Phys. Comm. 6 (2) 2022 : 71 - 78

Physics Communication

http://journal.unnes.ac.id/nju/index.php/pc

The Examination of the Wien's Displacement Constant with Simulation and Simple Numerical Approaches

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Article Info

Article history:
Submitted 28 May 2022
Revised 23 August 2022
Accepted 24 August 2022

Keywords:
Blackbody, Newton Raphson, PhET, Wien's constant

Abstract

The purpose of this research was to examine the value of the Wien's constant using PhET Simulation virtual laboratory and simple numerical approach. The independent and dependent variable is blackbody temperature (T) and maximum wavelength (λ_{max}). In the use of a virtual laboratory, research is carried out by shifting the black body temperature feature so the graph will display a spectral power density that varies to the wavelength. Numerical approach was used in this research is Newton Raphson methods by Python program. Both of simulation and numerical approach yield the value of the maximum wavelength (λ_{max}) for a black body temperature variation. The black body temperatures and their appropriate maximum wavelength data then analyzed using linear regression. Final result show that value Wien's constant using PhET is 2.93×10^{-3} mK with relative error obtained is 1.07% while using Newton Raphson the Wien's constant value obtained is 3.07×10^{-3} mK with relative error is 5.90%. The two approaches carried out produce data that slightly different, but still in a very good accuracy range when compared with theory. PhET Simulation and Newton Raphson methods effective to examine the value of the Wien's constant.

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p-ISSN 2528-5971
e-ISSN 2528-598X

INTRODUCTION

Physics is a science that studies natural phenomena in the scope of space and time. Physics is divided into two eras, classical physics and quantum physics. The study of classical physics, sometimes called Newtonian physics formed the technological foundation of more of modern technology. Classical physics is dominated by two fundamental concepts, concept of particle (position and momentum) and concept of an electromagnetic wave. Several phenomena failed to be explained by classical physics, for example is phenomenon of black body radiation and the photoelectric effect. The first development of quantum physics was marked of energy distribution law in the normal spectrum.

The classical physics era began to crumble when Max Planck published a theory of black body radiation. When radiation falls on an object, some of it might be absorbed and reflected. An idealized "black body" is a material object that absorbs all of the radiation falling on it. The intensity of this radiation depends on its temperature and frequency. So, black body is a system that has absorbance and emissivity values equal to one (Zettili, 2009). Planck provided an explanation of black body radiation by assuming that atoms emit and absorb discrete quanta of radiation with energy $\in = hv$, where v is the frequency of the radiation and h is a constant with value $h = 6.626 \times 10^{-34}$ Js. This constant is now called Planck's constant (Phillips, 2002)

There are several recent studies conducted to study the phenomenon of black body radiation including black body radiation and the photoelectric effect (Sutarno *et al*., 2017), history of thermal radiation computational aids and numerical methods (Stewart & Johnson, 2016), experimental study of infrared temperature measurement and blackbody radiation for the epidemic Covid-19 period (Alper & Aiordachioaiei, 2021), and new approach to the generalization of Planck's law of black body radiation (Choudhury & Paul, 2018). This proves that the topic of black body radiation is still interesting to study. However, this research is still relatively simple experiment to study Wien's Displacement Law.

A black body radiates more when it is hot than cold. The spectrum of a hot black body has its peak at a higher frequency that the peak in the spectrum of a cold black body. As a result of the thermal agitation of electrons on the surface of an object, when heated the object will emit electromagnetic energy. When a solid object heated, it glows and emits thermal radiation. As the temperature increases, the object becomes red, then yellow, and then white. Thermal radiation is the situation of an object emitting electromagnetic radiation with a radiation spectrum that depends on temperature. The radiation emitted every second will be equal to the amount of radiation absorbed (Zwinkles & Joan, 2015). The spectrum of black body radiation at several temperatures is shown in Figure 1.

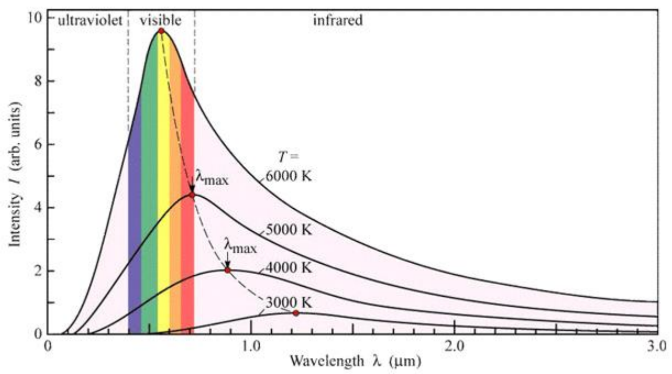

Figure 1. Blackbody Radiation Spectrum
Source : Schubert (2006) - Light-Emitting Diodes (Cambridge Univ. Press)

The total amount of energy (area under the curve) emitted increases with increasing temperature. Based on the Figure 1, as the temperature increases, the peak distribution displacements to a shorter wavelength. The rate in which the black body radiation is in peak is presented by Wien's Displacement Law and is the use of the body's abolute temperature. The implications of this law, which was confirmed based on the Figure 1 is the distribution at any black body temperature can be found if we know the spectral distribution of black body radiation at one temperature (Gasiorowicz, 2003). The maximum wavelength expressed in the following equation :

$$\lambda_{max} = \frac{C}{T} \tag{1}$$

where,

λ_{max} : maximum wavelength (nm)
C : 2.8989×10^{-3} mK
T : absolute temperature (K)

According to Wien, if a black body is heated continuously it will emit heat radiation with a colorful spectrum that depends on its wavelength. From this, it can be concluded that temperature affects the wavelength.

To prove the Wiens's Displacement Law, simple experiments based on simulations and mathematical analysis were carried out. Nisa, et al., (2018) determined the Wien's constant using a Virtual Laboratory, namely PhET simulation. Nisa only using linear regression to analyzed the data. Astuti & Handayani, (2018) determined the Wien's constant with software including PhET Simulation, Flash Player, and Java Run Time Environment. Meanwhile, Widagda (2016) uses the Modified Newton-Raphson analysis method to prove the Wien's Displacement Law numerically.

Of the various ways to determine the Wien's constant, we chose to use numerically analysis and virtual laboratory simulation. The use of virtual laboratories has the potential to provide significant improvements and a more effective learning experience. Therefore, this research uses Physics Education Technology (PhET) simulation. PhET has developed a series of interactive simulations that are very beneficial in integrating computer technology into learning (Prihatiningtyas et al., 2013). Numerical methods are used to approximate the solution equations whose exact solutions cannot be determined by algebraic method. The method we use is the search for one-dimensional roots Newton's method, or also called the Newton Raphson method (Remani, 2013; Rahman et al, 2022). The equation form of the Newton-Rapshon method is an iteration equation :

$$x_{i+1} = x_i - \frac{f(x)}{f'(x)} \tag{2}$$

where,
$i = 0,1,2,\ldots, n$
n = number of iterations
$f'(x) = \frac{df(x)}{dx} =$ first derivative of $f(x)$

Equation (2) is an iteration that denotes an iterative process in which the present value of $x(x_{i+1})$ is determined by the previous value of x (x_i) (Feldman, 2012). So, the focus of this research is determine the value of the Wien's constant using a virtual laboratory, namely PhET Simulation and using Newton Raphson analysis.

METHODS

This research uses a software-based experimental and numerically method. The software used is PhET simulation which is accessed at https://phet.colorado.edu/in/simulations/blackbody-spectrum. Numerical method used is modified Newton Raphson. Another instrument used to support this research is an analysis sheet (linear regression) to determine the magnitude of the Wien's constant. There are two types of variables used, namely the independent variable and the dependent variable. The independent variable used is the blackbody temperature. The dependent variable used is the maximum wavelength. Astuti & Handayani (2018) in their research entitled "Using a PhET Simulation-based Virtual Laboratory to Determine the Wien's Constant" uses an independent variable in the form of temperature (4440, 5200, 5680, 5860, 5900) K, so we use a different blackbody temperature variation are (5000, 5500, 6000, 6500, 7000, 7500) K.

The research by using PhET simulation was carried out by providing variations in temperature so that various maximum wavelengths were obtained. Experimental steps carried out: 1) Open the PhET software "Black body Spectrum"; 2) Set the temperature according to the design; 3) Write the maximum wavelength (λ_{max}); 4) Repeat the experiment for other temperature variations; 5) Make a data analysis; 6) Make a graph of the results of observations; 6) Making conclusions (Puspita, 2020).

In addition to using PhET, we also use Newton Raphson to find the value of black body maximum wavelength as a comparison. The Newton-Rapshon iteration equation is used to solve the function $f'(x)$ by determining the value of x which makes the value $f'(x) = 0$ so that equation (2) is modified to be :

$$x_{i+1} = x_i - \frac{f'(x)}{f''(x)} \tag{3}$$

where,

$f'(x) = \frac{df(x)}{dx} =$ first derivative of $f(x)$
$f''(x) = \frac{d^2f(x)}{dx^2} =$ second derivative of $f(x)$

The equations $f'(x)$ and $f''(x)$ can be determined numerically using the Central Difference method i.e. (Soegeng, 1993)

$$f'(x) = \frac{f(x+h) - f(x-h)}{2h} \tag{4}$$

$$f''(x) = \frac{f(x+h) - 2f(x) + f(x-h)}{h^2} \tag{5}$$

by substituting Equations (4) and (5) into Equation (3) we can obtain :

$$x_{i+1} = x_i - \frac{h}{2}\frac{f(x_i+h) - f(x_i-h)}{f(x_i+h) - 2f(x_i) + f(x_i-h)} \tag{6}$$

Where h is a lapse or interval whose value can be arbitrary and is usually a very small number. And then, we used the energy density of black body radiation (Equation 7) for solved by the modified Newton-Rapshon iteration equation (Equation (6)).

$$\tilde{u}(\lambda, T) = \frac{8\pi\, hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \qquad (7)$$

where :
h : $6.6261 \times 10^{-34}\, Js$
c : 2.99×10^{8} m/s
k : 1.38×10^{-23}

The solution of the above equation is done with the Python program so that the maximum wavelength value is obtained. The value of the black body temperature value and the maximum wavelength that has been obtained from PhET and Newton Raphson program are then analyzed to obtain the value of the Wien's constant with the linear regression equation $y = ax + b$, where the gradient equation $a = C$ in equation 1 is obtained.

RESULTS AND DISCUSSION

PhET Simulation-based virtual laboratory is used to apply the concept of Blackbody Spectrum to determine the Wien's constant which cannot be explained in real terms. The research was conducted by choosing the Blackbody Spectrum concept in the PhET Simulation application. The selected temperatures are (5000, 5500, 6000, 6500, 7000, 7500) K to analyze the Wien's constant value of the wavelength obtained when the temperature is selected.

At a temperature of 5000 K, the maximum wavelength (λ_{max}) of 580 nm is obtained as shown in Figure 2.

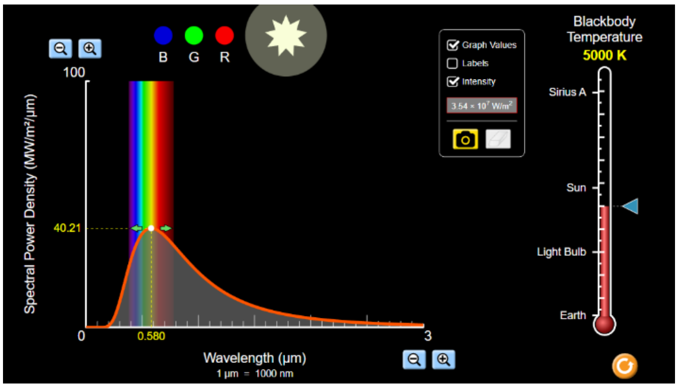

Figure 2. Wien's constant analysis at a temperature of 5000 K

At a temperature of 5500 K, the maximum wavelength (λ_{max}) of 527 nm is obtained as shown in Figure 3.

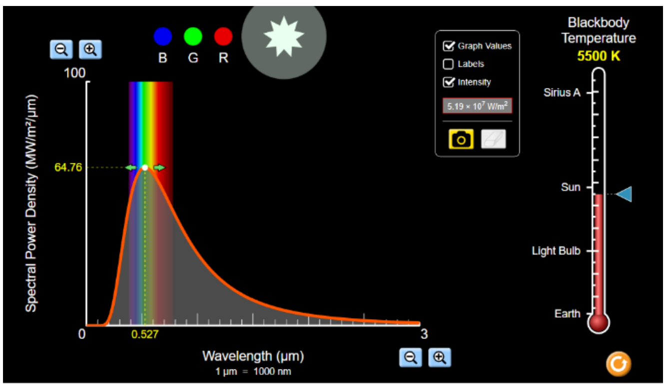

Figure 3. Wien's constant analysis at a temperature of 5500 K

At a temperature of 6000 K, the maximum wavelength (λ_{max}) of 483 nm is obtained as shown in Figure 4.

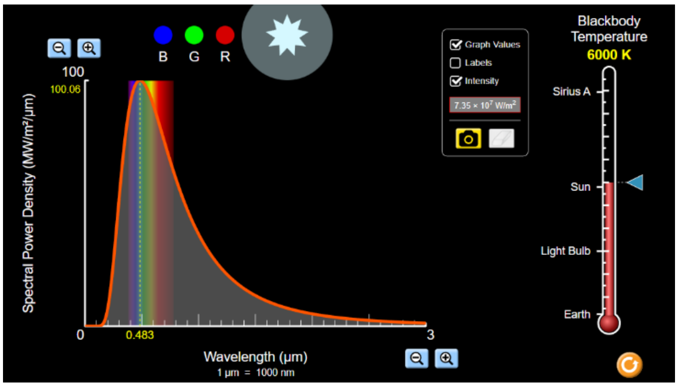

Figure 4. Wien's constant analysis at a temperature of 6000 K

At a temperature of 6500 K, maximum wavelength (λ_{max}) of 446 nm is obtained as shown in Figure 5.

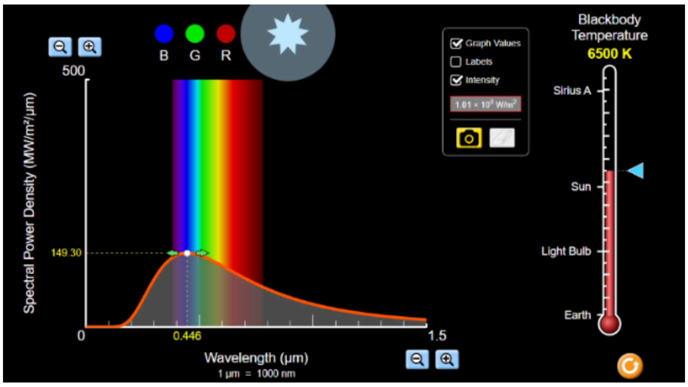

Figure 5. Wien's constant analysis at a temperature of 6500 K

At a temperature of 7000 K, maximum wavelength (λ_{max}) of 414 nm is obtained as shown in Figure 6.

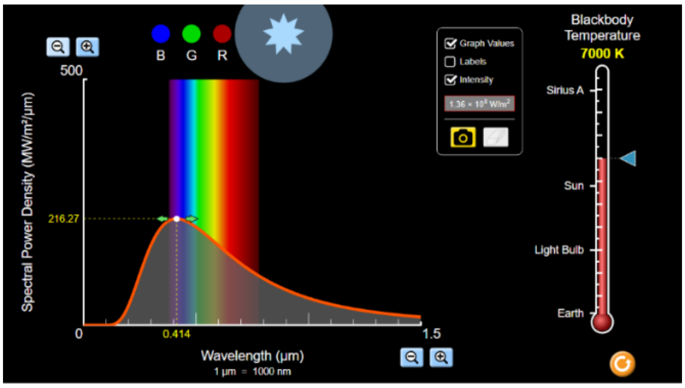

Figure 6. Wien's constant analysis at a temperature of 7000 K

At a temperature of 7500 K, maximum wavelength (λ_{max}) of 386 nm is obtained as shown in Figure 7.

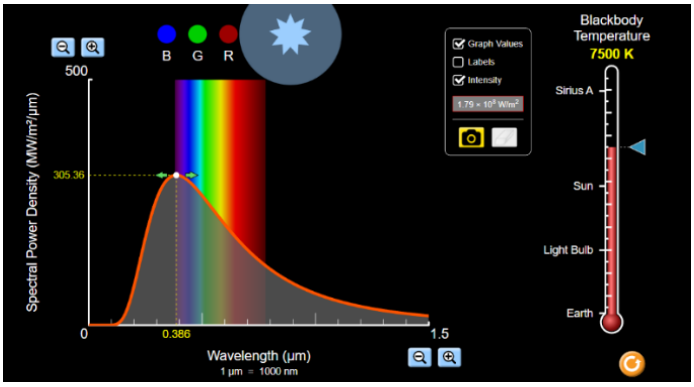

Figure 7. Wien's constant analysis at a temperature of 7500 K

Table 1. One-by-temperature correlation with maximum wavelength

No	1/T (1/K)	λ_{max} (m)	
		PhET	Newton Raphson
1	0.000200	5.8×10^{-7}	5.78×10^{-7}
2	0.000182	5.27×10^{-7}	5.26×10^{-7}
3	0.000167	4.83×10^{-7}	4.82×10^{-7}
4	0.000154	4.46×10^{-7}	4.45×10^{-7}
5	0.000143	4.14×10^{-7}	4.13×10^{-7}
6	0.000133	3.86×10^{-7}	3.66×10^{-7}

From these results obtained in linear regression according to the equation of Wien's displacement law, so that a one-per-temperature (1/T) have corellation with maximum wavelength (λ_{max}) show in Figure 8.

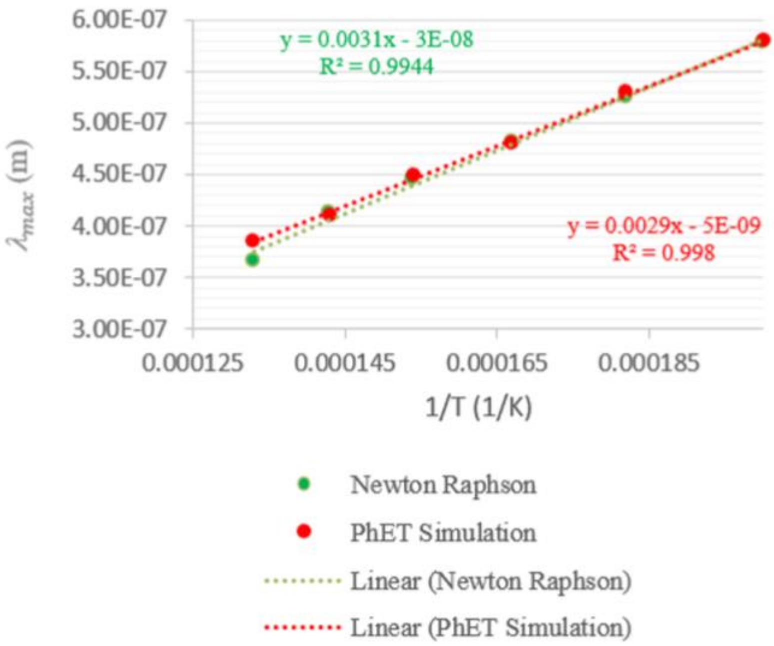

Figure 8. The graph of the corellation 1/T dan λ_{max}

The graph of the corellation between one-per-temperature 1/T (1/K) and maximum wavelength (λ_{max}) shows that the smaller the temperature, the larger the wavelength.

From the data analysis, the value of Wien's constant using PhET 2.93 × 10^{-3} mK with relative error obtained is 1.07 % and using Newton Raphson is 3.07 × 10^{-3} mK with relative error obtained is 5.90 %. The value of Wien's constant using PhET is closer to the theoretical value of 2.8989 × 10^{-3} mK. From this, the experiment of determining the value of the Wien's Constant with a PhET Simulation-based Virtual Laboratory proved to be able to examine the Wien's Constant. This value is also almost the same as the value of the Wien's constant in the research of Astuti & Handayani (2018) is 3 × 10^{-3} mK. The experimental results are also in line with Saparullah's research (2017) which states that temperature measurement is based on measuring the intensity distribution of infrared light emitted by the measuring object, the greater the temperature, the smaller the wavelength of the infrared light used.

CONCLUSION

Based on the results and data analysis of research, it was concluded that the value of Wien's constant using PhET is 2.93 × 10^{-3} mK with relative error obtained is 1.07% and using Newton Raphson is 3.07 × 10^{-3} mK with relative error obtained is 5.90%. The value of Wien's constant using PhET is closer to the theoretical value of 2.8989 × 10^{-3} mK. So, the use of PhET Simulation-based Virtual Laboratory is able to research effectively to determine the value of the Wien's constant close to the theoretical value.

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