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# Far Infrared Emissivity of Wood Material - Comparing the Three Heat Transfer Modes of Wood Box and Aluminum Box -*1

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## ABSTRACT

In case of wood flooring, the high emissivity would be one of the most important properties especially as the cover material of underfloor heating system. The FIR (Far Infrared) materials such as wood emit FIR energy by heating, which has been used as the medical therapy such as dry sauna. This research investigated the emissivity and the emission power of wood composites by comparing the amount of the three heat transfer modes transferred by infrared radiation which came from the increased temperature of the bottom board of the plywood box by the heater.

The results showed the value of radiation mode was the highest mode for the plywood box, and the convection mode was the main mode for the aluminum box. The rate of convection was 81.8% in the aluminum box and 48.2% in the plywood box, respectively. In case of the rate of radiation, the aluminum box showed only 15.4% and the plywood box showed 51%. The emissivity and the emission power of birch plywood showed the same values as those of wood. The amount of energy required for the temperature rising of water within vial in the aluminum box and in the plywood box were 3.32 kJ and 6.70 kJ respectively, which showed that the vial temperature of the plywood box was two times higher than that of the aluminum box.

*Keywords* : far-infrared ray, wood as a FIR material, radiation, emissivity, plywood

## 1. INTRODUCTION

Since wood has unique properties, for example, easy to be processed, relatively light weight but strong and so on, wood has been used as various purposes by mankind. And wood has been used as a major material for building and construction. Even though the structural steel, aluminum, concrete and reinforced plastic has been replaced wood as structural material, the environmental benefits such as naturally renewable, recyclable, biodegradable and sustainable properties make wood more significant material for the environmentally green structures as well as a prominent building interior material.

As a building material, wood could be the

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best insulator which provides less energy for heating and cooling. And the wood framing is a relatively good thermal insulator compared to steel framing. Moreover, the human friendly consideration prepare to wood because the wood building has been showed various benefits for natural living and human by many researches (Satou, 1986; Lee, 1996; Lee *et al.*, 2006).

Although the human friendly effects of wood, such as mental stability, increasing the health effect by natural grain, stress release by auditory properties, relaxation by phytoncide, comfortable contact and walking feeling, capacity for controlling temperature, humidification, wetting heat and lower radon gas radiation has been recognized, the special properties of wood, the radiation of Far Infrared Ray (FIR) has not been reported. Actually, there are no data of wood emissivity in the Wood Handbook (FPL, 1999) and only thermal properties of wood such as thermal conductivity, specific heat capacity, thermal diffusivity and thermal expansion coefficients could be found in the Wood Handbook. On the contrary, general textbook for heat transfer deals with conduction, radiation, and convection.

McAdams (1954) said that the relative importance of the several mechanisms of the transfer of heat from one body to another differs greatly with temperature. The phenomena of conduction and convection are affected primarily by temperature difference and very little by temperature level, whereas radiation interchange increases rapidly with increase in temperature level. It follows that, at very low temperature, conduction and convection are the major contributors to the total heat transfer: at very high temperatures, radiation is the controlling factor for roughly one-half of the total heat transmission. Generally, at low temperature and room temperature condition, radiation is ignored.

But at normal temperature, radiation is also important for our daily life. For example, earth's surface gains heat from the sun, earth's surface is warmed up and loses heat by infrared radiation. While the input of heat by solar radiation is restricted on the daytime hours, the outgoing terrestrial radiation is a nonstop process during day and night and depends only on the bodytemperature and the emissivity. After sunset the earth continues to radiate and therefore cools. With or without atmosphere every body loses heat, gets inevitably colder.

For another example, during the winter, 50～75% of heat loss through the ceiling of building and 65～80% of heat loss through walls is radiant. In the summer, up to 93% of heat gain is radient. Depending on R-value (resistance) alone to insulate against heat gain and loss of building means losing half the battle of insulation.

Even though aluminium is very good conductors, aluminium reflective insulation reflects back radiant (infra-red) energy from the sun so it does not penetrate the building and also reflect back radiant heat inside the house so it does not escape. Therefore the selected building material for the purpose had better be used among higher R value material, higher reflective material and higher FIR material.

Until now, the most cited reference book about IR property of wood has been "Heat Transmission" by McAdams (1954), which was originally based on Gesundheit 20(1) by Schmidt (1927) who reported calculated total emissivity of planed oak 0.90, for comparison of a lot of material, which was comparatively accurate value in those days with monochromatic techniques. As a wood scientist, Lee (2004) first reported recent data of great accuracy that wood is excellent as FIR material with 90～91% emissivity in the range of 5～20 μm at 40°C by the FTIR. Lee & Bender (2009) reviewed the emissivity values of some U.S. wood species, medium density fiberboard, and fancy maple veneered plywood before and after coatings for wood flooring by spectrometric measurement-and reported wood species, wood composites and fancy plywood before and after coatings, all showed the emissivity values of about 0.9 and far-infrared ray material at room temperature. Cengel (2007) has reported emissivity of Beech 0.94 and wood 0.82～0.92 in his book of "Heat and Mass Transfer", but he did not establish the identity of the origin and the testing method for emissivity. There are some data in the internet site of infrared thermometer companies because the infrared thermographic measurement is concerned with the emissivity-emittance of the materials, but they do not provide information about test method of emissivity.

Heat transfer due to emission of electromagnetic waves is known as thermal radiation of a wavelength longer than that of visible light (0.4～0.76 μm), but shorter than that of microwaves ($10^2$ μm). Thermal radiation is also defined as the portion of the electromagnetic spectrum that extends from about 0.1 to 100 μm, since the radiation emitted by bodies due to their temperature falls almost entirely into this wave length range (Cengel, 2007). It is true that objects at room temperature will emit radiation mostly concentrated in the 8 to 12 micrometer band. Emissivity of material is measured commonly at wavelength of 5～20 μm. The International Commission on Illumination (CIE) recommended the division of optical radiation into the following three bands: IR-A: 700～1,400 nm, IR-B: 1,400～3,000 nm, IR-C: 3,000 nm～1 mm. Henceforth, when we speak of radiation, we refer only to infrared rays, sometimes far infra red rays.

In Japan FIR heaters were used by the medical practitioners exclusively until 1979 when they were released for public use. FIR has the ability to penetrate, refract, radiate & reflect. The human body can absorb FIR because of its deep penetrating ability. FIR Heat Therapy allows increased blood circulation to carry great amounts of nutrients to the skin, thus promoting healthy tone, texture and mild cleansing of the skin (Wilson, 2006). Ogita *et al.* (1990) found that ceramics far-infrared radiation may be an effective remedy for enhancing lactation. Kihara *et al.* (2002) reported FIR (4～14 microns) repeated sauna treatment (60°C for 15 min) improves vascular endothelial function, resulting in an improvement in cardiac function and clinical symptoms. and Biro *et al.* (2003) this FIR heat therapy may be a promising therapy for patients with lifestyle-related diseases such as hypertension, hyperlipidemia, diabetes mellitus, obesity, and smoking. Repeated FIR sauna treatment improves ventricular arrhythmias in patients with CHF by Kihara *et al.* (2004) as well.

The fact that FIR heaters is used in infrared saunas to heat the occupants and used by the medical practitioners for therapy, needs to study FIR properties of wood as a merits of wood which is excellent FIR material. Wooden house, wooden floor, and wooden radiator cabinet or interior decoration with wood materials in building has heating system. Activated by heat of conventional heating, the FIR material, wood emits FIR energy like FIR heat dry sauna that is absorbed by human cells and organism cells. This means that wood has health effect on organism.

Olesen (2002) has mentioned advantages of radiant floor heating that include the efficient use of space, no noise system, uniform temperature distributed system, increasing the efficiency of heat generators, energy savings, and thermal comfort for occupants. He reported also that 30 to 50% of new residential buildings have radiant floor heating in Germany, Austria and Denmark. In Korea, about 90% of residences are heated by underfloor heating systems which Koreans have used from around 100 B.C. Nowadays in Korea, about 69% of private residence has wood flooring for underfloor heating systems. Sattari and Farhanieh (2006) reported that most important design parameters for the heating floor system are type and thickness of the cover and the radiation is the dominant mechanism of heat transmission in a floor heating system. In this case, the emissivity of wood material is very important property for the cover of underfloor heating system.

The aim of this study was to investigate that the radiation is also important at/above ambient temperature such as convection, and how wood, as a FIR material, warms up vial-water in wood material box by infrared radiation of wood which came from increased temperature of bottom board of plywood box by the underfloor heating source as a model of Ondol underfloor heating system. Comparison of amount of the three heat transfer modes transferred was made between plywood box and aluminum box. Emissivity and emission power of wood composites was measured too for radiation.

# 2. MATERIALS and METHODS

## 2.1. Materials

### 2.1.1. Aluminum Box and Plywood Box

Aluminum box is made of Aluminum alloy 5052 plate (Al 97.2, Mg 2.5, Cr 0.25 : AA5052, Thermal Conductivity: 137 W/mK, density: 2.64 g/cm$^3$) by welding and lid is sealed with aluminum tape (Reflectix tape). Baltic Birch plywood box was made of BB grade of plywood (density is 0.69 g/cm$^3$) by Elmer wood glue and lid is sealed with paper tape. Outer dimension of a regular hexahedron box was 25.4 cm length cube and their facet board has 3.17 mm thickness respectively.

### 2.1.2. Specimen Size for Emissivity Measurement

Baltic birch plywood (Density 0.69 g/cm$^3$) and aluminum alloy 5052 plate were used for the emissivity and the emission power. Specimen size was 40 mm × 40 mm × 4 mm.

### 2.1.3. Heating Source

Lidless wood box with a side-hole of 25.3 mm by 17.2 mm for heating source cord was used for heating. The side hole with electric cord was sealed with paper gum tape. Outer dimension was 246 mm by 186 mm by 131 mm and inner dimension was 210 mm by 150 mm by 113 mm. As a heating source, Hot plate (MS SCI. co, 350 W, to 380°C) in wood box was used for increasing temperature of the experimental birch plywood box for three hours.

### 2.1.4. Vial and Water

Vial was placed for checking temperature in the experimental box and hanging down in the air with a string from the lid-bottom of experimental box. Vial dimension was 129.05 mm of height and 67.40 mm of diameter. Vial weight was 208.81 g, internal volume 280.50 cm$^3$. Vial was filled with 200 g of water and sealed with parafilm.

### 2.1.5. Thermometer

Thermocouples and data logger (TM-747D, RS-232 data logger) was used for measuring the temperatures.

## 2.2. Experimental Process

As shown in Fig. 1, Vial was placed in the experimental box and hanging down in the air with a string from the lid-bottom of experimental box. For the comparison of heat modes through heat transfer, as a heating source, an electric hot plate in the wood box for heating was turned on for three hours to increase temperature of experimental box which was placed on the lidless wood box for heating. Tempera-

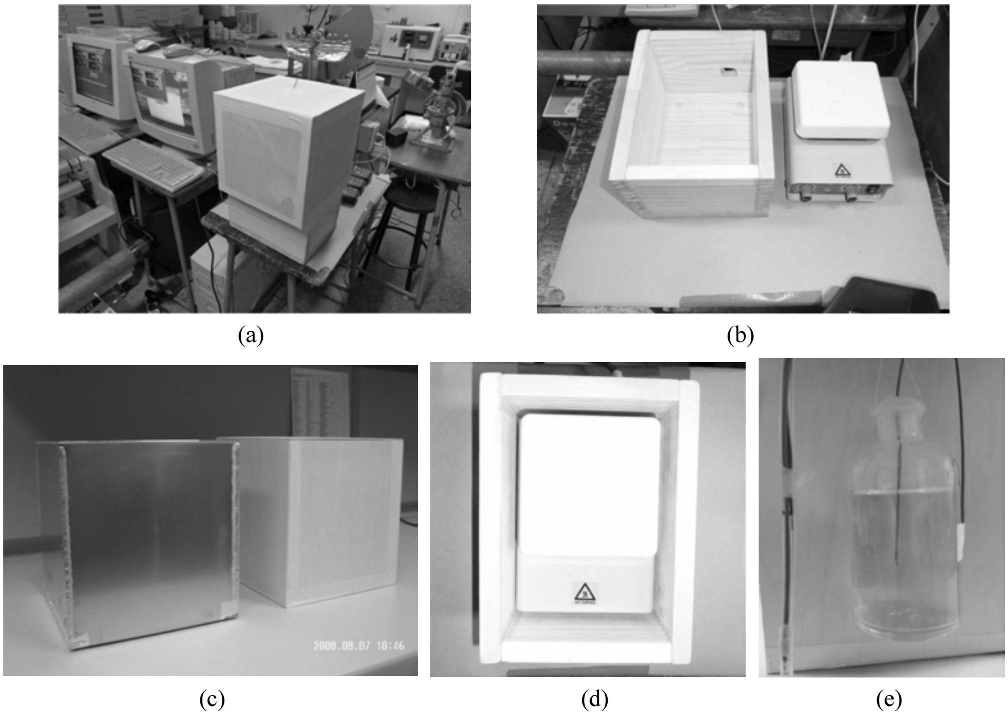


Fig. 1. Experimental device; (a) Plywood box and wood box for heating, (b) Electric hot plate and wood box for heating, (c) Plywood box and aluminum box, (d) Electric hot plate in wood box for heating, (e) Vial hanging down from the lid in the box.

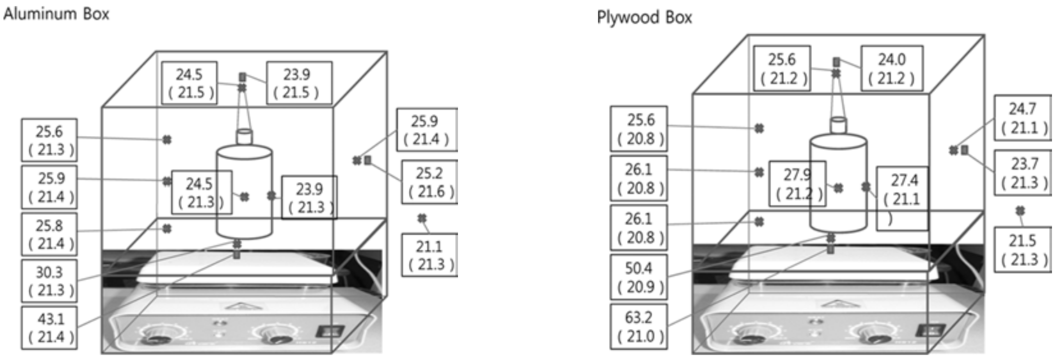


Fig. 2. Temperatures of inner parts of aluminum box (Left) and birch plywood box (Right).

ture was adjusted to about 60°C with slow increasing rate for the bottom side of plywood box and the same degree of temperature was applied to aluminum box. Temperature of every point as shown in Fig. 2 was measured at the same time by thermocouples with data logger for the comparison of heat mode.

Emissivity and emission power was measured at the temperature of 40°C and wavelength of 5 ∼20 μm by FT-IR (MIDAC Co., M2410-C).

Table 1. Thermal circuit for transfer mode

| Transfer mode | Amount of heat transferred | Thermal resistance |
|---|---|---|
| Conduction | $Q = \Delta T/L/(kA)$ | $L/(kA)$ |
| Convection | $Q = T_{surf}-T_{envr}/1/(h_{conv}A_{surf})$ | $1/(h_{conv}A_{surf})$ |
| Radiation | $Q = T_{surf}-T_{surr}/1/(h_rA_{surf})$ | $1/(h_rA_{surf})$ |

# 3. RESULTS and DISCUSSION

Heating system is one of main parts of building and house. Air or water is heated in one place and travels round a building through pipes and radiators. Especially in wood building and on ondol heating system under the wooden floor during winter, heated wood has influence on the residents and the plants in the room of the building. Modes of heat transfer were compared between plywood box and aluminum box for the study of radiation of wood. The emissivity and the emission power of wood composites were measured for far infra red radiation.

## 3.1. Comparison of Amounts of Heat Transferred in Box After Heating for 3 hours

A very useful concept used in heat transfer applications could be the representation of the thermal transfer by what is known as a thermal circuits. The thermal circuit is the representation of the resistance to heat flow as though it were an electric resistor. The heat transferred is analogous to the current and the thermal resistance is analogous to the electric resistor. By the Table 1, the amounts of heat transferred in the box after heating for three hours was calculated as shown in Table 2.

Table 2 showed the ratio of the three heat transfer modes from the amount of heat transferred in the box after 3 hours heating. Main transfer mode has turned out different between aluminum box and plywood box. Convection mode was the main mode of heat transfer in aluminum box, but radiation mode came in first in plywood box. The rate of convection was 81.8% in aluminum box and 48.2% in plywood box respectively. The rate of radiation was only 15.4% in aluminum box and 51% in plywood box respectively. Heat transfer by the conduction of air was a negligible quantity in both boxes.

Conduction energy ($\Sigma E_{in}$) measured by temperature of inner bottom plate surface of the box conducted through the thickness of the bottom plate from the heating source can be balanced to meet the balance equation ($\Sigma E_{out}$) for conduction, convection and radiation from the inner bottom surface in the box.

Conductivity (137 W/(m*°C)) and thermal diffusivity ($56.0*10^{-6}$ $m^2/s$, k137, cp900, d:2720) of aluminum box at room temperature are very

Table 2. Comparison of amounts of heat transferred between aluminum box and plywood box after three hour's heating

| Transfer mode | Amount of heat transferred | Comparion of Amounts of heat transferred in Box | |
|---|---|---|---|
| | | Aluminum | Plywood |
| Conduction | $Q = \Delta T/L/(kA)$ | 0.04 W (2.8%) | 0.16 W (0.8%) |
| Convectin | $Q = T_{surf}-T_{envr}/1/(h_{conv}A_{surf})$ | 0.17 W (81.8%) | 9.54 W (48.2%) |
| Radiation | $Q = T_{surf}-T_{surr}/1/(h_rA_{surf})$ | 0.22 W (15.4%) | 10.1 W (51.0%) |
| Total | | 1.43 W (100%) | 19.8 W (100%) |
| | Total energy transferred to (Vial + water) | 3.32 kJ | 6.70 kJ |

higher than those of birch plywood box (Wood Handbook, 1999): 0.18 W/(m*°C), $0.13*10^{-6}$ $m^2/s$). The differences in the thermal conductivity and diffusivity between aluminum and plywood showed 761 times, and 430 times respectively. The larger thermal diffusivity indicated, the faster the propagation of heat into the medium took a place. This demonstrated that heat was transferred a lot through four sides and one top plate to outward room not to inside box in case of aluminum box. A small value of thermal diffusivity means that heat was mostly absorbed by the material and a small amount of heat was conducted further. That was why plywood box showed the higher temperature of inner bottom surface than that of aluminum box and transferred the higher energy to the water and vial in the plywood box than those in aluminum box. Another reason could be the higher emissivity of plywood. The emissivity value of baltic birch plywood was 0.901 and the aluminum alloy plate showed the emissivity value of 0.118. Therefore, the amounts of energy needed to raise the temperature of water and the vial in aluminum box and plywood box were 3.32 kJ and 6.70 kJ respectively which came from the ratio of three heat transfer mode by Table 2.

The higher emissivity of FIR radiation of wood is expected to have the bigger effects on occupants from the results in these experiments.

#### 3.1.1. Aluminum Box (3.17 mm thickness)

##### 3.1.1.1. Total energy needed to raise the temperature of water and vial in Aluminum Box after 3 hour's heating: 3.32 k

The equation relating heat energy to specific heat capacity, where the unit quantity is in terms of mass is:

$$Q = mc\Delta T \tag{1}$$

Where Q is the heat energy transferred to vial (+water) in Aluminum Box after 3 hour's heating, m is the mass of the water and vial, c is the specific heat capacity (c$\rho$), and $\Delta$T is the change in temperature. Therefore total energy transferred was the sum of heat energy of water and vial as follow:

c$\rho$ of water : 25°C, 4.18 kJ/kg, c$\rho$ of glass : 0.84 kJ/kg

$$\begin{aligned} Q &= (mc\Delta T)_{water} + (mc\Delta T)_{vial} \\ &= (0.2\ kg*4.18\ kJ/kg*3.2°C)_{water} + (0.2088\ kg*0.84\ kJ/kg*3.7°C)_{vial} \\ &= 3.324\ kJ \end{aligned}$$

$\Delta T_{water}$ = 24.5-21.3 = 3.2°C,
$\Delta T_{vial}$ = 25.0-21.3 = 3.7°C

##### 3.1.1.2. Amount of heat transferred by air conduction: 0.038 W

Heat conduction is defined, Q:

$$Q = \Delta Q/\Delta t = k*A*\Delta T/L \tag{2}$$

Where $\Delta Q/\Delta t$ is the rate of heat flow, $k$ is the thermal conductivity, A is the total cross sectional area of conducting surface, $\Delta$T is the temperature difference, and L is the length of conducting surface separating the 2 temperatures. Thus, amount of heat transferred by air conduction was 0.038 W by equation $(2)^{A.}$

Thermal conductivity of air (25.8°C [(25.8 + 25.9 + 25.6)/3 = 25.77]): 0.02598 (W/(mk), Surface area A : 0.064516 $m^2$ Temperature of inner surface of Bottom board: 30.3°C, Temperature of inner surface of lid: 24.5°C, Length between bottom board and Lid (L): 0.254 m

$$\begin{aligned} Q_{cond} &= k_{25.8°C}\, A \frac{\Delta T}{L} \\ &= 0.02598\ w/(m°C) \times 0.064516\ m^2 \\ &\quad \times \frac{30.3-24.5°C}{0.254\ m} = 0.0383\ W \end{aligned} \tag{2}^A$$

3.1.1.3. Amount of heat transferred by natural convection: 1.17 W

Natural convection occurs when a system becomes unstable and therefore begins to mix by the movement of mass. The onset of natural convection is determined by the Rayleigh number (Ra). Amount of heat transferred by natural convection was 1.17 W by equation (3).

$$Q_{conv} = h_{conv} A_{surf} \Delta T \quad (3)$$

Where $Q_{conv}$ is amount of heat by convection, $h_{conv}$ is the convection heat transfer coefficient, A is the surface area, ΔT is the temperature difference. For the calculation of the convection heat transfer coefficient, Ra and Nu was calculated as follows.

Mean Temperature of air: 25.8°C [(25.8 + 25.9 + 25.6)/3 = 25.77], Temperature of inner surface of Bottom board: 30.3°C, Lc (characteristic Length) : $A_s/p = 0.254^2 / (4*0.254) = 0.254/4 = 0.0635$ $A_s$: Surface area, p:perimeter, g : 9.81 m/s$^2$, Pr : 0.712 (25.8°C), Kinematic Viscosity: $1.558*10^{-5}$ m$^2$/s (25.8°C). $N_u$: Nusselt Number

$$R_a = G_a \times P_r = \frac{g \times \beta (T_{surf} - T_{envr}) \times Lc^3}{\upsilon^2} \times P_r$$
$$= \frac{9.81\, m/s^2 \times 1/303.3 \times (303.3 - 298.8) \times (0.254/4)^3}{(1.558 \times 10^{-5} m^2/s)^2} \times 0.712 = 1.093 \times 10^5$$
$$N_u = 0.54 R_a^{1/4} = 0.54 \times (1.093 \times 10^5)^{1/4} = 9.82$$
$$h_{conv} = \frac{k}{L_C} \times N_u = \frac{0.02598\, w/m°C}{(0.254/4)m} \times 9.82 = 4.017\, w/(m^2 °C)$$
$$Q_{conv} = h_{conv} A_{surf} \Delta T = 4.017\, w/(m^2°C) \times 0.064516\, m^2 \times (30.3°C - 25.8°C) = 1.166\, w \quad (3)^A$$

3.1.1.4. Amount of heat transferred by radiation in box: 0.22 W

Radiation is emitted by every point on a plane surface in all directions into the hemisphere above the surface. Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even when they are separated by the colder medium than both. In box, between the temperature of bottom board (30.3°C) and mean temperature of other 5 sides (25.6°C), radiation mode of heat transfer was calculated by using the Stefan-Boltzman law (Eq. 4). The radiation heat of 1.87 W was occurred but considering emissivity 0.22 W in the box by Eq. $(4)^{A1}$.

$$Q = \sigma A_{surf} (T_1^4 - T_2^4) \quad (4)$$

Where $Q$ is amount of heat by radiation, $\sigma$ is the Stefan-Boltzman constant, $A_{surf}$ is the surface area, $T_1$ and $T_2$ is the temperatures of two bodies

$$Q = \sigma A_{surf} (T_1^4 - T_2^4) = 5.669 \times 10^{-8} \times 0.064516\, m^2 [(273 + 30.3)^4 - (273 + 25.6)^4]$$
$$= 5.669 \times 10^{-8} \times 0.064516\, m^2 \left((3.033 \times 10^2)^4 - (2.975 \times 10^2)^4\right)$$
$$= 5.669 \times 0.064516 \times (3.033^4 - 2.986^4)$$
$$= 1.87\, w \quad (4)^A$$

$$Q = A * \varepsilon * \sigma T^4 = Q * \varepsilon = 1.87 * 0.118 = 0.22\ (w) \quad (4)^{A1}$$

Emissivity (ε) of aluminum: 0.118

Amount Heat transferred by radiation from bottom board to vial

$$Q = \sigma A_{surf} (T_1^4 - T_2^4) = 5.669 \times 10^{-8} \times 0.064516\, m^2 [(273 + 30.3)^4 - (273 + 24.75)^4]$$
$$= 5.669 \times 10^{-8} \times 0.064516\, m^2 \left((3.033 \times 10^2)^4 - (2.9775 \times 10^2)^4\right)$$
$$= 5.669 \times 0.064516 \times (3.033^4 - 2.9776^4)$$
$$= 2.20\, w \quad (4)^{A2}$$

$Q = A*\varepsilon*\sigma\, T^4$ = 2.20 W*0.118 = 0.26 W (4)[A3]
Emissivity (ε) of aluminum: 0.118

### 3.1.2. Plywood Box (3.17 mm thickness)

#### 3.1.2.1. Total amount of energy needed to raise the temperature of water and vial in birch plywood box after 3 hour's heating:6.70 kJ

Total amount of energy needed to raise the temperature of water and vial in birch plywood box after 3 hour's heating was 6.70 kJ calculated by Eq.(1) above-mentioned in 3.1.1.1

$$Q = (mc\Delta T)_{water} + (mc\Delta T)_{vial} = (0.2\ kg*4.18\ kJ/kg*6.7°C)_{water} + (0.2088\ kg*0.84\ kJ/kg*6.3°C)_{vial} = 6.70\ kJ \quad (1)^{P}$$

Water : 200 g, $\Delta T$ = (27.9-21.2)°C = 6.7°C,
Vial : 208.8 g, $\Delta T$ = (27.4-21.1)°C = 6.3°C

#### 3.1.2.2. Amount of heat transferred by air conduction: 0.16 W

Amount of heat transferred by air conduction in plywood box was 0.1637 W calculated by Eq. (2) above-mentioned in 3.1.1.2.

Thermal conductivity of air (mean temperature: 25.9°C) : 0.02599 (W/(mk)), Surface area A : 0.064516 m$^2$ Temperature of inner surface of Bottom board: 50.4°C, Temperature of inner surface of lid: 25.6°C, Length between bottom board and Lid (L): 0.254 m

$$Q_{cond} = k_{25.9°C} A \frac{\Delta T}{L} = 0.2599\, w/(m°C) \times 0.064516\, m^2 \times \frac{50.4 - 25.6°C}{0.254\, m} = 0.1637\, W \quad (2)^{P}$$

#### 3.1.2.3. Amount of heat transferred by natural convection: 9.54 W

Amount of heat transferred by natural convection of plywood box was 9.54 W calculated by Eq. (3) above-mentioned in 3.1.1.3.

Mean Temperature of air: 25.9°C [(26.1 + 26.1 + 25.6)/3 = 25.9], Temperature of inner surface of Bottom board: 50.4°C, Length between bottom board and Lid: 0.254 m, g : 9.81 m/s$^2$, Pr : 0.712 (25.9°C), Kinematic Viscosity (25.9°C) : 1.559*10$^{-5}$ m$^2$/s, Ra: Rayleigh number, $N_u$: Nusselt Number

$$R_a = G_a \times P_r = \frac{g \times \beta(T_{surf} - T_{envr}) \times Lc^3}{\upsilon^2} \times P_r = \frac{9.81\, m/s^2 \times 1/323.4(323.4 - 298.9) \times (0.254/4)^3}{(1.559 \times 10^{-5} m^2/s)^2} \times 0.712 = 5.575 \times 10^5$$

$$N_u = 0.54 R_a^{1/4} = 0.54 \times (5.575 \times 10^5)^{1/4} = 14.756$$

$$h_{conv} = \frac{k}{L_c} \times N_u = \frac{0.02599\, w/m°C}{(0.254/4)m} \times 14.756 = 6.039\, w/(m^{2}°C)$$

$$\therefore Q_{conv} = h_{conv} A_{surf} \Delta T = 6.039\, w/(m^{2}°C) \times 0.064516\, m^2 \times (50.4°C - 25.9°C) = 9.545\, w \quad (3)^{P}$$

#### 3.1.2.4. Amount of heat transferred by radiation in box: 10.1 W

The radiation heat of 10.1 W was occurred by using the Stefan-Boltzman law above-mentioned in 3.1.1.4.

In plywood box, between the upper surface temperature of bottom board (50.4°C) and mean temperature of other 5 sides (24.88°C), the radiation mode of heat transfer was calculated by the Stefan-Boltzman law (Eq. 4). Radiation heat of 11.21 W occurred but considering emissivity 10.1 W in the box by Eq. 4[P1]. Amount of heat transferred by radiation from bottom board to vial 10.12 W, 9.12 W (heat considering emissivity) occurred in plywood box respectively.

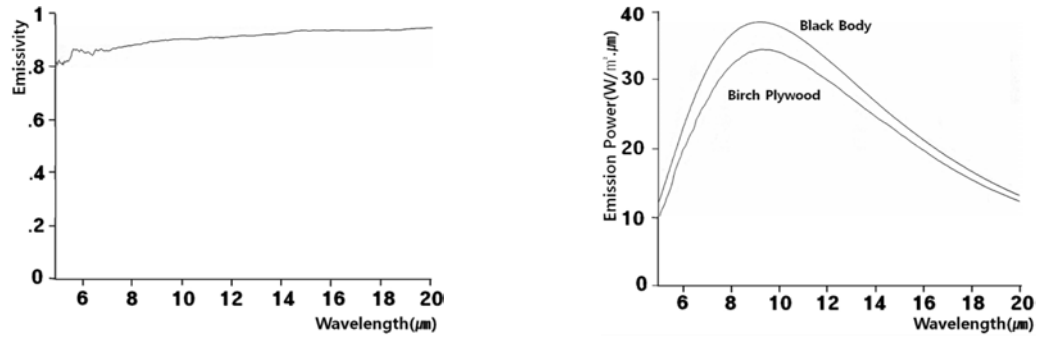


Fig. 3. Emissivity (Left) and emission power (Right) of birch plywood.

$$Q = \sigma A_{surf}(T_1^4 - T_2^4) = 5.669 \times 10^{-8} \times 0.064516\,m^2$$
$$[(273+50.4)^4 - (273+24.88)^4]$$
$$= 5.669 \times 10^{-8} \times 0.064516\,m^2$$
$$\left((3.234 \times 10^2)^4 - (2.9788 \times 10^2)^4\right)$$
$$= 5.669 \times 0.064516 \times (3.234^4 - 2.9788^4)$$
$$= 11.21\,w \quad (4)^{P}$$

$Q = A*\varepsilon*\sigma T^4$, Emissivity (ε) of Plywood: 0.901

$Q = A*\varepsilon*\sigma T^4$ = Q*ε = 11.21 W*0.901= 10.10 W $(4)^{P1}$

Amount Heat transferred by radiation from bottom board to vial

$$Q = \sigma A_{surf}(T_1^4 - T_2^4) = 5.669 \times 10^{-8} \times 0.064516\,m^2$$
$$[(273+50.4)^4 - (273+27.66)^4]$$
$$= 5.669 \times 10^{-8} \times 0.064516\,m^2$$
$$\left((3.234 \times 10^2)^4 - (3.0065 \times 10^2)^4\right)$$
$$= 5.669 \times 0.064516 \times (3.234^4 - 3.0065^4)$$
$$= 10.12\,w \quad (4)^{P2}$$

$Q = A*\varepsilon*\sigma T^4$, Emissivity (ε) of Plywood: 0.901

$Q = A*\varepsilon*\sigma T^4$ = Q*ε = 10.12 W*0.901= 9.12 W $(4)^{P3}$

### 3.2. Emissivity and Emission Power of Wood Composites

In case of wood flooring, high emissivity value of wood material is very important for the cover of underfloor heating system. The emissivity value and emission power of baltic birch plywood in Fig. 3 was 0.901 and 363 W/m$^2$ respectively. Aluminum alloy 5052 plate showed the emissivity value of 0.118 and 0.882 of reflectivity. Lee and Bender (2009) reported that wood species, wood composites and fancy maple plywood before and after coatings, all showed the emissivity values of about 0.9 and far-infrared ray material at room temperature. Birch plywood showed the same high emissivity values.

## 4. CONCLUSION

The results showed the value of radiation mode was the highest mode for the plywood box, and the convection mode was the main mode for the aluminum box. The rate of convection was 81.8% in the aluminum box and 48.2% in the plywood box, respectively. In case of the rate of radiation, the aluminum box showed only 15.4% and the plywood box showed 51%. The emissivity and the emission power of wood composites showed the same values as those of wood. The amount of energy required for the temperature rising of water within vial in the aluminum box and in the plywood box were 3.32 kJ and 6.70 kJ respectively, which showed that the vial temperature of the plywood box was two times higher than that of the aluminum box.

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