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Effect of Light Intensity on Indoor Temperature and Air Velocity: A Simulation Study

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ABSTRACT

It is essential to understand the factors influencing thermal responses to improve human comfort and properly reduce energy consumption. It has been confirmed that parameters unrelated to the thermal environment can influence the thermal responses of occupants. These factors are yet to be investigated and studied in detailed, especially under different environmental conditions because of insufficient knowledge about indoor environment factor interactions. Therefore, accurate and high-quality data of light intensity is highly important to be focused on. Accordingly, the influences of light intensity on the temperature and air velocity of the indoor environment were studied and investigated under natural and controlled environmental conditions. The main objectives are to investigate and evaluate various effects of light intensity parameters on the indoor room temperature and air velocity for the indoor environmental condition. An effect of light intensity and simulation analysis for the indoor environment was performed using the ANSYS platform. The main parameters such as indoor temperature and air velocity were measured. Based on the results obtained from simulation analysis, the halogen lamps possess an enormous influence on the indoor environmental parameters than the LED lamps; the light intensity is directly proportional to the air velocity and indoor temperature. Conclusively, the results of this study can be considered as a reinforcement step in emphasizing the actual effect of lighting intensity, and the required lighting must be in accordance with the daily duty.

Keywords: Light intensity, heat, indoor temperature, air velocity, environment

1. INTRODUCTION

Since ancient time light has been a phenomenon used by human beings. Light intensity is the amount or strength of light generated through a certain lamp source [1]. Diverse environmental factors play a role in the maintenance of a healthy and comfortable office environment. Satisfaction rates of the occupants mainly depend on the ambient temperature, air quality, light conditions, and acoustics. The light conditions and the ambient temperature are mainly focused in this study. Artificial light allows us to perceive our surroundings and perform cognitive tasks when there is not enough natural light. The spectral composition and light intensity of artificial light affects the light appraisals, visual performance, and atmosphere perception. In addition, using the right spectral composition and light intensity, light can affect subjective alertness, cognitive performance and affect the sleep-wake cycle due to melatonin suppression. On the contrary, if there is too much light, too little light, glare, veiling reflection, shadow or flicker; the lighting can lead to the experience of visual discomfort [2]. Visual discomfort complicates the extraction of information from the visual environment; therefore, likely to it can likely affect the work performance negatively.

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The thermal sensation is generated when diverse sensors send information from the body and evaluate this information in the brain. This information is not confined to physical factors like relative humidity and temperature; hence, thermal comfort sensation is not restricted to these factors. Thermal comfort has been defined by ASHRAE standard as "the situation of mind that explains the contentment with thermal environment" [3]. It is difficult and costly to achieve thermal comfort by modifying the physical parameters. Thus, achieving thermal comfort through non-physical parameters can enhance noticeable energy with cost-saving. A previous study had provided that a reduction of about 10% annually can be attained per 1°C increment in thermostat setting of the thermal comfort area [4]. Even though there is an increment of around 14% of heating transmission load annually, an aggregate of approximately 4% of energy cost can still be attained per 1°C improvement of the thermostat setting. In another past study, a noticeable influence of a claimed increase in temperature on recognized comfort had been observed with the unchanging actual temperature. This indicates that non–physical parameters can be essential in thermal comfort perception [5]. Another study by Kenshalo showed that changes in thermal sensation were closely related to changes in skin temperatures that were observed initially. These findings are supported by a more recent study by Jacquot *et al.* [6].

Ambient temperature below thermos-neutral conditions can benefits health, energy consumption and improves alertness and performance. The downside of exposure to mildly cold temperatures is that occupants might experience thermal discomfort and evaluate the thermal environment as colder. A possible solution for this problem might involve the application of a specific light setting. A recent study had discovered light-induced moderations in thermos-physiology [7]. However, the results were not consistent. Even though some studies had found that light can influence thermal processes like the regulation of core body temperature (CBT), skin temperature and the distal-proximal skin temperature gradient DPG [8], however, other studies failed to find light-induced effects [9]–[10]. The same holds for thermal perception, various studies had reported shreds of evidence for the light-induced effects on thermal perception [11]–[12], while many others failed to find significant effects [13]–[14]. This inconsistency can partially be explained through the large variations in experimental designs that were used in earlier studies. Many studies used relatively long exposure times and measured light effects hours after the actual exposure. Therefore, these findings do not reflect the acute effects of light on thermal experiences. Additionally, several earlier findings focused on either the effect of light intensity or the effect of correlated colour temperature (CCT), while there could be interaction effects in between.

A noticeable reduction in productivity to about 10% or more was reported in the previous study [15] as the indoor environmental conditions were unacceptable for comfort, indicating sudden organizational motivations for correcting measures [16], [17] on only the economic background. Summarily, previous studies on radiation systems had majorly concentrated on heat transfer features and thermal comfort under steady-state conditions [17], [18]. Nevertheless, the thermal environment can change because of inequalities in the indoor heat loads and exterior climate. Aside from this, a lot of studies carried out on heat transfer of the radiation system concentrated on ceiling/concrete groups [19]–[21], as the system control effect majorly relies on the indoor thermal surrounding. The existence of a time delay within the indoor thermal surrounding and system, a few studies had been carried out on dynamic heat transfer based on time delay [22].

Several studies had been performed on the essential of visual-thermal comfort within the workplace in relation to ambient thermal condition and adequate illumination [2], [23]–[25]. A lot of case studies on real-world occurrences mostly on current green buildings had been reported [26]–[29]. Digitalization of engineering and designing process of building and its interiors has been greatly enhanced by analysis tools and computational modelling; it mostly initiates a more effective evaluation of flaws and design merits. In the interdisciplinary computer science and engineering frontier, evolutionary algorithms and machine learning have authorized the latest structural designs that possess improved characteristics and assist in quick engineering inventions [30]–[31]. Another research works focussed on applying computational tools based on environmental control of building interior. The numerical analysis using computational fluid dynamics based on changes in the aggregate comfort within a small office or room due to the occurrence of no-heat generating and heat-generating components. This finding is important to understand the relationship between the indoor environment quality and internal heat generation by human beings [32].

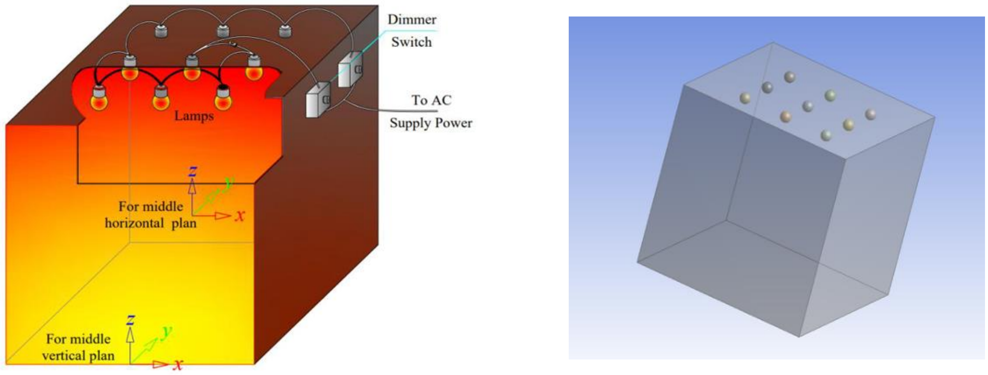
In this current study, it is essential to introduce an appropriate method of light intensity parameter measurement, including various sensors for data collection and prototype design to measure numbers of important parameters in the indoor environment (temperature and air velocity). Several investigations on indoor environments are unable to collect widespread indoor environment performance or occupant activity data which may negatively influence the building automation and control. Hence, the search for accurate and high-quality data of light intensity is highly important. The purpose of this study is to measure and determine the most appropriate light intensity parameters for indoor environment performance toward the significant understanding of energy usage in the indoor environmental quality and thermal comfort, and verification of the various effects of light intensity parameters on temperature and air velocity of the indoor environment condition using the simulation environment (ANSYS CFD).

2. METHODOLOGY

In this study, a Computational Fluid Dynamics (CFD) simulation was applied as previously reported that CFD only generate the light field and flow field information and perform optimized design effectively but also shorten the development cycle, thus reducing cost [33]. In order to evaluate the temperature and air velocity in a single room, CFD is increasingly applied to model the heat transfers and fluid flow used in the room. CFD is commonly used for different intricacy applications. It can reduce the cost of physical tests, particularly by increasing the speed of computers. CFD allows the consumer to predict the results before conducting the tests and to enhance the configuration of the experimental setup with high efficiency. The use of industrial codes to model cases in different engineering systems makes them much more powerful and desirable. Many system combinations can be addressed at the same time and at a cheaper cost relative to other experimental studies.

The geometry of a 3D model was developed using ANSYS Release 16.2 software. Then, the structure of the model was meshed to split the domain into subdomains (elements or cells) by utilizing a cell-cutting method. In this study, the Commercial CFD Code (FLUENT) is utilized to evaluate the effect of the lamp's temperature with various power supply on room temperature and air velocity. Grid and geometry creation are carried out by utilizing ANSYS Release 16.2, a pre-processor packaged with FLUENT. A mesh is generated and boundary conditions are provided as geometry is designed. A variety of meshes are evaluated to obtain an effective grid system, this is called the grid independence test (GIT). Dense mesh takes a wider duration to simulate the given problem, and low-density mesh produces incorrect results. The GIT then determines the appropriate density of the grid and saves the simulation time.

In order to simulate the room, the mathematical formulation of the single-phase model was used, this model treats fluid as homogeneous features and uses differential equations that clarify energy, momentum and conservation of mass for the governing equations and laminar modelling [34]. The physical model of the test section mainly consists of a schematic diagram of the computational domain is presented in Figure 1. After the geometry was drawn and saved, it was sent to render meshing and other operations to evaluate all quantities and then saved. Thereafter, it was transferred to ANSYS Release 16.2 for reading and making sure it is ready for model boundary conditions. The box was made of aluminium and tightly insulated from the impact of external conditions. The lamps were placed on the upper surface of the box using equal dimensions as shown in Figure 1 [35]. The lamps were powered by an external power source via a variable transformer to control the incoming power of the lamps. The inner box temperature was 28 °C, the airspeed was zero before the experiment began. Two types of lamps, 18-watt halogen and 20-watt LEDs were used in this experiment.



(a) (b)

Figure 1. (a) The experimental setup [35] and (b) schematic diagram of the computational domain.

In this present study, the unstructured mesh was used to estimate the numerical area to a finite number of control volumes by selecting the finite-volume method. The structured mesh was omitted due to its suitability for easy cases and to develop inadequacy; thus, the complicated geometries and time were consumed. Through the use of ANSYS software, the model meshed. It is well-known that simple numerical monitoring and simulation methods are very necessary to improve convergence and stability during the calculation process. By assuming the control-volume method, the algebraic equations that can be resolved numerically was used as FLUENT to shift the governing equations. The type of hexahedron element was used for surface meshing. Hexahedron components were utilized for 3D geometry; since it can favour advanced geometries. The mesh of this present model and mesh topology is shown in Figure 2.

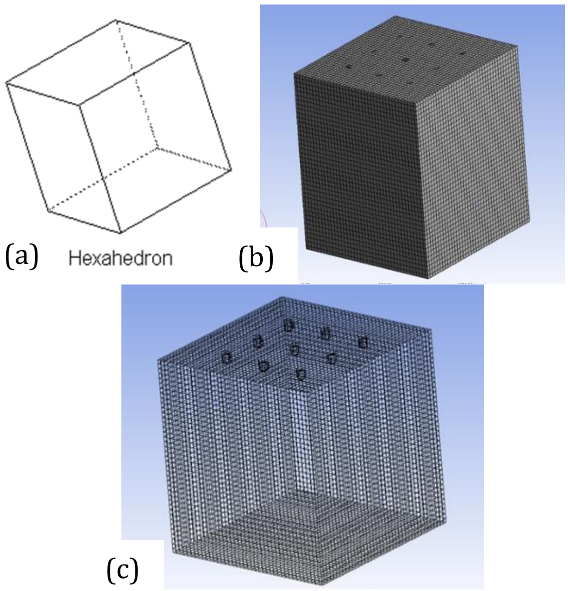


Figure 2. (a) Hexahedron element type, (b) mesh of present mode, (c) mesh topology.

In the analyses, it was recognized that the complexity of geometry allows the simulation to utilize a prolong time in finding appropriate solutions. In managing compound flows, the intricate model geometry and its mesh resolution place restrictions on the computational time stage. Essentially, the extreme mesh resolution will restrict the time stage. The number of cells used in this study was 1,367,631. In general, the accuracy of the numerical results depends on the grid resolution. In order to estimate the required grid size in this study, four different elements sizes (50, 40, 30, 20, 10, and 5 mm) were selected. The local temperatures in the centre-line of the room were investigated over these element sizes. Then, it was found that the element size of 10 mm ensures the grid-independency; it was therefore employed throughout this study. Figure 3 shows that the data does not diverge as the mesh was refined; this was carried out to validate the results of this study.

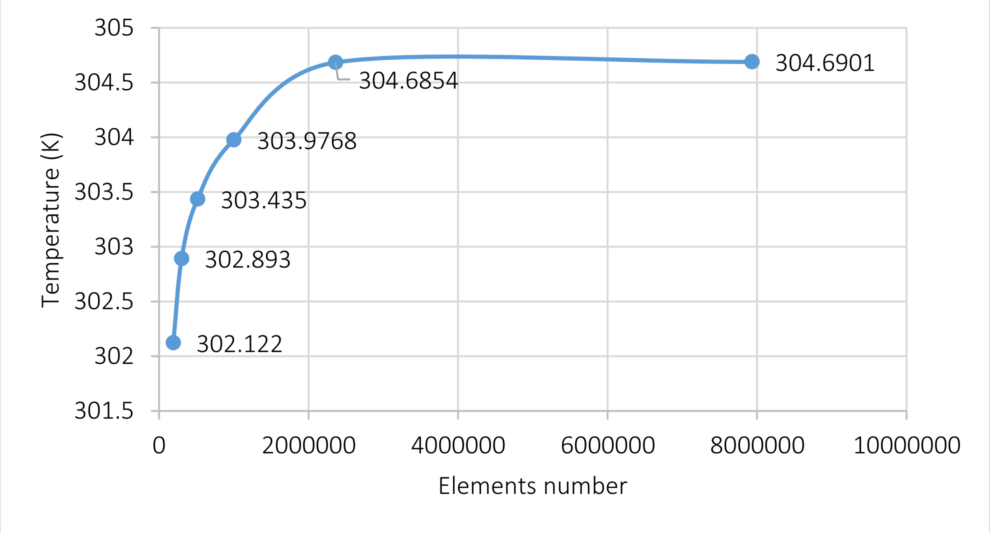
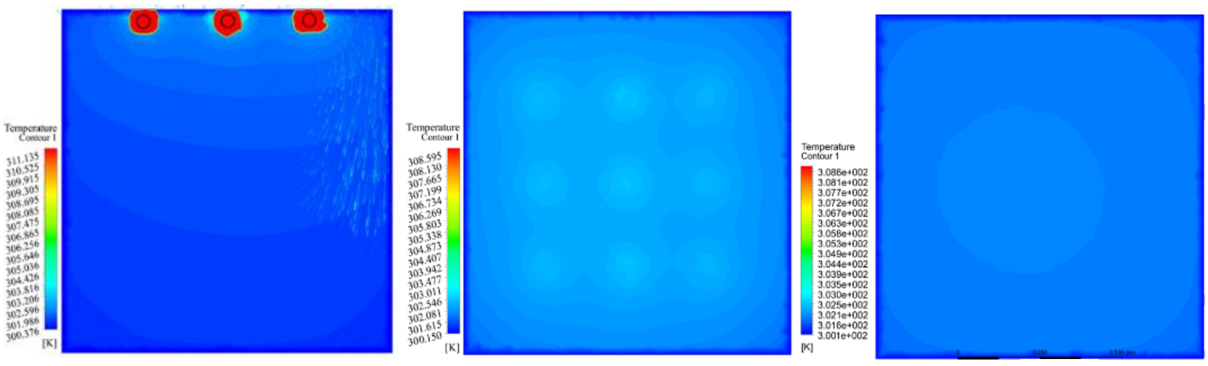


Figure 3. Validation for refined mesh.

3. RESULTS AND DISCUSSION

The results generated from this study is divided into three parts. In the first part, the simulation was implemented for three cases using halogen and two cases for LED lamps. Figure 4(a) shows the effect of light intensity on indoor room temperature using 9 lamps of halogen. The temperature distribution in a vertical plan was placed at the middle of the box (Figure 4(a)). The lamps have a clear effect on the air temperature, especially in the middle of the box. The temperature at the middle of the box was 303 K at operating period compared to room temperature before operating 301 K. This was due to the natural convection produced by the lamps. These lamps heat up the air atoms near the lamps, causing their random movement to increase. It then left its place by carrying the heat away from the lamps, this will be replaced by cool air atoms. According to the air homogeneity inside the room, the convection constantly kept light layer near the lamps and other layers at a constant temperature within the study-state. This issue was enhanced by eliminating any additional parameters.

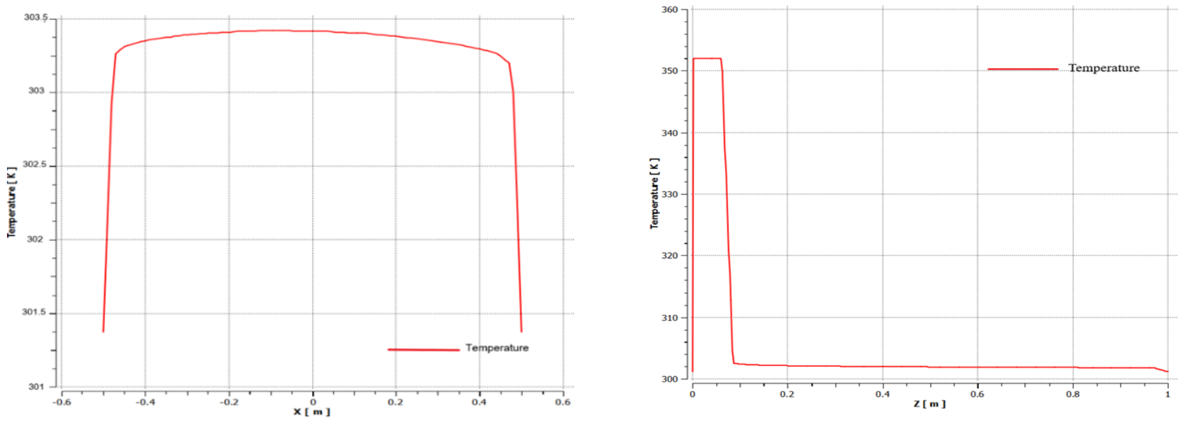
Figures 4(b) and 4(c) show the temperature distributions in two horizontal planes. The first plane was 10 cm away from the lamps and the other was placed at the centre of the box. It is noticed through the two figures that the temperature near the lamps is higher than the temperature in the middle of the box. Moreover, it is noted that the temperature at the ends of the box is the lowest except the top surface of the box. Knowing the distribution of temperature inside the box gives clear information to find appropriate solutions in reducing the impact of rising temperatures in the box. As noted seen in Figure 4(a), the temperature is higher at the centre and decreases near the walls; the reason is that the air velocity beside the walls is higher than the centre of the box.



(a) (b) (c)

Figure 4. Temperature distribution at: (a) a vertical section for 9 halogen lamps; (b) a horizontal section of 10 cm away from halogen lamps; (c) a horizontal section at the middle of the box for 9 halogen lamps.

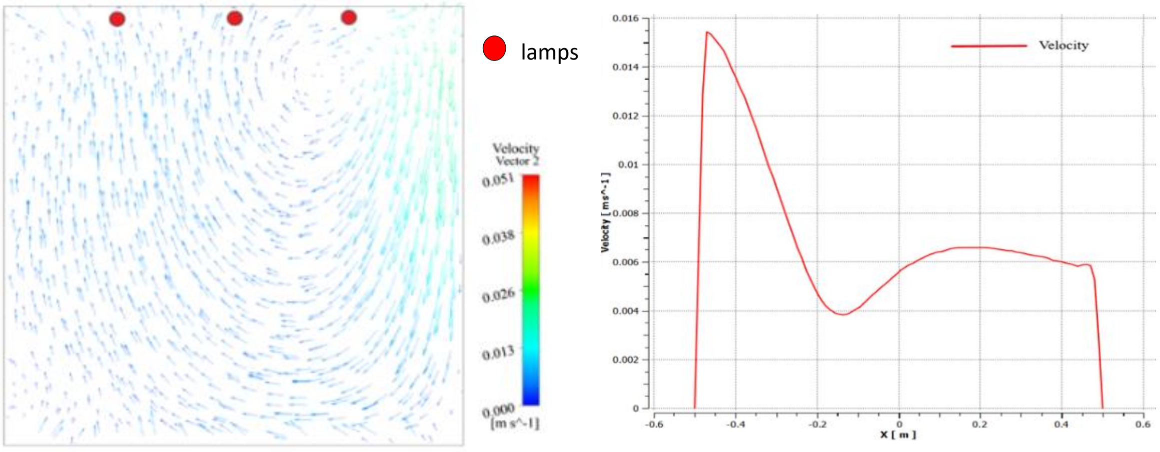
The temperature distribution was checked on a vertical line placed at the centre of the box. Figures 5(a) and 5(b) present the temperature distribution on this line as a result of heat generated from lamps indicate the presence of the highest temperature presence to address this effect. In addition, it shows that the highest temperature near the lamps and begins to decrease gradually when moving away from the lamps towards the centre.



(a) (b)

Figure 5. Temperature at the line: (a) in x-direction at the middle of the box for 9 halogen lamps; (b) in z-direction at the middle of the box for 9 halogen lamps.

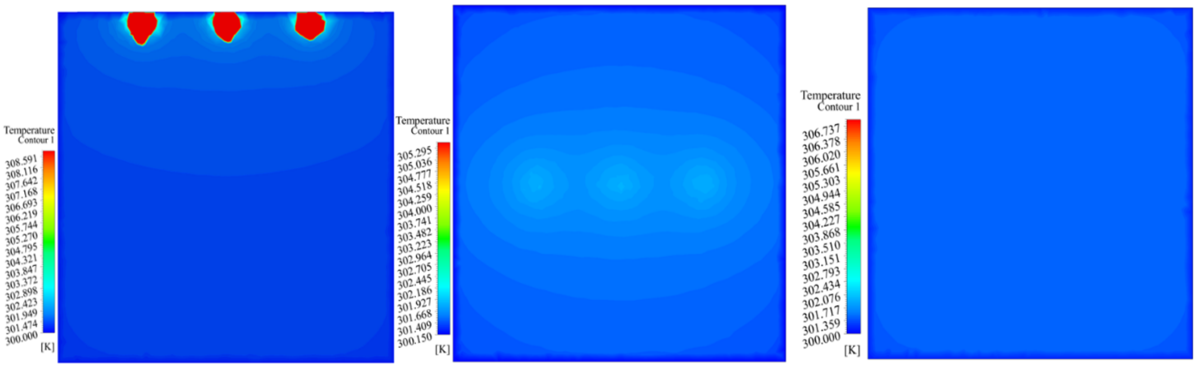
The study of air movement inside the buildings, whether it is rooms, offices, restaurants, or any place where people can be, is absolutely necessary. The movement of air may cause some kind of inconvenience to humans. In this study, the movement of air as a result of heat from the lamps was investigated. Figure 6(a) shows the movement of air inside the box as a result of the increase in air temperature due to natural convection. The movement of air in the form of swirl sporadic inside the box is clearly seen. The increase in air velocity inside the box accompanied by the occurrence of air swirls may cause discomfort for humans. Figure 6(b) shows the air velocity on a horizontal line placed at the centre of the box. As noted earlier, temperatures are higher in the middle of the box and gradually decrease towards the walls. In addition, it shows that the velocity near the wall is higher than the middle which causes the hot air expelled to be replaced by cold air since the velocity of the air in the middle is low, this leads to warm air.



(a) (b)

Figure 6. (a) Velocity vector at a vertical section for 9 halogen lamps; (b) velocity at the line in the x-direction of the middle of the box for 9 halogen lamps.

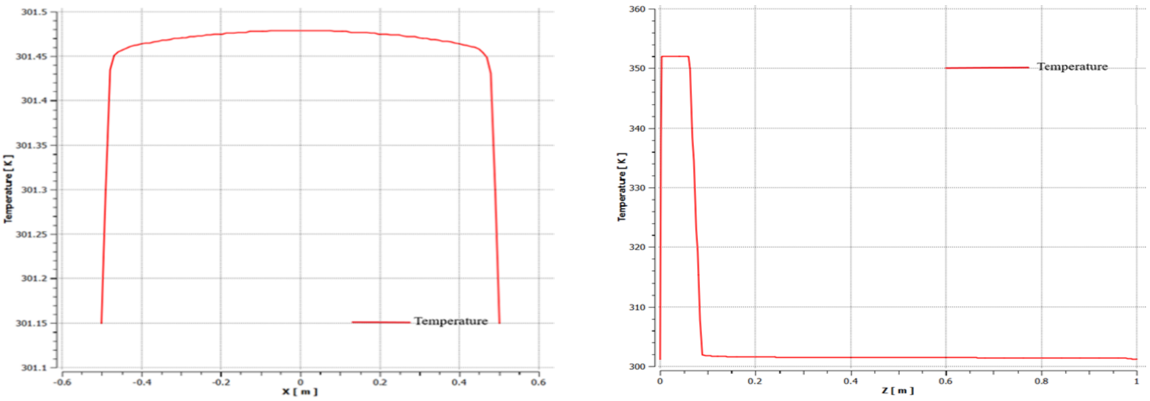
This simulation works also has examined the effect of temperature from three halogen lamps on the box temperature. The lamps were placed at the middle of the upper wall of the box with equal distances between them. The surface temperature of the lamps was experimentally measured at steady-state condition with temperature at 79 °C (352 K) [35]. In order to clearly see the effect of temperature distributions, temperatures at three planes within the box shown in Figure 8. The first plane was placed vertically at the middle of the box as shown in Figure 7(a). The second level was placed horizontally away from the bulbs at a distance of 10 cm as shown in Figure 7(b). The third (final) plane was placed horizontally at the middle of the box as shown in Figure 7(c). The figures show that the temperature evenly distributed on the sides of the lamps. It is also noted that the effect of lamp temperature on the air temperature was small, this is due to the fact that the air molecules did not heat up in a way that increases their random movement, causing their velocity to be slow.



(a) (b) (c)

Figure 7. Temperature distribution at: (a) a vertical section for 3 halogen lamps; (b) a horizontal section of 10 cm away from halogen lamps; (c) a horizontal section at the middle of the box for 3 halogen lamps.

Figure 8(a) shows the temperature distribution on a horizontal line in the middle of the box. It can be clearly seen that the temperature on this line is almost equal only in the middle where it increases slightly; this means that the 3 lamps do not have a clear effect on the distribution of temperature at the middle of the box because the heat of the lamps was not enough to increase the random movement of air molecules that forces air to move in all sides of the box carrying heat. Figure 8(b) shows the temperature distribution on a line vertically placed at the middle of the box to show the effect of temperature for 3 lamps on the temperature in this line. From this figure, it is clear that the temperature was high near the lamps due to heat of the lamps, but it appeared very low in the middle of the line.

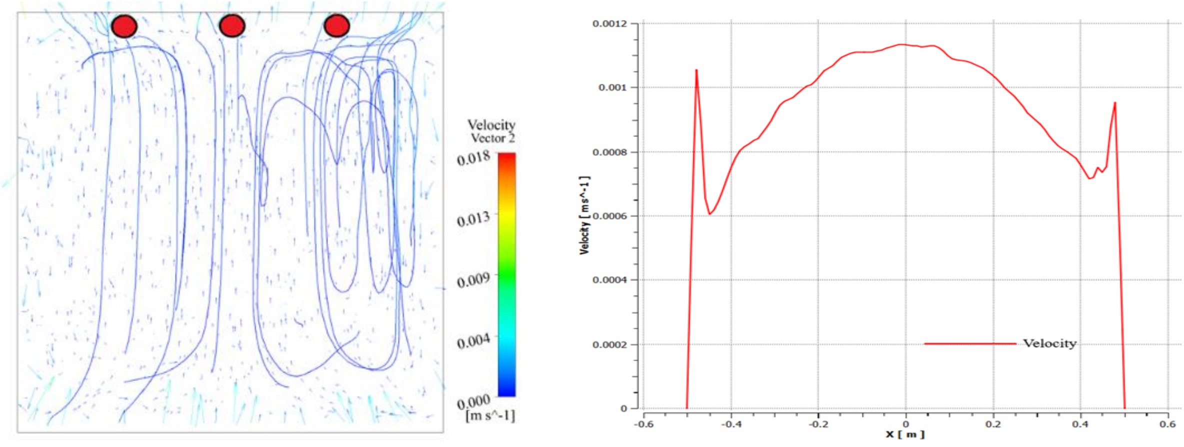


(a) (b)

Figure 8. Temperature at the line: (a) in x-direction at the middle of the box for 3 halogen lamps; (b) in z-direction at the middle of the box for 3 halogen lamps.

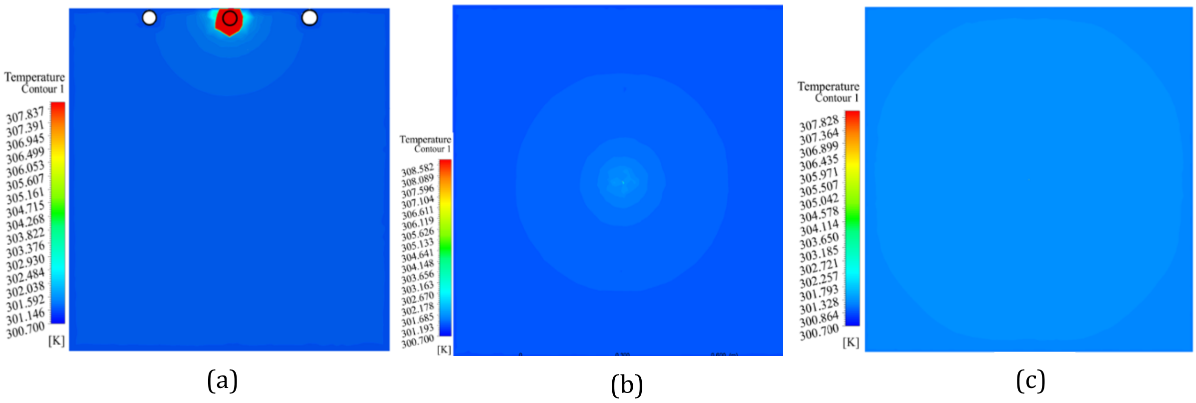
Figure 9(a) shows the temperature effect of three lamps on air velocity inside the box into two directions. First, the air velocity was studied at a horizontal plane in the middle of the box as shown in Figure 9(a). It can be clearly seen from the streamline and velocity vector that the air velocity was higher beside the lamps comparing to other regions of the box. Figure 9(b) shows that there is a slight effect next to the wall of the box due to the heat transfer coefficient, and the effect of lamp's temperature in the middle of the box was very small and does not directly affect air velocity or human comfort (Figure 9(a) has been scaled up to show effect values which are originally small values).

The effect of one lamp with a surface temperature of 79 °C (352 K) was also simulated. This lamp was placed at the middle of the upper surface of the box. The temperature distributes within the box to show its effect on comfort. Figure 10(a) shows the temperature distribution on a vertical position at the centre of the box. It can be clearly seen that the effect of the lamp was limited to an area adjacent to the lamp. Figures 10(b) and 10(c) show the effect of temperature in horizontal sections which the first section located at 10 cm from the lamps and the other located at the middle of the box. In addition, these two figures show that the effect of the lamp temperature was limited to an area beside the lamp.



(a) (b)

Figure 9. (a) Velocity vector at a vertical section for 3 halogen lamps; (b) velocity at the line in the x-direction of the middle of the box for 3 halogen lamps.

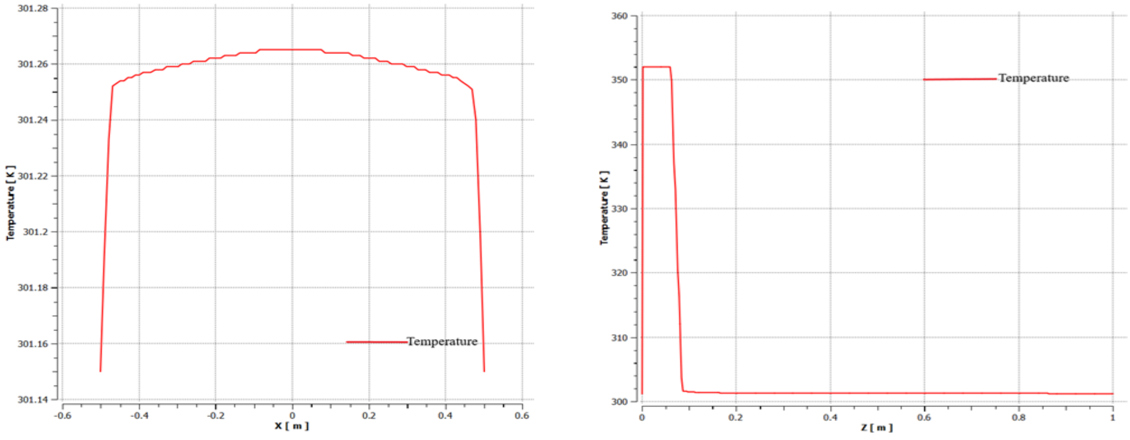


(a) (b) (c)

Figure 10. Temperature distribution at: (a) a vertical section for 1 halogen lamps; (b) a horizontal section of 10 cm away from halogen lamps; (c) a horizontal section at the middle of the box for 1 halogen lamps.

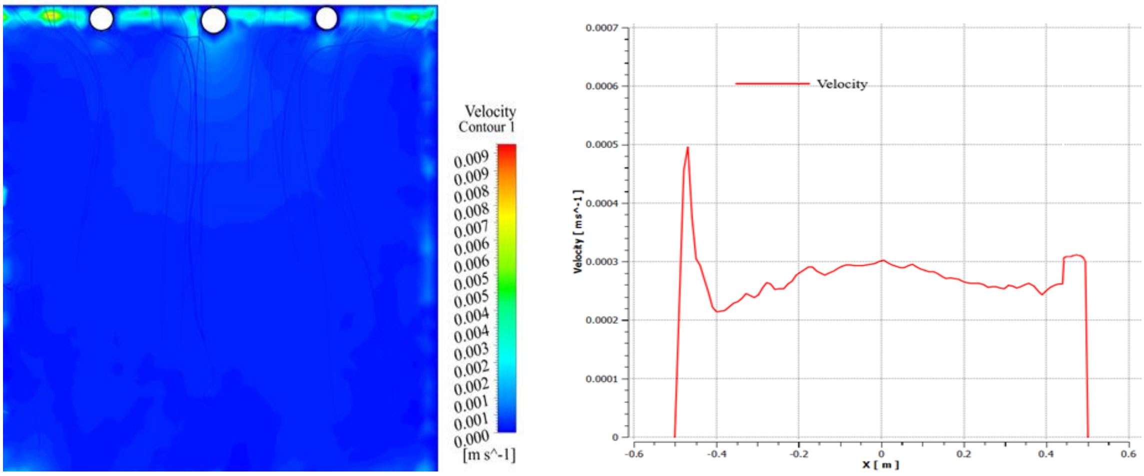
The effect of lamp temperature in box was studied on a horizontal line as shown in Figure 11(a). It can be noted that the heat did not change in a remarkable way. Figure 11(b) indicates the temperature distribution on the line placed vertically at the middle of the box. From this figure, it is clear that the temperature changed only near the lamp.

Furthermore, the effect of lamp temperature on air velocity inside the box was studied. It can be seen from Figures 12(a) and 12(b) that the air velocity changed slightly near the lamp and almost non-existent in other areas of the box because the air was not affected by the temperature of the lamp. In addition, it was confirmed that the effect of the lamp on the movement of air was almost non-existent.



(a) (b)

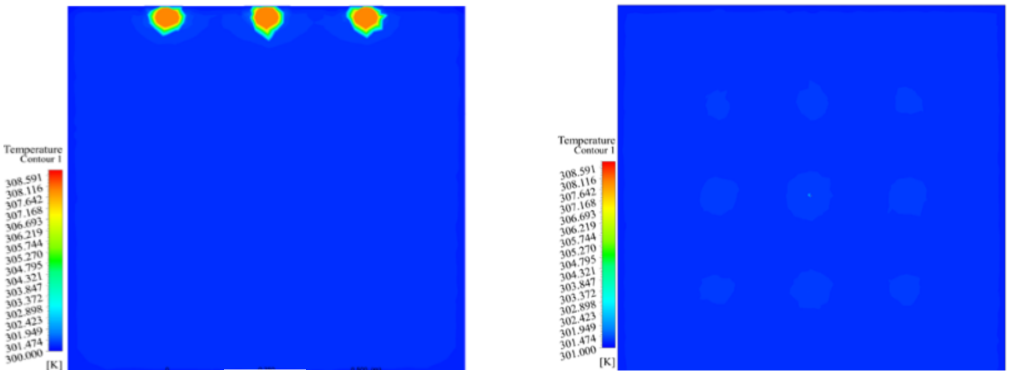
Figure 11. Temperature at the line: (a) in x-direction at the middle of the box for 1 halogen lamp; (b) in z-direction at the middle of the box for 1 halogen lamp.



(a) (b)

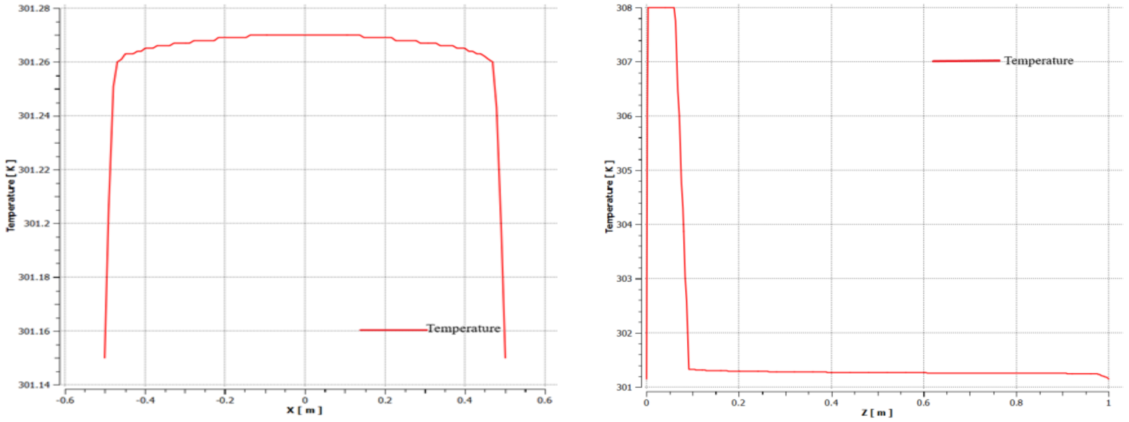
Figure 12. (a) Velocity contour at the vertical section in the middle of the box for 1 lamp; (b) velocity at the line in the x-direction of the middle of the box for 1 halogen lamp.

Moreover, the effects of 9 LEDs were studied to show their effects on the temperature of the box as well as the air velocity. On the other hand, the study adopts a comparison between different type of the lamps (halogen and LED), to indicate which one has a negative impact on human comfort. The effect of LED lamps on the temperature of the box in a vertical section located at the centre of the box. Figure 13(a) shows that the effect of LED lamps on mid-room temperature was almost non-existent because LED lamps are considered as cold light lamps. The temperature of surface lamps was experimentally measured to be 37.6 °C (310.6 K). The air temperature in the box was also measured to be 28 °C and the average wall temperature was 28 °C (301 K). Figure 13(b) shows the temperature distribution in a horizontal plane positioned at 10 cm away from the lamps. This figure shows that there is no effect drawn from the temperature of LED lamps. Figures 14(a) and 14(b) show the distribution of room temperature on a vertical line located at the centre of the box. It was noted that the temperature at this line was affected only in the vicinity of lamps, and the temperature distribution on the line vertically placed at the middle of the box. It is clear that the temperature has changed only near the lamp.



(a) (b)

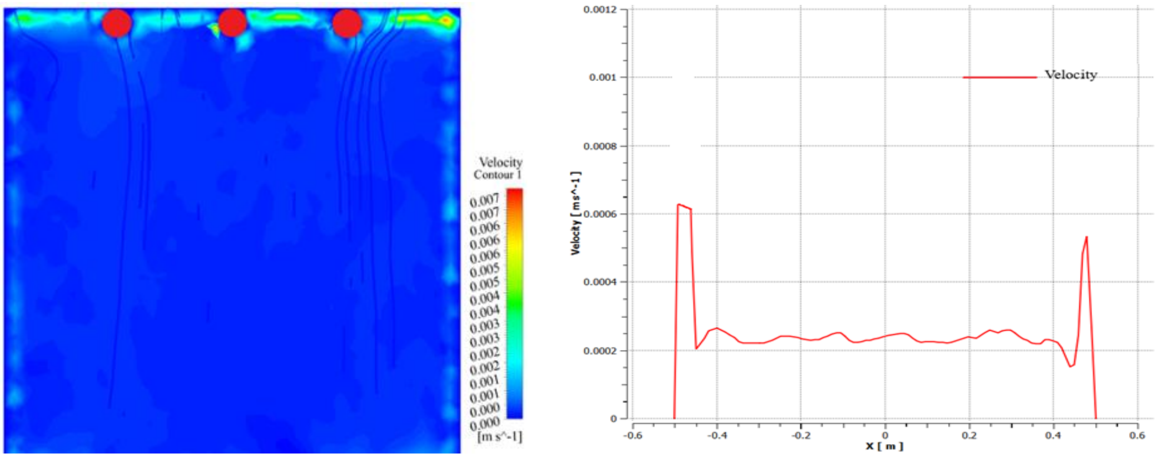
Figure 13. (a) Temperature distribution at: (a) a vertical section for 9 LED lamps; (b) a horizontal section of 10 cm away from 9 LED lamps;



(a) (b)

Figure 14. Temperature at the line: (a) in x-direction at the middle of the box for 9 LED lamps; (b) in z-direction at the middle of the box for 9 LED lamps.

Additionally, the air velocity inside the box was examined due to the effect of LED lamp temperature. It is indicated in Figures 15(a) and 15(b), that the impact of LED lamp temperature on air velocity was very small and insignificant (Figure 15(a) has been scaled up to show the effect values which are originally small values).



(a) (b)

Figure 15. (a) Velocity contour at the vertical section in the middle of the box for 9 LED lamps; (b) velocity at the line in the x-direction of the middle of the box for 9 LED lamps.

4. CONCLUSION

Different effects of light intensity parameters on temperature and humidity of the indoor environment in the simulation model were considered based on the location of lamps at the top of the box. As seen in the results obtained, it can be concluded that as the light intensity increased, the indoor temperature and air velocity increased; the effect of high light intensity on the indoor temperature and velocity is directly proportional. The method used gives room for evaluation and quick iteration of credible designs to improve building energy performance and indoor environmental quality. This indicates that the choice of lighting for any place must be studied according to the requirement needed by considering all the parameters and verify them to achieve a significant outcome.

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