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Comparison Study of Illuminance Measurements Emitted from Four Different Types of Gas Discharge Lamps and Uncertainty Evaluation

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Abstract
This study measured, calculated and compared the performance of four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor. The lamps were compared based on their illuminance levels and some important lighting parameters, such as the safe parameter of the ratio of UVA power to illuminance values (K). This parameter is a measure of the safety of the lamp, based on the amount of UV radiation emitted relative to the amount of visible light emitted. The other parameter (η) which is the ratio of UVA irradiance to electrical power. This parameter measures how efficiently the lamp converts electrical power into UV radiation. By comparing these parameters, the study was able to determine which type of the four gas discharge lamps has the best performance in terms of safety and efficiency. A set up based on Luxmeter is used for measuring illuminance. Another set up based on UVA/B silicon detector for irradiance measurements in UVA region. The Data were analyzed, performed and calculated to determine the uncertainty model which have all parameters affect on the measurements and the final results. The results show the Hydrogen discharge lamps are safer than Water vapor, Helium and Mercury vapor gas discharge lamps. According to the results, I recommended using Hydrogen discharge lamps at 15 cm and using Water vapor and Helium discharge lamps at 25 cm and then Mercury vapor discharge lamps should be used distance more than 25 cm when it used for physics laboratories specially with spectrometer experiment. These distances will be safer for students and instructors at the universities and schools.

Keywords:
Illumination Levels, UVA Radiation, Irradiance, Human Health, water vapor, helium, hydrogen, and mercury vapor discharge lamps, Uncertainty Analysis.

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I. Introduction

Gas discharge lamps are a type of artificial light source that produces light by sending an electric current through a gas. The gas used in the lamp is usually a noble gas, such as argon, neon, krypton, or xenon, or a mixture of these gases. Some lamps also include other substances, such as mercury, sodium, or metal halides, which vaporize during startup and become part of the gas mixture. When the electric current is turned on, the gas is ionized, meaning that some of the electrons are stripped from the atoms. This creates a plasma, which is a mixture of free electrons and positive ions. The electrons are attracted to the anode, while the positive ions are attracted to the cathode. As the electrons travel towards the anode, they collide with gas atoms and excite them. The excited atoms then emit photons of light as they return to their ground state. The color of the light emitted depends on the type of gas used in the lamp and the pressure of the gas. Gas discharge lamps can produce a wide range of colors, from white to red to blue to ultraviolet. Some lamps produce ultraviolet radiation, which is converted to visible light by a fluorescent coating on the inside of the lamp's glass surface. Fluorescent lamps are perhaps the best-known type of gas discharge lamp [1,2].

Gas discharge lamps are more efficient than incandescent lamps, but they are more expensive to make and more complex to operate. Most gas discharge lamps have negative resistance, which means that the resistance of the plasma decreases as the current flow increases. This can lead to a runaway current, which can damage the lamp or even cause a fire. To prevent this, gas discharge lamps usually require a ballast, which is an electronic device that controls the current flow through the lamp. Some gas discharge lamps also take a noticeable amount of time to reach their full brightness. However, despite these drawbacks, gas discharge lamps are replacing incandescent lamps in many applications because they are much more efficient [3]. Different gases emit different colors of light, depending on their atomic structure. This is called the emission spectrum of a gas. The International Commission on Illumination (CIE) developed the color rendering index (CRI) to measure how well a light source reproduces the colors of objects. Some gas discharge lamps have a relatively low CRI, which means that the colors of objects they illuminate can look different than they would under sunlight or other light sources with a high CRI. [4].

Gas discharge lamps are widely used in physics laboratories for various purposes involving light generation, including spectrometry, spectroscopy, and laser pumping. They are also used in a wide range of lighting applications, from street lights to indoor lighting. Due to their unique appearance, gas discharge lamps are often used by quacks and con artists to create illusions. However, this does not mean that gas discharge lamps are not useful or important. In fact, they are an essential part of many modern technologies. [5]. Gas discharge lamps are made of a tube with two metal electrodes (anode and cathode) at the ends and a gas inside the tube of the lamp. When a voltage is applied across the two metal electrodes in a vacuum tube, or sometimes at a pressure less than atmospheric pressure, the gas will break down into electrons and positive ions. Gas discharge lamps are a type of light bulb that uses electricity to create a plasma, which is a hot, glowing gas. The plasma emits light, and the color of the light depends on the type of gas used in the lamp. To create a plasma, a voltage is applied across two metal electrodes in a tube filled with gas. The voltage causes the gas to break down into electrons and positive ions. The electrons are accelerated and collide with gas atoms, which excites and ionizes the gas. This creates a self-sustaining plasma, which produces light. Gas discharge lamps can produce a wide range of colors, from white to red to blue to UV. They are used in a variety of applications, including street lighting, commercial lighting, and industrial lighting. [6]. Gas discharge lamps emits their own wavelengths and their own spectrum depending on the atomic structure of the gas filled in the tube. The spectrum of the gas discharge lamp determines the color of the light emit from this lamp. The International Commission on Illumination (CIE) introduced the color rendering index (CRI) to evaluate the ability of a light source to reproduce the colors of various objects being lit by the source [4]. Some gas-discharge lamps have a relatively low CRI, which means colors they illuminate appear strongly different from how they do under sunlight or other high-CRI illumination [4]. Helium discharge lamp produces pale yellow color and Mercury vapor lamp produce blue light [7].

Light is all around us and it affects our health in many ways. The type of light source we use and the amount of UV radiation it emits can have a big impact on our eyes and our overall health. For example, too much exposure to UV radiation can cause sunburn, premature skin aging, and skin cancer. It can also damage our eyes and increase the risk of cataracts and macular degeneration. On the other hand, exposure to bright light can help to regulate our circadian rhythms and improve our mood and energy levels. It can also help to improve our vision and cognitive function. When choosing light sources for our homes and workplaces, it is important to consider the spectrum of light they emit and the amount of UV radiation they produce. We should also try to get enough exposure to bright light during the day, especially in the morning. [8]. All gas discharge lamps emit some UV radiation, which is the most harmful type of radiation. UV radiation can damage valuable objects and cause health problems for people. Therefore, it is important to choose the right type of lighting for different situations. For example, if you are lighting an area where important or valuable objects are kept, you should choose a type of lighting that emits very little or no UV radiation. You should also choose a type of lighting that provides the right level of illumination for the activities that will be taking place in the area. For example, if you are lighting a workspace, you will need a different type of lighting than if you are lighting a museum display. By understanding the basics of UV radiation and illumination levels, you can choose the right type of lighting for any situation [9].

Ultraviolet (UV) radiation is a type of non-ionizing radiation, which means that it does not have enough energy to knock electrons out of atoms. It is produced by heating a body to a high temperature, such as the sun, or by passing an electric current through a gas. UV radiation has three regions of wavelengths: UVA, UVB, and UVC. UVA has wavelengths from 315 to 400 nanometers, UVB has wavelengths from 280 to 315 nanometers, and UVC has wavelengths from 100 to 280 nanometers. UVC radiation has the greatest health effects of the three types of UV radiation. It can cause sunburn, skin cancer, and eye damage. It can also damage the immune system and increase the risk of other health problems. [10-12].

The following equation describes the relationship between the intensity of the tested lamp and the amount of light it produces, known as illuminance:

$$E = \frac{I \cos \theta}{d^2} \tag{1}$$

where
E : is the quantity of illuminance,.
I : is the intensity of the tested lamps.
d : is the distance from the tested lamp to the surface of the detector.
Θ : is the angle between the normal of the receiving surface and the direction of emission [13].

The Spectral irradiance in the part of ultraviolet radiation in class A (UVA) is defined as the electromagnetic radiation power divided by area in ($W/m^2/nm$) hence,

$$I_\lambda(\lambda) = \int_{\lambda_1}^{\lambda_2} I_i(\lambda) d\lambda \tag{2}$$

where,
$I_\lambda(\lambda)$: is the spectral irradiance in ($W/m^2/nm$).
$I_i(\lambda)$: is the intensity.

The spectral power distribution (SPD) of a light source tells us how much power is emitted at each wavelength of light. It is a measure of the light source's spectrum, which is the range of wavelengths of light that it emits. The SPD is important for understanding how a light source will be perceived by humans and how it can be used for different applications. It is also important for radiometric and photometric measurements. [14].

To determine and calculate the ultraviolet radiation in class A (UVA) it will be helpful to use the following equation [10]:

$$\eta = \frac{\int_{\lambda_1}^{\lambda_2} E_{irr}(\lambda) d\lambda}{P} \tag{3}$$

Where,
$E_{irr}(\lambda)$: is the ultraviolet irradiance.
P : is the electrical lamp power.

To make a better comparative study between two different artificial light sources, it is necessary to determine the safe parameter (k).

$$K = \frac{\int_{\lambda_1}^{\lambda_2} E_{irr}(\lambda) d\lambda}{k_m \int_{400nm}^{800nm} E_{irr}(\lambda) d\lambda V(\lambda) d\lambda} \tag{4}$$

$E_{irr}(\lambda)$: is the spectral distribution of the radiant flux W/nm
$V(\lambda)$: is the spectral human eye response (CIE response curve).
k_m is photometric radiation constant and equal ($683 lm/W$).

This parameter can help us choose an artificial light source that emits less UV radiation. The equation above can be used to calculate the safe parameter, which depends on how far away the light source is from the area where people will be exposed to the light. The higher the safe parameter, the more UV radiation people will be exposed to. It is important to choose a light source with a low safe parameter for applications where people will be close to the light source, such as in a workspace. [10]

$$K = \frac{\int_{\lambda_1}^{\lambda_2} I_\lambda(\lambda) d\lambda}{k_m \int_{380nm}^{780nm} I_\lambda(\lambda) d\lambda V(\lambda) d\lambda} \tag{5}$$

The present study aimed to evaluate the relationships between UV emissions radiated and illuminance from four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor by comparing the data obtained in [15,16].

II. Experimental Method:

The gas discharge lamps (Spectrum tubes) manufactured by Electro-Technic Products, Inc. use research grade gasses and vapors to provide bright-line spectral lines of the highest clarity as shown in Figure 1. They are designed for optimum intensity and line resolution when examined in a student grade spectrometer equipped with ca. 200 line/mm (5000 line/inch) diffraction grating. The pressure of the various gasses in spectrum tubes is a carefully controlled value that will produce the maximum quality of brightness and clarity of the spectral lines. For some tubes it is not necessarily the same values of pressure that produces maximum continuous operating life of the spectral lines. Tubes energized with the Electro-Tech Model SP-200 Spectrum Tube Power Supply, which is made expressly for this purpose. Some tubes using helium and other gases found in cold cathode display sign can run continuously with less deterioration of the quality of the spectral lines. The others, such as hydrogen and water vapor, require more care in processing to increase the life. Pure nickel electrodes and the best research grade of gases are used, and meticulous care is taken in processing to increase service life.

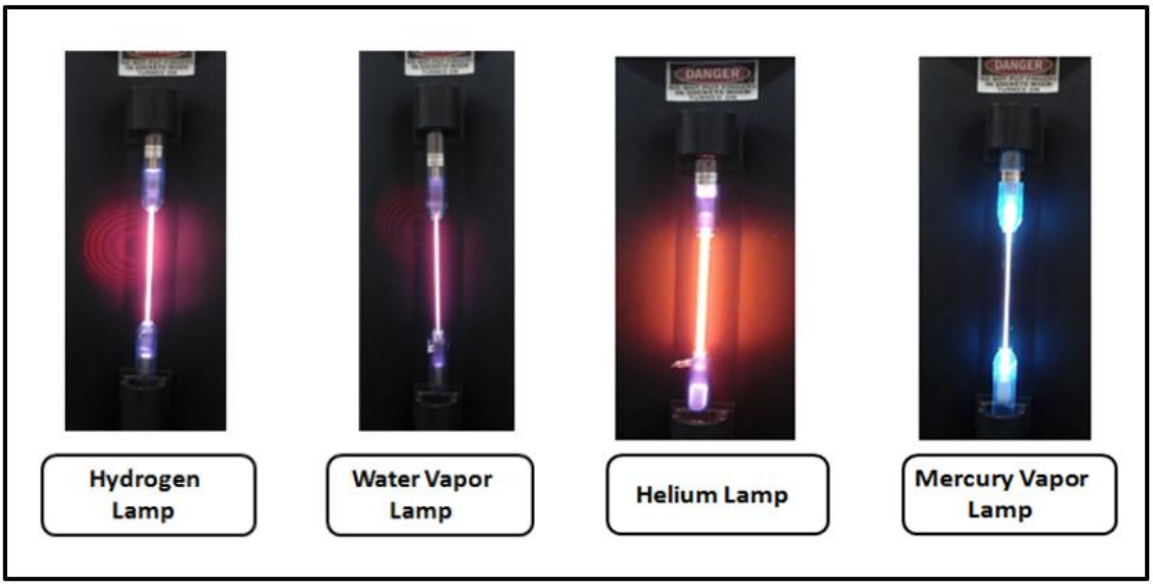
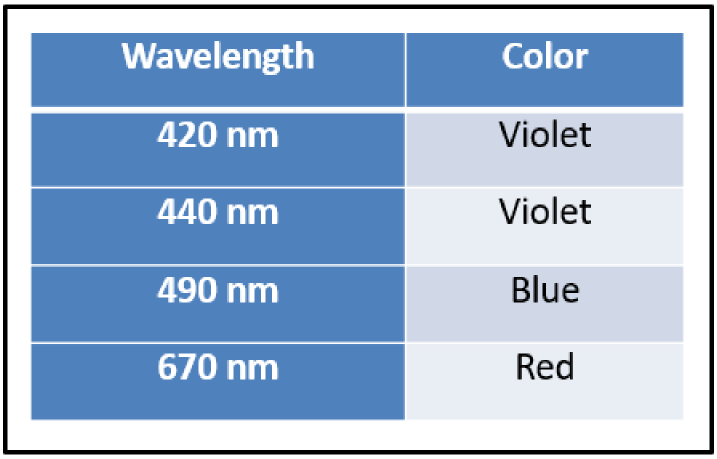
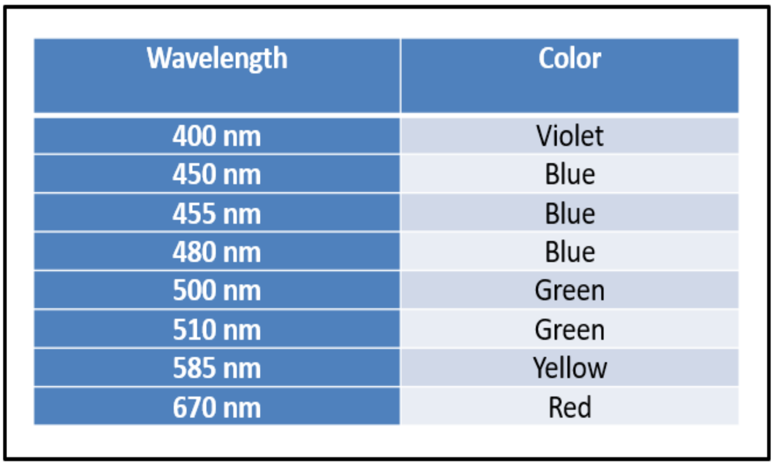


Figure. 1. Four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor.



Wavelength	Color
420 nm	Violet
440 nm	Violet
490 nm	Blue
670 nm	Red

Table 1. Emission Spectra of Hydrogen discharge lamps

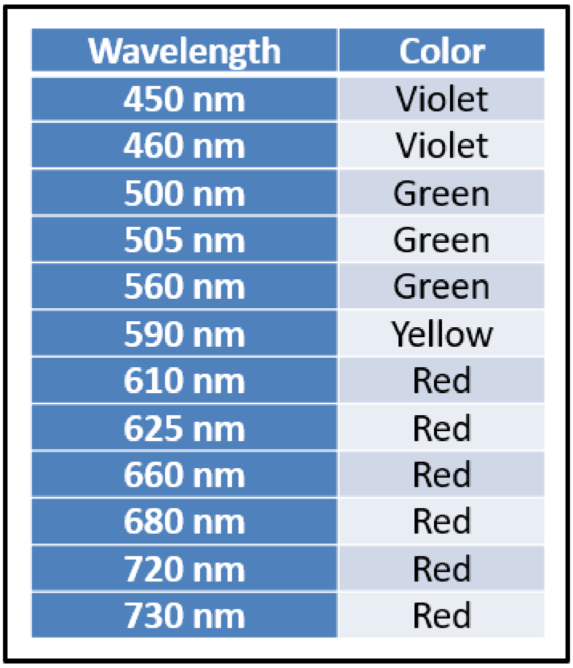


Wavelength	Color
400 nm	Violet
450 nm	Blue
455 nm	Blue
480 nm	Blue
500 nm	Green
510 nm	Green
585 nm	Yellow
670 nm	Red

Table 2. Emission Spectra of Helium discharge lamps

Wavelength	Color
430 nm	Violet
440 nm	Violet
490 nm	Blue
520 nm	Green
540 nm	Green
550 nm	Green
560 nm	Green
605 nm	Red
610 nm	Red
665 nm	Red

Table 3. Emission Spectra of Water Vapor discharge lamps



Wavelength	Color
450 nm	Violet
460 nm	Violet
500 nm	Green
505 nm	Green
560 nm	Green
590 nm	Yellow
610 nm	Red
625 nm	Red
660 nm	Red
680 nm	Red
720 nm	Red
730 nm	Red

Table 4. Emission Spectra of Mercury Vapor discharge lamps.

This study compared the ultraviolet (UV) irradiance and illuminance of four different gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor. The goal of the study was to evaluate the performance of the different lamps and to estimate the uncertainty of the measurements. [10,17,18]. All lamps were measured in the vertical position [19]. Different parameters determined for the types of lamps such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (η) and ratio of UVA power to luminous flux (K) at different distances. Measurements were performed in a conditioned black box around the set up of the measurements according to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommendations [20] and the temperature was maintained at $(25 \pm 2)^{o}C$.

The illuminance of each lamp was measured using a light meter called a Luxmeter TM-201Lux. The light meter was mounted on a movable stage and positioned at the same height as the artificial gas discharge lamps on the optical bench, as shown in Figure 2. Measurements were repeated for each lamp and then averaged together. The uncertainty in the light measurements was also calculated.

The photometric bench used in this study consisted of a Sper Scientific UVA/B Light Meter (Model 850009C) that was calibrated at the National Institute of Standard and Technology (NIST) in the USA. The UVA detector was mounted on a translation stage and positioned at the same height as the light source (four types of gas discharge lamps) on the optical bench, as shown in Figure 3. Before taking measurements, each lamp was warmed up for 15 minutes. Measurements were repeated for each lamp and then averaged together. The uncertainty in the irradiance measurements was also calculated.

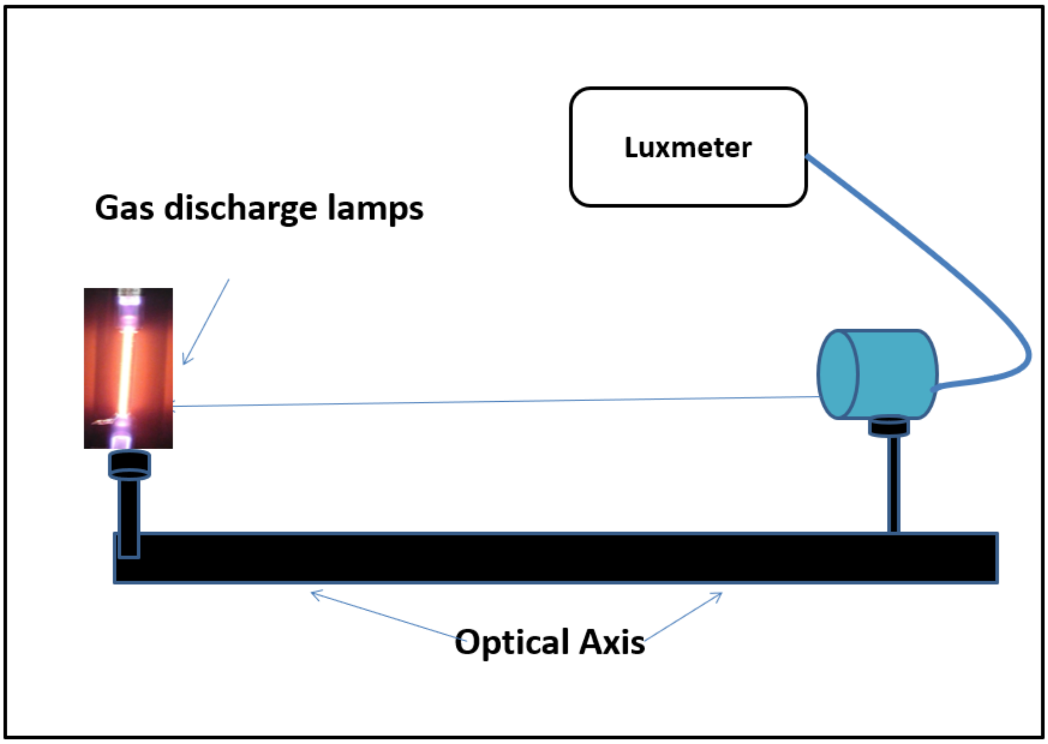


Figure. 2. A Set up diagram for measuring illuminance for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor.

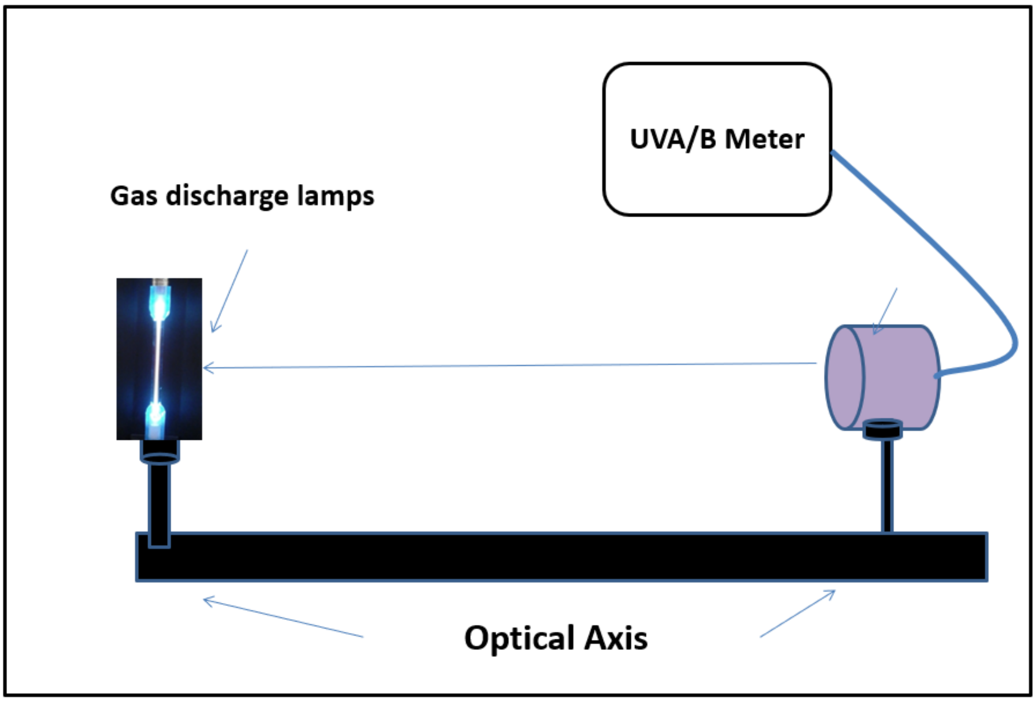
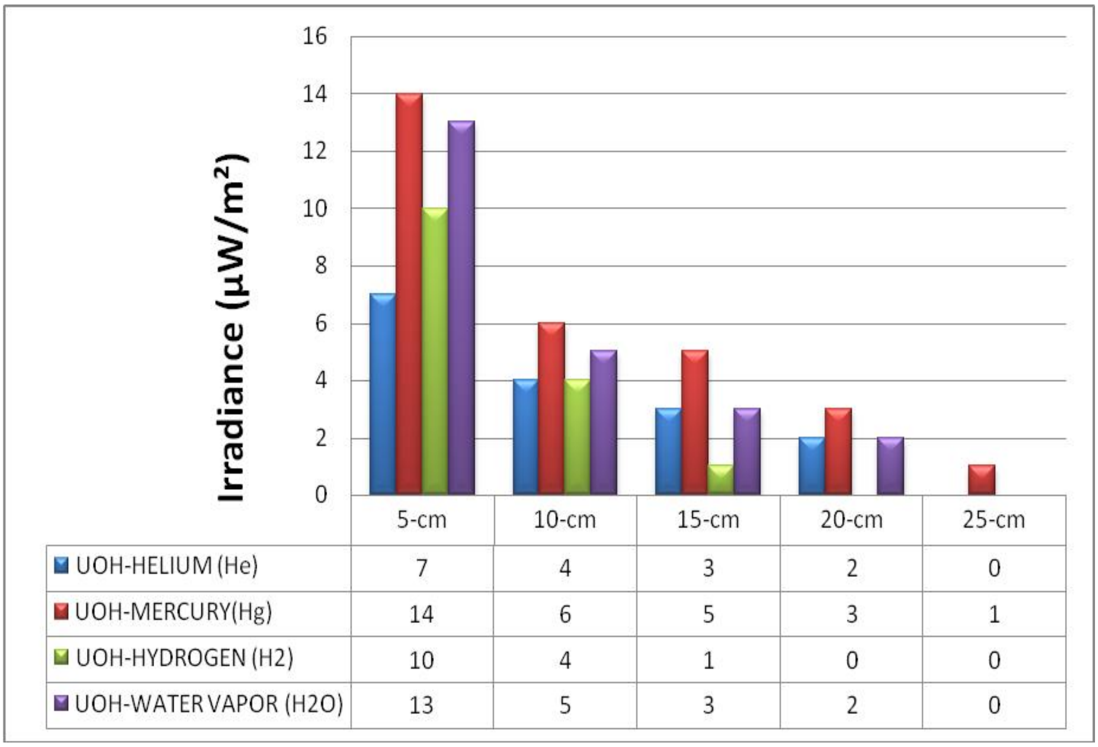


Figure. 3. A Set up diagram for measuring UVA irradiance for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor.

III. Results and Discussions

Illuminance and UVA irradiance were measured at the different distance for Helium and Mercury vapor discharge lamps. At the distance of 5 cm that was considered to be the closest distance that students and instructors would be exposed to the lamp especially in physics laboratories when using this lamp in spectrometer experiment. For analyzing the UV content at the short distance, the measurements were conducted at the distance of 5 cm. The description of these lamps as the following: UOH-Helium lamp and UOH- Mercury vapor lamp. These lamps are designed to emit their power in the visible region. In fact, they emit almost of their energy in the visible region but part of their energy is emitted in the UV region. Negligible amounts of UVA were detected at 15 cm from Hydrogen lamp. Therefore, only data relating to the UVA irradiance measured at 5 up to 25 cm were analyzed in this study. Also, Negligible amounts of UVA and UVB were detected at 25 cm from Mercury vapor discharge lamp.

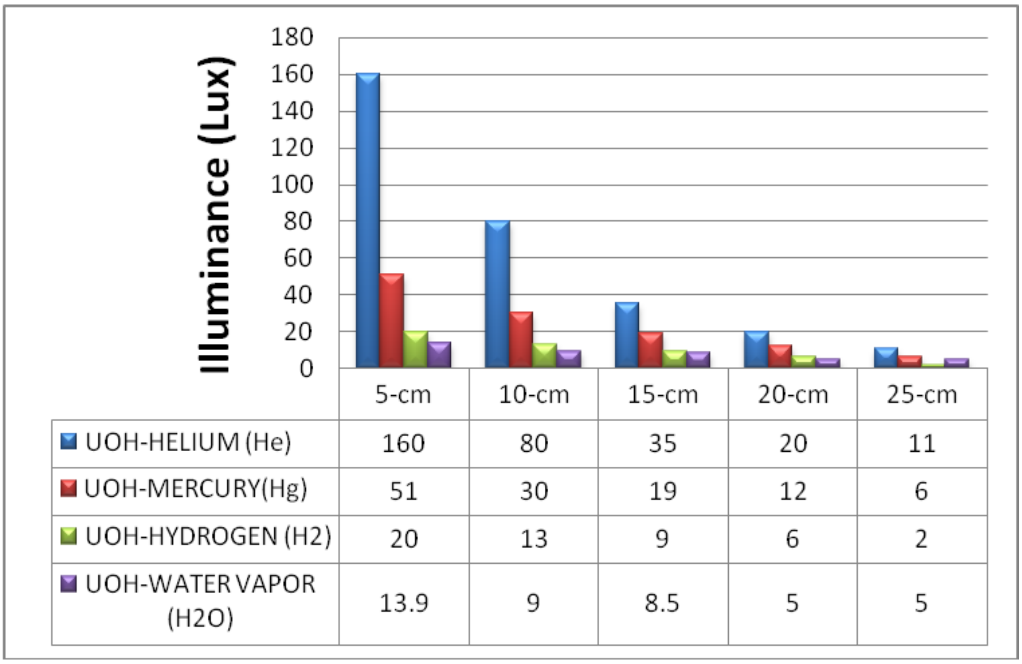
Figure 4 shows the comparison of UVA irradiance level between Helium and Mercury vapor discharge lamps at distance of 5 up to 25 cm. Each lamp measured at distances of 5 up to 25 cm from its central vertical axis respectively using Sper Scientific UVA/B Light Meter (Model 850009C) which calibrated at National Institute of Standard and Technology (NIST), USA. The UVA irradiance for four types of lamps at different distances varies from 0 to $14\mu W/m^2$. The results showed that the Mercury vapor discharge lamp has higher values of the UVA irradiance than water vapor, hydrogen, and helium discharge lamps.



	5-cm	10-cm	15-cm	20-cm	25-cm
🟦 UOH-HELIUM (He)	7	4	3	2	0
🟥 UOH-MERCURY(Hg)	14	6	5	3	1
🟩 UOH-HYDROGEN (H2)	10	4	1	0	0
🟪 UOH-WATER VAPOR (H2O)	13	5	3	2	0

Figure. 4. Comparison measurements of UVA absolute irradiance levels between four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances.

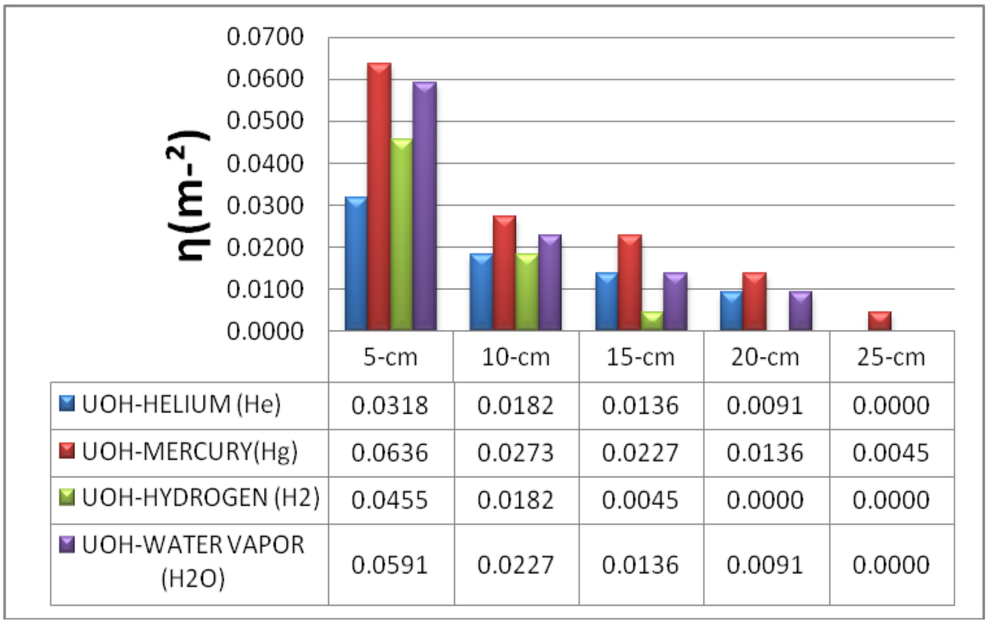
Figure 5 shows the comparison of illuminance level between Helium and Mercury vapor discharge lamps at different distances. Each lamp measured at distances of 5 up to 25 cm from its central vertical axis using a Luxmeter TM-201Lux. The illuminance level at distances of 5 up to 25 cm for all lamps varies from 2 lux to 160 lux. The results showed that Helium discharge lamps has higher values of the illuminance level than the Mercury vapor, Water vapor and Hydrogen, discharge lamps.



	5-cm	10-cm	15-cm	20-cm	25-cm
🟦 UOH-HELIUM (He)	160	80	35	20	11
🟥 UOH-MERCURY(Hg)	51	30	19	12	6
🟩 UOH-HYDROGEN (H2)	20	13	9	6	2
🟪 UOH-WATER VAPOR (H2O)	13.9	9	8.5	5	5

Figure. 5 Comparison measurements of Illuminance levels (Lux) between four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances.

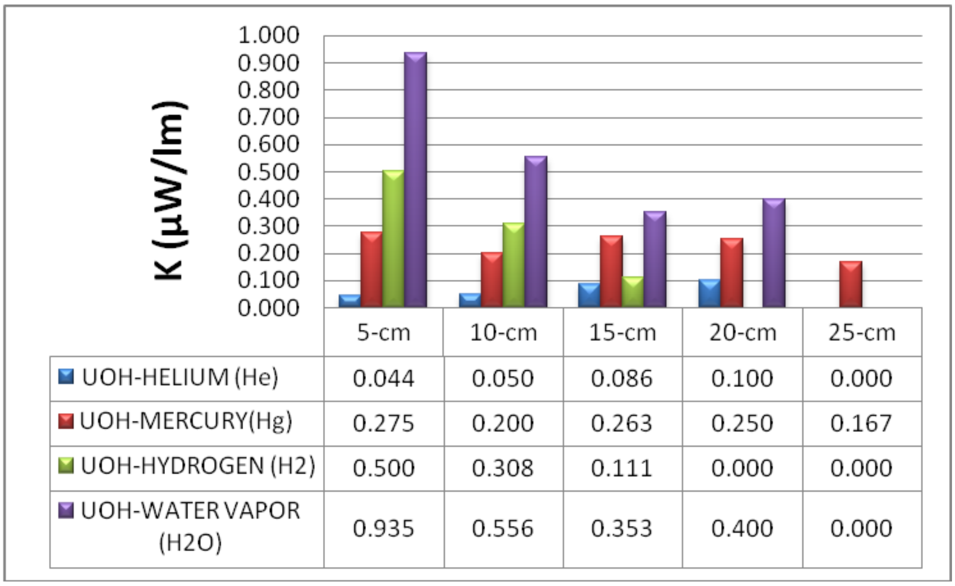
It would be more appropriate to analyze UVA irradiance per electrical wattages (η). Figure 6 show the histogram for comparison of UVA absolute irradiance levels per electrical power of (η) between four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances from 5 cm up to 25 cm which varies from 0 to $0.06 m^{-2}$.



	5-cm	10-cm	15-cm	20-cm	25-cm
🟦 UOH-HELIUM (He)	0.0318	0.0182	0.0136	0.0091	0.0000
🟥 UOH-MERCURY(Hg)	0.0636	0.0273	0.0227	0.0136	0.0045
🟩 UOH-HYDROGEN (H2)	0.0455	0.0182	0.0045	0.0000	0.0000
🟪 UOH-WATER VAPOR (H2O)	0.0591	0.0227	0.0136	0.0091	0.0000

Figure 6. Comparison measurements of UVA absolute irradiance levels per to electrical power (η) between four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances.

To make a better comparison in UVA concentration to illuminance ratio (K), is of more interest for analyzing the lamps radiation characteristics as shown in Figure 7. It shows the histogram for comparison of UVA concentration to illuminance ratio (K) for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances from 5 cm up to 25 cm which varies from 0 to 0.9 µW/lm.



	5-cm	10-cm	15-cm	20-cm	25-cm
🟦 UOH-HELIUM (He)	0.044	0.050	0.086	0.100	0.000
🟥 UOH-MERCURY(Hg)	0.275	0.200	0.263	0.250	0.167
🟩 UOH-HYDROGEN (H2)	0.500	0.308	0.111	0.000	0.000
🟪 UOH-WATER VAPOR (H2O)	0.935	0.556	0.353	0.400	0.000

Figure 7. UVA absolute irradiance levels per illuminance values (K) for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances.

According to occupational exposure limited (OEL), occupational UVB and UVA exposure should be limited to an effective irradiance of $3\mu W/m^2$ and $1.04166\,W/m^2$ in an 8 hr period, respectively [21,22].

IV. Uncertainty analysis

When you measure something, there is always some uncertainty about the accuracy of your measurement. This is because there are many factors that can affect the measurement, such as the quality of the measuring instrument, the skill of the person making the measurement, and the environmental conditions in which the measurement is made. It is important to report the uncertainty of your measurement so that other people can understand how reliable your measurement is. There are two main types of uncertainty. Type A uncertainty is caused by random errors, such as the variation in the readings of a measuring instrument. Type A uncertainty can be reduced by taking multiple measurements and averaging the results. Type B uncertainty is caused by systematic errors, such as the calibration of a measuring instrument being slightly off. Type B uncertainty cannot be reduced by taking multiple measurements. To evaluate the uncertainty of a measurement, it is important to identify all of the sources of uncertainty and to estimate the contribution of each source to the overall uncertainty. There are a number of different methods for evaluating uncertainty, depending on the type of measurement being made. Once the uncertainty of a measurement has been evaluated, it can be reported along with the measurement result. This allows other people to understand how reliable the measurement is and to compare it to other measurements.

The components in type A are characterized by the estimated variances s_i^2 (or the estimated "standard deviation" s_i) and the number of degrees of freedom v_i . The components in type B should be characterized by u_j^2, which may be considered as approximations to the corresponding variances, the existence of which is assumed. The quantities u_j^2 may be treated like variances and the quantities u_j like standard deviations. The combined uncertainty should be characterized by the numerical value obtained by applying the usual method for the combination of variances. The combined uncertainty and its components should be expressed in the form of "standard deviations". Expanded uncertainty is termed overall uncertainty. It is quantity of an interval about the results of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. Coverage factor is numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty [23].

Evaluation of the uncertainty is done by the Guide to the expression of uncertainty in Measurement (GUM) method. This method is adopted and described in details by International Organization for Standardization (ISO) [24]. The standard uncertainty $u(x_i)$ to be associated with input quantity is the estimated standard deviation of the mean [23]

$$u(x_i) = s(\bar{X}) = \left(\frac{1}{n(n-1)} \sum_{k=1}^{n} (X_{i,k} - \bar{X})^2 \right)^{1/2} \qquad (6)$$

The combined standard uncertainty $u(x_i)$ is obtained by combining the individual standard uncertainties u_i these can be evaluated as Type A and Type B. That is,

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \qquad (7)$$

Uncertainty model used for the determination of the UVA irradiance $E_{UVA}(\lambda)$ is [15]

$$E_{UVA}(\lambda) = E_S(\lambda) + \delta E_l + \delta E_r \qquad (8)$$

where, $E_S(\lambda)$ = uncertainty due to reference spectral irradiance UVA standard radiometer (obtained from the calibration certificate).

δE_l = uncertainty due to distance effect on the irradiance measurements (calculated by using the inverse square law).

δE_r = uncertainty due to repeatability of the measurements (standard deviation of repeated 5 times).

When reporting the results of a measurement, it is important to include the uncertainty of the measurement. This tells us how precise the measurement is. The uncertainty budgets for the illuminance and irradiance measurements are shown in Tables 1 and 2, respectively. The expanded uncertainties are calculated with a confidence level of 95% (coverage factor k=2). Finally, the UVA irradiance and illuminance measurements are calculated.

Uncertainty Component	*Relative Standard Uncertainty (%)*
Illuminance responsivity calibration of standard photometer	6
Distance measurements	0.015
Repeatability	0.020
Relative Expanded Uncertainty (*k*=2)	**12**

Table 5. Estimated Uncertainty budget of illuminance measurements for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor.

Uncertainty Component	*Relative Standard Uncertainty (%)*
Irradiance responsivity calibration of standard radiometer	5.2
Distance measurements	0.016
Repeatability	0.024
Relative Expanded Uncertainty (*k*=2)	**10.4**

Table 6. Estimated Uncertainty budget of UVA irradiance measurements for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor.

V.Conclusion

Illuminance and UVA emission were measured for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances from 5 cm up to 25 cm. UVA emission were studied to assess their unwanted output in the UVA region. Various parameters such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (ƞ) and ratio of UVA power to luminous flux (K), for four types of gas discharge lamps: water vapor, helium, hydrogen, and mercury vapor at different distances from 5 cm up to 25 cm to dedicate their performance. The higher values were measured in Mercury vapor discharge lamps than the other discharge lamps. The Hydrogen discharge lamps at 15 cm appeared to be the safer. Also, the smaller value of (ƞ) is safe for human being then Hydrogen discharge lamps appeared to be the safer at 15 cm distance. Data analysis was performed. Uncertainty model includes all parameters accompanied with the measurements are studied. The accompanied uncertainty in the absolute UVA irradiance measurements (10.4 %) and in the illuminance measurements (12%) are calculated respectively in Table. 5 and Table. 6 with confidence level 95% (*k*= 2). According to the results of this research I recommended using Hydrogen discharge lamps at 15 cm and using water vapor and helium discharge lamps at 25 cm and then Mercury vapor discharge lamps should be used distance more than 25 cm when it used for physics laboratories specially with spectrometer experiment. These distances will be safer for students and instructors at the universities and schools.

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