A Boiling Heat Transfer Experiment for Senior Level Engineering Laboratory

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Abstract

This paper presents a simple experiment that can be executed in an undergraduate laboratory to observe the boiling curve including the transition and film boiling regimes. The base for this experiment was originally presented by Guido Lavalle *et al*. (*Am. J. Phys.* **60**, 593-597, 1992), and involves submerging an instrumented copper sphere into liquid nitrogen and measuring the evolution of the temperature of the sphere. Besides providing excellent visualization of the film, transition and nucleate boiling regimes, from the measurements the boiling curve can be obtained. Quantitative results and uncertainty analysis are presented for the critical heat flux and minimum heat flux. A paradox is presented when insulation is added to the sphere, since it can prevent the creation of a vapor film, maintaining the more efficient transition and nucleate boiling heat transfer regime and thus cooling the copper sphere faster than with no insulation. As expected, when the copper sphere is insulated further, heat transfer diminishes, offsetting the gains made by maintaining nucleate heat transfer. The experiment also evaluates temperature gradients inside the sphere and the validity of the assumption of uniform sphere temperature. This experiment is best suited for a senior level experimental class or as a part of a Heat Transfer course.

Keywords

Boiling heat transfer; boiling regimes; critical heat flux

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Introduction

Boiling heat transfer is characterized with an S-shaped curve relating heat flux to the temperature difference between the fluid and the heated surface [1], see Fig. 1. This curve, first obtained by Nukiyama [2] is called the boiling or Nukiyama curve. There are two ways to cover the boiling curve, controlling temperature or controlling power. Externally powered systems like electrical heaters or nuclear fuel rods deliver power fairly independently of the heat transfer mechanism, and thus increase or decrease the heat flux continuously. Heat exchangers, steam generators or quenching experiments are subject to a surface at constant temperature, and thus evolution of the boiling curve happens at constantly changing temperature. The boiling curve is divided into four regimes characterized by different physical heat transfer mechanisms. In natural convection (regime I), the temperature difference between the fluid and object is low and vapor formation does not occur, thus the transfer of heat between the surface and the liquid occurs by natural convection due to density variations with temperature, a fairly inefficient process. As the heat flux increases (for a system with power control) the surface temperature increases and a transition to nucleate boiling heat transfer (regime II) occurs when bubbles are formed for the first time, resulting in a sudden decrease in the surface temperature. This point is called the onset of nucleate boiling (ONB). Nucleate boiling is an extremely efficient heat transfer mechanism, based on convection/condensation processes at and near the heated surface, where bubbles form in nucleation sites, thereby the name. In a temperature controlled experiment the transition from natural convection to nucleate boiling will exhibit a sharp increase in heat flux. Higher heat fluxes result in more violent boiling but little increase in surface temperature until the critical heat flux (CHF) is reached. At this level of heat flux the vapor generation is too high to allow bubbles grow stably from the surface, resulting in the formation of vapor patches that effectively insulate the heated surface. In a constant temperature experiment the size and frequency with which vapor patches appear increases with the surface overheating, and consequently the heat flux decreases. This region is called transition boiling (regime III), in which both nucleate and film boiling (regime IV) coexist. The film boiling regime exists for surface temperatures high enough to maintain a stable film of vapor over the heated surface. Notice that a constant power experiment cannot experience transition boiling heat transfer, transitioning on increasing power from the CHF point to a much higher temperature point in the film boiling regime. In pressurized water this temperature can be several thousand degrees, resulting in burnout of the surface. Similarly, decreasing power from the film boiling regime results in a quick transition to nucleate boiling and a decrease on the heated surface temperature. The minimum temperature at which film boiling is stable is termed the minimum heat flux (MHF).

Experimental demonstration of the boiling curve and its boiling regimes can be complex and expensive. Direct measurement of the transition boiling regime can only be achieved through a temperature controlled heating surface, which is hard to achieve with the budget of an undergraduate lab. A typical experiment to demonstrate boiling heat transfer for undergraduate students [3] utilizes the Leidenfrost phenomenon [4]. In this case a brass plate is heated and its temperature is measured using a thermocouple. A few drops of deionized water are added to the brass plate and the behavior of the water is observed. Depending on the temperature of the brass plate, the water will exhibit different types of boiling and heat transfer will vary. This experiment will allow for visualization of the different boiling regimes and observation of the Leidenfrost paradox: a hotter plate takes longer to fully evaporate the drops than a colder one;

however, since the temperature of the water is not measured, the heat flux cannot be calculated and the boiling curve is not measured.

Most undergraduate heat transfer laboratories resort to repeat Nukiyama's experiment using a modern refrigerant fluid like FC-72 or HFE-7000, which will achieve film boiling at moderately low temperatures. Such experiments involve submerging a platinum wire in a liquid bath of refrigerant fluid kept at or below saturation temperature. The wire is then electrically heated and the average temperature of the wire is determined by calculating the resistance of the wire, which is related to temperature. The resistance is calculated through measurements of voltage and current of the wire. This setup allows measurement of natural convection, nucleate and film boiling regimes. Being a controlled voltage or current experiment, the transition region cannot be accessed and measured.

A very simple way to obtain the complete boiling curve is to perform quenching experiments of high thermal inertia objects, as done by Guido Lavalle *et al*. [5], who obtained the boiling curve from an experiment dropping a copper sphere into liquid nitrogen, recording the evolution of the temperature. In this work, the analysis is extended to include error estimation and obtain derived quantities, with the focus on quantitative analysis of educational value. The experiment described herein is adequate for senior engineering students who took an undergraduate course in heat transfer, and is part of the Mechanical Engineering senior level class Experimental Engineering at The University of Iowa.

Experimental setup

The experimental setup is shown in Fig. 1, and consists of a transparent double walled, high vacuum glass Dewar filled with liquid nitrogen. Though heat losses are much worse than those of an equivalent coated cryogenic vessel, the losses are still small for a short experiment and a transparent container has a greater educational value because it allows visualization of the experiment. A copper sphere with a diameter 28.89 mm ± 0.12 mm was used as a heat storage body. Two 1.58 mm stainless steel sheathed K-type thermocouples [6] were attached to the copper sphere, one in the center and one at the wall, to respectively monitor core and surface temperature. The thermocouples were inserted through holes drilled in the copper sphere and silver soldered in place to optimize heat contact. Masking tape was used to insulate the copper sphere in order to observe the effect of insulation on heat transfer. The tape was 19 mm wide with an operational temperature of up to 339 K [7]. A heat gun was used to heat up the sphere to temperatures above ambient before the start of each test. The temperatures were measured using an IOTech DaqBook 260 [8] controlled with the data acquisition software DasyLab 8.0 [9].

Experimental procedure

Since the weight of the sphere is hard to measure once the thermocouples are soldered in place, area, volume and mass are computed based on the average diameter. In order to determine the diameter of the body, the copper sphere was measured five times at different positions using a digital caliper, and the average of the five measurements was calculated. Uncertainty throughout the experiment was obtained using a 95% confidence level [10]. Temperature values were recorded every 97.66 ms for both thermocouples, using an acquisition frequency of 20480 Hz and averaging a block size set to 2000 points. This resulted in temperature readings with acceptably low noise.

The thermocouples were then calibrated using the two easily available reference points: the freezing point of water and the boiling point of nitrogen. The freezing point of water is related to the local pressure by

$$p \ = -395.2[\,(T_r/273.16)^9 - 1] \qquad (1)$$

The local pressure p in the lab was measured to be 0.103 MPa, resulting in water freezing temperature of 273.15 K. The room temperature T_r was measured to be 296.4 K. In order to calibrate the thermocouples to the freezing point of water, the copper sphere was lowered into an ice bath with over 95% ice concentration. Temperature readings were acquired until the temperatures read by both thermocouples were stable. The thermocouples were then heated to above 373 K using a heat gun in order to evaporate any water on them and lowered into a Dewar 60% full of saturated liquid nitrogen. The copper sphere was fully submerged and kept away from the sides of the Dewar until temperature readings stabilized at the boiling point of liquid nitrogen, assumed to be 77.4 K, the value at atmospheric pressure.

Using the reference temperatures a linear calibration of the form

$$T_{corr} = a\,T_{TC} + b \qquad (2)$$

was used for each thermocouple, where T_{TC} is the temperature measured by the thermocouple and T_{corr} is the corrected temperature.

Data was acquired for the bare copper sphere for eleven trials. The bare copper sphere was first heated with a heat gun to above 373 K and immediately lowered into the Dewar. Data was collected until the temperature readings of the thermocouples approached the saturation temperature of liquid nitrogen. The data was stored and later processed and analyzed off line.

The copper sphere was then insulated using one layer of regular masking tape. The masking tape was applied in a way such that tape overlap and the amount of air trapped under the tape were minimized. The insulated copper sphere was only heated to around 313 K in order to prevent the tape from burning. The copper sphere was then lowered into the Dewar and data was acquired until the temperature readings appeared to stabilize around the saturation point of liquid nitrogen. This procedure was repeated six times.

Data was also acquired for more than one layer of tape. The copper sphere was insulated with up to five layers of tape. The procedure for each layer of tape was the same as the procedure for one layer of tape. Six trials were completed for each case with more than one layer of tape, with the exception of the case of five layers where three trials were completed.

Uncertainty analysis

Uncertainty analysis was performed following the procedures outlined in the ANSI/ASME PTC 19.1 standard [10]. Elemental systematic errors were due to the digital caliper (Mitutoyo 500-160) resolution ($\pm 0.01\, mm$) and accuracy ($\pm 0.02\, mm$), and to resolution ($\pm 0.5\ \mu V$) and accuracy ($\pm 76.3\ \mu V$) of the thermocouple data acquisition system.

The uncertainty for a result R is defined as

$$u_R = t_{\nu,95}\sqrt{b_R^2 + s_R^2} \tag{3}$$

with $b_R = \sqrt{\sum_{i=1}^{L}\left(\theta_i b_{\bar{x},i}\right)^2}$ and $s_R = \sqrt{\sum_{i=1}^{L}\left(\theta_i s_{\bar{x},i}\right)^2}$ the propagation of the L systematic and random errors $b_{\bar{x},i}$ and $s_{\bar{x},i}$, respectively. $\theta_i = \partial R/\partial x_i$ is the sensitivity of the result to a change in the variable x_i. In Eq. (3) $t_{\nu,95}$ is the Student's t distribution for 95% confidence for ν degrees of freedom, with ν obtained from the Welch-Satterthwaite formula [10]

$$\nu = \frac{\left[\sum_{i=1}^{L}\left(\theta_i s_{\bar{x},i}\right)^2 + \left(\theta_i b_{\bar{x},i}\right)^2\right]^2}{\sum_{i=1}^{L}\left(\theta_i s_{\bar{x},i}\right)^4/\nu_{si} + \sum_{i=1}^{L}\left(\theta_i b_{\bar{x},i}\right)^4/\nu_{bi}} \tag{4}$$

The uncertainty for the average (expected value) of each independent variable $\bar{x}$ is found as $b_{\bar{x}} = B_{\bar{x}}/2$ and $s_{\bar{x}} = s_x/\sqrt{N}$ for the systematic and random errors, respectively, where s_x is the standard deviation of N measurements, and $B_{\bar{x}}$ is the systematic error estimated at 95% confidence.

Experimental results

To obtain the heat flux from the measured time histories of temperature it was assumed that the temperature inside the copper sphere is uniform at all times, and that the heat stored by the thermocouples and masking paper is negligible. The second assumption is very realistic, since the thermocouples are small and therefore will not store significant amounts of heat, and the density of the masking paper is considerably smaller than the density of copper, thus has little heat storage capability. The validity of the first assumption can be tested by evaluating the temperature difference between the center and wall thermocouples. Since the temperature in the copper is assumed spatially uniform at all times and no other form of energy storage is considered, then

$$\rho V c \frac{dT}{dt} = -q"A \qquad (5)$$

where $V = \frac{4}{3}\pi r^3$ and $V = 4\pi r^2$ are the volume and surface area of the sphere, respectively, and ρ and c are the density and heat capacity of copper. While the density of copper ($\rho = 8933\, kg/m^3\ @\ 300K$) is fairly insensitive, the heat capacity of copper changes significantly with temperature, dropping from $397J/kgK\ @\ 400K$ to $252\, J/kgK\ @\ 100\, K$ [11]. A second order parabolic function was used to approximate the change of heat capacity with temperature. $\frac{dT}{dt}$ was obtained by taking the time derivative of the measured temperature, either at the wall or the center thermocouple, and it is then a function of the temperature. Using Eq. (5), the heat flux at the wall for each temperature can be obtained.

Bare sphere

Figure 2 shows the evolution of the temperature of the wall and center thermocouples of the bare copper sphere. It can be seen that the center temperature is always higher than the wall temperature, as expected since heat is transferred out of the sphere to the liquid nitrogen. The rate of temperature drop decreases until the sphere reaches a temperature of approximately 125K (the MHF point in Fig. 1), and then suddenly increases as the heat transfer mechanisms are transition and nucleate boiling. The difference between the center and wall thermocouples is shown in Fig. 3. Notice that the temperature difference drops from about 3K to 1.3K as the temperature decreases and the MHF point is reached. The temperature difference peaks at about 4K during CHF. Two sudden jumps in temperature difference between center and wall temperatures can be observed, one at the beginning of the transition boiling regime when local regions of high heat flux nucleate boiling develop, and once when CHF is reached.

Photos of the sphere under different temperatures and regimes are shown in Fig. 4. The corresponding high-speed movies can be found in [12]. In film boiling at high temperature the boiling process is violent but a film of vapor can be clearly seen attached to the copper sphere. When MHF point is reached, the layer of vapor is much thinner and the boiling process is very gentle. Beyond this point, as the temperature drops further, the evaporation rate is not high enough to maintain a stable layer of vapor and the transition boiling regime starts. The vapor film breaks first at the bottom of the sphere (see Fig. 4), causing transient coexistence of nucleate, characterized by small bubbles attached to the surface of the sphere, and film boiling.

The evaporation rate in nucleate boiling for this temperature of the sphere is too high, and a film is restored that then becomes instable because, as discussed before, the film boiling regime is not stable. The consequence is a pulsing of the vapor generation and transient switch between film and nucleate boiling at the bottom of the sphere. As the sphere cools nucleate boiling becomes stable and CHF is reached, with violent evaporation. Figure 4 also shows pure nucleate boiling at high and low heat flux, which exhibit clearly small bubbles in stable nucleation sites.

Using the ratio of volume to area as the characteristic length, the Biot number is defined as [11]

$$Bi = \frac{h\,r}{3\,k} \tag{6}$$

and relates the heat transfer to the fluid with the heat transfer inside the solid. Pure copper is an excellent heat conductor with a thermal conductivity $k = 482\,W/mK\ @\ 100K$ that drops to $k = 393\,W/mK\ @\ 400K$, and thus a parabolic function is used in Eq. (6) to account for this behavior. The heat transfer coefficient h can be computed from

$$h = \frac{q"}{(T_{wall-}T_{sat})} \tag{7}$$

where T_{sat} is the liquid nitrogen saturation temperature and $q"$ is obtained from Eq. (5). Figure 5 shows the heat transfer coefficient and Biot number as a function of the wall temperature for the same experimental data as Figs. 2 and 3. The heat transfer coefficient jumps two orders of magnitude from film boiling to nucleate boiling, and the Biot number essentially follows the same behavior. In Fig. 5 $Bi < 0.1$ for all conditions, which allows the use of the lumped capacitance model applied to derive Eq. (5) [11]. Furthermore, for all cases with insulation the condition $Bi < 0.1$ is also satisfied. However, as will be shown when the results for CHF are analyzed, errors are introduced by assuming that the temperature inside the sphere is uniform when in reality small gradients are observed.

The experimentally obtained boiling curve for the bare copper sphere computed using the wall temperature is shown in Fig. 6. At the beginning of the experiment the copper sphere overheating is approximately 300K and the heat transfer mechanism is film boiling. As the temperature decreases while in film boiling the heat flux decreases as do the fluctuations in heat flux as the boiling becomes less violent and the vapor film thickness more stable. This trend can clearly be observed in the visualization of the experiment. As transition boiling is approached the vapor films breaks and reestablishes periodically, creating zones in the lower part of the sphere with nucleate boiling and others with film boiling. These strong instabilities cause large fluctuations in the heat flux that complicate the determination of the exact occurrence of the MHF. The CHF occurs at $16.7\ W/cm^2$ and the nucleate boiling phase lasts a few seconds as the sphere cools down very efficiently.

Since the boiling curve is obtained using Eq. (5) with the time derivative of the temperature, the resulting CHF and MHF values depend on the location of the thermocouple. The temperature at which the CHF or MHF occur also depends on the location of the thermocouple. In the case of a sphere, the rate of change of the wall temperature will be faster than that of the center temperature, having direct contact with the cooled surface and experiencing the highest temperature gradient. Also of note is that in transient conduction in a solid the amplitude of the fluctuation decreases as the distance to the cooled boundary increases, and the decrease in amplitude is faster for faster transients [13, § 2.6]. It is for these reasons that the CHF obtained with the wall thermocouple is expected to be higher than that with the center thermocouple. The true heat flux will lie somewhere between those two values. For MHF the heat flux is 10 times smaller and the difference between center and wall temperatures is very small, so yielding similar results for heat flux.

Figure 7 shows the CHF values obtained with the wall and center temperatures. The measured CHF for the wall temperature is $q^{"}_{CHF} = 16.7 \pm 0.7\, W/cm^2$, while using the center temperature $q^{"}_{CHF} = 14.3 \pm 0.2\, W/cm^2$. This last number is close to the value of $13.8\, W/cm^2$ obtained by Guido Lavalle et al. [5], also using a center thermocouple. As shown in Fig. 7, scatter of the CHF for different repetitions was much higher for the wall thermocouple, and that reflects in the uncertainty of the measurement. The temperature at CHF was measured at $T_{CHF} = 85.3 \pm 0.5\, K$ and $T_{CHF} = 87.5 \pm 0.3\, K$ for the data processed with the wall and center temperatures, respectively.

In order to obtain MHF and the corresponding temperatures, smoothing was utilized to provide a consistent method of detecting the minimum of the heat flux in this highly unstable region of the curve. Smoothing was performed using a simple moving average with a fixed window width. The MHF experimental results using wall and center temperatures are shown in Fig. 8. The experimental results show that the MHF and its corresponding temperature are $q^{"}_{MHF} = 1.18 \pm 0.02\, W/cm^2$ at $T_{MHF} = 138.2 \pm 2.1\, K$ and $q^{"}_{MHF} = 1.17 \pm 0.02\, W/cm^2$ at $T_{MHF} = 138.9 \pm 1.8\, K$ for the wall and center thermocouples, respectively. These results show that the heat flux is very consistent, as expected since the heat flux is fairly constant as the sphere approaches the MHF point, but the temperature at which MHF is reached varies significantly, due to fluctuations in the temperature at which the first appearance of a nucleate boiling patch in transition boiling occurs.

Insulated sphere

An interesting paradox occurs when layers of insulation, in this case 3M paper masking tape, are added to the copper sphere. Adding one layer of tape results in a significant decrease of the total time for the sphere to cool down to liquid nitrogen saturation temperature respect to the tame it takes for a bare sphere. Figure 9 was produced by arbitrarily setting the initial time when the sphere is at $310\ K$ for different layers of insulation. The time it takes for the bare sphere is 190 s, decreases to 90 s for one layer of insulation and to 170 s for two layers of insulation, increasing to 260, 350 and 390 s for three, four and five layers of insulation.

From the results of the bare sphere using the center and the wall temperatures to compute the heat flux based on the lumped capacitance assumption, much higher errors can be expected in the computation of the heat flux if the sphere is insulated. The insulation, being a bad conductor, requires high temperature gradients to produce high heat fluxes, thus releasing large amounts of energy before the copper reacts. Note also that the wall thermocouple no longer measures the temperature at the wall (the exterior of the insulation), but the temperature of the copper surface. Notice also that the heat flux at the wall cannot be measured and thus the maximum heat flux measured to the sphere is not the CHF. However, the heat flux to the sphere can still be computed and, with some assumptions, some conclusions can be drawn.

The first assumption is that the process is in steady state, at first view an invalid assumption due to the transient nature of the experiment. However the experiment progresses slowly except for a strong initial transient where the insulation temperature at the wall cools down quickly to a temperature near the saturation temperature for liquid nitrogen. It can also be assumed that the heat capacity of the tape is negligible, a reasonable supposition since the mass of the copper sphere is much higher than that of the masking tape. Under these assumptions the heat flow $\dot{q}$ from the fluid to the wall, through the insulation, and into the sphere are equal,

$$\dot{q} = hA_w(T_{wall-}T_{sat}) \tag{8}$$

$$\dot{q} = k_{ins}\left(\frac{r_s}{A_s} - \frac{r_w}{A_w}\right)(T_{c-}T_{wall}) \tag{9}$$

$$\dot{q} = \rho V c \frac{dT_c}{dt} \tag{10}$$

where k_{ins} is the thermal conductivity of the insulation. So there are three equations and four unknowns: $\dot{q}$, k_{ins}, T_{wall} and h. $\dot{q}$ can be computed directly from Eq. (10), resulting in a heat flux shown in Fig. 10 for different layers of tape. With the exception of one layer of tape, all of the layers exhibit a similar trend with decreasing heat flux with temperature. In these cases the insulation is thick enough to maintain the surface of the insulation in nucleate boiling, and as the insulation gets thicker the heat flux decreases. When the copper ball is covered with only one layer of tape, heat flux rises before peaking at approximately 230 K of overheating. In this case the insulation is thin and at the beginning of the experiment the temperature of the insulation wall is high enough to maintain transition boiling, evidenced by the increasing heat flux as temperature decreases. As the sphere cools down it transitions to nucleate boiling and behaves as the cases with more insulation.

The heat transfer coefficient as a function of the wall temperature superheating T_{wall} was measured for the bare sphere and shown in Fig. 5. To obtain the wall temperature of the sphere insulated with one layer of tape, the boiling heat transfer coefficient h and the effective thermal conductivity of the insulation the following procedure can be followed:

a) Scale the heat flux for the insulated sphere with that of the bare sphere, so that the CHF of the bare sphere coincides with the maximum heat flux of the insulated sphere. This implies the assumption that the maximum heat flux measured with the insulated sphere is the critical heat flux,

b) find the wall temperature at which the heat flux in the bare sphere coincides with the heat flux of the insulated sphere,

c) solve for h Eq. (8) and

d) solve for k_{ins} Eq. (9).

The resulting wall temperature of the sphere insulated with one layer of tape is shown in Fig.11, while the boiling heat transfer coefficient and the effective thermal conductivity of the insulation are shown in Fig. 12. Notice that after an initial transient not shown in Fig. 11, the wall temperature is very low throughout the experiment. This effectively enables the system to operate in transition and nucleate boiling resulting in a much higher boiling heat transfer coefficient than in the case of the bare sphere, more than offsetting the increased resistance to heat flow provided by the insulation. The effective thermal conductivity increases throughout the experiment, with a much faster rate at the end. This probably is due to the presence of vapor within the masking tape at high temperatures that turns stable liquid as the temperature drops.

Conclusions

An experiment suitable to teach boiling heat transfer in a senior level undergraduate class has been presented. The experiment, consisting of immersing a copper sphere instrumented with thermocouples in liquid nitrogen, exhibits film, transition and nucleate boiling, and allows for easy visualization of the different boiling regimes. The minimum and critical heat flux points can be measured and the corresponding uncertainties evaluated. An analysis of the temperature gradients observed within the sphere and the validity of the lumped capacitance assumption is presented. The boiling heat transfer paradox presented by Guido-Lavalle et al. [5] is obtained by adding masking tape to the sphere as insulation, observing that the sphere cools faster when lightly insulated. An approximate analysis is then carried out showing that the addition of insulation allows for a higher boiling heat transfer coefficient by preventing the film boiling regime.

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Figure captions

Figure 1: The boiling curve.

Figure 1: Temperature as a function of time for a bare copper ball.

Figure 2: Temperature difference between the center thermocouple and the wall thermocouple as a function of time for a bare copper ball.

Figure 4: Images of the boiling sphere. High heat flux film boiling (top left), MHF (top center), transition boiling (top right), CHF (bottom left), high heat flux nucleate boiling (bottom center) and low heat flux nucleate boiling (bottom right).

Figure 5: Biot number and heat transfer coefficient as a function of temperature.

Figure 6: Heat flux as a function of superheating for a bare copper ball in liquid nitrogen.

Figure 7: Critical heat flux and corresponding temperature for a bare copper sphere.

Figure 8: Minimum heat flux and the corresponding temperature for a bare copper sphere.

Figure 9: Temperature as a result of time for a bare copper sphere (dash line) and with (a) one layer, (b) two layers, (c) three layers, (d) four layers and (e) five layers of tape.

Figure 10: Heat flux versus the temperature difference between the center thermocouple and the liquid nitrogen for the copper sphere insulated with (a) one layer, (b) two layers, (c) three layers, (d) four layers, and (e) five layers of tape.

Figure 11: Wall temperature of the sphere insulated with one layer of tape.

Figure 12: Boiling heat transfer coefficient and the effective thermal conductivity of the insulation for one layer of tape.