Characterization of Boiling Sound at Conditions Approaching Critical Heat Flux

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Characterization of Boiling Sound at Conditions Approaching Critical Heat Flux

by

Akshat Negi

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Mechanical Engineering

Thermal Analysis, Microfluidics, and Fuel Cell Lab
Department of Mechanical Engineering
Kate Gleason College of Engineering

ROCHESTER INSTITUTE OF TECHNOLOGY

Rochester, NY 14623

November 9, 2019
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Department of Mechanical Engineering
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Abstract

In industry, boiling heat transfer is extensively used to efficiently dissipate high heat fluxes from heated substrates. Such industrial applications of boiling include cooling of reactor cores in nuclear power plants, steam generation in industrial boilers, and cooling of high heat flux generating electronic equipment. The maximum heat flux dissipated during boiling is limited by critical heat flux (CHF). At CHF, due to very high bubble generation and coalescence rates, a stable insulating vapor film is formed on the heated surface that leads to very high surface temperatures in a short time. The sudden temperature overshoot causes thermal breakdown, and therefore CHF is disastrous in all industrial applications. Owing to limited visualization of the boiling surfaces and dependence on temperature monitoring only, boiling systems are run at relatively low heat fluxes, ~50% of CHF limit due to safety considerations. The study presented here is focused on developing a method for identifying and analyzing acoustic signatures in the nucleate boiling regimes and using acoustic mapping as a monitoring tool to detect impending CHF. Initially, the sound waves generated through bubble coalescence and bubble collapse during boiling are captured for the plain copper chip. It is observed that the boiling sound is dominant in the frequency range of 400-500 Hz, while additional amplitude peaks in the frequency range of 100-200 Hz are also observed at higher heat fluxes (>100 W/cm²). Further, it is observed that just before CHF, there is a sudden drop in amplitude in the frequency range of 400-500 Hz. A similar study was performed on two additional microporous surfaces and similar acoustic trends as that of the plain copper chip was observed for both the chips. Coupling these observations with high speed visualization, the study indicates that a continuous acoustic mapping during boiling can be used as a tool to predict the impending CHF in boiling systems.
Acknowledgement

I would like to sincerely thank Dr. Satish Kandlikar for giving me this great opportunity to work in the Thermal Analysis & Microfluidics laboratory and introducing me to the world of research. His continuous support and guidance helped me develop better understanding and liking for the subject. His confidence in my work always kept me motivated to work harder and deliver.

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I would like to thank my mentors Alyssa Recinella, Aniket Rishi and Aranya Chauhan without whom this work would not have been possible. Also a big thank you to all the other members of TAmFL lab for all the support and laughter.

Lastly I would like to thank my family for supporting my decisions and continuous encouragement. Thank you for all the sacrifices and guidance in helping me become a better person. I would also like to thank my friends, members of my weightlifting club for all the smiles. They helped me become a strong person.
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Abbreviations

CHF  Critical Heat Flux
HTC  Heat Transfer Coefficient
AE   Acoustic Emission
SPL  Sound Pressure Level
FFT  Fast Fourier Transform

Nomenclature

k    Polytrophic constant
f    Frequency, s⁻¹
$k_{cu}$ Thermal Conductivity, W m⁻¹ K⁻¹
$q''$ Heat Flux, W/m²
$\rho$ Liquid Density, kg m⁻³
$\sigma$ Surface Tension, N m⁻¹
$\omega$ Resonance Frequency, s⁻¹
1 Introduction

Increasing demand of technology has led to an evolution of innovative approaches, solutions and ideas. While there has been an increase in the use of electronic devices and demand for higher efficiency equipment, the cost has been increasing due to larger power consumption towards cooling of the devices. Firstly, more power is necessary for proper operation and secondly for the removal of heat dissipated by the device. Various approaches have been used to remove heat generated on these devices. Some approaches include enhanced single phase cooling such as elongation of fins on heated surface[1], fans for faster convection[2] or liquid/water cooling[3], while more recently, two phase cooling such as flow boiling and pool boiling have been exploited. Owing to the absorption of a large amount of latent heat, two phase cooling is one of the most effective techniques in terms of cost and applicability. However, it is very important to keep track of the limitations brought on by this cooling technology. To understand the basic mechanism involved in the process of boiling, a fundamental plot called the pool boiling curve is used. Figure 1 shows the typical pool boiling curve in which the heat flux is plotted on the y-axis and the wall superheat, which is the temperature difference between surface temperature and saturated temperature of the surrounding fluid is plotted on the x-axis. The pool boiling curve is divided into 4 distinct regimes; natural convection, nucleate boiling, transition boiling, and film boiling. The mechanism in each regime is explained in detail in the next section. The most important limiting factors of this process are the Critical Heat Flux (CHF) and the Heat Transfer Coefficient (HTC).
1.1 Basics of Pool Boiling Heat Transfer

1.1.1 Pool Boiling Curve:

Figure 1: Pool Boiling Curve, developed by Nukiyama[4]

1.1.2 Free Convection - Natural Convection Process
The pioneering work of Nukiyama[4] introduced different regions of the boiling curve plotted as heat flux versus wall superheat. Although it is conventional to plot the independent variable on the x-axis, the boiling curve used the independently controlled variable heat flux on the y-axis following Nukiyama’s representation of the boiling curve. Region 1 is free convection, at low superheats until point A; heat transfer takes place through natural convection and movement of liquid due to density changes. There are no bubbles in this region. When the temperature reaches point A, small vapor bubbles start to appear on the surface.

1.1.3 Nucleate Boiling
In region 2 of the curve at point A, onset of nucleate boiling (ONB) starts. Bubbles detach from the surface and rise in the bulk liquid providing space for liquid to take their place. The liquid motion causes an increase in the heat transfer coefficient. From point A to point B, bubble formation takes place at different nucleation sites. At point B, there is a transition from partial...
nucleate boiling to fully developed nucleate boiling as heat flux is increased. While heat flux continues to increase from point B to C, bubbles start to merge (coalesce) with bubbles on the neighboring nucleation sites. Large lumps of vapor columns form an insulating vapor film as point C is approached and prevent the wetting of the heater surface. This insulation of the surface causes the temperature of the surface to rise drastically and it can cause a meltdown or material degradation. This maximum limit of heat flux at point C is known as Critical Heat Flux (CHF) [2]. Various studies have been developed to predict this CHF. Zuber[5] developed a hydrodynamic prediction of CHF while Lienhard and wong[6] studied the effects of pressure and geometry on CHF. Kandlikar[7] also provides a theoretical model for CHF prediction.

1.1.4 Transition Boiling
The transition from nucleate boiling to film boiling occurs at point C in region 3, where vapor films start to form and cover the surface in the horizontal direction; this is due to a higher bubble generation rate than bubble detachment rate. This vapor column prevents the liquid from contacting the surface and the surface temperature may fluctuate rapidly. This region cannot be accessed with a heat flux-controlled power input. A constant temperature heat source is needed to traverse this region.

1.1.5 Film Boiling
In region 4, film boiling takes place causing the surface to be completely covered by a thin vapor film. Heat transfer now occurs mainly through conduction and radiation through the vapor film. The surface is nearly insulated from liquid columns by vapor film and the curve reaches point E, where burnout of surface can take place if the heat flux is not reduced. When the heat flux is reduced, a point is reached where the stable vapor film can no longer be sustained, and it collapses, reaching a minimum heat flux at point D.
1.2 Importance of acoustics during boiling:

With an increasing demand for efficient cooling without thermal runaway, CHF limitations have been pushed further after implementing various techniques such as changing surface geometries and shapes, and formation of various coatings using sintering and electrodeposition[8]. Even though many studies have focused on enhancing the heat fluxes using various modification techniques, the detection of the CHF condition is the most critical factor. During a boiling process, the CHF stage is achieved within a very short time duration on the order of milliseconds, and if this condition is not noticed, the surface temperature rises to a very high value such that it can melt down the system. Additionally, monitoring of the CHF can be very intricate for the systems with minimal or no visual access. Thus, the detection of the CHF condition is very important in order to avoid the destruction of the system. Current systems are mostly dependent on temperature data for identifying the CHF, however, the reliability is very low due to the random and rapid nature of CHF initiation points. Several studies [9] [10] have focused on studying the acoustic signatures which are emitted during boiling but many of these studies do not focus on characterizing the region close to the boiling crisis. Currently there are no acoustic criteria are available for detection of impending CHF. With new improved tools available for data analysis, a new approach is developed in this study to analyze acoustic emissions during boiling with focus on using the acoustic signals to indicate the approaching CHF condition.

1.3 Acoustic Properties: Basic terminologies in sound engineering

Many of the studies in the field of acoustics use similar terminology for acoustical analysis. Some of the basic terminology is discussed in the following section:

1.3.1 Frequency

The most relevant parameter of sound is frequency, which is measured in cycles per second or Hertz (Hz). In this study, we will focus on analyzing sound signatures at different frequencies with increasing heat flux. As we are dealing with a cluster of bubbles, the frequency spectrum will not
directly provide information about the shape of individual pulses but will instead be governed solely by the time distribution of the pulses and/or the time-amplitude distribution [11].

1.3.2 Sound Amplitude
Amplitude is the fluctuation or displacement of wave from its mean value with respect to time. In this study audio signal is recorded using a condenser microphone which converts the sound pressure signal into voltage (mV). Hence, the amplitude is represented in (mV).
2 Literature Review and Background

Literature Review and Background chapter is divided into four sections I) derivation of Minnaert equation, which provides the theoretical basis for sound generation from bubbles, II) acoustic emission by single bubbles, III) conditions favoring coalescence of bubbles and acoustic emissions after coalescence, and IV) acoustic emission in complete boiling systems, which can further be divided into two sub-sections: a) acoustic emission in subcooled boiling systems and b) acoustic emissions in saturated boiling systems.

2.1 Minnaert Equation
Minnaert’s [12] work laid the foundation for understanding the dynamic behavior of gas bubbles in a liquid. Minnaert after experimental observations stated that during the bubble formation in liquid, oscillations begin at the point of bubble formation. He derived [13] the resonant frequency of bubbles between 3 to 6 mm radius by comparing the potential energy at the minimum volume to the kinetic energy of the water molecules of density \( \rho \) at the equilibrium position. Leighton [14] studied the Minnaert frequency in detail after the comparison of ideal bubble oscillations with a spring-bob system. Bubble oscillation is considered to be a simple harmonic motion of low amplitude at natural frequency. Minnaert considered the mean radius of the bubble shown in Figure 2 to be \( R \) and \( \omega \) as resonance frequency.
Figure 2: Minnaert gas bubble

\[ K.E. = \int_{R}^{\infty} \frac{1}{2} (4\pi r^2 \rho dr) \dot{r}^2 \]  

(3)

Assuming incompressible liquid, so

\[ \frac{\dot{r}}{R} = \frac{R^2}{r^2} \]

\[ \dot{R} = R_0 \omega \]  

(4)

\[ E_{max} = \frac{1}{2} m_T (R_0 \omega)^2 \]  

(5)

\[ m_T = 4\pi R^3 \rho \]  

(6)

Here, \( m_T \) is known as the effective mass of the liquid. In the above equations, R – maximum bubble radius, m, E is the energy, J, and \( \omega \) is the angular frequency, rad-s\(^{-1}\).

Work done in compressing the bubble from R to R – R\(_o\) by pressure P\(_o\) from surrounding liquid is given by the following equation, where k is the polytrophic process and k is equal to \( \gamma \) for a reversible adiabatic process.

\[ W = 6\pi k P_o R R_o^2 \]  

(7)

On equating work done to kinetic energy, and angular frequency (\( \omega \)) to be \( 2\pi f \)
\[ 6\pi k P_o R R_o^2 = \frac{1}{2} m_T (R_o \omega)^2 \]  

(8)

\[ f = \frac{1}{2 \pi R} \sqrt{\frac{3 \gamma P_o}{\rho}} \]  

(9)

Minnaert expression shows that oscillating frequency and bubble radius are inversely proportional which was also backed by experimental observations. Minnaert also discussed the influence of bubble volume, formation velocity, and temperature of bulk liquid, gas type and liquid density on the frequency of the bubble. A decrease in sound frequency with increasing density was prominent. Vazquez et al [15], Husin and Mba [16] used the Minnaert equation to validate their experimental data. Devaud et al. [17] showed how Minnaert frequency can be derived by linearizing the Rayleigh-Plesset equation; this helps in considering capillarity and viscosity of an incompressible liquid into account.

2.2 Acoustic Emission in Single Bubble (Bubble Growth and Collapse)

\[ \text{Figure 3: Amplitude change during bubble pinch off [18]} \]
Czerski and Deane [18] [19] showed that sound is produced due to the collapse of the neck of air formed immediately after bubble pinch-off during bubble release from the nozzle as shown in Figure 3. This collapsing neck decreases the bubble volume which excites bubble oscillations. Surface energy resulting from surface tension is the driving force for collapsing the neck. In Figure 3(I) shows a bubble prior to neck rupture and Figure 3(II) shows a change in pressure amplitude immediately after neck rupture. Nikolovska et al.[20] measured the oscillating frequency from a chain of individual gas bubble generated from nozzle sizes of 2.5 mm and 1 mm. Recorded frequencies from the 2.5 mm nozzle were in the range of 670 Hz – 1310 Hz, and from 1 mm nozzle they were in the range of 840-2970 Hz. The reason for this wide frequency range is the number of bubbles generated per unit time. The peak frequency reduces with an increase in the number of bubbles.

2.3 Bubble Coalescence

Jiao et al. [21] studied different stages of bubble coalescence and factors affecting coalescence. Three main factors that affect coalescence are i) approach velocity of the bubbles, ii) force between the bubbles, and iii) fluid viscosity. They predicted the feasibility of coalescence by measuring Weber (W) number, as proposed by Postema and Jong[22]. The Weber number is given by:

*Figure 4: Bubble coalescence schematic*
\[ W = \frac{\rho U^2 R_{eq}}{\sigma} \]  

(10)

Where \( \rho \) is the liquid density, \( \sigma \) is surface tension, \( U \) is velocity of approach, and the equivalent radius \( R_{eq} \) is calculated by,

\[ \frac{2}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \]  

(11)

where \( R_1 \) and \( R_2 \) are the radii of two approaching bubbles. The bubbles will coalesce only if \( W < 0.18 \), otherwise the bubbles will rebound and will not coalesce. The whole process generally takes place in four steps as shown in Figure 4, with two bubbles approaching, followed by the formation of a thin liquid layer in between the two bubbles, drainage of the liquid layer, (Figure 4(iii)) and finally rupture of the liquid film leading to rapid coalescence of the bubbles.

Manasseh et al. [23] performed experiments to determine the sound generated during bubble coalescence and variation in resultant amplitude and frequency. Manasseh and Risso [24] observed a rise in sound pressure initially during coalescence. When liquid film between two bubbles starts to drain and the bubbles start to merge, the pressures inside the bubbles start to equalize during which bubble volume and shape remain frozen for a short time period. After this, volume oscillation starts causing sound emissions, which remain for a long time period. So, their experimental results suggest that this pressure equalizing mechanism in coalescing bubbles is the main driving factor for sound emission.

Kracht and Finch [25] showed by experimentation the variation in amplitude of the coalesced bubbles from those generated by the individual bubbles. Figure 5 shows coalescence at the nozzle instantaneously after the release of the first bubble. The resultant bubble has a higher amplitude of oscillation compared to the first bubble.
2.4 Acoustic emission in boiling systems

2.4.1 Acoustic emission in subcooled boiling systems

In pool boiling, the sound is generated due to bubble growth, oscillation during departure and bubble collapse. When the liquid is subcooled, bubble collapse is more dominant. Ponter and Haigh [27] tested sound pressure levels at different subcooled temperatures and recorded the change in sound intensities. Bubble size and bubble life changed due to subcooling and resulted in varying sound intensities at the same heat flux. They observed that the sound intensity increased with a reduction in water temperature under high pressure of 405 torr.

According to Osborne and Holland [28], the frequency distribution is dependent on the material and size of the boiling surface. For smaller wires, they observed that as the wire diameter decreases, the number of peaks in the frequency domain increases. But, for larger wires, the frequency of the peaks increased with heat input. Osborne[10] performed boiling experiments on a hot wire in subcooled water, and recorded multiple amplitude peaks in a closed setup. He found
that the amplitude increases in 3.5 – 7 kHz frequency domain with an increase in heat input. While for the open setup, peak frequency shifted towards high frequency around 10-20 kHz with increasing heat input.

Nishihara and Bessho[29] performed the experiments for subcooled nucleate boiling and observed a shift in peak frequency domain from 5 kHz to 3 kHz as heat flux increased. Sinha et al.[30] in their CHF detection feedback system, observed the gradual increase in amplitude without any significant change in the frequency domain (200–250 Hz) in the nucleate boiling region. A sudden rise in amplitude was observed by them after hitting the CHF followed by complete sound attenuation in film boiling. They observed a sudden shift in the frequency region (400–500 Hz) after hitting the CHF and the reason for the shift is said to be the change in bubble size from mushroom shape before the CHF to smaller bubbles post CHF. The high frequencies observed in the early part of the subcooled boiling at lower heat fluxes are the result of small nucleating bubbles collapsing after nucleation in the environment of subcooled liquid. The small bubble diameters give rise to large frequencies over several kHz. In the fully developed nucleate boiling, the bubbles do not collapse on the surface and the frequencies are shifted towards the lower frequency range, generally below 1 kHz.

Bode[31] using a reduced pressure system at 25kPa studied the pressure variation in liquid due to the bubble growth and collapse using a piezoelectric hydrophone and observed maxima and minima during bubble generation and collapse at 60 Hz.

Tang et al.[32] studied the acoustic emissions during subcooled pool boiling with an objective to correlate sound properties to different boiling domains. Figure 6 shows the shift of the amplitude spectrum from high frequency to low frequency. Initially, due to the subcooling of the liquid, bubble formation and collapse is rapid which generated an energy pulse that is dominant in high frequency around (5000 Hz). As the heat flux keeps increasing, and liquid temperature increases,
both smaller bubbles and larger coalesced bubbles are present on the surface, hence the amplitude spectrum is present in both low frequency and high frequency regions. In the third region, where the wall superheat is very high, the coalescence is completely dominant and small bubbles disappear, resulting in a complete shift of amplitude in low frequency region around 100 Hz.

Figure 6: Variation in bubble behavior, heat flux and amplitude spectrum with respect to changing wall super heat using a subcooled liquid[32]
Table 1: Frequency ranges in subcooled pool boiling

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Frequency range</th>
<th>Boiling Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tang[32]</td>
<td>(2017)</td>
<td>100 - 5000 Hz</td>
<td>Nucleate Boiling</td>
</tr>
<tr>
<td>Osborne and Holland[28]</td>
<td>(1947)</td>
<td>1 – 10 kHz</td>
<td>Complete process</td>
</tr>
<tr>
<td>Osborne[10]</td>
<td>(1947)</td>
<td>3.5 – 7 kHz</td>
<td>Complete process</td>
</tr>
<tr>
<td>Hideaki Nishihara[33]</td>
<td>(1977)</td>
<td>25 – 23 kHz</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td>Dunn Ohanian[34]</td>
<td>(1972)</td>
<td>25 – 50 kHz (1- 4 atm)</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td>Doney[35]</td>
<td>(1994)</td>
<td>Peaks between 1-2 kHz, 2-3 kHz, 4-5 kHz</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td>Shibahara[37]</td>
<td>(2018)</td>
<td>0 - 1000 Hz</td>
<td>Flow Boiling</td>
</tr>
</tbody>
</table>

Table 1 provides a summary of the relevant studies on acoustic studies in the subcooled boiling region. It can be observed from Table 1 that most of the acoustic studies performed with subcooled liquid have higher frequency domain which are indicative of the smaller bubble sizes. These bubbles tend to collapse and generate sound. The focus of the present work is saturated pool boiling which is discussed next.
2.4.2 Acoustic emissions in saturated boiling systems

Aoki and Welty [9] studied the sound generated during saturated boiling on the horizontal copper disk using pentane as the working fluid. The boiling sound was found to be increasing with heat flux, but a drop in sound level was observed near critical heat flux due to vapor layer formation over the surface. They observed the dominant frequencies in the 500 – 1000 Hz region.

Westwater [38] while working with methyl alcohol as the working fluid observed a continuous rise in sound pressure level in nucleate and transition boiling regions with increasing heat flux. Schwartz and Siler [39] used a hydrophone to capture the sound due to bubble dynamics and minimize the background noise during boiling. In their study, they found that the sound amplitude increases with an increase in heat flux in the nucleate boiling region and the sudden drop was observed during film boiling after CHF. The frequency spectrum for their study was in a low frequency domain from 25 Hz – 700 Hz.

Seo and Bang [40] quenched a stainless steel spherical sample in distilled water and the acoustic emissions during different boiling regimes – film boiling, transition boiling, and nucleate boiling - were recorded using a contact type pressure transducer. The temperature of the sphere was recorded at the center to monitor different boiling regimes. The center temperature continuously decreased due to boiling heat transfer at the surface. The amplitude of sound oscillations as captured by transducer increased from film boiling to transition boiling. This is due to bubble oscillations and coalescence during transition boiling as shown in Figure 7. Amplitude peaks were also observed in nucleate boiling as shown in Figure 8 due to continuous bubble nucleation on the sphere’s surface. Dominant frequency was observed in the range 0-150 kHz for all boiling regimes. This is indicative of bubble collapse on the heater surface. A black line after 580°C is shown to indicate that there are no peaks above that level (y-axis on the right). Since this level is quite low, it is concluded that the sound is negligibly weak in this region as compared to the lower frequency region below 580°C.
Lloveras et al.[41] performed quenching experiments and observed no peaks in the film boiling region. As specimen entered transition region, amplitude peaks start to appear due to bubble
formation, but these amplitude peaks decreased in nucleate boiling region as specimen temperature dropped quickly due to boiling heat transfer.

*Table 2: Frequency domain for studies using saturated liquid*

<table>
<thead>
<tr>
<th>Studies Using liquid at saturation temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Schwartz and Siller[39]</td>
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<td></td>
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<tr>
<td>Westwater[38]</td>
</tr>
<tr>
<td>Ravenik and Grum[42]</td>
</tr>
<tr>
<td>Seo et al.[40]</td>
</tr>
</tbody>
</table>

Table 2 shows some of the important works on acoustic detection in saturated boiling region. It is seen that the sound frequencies dominant in these studies are between 0-1000 Hz. Since we are interested in saturated boiling, our focus is in this frequency range. High frequency domains were only observed in quenching studies past the CHF condition and therefore are not considered here.
3 Objectives

During pool boiling the vapor bubbles nucleate from a heater surface and detach, rise, and burst after growing. During this process, the bubble bursting and liquid collision leads to energy release in the form of sound. It is hypothesized that at different heat fluxes, unique acoustic signatures will be generated and a change in boiling sound is expected near the CHF due to initiation of the vapor blanket on the heater surface. Thus, an acoustic mapping can be used as a detecting parameter to indicate the approaching critical heat flux (CHF). The study is focused on saturated pool boiling where the dominant frequencies are in 0-1000 Hz range. Also, as a detection tool, an external sound detection system is desirable. Hence an external microphone is used in the present study as opposed to a hydrophone inside the liquid. Further, the sound generated during the bubble coalescence process of air bubbles is obtained to correlate the bubble coalescence frequencies with the Minnaert equation which is applied in the boiling study. Based on this hypothesis, the objectives of the work are as follows:

1. Characterization of the sound generated during pool boiling
   - The acoustic parameters will be evaluated for different boiling regimes upto the CHF condition.
   - The acoustic trend on enhanced surfaces will also be evaluated and the trend will be compared with the plain copper surface.
   - An Analysis of acoustic parameters near critical heat flux (CHF) will be conducted to check whether an acoustic mapping can be used as a detection tool to predict the CHF in boiling systems.
2. Analysis of sound generated by coalesced air bubbles

- The comparison of sound signatures of air bubbles will be performed with boiling bubbles.
- The correlation between the experimental frequency and Minnaert frequency calculated from the bubble coalescence process will be studied.
4 Experimental Work

4.1 Pool Boiling Setup
Figure 9 shows a schematic of the pool boiling test setup. It consists of a water bath formed by a 14 mm × 14 mm × 38 mm quartz glass enclosure, a test chip, and a heater block. The test chip is placed in the ceramic chip holder with overlapping holes on both the block and the chip to facilitate insertion of the thermocouples. Rubber gasket is used to seal the contacting surfaces at the bottom and top of the quartz glass.

Four stainless steel screws hold the middle garolite plate with the bottom aluminum plate. A water reservoir is mounted between this middle garolite plate and top aluminum plate with the help of another two stainless steel head cap screws. The water reservoir is sealed with rubber gaskets on either side to prevent leakage. An auxiliary cartridge heater (60-VDC, 200W) of circular cross section is fitted on the top aluminum plate and a small hole is provided in the top plate to insert a thermocouple to measure the water bath temperature.

The bottom section consists of a copper heater block with four 120-VDC, 200 W capacity cartridge heaters and is placed on a ceramic block (following the setup described by Kalani and Kandlikar, [43]). A Grafoil (carbon fiber) sheet is placed between the heater and the test chip to minimize the air gap. The heater block is rested over the ceramic block to minimize heat losses and the ceramic block rests on another aluminum block which is supported by four compression springs. These springs provide the required degree of freedom to maintain contact between the chip and heater when there is thermal expansion during testing.
4.2 Test Section
Each test chip used in this study has a top surface area of 17 mm × 17 mm as shown in Figure 10 d). Only 10 mm × 10 mm area (shown in Figure 10 d)) of the test surface is exposed to the boiling liquid and the remaining region is covered with Kapton tape which act as insulation. An elongated 9 mm test section at the base of the test surface has three holes for inserting thermocouples. The three thermocouples are inserted, one in each hole for temperature measurement and for subsequent heat flux calculations.
Figure 10: Copper test surface showing a) 3D-View, b) Wireframe, c) Front View, and d) Top View

4.3 Data Acquisition
Temperature and sound data were required for analysis in this study. These were acquired using components discussed in the next sections. Figure 11 shows the schematic of an acoustic data acquisition system during pool boiling.
4.3.1 Temperature
As shown in Figure 11, a National Instruments data acquisition system cDAQ-9172 with NI-9211 module was used to record the temperature data from four thermocouples. Three thermocouples were inserted in the test chip and the recorded temperature data was used for heat flux and surface temperature calculations. Fourth thermocouple was inserted from top of the setup to measure the saturation temperature of the liquid. A LabVIEW VR was designed to display the temperature data from thermocouples and calculate the heat flux. These temperature curves are used to display the variation with respect to time and identification of Critical Heat Flux. For the test surfaces, (as shown in Fig. 12), thermocouple holes are 3 mm (Δx) apart and the distance of top thermocouple hole and the chip surface is 1.5 mm.
Figure 12: Schematic of data acquisition from test chip

Heat Flux is calculated using steady state ID conduction equation:

\[ q'' = -k_{Cu} \frac{dT}{dx} \]  \hspace{1cm} (12)

where, the temperature gradient dT/dx is calculated using the three-point backward Taylor’s series approximation:

\[ \frac{dT}{dx} = \frac{3T_1 - 4T_2 + T_3}{2\Delta x} \]  \hspace{1cm} (13)

T1, T2, and T3 are the temperatures corresponding to the top, middle and bottom thermocouples.

The boiling surface temperature Twall was obtained using eqn. (14) with the distance x1 between the surface and top thermocouple, which is equal to 1.5 mm.

\[ T_{wall} = T_1 - q'' \left( \frac{x_1}{k_{Cu}} \right) \]  \hspace{1cm} (14)
4.3.2 Acoustic Data Acquisition/Microphone setup

For this study, two Ecoopro EO-200 condenser microphones are used as shown in Figure 9. Their positions are kept fixed during the tests. The bottom microphone is placed 1 cm away from the test surface while the top microphone is placed 0.5 cm from the top water bath to ensure that there is no contact between the microphone and the experimental setup. These microphones are unidirectional cardioid microphones having sensitivity in 50-10000 Hz frequency range. It was observed that the distance from the water bath influenced only the amplitude while the signature pattern remained unaltered.

Water height in the water reservoir shown in Figure 9 is maintained 3 cm above the middle garolite plate throughout the experiment. The same water level is maintained in all the experiments and for all the test surfaces. The height and the distance of both the microphones are constant for all the tests. Once the microphones are placed at desired locations, the connections are made from microphones to Steinberg UR 44 audio interface in the microphone input jack. The Gain switch is turned on and the two pre-amp knobs are set at the markings shown in Figure 13. An audio interface is connected to the computer using a USB input and sound recordings are made in Audacity software at a sample rate of 44100 Hz. Since the sound recorded by both bottom and the top microphones were in the same frequency domain, the data from the top microphone is considered for all the tests since the sound output from this microphone was higher due to its proximity to the water bath in the region of the bubble burst. A preliminary evaluation of the water level indicated that the sound signatures were unaltered while the height was varied from 2 cm to 6 cm.
4.3.3 High Speed Visualization

High speed visualization is done using Photron FASTCAM 1024 PCI. High speed imaging at different stages of boiling was analyzed to understand bubble dynamics at different heat fluxes and its correlation to the generated sound. Although the camera is capable of recording at up to 100,000 fps, a frame rate of 1000 fps was found to be sufficient to capture the bubble sizes of interest from departure to coalescence. Also, variation in bubble formation patterns on different surfaces is recorded.
5 Uncertainty analysis

There are several sources of errors which occur while making measurements in an experiment and analysis of these measurement errors is known as uncertainty analysis. Uncertainty is mainly divided into two main components, bias error and precision error. Bias error is a systematic error which is related to system accuracy while precision error is the variation in measurement. Bias error can be determined by calculating the variation in calibration of the equipment and precision error is calculated using a statistical analysis of the data.

5.1 Uncertainty in Heat Flux

The standard expression to calculate uncertainties \( (U_p) \) is shown by Equation (15). Where \( p \) is any property dependent on independent variable \( \sigma \) over \( n \) variables. \( U_\sigma \) is the uncertainty associated to variable, \( \sigma \).

\[
U_p = \sqrt{n \sum_{i=1}^{n} \left( \frac{\partial p}{\partial \sigma_i} U_{\sigma_i} \right)^2} \tag{15}
\]

The heat flux was calculated by combining Equations (12) and (13). The final expression is shown by Equation (16)

\[
q^* = -k_{Cu} \left( \frac{3T_1 - 4T_2 + T_3}{2\Delta x} \right) \tag{16}
\]

Using Equations (15) and (16) the relative uncertainty associated with heat flux can be calculated as shown by Equation (17)

\[
U_{q^*} = \frac{q^*}{q^*} \sqrt{ \left( \frac{\partial q^*}{\partial k_{Cu}} U_{k_{Cu}} \right)^2 + \left( \frac{\partial q^*}{\partial \Delta x} U_{\Delta x} \right)^2 + \left( \frac{\partial q^*}{\partial T_1} U_{T_1} \right)^2 + \left( \frac{\partial q^*}{\partial T_2} U_{T_2} \right)^2 + \left( \frac{\partial q^*}{\partial T_3} U_{T_3} \right)^2} \tag{17}
\]

For further simplification of Equation (17), a variable \( \alpha \) is defined as shown in Equation (18)

\[
\alpha = 3T_1 - 4T_2 + T_3 \tag{18}
\]
The expressions of partial derivatives of variables in Equation (17) are derived using Equation (16) and are shown in Equations (19) – (23). The variable α was used to simplify the expressions.

\[
\frac{\partial q^*}{\partial k_{Cu}} = -\frac{\alpha}{2\Delta x} = \frac{q''}{k_{Cu}} \tag{19}
\]

\[
\frac{\partial q''}{\partial \Delta x} = k_{Cu} \frac{\alpha}{2\Delta x^2} = -\frac{q''}{\Delta x} \tag{20}
\]

\[
\frac{\partial q''}{\partial T_1} = -k_{Cu} \frac{3}{2\Delta x} = \frac{3q''}{\alpha} \tag{21}
\]

\[
\frac{\partial q''}{\partial T_2} = -k_{Cu} \frac{-4}{2\Delta x} = \frac{-4q''}{\alpha} \tag{22}
\]

\[
\frac{\partial q''}{\partial T_3} = -k_{Cu} \frac{1}{2\Delta x} = \frac{q''}{\alpha} \tag{23}
\]

Substituting the partial derivative terms in Equations (19) - (23) back in Equation (17), we obtain the following Equation (24)

\[
\frac{U_{q^*}}{q''} = \sqrt{\left(\frac{q''}{k_{Cu}} U_{k_{Cu}}\right)^2 + \left(-\frac{q''}{\Delta x} U_{\Delta x}\right)^2 + \left(\frac{3q''}{\alpha} U_{T_1}\right)^2 + \left(\frac{-4q''}{\alpha} U_{T_2}\right)^2 + \left(\frac{q''}{\alpha} U_{T_3}\right)^2} \tag{24}
\]

In Equation (24), by expanding the squared terms in the numerator and cancelling the \(q''^2\) terms, we obtain Equation (25)

\[
\frac{U_{q^*}}{q''} = \sqrt{\left(U_{k_{Cu}}\right)^2 + \left(U_{\Delta x}\right)^2 + \left(3U_{T_1}\right)^2 + \left(4U_{T_2}\right)^2 + \left(U_{T_3}\right)^2} \tag{25}
\]

### 5.2 Uncertainty in Wall Temperature

The fundamental expression to calculate the uncertainty associated to wall temperature \((T_s)\) is shown in Equation (26).
\[ U_{T_s} = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial T_s}{\partial \sigma_i} U_{\sigma_i} \right)^2 } \]  

(26)

The percentage uncertainty of \( T_s \) can be calculated by using Equations (26) and (14). The expression is shown by Equation (27)

\[
\frac{U_{T_s}}{T_s} = \sqrt{\left( \frac{\partial T_s}{\partial T_1} U_{T_1} \right)^2 + \left( \frac{\partial T_s}{\partial q} U_q \right)^2 + \left( \frac{\partial T_s}{\partial x_1} U_{x_1} \right)^2 + \left( \frac{\partial T_s}{\partial k_{Cu}} U_{k_{Cu}} \right)^2 \over T_s^2} 
\]

(27)

The partial derivative expressions of variables in Equation (27) are derived using Equation (14) and are shown in Equations (28) – (31).

\[
\frac{\partial T_s}{\partial T_1} = 1 - 0 = 1 
\]

(28)

\[
\frac{\partial T_s}{\partial q} = 0 - 1 \left( \frac{x_1}{k_{Cu}} \right) = - \left( \frac{x_1}{k_{Cu}} \right) 
\]

(29)

\[
\frac{\partial T_s}{\partial x_1} = - \left( \frac{q''}{k_{Cu}} \right) 
\]

(30)

\[
\frac{\partial T_s}{\partial k_{Cu}} = -q''x_1 
\]

(31)

Substituting the partial derivative terms from Equations (28) – (31) back in the Equation (27), we obtain Equation (32) as shown below.

\[
\frac{U_{T_s}}{T_s} = \sqrt{\left( U_{T_1} \right)^2 + \left( - \frac{x_1}{k_{Cu}} U_q \right)^2 + \left( - \frac{q''}{k_{Cu}} U_{x_1} \right)^2 + \left( -q''x_1 U_{k_{Cu}} \right)^2 \over T_s^2} 
\]

(32)

Now in Equation (32), by expanding the squared terms in the numerator, we obtain Equation (33)

\[
\frac{U_{T_s}}{T_s} = \sqrt{\frac{U_{T_1}^2}{T_s^2} + \frac{U_q^2}{k_{Cu}} \frac{x_1^2}{T_s^2} + \frac{U_{x_1}^2}{k_{Cu}} \frac{q''^2}{T_s^2} + \frac{U_{k_{Cu}}^2}{k_{Cu}^2} \frac{q''^2 x_1^2}{T_s^2} \over T_s^2} 
\]

(33)
**Biased Uncertainty**

The biased uncertainty for thermocouples was measured by calibrating the thermocouples in a hot cell. The temperature of hot cell was varied from 50°C to 250°C. For each steady state temperature, 80 data points were recorded for three thermocouples (T₁, T₂, and T₃). The true temperature value of the hot cell was known and the standard deviation for each thermocouple was calculated using the true value for all steady state conditions. Multiplying the average standard deviation value by two, the biased error was estimated for each thermocouple for 95% confidence interval.

The biased uncertainty for thermal conductivity was ±9 W/m·°C [44]. This value was provided by the material provider, ‘online metals’ for copper 110 stock which was used for machining test chips. Since the copper used was 99.99% pure, the biased uncertainty value depends on the impurities present in the material. The biased uncertainty for the distance between successive thermocouples (Δx) and the distance between the top thermocouple and the surface (x₁) was 0.1mm. This was based on the least count of the caliper used to measure the respective distances.

The absolute values and percentage of biased uncertainties for all the variables are shown in Table 3. The error associated with thermocouples (T₁, T₂, and T₃) is not constant, it varies depending on the actual temperature of the hot cell. Thus the actual uncertainties for temperatures are dependent on the actual temperatures recorded and hence are indicated as “varies” in Table 3.
### Table 3: Biased Uncertainty

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
<th>Biased Uncertainty (U_p)</th>
<th>% Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{Cu}$</td>
<td>391</td>
<td>W/m·°C</td>
<td>9.00</td>
<td>2%</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>3.00</td>
<td>Mm</td>
<td>0.1</td>
<td>3%</td>
</tr>
<tr>
<td>$x_1$</td>
<td>1.50</td>
<td>Mm</td>
<td>0.1</td>
<td>6%</td>
</tr>
<tr>
<td>$T_T$</td>
<td>Varies with temperature</td>
<td>°C</td>
<td>0.16</td>
<td>Varies with temperature</td>
</tr>
<tr>
<td>$T_M$</td>
<td>Varies with temperature</td>
<td>°C</td>
<td>0.40</td>
<td>Varies with temperature</td>
</tr>
<tr>
<td>$T_B$</td>
<td>Varies with temperature</td>
<td>°C</td>
<td>0.25</td>
<td>Varies with temperature</td>
</tr>
</tbody>
</table>

**Precision Uncertainty**

The precision uncertainty associated with the three thermocouples was calculated following a similar approach which was used for calculating biased uncertainty. Except, for using the true temperature value at a given heat flux, the mean temperature value of 80 data points at a particular heat flux was used for calculating the standard deviation. This method was adopted for all thermocouples for each heat flux value. Precision error in thermocouple after calibration and statistical calculation is found out to be ± 0.25 °C. The precision uncertainties for thermal
conductivity and distances ($\Delta x$ and $x_1$) was considered 0.1mm because these parameters do not change by varying heat flux during the experimental study.

**Total Uncertainty**

The total uncertainty ($U_y$) for all the parameters was calculated using biased and precision uncertainties, as shown in the following Equation (34). Where, $P_y$ is the precision error or random uncertainty and $B_y$ is the bias error or systematic uncertainty in the system.

$$U_y = \sqrt{B_y^2 + P_y^2} \quad (34)$$

The uncertainties are calculated at different heat fluxes from the above equations and are plotted as a function of heat flux in Figure 14.

![Figure 14: Uncertainty in heat flux for Plain copper chip](image-url)
It is observed from Figure 14 that uncertainty decreases with increasing heat flux. Uncertainty at higher heat fluxes (above 70 W/cm²) is observed to be less than 5% for this study. This is in the same range as reported in previous studies[44] [45].

5.3 Determination of Uncertainty in Frequency Measurement

Frequency is an important parameter in the characterization of sound during boiling. An analysis is performed to determine uncertainty associated with the frequency measurement. A condenser microphone was used to record the sound during boiling and air bubbles study. The output from the microphone was recorded and processed using the Audacity software. The same setup of the microphone was used in the boiling and air bubble sound measurements.

The procedure for determining the uncertainty in the frequency measurement is described in this section. A sound of desired frequency was generated in Sonic application developed by Von Bruno for iPhone. The accuracy of sound frequency generated by the app is not given by the manufacturer in their specification, however, the manufacturer claims to have better frequency accuracy over other brands. In the current work, the set frequency is taken as a set value. In the future, accurate calibration of the sound source is recommended. This sound was recorded in Audacity software which is also used for recording the boiling sound and air bubbles sound. For each frequency, five tracks of 10 seconds each are recorded. Frequency domain plots for each track are generated in the MATLAB using the code provided in Appendix 2. The generated frequency is considered as the true frequency value. The desired frequency was generated in the range of 150 Hz – 600 Hz. This range was selected based on the frequency range recordings obtained during the pool boiling study at different heat fluxes. The exact frequency values generated were 150.0 Hz, 250.0 Hz, 403.0 Hz, 508.0 Hz, and 603.0 Hz. The frequency response in one sample for each true frequency is shown in Figure 15. Similar plots were obtained for four additional samples at each frequency. The
Dominant peaks for each sample shows the recorded frequency value for the respective true frequency values. The standard deviation for each frequency was calculated using the five recorded tracks and the corresponding percentage error was evaluated as twice the standard deviation. The recorded peak frequency values, standard deviation value, and percentage error for each of the generated frequency are shown in Table 4. The maximum percentage error was 3.97% at 150 Hz frequency. Errors at other frequencies were below 0.5%. Since the frequency plots used in the boiling studies are in the range 0-600 Hz, the uncertainty bars for frequency are smaller than the symbol sizes and hence they are not shown in the boiling plots.

Table 4: Percentage error for different frequencies

<table>
<thead>
<tr>
<th>Frequency (f) (Hz)</th>
<th>Recording 1 (f)</th>
<th>Recording 2 (f)</th>
<th>Recording 3 (f)</th>
<th>Recording 4 (f)</th>
<th>Recording 5 (f)</th>
<th>Standard Deviation (σ)</th>
<th>error = 2 * σ</th>
<th>Percent error</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>153.0</td>
<td>153.0</td>
<td>152.9</td>
<td>153.0</td>
<td>153.0</td>
<td>2.98</td>
<td>0.0397</td>
<td>3.97</td>
</tr>
<tr>
<td>250</td>
<td>250.5</td>
<td>250.5</td>
<td>250.5</td>
<td>250.5</td>
<td>250.5</td>
<td>0.50</td>
<td>0.0040</td>
<td>0.40</td>
</tr>
<tr>
<td>403</td>
<td>403.9</td>
<td>403.9</td>
<td>403.9</td>
<td>404</td>
<td>404</td>
<td>0.94</td>
<td>0.0047</td>
<td>0.47</td>
</tr>
<tr>
<td>508</td>
<td>508.1</td>
<td>508.2</td>
<td>508.1</td>
<td>508.1</td>
<td>508.3</td>
<td>0.18</td>
<td>0.0007</td>
<td>0.07</td>
</tr>
<tr>
<td>603</td>
<td>604.0</td>
<td>604.0</td>
<td>604.0</td>
<td>604.0</td>
<td>604.0</td>
<td>1</td>
<td>0.0033</td>
<td>0.33</td>
</tr>
</tbody>
</table>
5.3 Uncertainty in Acoustic Data

Precision uncertainty was calculated using a relative method as there is no true value for amplitude data. In this method, a soundtrack of 15 seconds is divided into three different sections of 5 seconds each. Amplitude data is converted from the time domain to the frequency domain for each section. These frequency domain plots are smoothened using a moving weighted average calculated as shown in Appendix 1. Now, each frequency will have three amplitude values and the standard deviation of these amplitude values from mean value is calculated as shown in Equation 35, where the value of $N$ is 3.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (a_i - \bar{a})^2}{N}}$$  \hspace{1cm} (35)
The variation in amplitude with respect to frequency for different heat fluxes is shown in Figure 16. Equations (35) and (36) were used to determine the uncertainty at specific frequencies. The maximum uncertainty was observed at 450 Hz for 116 W/cm². This maximum uncertainty value was less than 8 % with respect to the mean amplitude value. In this study, the bias error is not calculated as the error in frequency measurement of the microphone is not provided by the manufacturer and there is a limited access to the instruments.

\[ U_s = 2 \ast \sigma \]  

(36)

*Figure 16: Uncertainty in amplitude at the same heat flux value*
6 Acoustic Data Filtering

Since the experiments were conducted only in the saturated boiling region, the frequencies of interest were below 1000 Hz as discussed in Chapter 2 (Section 2.4.2). Constant background noise during experimentation causes hindrance in collecting clean and clear data. Various electronic items such as rectifier for input power, HVAC unit, computer fans, and light sources are actively in use during experimentation which generate noise. These noisy signals get mixed up with boiling acoustic signals and can cause a discrepancy in the analysis. So, to get a better output, this noise should be minimized or completely removed. Figure 17 shows the fft of ambient sound with only light sources and HVAC system running. Figure 18 (a) shows the frequency spectrum of background noise when all the equipment are running but boiling has not started yet.

![Frequency spectrum of ambient sound without turning on the power supply](image.png)
In this study, during post processing, the noise reduction tool available in Audacity is used. In this process, a section in the track is recognized where only the noise is present. A profile for this noise is generated and is reduced from the rest of the track. Figure 18 (b) shows the track after noise reduction. Considering the sound generation from light sources and HVAC, it was noted that these corresponded to a frequency range in the 0-60 Hz. Since these frequencies were generally below the frequencies of interest in boiling (100-1000 Hz), their effect was neglected. These observations were confirmed by comparing the background sound signature with no light sources on.

Noise reduction tool in Audacity uses Fourier analysis. When noise profile is recognized, a frequency band is provided to this noise and when it is applied to the whole signal, the algorithm compares the amplitude of this noise with the rest of the samples in the track and if the amplitude difference is high, the noise signal is eliminated from the complete signal. This noise gating works well in this study as static is steady and narrowly confined in frequency. Figure 19 (a) shows track before noise reduction and Figure 19 (b) shows track after noise reduction and reduction in amplitude of noise between the samples could be seen.
Figure 19: Amplitude time plots for a) Without noise reduction b) With noise reduction
7. Signal Processing in Matlab

7.1 Amplitude time plot generation
After performing noise cancellation in Audacity, tracks are converted to .WAV format to be extracted in MATLAB. In MATLAB, data is converted to two arrays of amplitude and time using the inbuilt ‘audioread’ MATLAB function. These arrays are plotted later in results section 8 for analysis.

7.2 Fast Fourier Transforms (FFT)
Fourier transform is an important algorithm to transform data from time domain to frequency domain[46]. Two major types of Fourier transforms are generally used, discrete Fourier transform (DFT) and Fast Fourier transform (FFT). FFT is used to compute large data sets at faster rate, therefore FFT was used in this study using MATLAB functions.

MATLAB Function in this analysis considers only magnitude and neglects the phase difference. Therefore, absolute values are represented in the FFT plots. This normalization helps to remap the values to smaller values and using this technique even the high frequency noise gets reduced. Also, it is easier to remove noise and unwanted signals in the frequency domain, therefore this method is preferred. Frequency domain analysis is required to determine further variations and identify the regions where maximum variation is occurring. This analysis is explained below for analyzing sound captured during boiling on the plain copper chip.
8 Results

Pool boiling tests were performed on a plain copper chip and a microporous chip. Initially, the test chip was mounted on the ceramic holder. Three thermocouples were inserted into the thermocouple holes in the test chip. The test setup was assembled, and the glass bath and the reservoir were filled with degassed distilled water. One microphone was placed at the marked point near the reservoir and other microphone was placed near the boiling surface. The auxiliary heater was turned on and the water bath is brought to saturation temperature. Now main power supply was turned on and setup at 20 V to provide a small value of heat input to the heaters. Thermocouple temperatures are monitored in LabVIEW and temperature and sound data was recorded on reaching steady state. Temperature data is recorded for 10 seconds and sound data is recorded for 15 seconds. After recording the data, the voltage in the power supply was increased further in small increments, generally around 5V. This process is repeated until the system reaches CHF. More sound data is recorded at smaller voltage increments at high heat fluxes and close to CHF.

In the results section, initially, data for the plain copper chip is presented which includes amplitude time analysis, identification of frequency domain, and cumulative power spectrum analysis. A similar analysis is then performed on the microporous chip and electrodeposited porous chip. Additionally, the sound generated by air bubbles at different flow rates is also analyzed to compare the sound signatures by air bubbles with the boiling bubbles.

8.1 Plain copper chip:

8.1.1 Amplitude time data analysis for plain copper surface

As mentioned in section 7, the recorded sound data was analyzed using a Matlab code. The data was recorded till the CHF condition was attained. Since the acoustic emission (AE) detection method is highly sensitive, in addition to boiling sound it captures the background noise and other
signals as well. Thus, it is very important to identify the correct signal for the sound analysis. Due to sensor limitation, it is very difficult to analyze the sound data below 30 W/cm² since the sample size is small and it becomes very difficult to distinguish between the boiling signal and the signal from the noise. AE signals from boiling become dominating beyond heat fluxes in the range of 30 to 40 W/cm². Figure 20(a-i) show the amplitude-time plots obtained during boiling on a plain copper chip at different heat fluxes.

![Amplitude time plots at different heat fluxes for plain Copper chip](image)

*Figure 20: a) - i) Amplitude time plots at different heat fluxes for plain Copper chip*

At low heat fluxes (Fig. 20a–b), it is observed that the peak height is smaller, and peaks appear after a longer time period. However, as the heat flux increases, there is a reduction in the time gap between consecutive signals. At higher heat fluxes, bubbles generate and collapse at a faster rate resulting in the generation of continuous acoustic waves. Also, with an increased rate of boiling, coalesced bubbles oscillate at higher amplitudes resulting in higher peaks. Figure 20(d-h) shows a
constant rise in amplitude peaks. At 116 W/cm² (fig 20h) peaks with the maximum amplitude are seen. A drop in amplitude at the next heat flux step, as shown in Figure 20 (i), is observed for a heat flux of 127 W/cm² which is just before CHF.

![Graphs showing amplitude variation](image)

*Figure 21: Amplitude of signals in 20 milliseconds at different heat fluxes for plain copper chip*

To have an in depth understanding of the sound generated by the bubbles, a small time period of 20 ms is considered from plots in Fig. 20 for analyzing the variations in sample size and amplitude. Four different heat fluxes (as shown in Fig. 21) were considered for the analysis. On analyzing a small section of the signal in a short time frame, it is clear that the sample size varies continuously at different heat fluxes. It is hypothesized that this variation in size is correlated with the change in bubble size and number of bubbles. At lower heat fluxes, owing to less coalescence, bubble size is small and hence samples have smaller amplitudes as in Fig. 21(a). At higher heat fluxes, bubbles have higher coalescence rate, hence the resultant amplitude of the sound produced increases. While, just before CHF (Fig. 21 (d)), due to excessive coalescence and coverage of the heater
surface with large vapor lumps, the resultant sound decreases, hence there is a decrease in amplitude of the signal.

![Graphs](image.png)

*Figure 22: a) Weighted average amplitude with respect to heat flux for plain copper chip b)*

*Boiling curve for plain copper chip*

The frequency range 400-500 Hz is seen to be of particular importance as it shows significant variation as the CHF is approached. Average sound amplitude value in the frequency range 400-500 Hz for each heat flux is calculated and plotted against the heat flux. Figure 22 (b) shows the boiling curve for a plain copper chip where heat flux is plotted against the wall superheat. The amplitude curve with respect to heat flux shows a constant rise of amplitude value for each heat flux (Fig. 22 a)). The error bars are also shown with the maximum 8% uncertainty as discussed in section 5.3. The uncertainty in temperature values was 0.2 C, which is within the width of the symbols shown in Figure 22(b). Increased heat input results in more and faster boiling on the surface. As heat flux increases more liquid converts to vapor, resulting in an increased number of bubbles from the surface and thus the sound amplitude. High speed images and their comparison with the increased amplitude is explained in the discussion section.
8.1.2 Frequency domain analysis of boiling on a plain Copper surface
To understand the dominant frequency region at various stages during the pool boiling, the sound amplitude intensity vs. frequency plots were generated after converting the amplitude-time plot using Fast Fourier Transform (FFT). After plotting the amplitude vs. frequency, it was observed that for all the tests, the sound was generated only in the frequency region between 0 to 600 Hz and no amplitude peaks were noted in the frequency range beyond 600 Hz till 10000 Hz. Figure 23 shows the sample amplitude vs frequency plot for the plain copper chip showing the frequency range from 0 Hz to 10000 Hz. It is clearly seen that there are no amplitude peaks beyond 600 Hz frequency. This confirms that the sound signature in saturated pool boiling is mainly in a frequency range below 1000 Hz.

Figure 23: Frequency spectrum for boiling dominant in 0-600 Hz region, no peaks in 600 – 10000Hz
Figure 24 (a-d) shows the amplitude vs. frequency plots for four different heat fluxes. These plots assist in comparing the bubble behavior with corresponding sound pressure levels and frequency distribution at different heat fluxes.

![Amplitude vs. Frequency Plots](image)

*Figure 24: Frequency domain of a plain copper chip at varying heat fluxes (CHF=130 W/cm²)*

Typically, at lower heat fluxes (around 30 W/cm²) peaks start to appear in the 400-500 Hz range. In this region, the acoustic emissions are primarily due to individual and smaller size bubbles. As heat flux is increased from 36 W/cm² to 71 W/cm², there is a gradual rise in sound amplitude intensity as observed in Figure 24 (b). From Fig. 24 (a) and 24 (b), it is observed that the increase in heat flux only leads to increment in amplitude without significant change in the frequency domain in the nucleate boiling region. A similar variation of amplitude intensity and frequency has also been observed by other researchers[39][38] [27].
With further increase in heat flux (at 116 W/cm²), acoustic emission (AE) variations start to appear in other frequency domains as well. During this stage, along with the increment of amplitude in the higher frequency region, the rise of peaks in the low frequency domain (100-200 Hz) is also observed (Fig. 24 c)). Due to continuous coalescence at these high heat fluxes, vapor lumps take the shape of vapor columns and the collapse of these columns causes sound which is dominant in the low frequency region. The time interval between the formations of these vapor columns is more, hence the sound produced by vapor columns is dominant in the lower frequency region.

At the heat flux of 127 W/cm² (just before CHF), when boiling is very close to the CHF condition, peak intensity in the higher frequency region (400-500 Hz) decreases. However, peaks in the lower frequency region are still consistent. This is believed to be due to the fact that the vapor columns are more consistent in this region which resulted in amplitude still dominating in the low frequency region. While owing to the development of the vapor layer over the entire heater surface, the decrease in sound intensity peaks in large frequency (400-450 Hz) region was observed (Fig. 24 (c) vs Fig. 24 (d)).

8.1.3 Cumulative power spectrum for plain Copper surface

The cumulative power spectrum is a statistical technique to understand or describe the variation in amplitude power in the frequency domain. Figure 25 shows the percent power of dominant frequencies at different heat fluxes for the plain copper chip.
Figure 25: Plot showing variation of percent power with respect to frequency for plain copper chip at different heat fluxes

It is believed that due to less coalescence of the bubbles at lower heat fluxes, the departure diameter of these bubbles is smaller, these smaller bubbles depart from the surface at the faster rate. Therefore, at low heat fluxes (36 W/cm²), the resultant frequency of these bubbles is higher. It can be seen in the figure that the cumulative amplitude of sound at this heat flux is small, as smaller bubbles have smaller oscillating amplitudes. But, as heat flux goes on increasing (from 36 W/cm² to 127 W/cm²), a large increment of cumulative power towards lower frequency region is seen from Figure 24.

There is an overall increment in the cumulative power amplitude of acoustic emissions at higher heat fluxes (111 W/cm² – 127 W/cm²), however, a more dominant increment is observed in the region of 100 - 400 Hz (marked with blue arrow). It can be said that the bubble size had increased at successive heat fluxes and this increased size of the vapor bubble is responsible for increased amplitude.
8.2 Microporous chip
After performing acoustic analysis on the plain copper chip, it was observed that the acoustic method can be used as an indication technique to detect the stage of pool boiling and the impending CHF condition. To examine whether this acoustic method can be used for the microporous surfaces and to compare the acoustic data obtained via plain copper chip, a similar testing with the same experimental setup was performed on the microporous chip. A sintering technique was used to develop a microporous coating on a plain copper chip using 5% graphene nanoplatelets (GNP)/Copper particle mixture. A similar test procedure as mentioned in Jaikumar et al. [47] was followed to develop a highly microporous coating on the heater surface. Powder to sintering oil weight ratio of 2:1 was used during the screen-printing of the GNP/Cu composite on the plain copper chip. The deposited coating was then sintered using a furnace at a sintering temperature of 800°C for 1 hr. An additional step at 450°C for 0.5 hours was added to evaporate the sintering oil and to develop a microporous coating. Finally, the Laser confocal microscope image of the sintered surface was captured to observe the morphological changes and to compare the morphology with the plain copper chip. Figure 26 shows the comparison of morphologies of the plain and microporous chips. From Fig.26 (b) it was observed that a large number of pores were achieved for the GNP/Cu composite coating.
8.2.1 Amplitude time data analysis for microporous surface
Porous surfaces typically perform better than the plain surfaces in pool boiling. So the increment in power input to reach high heat fluxes is higher as compared to plain surface. At high heat fluxes power input is slowly increased and more data points are recorded due to uncertainty of hitting CHF. Similar to the plain copper surface, the amplitude-time plot of boiling on a microporous chip at different heat fluxes was plotted. Porous surface gave enhanced performance and the CHF is delayed as compared to the plain copper surface.

Figure 27: Amplitude time series for boiling on microporous chip
From the plot shown in Figure 27, an amplitude change with respect to time is observed. At very low heat fluxes, below 30 W/cm², amplitude peaks start to appear. At this point, individual bubbles are formed at distinct nucleating sites and these bubbles depart at different time intervals. Also due to the dominant background noise at this heat flux, very few peaks are observed. Additionally, each nucleating site leads to the bubble formation of unique sizes. With an increase in heat flux, a similar trend of increment in amplitude and reduction in time gap between the two peaks was observed. Due to continuous boiling on multiple nucleating sites on the microporous surface, there is a drastic increment in sample size. At very high heat fluxes (190 W/cm² and 201 W/cm²), the high amplitude peaks are observed and the amplitude was observed to be much higher than the plain copper chip. A similar trend as that of the plain cooper chip of very high amplitude peaks at high heat flux (here at 190 W/cm², shown in Figure 27e), followed by decrease in amplitude just before a CHF of 201 W/cm², shown in Figure 27f, was observed for the microporous chip.

![Graphs showing amplitude change with respect to heat flux](image)

**Figure 28:** a) Weighted moving average sound intensity with respect to heat flux plot for microporous chip, b) Boiling curve for microporous surface

Similar to plain copper surface, Figure 28 shows rising amplitude with heat flux and drop in amplitude value near boiling crisis in case of a microporous surface. The porous surface gives an
enhanced performance and hence a very high CHF value was attained in this test as shown in Figure 28(b). Amplitude variation continued even at high heat flux values and only when vapor layer covers the surface and a drop in average amplitude value is recorded.

8.2.2 Frequency domain analysis of boiling on microporous chip

To understand the dominant frequency region during the boiling on the porous surface, the amplitude vs. frequency data was extracted. Variations similar to the plain copper chip are observed in power spectrum analysis where amplitude peaks are spread throughout the frequency range (200-400 Hz) at low heat fluxes around 40-68 W/cm². As heat flux keeps increasing, these peaks start getting concentrated around 300-500 Hz range (86-112 W/cm²). At heat fluxes after 134 W/cm², rise in amplitude in the low frequency region can be observed. The amplitude of these low frequency peaks continues to increase as heat input keeps increasing. At very high heat fluxes (190 W/cm²) we can see high intensity peaks which are produced at higher frequencies in the 400-500 Hz region.

It can be hypothesized that vapor column formation starts at high heat fluxes and is the reason for peaks in low frequency region. At high heat fluxes, the combination of fully-grown vapor bubbles and vapor columns produces sound, therefore, peaks are distributed throughout the frequency range. This means that bubbles which were formed on different nucleating sites have merged together and formed a larger bubble which later collapses and creates a sound which is sensed by the microphone. There is a sudden drop in peak power amplitude (201 W/cm²) as we are very close to CHF. It can be said that bubbles on different nucleating sites have merged over the surface and vapor layer formation over the surface has initiated and hence departure of large vapor bubbles is not consistent leading to a reduction in the amplitude of sound observed at this point.
Figure 29: Amplitude variation in frequency domain for the microporous chip (CHF = 204 W/cm²)
8.2.3 Cumulative power spectrum for microporous surface

The cumulative power spectrum for porous surface behaves differently than the plain copper surface due to different bubble dynamics as shown in Figure 30. Initially, due to multiple pores acting as nucleating sites, at low heat fluxes (20-30 W/cm²), growth and departure times of individual bubbles vary with respect to the size of the pores. Generally, bubbles have a very small diameter and the frequency of these bubbles is not sensed accurately by the sensor. As heat flux increases, bubbles start to merge together and depart as larger bubbles. These larger bubbles around 86 W/cm² have dominant frequency in 400-500 Hz. Coalescence of bubbles from multiple nucleating sites is not so rapid at lower heat input but as the heat flux keeps increasing, bubble coalescence rate increases and sound intensity increases throughout the frequency range. At 190 W/cm², a decrease in intensity in (200-300 Hz) frequency region and a sudden rise of sound intensity in (400-500 Hz) frequency region are observed which can be correlated to the frequency spectrum in Figure 28 where high amplitude peaks were observed in this frequency range.

Figure 30: Cumulative power spectrum in frequency domain of boiling on microporous chip
8.3 Comparison of acoustic signature trend of microporous chip with the plain copper chip:
To compare the acoustic signature trend of the plain copper chip and the microporous chip, the amplitude frequency curves shown in Fig. 24 and 29 were averaged and smoothened as shown in Appendix 1. These curves assist in providing a better understanding of dominant frequency region for nucleate boiling and variation in amplitude as heat input increases. Figure 31 shows the comparison of average amplitude vs. frequency plots for the plain copper chip and the microporous chip. To avoid clustering, the amplitude for just higher heat fluxes (~above 100 W/cm²) is plotted in this plot.

![Weighted average amplitude vs frequency plot showing the variation of amplitude at high heat fluxes for plain copper chip and microporous chip](image)

*Figure 31: Weighted average amplitude vs frequency plot showing the variation of amplitude at high heat fluxes for plain copper chip and microporous chip*

It is observed that both plain and microporous chips follow a similar trend of amplitude in both low (100-200 Hz) and high (400-500) frequency regions. When considering the change of amplitude in high frequency region (400-500 Hz), a constant rise in amplitude is observed for both...
the plain chip and the microporous chip. However, a sudden drop in amplitude is observed in high frequency region just before CHF in both the chips (Fig. 31). In case of amplitude variation in low frequency region (100-200 Hz), unlike high frequency region, a continuous rise in amplitude is observed. This shows that an enhanced chip also follows a similar acoustic trend as that of the plain copper chip.

The plots shown in Figure 32 show the frequency-amplitude plot for different heat fluxes. The enlarged inset shows the amplitude values at 450 Hz for the three heat fluxes with their respective error bars. It is clearly seen that the amplitude increases as the heat flux increases from 97 to 116 W/cm$^2$, while there is a drop as the heat flux further increases to 127 W/cm$^2$ at the dominant frequency of 450 Hz. It is noted that these variations are larger than the respective uncertainty bars shown Figure 32. Both plain cooper chip and microporous chip showed similar variations, as shown in Figures 32 and 33 respectively, in amplitude after accounting for the uncertainty.

Figure 32: Amplitude error analysis for plain copper surface at 450 Hz (the region of interest)
8.4 Additional experiments on different surfaces to analyze the acoustic trends generated by the boiling sound:

In addition to the microporous surface, in order to observe whether the similar acoustic trends as that of the plain copper chip are followed, boiling sound signatures were captured on a copper-graphene based electrodeposited chip. A similar experimental setup as for the previous test chips was used for capturing the boiling sound and the same test procedure was followed during the tests. The sound captured by microphones was then analyzed and different plots were generated to analyze the acoustic trends.

8.4.1 Electrodeposited porous chip:

Similar to previous chips, the sound amplitude intensity vs frequency plots were generated for electrodeposited porous chip after converting amplitude-time plot using Fast Fourier Transform (FFT). Figure 34 (a-d) shows the amplitude vs. frequency plots for four different heat fluxes. These plots provide a better representation of dominant frequency region and the corresponding sound amplitude at different heat fluxes.

Figure 33: Amplitude error analysis for microporous surface at 450 Hz (the region of interest)
Very distinctive peaks and acoustic signatures were observed during boiling on the electrodeposited porous chip. Plots of amplitude vs. frequency at different heat fluxes for the electrodeposited porous chip are shown in Fig. 34. Initially, at 64 W/cm², a small amplitude is observed in the frequency region of 400-500 Hz. With further increase in heat input, the peaks in low frequency region (100-200 Hz) start to appear along with the peaks in high frequency region (400-500 Hz). At a heat flux of 170 W/cm², the amplitude attains the highest values for both low and high frequency regions. However, as observed in previous chips, a sudden drop in amplitude is observed at a heat flux of 179 W/cm² in the high frequency region (400-500 Hz) and an increment in amplitude in low frequency region (100-200 Hz). This similar trend in all the surfaces can be very useful for a wide variety of heater surfaces and thus the acoustic mapping during boiling can be applied in various boiling systems. A CHF of 204 W/cm² was achieved for this chip.
Figure 34: Plot showing the amplitude variation in frequency domain for the electrodeposited porous chip at different heat fluxes (CHF = 204 W/cm²)

8.4.2 Comparison of acoustic signature trends of the electrodeposited porous chip with the plain copper chip:

To compare the acoustic signature trend of the electrodeposited porous chip with the plain copper chip, the weighted average amplitude frequency curves shown in Fig. 35 were plotted. These curves assist in providing a better understanding of the dominant frequency region for nucleate
boiling and variation in amplitude as heat input increases. Figure 35 shows the two different plots of amplitude vs frequency for plain copper chip and the electrodeposited porous chip.

After comparing these two plots, it is clearly seen that similar to plain copper chip, the electrodeposited porous chip followed a similar acoustic trend of amplitude rise in low (100-200 Hz) frequency region and amplitude reduction in high (400-500) frequency region just before the CHF condition.

![Weighted average amplitude vs frequency plot showing the variation of amplitude at different heat fluxes comparing plain copper chip with electrodeposited porous chip](image)

*Figure 35: Weighted average amplitude vs frequency plot showing the variation of amplitude at different heat fluxes comparing plain copper chip with electrodeposited porous chip*

When considering the change of amplitude in high frequency region (400-500 Hz), a constant rise in amplitude is observed for all the three chips considered in this study. However, a sudden drop in amplitude is observed in high frequency region just before CHF (Fig. 35). In case of amplitude variation in low frequency region (100-200 Hz), unlike in the high frequency region, a continuous rise in amplitude is observed. This data further assists in confirming that irrespective of the heater surface material and enhancement, the acoustic trend follows a similar pattern. This analysis is extremely valuable as this can be implemented in any boiling system with the heater surfaces of any substrate morphology. This trend of a sudden drop of amplitude in high frequency region (400-
500 Hz) and a continuous rise of amplitude in low frequency region (100-200 Hz) can be very vital in determining the approaching CHF condition and thus the acoustic signatures during pool boiling can be used as a tool to detect the CHF condition to avoid the melt down of the system and to enhance the operational range of the systems.

8.5 Analysis of sound generated by air bubbles:
To understand the sound generated by air bubbles and the effect of different flow patterns for different air flow rates on the dominant frequency region, a special test chip was designed. Specifically, the purpose of this study was to compare the dominant frequency regions of air bubbles with those of the boiling bubbles. Figure 36 shows the 3-dimensional view of the specially designed chip holder and the chip with holes for air injection. Three different holes were drilled from the side for the air injection and an array of 21 holes was drilled in the chip for the air outlet. A brass fitting was used to inject the air in the chip at various flow rates. The brass fitting was securely inserted in specially designed chip holder. The air was supplied from the air cylinder at ambient temperature of 25°C. This assembly was used in the pool boiling setup shown in Fig. 9. Air was injected at 4 different flow rates, 200 mL/min, 400 mL/min, 600 mL/min, and 800 mL/min. Similar to boiling sound capture, two microphones were used to capture the sound generated by the air bubbles and the amplitude frequency variation plot was plotted. The high-speed images were also captured to understand the effect of different air flow rates on air bubble coalescence and to calculate the bubble diameters.
Figure 36: 3-dimensional view showing the chip holder, chip with holes drilled for air supply, and miniature brass fitting

Figure 37 shows the comparison of dominant frequency regions and the corresponding amplitudes for various air flow rates. Initially, at a very low air flow rate of 200 mL/min, there is very less coalescence between the air bubbles and the dominant frequency in the range of 850-1000 Hz is observed with a very small amplitude. With increment in air flow rate to 400 mL/min, an increased coalescence of air bubbles is observed and in addition to the peaks in 850-1000 Hz range, peaks in the 400-700 Hz range also start appearing. With further increments in air flow rates, i.e., 600 mL/min and 800 mL/min, a large air bubble coalescence is noticed from the high speed images. Additionally, the increment in amplitude of the peaks is also observed owing to the sound generated by the coalesced air bubbles. Increased air flow rate results in amplitude peaks in two distinct dominant frequency ranges (300-450 Hz and 850-1000 Hz) as shown in Fig. 37 c and d. It is seen that the experimental frequency correlates well with the Minnaert frequency in the high
frequency region (900-1000 Hz) corresponding to lower air flow rates as shown later in Section 9.5. At higher flow rates, the coalescence causes a shift towards lower frequency regions of 300-500 Hz. This confirms that the sound generated by bubbles are the main sources of sound.

Figure 37: Frequency domain of a copper chip for air bubbles at varying air flow rates
9 Discussion

9.1 Amplitude variations of the heater surfaces at different heat fluxes:
Typically, to ensure the safety of the overall plant, industrial boiling systems run only at 50-60% of the CHF condition. This safety is necessary to avoid the catastrophic burnout of the systems. With the implementation of a continuous acoustic mapping, these operational ranges of the boiling systems can be increased. To have a better visualization, an amplitude trend at a dominant frequency region is plotted against the ratio of \( q''/q''_{CHF} \). This plot can assist in determining the maximum heat flux at which the boiling system can operate. Figure 38 shows the amplitude vs \( q''/q''_{CHF} \) plot for the plain copper chip and a microporous chip.

![Amplitude variations of plain copper chip and microporous chip at different fluxes](image)

**Figure 38:** Amplitude variations of plain copper chip and microporous chip at different fluxes to determine the operational range
The dominant frequency values for the plain copper chip and the microporous chip are ~450 Hz and ~350 Hz, respectively. The average amplitudes at these frequencies are calculated for each heat flux and are plotted against the $q''/q''_{CHF}$ ratio. The thick line in the plot indicates the condition at which the heat flux is equal to the critical heat flux (CHF) of the surface. While, the dotted lines represent the last steady state safe operating point obtained in this study. More specifically, the black dotted line indicates the upper operational limit for the plain copper chip, while the red dotted line indicates the upper operational limit for the microporous chip. Thus, with the continuous acoustic mapping, the operational ranges of the industrial boiling applications can be enhanced.

![Graph showing amplitude variations of plain copper chip and microporous chip at different fluxes to determine the operational range.]

Figure 39: Amplitude variations of plain copper chip and microporous chip at different fluxes to determine the operational range

Similarly, the plot for the electrodeposited porous chip is plotted to understand the variation in amplitude with respect to the $q''/q''_{CHF}$ ratio in Fig. 39. From the plot, it is observed that the acoustic
mapping is helpful to detect the impending CHF condition before the CHF is reached. With continuous acoustic mapping, heat removal capacity of the heater surfaces can be drastically improved. The drop in amplitude gives a clear indication of approaching CHF condition for the heater surfaces. From Fig. 39, the thick gray line shows the heat flux equal to CHF. The dotted blue line indicates the upper limit reached in the present study from a plain aluminum chip (not discussed earlier) while the dotted blue line shows the same for the electrodeposited porous chip. The sudden drop in amplitude is clearly observed in all the tested surfaces and thus this method of acoustic mapping can be used as a tool to detect the CHF. However, the analysis on large number of different heater surfaces is desired for applying this acoustic during boiling in industrial boiling systems.

9.2 Visualization study of formation of coalesced bubbles:
To understand the coalescence phenomenon of the vapor bubbles, visualization study was performed on the plain copper chip. As heat flux increases, more number of bubbles form on the surface and coalesce at faster rates. Figure 40 (a) shows two bubbles approaching, the bubble on the left side is 1.4 mm and the bubble on the right side is 1.35 mm. Figure 40 (b) shows the beginning of coalescence, and Fig. 40 (c) shows the resultant coalesced bubble with a larger diameter of 2.4 mm.

Figure 40 a) Two bubbles approaching b) Bubble coalescence begins c) Resultant bubble
Figure 41 (a-c) show that two bubbles have already coalesced and third bubble is approaching to coalesce with the larger coalesced bubble. Due to this rapid coalescence and continuous oscillation, these bubbles start to merge with neighboring bubbles according to the conditions mentioned in the literature review in the section 2.3.

![Three bubble coalescing](image)

*Figure 41 a-c) Three bubble coalescing*

Similarly, with increment in heat input, boiling process on the surface increases. Multiple bubbles form on the surface at same time and coalescence takes place simultaneously in very short period of time and finally a resultant large vapor bubble departs from the surface. This large vapor lump has its own frequency of oscillation when it moves through the bulk liquid depending on the resultant bubble diameter. Sound generated from each bubble collapse has a unique amplitude with respect to frequency. With increase in this bubble size, this sound pressure amplitude keeps increasing as seen in Figure 22, 28.

### 9.3 Comparison of acoustic data with visual images of boiling on a plain copper surface at different heat fluxes
To understand the bubble dynamics and to study the formation and behavior of vapor bubbles and vapor columns during boiling on a plain copper surface, different test setup was used. This setup was used to perform the high speed imaging with the focus on the bulk liquid and vapor behavior.

![Images of bubble formation at different heat fluxes](image)

**Figure 42** a) Individual bubble formation at 22 W/cm² b-c) fully developed vapor bubble after multiple bubble coalescence d) Vapor column formation before CHF

The visual images were captured using high-speed camera and were correlated to the acoustic data at different heat fluxes (section 9.5). It is observed from Figure 42 that at low heat fluxes around 20-30 W/cm², individual bubbles could be seen departing the surface, and during this departure they have different shapes due to oscillation of the bubbles. Each bubble oscillates with its own frequency depending on its equivalent radius. As these bubbles keep merging together and forming a large vapor bubble their oscillating frequency changes and also sound generated during its
collapse changes. It can be said after visual inspection and relating them to the sound generated at those heat fluxes that collapse sound is directly related to the bubble size or bubble radius. From Figure 42(b-c) around 40-74 W/cm² it can be seen that bubble size has increased due to continuous coalescence. In Figure 42(c) at 74 W/cm² it is seen that as fully-grown vapor bubble departs next vapor bubble is growing in size over the surface. Later on, increasing the heat flux and as shown here in Figure 42 (d) around 97 W/cm² second bubble forms really quickly and merges with the fully grown vapor bubble. Coalescence of these fully-grown vapor bubbles and formation of these vapor columns is explained in next section.
While performing the boiling test on the plain copper chip in different setup, due to variation in surface roughness, a CHF was attained at 100 W/cm². With the use of high-speed imaging, formation and departure of vapor column is analyzed just before CHF. Due to continuous coalescence, vapor lumps start to merge with each other and form a continuous column of vapor. In Figure 43 (a-e) mushroom shaped vapor lump is observed while leaving the copper surface, as it fully grows, another vapor lump merges with it and starts expanding. It can be seen that vapor column takes the shape of vapor jets in very little time, in just 74 ms vapor jet forms and leaves the surface and the next vapor jet initiates instantly. Vapor column continues to grow in length till its tail finally pinches off from the surface as seen in Fig. 43 (e). Vapor column formation prevents...
the surrounding liquid from rewetting the surface and at this point surface temperature starts to rise rapidly and if heat input is not stopped, the heater surface would reach the burnout condition.

At this heat flux, the combination of large vapor lumps and fully-grown vapor bubbles are responsible for the sound generation. It is hypothesized that as these vapor columns collapse, they produce sound at low frequency similar to what was observed for plain surface at Figure 23 (d). Fully grown vapor bubbles create a larger cavity during their sudden collapse and their sound intensity is higher and is dominant in the higher frequency region.

**9.5 Comparison of experimental Frequency and Minnaert frequency for air bubbles:**

The experimental frequencies achieved from air bubbles were compared with the theoretical Minnaert frequencies. High speed images were captured at different air flow rates to measure the air bubble diameters which could further be used while calculating the Minnaert frequencies for each flow rate. Equivalent diameter was calculated by measuring horizontal and vertical diameter and using the expression \((D_h^2 * D_v)^{\frac{1}{3}}\). The Minnaert frequencies were calculated using the following equation:
Figure 44: Bubble diameter calculation using high speed imaging at 200 ml/min flow rate

\[ f = \frac{1}{2\pi R} \sqrt{\frac{3\gamma P_0}{\rho}} \]

For the air flow rates above 600 mL/min, due to excessive coalescence of air bubbles, the air bubble diameters could not be measured. Table 5 below shows the comparison of the experimental and theoretical frequencies obtained from the experimental data and the theoretical calculations.
Initially, at lower air flow rates, a small discrepancy in experimental and theoretical Minnaert frequencies is observed. Minneart frequency is calculated for the single air bubble departing through the water. However, researchers[20] have established that the experimental frequencies decrease with increase in number of bubbles. This can be seen from the high-speed images of the air bubbles at flow rates of 200 and 400 mL/min. Additionally, owing to a very low bubble coalescence, the experimental frequency does not decrease.

9.6 Comparison of experimental Frequency and Minnaert frequency for boiling bubbles:

Frequency range from experiments on plain copper surface were compared to Minnaert frequency. The Minnaert frequency for each heat flux was calculated from the visual data. Tables 6 and 7 show the comparison of the frequencies on plain copper surface. A filter (0.5 mPa) was applied and only peaks above this amplitude power were considered. Frequency range of all the peaks above this cutoff value were recorded. Minnaert’s [27] analysis was performed for the gas bubble of fixed mass. However, in the boiling systems, mass transfer takes places across the boundary as bubble is growing, so this equation is not directly applicable for the growing bubble, but nevertheless can be used for calculating the estimated frequency range. In this study, major sound produced is from the oscillation and collapse of fully-grown vapor bubble. So, the Minnaert
equation can be used here considering vapor bubble are fully grown and using boiling conditions for density of liquid. Equivalent radius of these vapor bubbles is measured from visual images using Photron-Fastcam software and this radius is used in Eq. 9 to determine the frequency of sound generated by these bubbles.

Figure 45: Peaks above the cut-off of amplitude shown with red line considered for determining frequency range for a certain heat flux.

These calculated Minnaert frequencies are compared with the experimental frequencies Table 6. As the sensor used in this study detects the sound signatures only after a certain heat flux so comparisons are made after 30 W/cm². Heat fluxes in similar range for plain copper surface are compared from visual inspection and recorded data. It can be seen from the data that experimental frequency range keeps increasing as heat flux increases. As observed from the data that around 36 W/cm² amplitude peaks are only dominant in 400-530 Hz frequency range while when sound pressure peaks around 127 W/cm² are spread out from 79-617 Hz. It is observed from Minnaert frequency in Table 6 that as bubble size increases, frequency of the bubbles is reduced. From
Minneart frequencies dominant frequencies of are observed to be in 400-600 Hz region which is similar to our experimental dominant frequency region.

**Table 6: Minnaert frequency calculation from Visual Data**

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<thead>
<tr>
<th>Heat Flux</th>
<th>Diameter Range (Visualization) (mm)</th>
<th>Frequency Range (Minnaert) (Hz)</th>
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<td>16 W/cm²</td>
<td>2.72 - 4.52</td>
<td>147-2451</td>
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<tr>
<td>22 W/cm²</td>
<td>5.54 - 6.9</td>
<td>966 -1203</td>
</tr>
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<td>30 W/cm²</td>
<td>9.12 - 10.1</td>
<td>660-731</td>
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<td>10.9 - 12.8</td>
<td>520-611</td>
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<td>67 W/cm²</td>
<td>13.46 - 14.54</td>
<td>458-495</td>
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<td>14.22 - 14.86</td>
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</tr>
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<td>13.48 - 14.5</td>
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<tr>
<td>97 W/cm²</td>
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Table 7 Frequency ranges at different heat fluxes

<table>
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<tr>
<th>Heat Flux (W/cm²)</th>
<th>Frequency Range (Hz)</th>
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<td>400-530</td>
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<tr>
<td>45</td>
<td>377-491</td>
</tr>
<tr>
<td>51</td>
<td>377-493</td>
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<tr>
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<td>309-506</td>
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<tr>
<td>71</td>
<td>302-533</td>
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<tr>
<td>86</td>
<td>300-532</td>
</tr>
<tr>
<td>97</td>
<td>120-567</td>
</tr>
<tr>
<td>109</td>
<td>85-569</td>
</tr>
<tr>
<td>116</td>
<td>83-597</td>
</tr>
<tr>
<td>127</td>
<td>79-617</td>
</tr>
</tbody>
</table>
10 Limitations of the study

1) In this study, all the experiments were performed on the pool boiling setup shown in section 4.1 and Fig. 9. So, the variation of acoustic parameters with other geometries and materials were not studied. However, preliminary tests indicated that the variation in microphone location resulted only in a change in the amplitude, but the signature pattern remained unaltered.

2) During this study, distilled water was used at saturation temperature (100°C) at atmospheric pressure for all the experiments. Thus, the variation of acoustic parameters with a change in the liquid properties and liquid temperature is not studied. And the variation in sound parameters such as amplitude and frequency with change in pressure is not studied here. Also, the effect is not verified with different working fluids such as refrigerants.

3) Microphone position in this study is kept fixed for all the tests. The change in microphone position and its effect on amplitude and frequency is not studied in this work. As stated in comment 1 above, the location of the microphone did not affect the signature pattern, only the amplitude was lowered.

4) As all the tests were performed in the same lab, so background noise was constant for all the tests which was later reduced during noise reduction. To make sure there is minimum background noise, all the tests were performed during the weekends and with minimum light sources turned on. However, to get the best data, the tests can be performed in the sound proof labs.

5) This study was performed in the lab and before applying this acoustic mapping as a tool in the industrial applications, further experiments need to be performed on actual heat
exchangers which will have multiple boiling regions present at the same time on different heat transfer surfaces.

6) The sensitivity of the microphone sensors used in this study is limited. So, the sound generated from bubble nucleation and bubble oscillation in the liquid could not be recorded. Since the bubble coalescence and departure were the main sources of sound in the present study, this limitation does not alter the conclusions from the present study.

7) As microphones during all the tests are placed outside the setup, boiling sound travels through the reservoir glass and air before reaching the microphone. Reflection of sound from the glass is not analyzed and hence the use of hydrophone for future studies is recommended to eliminate these parameters. It is noted that this configuration of external placement of microphones is of practical interest since monitoring is desired from external locations in equipment such as heat exchangers and nuclear reactors.

8) Even though a good quality microphones (frequency range: 10 Hz to 10000 Hz) and the amplifier (frequency range: 20 Hz to 22000 Hz) were used in this study, the best quality of the microphones and the amplifier can be used for capturing the boiling sound data.

9) The natural frequency of the pool boiling setup was not determined. It will be helpful to determine this frequency to ascertain that they do not interfere with the boiling sound data.
11 Conclusions

Acoustic signatures during boiling are studied in this work. Boiling experiments were performed on plain and enhanced surfaces. Sound data are recorded at each heat flux in small increments upto CHF. Variation of acoustic data at each heat flux is studied and compared with bubble dynamics at that heat flux.

Saturated Pool Boiling

- The sound was captured using external microphones. This configuration is of practical interest for monitoring the boiling levels in equipment such as heat exchangers and nuclear reactors. The sound intensity increases with an increase in heat flux due to larger coalesced bubble diameter on plain and porous surfaces. The rapid bubble nucleation and coalescence results in larger bubble size at high heat fluxes.

- The boiling sound attained maximum amplitude in the nucleate boiling regime. A significant sound amplitude was recorded in the 300-500 Hz frequency range during saturated nucleate boiling.

- At high heat fluxes, 100 - 127 W/cm² on the plain chip and 134 – 201 W/cm² on the porous chip, amplitude peaks were observed in low frequency region 100-200 Hz along with high frequency range 400-500 Hz. The vapor columns are formed due to bubble coalescence at high heat fluxes emitting sound at low frequencies.

- During fully developed nucleate boiling maximum sound intensity was recorded at a heat flux of 116 W/cm² for plain copper surface, and 190 W/cm² for the microporous surface. This was due to the sound superposition from large vapor bubbles and vapor jet columns.

- With an increase in heat flux, continuous increment in amplitude was observed in high frequency region (400-500 Hz). However, just before CHF, a sudden drop in amplitude was observed for both the plain and microporous surfaces. The CHF values of plain and
microporous surfaces are 127 W/cm² and 201 W/cm², respectively. The trend has been confirmed for different surfaces that have distinctly different CHF values. It is noted that the amplitude drop occurs at heat fluxes around 98% of CHF values for all surfaces.

- Based on the current work, it can be concluded that this technique along with visual and temperature recordings can be used for monitoring if the surface is approaching the CHF condition by continuously monitoring the amplitude for various heat fluxes.
- The bubble coalescence along the heated surface near CHF initiates the formation of stable vapor film. The peak amplitude drops due to the vapor film on plain and microporous surfaces as CHF condition is approached.

**Air Bubbles:**

The sound generated by coalesced air bubbles were studied at different flow rates. At lower flow rates, individual bubbles were observed but as the flow rate increased, the bubble size increased due to coalescence.

- Air bubbles at 200 ml/min flow rate have a frequency domain which is dominant in the 900 -1000 Hz region.
- The experimental frequency correlated well with the calculated Minnaert frequency for smaller air bubbles.
- As the bubble coalescence increases with increased flow rate, frequency domain shifts towards lower frequency region (300 – 400 Hz)

**Visualization:**

Visualization helped in analyzing bubble dynamics during boiling and also in correlating different events with the sound generated during those events.
• The bubble nucleation and collapse processes were observed at low heat fluxes during nucleate boiling. The acoustic emissions recorded resulted from individual bubble generation and collapse processes.

• At higher heat fluxes, bubble coalescence was recorded to form large bubbles and vapor jet columns. The bubble coalescence and column collapse generated high amplitude sounds.

• Near the CHF condition, the formation of vapor columns were observed on the heated test surface.
12 Lessons Learned

1) In this study, background noise causes interference with the boiling sound. So, sources of this noise are identified and attenuated from the boiling signal.

2) Noise reduction can be performed in both the time domain and frequency domain. In this study, noise reduction in the time domain was performed and the frequency domain of background noise was also identified to ensure that it does not overlap with the boiling frequency domain.

3) Initial tests were performed during the weekdays. However, it was noted that the tests performed during the weekends and in a quiet environment with the minimum lighting give the best results. Thus, all the tests were then performed during the weekends in a quiet environment with the very less lighting present during the test.

4) The vibration isolation table is essential while performing the pool boiling tests and capturing the sound, since the vibration from the floor is absorbed by this table.

5) As the power source is identified as the main source of background noise, it is recommended for future studies to keep the pool boiling setup at a maximum possible distance from the power source.

6) In pool boiling, the sound is generated due to bubble formation, departure and collapse of these bubbles. In this study, due to a relatively low sensitivity of the sensors, sensors start to record the acoustic data when vapor bubbles are fully grown and coalescence is fully active. Due to this limiting factor, major sound recorded by the sensor is from bubble collapse.

7) Condenser microphones are unidirectional and therefore changing the position of microphones caused the variation in sound parameters. Hence, the microphone’s position was kept fixed throughout all the experiments conducted in this study and all the recordings
13 Future Work

In this study, microphones were used and were placed outside the pool of the liquid. An in-depth study can be performed using a high sensitivity hydrophone to record boiling sound with a focus at low heat fluxes to capture sound generated from individual bubbles. Hydrophones will capture the acoustic pressure from bubbles directly.

Digital noise cancellation was performed in this study. Implementation of active noise cancellation during recording can be helpful in obtaining clean data. Active noise cancellation removes unwanted signals at the moment of recording.

Boiling tests can be performed on microchannel and other enhanced surfaces using a hydrophone to capture the sound data to understand the trend and sound signatures. In industrial applications, many systems operate with refrigerants or dielectric fluids as the working fluid. Capturing the boiling acoustics in a closed pool boiling setup with refrigerants or other fluids will also be beneficial for industrial applications.

Boiling acoustic emission sound can be used for determining the resonant frequencies for bubbles formed during different stages of boiling. A transducer can be used to provide similar resonant frequency over the surface. This resonant frequency can be used to delay CHF and hence increase the performance of the surface.
References


[38] “Sound of Boiling Westwater.Pdf.”


Appendix 1

Weighted average calculations for smoothing the amplitude curves in frequency domain

After observing amplitude variation in the frequency domain, for a clear understanding of amplitude variation with frequency smoothened curves were drawn using weighted average formula shown in equation. A window of 100 Hz each is considered and averaged amplitude and frequency and amplitude is calculated for each window. Finally, the smoothened plot for amplitude with respect to frequency is calculated for a particular heat flux by interpolating these averaged values.

\[
\bar{A} = \frac{\sum_{i=1}^{n} A_i f_i}{\sum_{i=1}^{n} f_i} \tag{1}
\]

\[
\bar{f} = \frac{\sum_{i=1}^{n} A_i f_i}{\sum_{i=1}^{n} A_i} \tag{2}
\]

Here, \( A \) and \( f \) are amplitude and frequency respectively and \( \bar{A} \) and \( \bar{f} \) are weighted averaged amplitude and frequency.
Appendix 2

Matlab code for FFT generation

```matlab
clear
close all
% nTimePerO=15;nTimePerA=10; % for snapshots of line spectrum
tFrac=1; % fraction of time used
fFrac=.5; % fraction of frequency for 2nd spectrogram
% minPower=1e-8; % min power for spectrogram plot
dBmin=-90;
minPowerCloseUp=1e-8;
maxSpectroG=inf;
maxPower=inf;
% fMaxAC=100;
A=108;B=42; % for spectrogram
dirOfWave='C:\thesis\u';
%dirOfWave=CallInputChar(dirOfWave,'enter directory containing wave ');
cd(dirOfWave);
%iType=1;
%iType=CallInput(iType,'mat (1) or wav (2) ');
directory = dir('.wav');
a = cellstr({directory.name});
for i = 1:5
    temp = string(a(i));
    fileName = input((temp));
    if iType==1
        load(fileName)
    elseif iType==2
        [ywave,Fs]=audioread(temp);
    end
    disp('The following variables are in memory. Look for the variable name (like yC)')
    whos
    varName='ywave';
    varName=CallInputChar(varName,'from this list, enter the variable name for reading-in ');
    name='Test Run';
    name=CallInputChar(name,'enter the wave name for use in titles of graphs (ex: Knabe D3# ');
    y=eval(varName);
    fFund=32.7;
    fFund=CallInput(fFund,'enter estimated fundamental frequency (Hz) ');
    fCenterFG=-1;
    fCenterFG=CallInputChar(fCenterFG,'enter center of fine grid line spectrum ');
    fL=0;
    fR=2000;
    fR=CallInput(fR,'enter the max frequency for plotting spectra ');
    fmax=fR;
    % minPower=CallInput(minPower,'enter minimum power for spectrogram ');
    dBmin=CallInput(dBmin,'enter minimum dB for line spectrum ');
    %if iType==1
    %Fs=44100;
    %Fs=CallInput(Fs,'enter Fs ');
    %end
N=length(y);
```

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h=1/Fs;
fny=Fs/2;
t=(0:N-1)*h;
tmax=max(t);
disp(['duration of wave = ' num2str(tmax) ' s '])
tDurDes=tmax;
tDurDes=CallInput(tDurDes,'enter desired duration (less than actual) ');
iEnd=find(t>=tDurDes,1,'first');
tmax=t(iEnd);
y=y(1:iEnd);
N=iEnd;
t=(0:N-1)*h;

%%%get overall tone center
[~,~,TC0]=SpectralCentroidFast(y,h);
disp(['Tone center for ' name ' = ' num2str(TC0)]

%%%time domain
%%figure
%plot(t,y),grid
%title(['Time Trace of ' name],'fontweight','bold')
%xlabel('time (s)')
%ylabel('amplitude')
%axis([0 tmax -inf inf])

% subplot(212)
% plot(tRms,yRms),grid
% title('RMS of Wave','fontweight','bold')
% xlabel('time (s)')
% ylabel('amplitude (rms)')
% axis([0 tmax -inf inf])
% pause

fMaxAC=fFund;
fLFG=fCenterFG-5;
fRFG=fCenterFG+5;

%%%set up harmonics for background
if fFund>0
    nHarms=round(fR/fFund);
    fHarms=zeros(1,nHarms);
    for k=1:nHarms
        fHarms(k)=k*fFund;
    end
end
freqInd=1:nHarms;

%%%line spectrum
fSep=1/(N*h);
disp(['FFT frequency separation = ' num2str(fSep) ' Hz'])
[Y,f,YdB]=SimpleLineSpectrum2(y,h,0,fny);
figure
%subplot(211)
plot(f,Y,'LineWidth',1.5),grid
title(['Line Spectrum of ' name],'fontweight','bold','fontsize',10)
ylabel('Amplitude|V|')
xlabel('Frequency (Hz)')
axis([fL fR 0 max(Y)])
end