

Performance Evaluation of Infrared Bake-Out for Reducing VOCs and Formaldehyde Emission in MDF Panels

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Building materials can release a wide range of pollutants, particularly the volatile organic compounds (VOCs) and formaldehyde, which can cause indoor air related health problems. Bake-out technology is a cost-efficient method to reduce emissions of toxic substance from building materials in residential housing units. The temperature rise and the bake-out performance of MDF panels were evaluated in this work with three types of infrared radiation apparatus. Each MDF panel was radiated from three types of infrared radiation apparatus over 24 hours. The temperature was confirmed using data logging equipment according to elapsed time of infrared radiation. The formaldehyde emission was analyzed by desiccator method. In addition, thermal extractor (TE) analysis was used to determine the effect of NIR radiation on elapsed time. From the results it was determined that the NIR radiation method can be regarded as an effective way to transfer heat from material's surface to the other side. Furthermore, the bake-out performance confirmed that the NIR radiation had a significant effect on reducing the formaldehyde concentration within a short period of radiation time.

Keywords: Indoor air quality (IAQ); Wood-based material; Bake-out; Infrared radiation; Formaldehyde emission

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INTRODUCTION

Indoor air quality (IAQ) has become a major factor in residential environments due to the higher risk of inhalation of air pollutants by humans (Park *et al.* 2015). People spend most of their time in indoor spaces, exposing themselves to indoor air pollutants. It has been reported in recent years that many people, after spending some time in new buildings or newly renovated housing, complained of symptoms of illness, such as headaches, irritation of the nose, nausea, skin disorders, and fatigue. Sick building syndrome (SBS) is a serious problem and is a result of poor air quality, caused by indoor contaminants in the home and work place (Menzies and Bourbeau 1997; Hodgson 2002; Lee *et al.* 2007, 2012).

Building materials play an important role in determining the indoor air quality because of their large surface areas and permanent exposure to indoor air. Building materials can release a wide range of pollutants, particularly the VOCs (Volatile organic compounds), which can cause indoor air related health problems. Since building materials are important sources of VOCs in indoor environments, their emission characteristics should be studied. Wood-based panels, such as particleboard (PB), medium density fiberboard (MDF), and veneer, are widely used in the manufacturing of furniture, flooring, housing, and other industrial products.

Wood-based panels bonded with urea-formaldehyde (UF) resin emit formaldehyde, which is toxic and is associated with possible health hazards, such as irritation of the eyes and the upper respiratory tract. In particular, there has been an increasing focus on formaldehyde because of its potential for causing harmful diseases such as cancer and asthma (Yrieix *et al.* 2010; Kim 2010; Yu and Kim 2012). Formaldehyde was reclassified from ‘probably carcinogenic to humans (Group 2A)’ to ‘carcinogenic to humans (Group 1)’ in June 2004 by the International Agency for Research on Cancer (IARC), part of the World Health Organization (WHO).

In order to reduce VOCs emitted from building materials and furnishings, bake-out technology has been developed and conducted in buildings prior to occupancy. The theoretical concept of the bake-out is to remove VOCs from the material into the indoor air by raising the temperature. The elevated temperature accelerates the diffusion of VOCs in the material, and it decreases the amount of VOCs adsorbed, resulting in a lower equilibrium partition coefficient, thereby allowing VOCs content to rapidly decrease (Chiang *et al.* 2001; Wiglusz *et al.* 2002; Kim and Kim 2005; Zhang *et al.* 2007; Choi *et al.* 2010).

In previous studies, bake-out treatments showed some disadvantages. It was shown that damage to the plywood flooring was the largest concern because the plywood flooring is directly heated by the floor heating system. Thus, Kang *et al.* (2010) conducted the bake-out based on 35 °C as an optimal bake-out temperature with the radiant floor heating system. Consequently, they found no material damage in the investigated residential housing units even though the floor temperature reached 37 °C. Usually, plywood flooring in Korean markets is designed to resist high temperatures. This is because the range of thermally comfortable floor surface temperatures for Koreans is somewhat higher because of the Korean habit of sitting on the floor (Yeo *et al.* 2003). Several studies determined that the comfortable floor surface temperature in Korea ranged from 28.1 °C to 38.8 °C. From those results, no damage to the building materials would be caused by heating at a typical bake-out temperature (Kong and Sohn 1988; Yoon *et al.* 1991). Accordingly, bake-out is generally implemented at 35 °C to prevent the damage of building materials and to reduce VOCs by contractors in Korea.

The effect of temperature on the formaldehyde emissions has two effects. First, the increase of temperature can decrease the material/air partition coefficient, which can promote more formaldehyde emission into the gas phase of the tested system. Moreover, high temperature can increase the initial emittable concentration, which is also beneficial for reduction of subsequent formaldehyde emissions (Huang *et al.* 2015).

However, in the case of the radiant floor heating system, the furnishing materials of residential housing unit take a lot of time to reach the desired temperature in comparison with other building materials due to the large thermal mass of the particleboard, which results in a relatively small reduction in the emission (Kang *et al.* 2010). In addition, the bake-out with a radiant floor heating system has a weakness from the perspective of the indoor temperature. Jeon and coworkers studied various heating systems and confirmed that the radiant floor heating system represents a rapid temperature decrease curve toward the upper part of the indoor space (Jeon *et al.* 2013; Kim and Kim 2006). Therefore, there is a possibility that the building materials in the upper part of the indoor space may not be able to reach the desired bake-out temperature.

Recently, drying using infrared radiation has been used in various fields. Among various types of infrared radiation, the usage of near-infrared radiation (NIR) has been expanding for drying applications. NIR provides fast drying time and high quality. The

transfer efficiency is more than 85% of initial heat energy without heat loss. NIR is transmitted as a form of light energy, similar to transmission of radiant heat to the inner materials. Such an approach also allows for evaporable substances to evaporate from the materials through deep infiltration of infrared rays (Mujumdar 1987; Jang 2004; Bae 2009).

In this study, the temperature variation and the bake-out effect on building materials according to infrared radiation were measured to study the effect of the bake-out technology for the building material of the upper part of the indoor space.

EXPERIMENTAL

Preparation of Specimens

The MDF panels used for manufacturing the furniture and interior finishing material were prepared in the commercial market in South Korea with excluded grade (over 1.5 mg/L). The MDF panels were cut to have same radiation surface area (width 80 cm, height 40 cm, thickness 1.5 cm) for confirming the bake-out performance of three types of infrared radiation. The experimental setup is illustrated in Fig. 1.

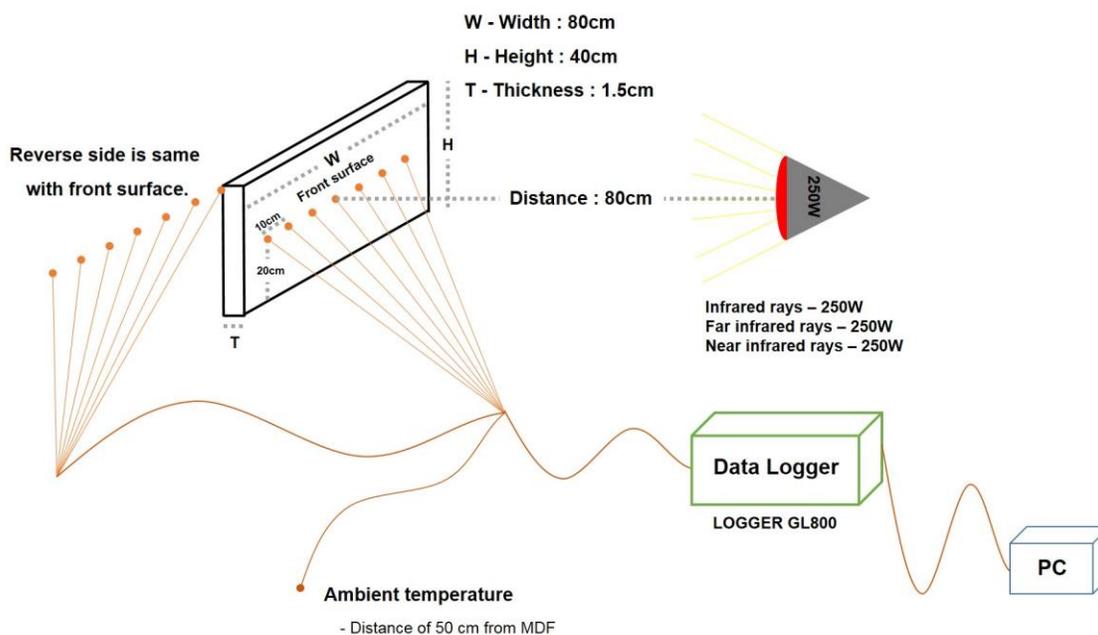
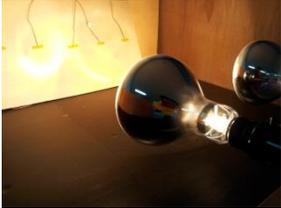


Fig. 1. Schematic image of experimental set-up

The range of area radiated by an infrared lamp on the MDF was not as wide as the whole surface area of the samples, which would lead to the limited range of infrared bake-out. Each infrared radiation type exposed MDF specimens for 24 h to compare the bake-out efficiency and the temperature on the material surface. The ambient temperature of the laboratory during the experiment was maintained at 20 ± 1 °C and 55 ± 10 R.H. %. All of the lamps used had the same electric power consumption, 250 W. The infrared radiation and test conditions are shown in Table 1.

Table 1. Test Conditions of Infrared Radiation

	Infrared rays (250W)	Far infrared rays (250W)	NIR (250W)
Appearance of radiation			
Major radiation wavelength (nm)	780 to 1000000 (0.78 to 1000 μm)	4000 to 1000000 (4 to 1000 μm)	780 to 2000 (0.78 to 2 μm)

Surface Temperature Variation Analysis

Data logging equipment was installed to measure surface temperature variation of each specimen. The data logger was a midi LOGGER GL800 by Graphtec, and thermocouple sensors were prepared to measure the temperature changes on the surface and the backside of MDF. In this experiment, 14 sensors were placed on the forward surface and reverse side area at intervals of 10 cm. Each sensor was set at 20 cm of height. The surface temperature variation analysis according to the three types of infrared radiation was carried out for a room-size space with ambient temperature. Then the room air was ventilated to remove the emitted air pollutants from MDF panels after infrared radiation. Temperature variation data was recorded at 1-min intervals during 24 h of radiated infrared. In addition, ambient temperature was also recorded to confirm the effect of indoor temperature caused by infrared radiation. The ambient temperature was measured at the distance of 50 cm from MDF on the points not radiated.

Formaldehyde Emission by Desiccator Method

The formaldehyde emissions from particleboards were determined using a desiccator according to the Korean standard KS M 1998 method (Determination of the emission rate of formaldehyde and VOCs in building interior products). The desiccator test was used to determine the quantity of formaldehyde emitted from the building boards; the test was carried out using a 10 L volume glass desiccator. The quantity of formaldehyde emitted was determined from the concentration of formaldehyde absorbed in the distilled or deionized water when the test pieces at the specified surface area were placed in a desiccator filled with a specified amount of distilled or deionized water after 24 h had elapsed. The sample surface areas were 1800 mm², as specified by the Japanese JIS A 1460 (Building boards determination of formaldehyde emission – Desiccator method) and Korean standards KS M 1998. Throughout the 24 h, the temperature of the dry oven containing the desiccators was set to 20 °C.

Thermal Extractor Analysis of Materials

Thermal extractor (TE) analysis was used to measure the VOCs and formaldehyde emitted from construction materials, such as medium density fiberboard (MDF), particleboard, paints, adhesives, and floorings. The TE experiment has the advantage that particle- or powder-type materials can be installed due to its minimal specimen requirement. In addition, the TE method can be conducted at a desired temperature from room temperature to 350 °C by an adjustable oven in the TE.

The emission rates of formaldehyde and TVOC emitted from MDF were evaluated by TE to determine the effect of NIR radiation with elapsed time. The specimens were manufactured with the size of $10 \times 10 \times 20$ mm to install in the glass tube of TE. Four types of MDF specimens were manufactured: untreated, 24 h, 48 h, and 72 h of radiation.

RESULTS AND DISCUSSION

Temperature Rise Performance on Surface in Accordance with Infrared Type

The temperature variations of three types of infrared radiation are shown in Fig. 2. All of the infrared radiation types showed rapid surface temperature rise performance. Within 360 min, the highest surface temperature values were reached and maintained during the experiments. In particular, the highest surface temperature of MDF was recorded when it was exposed to NIR type radiation, reaching about 57 ± 1 °C. General infrared and far-infrared radiation types showed similar surface temperatures of 41 ± 1 °C. The reverse side temperatures also rapidly increased within 360 min. The MDF radiated NIR showed the highest reverse-side temperature, 49 ± 1 °C. The reverse-side temperature of MDF radiated general infrared was somewhat higher than the MDF radiated far infrared, 31 ± 1 °C. In addition, the reverse side temperature of MDF radiated far infrared reached 29 ± 1 °C.

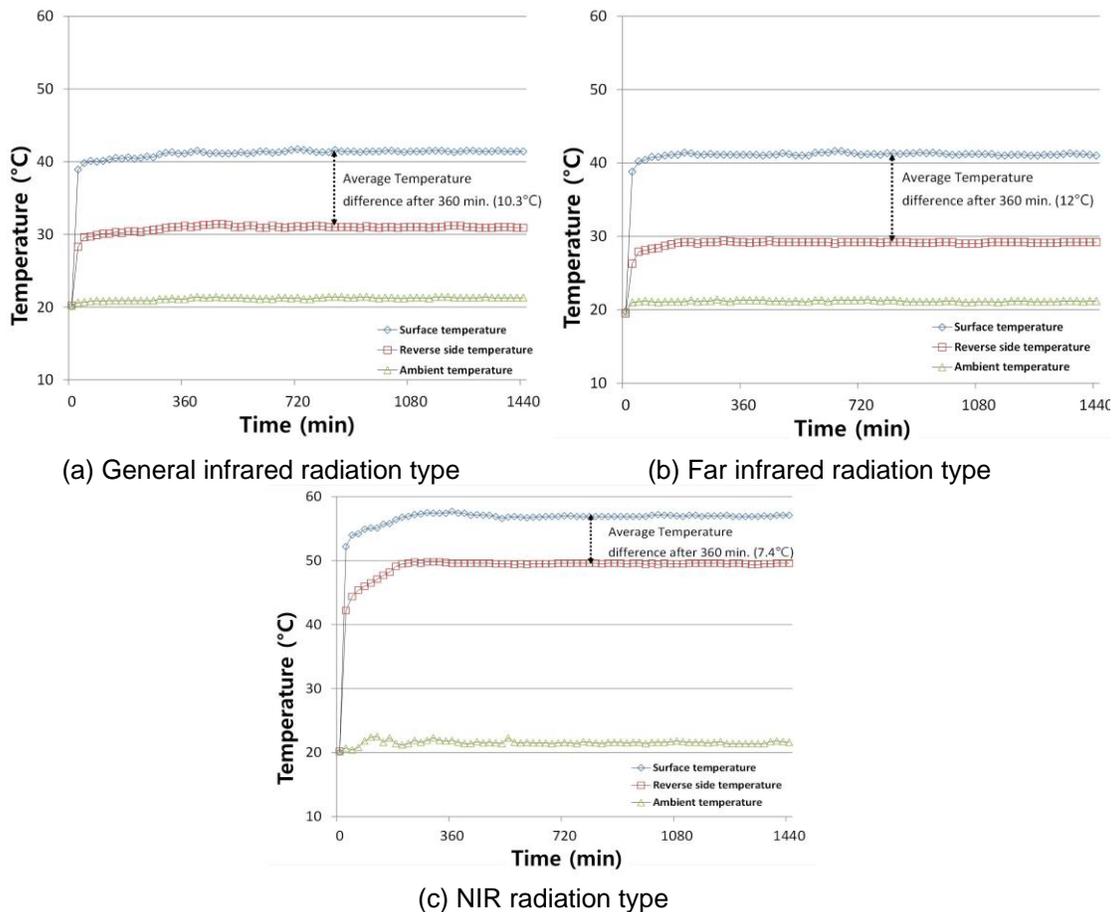


Fig. 2. Comparison of temperature variation in accordance with infra radiation type

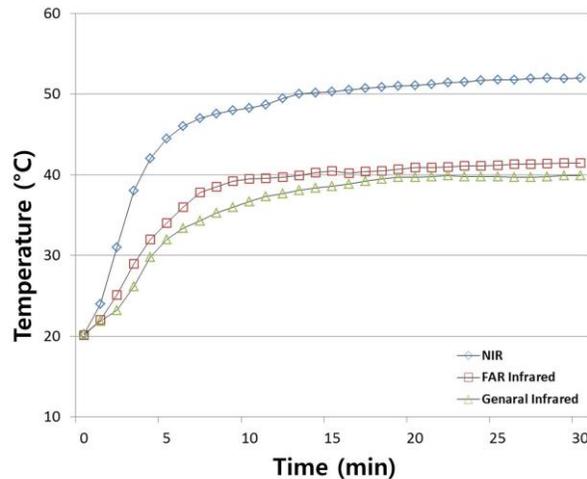


Fig. 3. Temperature variation of MDF in accordance with infrared radiation types during the first 30 min

Table 2. Results of Temperature Variation

	Infrared rays	Far infrared rays	NIR
¹ Time to reach 40 °C	32 min	14 min	4 min
¹ Time to reach 50 °C	Unreached	Unreached	13 min
¹ Maximum temperature (°C)	41±1	41±1	57±1
^{1,2} Temperature difference (°C)	10.3	12	7.4
Average ambient temperature (°C)	21.3	21.2	21.8

¹ The average temperature was measured after 360 min of radiation until reaching 24 h.

² The average temperature difference between surface and reverse side of temperature.

The temperature difference between the forward surface and the reverse side of the MDF by the NIR radiation type showed a narrow temperature variation within an average value of 7.4 °C after 360 min. Therefore, the NIR radiation method was considered to be an effective way to transfer heat from the material's forward surface to the other side with those results. In the case of the ambient temperature, both the general infrared radiation type and the far infrared radiation type showed that the ambient temperatures were increased by about 1.0 to 1.5 °C with the similar patterns during the experiment. However, the ambient temperature of NIR radiation type showed a slightly higher temperature variation, 1.5 to 2 °C. As a result of the ambient temperature, the influence of the indoor space warming was hardly affected by the infrared radiation. After infrared radiation, it was confirmed that the used MDF panels maintained their shape and surface attributes even though all MDF panels reached maximum 57±1 °C of surface temperature.

Figure 3 shows the surface temperature variation of the three types MDF during the first 30 minutes. In the case of the general infrared type, its temperature was slowly increased at the beginning in comparison with the other infrared radiation types. However the temperature showed a moderate increase of rate after 10 min. The far infrared type and NIR showed a steep temperature increase rate from the beginning stage. Moreover, NIR

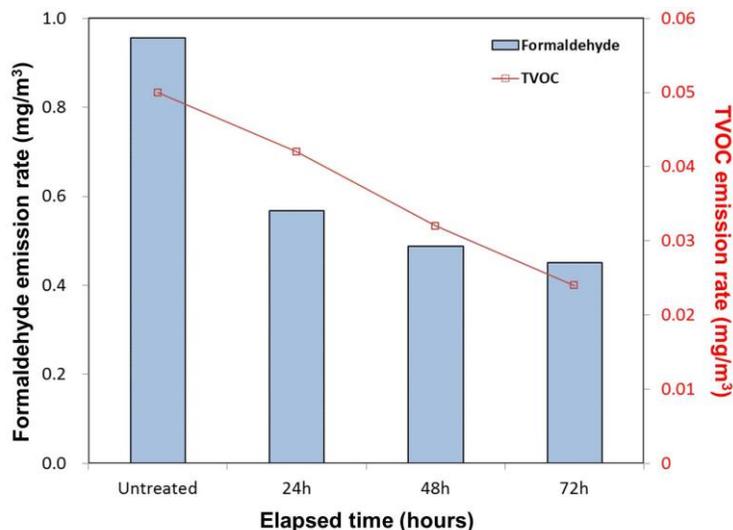


Fig. 4. Formaldehyde and TVOC emission rates in accordance with NIR radiation elapsed time.

showed the highest temperature increase rate among the three types of infrared radiation. Summarized result values are shown in Table 2.

The Bake-Out Effect of Infrared Radiation on Formaldehyde Emission

In the desiccator method, the formaldehyde emission of four specimens was verified by the infrared bake-out performance for reducing subsequent formaldehyde emissions. The formaldehyde emission of MDF panels was lowered by undergoing infrared radiation over 24 h. The formaldehyde emission value of reference for MDF was 8.56 mg/L. General infrared and far infrared radiation types, which had shown similar temperature rise performance, also showed similar levels in formaldehyde emission, 6.70 mg/L and 6.22 mg/L. Equivalent with the temperature rise performance, the NIR radiation type showed the significant formaldehyde reduction performance. The formaldehyde emission value of the MDF radiated NIR was 5.73 mg/L, and the reduction ratio was approximately 33% compared to the reference value.

Before the use of infrared radiation apparatus, it was necessary to check the bake-out target material's proper bake-out temperature to prevent any damage concerning transformation and fading, as the peak surface temperature of MDF radiated with NIR was recorded as approximately 57 ± 1 °C. In addition, the infrared radiation apparatus had a weakness in the fact that it would only be able to radiate a sectional area. Consequently, the bake-out technology must be developed for sectional area or the form of optional bake-out technology equivalent with its intended use.

Formaldehyde and TVOC Emission Rates According to NIR Radiation Times

The effect of NIR radiation in accordance with radiation elapsed time was evaluated, as shown in Fig. 4. The formaldehyde emission showed a rapid reduction tendency in the initial 24 h of NIR radiation. After 24 h of NIR radiation, the reduction tendency rate gradually decreased. The formaldehyde reduction rates in accordance with elapsed time were about 41%, 49%, and 53%, respectively. In the case of TVOC emission rate, the reduction tendency of the initial 24 h smoothly decreased in comparison to the reduction

rate of formaldehyde. The reduction rate showed a linear decrease. The TVOC reduction rates in accordance with elapsed time were about 16%, 36%, and 52%, respectively. As a result, the bake-out effect of NIR radiation was confirmed, and it was found to be very effective in a short period.

CONCLUSIONS

1. The temperature rise performance of radiated material and the bake-out performance were investigated in accordance with three types of infrared radiation. In contrast with the bake-out technology based on the radiant heat floor system, the infrared radiation apparatus showed a rapid temperature rise performance for furnishing materials.
2. From the results, it was determined that the NIR radiation method can be considered to be an effective way to transfer heat from material's forward surface to the other side. Furthermore, the bake-out performance test results confirmed that the NIR radiation had a significant effect on reducing a formaldehyde concentration within a short period of radiation time.
3. Therefore, both of the NIR radiation treatments considered can be considered for development as a bake-out technology for building materials positioned on vertically oriented upper sections in residential housing units.

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