FABRICATION AND CHARACTERIZATION OF PHOTODIODE FLAME DISTANCE SENSOR

FABRIKASI DAN KARAKTERISASI SENSOR JARAK API FOTODIODA

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ABSTRACT

The flame distance sensor is designed to use when open flaming fires occur. It responds to the light emitted by flame during combustion. The detector discriminates between flame and other light sources by responding only to particular optical wavelengths. The physical quantity that can be used as a reference for determining the distance of the flame is the intensity of radiation emitted by the flame. Intensity of radiation can be measured by the photodiode output, when the photodiode receives the radiation. In this research, the writers propose to develop a new prototype of simple, low-cost flame sensing device using a photodiode. The photodiode is integrated with an infrared filter, which is made of black film inside the floppy disk, to block certain wavelengths other than infrared. The photodiode is operated in photoconductive mode, where a positive regulated DC power supply is connected to the cathode. The anode is connected to the output terminal and a resistor that acts as a voltage divider. The voltage will be changed at the output terminal as the photodiode receives different intensity of radiation. The relationship between output voltage and intensity can be obtained and verified by using a calibrated lux meter. The radiation intensity is inversely proportional to the square of the distance from the radiation source. Given this relationship, the distance can be calculated with a flame coming from the photodiode output. As the result, the maximum detection distance and intensity of the sensor is 107 cm and 1783 lux.

Keywords: characterization, filter, flame distance, infrared, photodiode, sensor

ABSTRAK

Sensor jarak api ini dirancang untuk digunakan pada saat terjadi kebakaran. Sensor ini menerima cahaya yang dipancarkan oleh api selama pembakaran. Detektor dapat membedakan sumber cahaya seperti api dan sumber cahaya lain dengan hanya merespons panjang gelombang optik tertentu. Besaran fisis yang dapat dijadikan acuan untuk menentukan jarak api adalah intensitas radiasi yang dipancarkan oleh api. Intensitas dari radiasi dapat diestimasi dengan keluaran fotodioda ketika fotodioda menerima radiasi tersebut. Dalam penelitian ini, penulis mengusulkan untuk mengembangkan prototipe baru, murah, dan sederhana, berupa perangkat penginderaan jarak api yang terbuat dari fotodioda. Fotodioda ini terintegrasi dengan filter inframerah, yang terbuat dari film hitam dalam floppy disk*, yang digunakan untuk memblokir panjang gelombang tertentu selain inframerah. Fotodioda dioperasikan dalam mode fotokonduktif, di mana sumber tegangan positif DC terhubung ke katoda. Anoda terhubung ke* output *terminal dan resistor bertindak sebagai pembagi tegangan. Tegangan pada terminal* output *akan berubah ketika fotodioda menerima intensitas radiasi yang berbeda. Hubungan antara tegangan dan intensitas* output *dapat diperoleh dan diverifikasi dengan menggunakan meter lux yang sudah terkalibrasi. Intensitas radiasi akan berbanding terbalik dengan kuadrat jarak dari sumber radiasi. Dengan adanya hubungan tersebut, jarak api dapat dikalkulasi dari keluaran yang berasal dari fotodioda. Sebagai hasilnya, jarak dan intensitas deteksi maksimum yang dapat diukur oleh sensor adalah 107 cm dan 1.783 lux.*

Kata Kunci: *karakterisasi, filter, jarak api, inframerah, fotodioda, sensor*

1. INTRODUCTION

The use of diode has become a state of the art for measuring physical quantities. Specifically, there are some of these advanced technologies which use a photodiode.[1–5] Photodiode is used to convert the electromagnetic rays to several physical properties, such as current and output voltage, depended by the operating mode of the photodiode itself.[6] The physical quantities that can be used as a reference for determining the distance of the flame is the intensity of radiation emitted by the flame. Intensity of radiation can be estimated by the photodiode output, when the photodiode receives the radiation. Several ways of sensing flame are known. One of them is disclosed by Muller in his patent named U.S. Pat. No. 3,742,474. In this patent, Muller discloses a flame detector which comprises of photosensitive transducer such as photodiode. His flame detector is set to be sensitive to the radiation emitted by flame. His device can discriminate radiation from a random flame by picking a higher proportion of an infrared radiation. By discriminating the radiation, the correlation of the physical properties of the flame and the detector can be determined.[7]

Inspired by this patent, the writers propose to develop a new prototype of simple, low-cost flame sensing device using a photodiode in photoconductive mode. In order to limit the current from a certain radiation, it needs such a simple yet useful filter made from used material. In contrast with several commercial products, the proposed flame distance sensor does not contain electrical signal conditioning blocks because of its simplicity. Instead, the infrared filter has been used to block radiation wavelength other than infrared, which can minimize electrical noise made by photodiode. In several commercial products, however, the ultraviolet filter has been used to determine the temperature range of the flame, which is commonly used in oil and gas flame detector.

In this paper, the writers present a detailed and rigorous analysis of a new flame distance sensor, which is constructed from a photodiode and an infrared filter made from black film inside a floppy disk. Here, the writers examine the output voltage from the detector using a digital multimeter, the intensity of the flame source using a calibrated lux meter, and the distance of the flame detector to the source. Furthermore, the correlation between each of them is determined so that the transfer function between those physical properties above can be made.

2. THEORETICAL BACKGROUND

2.1 Photodiode

Silicon photodiodes are semiconductor devices responsive to high-energy particles and photons. Photodiodes are operated by absorption of photons or charged particles and generate a flow of current in an external circuit, proportional to the incident power. A silicon photodiode can be operated in either the photovoltaic or photoconductive mode. In the photovoltaic mode, the photodiode is unbiased; while for the photoconductive mode, an external reverse bias is applied. Mode selection depends upon the speed requirements of the application and the amount of dark current that is tolerable. In the photovoltaic mode, dark current is at a minimum. Photodiodes exhibit their fastest switching speeds when operated in the photoconductive mode.[8]

The p-n junction and the depletion region are of major importance to the operation of a photodiode. These photodiode regions are created when the p-type dopant with acceptor impurities (excess holes) comes into contact with the n-type silicon, doped with donor im-

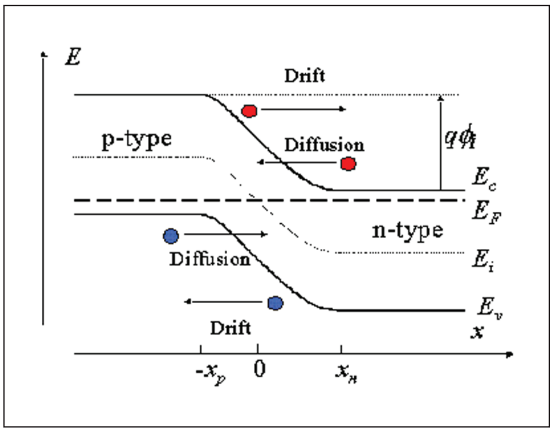

Figure 1. Energy Band Diagram of a p-n Junction in Thermal Equilibrium[10]

purities (excess electrons). The electrons move to the lower potential and diffuse with the holes, causing an electric field, which in turn causes a drift of carriers in the opposite direction. The diffusion of carriers (electrons-holes) continues until the drift current balances the diffusion current, thereby reaching thermal equilibrium as indicated by a constant Fermi energy (E_F), which is slightly different from intrinsic Fermy energy (E_i), and creating a depletion region from $x=-x_p$ to $x=x_n$ with a barrier potential φ_i, as seen in Figure 1.[9–10]

When photons of energy are greater than 1.1 eV (the bandgap of silicon, E_c-E_v) fall on the device, they are absorbed and electron-hole pairs are created. The depth at which the photons are absorbed depends upon their energy; the lower the energy of the photons, the deeper the photons are absorbed. The electron-hole pairs drift apart and when the minority carriers reach the junction, they are swept across by the electric field. If the two sides are electrically connected, an external current flows through the connection. If the created minority carriers of that region recombine with the bulk carriers of that region before reaching the junction field, the carriers are lost and no external current flows.[10]

2.2 Infrared Filter

In general, EM radiation (the designation 'radiation' excludes static electric and magnetic and near fields) is classified by wavelength into radio, microwave, infrared, the visible spectrum perceived as visible light, ultraviolet, X-rays, and gamma rays. However, this EM radiation will be noise in the measurement of distance. Therefore, another mechanism is needed for more precise measurements. The mechanism is filtering EM radiation and passing infrared radiation. In order to filter an infrared radiation with its specific wavelength, the writers shall use a filter which also has a wavelength like infrared has. This infrared filter can simply be made by using a black film inside the floppy disk.

2.3 Radiation Intensity

The inverse-square law for light intensity states: The intensity of illumination is proportional to the inverse square of the distance from the light source. The correlation of the distance between the source and the sensor is expressed by the following equations.

$$I(r,t)=\frac{1}{r^2}\left(Ae^{i\left(\bar{k}\cdot\bar{r}-\omega t\right)}\right)^2 \quad (1)$$

$$V\sim\frac{1}{r^2} \quad (2)$$

There are several variables used in these equations. Variable I represents the intensity of wave, A states the amplitude of wave, $\vec{r}$ is position vector of one point measured from the source, $\vec{k}$ is a wave number, t states time of the wave, and ω states the angular frequency of wave. The second equation shows that the intensity of the source flame (I) is proportional to the output voltage of the detector (V). In other words, the output voltage of the detector (V) is proportional to the inverse square of the distance between the source and the detector (r).

3. RESEARCH METHODOLOGY

3.1 Design of Flame Distance Sensor

Based on the theory, flame distance sensor can be made using the photodiode. In order to make the value of the voltage/current generated more specific, the voltage/current generated from the photodiode is derived from a specific wavelength. The aim is that noise coming from the light with other wavelengths has small effect. With an additional filter derived from a black coating on the floppy disk, it can be used as a filter that can pass infrared light and block the other EM radiation.[11] Thus, the output voltage of the photodiode is only affected by the intensity of the infrared. As explained in the theory, the radiation intensity of a wave will be reduced proportional to $1/r^2$.

However, the filter has a bandwidth that is still wide. This was evident when the filter can still be penetrated by a He-Ne laser with $\lambda = 680$ nm although the intensity is small. In addition to floppy disks, negative films can also be used as a filter, but a thick layer used to filter is more efficient.[12]

The circuit scheme of flame distance sensor can be seen in Figure 2.

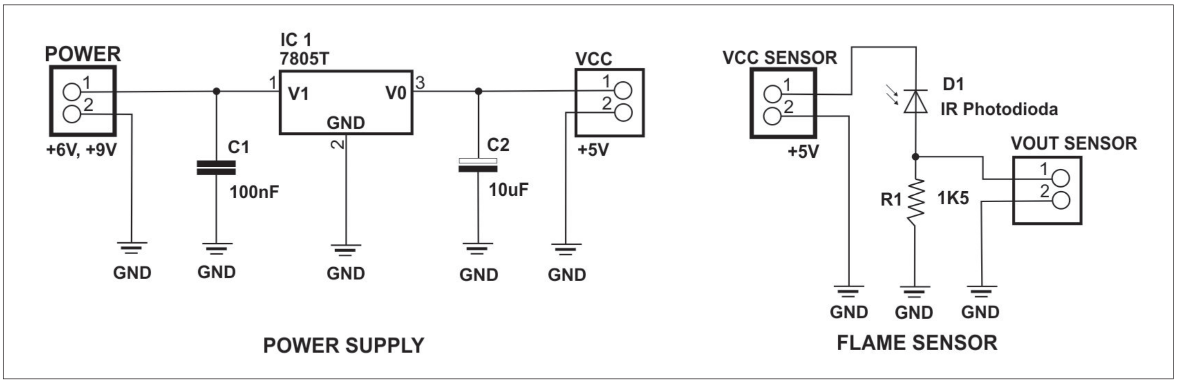

Figure 2. The Circuit Scheme of Flame Distance Sensor

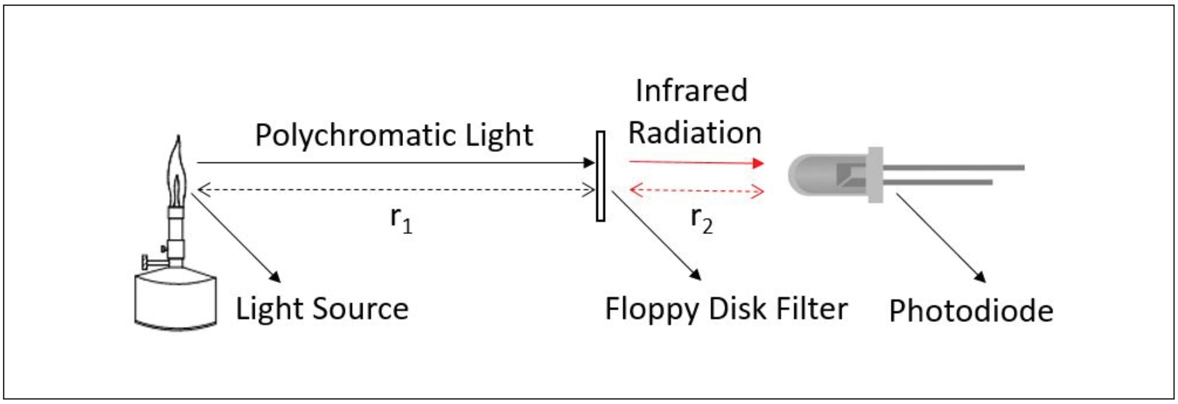

Figure 3. Cross-Section of Flame Detector Made from Photodiode and Infrared Filter

The regulated power supply circuit is used to generate a stable-fixed 5V DC power source from 6V to 9V power input, i.e. battery or DC adaptor, using IC 7805, 100nF, and 10uF capacitors to reduce noise. This output is connected to the flame sensor, giving a reverse bias current to the photodiode. The anode of photodiode is connected to R1 and output, while the cathode is connected to the 5V DC power supply. This will create a voltage divider circuit. Therefore, the output voltage measured by multimeter depends on the resistance or voltage generated by photodiode, which is proportional to the intensity of the absorbed photons.

3.2 Experiment Method

There are two different types of flames, diffusion flames, and premixed flames. Diffusion flames are phenomenan in which fuel and oxidizer come together in a reaction zone through molecular and turbulent diffusion.[13] It is the most common type of flame that is easy to find in our day to day life. The candle flame and the flame that are produced when we light a matchstick are some of the examples of diffusion flame. The forest fires also fall under this category. Premixed flames are kind of flame in which the fuel and the oxidizer are pre-mixed. This kind of flame is produced at a high temperature. It is usually very dangerous. The color of this flame usually varies from yellow to green. A non-luminous flame of the bunsen burner is a perfect example. This kind of flame does not produce soot. Soot is an air polluting agent. Moreover, it does not cause any pollution. This kind of flame requires very high temperature for burning.[14]

In this experiment, a diffusion flame (oil-based lamp) is used as a source. Because it can radiate a polychromatic light consisting of a few wavelengths and one of them is infrared wavelengths. On the other hand, a diffusion flames is easy to find, more safety and does not need a high temperature for burning.

First experiment is performed by varying the distance between the flame detectors to the source (r_1), as seen in Figure 3. The distance is varied from 5 cm up to 60 cm. This experiment divided into two steps, increasing the distance between detector to the source and decreasing the distance between detector and the source. Both processes provide a voltage data which can be used later to obtain the transfer function between the average voltage and the distance. The distance between filter and photodiode (r_2) is set about as close as possible in order to reduce noise due to other wavelengths and absorb the maximum intensity of infrared radiation.

The process of finding the transfer function from the physical properties begins with firing the source in order to emitt the visible light radiation. This light radiation which comes from the source has several wavelengths, such as ultraviolet wavelength and infrared wavelength. The EM radiation can be filtered and the infrared wavelength can be passed by a filter made from black film inside the floppy disk. Related to this, photodiode can get a narrow range of wavelength, which comes from the infrared radiation. This can make a better result for the experiment because the noises from other radiations are filtered and can not be detected by photodiode. Therefore, the transfer function of this experiment will describe the characterization of photodiode sensor. The assumption in this experiment is the radiation intensity of a wave will be reduced proportional to distance. If the distance increases, the radiation intensity will descrease.

The second experiment is performed by varying the radiation intensity of the source. The distance between source and detector is constant about 40 cm. The intensity is raised in particular yet not too strict enough. Therefore, the correlation between raised intensity and the output voltage from the detector can be seen. In order to reduce noise from EM radiation, the experiment is done in a dark room so that the transfer function of physical properties can be interpreted as a detailed and rigorous analysis of a flame distance sensor. The assumption in this experiment is the radiation intensity of the source is proportional to the voltage because intensity is the power per unit area and power is the rate at which electric energy is transferred by an electric circuit. The correlation between intensity and voltage will be presented from the transfer function in Figure 6.

Figure 4. The Detector Above is Created from A Photodiode and An Infrared Filter Made From Black Film Inside the Floppy Disk

4. RESULTS AND DISCUSSION

The set of experiment, as depicted in Figure 4, consists of an implemented flame detector, 9V battery with 5V fixed-regulator circuit, and source flame emitted by an oil-based lamp. The output terminal of the detector is connected to multimeter to obtain the voltage. The lux meter, alongside with multimeter, is used to calibrate the detector so that the relationship between voltage and intensity can be obtained.

Table 1 summarizes output voltage of the flame by increasing and decreasing the distance between detector and the flame itself.

Tabel 1. The Variations of Distance from the Experiment

Experiment Distance (cm)	Increased-Distance (Volt)	Decreased-Distance (Volt)	Average Voltage (Volt)
5	0.512	0.49	0.501
10	0.205	0.115	0.16
15	0.11	0.09	0.1
20	0.075	0.06	0.0675
25	0.053	0.044	0.0485
30	0.041	0.034	0.0375
35	0.031	0.03	0.0305
40	0.024	0.024	0.024
45	0.02	0.02	0.02
50	0.016	0.016	0.016
55	0.013	0.014	0.0135
60	0.012	0.012	0.012

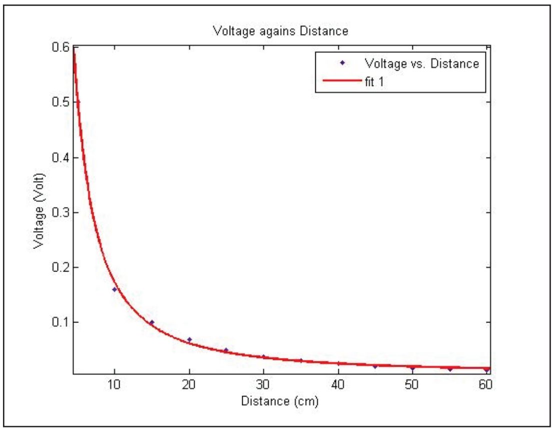

Figure 5. Characterization of Flame Distance Sensor in Variation of Distance (cm); R-Square = 0.9987

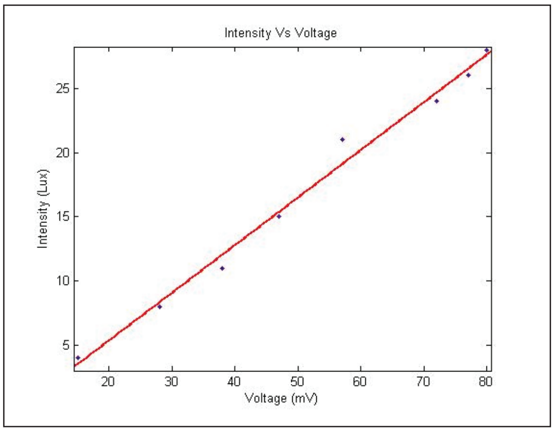

Figure 6. The Correlation Between Intensity and Voltage; R-Square: 0.9891

Average voltage from each varied distance is also presented in Table 1. Furthermore, correlation between the average voltage and varied distance is shown in Figure 5. This figure shows the trends and relationship among those two properties explained previously. This figure quite approaches the response values and the predicted response value. It can be seen from the R-square value of this figure, which is closer to 1 (R>0.9). The closer the R-square is to 1, the better proportion of the computed variance is.

Based on Figures 5, it can be interpreted that the radiation intensity reduces proportional to increasing distance. The red line is curve fitting between the voltage and the variation of distance. The transformation function from the curve is $f(x) = 6.624x^{-1.579} + 0.005867$ with R-square = 0.9987. Experimental results show that the transformation function is obtained in the form of the power function which is close to inverse-square law for light intensity. The results are not really in accordance with inverse-square law for light intensity because the infrared radiation is detected by a photodiode derived from not only the flame, but also the possibility of infrared radiation coming from other sources, such as the human body (the person doing the experiment), co-detected by photodiode. IR radiation is one of the three ways of heat transferred from one place to another, the other two are convection and conduction. Everything with a temperature above about 5°K (-450°F or -268°C) emits IR radiation. The sun gives off half of its total energy as IR, and much of its visible light is absorbed and re-emitted as IR, according to the University of Tennessee.[15]

Tabel 2. The Intensity and Voltage Data from the Experiment

Intensity (Lux)	Voltage (mV)
4	15
8	28
11	38
15	47
21	57
24	72
26	77
28	80

On the other hand, in the experiment, the writers did not use the amplifier in the sensor. Instrumentation amplifier is needed to avoid loading the circuit, so the output will get better and be in accordance with the mathematical expression. From this transfer function, the writers can calculate the maximum distance that can be detected by the sensor. The sensor can detect a voltage until 1 mV, so the maximum detection distance of the sensor is 107 cm.

In the second experiment, several numbers of intensity and voltage data are presented in Table 2. The voltage data is varying, mostly due to some external factors such as the surrounding air where this experiment takes place and the variable intensity itself.

The transformation function of the curve is linear. The R-square of the equation is 0.9891, and the equation is $f(x) = 0.3711x - 2.08$. This shows that the assumptions are correct that the intensity is directly proportional to the voltage. In this case, the maximum voltage is 4.8 V, which means that the maximum detection intensity of the sensor is 1783 lux.

5. CONCLUSION

From the experimental results, it can be concluded that the transformation function, which relates between the voltage or intensity with the distance of source flame, is obtained in the form of power function with exponent -1.579, which is approximately close to inverse-square law. Also, the intensity is directly proportional to the voltage. The maximum detection distance of the sensor is 107 cm and the maximum detection intensity of the sensor is 1783 lux.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Ishi, Tsutomu, Junichi Fujikata, Kikuo Makita, Toshio Baba, and Keishi Ohashi. 2005. "Si Nano-Photodiode with a Surface Plasmon Antenna". *JJAP* Volume 44 (2)**,** 12–14.

[2] Blynskii, V. I., Y. G. Vasileuskii, S. A. Malyshev and A.L. Chizh. 2007. "Silicon Photodiode with a Grid PN Junction". *Semiconductors*, and 41(2), 223–226.

[3] Ishi, T., J. Fujikata, K. Makita, T. Baba dan K. Ohashi. 2005. "Si Nano-Photodiode with A Surface Plasmon Antenna". *Japanese Journal of Applied Physics* 44(3L), L364.

[4] Tian, H., Fowler B. and A.E. Gamal. 2001. "Analysis of Temporal Noise in CMOS Photodiode Active Pixel Sensor". *Solid-State Circuits, IEEE Journal of* 36(1), 92–101.

[5] Brown, D. M., J.B. Fedison, J.R. Hibshman, J.W. Kretchmer, L. Lombardo, K.S. Matocha, and P.M. Sandvik. 2005. "Silicon Carbide Photodiode Sensor for Combustion Control". *Sensors Journal, IEEE* 5(5), 983–988.

[6] Smestad, Greg. P. 2004. *Solar Energy Materials and Solar Cells*, Volume 82, p. 227–240.

[7] Cabalfin, R.V. 1993. *Infrared Flame Sensor Responsive to Infrared Radiation*. United State: Publication number US5245196A, Patent Number 5,245,196.

[8] Olivia, M. 2009. *Fundamentals of Photovoltaic Materials*. California: National Solar Power Research Institute. p.1–2.

[9] Sproul, Alistair. 2003. *Understanding the PN Junction*. Solar Cells: Resource for the Secondary Science Teacher.

[10] Zeghbroeck, B.V. 2011. *Principles of Semiconductor Devices*, Accessed on: 17 September 2015, Web: http://ecee.colorado.edu/~bart/book/book/chapter4/ch4_2.htm#fig4_2_4

[11] Hollingum, Jack. 1981. "Flame Sensor". *Sensor Review* 21 (1). Emerald Group Publishing Limited.

[12] Coates, John. 2000. "Interpretation of Infrared Spectra". *A Practical Approach*. USA: John Wiley & Sons Ltd.

[13] Glassman, Irvin dan Richard A (ed). Yetter. 2008. "Chapter 6-Diffusion Flames". *In Combustion (Fourth Edition).*Burlington: Academic Press.

[14] Bychkov, V., M.A. Liberman. 2000. Dynamics and Stability of Premixed Flames". *Physics Reports 325 (4–5), March 2000*, http://dx.doi.org/10.1016/S03701573(99)00081-2.

[15] Lucas, Jim. 2015. *What Is Infrared?*. Accessed on: 2 November 2015. http://www.livescience.com/50260-infrared-radiation.html