Heat Transfer

Assessment name: Heated Box Evaluation

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1. Abstract

This experiment is aimed to evaluate several bulbs with different rated power assembled into a box to analyse the heat transfer for both steady and transient state.
The methods used in this experiment have included the 1st law of the thermodynamic, the lumped heat capacity model and numerical method for solving the temperature at transient state has implemented as well. Especially, in the experiment, the outside temperature for each plate from the box were assumed for the analysis purpose. The top plate was the object for evaluating the transient heat transfer.
In this report, the experimental setting was discussed, and the detailed analysis methods and relevant calculations were explained.

2. Introduction

2.1 Rationale

In this experiment, for the steady state, the outside surface temperature of the plate was assumed, and by using the 1st law of the thermodynamic:

$$\Delta U = Q - W \qquad (1)$$

In the steady state, the internal energy changes are zero (ΔU), hence, it can determine that the energy in (Q) is equal to the energy out (W), then, based on this rule, once convection and radiation happen at the outside of the box was determined, the heat transfer through each plate by conduction can be determined as well.
For the transient state, the internal energy is changing over time. Hence, from the 1st law of thermodynamic, by using the numerical method, with using the time step of 60 seconds, the convection and radiation heat transfer in each time step can be calculated and based on the lumped heat capacity model with some modifications, the energy out at each time step can be solved and the energy stored in the box can be determined as well, so that total energy stored and transferred can be obtained. And the next step is the verification of these theoretical results by experimenting.
The heat transfer that happens at this box can be modelled as shown in figure 1.
The conduction through the wall, the convection and radiation heat transfer at the outside of the box are the main objects for the evaluation.

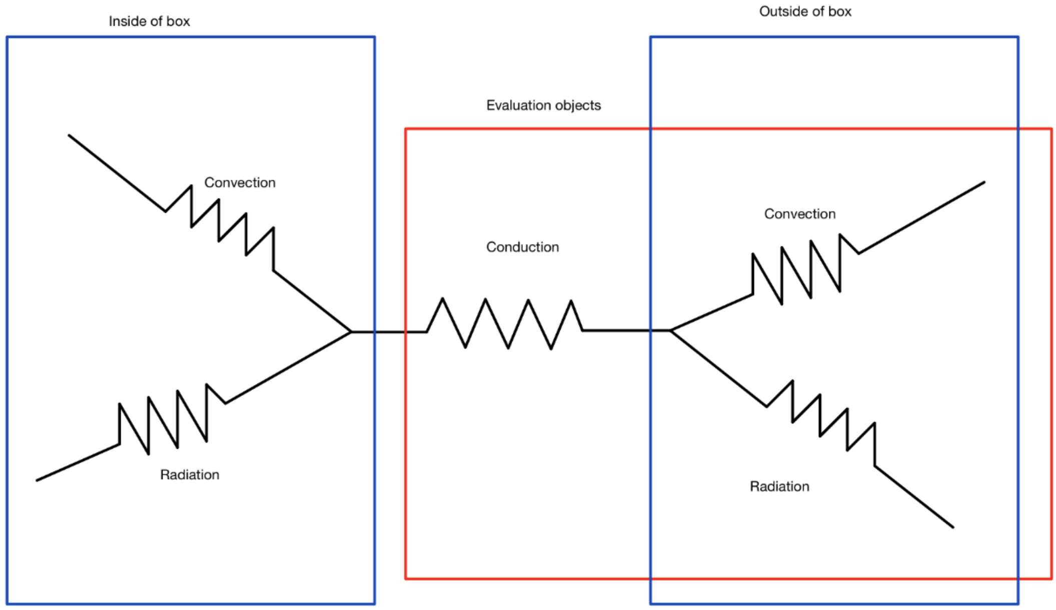

Figure 1 Heat transfer network through one side in this model

2.2 Objectives

The purpose of the lab is to evaluate the heat transfer process for a closed system (a box with a bulb inside). Then, by experimenting to identify and compare the difference between the theoretical result and experiment result.

2.3 Conduction, Convection and Radiation

In figure 1, it has shown that there are three types of heat transfer. Consequently, the discussion of each type of heat transfer was carried out.

- **Conduction**

  The heat transfer happens when the existence of the temperature difference, and in this experiment, for each side from the box, the temperature difference happens when the inside surface temperature is differing from the outside temperature, and it can be determined that the inside surface is hot than the outside surface of the plate as the inside surface has received the convection and radiation from the heat source directly. Hence, the heat flux is determined that from the inside surface towards the outside surface.

  Based on Fourier's law, the heat transfer by conduction is given:

$$\dot{Q}_{cond} = -k \cdot A \cdot \frac{dT}{dx} \qquad (2)$$

  Where:

  $\dot{Q}_{cond}$ is the heat transfer rate $[W]$

  k is the thermal conductivity $[W/m \cdot ℃]$

  A is the area for heat transfer $[m^2]$

dT is the temperature difference $[℃]$
dx is the thickness of the wall $[m]$

- **Convection**

  The convection has two forms which are 1). Natural convection. 2). Forced convection.
  Natural convection is defined as the flow of the air or liquid only because the density difference at internal and without any other forces applied.
  In this lab, in an ideal situation, there are no external forces applied to both internal and external of the box so that the natural convection stand.
  The heat transfer formula for convection gives:

$$\dot{Q}_{conv} = h \cdot A \cdot (T_s - T_\infty) \qquad (3)$$

  Where
  $\dot{Q}_{conv}$ is the heat transfer rate by convection $[W]$
  h is the convective heat transfer coefficient $[W/m^2 \cdot K]$
  A is the surface area for convection heat transfer $[m^2]$
  T_s is the surface temperature $[℃]$
  T_∞ is the surrounding temperature $[℃]$

- **Radiation**

  Heat transfer by radiation does not require the medium and is transferred by the electromagnetic wave. The rate of heat transfer by radiation is affected by the emissivity of the object. The radiation formula is given:

$$\dot{Q}_{rad} = \sigma \cdot \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right) \qquad (4)$$

  Where
  $\dot{Q}_{rad}$ is the heat transfer rate $[W]$
  σ is the Stefan-Boltzman's constant $[W/m^2 \cdot K^{-4}]$
  ε is the emissivity of the object comparing to the black body $[-]$
  A is the surface area $[m^2]$
  T_s is the surface temperature $[K]$
  T_∞ is the surrounding temperature $[K]$

3. Experiment

3.1 Apparatus

This experiment aims to analyse the temperature changes by time. Hence, several temperature sensors are needed to record the temperature changes, which P.A Hilton thermocouple recorder can be used.
Then, a timer is needed to record the time.
Besides, the bulbs with rated power 25W, 30W, 35W, 40W are needed.
A box with dimension shown below:

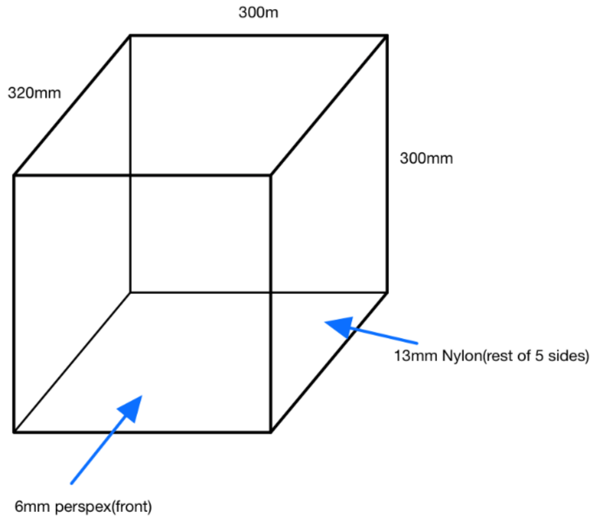

Figure 2 Dimension for box

3.2 Experiment design

In this experiment, it has evaluated the temperature at 12 different places, and if put a steel block into the box, it will be 14 places needed to be recorded which is corresponding to 15 temperature sensors.
For each place, the position is shown in table 1:

Postion	
Sensor 1	Front outer surface
Sensor 2	Back outer surface
Sensor 3	Right outer surface
Sensor 4	Left outer surface
Sensor 5	Top outer surface
Sensor 6	Bottom outer surface
Sensor 7	Front inner surface
Sensor 8	Back inner surface
Sensor 9	Right inner surface
Sensor 10	Left inner surface
Sensor 11	Top inner surface
Sensor 12	Bottom inner surface
Sensor 13	Top surface of steel block
Sensor 14	Bottom surface of steel block

Table 1 Position for each sensor

Besides, to avoid the heat transfer between the box to the ground, the box should be hanged by a bracket at the air with a string and the windows should be closed to avoid the wind from the outside of the room breaks the natural convection status.
Then, the lab is better running at night which the temperature changes at night are typically smaller than in the daytime which will help to get a more accurate

experiment result.

4. Properties of Air

In a transient state, with the changes of the temperature inside and outside of the box, the properties of the air will change as well. And this will generate lots of different data in using numerical method, which it is impossible to check the air properties manually. However, the property of the air is related to the temperature, so the properties of air in different temperature can be determined. Note: The formulas shown as follow were carried out by checking the source code on a website called Fluid Properties calculator by analysing its JavaScript codes("Fluid Properties Calculator," n.d.). The author has tested the accuracy and the feasibility of its code by comparing it to the table in the textbook("030 HEAT4 Tables V3.pdf," n.d.) which the result is the same as in the textbook.

- **Density**

$$\rho = \frac{351.99}{T} + \frac{344.84}{T^2} \qquad (5)$$

- **Dynamic Viscosity**

$$\mu = \frac{(1.459 \times 10^{-6}) \times T^{\frac{3}{2}}}{T + 109.1} \qquad (6)$$

- **Heat capacity**

$$c_p = 1030.5 - 0.19975 \times T + (3.9734 \times 10^{-4}) \times T^2 \quad (7)$$

- **Thermal conductivity**

$$k = \frac{(2.334 \times 10^{-3} \times T^{\frac{3}{2}})}{T + 164.54} \qquad (8)$$

For these formulas, where:
T is the temperature $[K]$

5. Analysis

The box is a closed system, and in this lab, it is seen as a control volume where in this control volume, for the steady state, based on the 1st law of thermodynamic, it gives:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{gen} - \dot{Q}_{store} = 0 \qquad (9)$$

And in steady state, $\dot{Q}_{in} = 0$, $\dot{Q}_{store} = 0$. So, the formula can be simplified as:

$$\dot{Q}_{gen} = \dot{Q}_{out} \qquad (10)$$

In figure 1, it has stated that the heat transfer through the wall and convection and radiation heat transfer at the outside of the box are the lab objects. Hence, in steady state, it has:

$$\dot{Q}_{out} = \dot{Q}_{cond} = \dot{Q}_{rad} + \dot{Q}_{conv} \quad (11)$$

The $\dot{Q}_{gen}$ is the rated power of the bulb.

Then, for the transient state, the equation (11) still stands, but the energy transfer for the box is changed as:

$$\dot{Q}_{gen} = \dot{Q}_{store} + \dot{Q}_{out} \quad (12)$$

It is not the object of the lab, but inside of the box, it has:

$$\dot{Q}_{gen} = \dot{Q}_{rad,inside} + \dot{Q}_{conv,inside} + \dot{Q}_{store} \quad (13)$$

6. Evaluation

6.1 Assumption

1. Ideal air in the room
2. For each plate of the box, due to the hot heat is raise and falls when is cooled down, the density of the air inside the box is not distributed averagely, hence, for each plate, the surface temperature will be slightly different. Besides, assume the bulb is mounted at the back plate and the centre of the plate so that the average temperature of the left and right side of the plate will be the same.
   And in this lab, it is assumed the following surface temperature for each bulb:

$\dot{Q}_{gen} =$ 25 [W]				$\dot{Q}_{gen} =$ 30			
Average Outside Surface Temperature (Front)	T_s	20.4	[℃]	Average Outside Surface Temperature (Front)	T_s	21	[℃]
Average Outside Surface Temperature (Back)	T_s	24.5	[℃]	Average Outside Surface Temperature (Back)	T_s	25.5	[℃]
Average Outside Surface Temperature (Right & Left)	T_s	25	[℃]	Average Outside Surface Temperature (Right & Left)	T_s	26	[℃]
Average Outside Surface Temperature (Top)	T_s	25.5	[℃]	Average Outside Surface Temperature (Top)	T_s	26.5	[℃]
Average Outside Surface Temperature (Bottom)	T_s	19.5	[℃]	Average Outside Surface Temperature (Bottom)	T_s	20.5	[℃]
Surround Temperature	T_∞	18	[℃]	Surround Temperature	T_∞	18	[℃]
Energy for each side	$\dot{Q}_{each}$	4.167	[W]	Energy for each side	$\dot{Q}_{each}$	5.000	[W]
Acceleration of Gravity	g	9.81	[m/s^2]	Acceleration of Gravity	g	9.81	[m/s^2]

Table 2: 25W and 30W outside surface temperature for each side

$\dot{Q}_{gen}=$ 35				$\dot{Q}_{gen}=$ 40			
Average Outside Surface Temperature (Front)	T_s	21.7	[℃]	Average Outside Surface Temperature (Front)	T_s	22	[℃]
Average Outside Surface Temperature (Back)	T_s	26.5	[℃]	Average Outside Surface Temperature (Back)	T_s	27.5	[℃]
Average Outside Surface Temperature (Right & Left)	T_s	27	[℃]	Average Outside Surface Temperature (Right & Left)	T_s	28	[℃]
Average Outside Surface Temperature (Top)	T_s	27.5	[℃]	Average Outside Surface Temperature (Top)	T_s	28.5	[℃]
Average Outside Surface Temperature (Bottom)	T_s	21.5	[℃]	Average Outside Surface Temperature (Bottom)	T_s	22.5	[℃]
Surround Temperature	T_∞	18	[℃]	Surround Temperature	T_∞	18	[℃]
Energy for each side	$\dot{Q}_{each}$	5.833	[W]	Energy for each side	$\dot{Q}_{each}$	6.667	[W]
Acceleration of Gravity	g	9.81	[m/s^2]	Acceleration of Gravity	g	9.81	[m/s^2]

Table 3 35W and 40W outside surface temperature for each side at steady state

3. The shape of the box is perfect, and it is hanged in the air as its top and bottom side is perpendicular to the ground.
4. When the temperature changed at transient state, the properties of the box (Conductivity, Emissivity) have not changed
5. The temperature on the box anywhere is same as surrounding temperature initially.

6.2 Calculation & Evaluation

- Steady state

  In table 2 and 3. It has given the surface temperature of each plate in steady state.

  Then, to determine the convection and radiation at the outside of the box. The formulas were given in (3) and (4).

  For the radiation heat transfer, as it is not affected by the medium property, by substitute the surface temperature and surrounding temperature, with the given dimensions, the heat transfer by radiation can be determined.

  However, for convection heat transfer, to the different temperature, the convective heat transfer coefficient will be different.

  Consequently, it is necessary to determine the convective heat transfer coefficient firstly, and it can be determined as:

  1. Heat transfer coefficient

$$Nu = \frac{h \cdot L}{k} \rightarrow h = Nu \cdot \frac{k}{L} \qquad (14)$$

Where:

Nu is the Nusselt number $[-]$

k is the thermal conductivity of the air $[\frac{W}{m} \cdot K]$

L is the characteristic length for the plate $[m]$

2. Nusselt number

The Nusselt number is the ratio of convective to conductive heat transfer at a boundary in a fluid(“Nusselt number,” 2021). And for different position of the plate, the Nusselt number is determined as(“030 HEAT4 Tables V3.pdf,” n.d.):

1. Vertical plate

$$Nu = \{0.825 + \frac{0.387 \times Ra^{\frac{1}{6}}}{[1 + (\frac{0.492}{Pr})^{\frac{9}{16}}]^{\frac{8}{27}}}\}^2 \qquad (15)$$

Where:
Ra is the Rayleigh number $[-]$
Pr is the Prandtl number of the air at film temperature $[-]$

2. Horizontal plate

$$Nu = 0.54 \cdot Ra^{\frac{1}{4}} \ while\ Ra \in (10^4, 10^7) \qquad (16)$$

$$Nu = 0.15 \cdot Ra^{\frac{1}{3}} \ while\ Ra \in (10^7, 10^{11}) \qquad (17)$$

$$Nu = 0.27 \cdot Ra^{\frac{1}{4}} \ while\ Ra \in (10^5, 10^{11}) \qquad (18)$$

Where:
Ra is the Rayleigh number $[-]$

3. Rayleigh number

Rayleigh number can be determined as:

$$Ra = Gr_L \cdot Pr \qquad (19)$$

Where:
Gr_L is the Grashof number $[-]$

4. Grashof number

The Grashof number can be determined as:

$$Gr_L = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot L^3}{v^2} \qquad (20)$$

Where:

g is the gravity $[\frac{m}{s}]$

β is the volume expansion coefficient $[K^{-1}]$
T_s is the surface temperature $[℃]$
T_∞ is the surrounding temperature $[℃]$
L is the characteristic length for the plate $[m]$
v is the kinematic viscosity $[m^2/s]$

5. Prandtl number

The equation of Prandtl number is given:

$$Pr = \frac{c_p \cdot \mu}{k} \qquad (21)$$

Where:

c_p is the specific heat capacity of the air $[J/kg^3 \cdot K]$

μ is the dynamic viscosity $[kg/m \cdot s]$

k is the thermal conductivity of the air $[\frac{W}{m} \cdot K]$

6. Characteristic length

The characteristic length is varying depending on the placement method, which gives:

1. Vertical plate

$$L = Height \qquad (22)$$

2. Horizontal plate

$$L = \frac{A}{P} = \frac{The\ area\ of\ the\ plate}{The\ perimeter\ of\ the\ plate} \qquad (23)$$

7. Film temperature

The film temperature can be determined as:

$$T_f = \frac{T_s + T_\infty}{2} \qquad (24)$$

By applying these equations and using the equation (3) of $\dot{Q}_{conv} = h \cdot A \cdot (T_s - T_\infty)$, the convective heat transfer coefficient can be determined.

And for 25W bulb front plate, which as shown:

Air properties @292.35K (Front)			
Density	ρ_{air}	1.2080	kg/m^3
Specific Heat Capacity	$c_{p,air}$	1006.13	$J/kg^3 \cdot K$
Thermal Conductivity	k_{air}	0.0255	[W/m·K]
Dynamic Viscosity	μ_{air}	1.817E-05	kg/m·s
Prandtl Number of Air at Film Temperature	Pr	0.716	[-]
	β	0.00342	$[K^{-1}]$
Kinematic Viscosity	ν	1.504E-05	$[m^2/s]$

Analysis(Steady state)			
Front Plate(Perspex) (Vertical)			
Grashof Number	Gr_L	9614888.6	[-]
Rayleigh Number	Ra_L	6882301.2	[-]
Nusselt Number(Vertical Plate)	Nu	28.11	[-]
Convection Heat Transfer Coefficient	h	2.4	$[W/m^2 \cdot K]$
Convection	$\dot{Q}_{conv}$	0.52	[W]
Stefan-Boltzmann's Constant	σ	5.67E-08	$[W/m^2 \cdot K^{-4}]$
Radiation	$\dot{Q}_{rad}$	1.05	[W]
Conduction(Energy Out)	$\dot{Q}_{cond,f}$	1.57	[W]
Temperature Difference	ΔT	0.50	[℃]
Inner Surface Temperature	T_{is}	20.90	[℃]

Table 4 25W bulb heat transfer for front plate

From table 4, it gives that in steady state the heat transfer rate by convection is 0.52 [W] and by radiation is 1.05 [W], then, by using the equation (11) of $\dot{Q}_{out} =$

$\dot{Q}_{cond} = \dot{Q}_{rad} + \dot{Q}_{conv}$, the heat transfer rate by conduction can be determined as 1.57 [W].

And recalling the equation (2) of $\dot{Q}_{cond} = -k \cdot A \cdot \frac{dT}{dx}$, the temperature difference between outside and inside surface can be determined as:

$$\Delta T = \frac{\dot{Q}_{cond}}{k \cdot A} \cdot \Delta x \qquad (25)$$

Where:

Δx is the thickness of plate $[m]$

Besides, the temperature difference between the inside and outside surface is 0.5 [°C] as shown in table 4. As a result, the temperature of the inside surface can be calculated as follows:

$$T_{inside} = T_{outside} + \Delta T \qquad (26)$$

Then, the inner surface temperature for the front is calculated as 20.9 [℃].

Similarly, by applying the same method to each plate, and adding the conduction heat transfer rate from each plate together, then recalling the equation (11) of $\dot{Q}_{out} = \dot{Q}_{cond} = \dot{Q}_{rad} + \dot{Q}_{conv}$, for each bulb, it has:

Result(Steady state) 25W			
Total energy transfer rate	$\dot{Q}_{out}$	24.94	[W]
Result(Steady state) 30W			
Total energy transfer rate	$\dot{Q}_{out}$	29.86	[W]
Result(Steady state) 35W			
Total energy transfer rate	$\dot{Q}_{out}$	34.98	[W]
Result(Steady state) 40W			
Total energy transfer rate	$\dot{Q}_{out}$	39.92	[W]

Table 5 Result table

It can be obtained that the heat transfer rate for the box to the different bulb is around equal to the power of the bulb assigned. Which meets the equation (10) of $\dot{Q}_{gen} = \dot{Q}_{out}$ of steady state characteristic.

- Transient state

The 1st law of thermodynamic for a closed system requires:

$$\dot{Q}(t) = \frac{dU(t)}{dt} \qquad (27)$$

Which explained as the heat transfer to spud per unit time is the rate of change of internal energy(“002.0 HEAT4 Heat Transfer - Introduction V1.pdf,” n.d.).

And in this question, the heat transfer rate happens at outside has contains the convection and radiation which has shown in figure 1, then, consider the lumped capacitance, the surface temperature of the plate is the internal temperature of the plate, and its internal energy can be determined:

$$U = m \cdot c_p \cdot T \qquad (28)$$

Then, in steady state condition, it has determined the heat transfer rate distribution for each plate with each bulb (table 4, it has shown the heat transfer rate through the front plate $\dot{Q}_{cond,f}$). And in the transient state assume the heat transfer rate target to each plate remains the same value as in the steady state despite the heat transfer rate through each plate is not equal to this value as the energy will be stored in the box.

Treat each plate as the lumped capacitance model, recalling the equations for calculating convection and radiation at equation (3) and (4), and recalling equation (12) of $\dot{Q}_{gen} = \dot{Q}_{store} + \dot{Q}_{out}$, and equation (27) and (28), it has:

$$\dot{Q}_{gen} = m \cdot c_p \cdot \frac{dT}{dt} + \dot{Q}_{conv,outside} + \dot{Q}_{rad,outside}$$

$$\rightarrow \dot{Q}_{gen} = m \cdot c_p \cdot \frac{dT}{dt} + h \cdot A \cdot (T_s - T_\infty) + \sigma \cdot \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right)$$

$$\rightarrow m \cdot c_p \cdot \frac{dT}{dt} = \dot{Q}_{gen} - h \cdot A \cdot (T_s - T_\infty) - \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right)$$

$$\rightarrow \frac{dT}{dt} = \frac{\dot{Q}_{gen} - h \cdot A \cdot (T_s - T_\infty) - \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right)}{m \cdot c_p} \qquad (29)$$

Then by using the numerical method, with a time step of $\Delta t = 60s$ set, replacing the left part of the equation (29) by $\frac{T-T_p}{\Delta t}$, then, the new equation is shown:

$$\frac{T - T_p}{\Delta t} = \frac{\dot{Q}_{gen} - h \cdot A \cdot (T_s - T_\infty) - \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right)}{m \cdot c_p}$$

$$T = T_p + \Delta t \left(\frac{\dot{Q}_{gen,each} - h \cdot A \cdot (T_s - T_\infty) - \varepsilon \cdot A \cdot \left({T_s}^4 - {T_\infty}^4\right)}{m \cdot c_p}\right) \qquad (30)$$

Where:

T is the current temperature $[K]$

T_p is the last temperature $[K]$
T_∞ is the surrounding temperature $[K]$
T_s is the surface temperature (Internal temperature) $[°C]$
m is the mass of the plate $[kg]$
c_p is the specific heat capacity of the plate $[J/kg^3 \cdot °C]$
h is the convection heat transfer coefficient of air $[\frac{W}{m^2} \cdot K]$
A is the surface area of the plate $[m^2]$
$\dot{Q}_{gen,each}$ is the heat transfer rate target to each plate direction, its value was assumed as a constant that equal to the heat transfer rate by conduction through the wall in steady state condition.

Then, for each increment of the time, the air property at this period will remain constant which by applying the equation (5), (6), (7), (8), at each time step, the air property can be determined. Then, use the equations introduced in steady state the convective heat transfer coefficient can be calculated.
Hence, by applying the equation (30), with the increasing of time, at each time step, the temperature of each plate can be solved.

Once the convective heat transfer coefficient and temperature for each time step was determined, recalling the equation (11) of $\dot{Q}_{out} = \dot{Q}_{cond} = \dot{Q}_{rad} + \dot{Q}_{conv}$, its corresponding heat transfer rate by conduction can be determined so that at each time step, the energy transferred by the plate can be determined as:

$$\Delta E_{out} = \Delta E_{cond} = \dot{Q}_{out} \cdot \Delta t = \dot{Q}_{cond} \cdot \Delta t \quad (31)$$

The experiment has continued 8 hours, so, the total energy transferred through the box can be determined as:

$$E_{out} = E_{cond} = \sum \Delta E_{cond,i} \quad (32)$$

Recalling equation (12) of $\dot{Q}_{gen} = \dot{Q}_{store} + \dot{Q}_{out}$, the transient state in this question gives:

$$E_{gen} = E_{store} + E_{out} \quad (33)$$

Then, the energy stored can be determined as:

$$E_{store} = E_{gen} - E_{out} \quad (34)$$

The total energy generated in the process is:

$$E_{gen} = P \times t \quad (35)$$

Where:
P is the rated power of the bulb $[W]$
t is the time of experiment $[s]$

In excel sheet, for each bulb, by using the solution presented above, the evaluation for the top plate is:

Result		
Experiment running time	28800.00	[s]
	8.00	[h]
Maximum temperature	25.50	[℃]
Total energy consumed at top plate	0.05	[kW·h]
	170.651	[kJ]
Rated Power of the bulb	25.00	[W]
Total energy from the electricity	0.20	[kW·h]
	720	[kJ]
The stored energy and energy transferred by the other plates	0.15	[kW·h]

Result		
Experiment running time	28800.00	[s]
	8.00	[h]
Maximum temperature	26.50	[℃]
Total energy consumed at top plate	0.05	[kW·h]
	197.2204	[kJ]
Rated Power of the bulb	30.00	[W]
Total energy from the electricity	0.24	[kW·h]
	864	[kJ]
The stored energy and energy transfer by the other plates	0.19	[kW·h]

Table 6 Transient state analysis result for 25W and 30W bulb

Result		
Experiment running time	28800.00	[s]
	8.00	[h]
Maximum temperature	27.50	[℃]
Total energy consumed at top plate	0.06	[kW·h]
	224.3776	[kJ]
Rated Power of the bulb	35.00	[W]
Total energy from the electricity	0.28	[kW·h]
	1008	[kJ]
The stored energy and energy transfer by the other plates	0.22	[kW·h]

Result		
Experiment running time	28800.00	[s]
	8.00	[h]
Maximum temperature	28.50	[℃]
Total energy consumed at top plate	0.07	[kW·h]
	252.0854	[kJ]
Rated Power of the bulb	40.00	[W]
Total energy from the electricity	0.32	[kW·h]
	1152	[kJ]
The stored energy and energy transfer by the other plates	0.25	[kW·h]

Table 7 Transient state analysis result for 25W and 30W bulb

From table 6 and table 7, in 8 hours of the theoretical experiment time, the top plate's temperature has all converged to the temperature set for the steady state (table 2, 3).

It has used the lumped capacitance model in the calculation, which the surface temperature will be the same as the average temperature and internal temperature, however, based on the result, the maximum temperature for the top plate is close to the steady state temperature of the surface temperature, hence, the surface temperature stands, so that by applying the equation (25) of $\Delta T = \frac{\dot{Q}_{cond}}{k \cdot A} \cdot \Delta x$, the inside surface temperature can be determined. And for each bulb of the top plate, the temperature function of time is shown:

Then, for each bulb, its temperature function of time is shown:

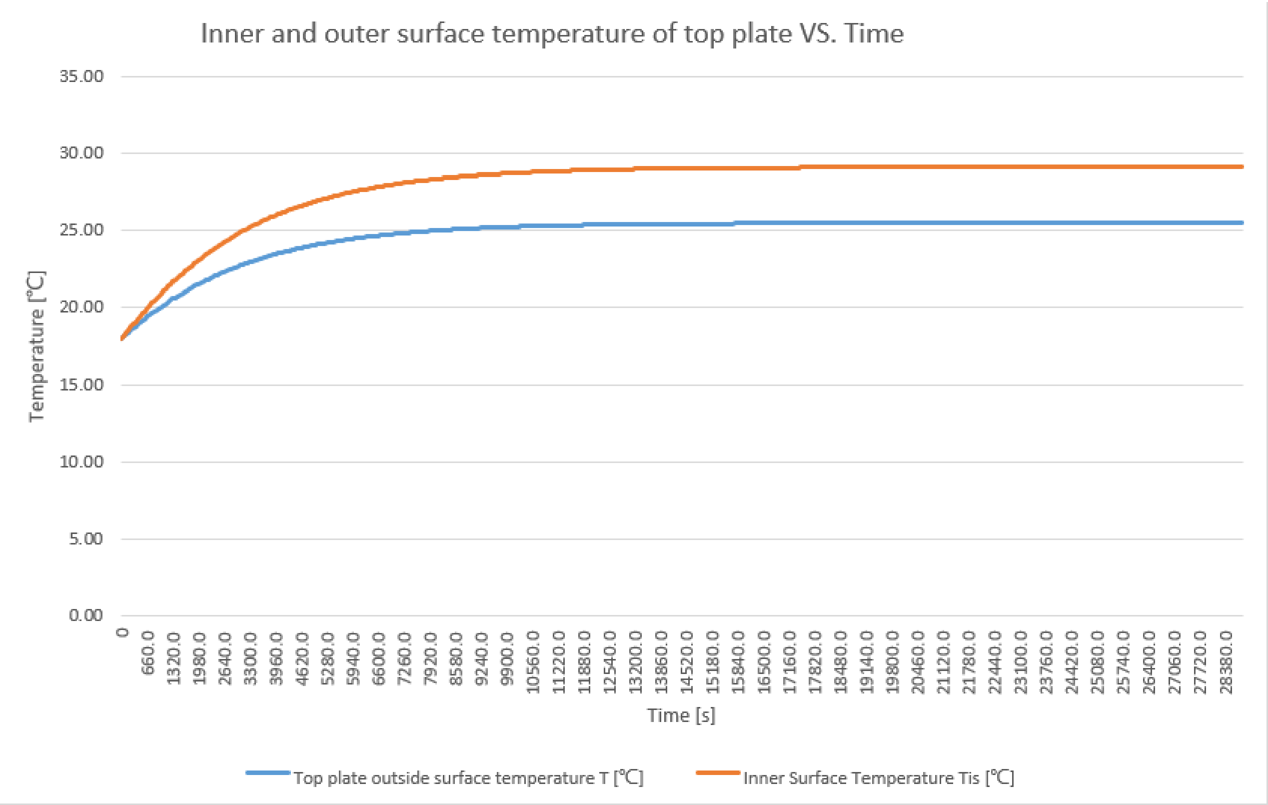

Figure 3: 25W bulb

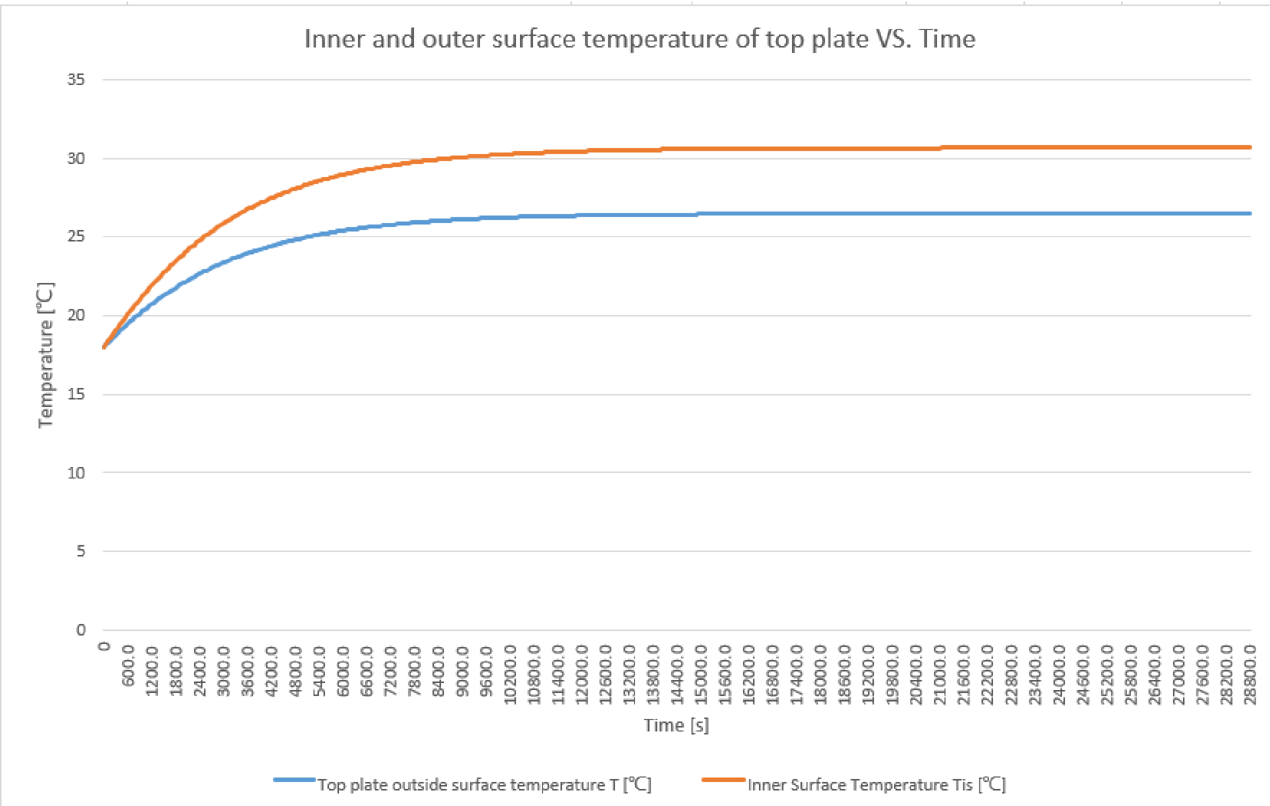

Figure 4: 30W bulb

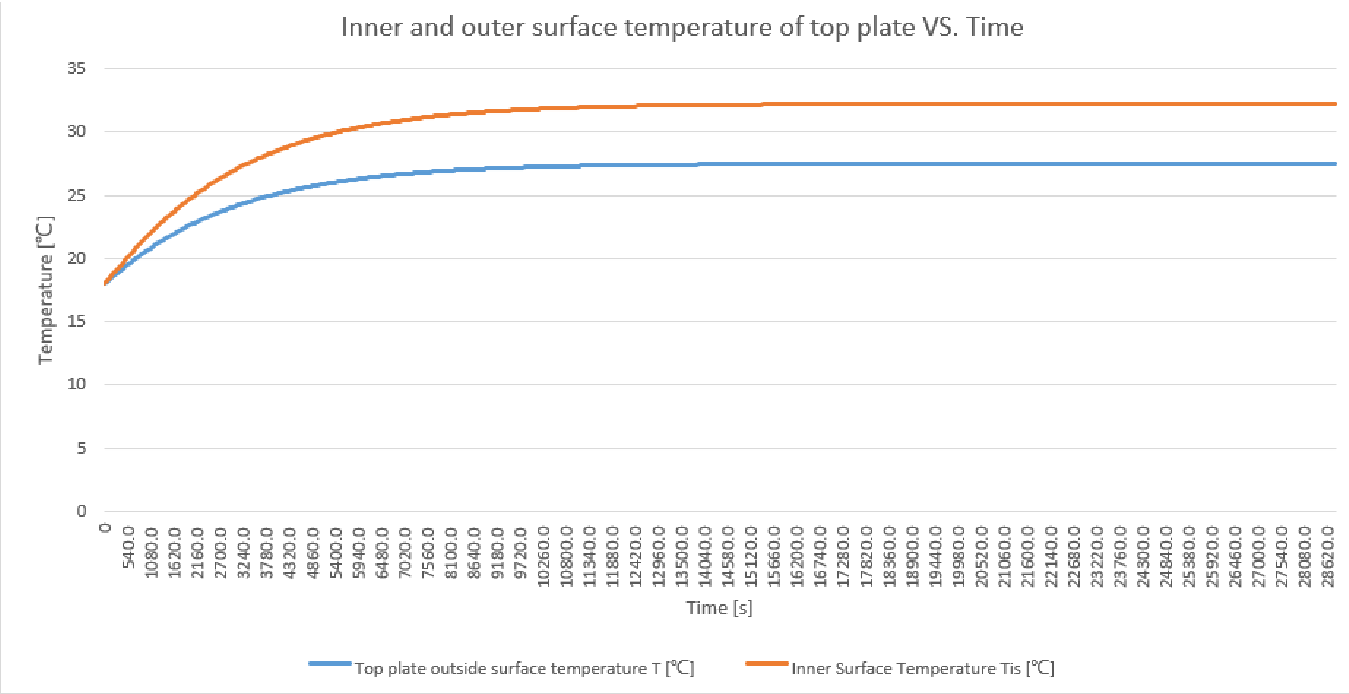

Figure 5: 35W Bulb

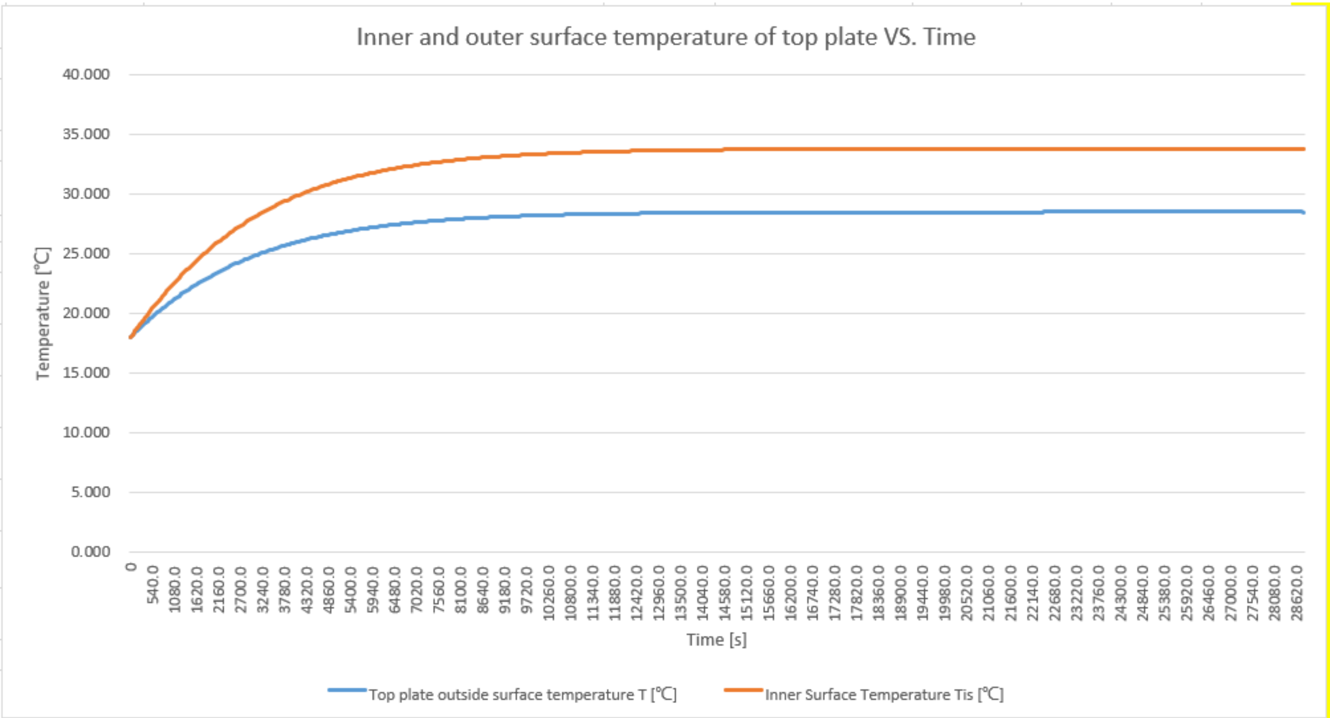

Figure 6: 40W bulb

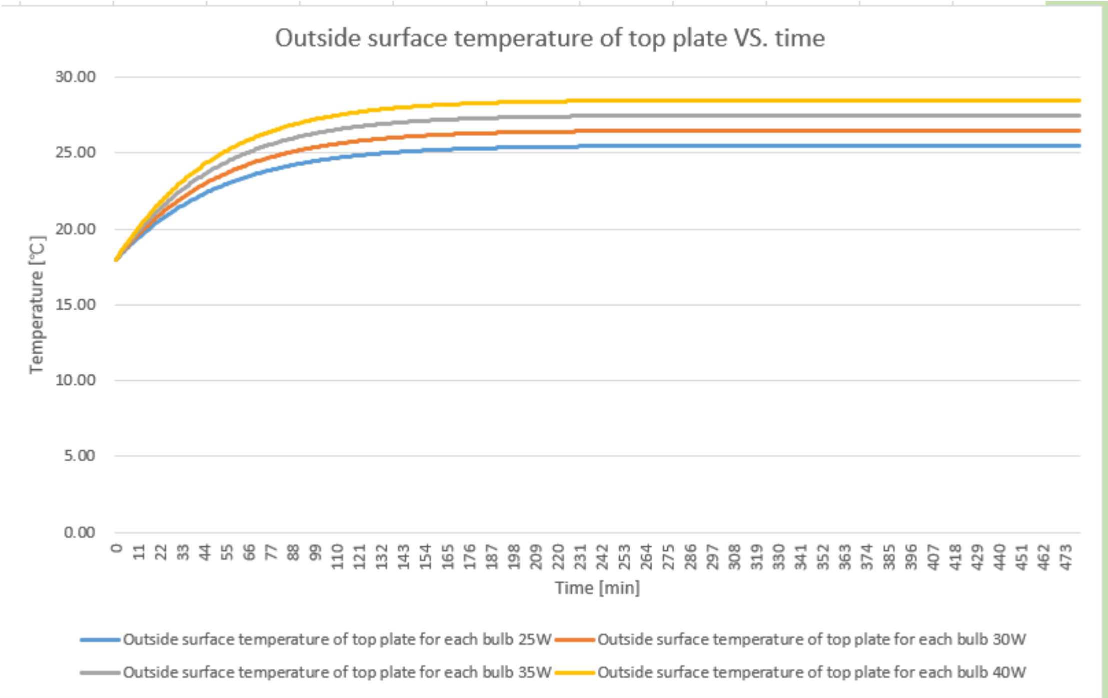

Figure 7: Top plate temperature

It can be seen that with the increase of rated power of the bulb, the temperature of the top plate will increase more rapid at the initial few hours, and as time goes by, the final temperature of the top plate will gradually close to the temperature at the steady state, which it can tell that a control volume with a constant energy input, the transient state always exists in this system, but the system has the trend to the steady state.

Especially, for the 25 [W] bulb, by using the same solution, for each plate on the box, its temperature changes by the time are shown:

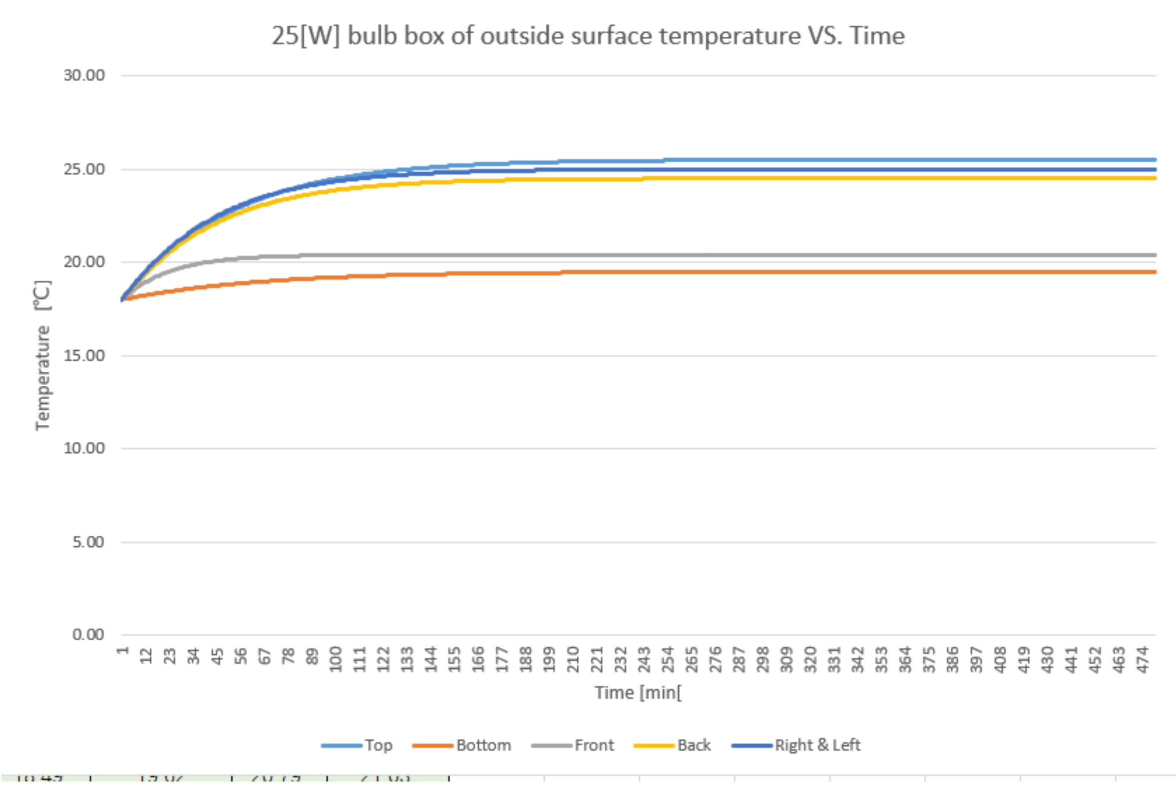

Figure 8: Temperature changes by the time for each plate of 25W bulb

It can be seen that the final temperature at the top plate is highest and the bottom plate is lowest as the hot air will rise and the cooled down air will fall. Due to the position of the bulb as it is far from the heat source and thermal conductivity of the Perspex (0.209 $[W/m\cdot ℃]$) lower than Nylon (0.25 $[W/m\cdot ℃]$), its final temperature is lower than the other plate except for the bottom plate.

Besides, for 25 [W] bulb, its energy stored in the period of experiment was determined as shown:

For 25 W bulb		
Total energy generated in 8 hours	0.2	[kW·h]
Energy through top plate	0.0474	[kW·h]
Energy through bottom plate	0.0076	[kW·h]
Energy through front plate	0.012	[kW·h]
Energy through back plate	0.034	[kW·h]
Energy through right & left plate	0.0395	[kW·h]
Total energy stored	0.0201	[kW·h]
	72.231	[kJ]

Table 8: Energy distribution for 25 W bulb box

It was obtained that the 8 hours of the experiment has consumed $0.2\ [kW\cdot h]$, and the energy stored in the box was $0.0201\ [kW\cdot h]$, which is $172.231 [kJ]$ of energy.

7. Conclusion

7.1 Summary

There are four bulbs of rated power 25W, 30W, 35W, 40W were the objects for the theoretical research in both steady and transient state. By experimenting on the excel sheet, it has found that with the increase of the rated power, a top plate, the temperature will increase quicker at initial 1-2 hours, then, the temperature will gradually converge to the steady state temperature.
Besides, specifically for the 25 W bulb in the box, the energy stored in the box has determined as $0.0201\ [kW \cdot h]$ and the temperature changes along the time have been calculated (figure 8) as well so that the further experiment result can be used for comparison.

7.2 Discussion

When evaluating the transient state, the lumped capacitance model was used, however, because the internal and average temperature are seen as equal to the surface temperature, which will lead to the errors of the result, but by observing the result, it has found that the surface temperature at outside in the evaluation at the end is still very close to the steady state. So, it is necessary to verify the result by experimenting.

The method for solving the temperature is by using the derivative method (numerical method), which has divided the time into several time steps, and for each time step, the heat transfer rate is seen as a constant value, but, even in a tiny time step, the air properties and heat transfer rate are changing, so that the error will occur.
Consequently, for the derivative method, reducing the magnitude of time step Δt will increase the accuracy of the result.
And for most of the situations, the choice of the time step magnitude is depending on different scenarios. And in this question, the time step 60s was set as the heat exchange happens at the box is a slow process.
In this report and excel simulation, the box with a steel block situation has not discussed, but the solutions of research are common that has demonstrated in this report.

8. Reference

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YEAR: 4th year

MODULE: Heat transfer

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ASSIGNMENT TITLE: Heated box Evaluation

DUE DATE: 20/04/2021

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