

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 11

Lecture - 51

Chemiluminescence Measurements – 1

In this session, we are going to provide a brief introduction to chemiluminescence and discuss its importance in combustion diagnostic studies with different radicals from the film. Later, we will be discussing the key components related to the chemiluminescence measurements, and briefly, we will showcase the working principle behind it. Following that, we will be showcasing the components in the demonstration session, as we discussed earlier in the previous lectures. The chemiluminescent signal is very weak; thus, it needs specific intensifiers or amplifiers to detect the signal accurately. Chemiluminescence is used to detect specific chemical species through spectral signature or detecting the concentration of the emitting species based on the intensity of the radiation often during combustion; the emitting species are either short-lived intermediate species or combustion products in an electronically excited state.

Chemiluminescence



- The chemiluminescence signal is weaker and thus needs specific intensifiers or amplifiers to detect the signal accurately.
- Chemiluminescence is used to detect specific chemical species through spectral signature or detect the concentration of the emitting species based on the intensity of radiation.
- Often, during combustion, the emitting species are either short-lived intermediate species or a combustion product in electronically excited state.
- Thus, the concentration of the emitting species depends on the rate of reaction producing those species.
- Chemiluminescence usually does not need wavelength specific measurements (emission spectrophotometry), i.e., the detector only **measures total intensity** of light at a specific wavelength – **emission photometry**.

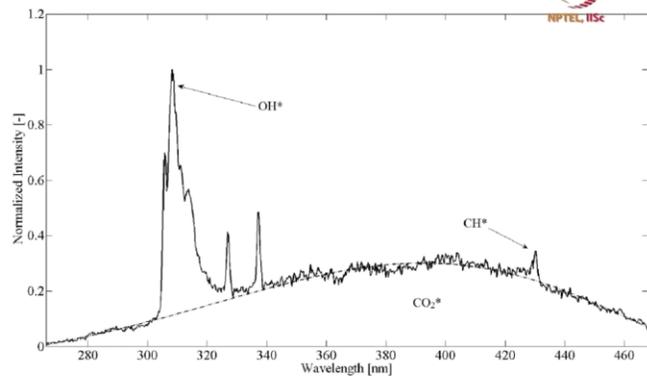
Here, I mean short-lived intermediates. Species means it's nothing but radicals that come and go during the chemical reaction processes; thus, the concentration of the emitting

species depends on the rate of reaction producing those species. Chemiluminescence usually does not need wavelength-specific measurements; that is, the detector only measures the total intensity of the light at the specific wavelength. Now, coming to the importance of chemiluminescence in combustion diagnostics.

Chemiluminescence results from the relaxation of different electronically excited species that are produced via chemical reactions in the combustion zone. In oxygen hydrocarbon flames, the species CH^* , OH^* , C_2^* , and CO_2^* are responsible for much of the light emission in visible as well as ultraviolet wavelengths since the excitation energy, which is chemical in nature, is higher in combustion reactions; the dominant emissions occur in lower wavelengths, which correspond to a higher energy spectrum, specifically in the UV range most commonly.

Importance of Chemiluminescence in Combustion diagnostics

- Chemiluminescence results from the relaxation of the different electronically excited species that are produced via chemical reaction in the combustion zone.
- In oxygen-hydrocarbon flames the species CH^* , OH^* , C_2^* , and CO_2^* are responsible for much of the light emission in the visible and ultraviolet wavelengths.
- Since, the excitation energy which is chemical in nature is higher in combustion reactions, the dominant emissions occur in lower wavelengths (higher energy), specifically in UV range.
- Most commonly, chemiluminescence from the OH^* and CH^* species is used for analyzing combustion, as a heat release indicator.
- The different chemiluminescence emission signals from different species have different spectral signatures (wavelength) and thus, a band pass filter at a desired wavelength is often used to only allow the emission at a specific wavelength, to measure the corresponding chemiluminescence from that specific species.



H. Watanabe, K. Kendall, Flame spectrograms: I. Common metals Appl. Spectrosc., 9 (3) (1955), pp. 132-140

The chemiluminescence from the OH and CH star species is used for analyzing combustion as a heat release indicator. As we observe in the graph illustrating the chemical reaction of combustion, individual radicals emit light at distinct wavelengths. Each radical, such as OH star, CH star, and CO_2 star, corresponds to a specific spectral signature, making it possible to identify and study them individually.

To capture a particular wavelength corresponding to a specific radical, we need to isolate that wavelength from the broader spectrum of emitted light. This is achieved using filters that allow only the desired wavelength to pass through while blocking others. The role of these filters and their application in combustion diagnostics will be discussed in detail as

we progress through the session. Among the various radicals involved in combustion, OH-star and C-star are particularly significant. These radicals play a crucial role as indicators of heat release during the combustion process.

OH-star chemiluminescence is often associated with high-energy reactions and serves as a marker for the primary reaction zone. While CH star provides insight into the intermediate reaction stages, together these emissions offer valuable information about combustion dynamics. The OH radical emits at a wavelength of 306 nanometers, making this OH star a highly reactive species and a key intermediate during oxidation reactions in combustion. So, these can be used to estimate a local heat release rate in the region of the flame. This also provides information about the flame structure, flame propagation, and flame shape.

Importance of Chemiluminescence in Combustion diagnostics



- The important species or radicals formed during reaction pathways in combustion reactions :
 - **OH radical (OH*) – emits at 306nm wavelength**
 - OH* (hydroxyl radical) is a highly reactive species, and is a key intermediate during oxidation reactions in combustion.
 - Can be used to estimate local heat release rates.
 - Provides information about flame structure, shape and propagation.
 - **CH radical (CH*) – emits at 431nm wavelength**
 - The presence of CH radicals is indicative of fuel-rich regions in a flame.
 - It signifies the breakdown of hydrocarbon fuels into smaller fragments and CH* is key intermediate species in complex combustion reaction.
 - The concentration of CH radicals can influence the formation of soot, a major pollutant in combustion processes.
 - By mapping the distribution of CH radicals within a flame, one can visualize the flame structure and identify regions of high reactivity.
- Thus, different emissions at specific wavelengths can provide crucial information in understanding, analyzing and optimizing the combustion processes.

Similarly, CGH radicals emit at a wavelength of 431 nanometers. The presence of the CH radical is indicative of fuel-rich regions in the flame. It signifies the breakdown of hydrocarbon fuels into smaller fragments, and CH* is a key intermediate species in complex combustion reactions. The concentration of CH star radicals can influence the formation of soot, which is a major pollutant from the combustion process. By mapping the distribution of CH radicals within a flame, one can visualize the flame structure and identify the regions of high reactivity.

Thus, different emissions at specific wavelengths can provide crucial information in understanding, analyzing, and optimizing the combustion processes. Now, we will

discuss the measurement of OH star chemiluminescence. For this, we first need a UV range transparent optical lens. As the majority of the emissions are in the visible and UV range. This UV-transparent lens allows us to capture both visible and UV-range signals.

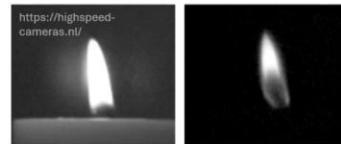
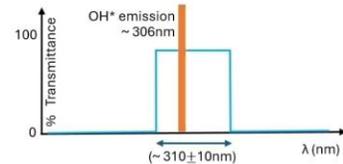
The OH star chemiluminescence is experimentally measured by capturing the emission from the flame limited to the spectral band of around 310 nanometers. An OH bandpass filter is used to allow only a specific spectral band corresponding to OH star radical emissions. So here, as you see in the transmittivity graph, the allowable signal is restricted only around 310 nanometers. This filter will not allow any other signals into the camera, as we can see the transmittivity is almost 0% other than at 310 nanometers. This drastically reduces the flame intensity, as a small portion of the flame luminosity is captured during OH chemiluminescence.

OH* Chemiluminescence – Measurement

- UV-VIS range transparent optical lens is firstly necessary for chemiluminescence, as the majority of the emissions are in visible and UV range.
- The OH* Chemiluminescence is experimentally measured by capturing the emission from the flame limited to the spectral band of $\sim 310 \pm 10$ nm.
- An OH* band pass filter is used to allow only a specific spectral band corresponding to OH* radical emission (~ 306 nm) into the camera.
- However, this drastically reduces the flame intensity, as a small portion of the flame luminosity is captured during OH* Chemiluminescence.
- This necessitates the requirement of an intensifier.



Newport 310nm Band pass filter



T3610-UV
UV lens, no filter
24 us exposure

T3610-UV
UV lens, 310nm filter
6000 us exposure

This necessitates the requirement of an intensifier. Here, this is the typical experimental setup for the measurement of chemiluminescence. This has a high-speed camera, a high-speed IRO, which is nothing but an intensifier, a UV transparent lens, a bandpass filter, and a PTU, which is nothing but a programmable timing unit. Here, the PTU works as a control unit for the intensifier; this will be further demonstrated in the lab session. Now we will briefly discuss the intensified relay optics, which is shortly called IRO.

This IRO has a two-stage image intensifier; one is an MCP, which is nothing but a micro-channel plate, and the other is a booster. This combination gives a 10-fold signal output from the incident signal. The key components inside IRO are a photocathode, a microchannel plate, a phosphor screen, a fiber optic connector, and a coupled lens. All these things are kept inside this vacuum tube. Now for stage 1, the incident particles, which are photons, enter the intensifier through a camera lens and pass through the photocathode charged with high voltage.

This converts the photons into photoelectrons. This photoelectron passes through millions of microchannel plates, which are accelerated by variable high voltage and amplified with each collision on the channel walls. These photoelectrons are further converted back to photons as they pass through a phosphor screen, which is also charged with a higher voltage. A fiber optic connector passes the amplified image signal to the

booster for additional intensification in stage 2; that is the booster. This also contains a second photocathode and a phosphor screen charged with high voltage to convert and

Typical Experimental setup



amplify the photoelectrons for increased resolution.

for high-speed and ultra-high-speed imaging. Finally, the fiber optic connector efficiently transfers amplified light from the booster to the coupled lens. These are used to optimize the exposure, match the size of the camera sensor, and maximize the spatial resolution of the intensified image.

For measuring the chemiluminescence, we can also use a device called a photomultiplier tube, which is nothing but a PMT. Unlike IRO, which provides an image as the final output, the photomultiplier tube outputs an electrical signal corresponding to the intensity

Chemiluminescence – Intensified Relay Optics

Specifications:

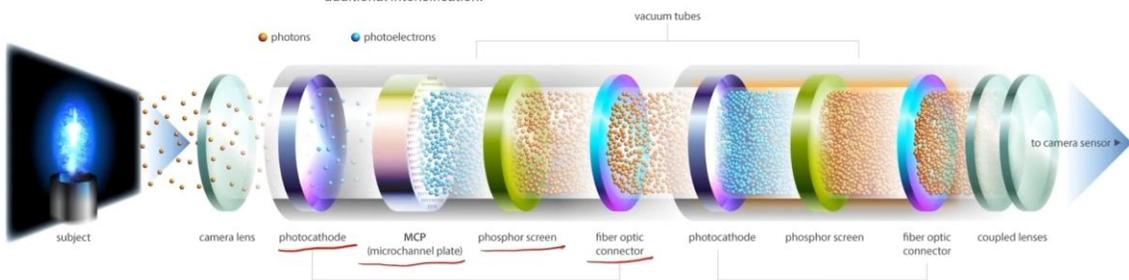
- 2-Stage image intensifier (MCP -Micro-channel plate + Booster) – 10 times signal output
- S20 or S25 Photocathodes
- P46 Phosphor screens
- Spectral range of 190–800 nanometers
- Highest UV sensitivity
- Sensitivity peak within visible range
- Short gating times down to 10 ns

Stage One – MCP

- Incident particles (photons) enter the intensifier (a vacuum tube) through a camera lens and pass through a photocathode charged with high voltage, which converts the photons to photoelectrons.
- Photoelectrons pass through millions of channels in the MCP (microchannel plate), accelerated by variable high voltage and amplifying with each collision on the channel walls.
- Photoelectrons are reverted to photons as they pass through a phosphor screen charged with high voltage. A fiber optic connector passes the amplified image signal to the booster (stage two) for additional intensification.

Stage Two – Booster

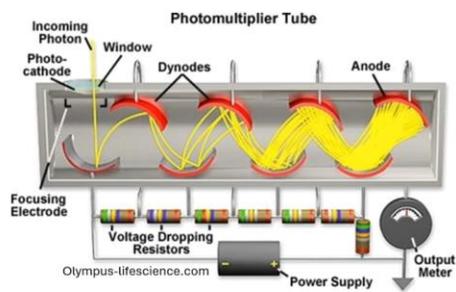
- The booster consists of a second photocathode and phosphor screen, charged with high voltage to convert and amplify photoelectrons for increased resolution for high-speed & ultra high-speed imaging.
- Fiber optic connectors efficiently transfer amplified light from the booster and to the coupled lenses. These are used to optimize the exposure, match the size of the camera's sensor and to maximize spatial resolution of the intensified image.



of light it detects.

Chemiluminescence – Photo-multiplier tube (PMT)

- Photo multiplier tube can also be used for amplifying the input signal.
- PMT is a photoemissive device in which the absorption of a photon results in the emission of an electron.
- These detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.
- The generated electrons are multiplied by electrodes known as metal channel dynodes.
- At the end of the dynode chain is either an anode or a collection electrode, to get the output signals.



This makes the PMT highly sensitive to low-intensity signals, allowing it to capture even faint chemiluminescence emissions with excellent precision. However, the PMT does not provide spatial information as it lacks the imaging capability. Instead, it focuses on delivering highly accurate and rapid measurements of light intensity. Now, coming to the brief working principle, a PMT is a photo-emissive device in which the absorption of a photon results in the emission of an electron; that means a photon is converted into an electron.

These detectors work by amplifying the electrons generated by the photocathode exposed to a photon flux. The generated electrons are multiplied by electrodes known as metal channel diodes. As you can see in this image, the incoming electrons are getting amplified with each dynode. At the end of the dynode chain is either an anode or a collecting electrode to get the output signals. This session takes you through the process of optimizing the setup for capturing high-speed images and interpreting the data for high-speed chemiluminescence imaging.

We will show you how to vary different settings such as frame rates, exposure time, and gain, etc. Affect the image quality. By the end of this session, you will have a clear understanding of how chemiluminescence imaging works. How to optimize the experimental setup for different combustion conditions and how to analyze the resulting

data to gain insights into combustion behavior. To begin, let's take a look at the experimental setup.



At the heart of our system, we have a high-speed camera that is essential for capturing fast-moving flame dynamics. As you can imagine, the combustion process happens extremely quickly. So, we need a camera that can record at an elevated acquisition rate. Since the luminescence signals are very low intensity, as explained before, we need to enhance the intensity using an intensifier. Here in this setup, we use a high-speed IRO, which stands for intensified relay optics, to intensify the incoming chemiluminescence signal before it is captured by the high-speed camera.

So, as shown here, the IRO is in front of the camera, which amplifies the input signal and produces a sufficient light signal for optimal intensity in the camera. Next, let's talk about the optics for the current experiments; it is known that the flame emits radiation. In a wide spectral range, that is, from infrared to visible and beyond. However, each of these radicals inside the flame emits radiation at specific wavelengths. So, for this demonstration's purposes, in this experiment, we will be performing overscheme luminescence imaging.

To capture this overscheme luminescence, we need to isolate specific wavelengths of light, which correspond to overs emissions from the flame. As explained before, the overs emissions are primarily in the UV spectrum, specifically around 310 nanometers. Thus, to ensure that only this specific wavelength is captured, we use a special OH bandpass

filter at 310 nanometers, as shown here. So, this will be mounted in front of this UV lens, and this combination of the UV lens and this bandpass filter ensures that we only catch the relevant OH emissions wavelength, which is 310 nanometers, from the flip. Here you can see the UV lens with the OS filter mounted in front of the IR.

The lens has adjustable dials which allow us to adjust the focus, zoom, and aperture. These adjustments help us focus specifically on the central plane of the flame inside this combustor. For this demonstration, we will burn meat dead with atmospheric air inside this combustor. This combustor is provided with an optically accessible window so that we can record using a high-speed camera. However, specifically for skin illumination imaging, the transparent quartz material is used for this window.

And this quartz material is transparent to UV rays in addition to the visible rays. As you know, the OH emission signal is present only in the UV rays. Here, one can ask, "Why can't we use a normal glass?" Because normal glass can transmit signals only in the visible spectrum. But it completely cut off the UV signals, which are not desirable. So using this focus ring in the lens, we can ensure that the lens is perfectly aligned with the central plane of the area inside the combustor for proper plane visualization.

The camera and Iago are synchronized using a programmable timing unit as the PD. All the components, such as the camera and Iago, are controlled using commercial software called Davis, which is installed on the computer. The software allows us to fine-tune several important parameters related to high-speed camera recording, such as frame rates, resolution, and the region of interest where we will be seeing the film. In high-speed imaging, the frame rate, also known as the acquisition rate, is very crucial. This refers to how many frames the camera records per second.

Usually, combustion is characterized by high-speed flame dynamics and flame movement. For capturing such combustion phenomena, we generally prefer higher frame rates to capture different high-speed flame dynamics. So, we adjust the frame rate based on the speed of the flame movement we intend to observe. It is to be noted that the maximum exposure time that can be allowed is equal to 1 divided by FPS, which is frames per second. This implies that the higher FPS may result in reduced image intensity because less time is available for the image to be recorded by the camera sensor.

As I mentioned earlier, PTU is used for synchronizing the camera and IRO. Additionally, the same video is responsible for adjusting two key settings, which are gate and rate. Firstly, let's start with the gate. Gate is essentially the exposure time of IRO, which is the amount of time during which light is allowed onto the camera sensor for each frame recorded by the camera. The longer exposure time means that more light is

captured by the camera sensor, resulting in a brighter image with good contrast.

However, if we need to capture very fast flame movements during combustion, a shorter exposure time is needed to freeze the movement of the flame in each frame while recording. Thus, for better temporal resolution and to capture the faster flame movements, a lower gate is preferred. For experiments like the one we are going to conduct today, a typical gate of 70,000 nanoseconds is used, and we have to strike a balance between capturing high-speed flame dynamics and maintaining good quality images. The only downside to using lower gate is the intensity of the flame image. The recorder will be dimmer and have a lower contrast for the signal-to-noise ratio.

Now that we have discussed the usage and the limitations of scale or exposure time while using the IRO. The main question that remains is, how do we balance image quality without compromising the temporal resolution of high-speed flight dynamics? To answer this question, we use the second key setting associated with the IRO, which is GATE. So, to address the low image intensity due to shorter gate setting, we can utilize gain settings. The gain is nothing but a multiplier that amplifies the intensity of the incoming light signal inside the IRO. After amplifying this signal, the IRO produces an enhanced light signal and supplies it to a high-speed camera for recording.



Flame video using DSLR



Flame video Using IRO & Filter

This amplification basically widens the intensity histogram of the image, thus enhancing the contrast of the flame image that is captured even at high-speed recording. While this process increases the flame intensity, it also amplifies any background noise so it's

crucial that we perform these experiments in completely dark room to minimize external light interferences now we will be demonstrating how to focus the camera at the central plane of the plane in the combustor for this purpose We will be using this calibration plate, which contains equally distant doors with predetermined spacing. So, now I will place this calibration plate at the central plane of the combustor where the plane will be stabilized. We have placed the calibration plate at the center of the combustor, as shown. Using the focus ring of the UD lens, we can align the focal plane with the calibration plate that is placed at the center of the combustor.

This process not only allows us to focus on the center of the combustor, but also enables us to find the pixel resolution of the flame recording by using the dark spacing of the calibration plate. Thus, after this calibration process, we will be able to measure the actual flame dimensions using the line-of-sight imaging obtained through chemiluminescence. Now we will remove the calibration plate and close the combustor and ignite the TULR mixture to obtain the flame Now this is how the flame appears to the naked eye as captured using the DSLR camera On the right hand side you can see a video captured with a high speed camera With an IRO and a filter, we will discuss these details of the imaging procedure in the next session.