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MCEN 5051-001

Image Video 2 Report

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This video is intended to create a dramatic representation of different boiling regimes. Using an electrical power dissipating wire submerged in water, nucleate boiling can be observed as individual steam bubbles form on the wire and then rise through the water. When increased power is dissipated by the wire the onset of film boiling can be observed. This steam film insulates the wire from the water-cooling effect, allowing the wire to reach a very high temperature and catastrophically fail.

To conduct the experiment, a 12V car battery was connected across Kanthal resistance wire. Three 26 gauge strands of the FeCrAl alloy wire were twisted together to increase the power dissipation. Lower gauge wire or higher voltage could have been employed for the same effect. To create the nucleate boiling shown in the first clip, 20 gauge copper wire was used to connect the battery to the Kanthal. This gave the entire setup a resistance of about 1.3 Ohms. In order to achieve the film boiling regime, more power needed to be dissipated. For this case the 20 gauge copper wire was replaced with 16 gauge copper wire. Instead of alligator clips to make the connection to the Kanthal the 16 gauge wire was twisted around it. This resulted in a 0.8 Ohm overall resistance, dissipating more power. A simple schematic of the circuit can be seen below in Figure 1. In both cases the resistance wire bundle was approximately 2” in length.

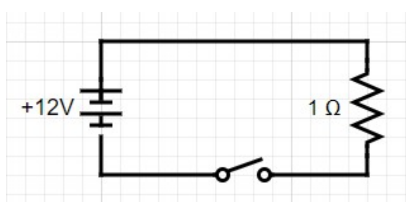

Figure 1. A circuit schematic depicting the Kanthal as a resistor connected to the voltage source. One of the battery terminals was able to be connected / disconnected as a switch.

In the case of the nucleate boiling, a rough approximation of the heat transfer coefficient may be determined, as well energy per bubble. The scale of this case can be noted in Figure 2 on the following page. Average bubble size in this figure corresponds to a diameter of about 0.015”. This bubble diameter results in a bubble volume of about $2*10^{-4}$ mL. Neglecting the minimal hydrostatic pressure related to water depth and any superheating, the steam can be assumed to have a density of 0.5 kg/m^3 and latent heat of vaporization of 2300 kJ/kg[1]. Given these figures, it can be assumed that each bubble takes approximately $3*10^{-4}$ Joules of energy to create.

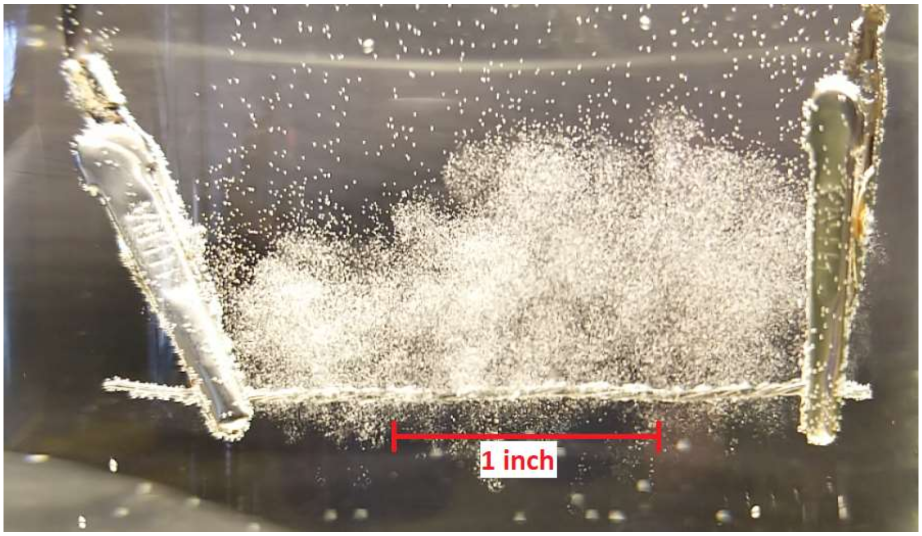

Figure 2. Approximate scale of the nucleate boiling phase.

More interestingly, the experimental heat transfer coefficient can be estimated and analyzed. Given 10 Amps of current being dissipated by the ~0.5 Ohm Kanthal, 50 Watts can be expected to be dissipated. Modeling the Kanthal as a 1.6 mm diameter, 30 mm long cylinder it can be assumed to have a surface area of 150 mm^2. The ratio of the power over the surface area gives a heat flux of about 300,000 W/m^2. This agrees with Theodore Bergman's text, claiming that the heat flux for nucleate boiling ranges from 10^4 to 10^6 W/m^2 in water at 1 Bar. This corresponds to a temperature difference between the water and the wire of about 10 degrees C.[2] The heat transfer coefficient is the ratio of the heat flux over this excess temperature, or 30,000 W/m^2-K. This point is marked in red on a figure from E.A. Farber's paper seen below in Figure 3.[3]

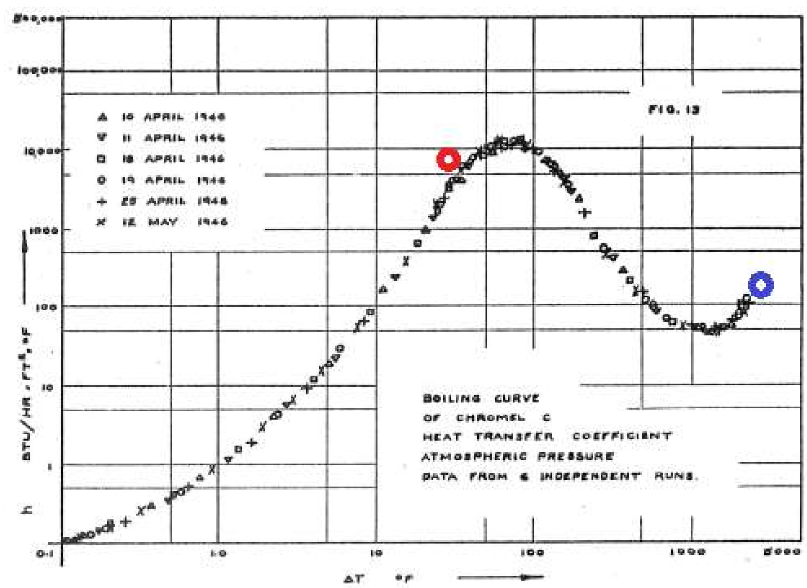

Figure 3. A figure from E.A. Farber's publication[3] showing his experimental boiling curve for water. A red and blue point have been added to demonstrate the approximate regions for the first and second video clips, respectively.

A very similar calculation can be conducted for the film boiling video. In this case, 15 Amps flows through a wire of similar physical size. 110 Watts being dissipated results in a heat flux of about 700,000 W/m^2. Bergman's text correlates this with an excess temperature of about 1000 degrees C.[2] The resulting heat transfer coefficient in the film boiling case is a much lower 700 W/m^2-K. This point is marked with a blue dot on Figure 3 above. The experimental approximations line up quite closely with the results found by Farber[3], and match well with the different boiling regimes on his boiling curve.

This demonstrates while the overall power dissipated by the wire increased by a factor of two in the film boiling clip, the effective heat transfer coefficient decreased by almost two orders of magnitude. This can be a very critical design consideration in multiphase liquid cooling applications.

Another very interesting phenomenon is the video's sound. In the second clip, an eerie woosh sound can be heard as the last bit of the boiling film begins to disappear. At the 1:06 minute mark the boiling film ceases to envelop the wire and the sound stops. M. F. M. Osborne discusses this phenomenon in a publication in the Journal of the Acoustical Society of America. He notes that heating wires submerged in subcooled or saturated water to induce boiling results in audible sound.[4] This sound intensity varies with the heat flux and subsequently the boiling regime of the fluid. Osborne was able to determine that sound intensity increased substantially in the transition between nucleate and film boiling regimes.[4] This sound emission variation seems to match well with the video with the acoustic volume being reduced dramatically upon the outset of the film boiling regime. This outset of the boiling film can be seen below in Figure 4.

Figure 4. The length of the film boiling regime underlined in red on the cooling wire.

While no particular flow visualization technique was used, the boiling was very well lit. A 19 Watt, 1600 lumen LED lightbulb was placed directly above the liquid. This light was placed approximately 8" away in a trouble light housing. A reasonable amount of natural and indoor light was present as well.

The videos were recorded on a Samsung Galaxy Note 8 cell phone at 240 frames per second with 1280 x 720 resolution. The lens has a 77-degree field of view and an F stop of 1.7. In slow motion mode the camera automatically selects the shutter speed and ISO setting. These settings are unavailable for viewing. The camera was approximately 6” away from the flow.

The first segment showing the nucleate boiling is played back at 1/8 speed. The second segment showing the film boiling is adjusted to be played at 1/10 speed. The audio from the final video was stripped, boosted by 24 dB, and re-added to the video. This was to make the sound a bit more audible.

This image provides insight into different boiling regimes in water. By being able to observe the nucleation of bubbles, and then the boiling film itself, the difference is rather apparent. One of the strengths of the video is that it shows a very nice periodicity of the initial film boiling and captures a rather dramatic situation. Further developing a method to achieve a more neutral background may clean up the scene and create a more powerful video. Less overhead light in the film boiling clip may have resulted in the red-hot wire appearing to glow more brightly, creating a more dramatic image as well. To best develop this idea further, a variable power supply could be used to more easily control the amount of heat dissipated and more easily show various boiling regimes.

Works Cited

[1] – Engineering ToolBox, (2003). Properties of Saturated Steam – Pressure in Bar. [online] Available at: https://www.engineeringtoolbox.com/saturated-steam-properties-d_457.html [12 October. 2020].

[2] – Bergman, T. L., & Incropera, F. P. (2011). Boiling and Condensation. In Fundamentals of heat and mass transfer (pp. 654-666). Hoboken, NJ: Wiley.

[3] – Farber, E. A., & Scorah, R. L. (1951). Heat transfer to water boiling under pressure. University of Missouri.

[4] – Osborne, M. F. M., & Holland, F. H. (1947). The acoustical concomitants of cavitation and boiling, produced by a hot wire. I. The Journal of the Acoustical Society of America, 19(1), 13-20.