Analysis of heat transfer at electron beam machine 300 kV/20 mA laboratory

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Abstract. Experimental and theoretical analysis of heat transfer at Electron Beam Machine (EBM) Laboratory in Center for Accelerator Science and Technology, National Nuclear Energy Agency (BATAN) are required to understand the heat transfer phenomena. The BATAN’s EBM is a typical 300 kV/20 mA. The room where EBM is based has to be set up according to the laboratory standard to perform at an optimum level. This work aims to evaluate if the installed two air conditioners with a total cooling capacity 160,000 Btu/hr inside the laboratory are sufficient to reach a temperature of 20 °C and atmospheric relative humidity (RH) from 45% to 55%. The laboratory was stacked up with brick, tinted glass window, aluminum door, and rolling door with a total volume of 836 m³. The experiment was performed in cloudy weather for six days from 8:00 a.m. to 4:00 p.m. and the data of temperatures at each spot were taken every one hour. There were three conditions of this experiment, air conditioner running with laboratory lamps set to be off, air conditioner running with laboratory lamps set to be on, and air conditioner running with laboratory lamps set to be on and insulating 10.5 m² rolling door with 50 mm Styrofoam respectively every two days. The result showed that for the first condition, the average temperature of laboratory and atmospheric relative humidity (RH) was 22.5 °C and 59%, respectively. In the second condition, the average temperature of laboratory and atmospheric relative humidity (RH) was 21.9 °C and 65% respectively, whereas, in the third condition, the average temperature of laboratory and atmospheric relative humidity (RH) were 19.9 °C and 49% respectively. This result indicates that adding thermal insulation such as Styrofoam inside the building helps the air conditioners to reach its targeted temperature and RH.

1. Introduction
Electron Beam Machine (EBM) is one of the radiation sources for the irradiation process. The radiation process is carried out to improve the quality of an industrial product, such as latex gloves [1]. The raw material of this product is natural rubber, which is very abundant in Indonesia [2]. In terms of technology, the Center for Accelerator Science and Technology, National Nuclear Energy Agency (BATAN) utilizes this condition by manufacturing and testing EBM with a capacity of 300 kV/20 mA to achieve prototype EBM for pre-vulcanizing natural rubber processing [3].

EBM laboratory is a building that acts as thermal interfaces between the outdoor and indoor environments. Heat transfer between those two environments depends on the performance of exterior envelopes. Building envelope exposed outdoor environment conditions such as humidity, temperature, and air velocity. Heat transfer through this envelope can be related to a combination of convective, radiative, and conductive heat transfer components determined by the constituent material and its
microstructure [4]. The development of high-performance exterior envelopes is to achieve high indoor thermal comfort for a building [5] and to reduce Heat Energy Loss. Heat Energy Loss is caused by construction components of the building envelopes, and Fabric Heat Loss is the main factor of it. Exterior walls and openings do significant roles, about 70% of the total Fabric Heat Loss in buildings [6]. The EBM laboratory is stacked up with bricks, tinted glass windows, aluminum doors, and a rolling door. These components do significant roles of Heat Energy Loss or Heat Energy Gain through the building.

EBM laboratory needs set up according to laboratory standards in order to perform optimally. EBM laboratory air specification is 20 °C of temperature condition, with a pressure of 101.325 kPa, and relative humidity controlled within the range from 45% to 55% [7]. Therefore Air Conditioner (A/C) systems with total cooling capacity 160,000 Btu/hr are installed inside the building to maintain its condition and to remove heat energy gain from the outdoor environment. Air conditioning (A/C) systems have a function of humidity and temperature control of the room [8]. EBM component's performance also depends on the relative humidity level. The atmospheric relative humidity (RH) has a great impact on the partial discharge (PD) process, which can damage the insulation of this machine during its operation [9].

Air Conditioner (A/C) systems with high total cooling capacity are not always sufficient to achieve its targeted RH and temperature. Thus, some insulation needs to install to help air conditioner (A/C) systems. One of insulation is Styrofoam that known as expanded polystyrene. It is widely used for multiple purposes, including thermal insulation, plates, food trays, fabrication of car parts, coffee cups, and so on. Styrofoam has many benefits with high durability, insulating quality, and strength [10]. Previous studies have reported that the lowest thermal conductivity among the poplar and pine, used to produce wood–Styrofoam composite (WSC) and traditional plywood, was poplar panels manufactured with high-density Styrofoam [11]. Another study of the inclusion of Styrofoam balls in a concrete cast and the consequence of a change in thermal conductivity have been investigated. The result shows that SFB concrete with a 32% volume of Styrofoam has smaller thermal conductivity than plain concrete with a 0% volume of Styrofoam, about 50% [12]. Furthermore, another study of Ceramic shell foams (containing 70% volume of expandable Styrofoam powder beads) has a thermal conductivity of 0.061 W/mK [13].

However, experimental and theoretical analysis of heat transfer at Electron Beam Machine (EBM) Laboratory to evaluate this air conditioner (A/C) systems using insulation of Styrofoam is not yet conducted. The objective of this study is to investigate the heat transfer condition with and without Styrofoam as thermal insulation for the rolling door of the laboratory.

2. Methods
Data collection before carrying out calculations and analyzes need to be done. Without having valid and accurate data, a comprehensive calculation cannot be carried out properly. Initial data that must be possessed before carrying out calculations is the dimension of the building that will be used as the object of research. EBM Laboratory is a fairly old building, so the blueprints and design details of EBM Laboratory are difficult to find. Therefore, the dimension data achieved by measured it directly. Data obtained from measurements were 16 meters of length, 9.5 meters of wide, 5.5 meters of high of the wall, and has a concrete roof thickness of 0.3 meters.

The four sides of the EBM Laboratory had different component materials. The height of the west concreted wall & tinted windows glass above the wall were 3.85 and 1.65 meters, respectively. At the end of the west wall, there was a rolling door with a height and width of 3 meters and 3.5 meters, respectively. The height of the north concrete wall was 5.5 meters without any glass. The height of the east concreted wall & tinted windows glass above the wall were 3.85 and 1.65 meters, respectively. The south wall consists of a concrete wall, two aluminum doors with a total area of 4.6 m² and 1.92 m² of glass. To make it easier to understand, the spatial dimensions for EBM Laboratory were drawn using Autodesk Inventor 2016 software, as shown in Figures 1 and 2.
The experiment was performed in cloudy weather for six days from 8:00 a.m. to 4:00 p.m., and the data of temperatures at each spot were taken every one hour. Those spots are the west wall, north wall, east wall, south wall, rooftop, ground, rolling door, and aluminum door. There were three conditions of this experiment, air conditioner running with laboratory lamps set to be off, air conditioner running with laboratory lamps set to be on, and air conditioner running with laboratory lamps set to be on and insulating 10.5 m² rolling door with 50 mm Styrofoam respectively every two days. The lamps used in this experiment were 9 pieces of LED lamps with a power of 100 W each. According to Nilima A Bachhuwar and Kumar D Sapate, 80% of the energy emitted from LED lamps is converted to heat [14]. Nevertheless, LED lamps do not create additional heat in a room, the heat leaves the LED through the heat sink, in a process called conduction, without emitting heat [15].

![Figure 1. West and North Side of the Laboratory](image1)

![Figure 2. West and North Side of the Laboratory](image2)
The Method to get the heat energy gain value from EBM Laboratory was calculated by the heat transfer that occurs by conduction only in this experiment for approximation. Conduction is generally calculated by using the conventional formula [16]:

$$Q_{\text{cond}} = \frac{kA(T_1 - T_2)}{t}$$

(1)

where $Q_{\text{cond}}$ is the amount of energy/heat transferred, $k$ is the coefficient of conduction or thermal conductivity, $A$ is the cross-sectional area of the object, $T_1$ and $T_2$ are the surface temperature of the outside and inside wall respectively, and $t$ is the thickness of the object. Heat transfer that occurs by radiation and convection is not included since using the formula of conduction is enough. Heat transfer rate is equal from the warm environment (outside), through the solid, and then to a cool environment (inside)[17]. Under steady condition [16]:

$$Q = h_1A(T_{\infty 1} - T_1) = \frac{kA(T_1 - T_2)}{t} = h_2A(T_2 - T_{\infty 2})$$

(2)

where $h_1$ and $h_2$ are heat transfer coefficient, $T_{\infty 1}$ and $T_{\infty 2}$ are temperature far enough from the surface of the outside and inside wall of the laboratory, respectively. EBM Laboratory has several materials, which are concrete or building brick, 7 mm window tinted window glass, 1.5 mm thick aluminum alloy as material from the door, and 5 mm thick painted carbon steel as material from rolling door. Based on references, the thermal conductivity ($k$) data of the type of material in EBM Laboratory in detail are listed in Table 1.

### Table 1. Thermal conductivity some materials [18][19]

| Materials          | $k$ (W/(mK)) | $k$ (W/(m°C)) |
|--------------------|--------------|---------------|
| Aluminum Alloy     | 117          | 117           |
| Building Brick     | 1            | 1             |
| Glass, Window      | 0.96         | 0.96          |
| Painted Carbon Steel | 18          | 18            |
| Styrofoam          | 0.03         | 0.03          |

### 3. Result & Discussion

#### 3.1. Conduction

Heat transfer through conduction is calculated using Eq. 1. The results are illustrated in Table 2., Figures 3 and 4.

#### Table 2. Heat transfer ($Q$) due to conduction in Btu/hr

| Day | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. |
|-----|--------|---------|---------|---------|--------|--------|--------|--------|
| Day 1 | 96101 | 137730 | 179942 | 72743 | 175940 | 162908 | 171884 | 120144 |
| Day 2 | 75991 | 153252 | 164334 | 100402 | 192522 | 101621 | 162816 | 82414 |
| Day 3 | 85827 | 118995 | 192511 | 144494 | 110286 | 89970 | 160715 | 107244 |
Table 3. Top 4 highest position transferred heat energy into laboratory due to conduction in Btu/hr

| Day 4 | Day 5 | Day 6 |
|-------|-------|-------|
| 130906 | 48249 | 23816 |
| 181654 | 61290 | 49644 |
| 146135 | 70991 | 59493 |
| 125503 | 77687 | 67524 |
| 186786 | 80289 | 73163 |
| 170671 | 78933 | 75461 |
| 225224 | 25491 | 71902 |
| 89977  | 35264 | 51578 |

Figure 3. $Q$ due to conduction during 6 days of the experiment

Figure 4. Each hour $Q$ total due to conduction during 6 days of the experiment

Figures 3 and 4 show the heat transfer due to conduction. The initial condition of the air conditioner (A/C) systems started at 8:00 a.m. Building gaining heat energy from the outdoor environment recorded from 9:00 a.m. to 4:00 p.m. The heat energy gain from day 1 to 4 was high and some of it reached more than 160,000 Btu/hr and this condition is beyond the air condition (A/C) systems could handle. However, on day 5 and 6 were low, it was happened due to 50 mm Styrofoam covered the rolling door. Figure 3. shows that the heat transfer in day 5 and 6 increase linearly from 9:00 a.m. to 2:00 p.m. and after that start to decrease. The highest heat transfer during day 5 and 6 only 78933 Btu/hr. The three highest $Q$ total was at 1:00 p.m., 3:00 p.m., and 11:00 a.m. during 6 days experiment. The reason that $Q$ of conduction was lower at 2:00 p.m. and 12:00 p.m. due to the cloud covering the sun, so the outdoor temperature was dropped than at 1:00 p.m., 3:00 p.m., or 11:00 a.m.

Table 3. Top 4 highest position transferred heat energy into laboratory due to conduction in Btu/hr
The most heat energy gain was from rolling door without Styrofoam cover in day 1 to 4 as illustrated in Figure 5 and Table 3. However, in day 5 and 6, the heat energy gain from rolling door dropped sharply from above 70000 Btu/hr on average into 2500 Btu/hr only. This means 50 mm Styrofoam was effective in holding back the heat transfer into the laboratory. The other position, such as ground, rooftop, and north wall is remaining in the same position without any huge difference \( Q \) during 6 days of the experiment.

### 3.2. Relative Humidity & Room Temperature.
Relative humidity & room temperature data was taken by experiments in the EBM Laboratory. The results of the measurement are shown in Tables 4 and 5.

#### Table 4. Relative humidity (RH) in %

| Time   | Day 1  | Day 2  | Day 3  | Day 4  | Day 5  | Day 6  |
|--------|--------|--------|--------|--------|--------|--------|
| 8 a.m. | 70     | 60     | 61     | 64     | 63     | 58     |
| 9 a.m. |        |        |        |        |        |        |
| 10 a.m.|        |        |        |        |        |        |
| 11 a.m.|        |        |        |        |        |        |
| 12 p.m.|        |        |        |        |        |        |
| 1 p.m. |        |        |        |        |        |        |
| 2 p.m. |        |        |        |        |        |        |
| 3 p.m. |        |        |        |        |        |        |
| 4 p.m. |        |        |        |        |        |        |

Figure 5. Rolling door contribute most heat transfer into the laboratory from day 1 to 4

### Table 3. Heat transfer (Q) into the laboratory from rolling door

| Day     | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 |
|---------|-------|-------|-------|-------|-------|-------|
| Ground | 11628 | 12060 | 13536 | 9036  | 14382 | 12528 |
| Rooftop| 8640  | 8478  | 8244  | 6444  | 10656 | 8838  |
| North wall | 7583  | 7059  | 7405  | 6336  | 9593  | 8405  |
Table 5. Laboratory temperature in °C

| Day   | 8 a.m. | 9 a.m. | 10 a.m. | 11 a.m. | 12 p.m. | 1 p.m. | 2 p.m. | 3 p.m. | 4 p.m. |
|-------|--------|--------|---------|---------|---------|--------|--------|--------|--------|
| Day 1 | 27     | 22.6   | 23      | 23      | 22      | 22     | 22     | 22     | 22     |
| Day 2 | 25.8   | 22.3   | 22.1    | 22.1    | 22.6    | 22.2   | 24.3   | 23.3   | 22.4   |
| Day 3 | 24.7   | 21.9   | 22.1    | 22.2    | 21.5    | 23.1   | 22     | 21.9   | 21.8   |
| Day 4 | 26.8   | 22     | 22      | 22      | 21.5    | 21.5   | 21     | 21.5   | 22     |
| Day 5 | 25.4   | 21     | 19.7    | 19.9    | 19.6    | 19.7   | 19.5   | 19.7   | 19.7   |
| Day 6 | 28.9   | 20.8   | 19.9    | 20.3    | 19.7    | 19.7   | 19.5   | 19.8   | 19.9   |

Figure 6. Relative humidity (RH) during 6 days of the experiment
Figure 7. Laboratory temperature during 6 days of the experiment

Figures 6 and 7 show that the graphics of relative humidity (RH) could not reach a level between 45 to 55% from day 1 to 4. Therefore, Styrofoam used for covering the rolling door to help the Air Conditioner (A/C) systems to achieve its targeted level of RH in day 5 and 6 of the experiment. This also happens with the laboratory temperature from day 1 to 4 could not reach a temperature of 20 °C, it only reached around 22 °C. However, the laboratory temperature drops to 20°C on day 5 and 6. Figure 6 and Figure 7 also show that for the first condition (day 1 and 2), the average temperature of laboratory and atmospheric relative humidity (RH) were 22.5°C and 59% respectively. In the second condition (day 3 and 4), the average temperature of laboratory and atmospheric relative humidity (RH) were 21.9 °C and 65% respectively, whereas, in the third condition (day 5 and 6), the average temperature of laboratory and atmospheric relative humidity (RH) was 19.9 °C and 49% respectively. This result indicates that adding thermal insulation such as Styrofoam inside the Laboratory helps the air conditioner (A/C) systems to reach its targeted temperature and RH.

3.3. Ansys Simulation.
Simulation of air conditioners with a total cooling capacity of 160,000 Btu/hr conducted using Ansys Fluent. Each air conditioner has an airflow of 902 L/s or 1,910 CFM [20] with a dimension of 1,870 x 950 x 510 mm and air velocity inlet area of 0.272 m². Therefore, the velocity of the air comes out from the air conditioners approximately 4 m/s based on the specification datasheet. Air conditioner's position and EBM Laboratory set up are illustrated in Figure 8.
Figure 8. Electron Beam Machine Laboratory set up with two air conditioners

Figure 9. Airflow circulation simulation using Ansys Software

Figure 9 shows that airflow circulation filled up the entire laboratory room based on Ansys Simulation using velocity volume rendering mode. The velocity of the airflow about 0 (dark blue color) to 6.8 m/s (red color) inside the room. Most of the airflow circulation velocity is between 1.7 to 3.4 m/s (indicate with light blue to green color) and only small areas have velocity more than 5 m/s (indicate with yellow to red color). The blue string shows the track of the airflow, and it indicates that turbulent flow has occurred.

Most portion of turbulent flow occurred on the north side of the air conditioner, whereas on the south side of it only has a small portion. This small turbulent really affects the cooling rate of the rolling door and make the rolling door in Table 3 has the highest heat transfer energy rate into the laboratory when there is no Styrofoam to cover it. Besides materials, thickness, and area of the rolling door are really affect this heat transfer energy rate, the velocity of cool airflow circulation in this area also has an effect. The higher the velocity of cool airflow circulation, the heat energy that dissipates is better. As shown in Figure 9, the velocity of airflow circulation is less than 1.7 m/s, and this is ineffective set up for the air conditioner position in the room. The laboratory needs a new set up to move the air conditioner position to get more effective air circulation.

4. Conclusion
According to the above experimental results, this work concludes that

a. Air Conditioner (A/C) systems with a total cooling capacity of 160,000 Btu/hr is sufficient to achieve average temperature and RH of 19.9 °C & 49% for EBM Laboratory on the condition that 50 mm Styrofoam is covering the rolling door.

b. There is no influence on heat transfer, whether all LED lamps of the laboratory are turned on or off.

c. The heat energy gain mostly comes from the rolling door with an average of 80594 Btu/hr in the first 4 days.

d. Air conditioners position affect the velocity of airflow circulation that hit the rolling door about less than 1.7 m/s, and this is ineffective for heat dissipation.

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