SIEMENS-UV OPTICAL FLAME DETECTION

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Abstract:

The increasingly stringent air pollution standards that prompted the transition from traditional diffusion based combustion to premixed-type combustion in the early 1990s has significantly increased the need to detect flame presence in gas turbines. However, using premixed air reduces the stability of the flame and thereby increases the likelihood of flashback phenomena. Water accumulation on the lens of the flame sensor reduces the system's ability to correctly monitor flame inside the turbine. Furthermore, multi-fuel gas turbines are able to burn diesel fuel, and there is an occasional build-up of oil in the combustor can. In effect, water and oil buildup on the lens may change the focal length of the lens causing limited light wave transmission.

To determine the response of sensors to flame flicker, background radiation and water-oil buildup on lenses, three tests were conducted in the combustion lab at the University of California, Berkeley under atmospheric conditions. A hydrocarbon flame spectra mainly comprises of shorter wavelengths i.e. UV wavelengths. Hence, all the sensors selected were UV sensors. Five sensors - General Electric Reuter Stokes (GE), Ametek, Azbil, Forney, and Industrial Turbine Services (ITS) were chosen for testing. The results of the three tests indicate GE, ITS, and Ametek are the best sensors with similar performance. Hence, based on the series of tests conducted, as well as a cost and market analysis, the recommendation for Siemens would be to use either Ametek or ITS sensor.

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BY

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THESIS

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Professor Albert P. Pisano

ABSTRACT

The increasingly stringent air pollution standards that prompted the transition from traditional diffusion based combustion to premixed-type combustion in the early 1990s has significantly increased the need to detect flame presence in gas turbines. However, using premixed air reduces the stability of the flame and thereby increases the likelihood of flashback phenomena. Water accumulation on the lens of the flame sensor reduces the system's ability to correctly monitor flame inside the turbine. Furthermore, multi-fuel gas turbines are able to burn diesel fuel, and there is an occasional build-up of oil in the combustor can. In effect, water and oil buildup on the lens may change the focal length of the lens causing limited light wave transmission.

To determine the response of sensors to flame flicker, background radiation and water-oil buildup on lenses, three tests were conducted in the combustion lab at the University of California, Berkeley under atmospheric conditions. A hydrocarbon flame spectra mainly comprises of shorter wavelengths i.e. UV wavelengths. Hence, all the sensors selected were UV sensors. Five sensors - General Electric Reuter Stokes (GE), Ametek, Azbil, Forney, and Industrial Turbine Services (ITS) were chosen for testing. The results of the three tests indicate GE, ITS, and Ametek are the best sensors with similar performance. Hence, based on the series of tests conducted, as well as a cost and market analysis, the recommendation for Siemens would be to use either Ametek or ITS sensor.

To my Family

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CHAPTER 1: INTRODUCTION

Detecting the presence of flame in the combustion chamber of gas turbines plays a vital role in increasing the turbines' reliability and safety, especially during the start-up cycle when flame may not be completely established. Flame instability in gas turbines can either lead to a flashback or a flameout condition, either of which can lead to a catastrophic failure of the entire engine. Ensuring that the flame remains stable throughout the operation of turbine can prevent the catastrophic failure. However, new demands being imposed on combustion systems to reduce the emissions of nitrogen oxides (NOx), carbon monoxide (CO) and unburned hydrocarbons (UHCs) require tighter control of parameters at which combustor operates. To meet this requirement, there is a shift from diffusion combustion to lean pre-mixed combustion (Brown, Lombardo and Palmer). The lean pre-mixed combustion decreases flame stability, which increases the likelihood of flashback phenomena (Lieuwen, McDoneell and Peterson). Hence, a flame detection system is needed to be able to correctly identify flame presence.

The optical flame detection system used to identify flame presence is blinded by the presence of water and oil on its lens. Water, the product of combustion is present inside the combustor during the cold start up times and interferes with the proper functioning of the flame sensor. A flame sensor is comprised of an electronic circuit with an electromagnetic radiation receiver and converts it to voltage output. However, strong absorption by water occurs in the shorter wavelengths of light (UV region), which downgrades the performance of the sensor (Myher, Scholz and Severtson). Hence, during cold start up times when water is present inside the combustor the flame sensor send a false signal of no flame. This would activate the fuel shut off valve and stop fuel injection, which means the turbine shutdowns and a lot of revenue as well as time are lost to restart the turbine.

The team tested five difference sensors- GE Reuter Stokes, Ametek, Azbil, Forney and ITS to see how flame flicker, water-oil presence, and presence of background radiation affect their performance. Based on the results, this paper makes a recommendation for Siemens.

CHAPTER 2: LITERATURE REVIEW

Gas turbine manufacturers install flame detectors in combustors to monitor the flame presence. Conventional flame detector consisted of diffusion based smoke detection, rate of temperature rise detection, fire loops, etc. These methods had slow response times. Hence, optical flame detectors were introduced to detect electromagnetic radiation from a flame source. They have faster response times for less than 25 milliseconds (Myher, Scholz and Severtson).

2.1. Geiger Muller Tube

The most commonly used optical flame detector for gas turbine is the Geiger Muller tube (GM tube). However, it has some drawbacks. GM tubes have been useful in monitoring flameout conditions but have not been useful in detecting flashback because of their large size and lack of viewing area discrimination. GM tubes can usually respond to a flame on or flame out condition in about 100-200 milliseconds (ms) (Knoll). However, for modern gas turbines, this is considered to be extremely slow to effectively signal the appropriate control valves to stop the flow of fuel to the combustor, and thereby too slow to prevent damage to the engine. Another disadvantage of GM tubes is that they operate at very high voltage levels (>300V), which require special power supplies and can be dangerous to personnel (US NRC).

2.2. Thermocouple

To detect the flashback phenomena, the most commonly used sensors are thermocouple-based sensors, which utilize the most obvious characteristics of the flame, viz. the heat generated. Thermocouples specifically look for sharp temperature rises that are indicative of a flashback condition. However, they have relatively slow response (2-3 minutes) and can be damaged when exposed to higher temperatures (Measurement Specialities) (Nussbaum, Liptak and Pate). Since thermocouples are capable of measuring only local temperatures a large number of thermocouples are needed to provide an effective detection system in all areas of the combustor. It is also difficult, time consuming, and costly to repair if thermocouple becomes damaged during operation of the engine.

Consequently, the turbine industry needs a flame detection system that is reliable for accurately detecting both flame out and flashback conditions that is easy to install, provide fast time response, and minimize the number of installations in combustor. This is why optical flame sensors are introduced. They are designed to sense the absorption of light at specific wavelengths and can discriminate between flame and false alarms. The work done by others in the area of optical flame detection for gas turbines is described below.

2.3. Infrared Sensor

The IR sensors are good for detecting most flames, since infrared radiation is present in most flames. However, these flames are not the only source of IR radiation. Any hot surface emits IR radiation, which coincides with the flame IR wavelengths. Hence, some IR sensors have flicker and statistical analysis algorithms to minimize the effect from such black body sources. Some other IR sensors have an optical filter and a low frequency electronic band pass filter. However, these single frequency detectors respond only to a certain flicker and radiation, which correspond to the optical band filter. This causes false alarms. In order to minimize the false alarms, dual wavelength sensors such as UV-IR sensors are designed. They are not used in gas turbines because they are prone to false alarm as well.

Hence, UV sensors are introduced. UV sensors are good for detecting hydrogen and methanol fueled flames because these fires predominantly emit wavelengths in the UV spectrum (Zizak). They also have fast response times (typically 30 ms) (Nussbaum, Liptak and Pate). However, they are prone to false alarms from UV sources such as arc welding etc. Hence, they should be used in enclosed spaces. GE Flame Tracker, Ametek, and ITS detectors are UV sensors. They are described in more detail below:

2.4. General Electric Flame Tracker

To monitor the flame correctly inside the combustor, General Electric (GE) uses an ultraviolet (UV) flame sensor. The uniqueness of this sensor is described in patent US4039844A (March 20, 1975) in that its circuit has two responses, which are combined to provide an enhanced flame signal representative of the monitored flame (MacDonald). The GE flame sensor senses both higher and lower frequencies of the flame that are sensed along a line of sight, which passes through the root portion of the flame being monitored. It comprises of a silicon carbide (SiC) photodiode tube. The light from the flame reaches the photodiode and excites the electrons. When the energy of light exceeds the band gap of the material, the electrons separate, forming electron-hole pairs, which then produce a current. The reason for using a SiC photodiode is because SiC a band gap of 3.1 electron volt (eV), which corresponds to a response peak at about 270 nm in the ultraviolet region and has a wavelength limit of 400 nm (GE/Reuter-Stokes). The oxygen-hydrogen molecule emits a light of 310 nm during combustion, which lies well below the cut-off of SiC detector's wavelength of 400 nm (Chemistry Department, University of Florida) (Brown, Lombardo and Palmer). Furthermore, SiC can go up to very high temperatures, around of 2730 ^{0}C,before melting, which makes it suitable for flame detection (Casady and Johnson). Figure 2.1 shows the responsiveness of SiC photodiode as a function of the wavelength of light.

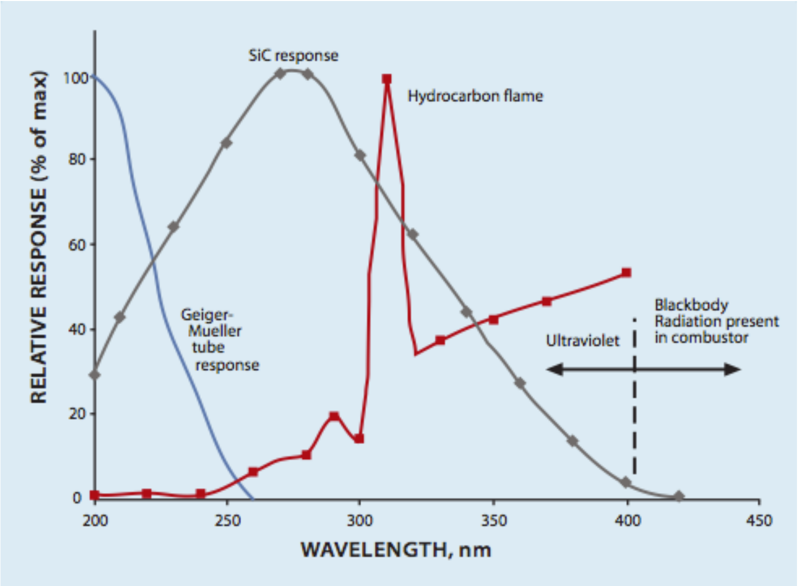

Figure 2.1. SiC Photodiode Performance vs. wavelength (GE/Reuter-Stokes)

2.5. Ametek Flame Sensor

Ametek, a flame detector manufacturing company has designed a UV sensor named Spectra^{TM} GT30 Flame Sensor. It receives energy from the ultraviolet region of flame and transmits a 4-20mA analog signal proportional to the flame intensity (Ametek Inc.). The uniqueness of this sensor is described in patent US005763888A (Jan 30, 1995) in that it has multiple preferred embodiments of a high temperature gas stream optical flame sensor. It temperature range is from -30^{0}C to 150^{0}C without cooling and up to 235^{0}C with cooling (Ametek Inc.). In one embodiment, the sensor is comprised of a detector assembly, amplifier assembly and an optical assembly (Glasheen, Cusack and Steglich). The additional embodiment consists of a detector, which is non-collinearly aligned with the optical lens. Furthermore, there is a mirrored optical block assembly, which directs the incident radiation onto the detector. The mirrors may be coated to reject the incident radiation with wavelengths greater than 270nm (Glasheen, Cusack and Steglich). Hence, this feature would not give false indications that flame is present when it receives longer wavelength radiations from another comparable brightness, such as the furnace wall or adjacent flame. This is desired in a flame sensor.

2.6. Industrial Turbine Services (ITS) Flame Scanner

The UV flame sensor designed by ITS uses a silicon carbide photodiode and a quarzglass window. Its temperature range is the same as that of the Ametek flame sensor and its spectral sensitivity is from 210-380nm (ITS- Industrial Turbine Services). This sensor was introduced in 2012 and no patents have been filed yet. However, its components are the same as the other sensors and hence the performance should be similar as well.

Based on the previous work done, it is evident that a UV sensor is the best approach to solve our problem. A SiC photodiode peaks at the right wavelengths, which makes is suitable for turbine use. To see which sensor is the best, a series of tests would be done on the sensors. The sensor with best results would be suggested to Siemens. The method used to carry the tests is describe in the section below.

CHAPTER 3: METHODOLOGY

Three series of tests (chopper wheel, water-oil, and infrared) were done to evaluate the performance of GE Reuter Stokes, Ametek, Forney, ITS and Azbil flame sensor. I did the chopper wheel test and water- oil test with another team member, and the results were analyzed together. However, all the tests and results are mentioned in this report so that final conclusion can be reached.

3.1. Materials

Five UV flame sensors- GE Reuter Stokes, Ametek, Forney, ITS and Azbil were used to perform the test. The criterion for choosing the sensor was based on its operating temperature and the range of wavelength detection. The details are summarized in Table 3.1. The tests were carried out in 33 Hesse Hall of UC Berkeley. A Bunsen burner was used to emit a flame and a spectrometer was used to measure its spectral emission. Clamp stands were used to hold sensors and a 24V DC power supply was used to power the flame sensors. A chopper wheel with varying frequency (15Hz-200Hz) was used mimic the flame flicker. To carry out the oil and water test, an additional container was custom made, which had adjustable quartz lens at both ends to give different oil and water thickness. No. 2 diesel was used since it is this diesel that builds up in front of the lens in gas turbines. For infrared test, a propane torch was used to heat the steel until it was red-hot. The spectrometer was used to know the exact spectral emission of the infrared waves from the red-hot steel. To record the output a DAQ (digital acquisition) board was used, which converts the output into digital numeric values. These results were then plotted with the help of Labview and Microsoft Excel to carry out frequency analysis.

Table 3.1. Properties of Sensors

Name	Temperature (with cooling)	Detection Range	Cost ($)
Target	450 ^{0}C	UV	-
GE	150 ^{0}C (235 ^{0}C)	UV (200-400 nm)	3800
Ametek	125 ^{0}C (371 ^{0}C)	UV (200-400 nm)	1800
Forney	65 ^{0}C (400 ^{0}C)	UV (295-340 nm)	1400
ITS	150 ^{0}C (235 ^{0}C)	UV (210-380nm)	4000
Azbil	100 ^{0}C	UV (200-400 nm)	N/A

3.2. Methodology

All the flame sensors were placed so that they faced a flame set 10’’ away. The height of the flame sensor varies depending on its lens position; hence it was ensured (by using a ruler as a reference) that the entire lens could see the blue cone inside the flame (fig. 3.1). The advantage of this set up is that all the sensors can be tested simultaneously, giving consistent results and saving time. The sensors were connected as shown in fig.3.2. A 390-Ω resistor was used to complete the DAQ circuit. This was chosen based on the current output range of the sensor and the optimum voltage output of the DAQ board. All sensors performed in the range of 20-40mA and the maximum voltage of the DAQ board was 10V. Based on the results of ohm’s law (V=IR) a 390-Ω resistor was used. (Ametek Inc.) (GE/Reuter-Stokes) (ITS- Industrial Turbine Services). The code used in lab view converts signal to graphical form (Appendix A). Once this preparation was done, the flame was turned on and the airflow was adjusted until the inner blue cone of the flame was seen. To identify the flame on voltage, the flame sensor viewed the flame and the data was recorded on Labview. To find the flame off voltage, we put a hand in between the flame and the sensor. It was assumed that the hand would not allow radiation to pass through and wouldn’t get hot quickly enough as to act like a secondary radiation source. This data was recorded on Labview as well. The procedure for each test is described below.

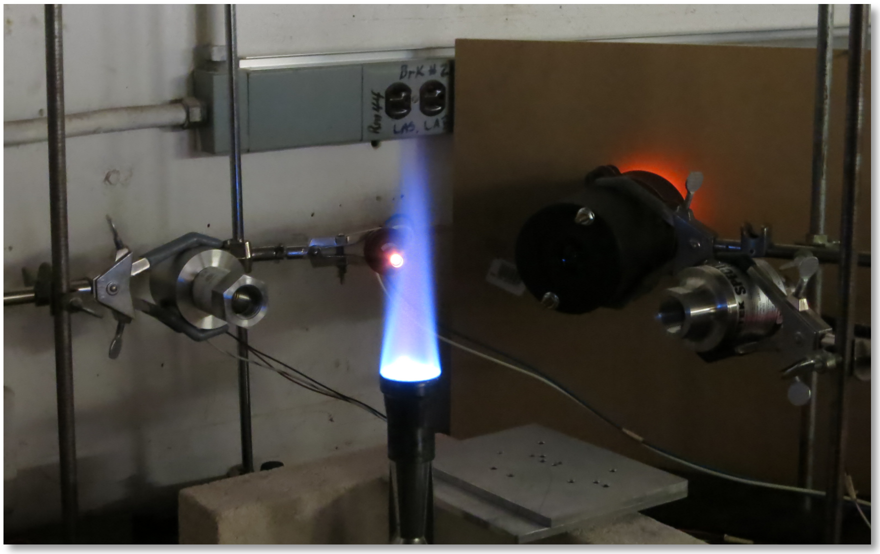

Figure 3.1. Horizontal test set up

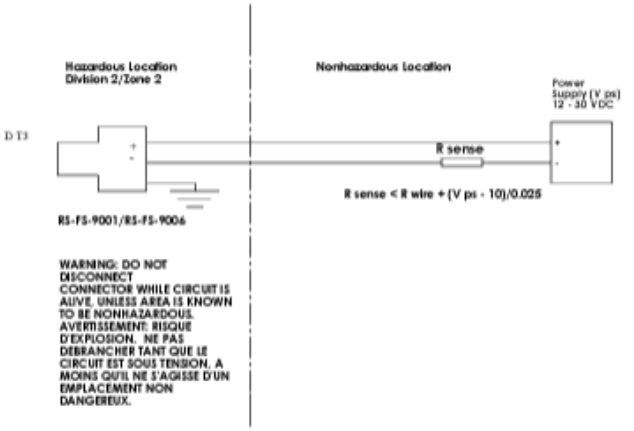

Figure 3.2. Connection from flame sensor to the power supply and DAQ board (GE/Reuter-Stokes)

3.2.1. Sensor Sensitivity Test

The motivation for this test was to identify the sensor with fastest response time. A chopper wheel was placed between the flame and the sensor (fig. 3.3). The chopper wheel was made to rotate at different frequencies ranging from 15Hz to 200 Hz. The lower frequency corresponds to lower flame flicker and vice versa. With this, it was possible to see how sensors are able to match up with the chopper wheel frequency. The data was collected through Labview, and analyzed in Excel. It should be noted that flame flicker is especially important for IR flame sensors because they rely on flicker to differentiate between radiations from flame and from black body source. UV sensors, on the other hand, rely on UV radiation emitted from the flame. This test would help determine the response time of each sensor.

Figure 3.3. Chopper Wheel Test Set up

3.2.2. Oil and Water Test

The motivation of this test was to see how much water and oil buildup would be required for a sensor to shut down and give false feedback. The chopper wheel from Test 2 was replaced with a container containing water. The container was aligned such that the sensor looks directly through the quartz lens (fig.3.4). The data was recorded at 4’’, 5’’ and 5.5’’ water thickness. Same procedure was repeated for thin film and a quarter inch oil thickness.

A spectrometer was used to determine the wavelengths are absorbed by water. To do this, a container filled with water was placed between the flame and the spectrometer and the results were recorded. The same process was repeated to determine absorption by oil.

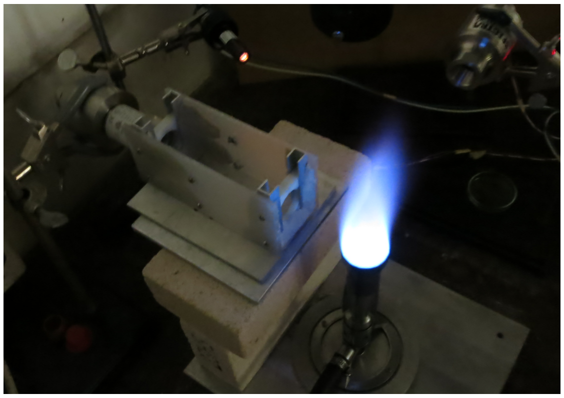

Figure 3.4. Oil-Water Test Set up

3.2.3. Infrared Background Test

The details of this test are not included in this paper since I did not carry out this test. However, the method and results are included in Appendix D for reference.

3.3. Methodological issues encountered

The problem encountered was to figure out the way of aligning all the sensors. The first option was to mount the sensors vertically below the flame, which is at a 45 degrees angle to the viewing tube. This option was appealing because of two reasons. Firstly, having the flame at a 45-degree angle provides dynamic flame flicker signal needed for the evaluation (Shepherd, Cheng and Day). Secondly, a vertically aligned viewing tube allows for accumulation of water and oil on the lens. The disadvantage, however, is that none of the sensor are designed to accumulate enough oil and water in front of its lens. Therefore, the vertical set up was not preferred.

The problem was addressed by using a set up where sensors were placed horizontally, all looking at the flame simultaneously (fig.3.1). The advantage is that it is more consistent, quicker and avoids repetitiveness. However, the major problem encountered regarded testing with oil and water. The requirements demanded the container to have a flat edge, be adjustable, and made out of material, which does not attenuate the signal. A standard glass container couldn't be used because glass absorbs signal. This problem was addressed by making a custom made container with adjustable quartz lens. Quartz lenses were used because they do not absorb any UV signal. This custom made container addressed the issue of oil and water container.

CHAPTER 4: DISCUSSION

The results and discussion of the test are summarized below:

4.1. Chopper Wheel

The results of chopper wheel test (Table. 4.1) show that ITS and Ametek take the same amount of time to reach their respective maximum voltages while GE takes a little longer. The response times from three trials of GE, ITS and Ametek sensor (fig 4.1) show that ITS and Ametek have steep slopes. Hence, they can reach 80% of their maximum voltage faster than GE. The GE sensor takes a few milliseconds more but it is still comparable to the response times of Ametek and ITS. Any sensor with response time less than 25millisecond is considered to be a fast sensor.

From the raw data (Appendix B, fig.1-5), it was also concluded that all sensors match the chopper wheel frequency until 50 Hz. The sensors are unable to reach their minimum voltage after 50 Hz. Consequently; the range (the difference between the maximum and minimum voltage) decreases with frequency increase. It can be deduced that all three sensors (GE, Ametek and ITS) would give accurate response if flame flicker is below 50 Hz. Overall, the results indicate that all the UV sensors have fast response times and can match up with the chopper wheel frequency quickly.

Based on this test, the recommendation to Siemens would be a GE, Ametek or ITS sensor.

Table 4.1. Actual and Observed Response Times of all Sensors

Sensor	Specified Response Time	Observed Response Time

Azbil	N/A	6.4s
GE	<25ms	19.6ms
ITS	<20ms	16.3ms
Ametek	<25ms	16.3ms
Forney	2.5s	>0.1s

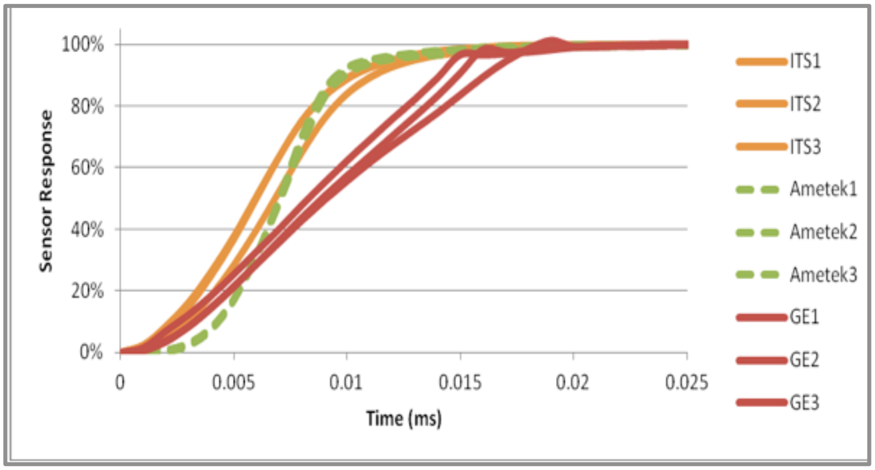

Figure 4.1. Response time for each sensor at 20Hz chopper wheel frequency

4.2. Water-Oil Test

The spectrometer data (fig. 4.2) shows that water absorbs more than half of radiation intensity in UV region but has no absorption in the IR region. The raw data of water-oil test for all sensors presented in Appendix C (fig. 1-5) shows that Ametek, ITS and GE did well while Forney and Azbil reported flame off. Amongst Ametek, ITS and GE, ITS has higher transmission at all water thickness. The percent transmission of radiation of all the sensors is summarized in Table 4.2. From the theoretical absorption spectrum of water graph (Appendix C fig. 8), it can be seen that liquid water absorbs in ultraviolet and near infrared region the most. Hence, it wasn't surprising that the sensors could not report the maximum voltage.

The Beer-Lamber Law can be used to explain why transmission of light decreases when it passes through water. The collisions between photons and atoms of water result in absorption and scattering of photons, which in turn attenuates the radiation. In our case, we would only be considering absorption because it shows how quickly the wavelength loses intensity due to absorption alone. The theoretical transmitted radiation can be calculated using the Beer-Lambert Law:

$$I = I_0 e^{-\alpha x} \tag{1}$$

where I and I_0 are the transmitted and incident radiation intensities, and α is the attenuation coefficient. With this equation, one can find the maximum thickness of water buildup allowed at particular flame off threshold. This analysis was not done since the flame-off threshold was not known.

For the oil test, all sensors indicate flame off with ¼ inch of oil but show some response if it is thin film oil (Appendix B fig 6, 7). The reason is that oil absorbs almost all of the radiation in the UV region but very little in IR (fig. 4.2). Again, it can be seen that GE, Ametek and ITS have similar performances when a thin film of oil is present. However, all of them give a flame off signal when oil buildup increases. Hence, UV sensors are not suitable if more than thin layer of oil is present inside the combustor.

The reduction in sensitivity when the window of the IR sensor is contaminated is presented in Table 4.3 (Flame Detector User Manual). It can be seen that the IR sensor has 75% transmission with water and about 85% transmission of signal with oil. Therefore, a UV sensor is good for water contamination but an IR sensor is good for oil contamination.

Based on the water-oil test, *the recommendation to Siemens would be to use GE, Ametek or ITS sensor if water buildup is an issue. Either of the sensors is fine because they transmit about 95% at all thickness of water. If only oil is present, UV sensors do not perform well and* *hence an IR sensor should be used. . However, if both oil and water is present, an IR sensor should be used in conjunction with a UV sensor.*

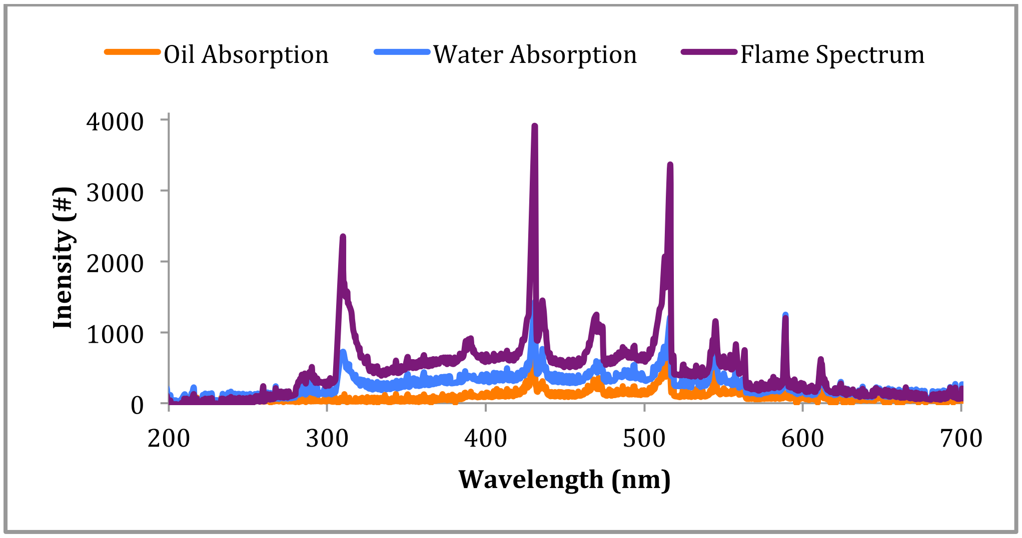

Figure 4.2. Absorption of spectra from water and oil

Table 4.2. UV Detector Window Contamination

Sensor	**Water**			**Oil**	
	4 inch	**5 inch**	**5.5 inch**	**Thin Film**	**¼ inch**
Azbil	37%	35%	32%	41%	0%
GE	98%	97%	95%	94%	0%
ITS	98%	97%	97%	90%	0%
Ametek	96%	96%	94%	91%	0%
Forney				43%	0%

Table 4.3. IR Detector Window Contamination

Contamination	**Typical percentage of normal response**

Water spray	75%
Steam	75%
Smoke	75%
Oil film	86%

CHAPTER 5: CONCLUSION

The main problem the project was to find a reliable flame sensor for gas turbine, which would improve turbine's reliability and safety. From this project, it was concluded that UV sensors had all the desirable qualities of being able to correctly identify flame presence with water contamination and had fast response times. Based on the results, ITS or Ametek sensor was recommended to Siemens.

The project had several strengths and some shortcomings. The strength of the project was that we were able to mimic the turbine wall radiation and carry out the oil tests, both of which were extremely difficult to do. A shortcoming of the project would be the inability to test robustness of flame sensors. For example, all the tests were done in a stable environment condition with no vibrations and dust/smog, which is far different from the real working environment of sensors. Another weakness was to not test sensors with flame as big, as intense, and as hot as the actual flame inside the combustor. However, given the constraints of the experiment, best results were achieved and were as expected.

As future work, we plan to improvise this technology by incorporating fiber optic cables to transmit the spectral energy from the combustion process to the electronics unit. This feature would allow of remote mounting of the electronics thereby eliminating complex and expensive cooling systems usual in flame sensors. Additionally, we plan to explore the applications of this technology to other industries such as the ones that use highly flammable solvents such as Methyl Isobutyl Ketone (MIBK).

REFERNCES

Ametek Inc. "SpectraTM GT30 Gas Turbine Flame Sensor." Manual. 2005.

Brown, Dale, et al. "Experience Using Flame Tracker." General Electric, 2006.

Casady, J. B. and R. W Johnson. "Status of Silicon Carbide (SiC) as a Wide- Bandgap Semiconductor for High-Temperature Applications: A Review." Solid-State Electronics 39 (1996).

Chemistry Department, University of Florida. 15 April 2013 <http://www.chem.ufl.edu/~itl/4411L_f00/OH/OH.html>.

"Flame Detector User Manual." www.talentum.co.uk. 01 May 2013 <http://www.talentum.co.uk/wp-content/uploads/2009/07/FD-User-Manual.pdf>.

GE/Reuter-Stokes. Flame TRacker SiC Two Wire Flame Sensor (4-20mA), Operation and Maintenance Manualand M. Manual. Twinsburg: Reuter-Stokes, 2003.

Glasheen, William M., et al. High Temperature Gas Stream Optical Flame Sensor and Method for Fabricating Same. United States of America: Patent 5763888. 27 July 1999.

ITS- Industrial Turbine Services. "Technical Specification Flame Scanner- ITS 184X0254M029." Technical Specification Manual. 2013.

JSC "Electronstandart-Pribor". "Fire Detection Introduction." www.esp.com.ru. 01 May 2013 <http://electronstandart-pribor.com/shared/docs/pres.pdf>.

Knoll, Glenn F. Radiation Detection and Measurement. Third. John Vilegy and Sons, 2000.
Lieuwen, Tim, et al. "Fuel Flexibility Influences on Premixed Combustor Blowout, Flashback, Autoignition, and Stability." Journal of Engineering for Gas Turbines and Power 130 (2008).

MacDonald, Malcolm F. Flame Monitoring System. United States of America: Patent 4039844. 2 August 1977.

Measurement Specialities. Temperature Sensors: Advantages and Disadvantages. Electronic. Dayton, October 2003.

Myher, Douglas C., et al. Apparatus for Detecting Flame Conditions in Combustion Systems. United States of America: Patent 5961314. 5 October 1999.

Nussbaum, R, B. G. Liptak and S Pate. "Flame, Fire, and Smoke Detectors." Instrument Enginer's Handbook, Process Measurement and Analysis. Vol. I. CRC Press, 1995.

Schneider, Donald A. and Leo Lombardo. Flame Sensor with Dynamic Sensitivity Adjustment. USA: Patent 6013919. 11 January 2000.

Shepherd, I.G., R.K. Cheng and M.S. Day. "The Dyanamics of Flame Flicker in Conical Premixed Flames: An Experimental and Numerical Study." Publication. Lawrence Berkeley National Laboratory, n.d.

US NRC. Intrumentation.

Wikipedia. 01 May 2013 <http://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water>.

Zizak, Giorgio. Flame Emission Spectroscopy: Fundamentals and Applications. Istituto per la Tecnologia dei Materiali e dei Processi Energetici. Milano, n.d.

APPENDIX A: Lab view Code

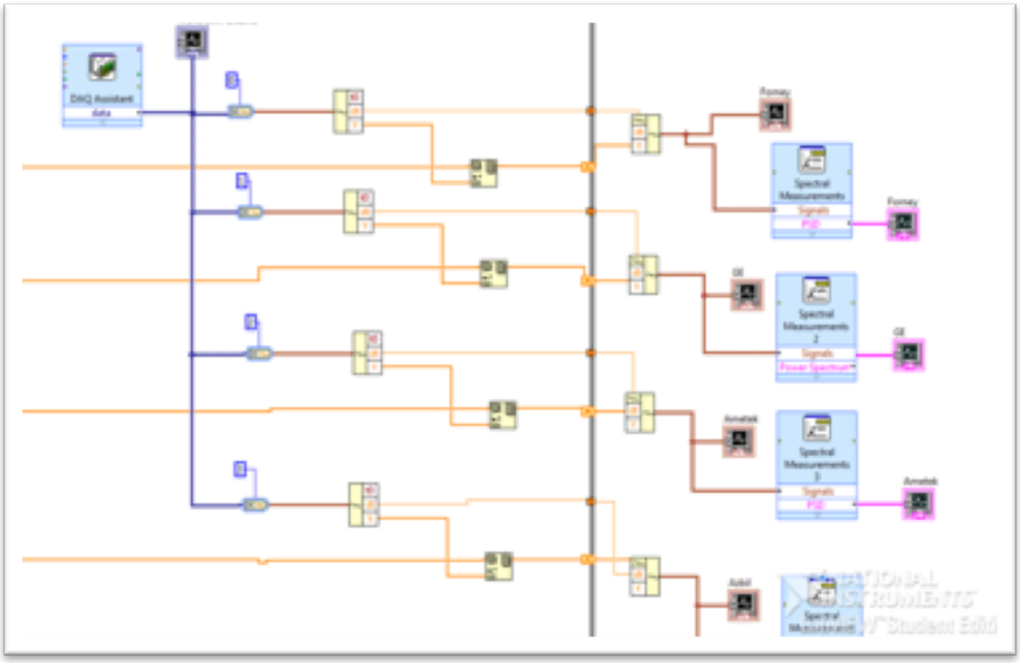

Figure 1. Lab view Code

Appendix B: Chopper Wheel Test Data

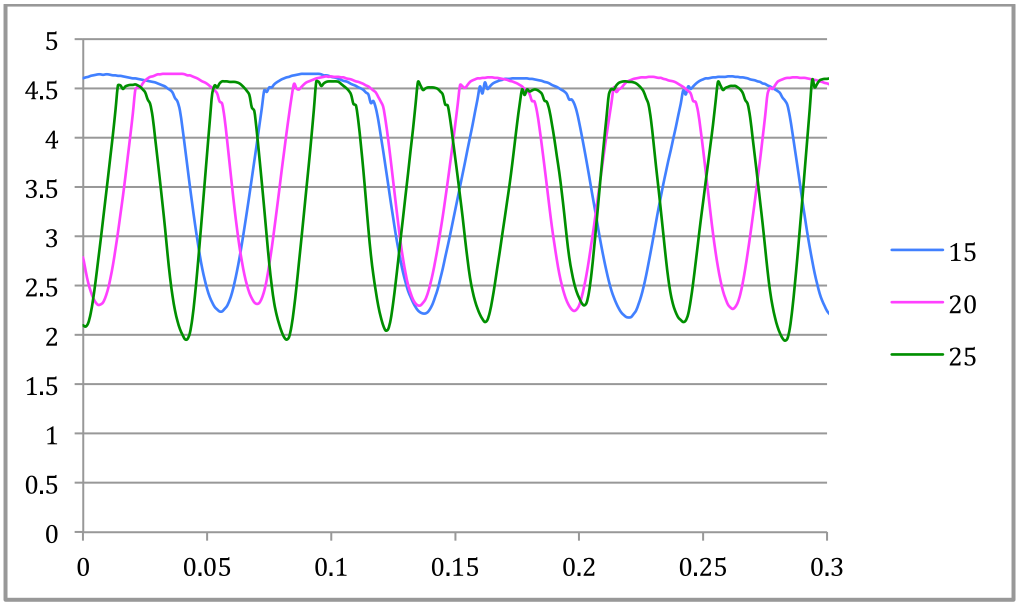

Figure. 1. Chopper Wheel Test data for GE at 15, 20 and 25 Hz

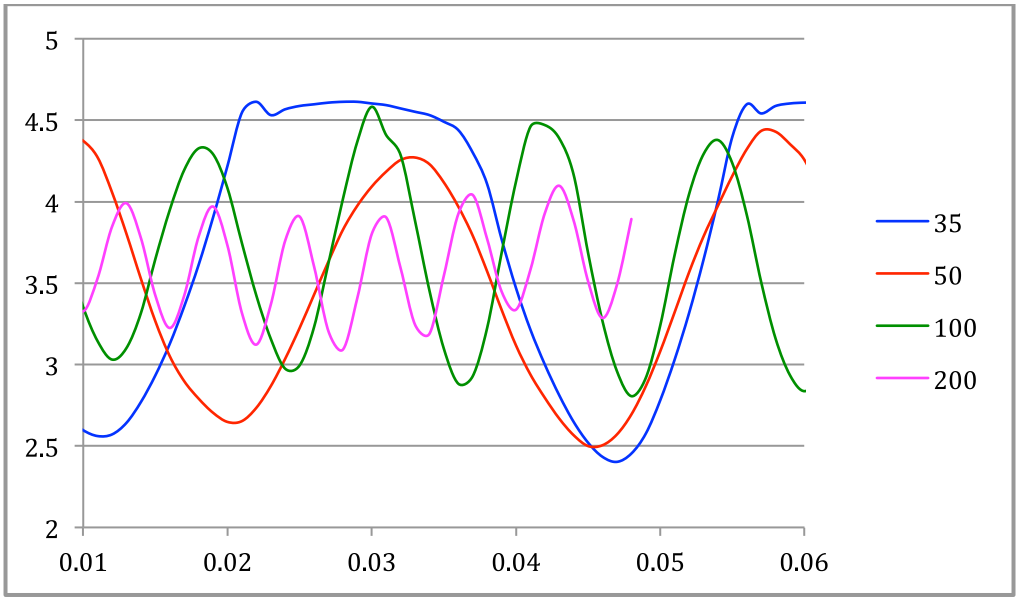

Figure 2. Chopper wheel test data for GE at 35, 50, 100 and 200 Hz

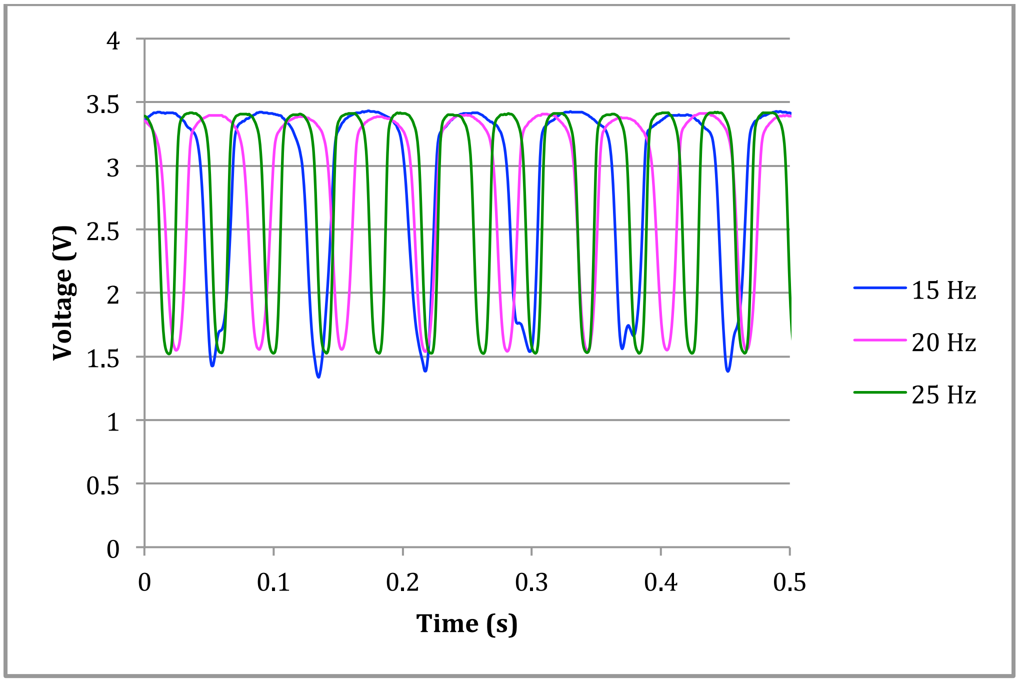

Figure 3. Chopper wheel test data for Ametek at 15, 20 and 25 Hz

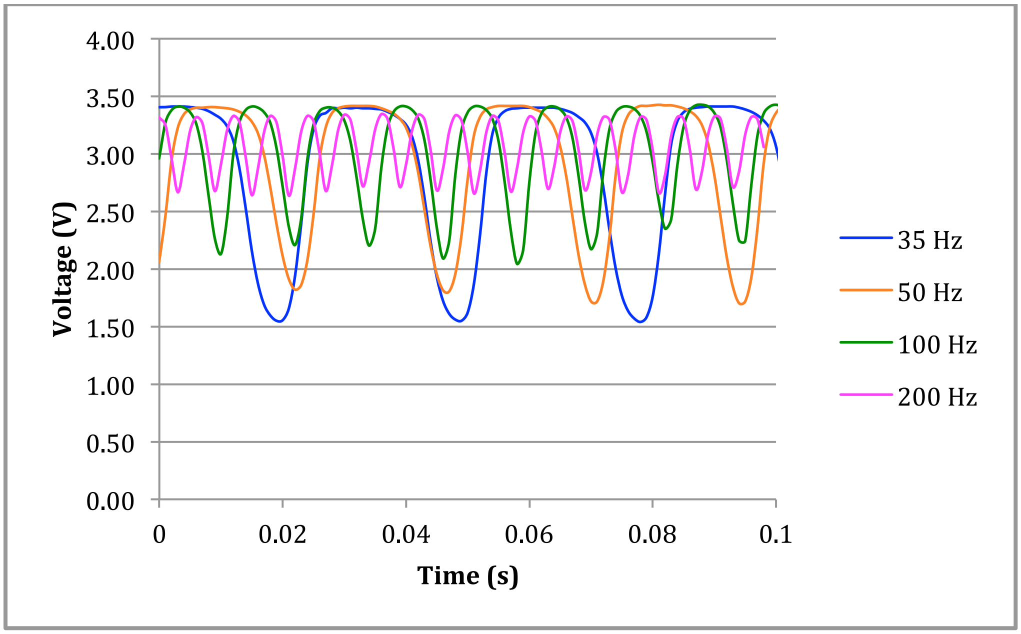

Figure 4. Chopper Wheel Test Data for Ametek at 35, 50, 100 and 200 Hz

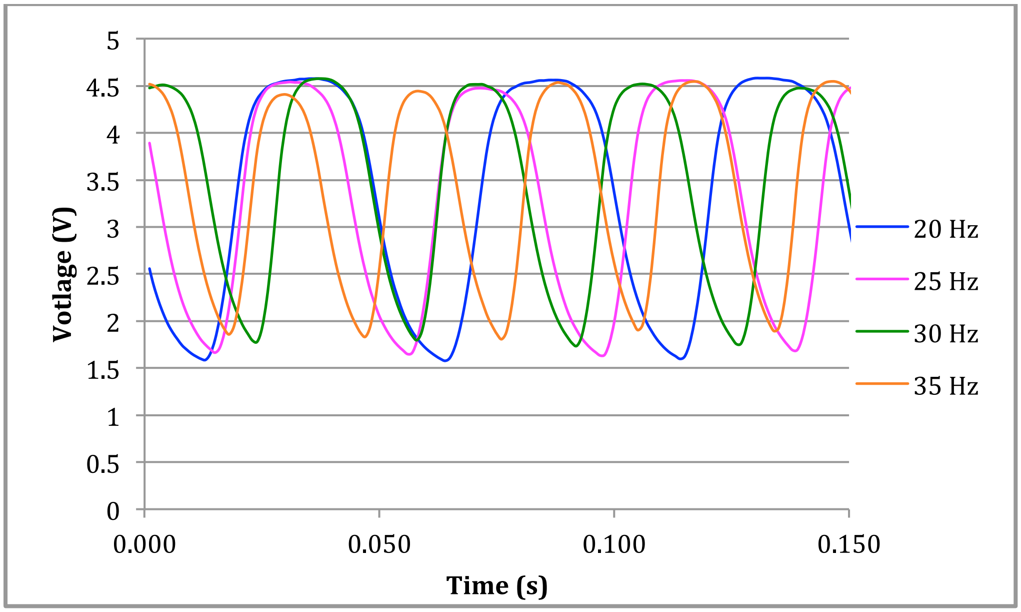

Figure 5. Chopper Wheel Test Data for ITS sensor at 20, 25, 30 and 35 Hz

Appendix C: Water - Oil Test Data

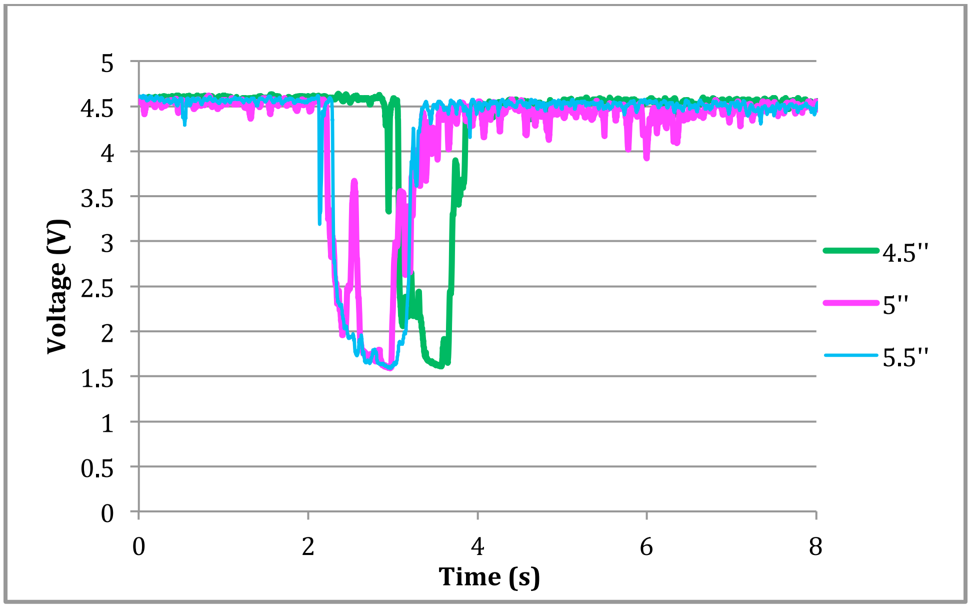

Figure 1. Water Data for GE sensor at 4.5'', 5'' and 5.5'' buildup

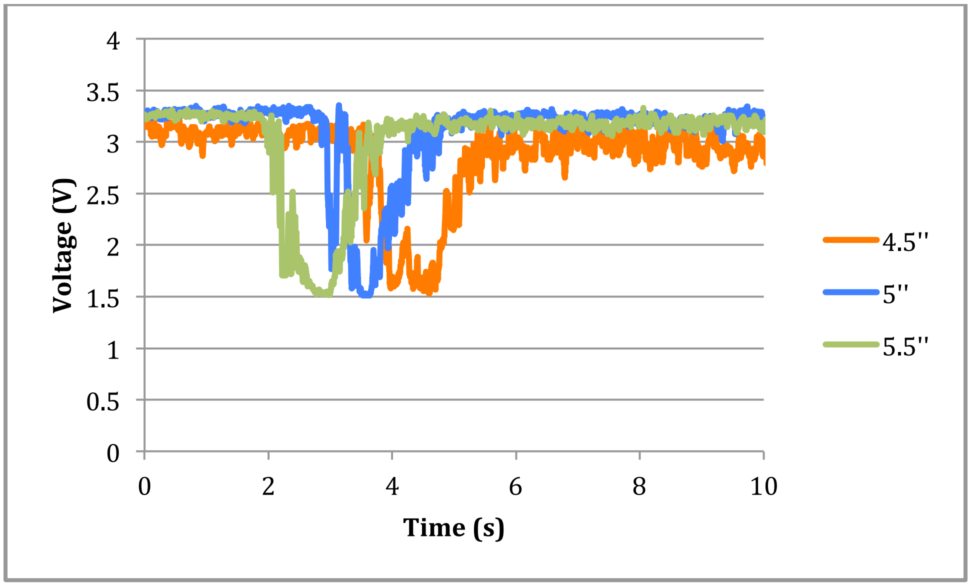

Figure 2. Water Test Data for Ametek at 4.5'', 5'' and 5.5'' buildup

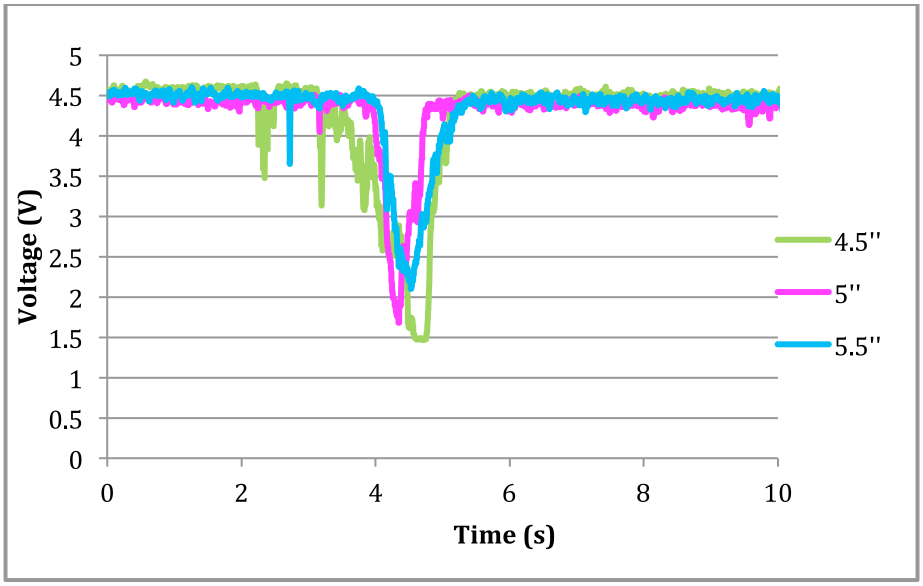

Figure 3. Water test data for ITS sensor at 4.5'', 5'' and 5.5'' buildup

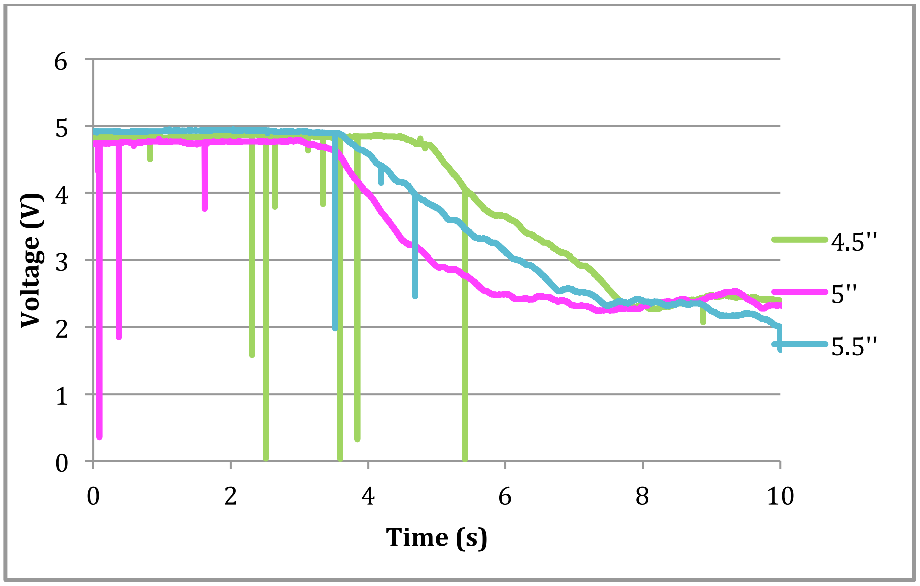

Figure 4. Water test data for Azbil at 4.5'', 5'' and 5.5'' buildup

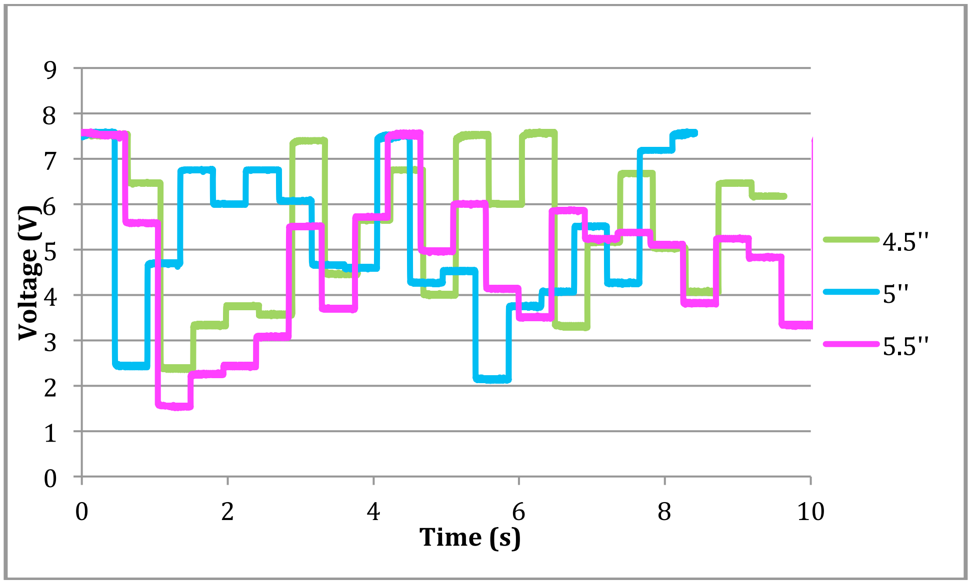

Figure 5. Water Test Data for Forney at 4.5'', 5'' and 5.5'' buildup

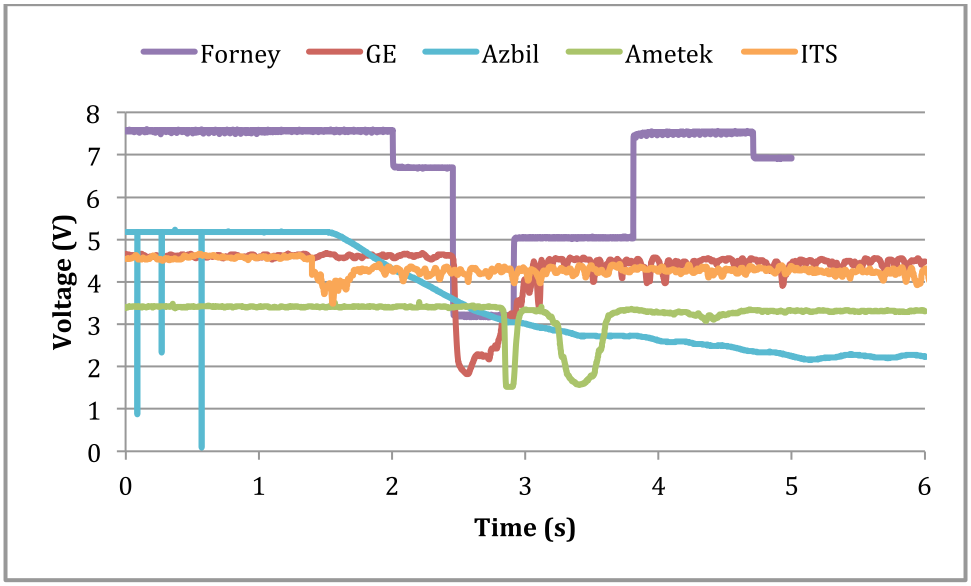

Figure 6. Oil Test Data for all sensors at thin film buildup

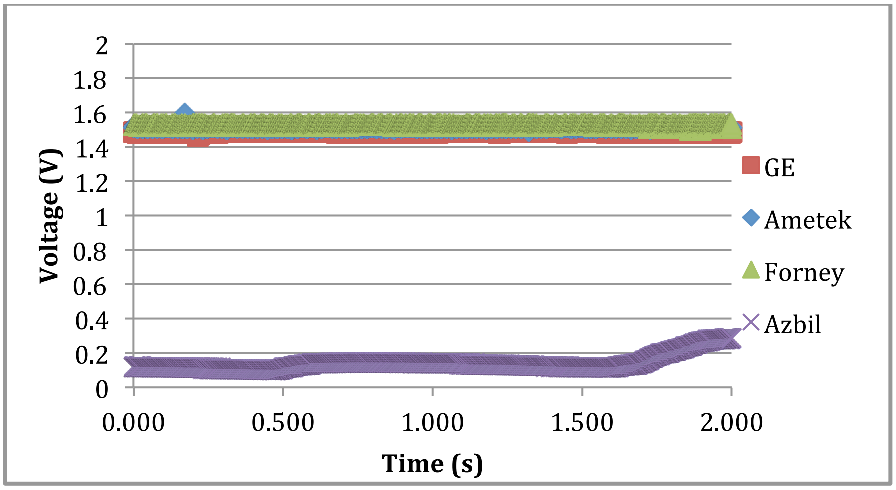

Figure 7. Oil Test Data for GE, Ametek, Forney and Azbil sensor at ¼’’ oil buildup

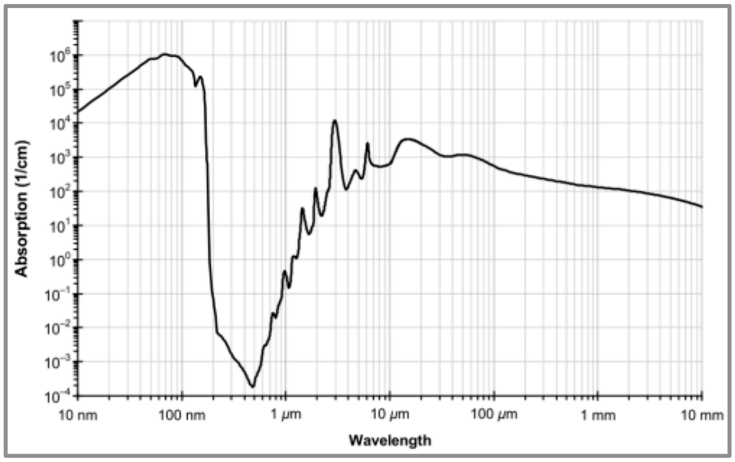

Figure 8. Water Absorption Spectrum of liquid water (Wikipedia)

Appendix D: Infrared Test Description

Method

The objective of this test is to simulate hot combustor walls and see if the sensors report flame on or flame off. For this test, a propane torch was used to heat the steel plate. Once red-hot, the spectrometer was used to study its spectral emission. The hot steel plate was placed in front of the sensor and the sensor response was recorded like the previous tests (fig. 3.5). The results were analyzed in Excel.

Furthermore, to study which wavelengths contributed the most to the output for each sensor; a glass filter was put in front of the flame sensor. The data was recorded and graphed in excel.

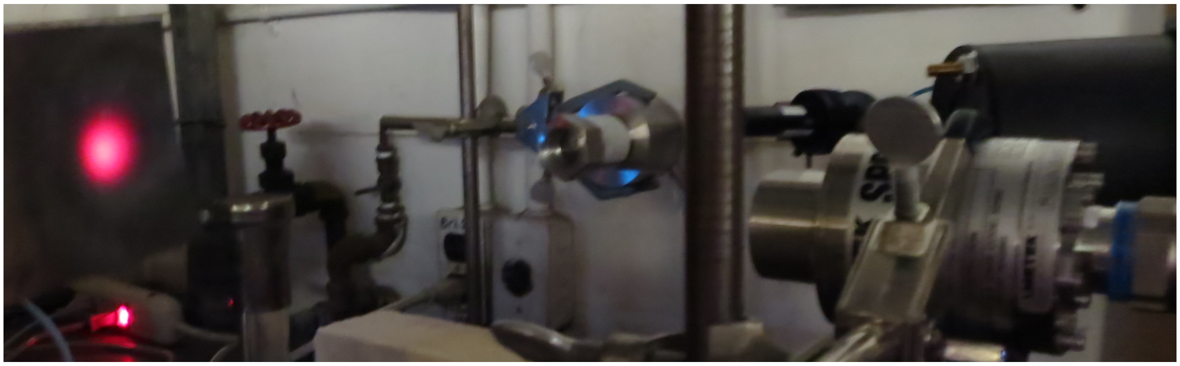

Figure 1. Infrared Test Setup

Results

The infrared spectrum test shows that the IR wavelengths dominate radiations from the red-hot steel (fig. 2). All sensors, when exposed to IR wavelength (fig. 3) indicate flame-off voltage. The flame off voltages of all the sensors is listed in Table 1. Hence, this test verifies that none of these sensors respond to wavelengths higher than 600 nm i.e. the infrared radiations. Consequently, using a UV sensor solves the problem of false feedback from longer wavelength radiations from furnace walls. However, there is a limitation of this test. The steel emits wavelengths of 650-900nm. All of these sensors claim to detect within 210-400nm. Hence, it is not sure whether the sensors are sensitive to wavelengths between 400-650nm.

The limitation of this test is that we weren't able to heat the steel plate until temperatures were as high as turbine walls would be. The maximum of the intensity shifts to shorter wavelengths as the black body temperature increases (fig. 4). It can be seen from fig. 4 that temperatures need to be greater than 6000K to start emitting radiation in shorter wavelengths (JSC "Electronstandart-Pribor").

Additionally, the results of using a glass filter (fig. 3) indicate that the glass filter attenuates radiation in the UV region. The calculation shown below helps in identifying contribution of 310 nm wavelength to the flame sensor output.

$$1 - \left(\frac{4.68-1.98}{2.73-1.98}\right) = 0.72 \text{ (For GE sensor)}$$

From this calculation, it can be seen that 310nm wavelength contributes to about three-fourths of the output voltage for GE sensor. The radiation at 310nm no longer contributes to the output while using glass because glass filters out that wavelength. This leads to a significant drop in voltage of GE sensor. This result is consistent with the information given in GE patent (US 6013919A), which claims that the sensor detects EM radiation having a wavelength in the range of about 190-400nm (Schneider and Lombardo). Similarly, 310 nanometers wavelength in the EM radiation contributes to about 70% of final output of ITS sensor. On the other hand, Ametek sensor is not so sensitive to the 310 nm peak. This fact is also consistent with Ametek patent (US 5929450), which claims the spectral range of sensor of about 190-400 nanometers, preferably within the UV range of from about 190-270 nanometers (Glasheen, Cusack and Steglich).

Based on this test, the recommendation to Siemens would be to use either a GE, ITS or Ametek flame sensor because they don't cause false alarms. If the actual spectrum of the flame inside the combustor consists of a 310nm peak, use a GE or ITS sensor because they are more sensitive to that peak. For example, if the 310nm peak disappears when the flame is not present, the sensors would detect flame off instead of flame off, thus making gas turbine operation safer.

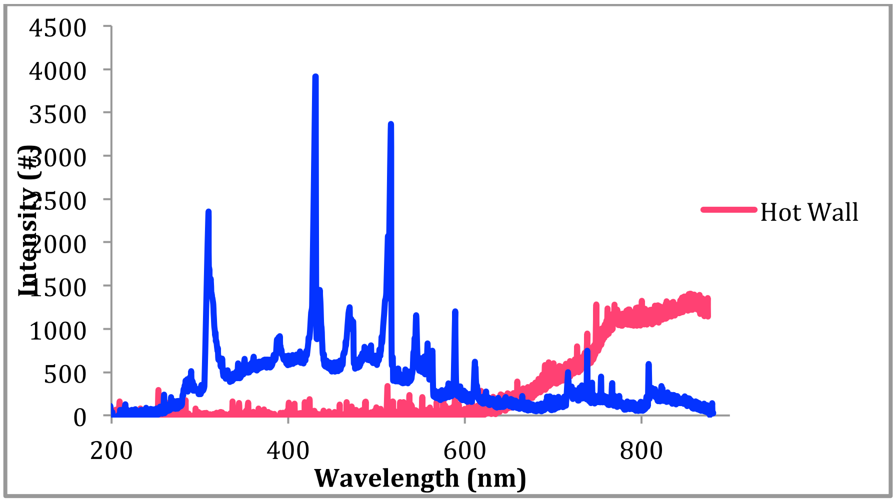

Figure 2. Emission spectra from the hot wall

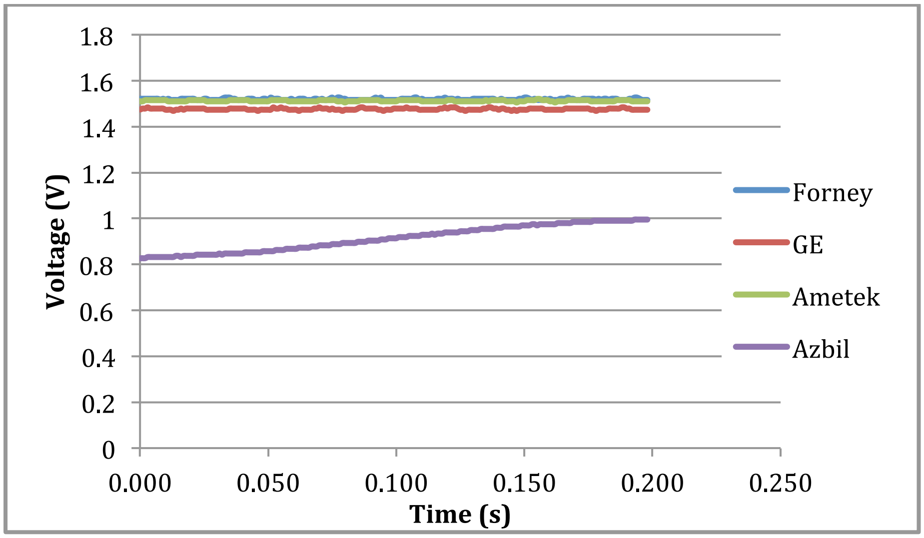

Figure 3. Response of flame sensor with IR radiation background

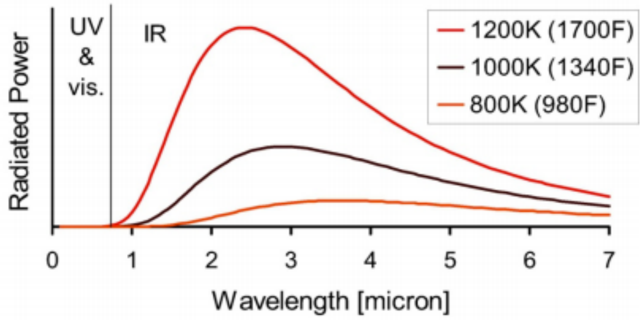

Figure 4. Spectral intensity distribution of Plank’s Black Body radiation (JSC "Electronstandart-Pribor")

Table 1. Flame On and Flame Off Voltage for different sensors

Sensor	Flame On Voltage	Flame Off Voltage	Filtered Signal (V)	310nm Sensitivity
GE	4.68	1.98	2.73	72%
Ametek	3.43	1.56	2.53	48%
Azbil	5.22	0.84	0.1	100%
Forney	7.81	1.56	1.56	100%
ITS	4.74	1.56	2.54	69%

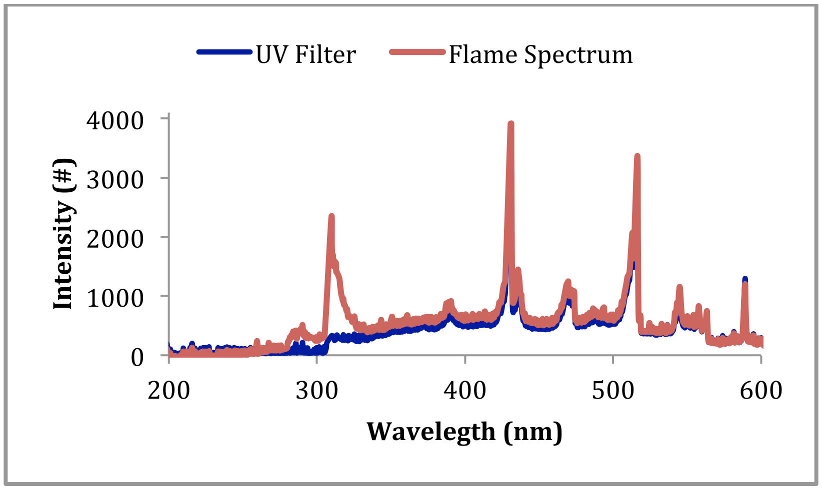

Figure 5. Flame spectrum with and without UV filter-glass