heat transfer coefficient is defined by the temperature difference between the wall temperature and the bulk temperature.

If the temperature difference is increased beyond the onset of nucleate boiling,

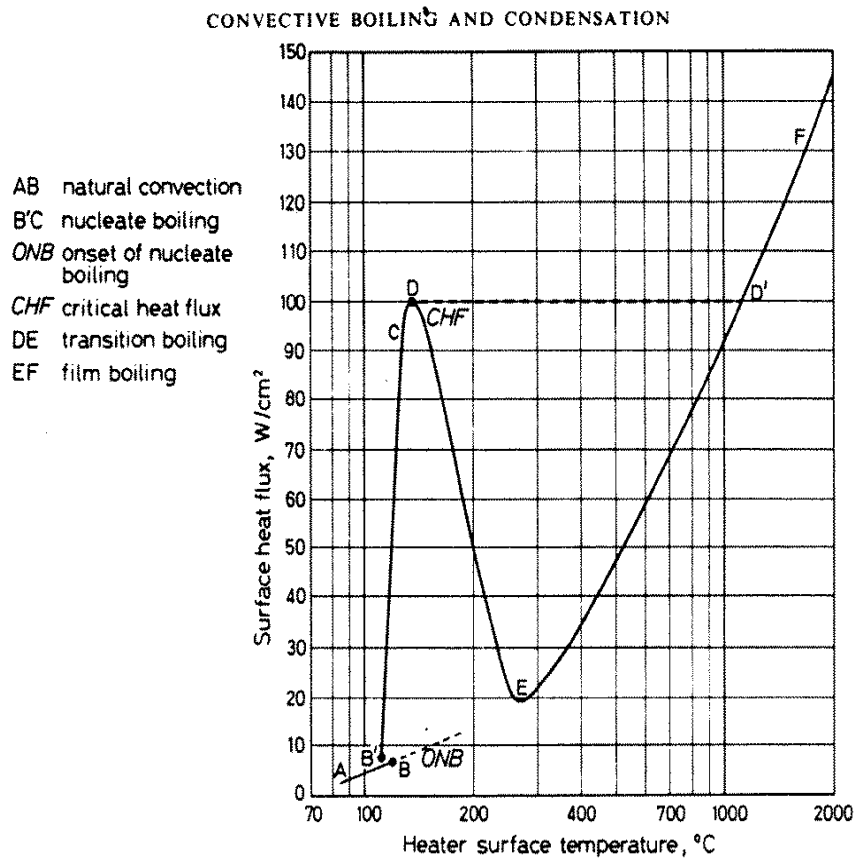


Figure 1: Pool boiling curve for water at atmospheric pressure (from Collier, pp. 122–123).

more bubbles are created per unit time. The bubbles induce a more violent motion of the surrounding liquid that further increases the heat transfer coefficient. This process only occurs up to a point that is labelled in the figure as the critical heat flux. At the critical point, the vapor forms patches and columns near the heater surface. Because of the differences in thermal properties of the two phases, the heat transfer rate to the vapor is considerably less than that to the liquid. Therefore, the vapor effectively insulates the surface. With increasing the surface temperature, the vapor covers more of the heating surface until a maximum value for the heat transfer rate is reached.

Beyond the critical heat flux two possibilities exist depending on the heating conditions. If the surface heat flux is controlled and increased beyond critical point, the surface temperature increases dramatically as shown by the dashed line from point D to D' in Figure 1. The temperature at D' is often higher than the maximum temperature that heater surface can maintain, and thus this heat flux is referred to as the burn out point. If the surface temperature is controlled and increased beyond the temperature at D' , the insulating effect continues and the heat transfer rate decreases. This regime called transition boiling is

characterized by the unstable vapor blanket that covers the surface. The vapor blanket collapses periodically and allows the fluid to contact the surface. This periodic motion results in large variations in surface temperature and a highly unstable flow.

At large temperature differences, greater than 250° for water at atmospheric pressure, the vapor film completely blankets the heated surface. Vapor bubbles are released regularly from the surface and the film is considered stable. Increasing the surface temperature results in a corresponding increase in heat transfer. However, due to the large temperature difference the transport is generally governed by radiative transfer and not by the fluid motion.

2 Experiment

The experiments consist of qualitative and quantitative observations of boiling from solid spheres initially at room temperature and suddenly immersed in liquid nitrogen. Four different spheres will be used: two of copper with 2.903- and 2.477-inch diameters, one bronze with a 2.5-inch diameter and one mild steel with an 1-inch diameter. Each sphere contains two thermocouples that are flush mounted to the surface (see the attached handout for a discussion of thermocouple thermometry). To measure directly the temperature difference between the sphere surface and the liquid nitrogen the surface thermocouples are connected to another thermocouple that measures the liquid nitrogen temperature. Note that the boiling point of liquid nitrogen at atmospheric pressure is $-195.8^\circ\text{C} = 77.2\text{ K}$.

The voltage from the thermocouples is amplified and measured by the data acquisition system at a sampling rate of 2.0 Hz. The data acquisition program converts the thermocouple voltage, v_t , into the temperature difference using the following formula,

$$T_{sphere} - T_{LN_2} = 0.028 + 44.24v_t - 1.67v_t^2$$

The program calculates the time rate of change of the temperature difference and graphs the temperature and the rate of change of temperature as a function of immersion time.

Before beginning the experiments, the glass dewar must be filled with liquid nitrogen. Use caution in filling the dewar and do **not** touch the liquid nitrogen, the fill tube or any iced parts of the tank nozzle. After the dewar is filled, the cover must be placed over the dewar before the sphere is attached to the support hook. Then connect the thermocouple wires (make sure the connections are done correctly) and lower the sphere into the liquid nitrogen while starting the data acquisition program. Make sure that the reference thermocouples are fully immersed in the liquid nitrogen.

To run the data acquisition system, turn on the computer and the data acquisition components. Use the mouse to select the heat transfer file and hit the mouse twice to start the program. Following the immersion of the sphere, quickly type the character "B" to begin the data sampling. The program will

plot the difference in the liquid nitrogen and sphere temperature and the time rate of change of these temperatures as functions of immersion time. After the sphere surface reaches the liquid nitrogen temperature, the program can be stopped by typing “S.” Then exit the program and rename the data files before beginning the next run.

Besides acquiring the temperature-time response of the sphere record the flow characteristic of the boiling liquid nitrogen. The distinct characteristics of the boiling curve should be visible and these observation included with the discussion of the heat transfer measurements. The observed flow patterns should be recorded in your lab report.

After the sphere has reached the liquid nitrogen temperature, the sphere can be removed from the dewar. Replace the cover over the dewar and do not touch the sphere. The subsequent warm-up process is interesting to monitor. The water vapor in the room, first condenses and then freezes to the surface forming an ice layer around the sphere. Since the natural convective heat transfer from the room to the sphere (even with condensation and freezing) is much lower than for boiling, the warm-up period is much slower than the cooling process. The warm-up time can be increased by immersing the sphere in a bath of water. This can be done by using the hook to remove the sphere and carefully lowering the sphere into the sink filled with water. The amount of ice formed can be measured using the balance.

3 Analysis

The boiling curve for these experiments can be determined by calculating the heat transfer rate from the sphere to the liquid nitrogen. The unsteady energy equation for the sphere is

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 k \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin^2 \Psi} \frac{\partial}{\partial \phi} \left(k \frac{\partial T}{\partial \phi} \right) + \frac{1}{r^2 \sin \Psi} \left(k \sin \Psi \frac{\partial T}{\partial \Psi} \right) \quad (1)$$

where T is the temperature, t the time, k the thermal conductivity, r the radial coordinate, ϕ the azimuthal angle and Ψ the circumferential angle. The boundary condition at the sphere surface is

$$h [T(t, r = a, \phi, \Psi) - T_b] = -k \left. \frac{\partial T}{\partial r} \right|_{r=a} \quad (2)$$

where h is the local heat transfer coefficient, a the radius, and T_b the temperature of the bulk of the fluid. The initial condition for the sphere is

$$T(t = 0, r, \phi, \Psi) = T_i \quad (3)$$

where T_i is the initial sphere temperature. It is anticipated that the temperature in the circumferential direction will not vary. However, the temperature will not be constant in the radial and azimuthal directions. Therefore, the heat transfer rate must be calculated by solving the inverse heat transfer problem as done by Irving and Westwater (1986). This involves solving Equation (1) by assuming

a heat flux at the surface, solving for the temperature distribution and then iterating until the solution converges. This process is beyond the scope of the lab; therefore, certain assumptions will be made to estimate the heat transfer rates and the boiling curve.

First the temperature distribution is assumed to be independent of azimuthal angle. Secondly, for small Biot numbers ($Bi = hr_0/(3k) \ll 1$) the sphere can be treated as a lumped system so that the temperature is also independent of radial distance. With these assumptions the energy equation is rewritten to include the heat transfer from the surface,

$$-\rho cV \frac{\partial T}{\partial t} = hA [T(r = a) - T_b] = q \quad (4)$$

where V is the volume of the sphere and A is the area. This equation can be used to determine the heat-transfer coefficient and the heat-transfer rate (or heat flux, $q'' = q/A$) and subsequently the boiling curves. Remember that the thermal properties are functions of temperature, but in Equation (4) we have assumed the properties are constant.

Predictions for the critical heat flux have been made based on stability analysis of the liquid-vapor interface. One analysis presented by Zuber (1958) and later re-examined by Lienhard and Dhir (1973) (see also Incropera & DeWitt, 1990) suggests that the critical heat flux can be predicted from the following relation

$$q'' = 0.118h_{fg}\rho_g^{1/2} [\sigma g(\rho_f - \rho_g)]^{1/4} \quad (5)$$

where h_{fg} is the latent heat of vaporization, ρ_f the liquid density, ρ_g the vapor density, g the gravitational constant, and σ the surface tension of the liquid.

The minimum in the boiling curve can also be predicted using a similar stability analysis. The analysis by Zuber, and by Lienhard and Dhir yield the following correlation for the minimum heat flux

$$q'' = 0.09\rho_g h'_{fg} \left[\frac{\sigma g(\rho_f - \rho_g)}{(\rho_f + \rho_g)^2} \right]^{1/4} \quad (6)$$

Since the vapor is superheated, h'_{fg} is a corrected latent heat to account for super-heating, $h'_{fg} = h_{fg} + c_{pg}(T_w - T_{sat})$ where c_{pg} is the specific heat of the vapor and $(T_w - T_g)$ is the temperature difference between the wall and the saturation temperature of the fluid.

The amount of liquid nitrogen that is evaporated due to the immersion of the sphere can be found by doing an integral heat and mass balance. By integrating the rate of heat transfer over time, one can find the total amount of energy transferred from the sphere to the liquid nitrogen. This energy evaporates the liquid nitrogen. Hence, the following equation can be written,

$$\int_0^\infty q dt = m_{N_2} h_{fg} \quad (7)$$

where m_{N_2} is the mass of nitrogen evaporated by and h_{fg} is the latent heat of the nitrogen (the latent heat is the energy per unit mass that is required to convert a saturated liquid to a saturated vapor at a given pressure). Note that

evaporation of the liquid nitrogen also results from heat transfer from the room and from the dewar.

From the following energy balance, it is possible to estimate the amount of ice formed when the cold sphere is immersed in the water bath,

$$\int_0^{t_f} q dt = - \int_0^{t_f} cm \frac{dT}{dt} dt = m_i (h_{se} + c_p + \Delta T) \quad (8)$$

The integral expression is the amount of heat absorbed by the sphere during the time from the immersion of the sphere to the time when the ice is formed. The right-hand side is the enthalpy change of the water, where m_i is the mass of ice formed, h_{se} is the heat of fusion, c_p is an average specific heat of the water, and ΔT is the temperature change of the water.

4 Laboratory Report

The report should contain the following results for two of the spheres (do not present the results for both copper spheres). The Results Section should include:

- temperature–time data
- a graph of the heat transfer rate, q , as a function of time
- a boiling curve in terms of q'' in W/cm^2 as a function of T in $^\circ\text{C}$. This figure should be qualitatively similar to Fig. 1; however, Fig. 1 is for water.
- comparison of your results for the critical heat flux and the minimum in the boiling curve with the results predicted by Equation (5) and (6)
- calculation and comparison of the total amount of nitrogen evaporated
- a discussion of which sphere should correspond best with the predicted results
- a description of the observed boiling process including a few sketches
- an estimate of the amount of ice formed and comparison with the measured amount

The discussion section should include (but not be limited to) the following:

- Is the small Biot number approximation appropriate for the experiments?
- Are there other assumptions that influence the results?
- How much affect do the variations in thermophysical properties have on the predictions for the critical and minimum heat flux?

Properties

- copper at 300 K: $\rho = 8900 \text{ kg/m}^3$, $c = 385 \text{ J/kg K}$, $k = 400 \text{ W/m K}$
- bronze at 300 K: $\rho = 8800 \text{ kg/m}^3$, $c = 420 \text{ J/kg K}$, $k = 52 \text{ W/m K}$
- steel at 300 K: $\rho = 7800 \text{ kg/m}^3$, $c = 440 \text{ J/kg K}$, $k = 40 \text{ W/m K}$
- nitrogen at 77 K: $h_{fg} = 199 \text{ kJ/kg}$, $\rho_f = 806 \text{ kg/m}^3$, $\sigma = 0.00893 \text{ N/m}$, $c_{pg} = 0.75 \text{ kJ/kg K}$, and $\rho_g = 4.66 \text{ kg/m}^3$
- water at 273 K: $h_{se} = 333 \text{ kJ/kg}$; $c_{pf} = 4.2 \text{ kJ/kg K}$

Note that the properties for nitrogen are a strong function of temperature.

5 References

1. Collier, J. G., 1981, *Convective Boiling and Condensation*, McGraw-Hill Co., New York.
2. Incropera, F. and DeWitt, D., 1990, *Fundamentals of Heat and Mass Transfer*, 3rd edition, John Wiley & Sons, New York.
3. Irving, M. E. and Westwater, J. W., 1986, "Limitations for Obtaining Boiling Curves by the Quenching Method with Spheres," *Heat Transfer*, 1986, Vol. 4, pp. 2061–2066.
4. Lienhard, J. H. and Dhir, V. K., 1973, "Extended Hydrodynamic Theory of the Peak and Minimum Pool Boiling Heat Fluxes," NASA-CR-2270. See J. H. Lienhard, *A Heat Transfer Textbook*, Prentice Hall, 1981.
5. Zuber, N., 1958, "On the Stability of Boiling Heat Transfer," *Trans. ASME*, Vol. 80, p. 711.

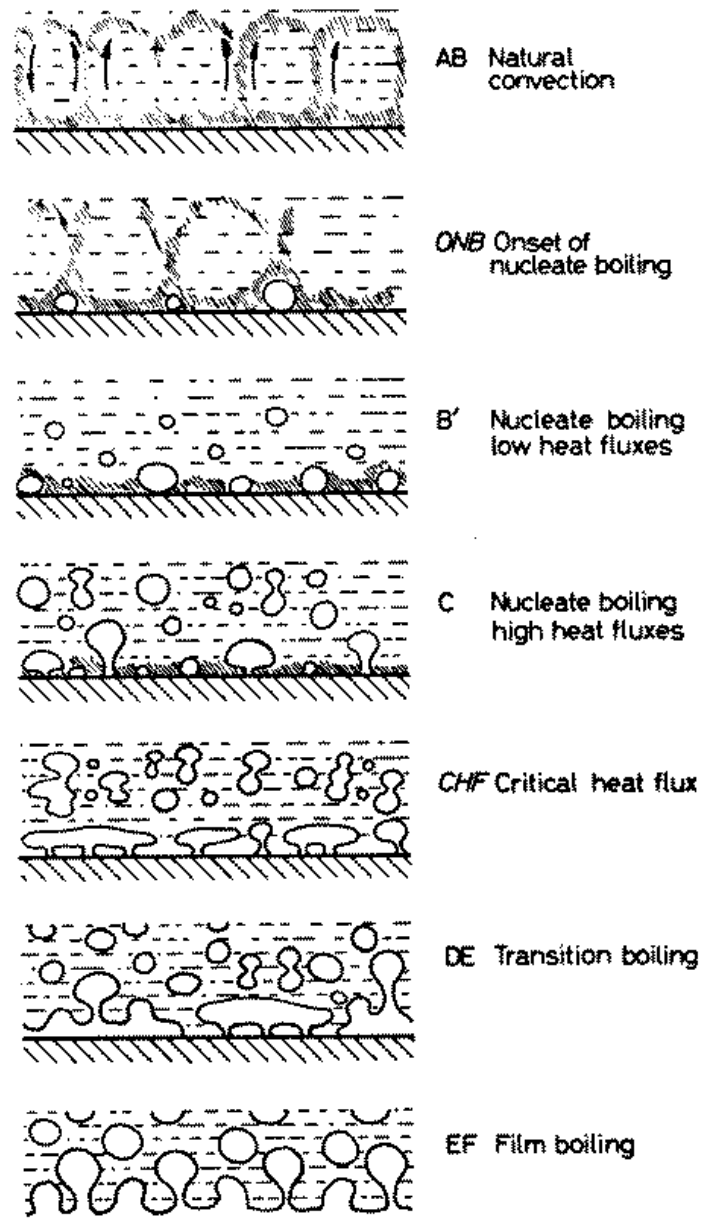


Figure 2: The various stages in the pool boiling curve.

Prelab

1. Calculate how much heat must be removed from copper per unit volume to bring it from room temperature to the boiling point of liquid nitrogen.
2. Explain how a thermocouple works.
3. Estimate the Biot number for a 10 cm diameter copper sphere in boiling *water*.
4. Consider the problem of a sphere initially at uniform temperature T_i that at time $t = 0$ is suddenly immersed in liquid at temperature T_b . Assume for simplicity that the heat transfer coefficient h is constant in time and uniform over the sphere. Solve numerically for the temperature distribution inside the sphere as a function of time using equations (1), (2), and (3). Note that T will be independent of (θ, ϕ) by symmetry, since neither the boundary nor the initial conditions depend on (θ, ϕ) . Equation (1) simplifies considerably in this case. Also, the boundary condition at the center of the sphere is

$$\left(\frac{\partial T}{\partial r}\right)_{r=0} = 0. \quad (9)$$

One way to solve this problem is to use MATLAB function `pdepe`, which is designed specifically for PDEs like this one. All you need to do is provide MATLAB functions that evaluate the various terms in the equation.

Another way to integrate equation (1) is to replace the derivatives by their finite-difference approximations, and solve the resulting system of linear equations in an Excel spreadsheet. For example, let the value in cell (m, n) represent the temperature at location $r = m\Delta r$ and $t = n\Delta t$. You can approximate the time derivative using:

$$\frac{\partial T}{\partial t} \approx \frac{T(m, n) - T(m, n - 1)}{\Delta t} \quad (10)$$

and the interior spatial derivatives using:

$$\frac{\partial T}{\partial r} \approx \frac{T(m + 1, n) - 2T(m, n) + T(m - 1, n)}{2\Delta r} \quad (11)$$

$$\frac{\partial^2 T}{\partial r^2} \approx \frac{T(m + 1, n) - 2T(m, n) + T(m - 1, n)}{\Delta r^2} \quad (12)$$

The result is a set of equations linking the value in each cell to the values in neighboring cells. Excel will iteratively update the cell values to try to satisfy all equations simultaneously, and will recompute them (and any plots that depend on them) automatically if you change parameters.

However you do it, explore the effect of changing the Biot number from large to small values. Make a plot or plots showing how the temperature evolves in time for Biot number much less than one, and for Biot number much larger than one.

To what extent do you think this analysis applies to this experiment?