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# Comparison Study of Measured and Calculated Correlated Color Temperature (CCT) for Different Light Sources

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***Abstract:***
*The correlated color temperature (CCT) values are intended by the lighting industry to give a general indication of the apparent "warmth" or "coolness" of the light emitted by a light source. For many lighting applications, in offices, hotels, galleries, the textile industry, etc., the correlated color temperature (CCT) is the most important factor governing the choice of appropriate light sources. The computation of the correlated color temperature (CCT) based on the given spectral power distribution (SPD) of a light source has a long history. The correlated color temperature of a source is normally determined either by a direct experimental method, such as red/blue ratio method, or graphically from the chromaticity coordinates. In the present research, both of correlated color temperature and the chromaticity coordinates are determined for eight incandescent lamps at different electrical current values. Comparing measured and calculated color temperature (CT) values are presented in curves. A set up based on NIS Spectroradiometer Ocean optics HR 2000 with uncertainty 4.7% and photometric bench have been used to measure the correlated color temperature for the lamps. The spectroradiometer was used to measure the lamps' spectral output. The setup involved directly measuring the spectral power distribution across different wattages (100 W, 150 W, and 200 W) of eight incandescent lamps using a photometric bench and the Ocean Optics HR 2000 Spectroradiometer at NIS and the obtained results had an uncertainty of 4.7%. The color temperature (CT) and the chromaticity color coordinates across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps were measured by using NIS colorimeter. I used the McCamy method to compute the color temperature (CT) for the eight incandescent lamps. Also, I developed an Excel program acting as a tool for calculating the lamp's color temperature (CT). This Excel program allows to the calculation of the X,Y, Z, u, v,* $\bar{u}$ *and* $\bar{v}$ *chromaticity coordinates. The difference values between measured and calculated values of color temperature (CT) are varied from 16 Kelvin to 43Kelvin for the eight incandescent lamps which are acceptable values for using McCamy Method. The uncertainty values for correlated color temperature (CCT) estimated to be 0.008 to 0.021 for the eight incandescent lamps.*
***Keywords:*** *McCamy Method, Color Temperature (CT), Correlated Color Temperature (CCT), Spectral Power Distribution (SPD), Blackbody, Chromaticity Coordinates.*

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## I. Introduction

The significance of the blackbody in various scientific and technological domains, especially concerning photometry and radiometry, is widely acknowledged. For instance, exploring the characteristics of the blackbody holds particular significance in daylighting since the Sun can be simplistically regarded as a blackbody radiation emitter functioning at approximately 5780 K. The primary defining factor governing a blackbody's radiation characteristics is its temperature, denoted as T. The correlated color temperature (CCT) is described as "the temperature of a Planckian radiator that appears most similar in color to a given stimulus when viewed under specific conditions of brightness." This value serves as a basis for determining all its other physical traits. As the temperature changes, the perceived color of the radiation emitted by a blackbody also changes. In the realm of color science, each temperature of a blackbody corresponds to a specific pair of color coordinates, visually depicted on a chromaticity diagram. This correlation leads to the concept of color temperature, which signifies the temperature at which a given radiator's color matches that of a blackbody. In cases where a radiation source deviates significantly from a blackbody's emission (due to a different spectral distribution resulting in distinct color coordinates), we employ the idea of correlated color temperature (CCT). This correlated color temperature (CCT) signifies the temperature of a blackbody whose color on the chromaticity diagram most closely resembles that of the radiation source in question. The notion of correlated color temperature (CCT) finds extensive use in characterizing diverse light sources, whether natural or artificial, within the realm of photometry [1]. Spectroradiometers are widely employed instruments for measuring the spectral power distribution (SPD) emitted by light or radiation sources. These tools have extensive applications across diverse scientific and technological fields. In photometry, these measurement systems are pivotal for evaluating the properties of light sources, aiding in quantifying and comprehending their brightness characteristics. Radiometry, another significant field, heavily relies on these systems to assess and study the radiation emitted by sources across varying wavelengths, enabling precise assessments of energy levels and spectral makeup. Furthermore, in colorimetry, these systems are essential for analyzing the color attributes of light sources. They facilitate the extraction of detailed insights into the array of colors emitted by a source, offering valuable information about its chromatic qualities and assisting in color analysis and replication. The adaptable nature of Spectroradiometers systems makes them indispensable across numerous applications in photometry, radiometry, and colorimetry, where accurate spectral measurements are crucial. Their utilization significantly contributes to advancements in various scientific disciplines and technological innovations reliant on precise characterization of light and radiation sources [2-6]. Color coordinates and centroid wavelength serve as crucial parameters within colorimetry, essential for characterizing either an object or a radiation source. These metrics are obtained through a process of weighted integration across a range of wavelengths within the spectral power distribution (SPD). The correlated color temperature (CCT) has been defined as “the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus seen at the same brightness and under specified viewing conditions” [7,8]. The correlated color temperature (CCT) of a light source, also expressed in Kelvins, is defined as the temperature of the blackbody source that is closest to the chromaticity of the source in the CIE 1960 UCS (u, v) system. Correlated color temperature (CCT) is an essential metric in the general lighting industry to specify the perceived color of fluorescent lights and other non-incandescent white-light sources such as LEDs and high intensity discharge HID lamps [9]. Before the widespread use of fluorescent and other discharge lamps, most light sources were incandescent and therefore had a color similar to a blackbody radiator. Because of this, it became common to describe the color of a light source by its "correlated color temperature" [10,11]. In color science, each temperature of a blackbody corresponds to specific color coordinates represented on a chromaticity diagram. This gives rise to the concept of color temperature, indicating the temperature at which a radiator's color matches that of a blackbody. However, when a radiation source differs significantly from a blackbody due to a distinct spectral distribution, resulting in different color coordinates, the concept of correlated color temperature (CCT) is employed. Correlated color temperature (CCT) signifies the temperature of a blackbody whose color on the chromaticity diagram closely resembles that of the radiation source. The idea behind correlated color temperature (CCT) aligns with our intuitive understanding that various light sources evoke different visual feelings: fluorescent lights often create a sense of coldness in a space, whereas tungsten or halogen lamps may impart a warmer ambiance. Similarly, rooms painted in warm hues like light yellow, orange, or ochre tend to feel more inviting and soothing due to their associations with warmth. Correlated color temperature (CCT) provides a standardized measure by assigning a specific temperature value to these visual perceptions, allowing for a standardized understanding of how different light sources affect our visual experiences [1].

In this research, the spectral power distribution was measured and the color temperature (CT) using McCamy Method [12] and chromaticity color coordinates for eight incandescent lamps were measured and calculated by an excel program and compared the results. These measurements entailed using the NIS setup, which consists of an optical bench and a spectroradiometer. The color temperature (CT), chromaticity color coordinates, and estimated uncertainty are calculated and compared for all incandescent lamps.

## II. Theoretical Principle:

A basic equation for calculating color temperature (CT) or correlated color temperature (CCT) from CIE 1931 chromaticity coordinates x and y. Within the color science spectrum, this equation demonstrates minimal errors across the relevant range. It was formulated based on the observation that isotemperature lines for crucial CCTs almost converge towards a specific point on the chromaticity diagram. This equation assumes that correlated color temperature (CCT) can be expressed through a third-order polynomial function involving the reciprocal of the slope of the line from that particular point to the chromaticity of the light source. This equation proves valuable in the development of light sources aimed at replicating CIE colorimetric illuminants, facilitating the design process to simulate specific lighting conditions accurately illuminants [12]. In 2000, Gardner [13] proposed the use of the Newton method to compute the CCT from the chromaticity coordinates u, v of a light source. In 1992, the McCamy method was introduced, proposing the utilization of a third-degree polynomial to calculate correlated color temperature (CCT) as in Equation (1). This polynomial was derived from the presumption that all temperature lines intersect at a specific point on the X,Y, Z, u, v, $\bar{u}$ and $\bar{v}$

chromaticity coordinates . Assessments of the correlated color temperature (CCT) calculation's accuracy using this method within the temperature range of 1700 to 10000 K, the maximum error amounted to 285.4 K [1,14].

$$CCT(x, y) = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \qquad \text{Eq. (1)}$$

where

$n = (x - x_e)/(y - y_e)$ is the inverse slope line.

$x_e = 0.3320$

$y_e = 0.1858$

$$x = \sum E_i \bar{x}_i / \sum E_i \bar{t}_i$$

$$y = \sum E_i \bar{y}_i / \sum E_i \bar{t}_i$$

$E_i$ is the (relative ) spectral irradiance at wavelength $i$

and $\bar{t}_i = \bar{x}_i + \bar{y}_i + \bar{z}_i$

The $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ color matching functions are tabulated over the spectral range from 400-780 nm [1,15]. If spectral of irradiance E (λ) are made at the corresponding wavelengths, the tristimulus response are in Equations from (2-4),

$$X = \sum_i E_i \bar{x}_i \quad , \quad Y = \sum_i E_i \bar{y}_i \quad \text{and} \quad Z = \sum_i E_i \bar{z}_i$$

Where $\bar{x}_i$, $\bar{y}_i$ and $\bar{z}_i$ are tabulated values of the tristimulus response functions.

## III. Experiments and Measurements

A spectroradiometer was used to measure the lamps' spectral output. The setup, shown in Figure 1, involved directly measuring the spectral power distribution across different wattages (100 W, 150 W, and 200 W) of eight incandescent lamps using a photometric bench and the Ocean Optics HR 2000 Spectroradiometer at NIS and the obtained results had an uncertainty of 4.7%. The color temperature (CT) and the chromaticity color coordinates across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps were measured by using NIS colorimeter. [15, 16.]. The photometric bench and spectroradiometer were used to directly evaluate the spectral power distribution of light. An optical fiber was employed to guide the examined light into the spectroradiometer, and its spectrum was then transmitted to a computer for data collection via a USB port. Using the optical fiber for light input enabled flexible measurement configurations. The measurement procedure adhered to the CIE 63-1984 guidelines recommended by the International Electrotechnical Commission (IEC) [17]. The spectroradiometer underwent regular calibration according to the ASTM G138 standards procedure. [18]. Spectroradiometers are known for their high accuracy in analyzing the spectral energy distribution of different light sources. Each lamp under examination was placed individually at a distance of half a meter above the spectroradiometer. Following a five-minute interval, data for each lamp was recorded. All measurements were conducted in a controlled dark setting with carefully regulated temperature $(25 \pm 2)^0 C$ .

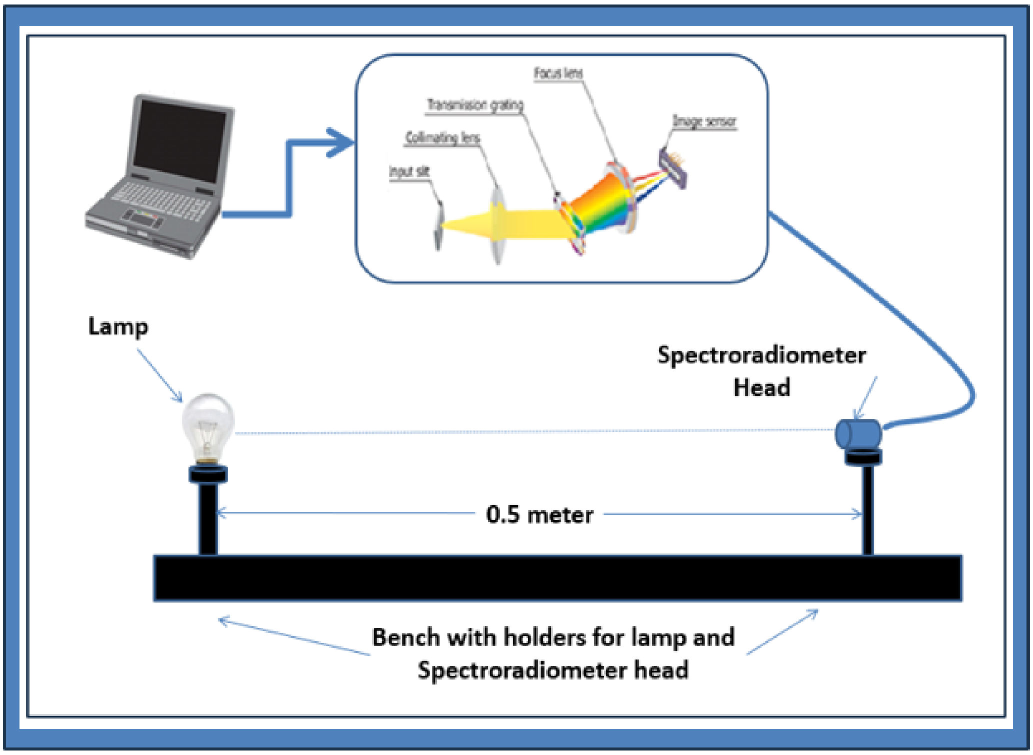


**Figure 1. NIS setup for measuring the spectral power distribution.**

I used the McCamy [12] method to compute the correlated color temperature (CCT) for the eight incandescent lamps. To simplify this process, I developed an Excel program acting as a tool for calculating the lamp's color temperature (CT). Also, I developed an Excel program acting as a tool for calculating the lamp's color temperature (CT). This program allows for the calculation of the X,Y, Z, u, v, $\bar{u}$ and $\bar{v}$ chromaticity coordinates. While the X,Y, Z, u, v, $\bar{u}$ and $\bar{v}$ chromaticity coordinates are within the range of human eye perception, considering the lamp's emissions across a wider spectrum, from near UV to near IR, enables the calculation of additional values like the melatonin suppression index. Calculating the X,Y, Z, u, v, $\bar{u}$ and $\bar{v}$ chromaticity coordinates aids in understanding how the lamp appears to the human eye under photoptic conditions.

## IV. Results and Discussions

Figures 2 through 9 display spectral power distribution (SPD) charts of eight different incandescent lamps, showcasing their radiant power emission across the visible spectrum (400 to 700 nanometers) at various current levels. These visuals illustrate how each lamp emits light within the range visible to the human eye. Each lamp's SPD chart demonstrates its unique emission patterns, displaying peaks and variations across the visible spectrum depending on the current level. These distinct peaks and patterns pinpoint the specific wavelengths at which each lamp emits light most strongly. Collectively, these figures provide a visual comparison of how these lamps emit radiant power across the visible spectrum, allowing for a thorough examination of their spectral traits. Analyzing these spectral power distributions assists in evaluating the lamps' suitability for diverse lighting requirements, considering aspects like color temperature, color rendering, chromaticity color coordinates across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps.

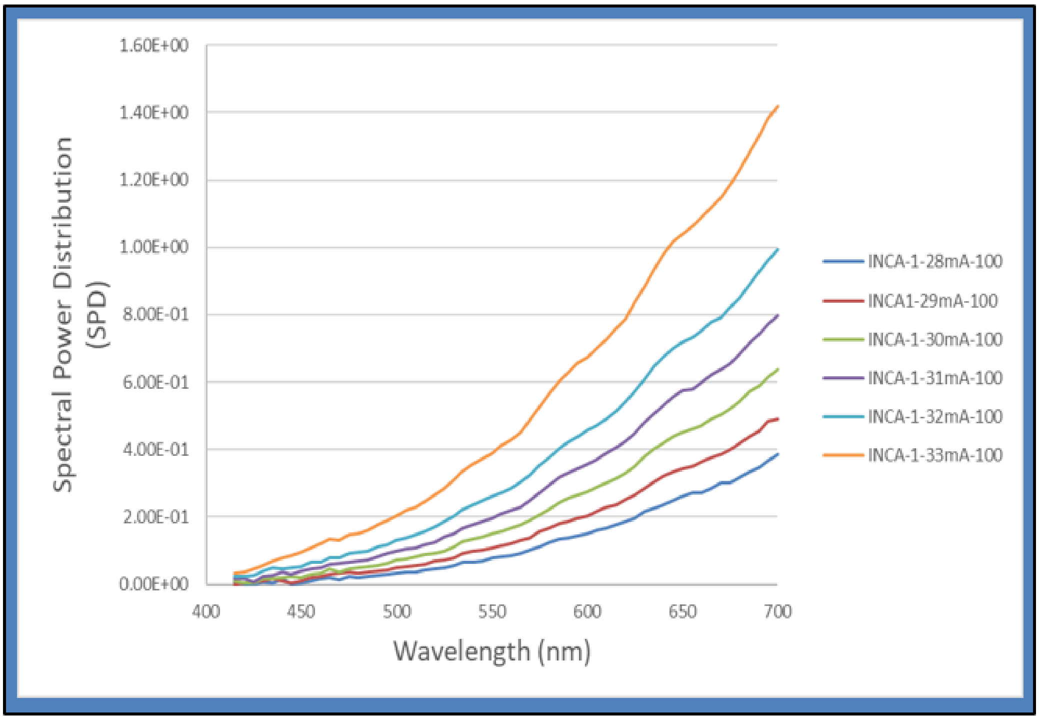


**Figure 2. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-1-100W lamp at various current levels.**

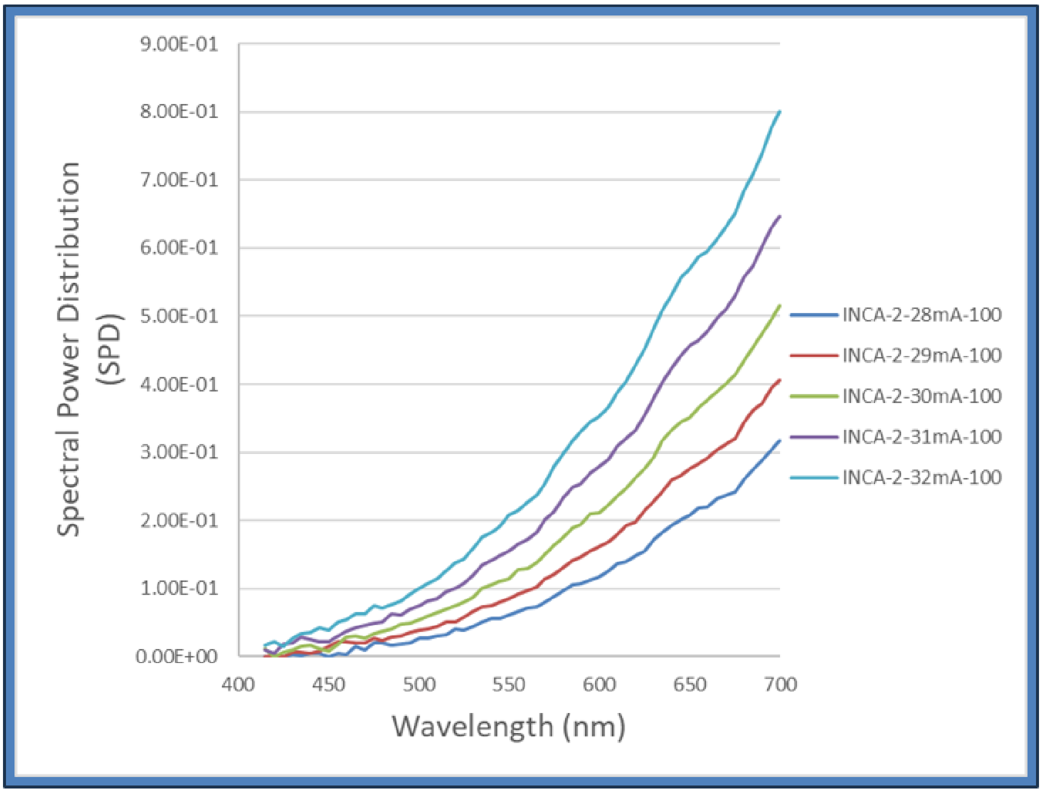


**Figure 3. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-2-100W lamp at various current levels.**

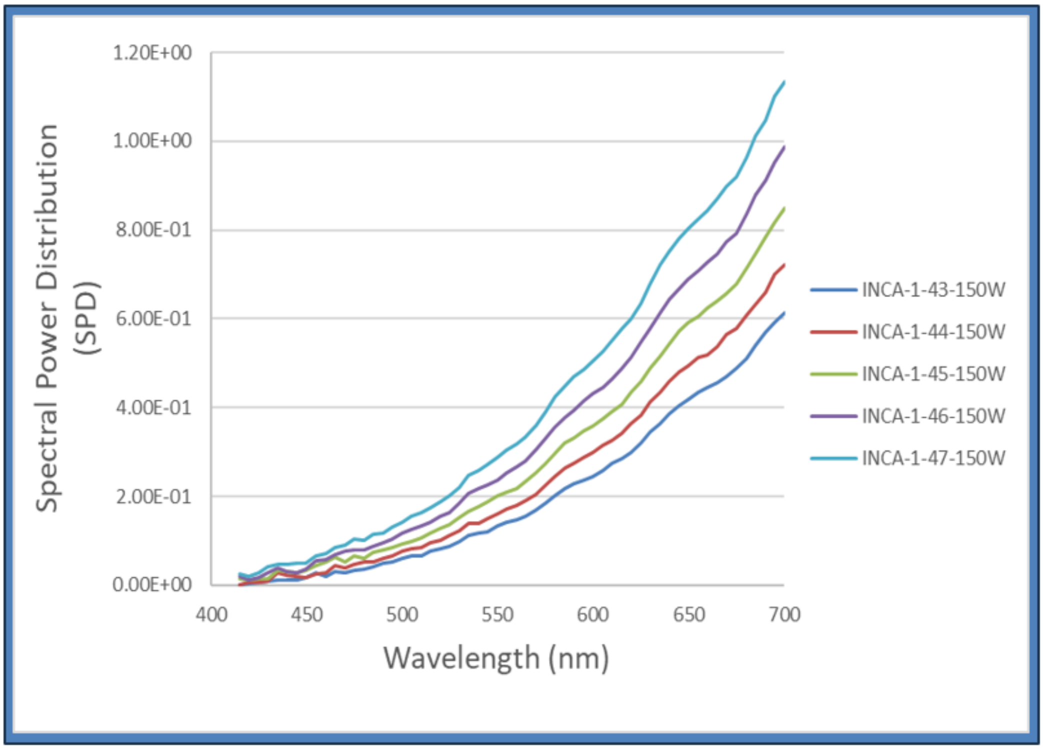


**Figure 4. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-1-150W lamp at various current levels.**

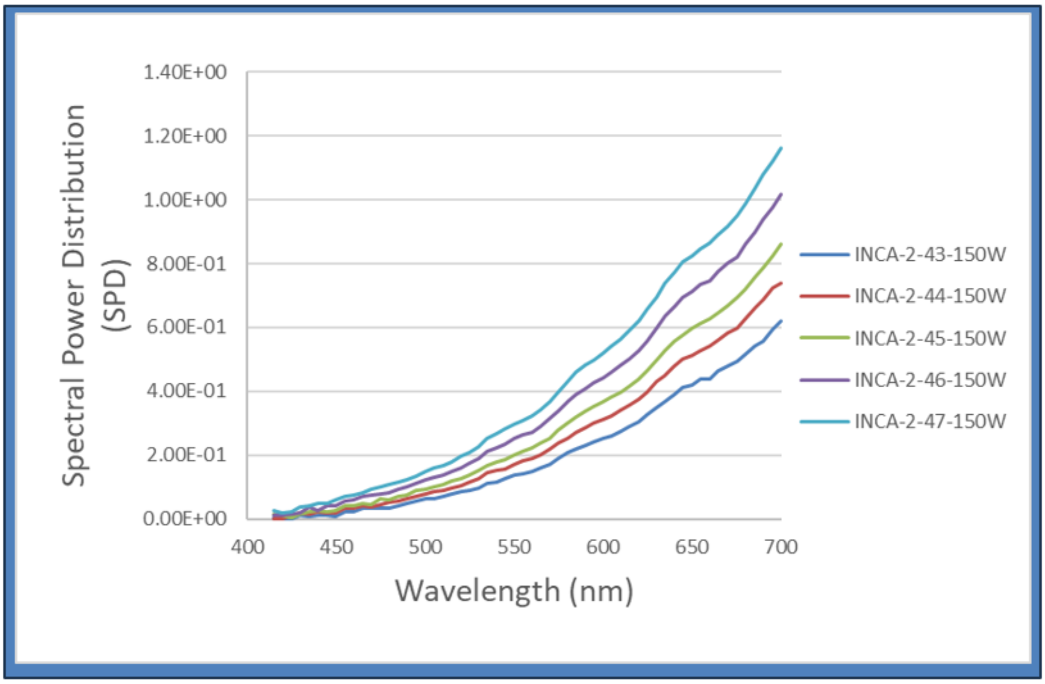


**Figure 5. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-2-150W lamp at various current levels.**

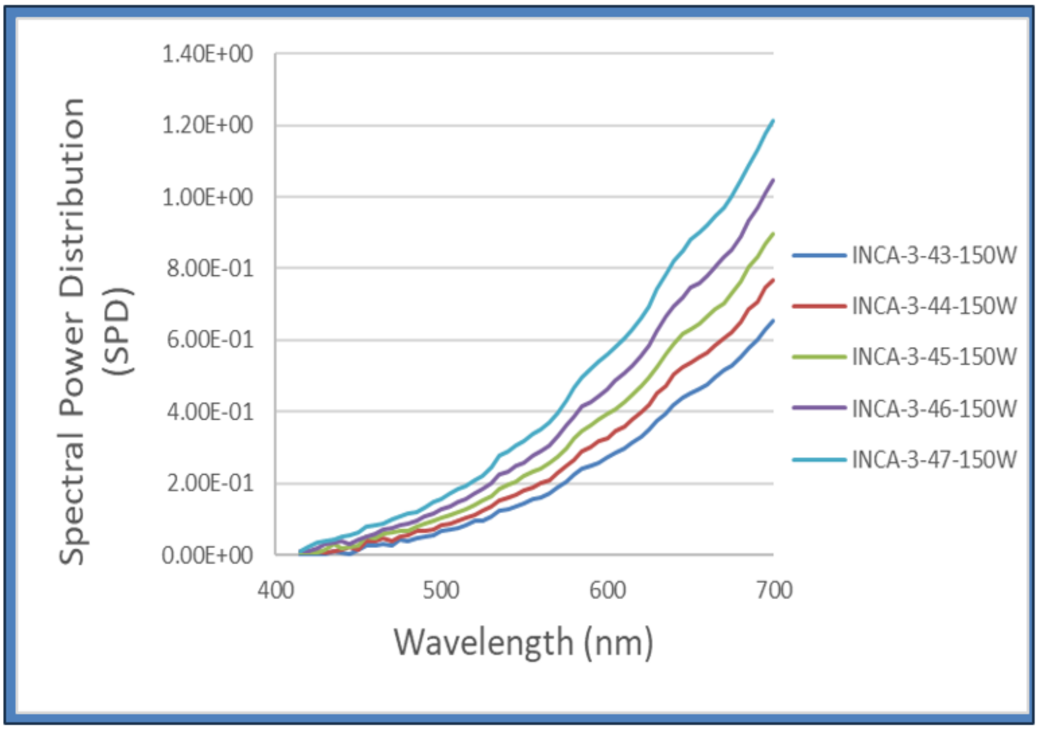


**Figure 6. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-3-150W lamp at various current levels.**

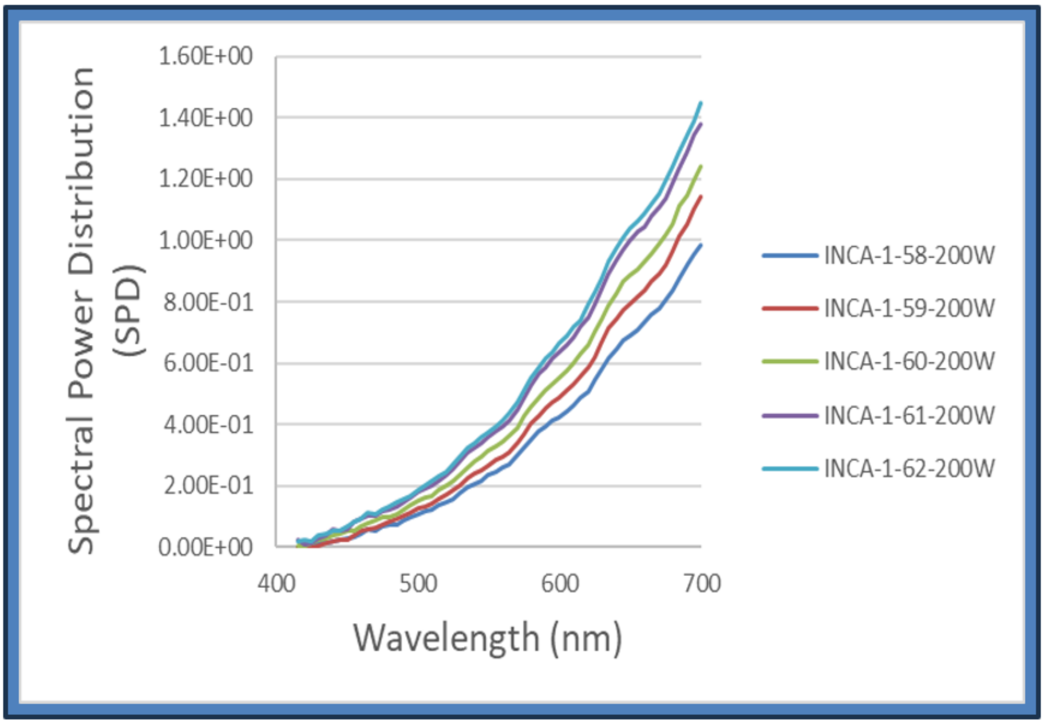


**Figure 7. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-1-200W lamp at various current levels.**

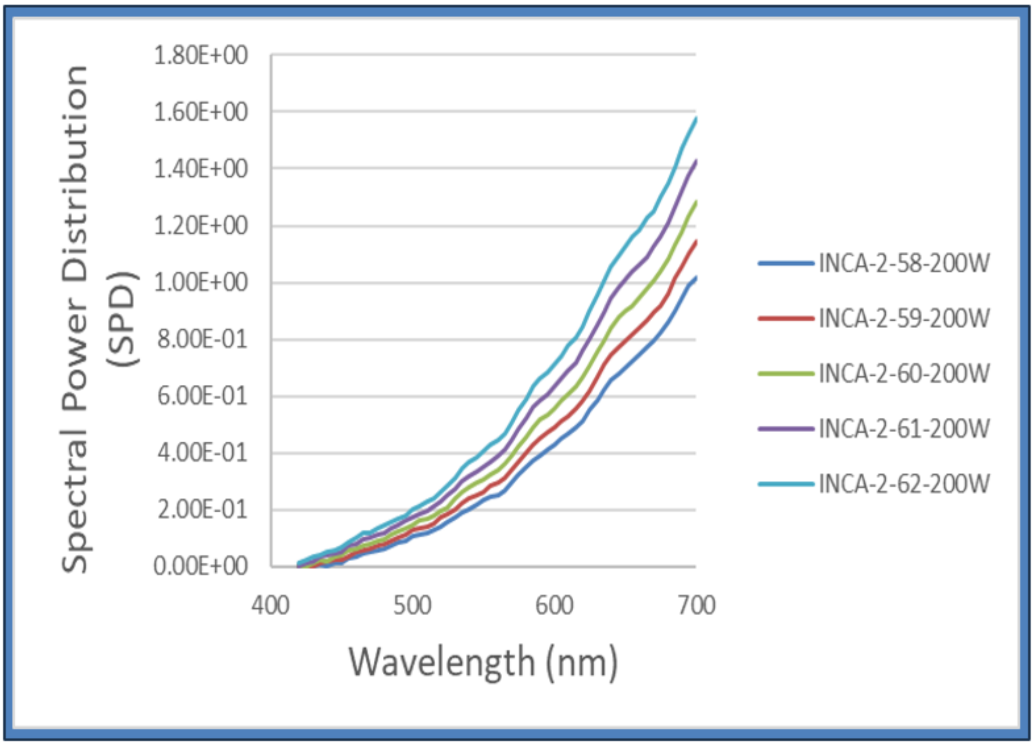


**Figure 8. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-2-200W lamp at various current levels.**

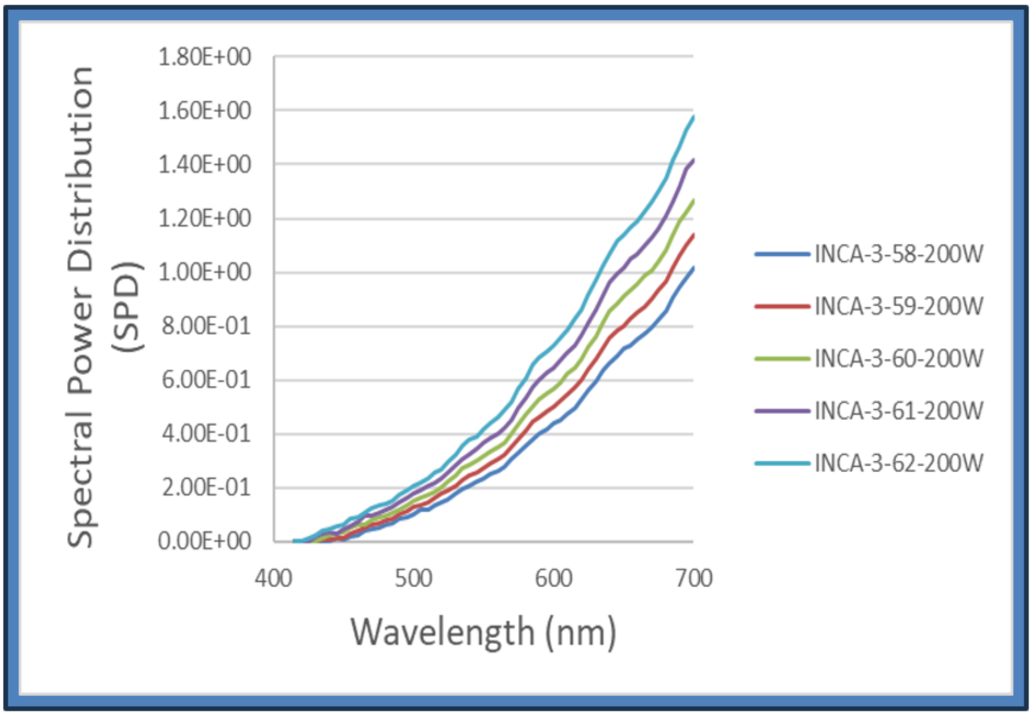


**Figure 9. Spectral power distribution (SPD) diagrams across the visible spectrum of INCA-3-200W lamp at various current levels.**

Table (1). Shows the color temperature and chromaticity color coordinates across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps.

**Table (1). Chromaticity Color Coordinates for the Incandescent Lamps**.

| Lamp | CT (Kelvin) | X | Y | Z | $u$ | $v$ | $\bar{u}$ | $\bar{v}$ |
|---|---|---|---|---|---|---|---|---|
| **INCA-1-100W** | 2043 | 0.402 | 0.373 | 0.225 | 0.241 | 0.335 | 0.241 | 0.503 |
| **INCA-2-100W** | 2049 | 0.403 | 0.373 | 0.223 | 0.242 | 0.336 | 0.242 | 0.504 |
| **INCA-1-150W** | 2084 | 0.402 | 0.372 | 0.226 | 0.241 | 0.335 | 0.241 | 0.503 |
| **INCA-2-150W** | 2054 | 0.401 | 0.372 | 0.227 | 0.241 | 0.335 | 0.241 | 0.502 |
| **INCA-3-150W** | 2074 | 0.400 | 0.371 | 0.228 | 0.240 | 0.335 | 0.240 | 0.502 |
| **INCA-1-200W** | 2073 | 0.400 | 0.372 | 0.228 | 0.240 | 0.335 | 0.240 | 0.502 |
| **INCA-2-200W** | 2070 | 0.400 | 0.372 | 0.228 | 0.240 | 0.335 | 0.240 | 0.502 |
| **INCA-3-200W** | 2095 | 0.400 | 0.372 | 0.228 | 0.240 | 0.335 | 0.240 | 0.502 |

Figures 10 through 17 display curves of measured and calculated color temperature (CT) across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps. I utilized the McCamy [12] technique to determine the correlated color temperature (CCT) of the eight incandescent lamps. Simplifying this procedure, I designed an Excel tool for CCT calculations. This tool facilitates the choice of color space, a white reference, and computes XYZ (or RGB) coordinates. While XYZ and RGB coordinates fall within human eye perception, examining the lamp's emissions across a broader spectrum, spanning from near UV to near IR, allows for additional computations such as the melatonin suppression index. The computation of XYZ coordinates offers insights into how the lamp is perceived by the human eye under photopic conditions.

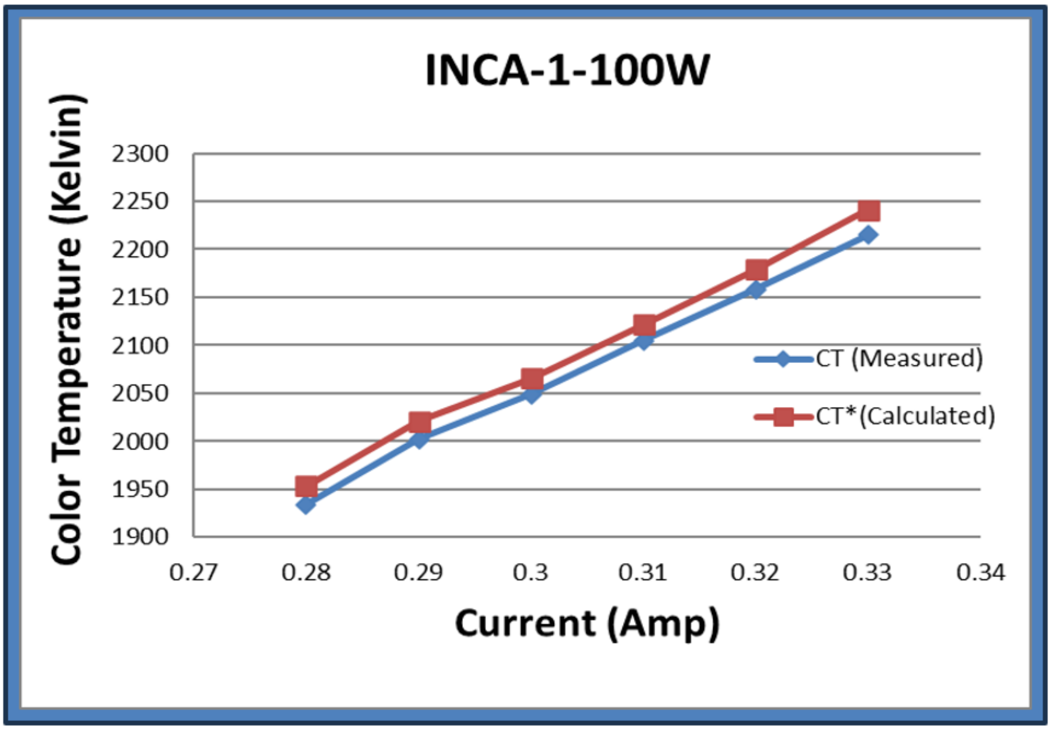


**Figure 10. Measured and Calculated Color Temperature (CT) for INCA-1-100W lamp at various current levels.**

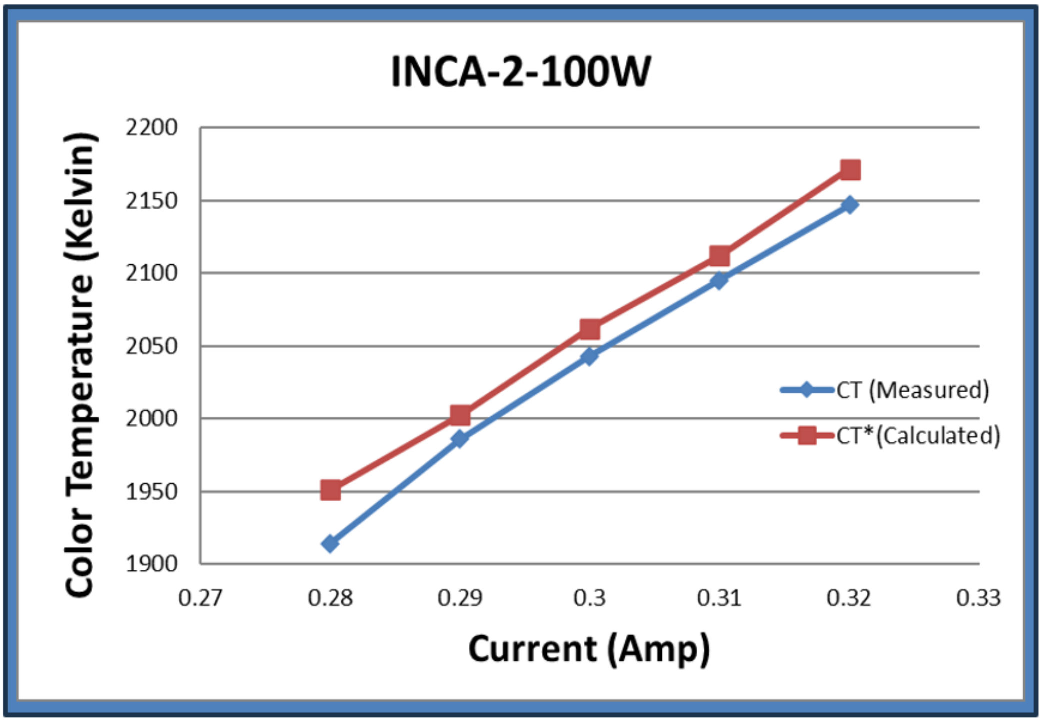


**Figure 11. Measured and Calculated Color Temperature (CT) for INCA-2-100W lamp at various current levels.**

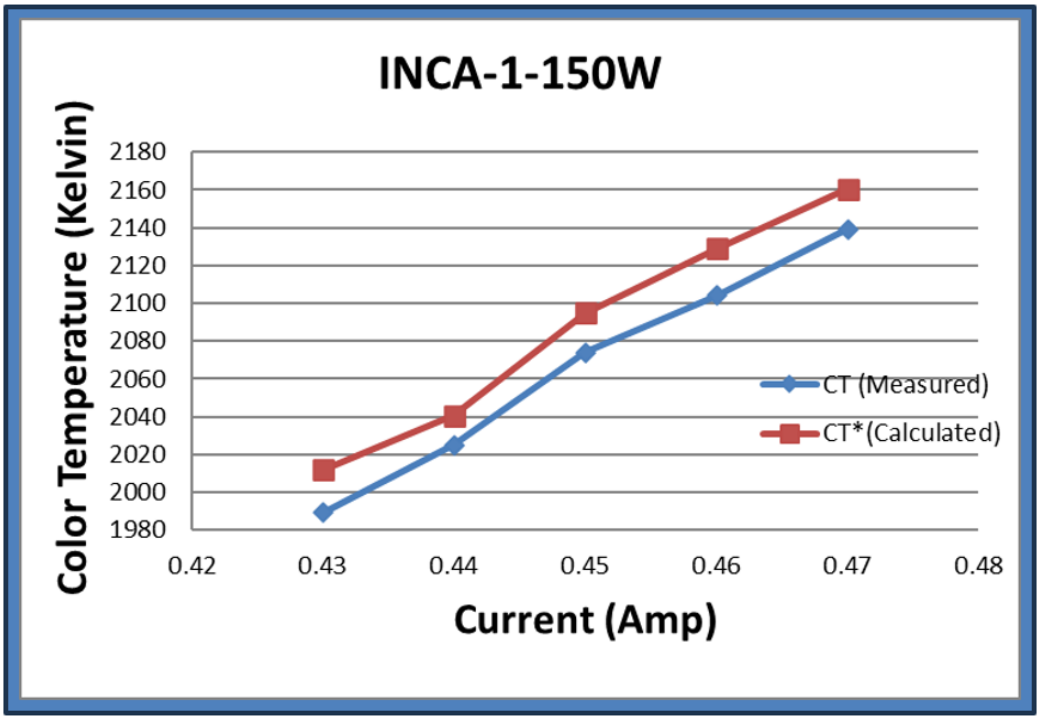


**Figure 12. Measured and Calculated Color Temperature (CT) for INCA-1-150W lamp at various current levels.**

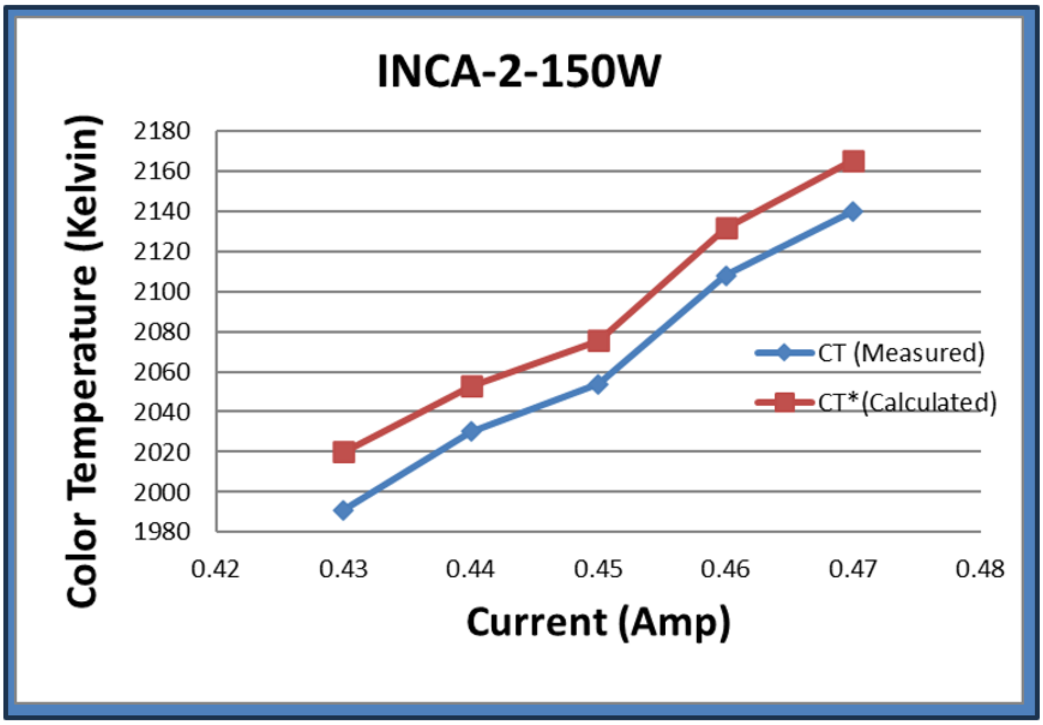


**Figure 13. Measured and Calculated Color Temperature (CT) for INCA-2-150W lamp at various current levels.**

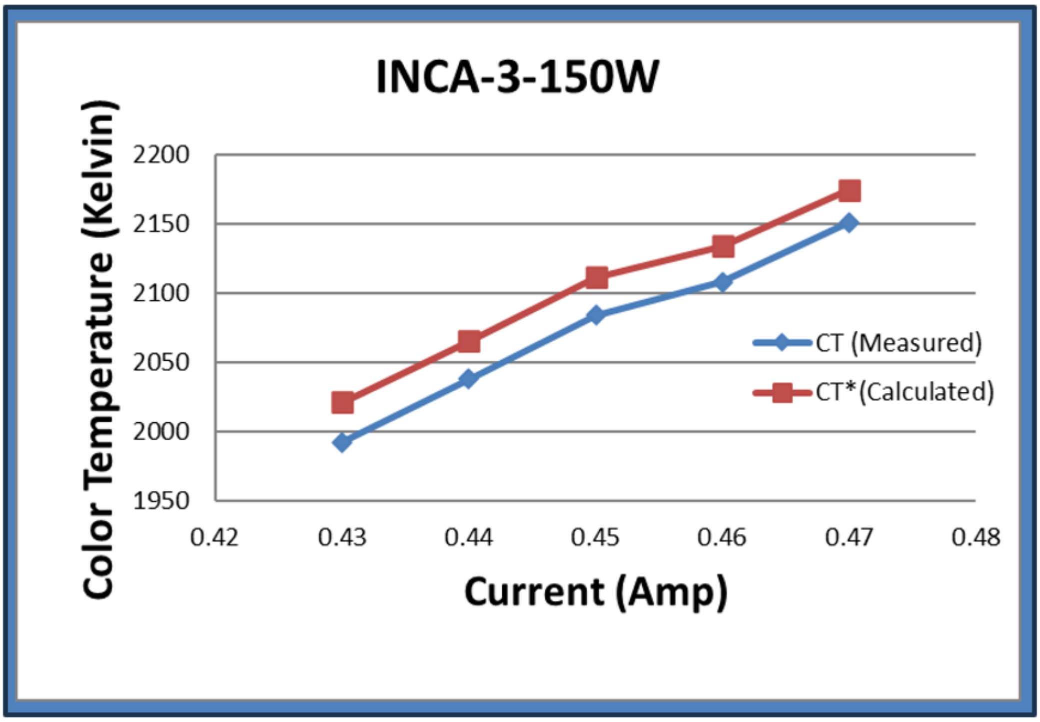


**Figure 14. Measured and Calculated Color Temperature (CT) for INCA-3-150W lamp at various current levels.**

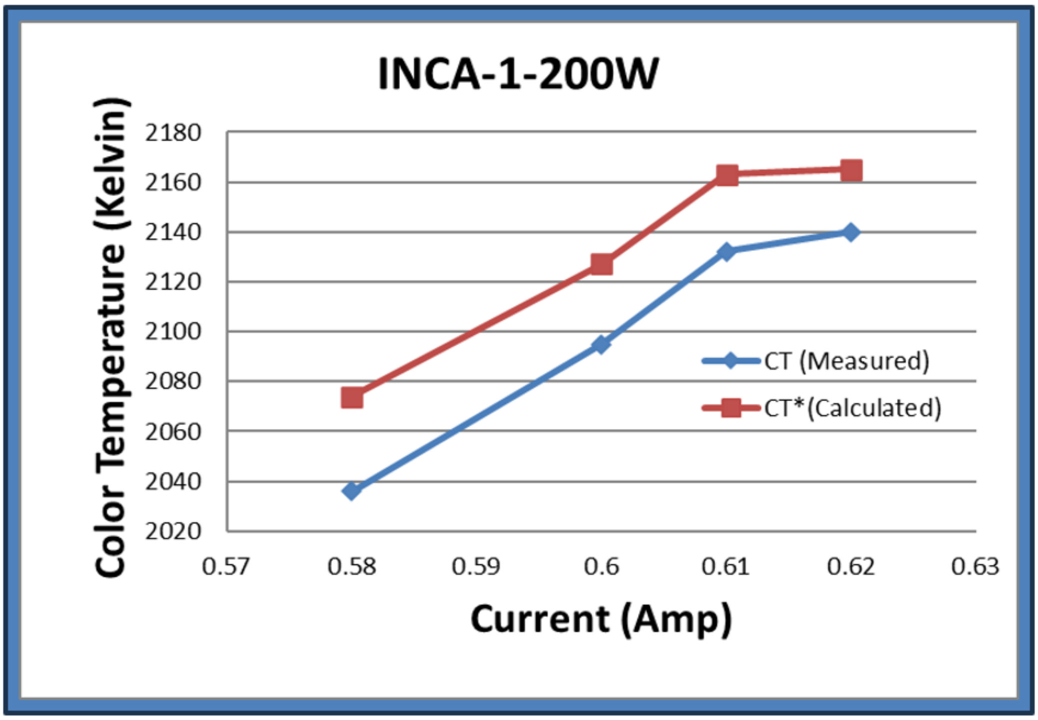


**Figure 15. Measured and Calculated Color Temperature (CT) for INCA-1-200W lamp at various current levels.**

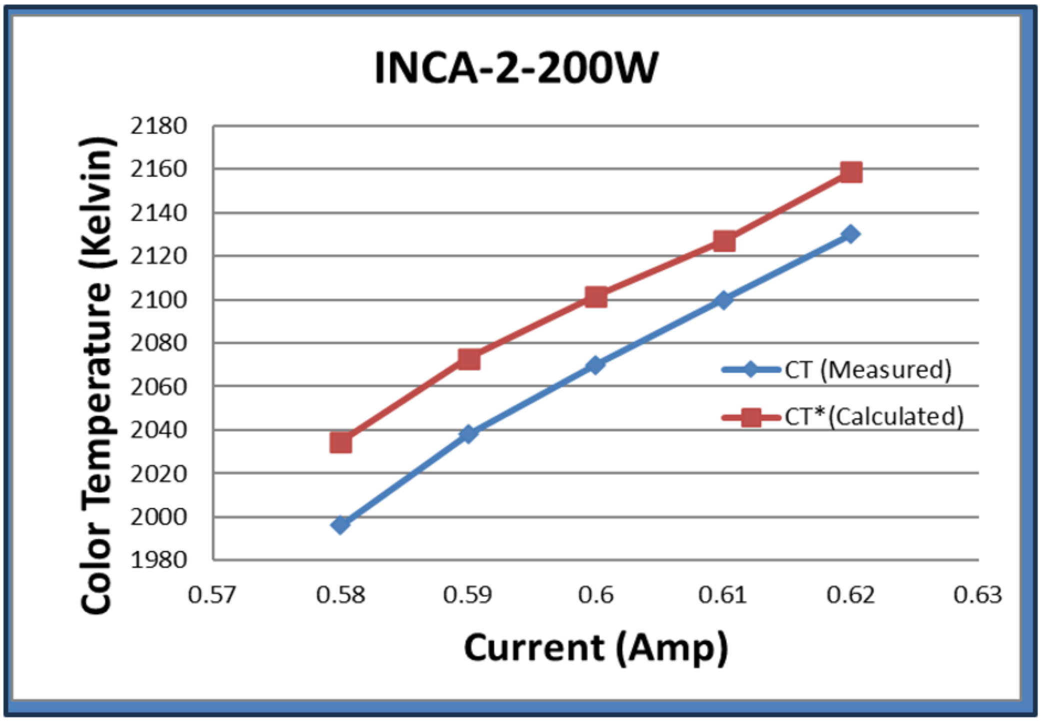


**Figure 16. Measured and Calculated Color Temperature (CT) for INCA-2-200W lamp at various current levels.**

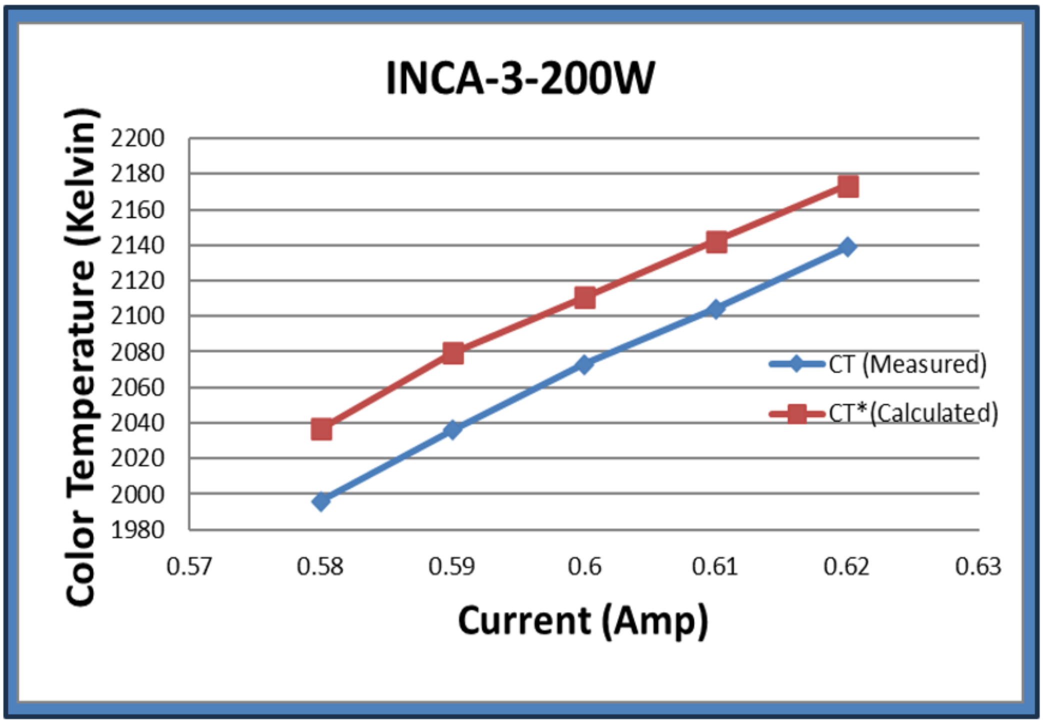


**Figure 17. Measured and Calculated Color Temperature (CT) for INCA-3-200W lamp at various current levels.**

## V. Conclusion

In this study, eight incandescent lamps were examined across various electrical current levels to determine their correlated color temperature and chromaticity coordinates. The comparison between calculated and measured color temperature values is showcased through curves. The assessment was conducted using an NIS Spectroradiometer Ocean Optics HR 2000 setup and a photometric bench to measure the lamps' correlated color temperature and spectral output. The experimental setup directly measured the spectral power distribution of the lamps at different wattages (100 W, 150 W, and 200 W) using the Ocean Optics HR 2000 Spectroradiometer at NIS, with results having a 4.7% uncertainty. The NIS colorimeter was employed to measure the color temperature and chromaticity coordinates across the various wattages of the eight incandescent lamps. The spectral power distribution (SPD) diagrams depict distinctive lamp responses characterized by their spectral distribution. Each lamp exhibits unique characteristics, emitting their spectrum in the visible region with varying distributions. Figures 2 to 9 exhibit spectral power distribution (SPD) graphs for eight different incandescent lamps, demonstrating how they emit radiant power within the visible spectrum (400 to 700 nanometers) at varying current levels. These visuals show how each lamp produces light visible to humans. The spectral power distribution (SPD) charts for each lamp display unique emission patterns, showcasing peaks and changes across the visible spectrum based on the current level. These distinct peaks and patterns highlight the specific wavelengths where each lamp emits light most intensely. Together, these figures offer a visual comparison of how these lamps emit radiant power across the visible spectrum, enabling a comprehensive analysis of their spectral characteristics. Studying these spectral power distributions (SPD) assists in evaluating the lamps' suitability for diverse lighting requirements, considering aspects like color temperature, color rendering, chromaticity color coordinates across different wattages (100 W, 150 W, and 200 W) of the eight incandescent lamps. Table 1 displays the color temperature and chromaticity color coordinates for the eight incandescent lamps at varying wattages (100 W, 150 W, and 200 W). The McCamy method was used to compute the color temperature for these lamps, and an Excel program was developed to facilitate this calculation, allowing for the determination of chromaticity coordinates. The discrepancy between measured and calculated color temperature values ranged from 16 Kelvin to 43 Kelvin for the eight incandescent lamps as shown in figures from (10) to (17), which falls within an acceptable range when using the McCamy Method. The estimated uncertainty values for correlated color temperature varied from 0.008 to 0.021 for the lamps.

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