Flame Spread Mechanism through Analysis of Fire Behavior of Bed Mattress by the ISO 12949 Test

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Abstract
This paper aims to explain and analyze the test results of the fire behavior of real-size bed mattress products when subjected to an open flame burner system with a total heat supply of 27 kW according to the ISO 12949 method. These results were analyzed in terms of the heat release rate, flame height, temperature, and flame-spread rate using an equation. A normal bed mattress without any fire retardant treatment has a peak heat release rate (HRR) of more than 3 MW before 300 s. After ignition, only a few minutes are allowable for the evacuation of the occupants, making it important to prevent the ignition of the bed mattress or to adopt a retardant bed mattress. The flame heights measured by analyzing a video showed good agreement with the mean flame height estimated from the dimensionless HRR calculated using the burning area in an experiment with a non-flame retardant bed mattress. Finally, the mean flame-spread rate interpolated from the measured temperature rising data at several points on the bed mattress in an experiment with a non-flame retardant bed mattress was consistent with the proposed calculation model.

Keywords: fire safety; bed mattress; flame spread; ISO 12949; HRR; flame height

1. Introduction
1.1 Background
A burning mattress is generally the primary energy contributor in a typical bedroom fire. Once a mattress ignites, fire develops rapidly, potentially leading to room flashover (FO). As a burning room reaches FO, it becomes untenable, preventing escape from the fire (Ohlemiller and Gann, 2002). Therefore, a flammable bed mattress is considered one of the main factors that induce a fully developed compartment fire. Reducing a bed mattress's fire risk could minimize residential fire casualties. A bed mattress is relatively larger than the combustible items normally found in the living room. Therefore, a fire originating in the living room can rapidly spread to the bed mattress. Fig.1. shows data (Yoo, 2008) for the maximum heat release rate (HRR) and fire growth rate (FIGRA) of various burning furniture in residential buildings. As can be seen, a mattress has the highest FIGRA value and one of the highest HRR values.

In Korea, in 2010, 9,414 residential fires were reported, accounting for 24.9% of all domestic fires (Seoul Metropolitan Fire and Disaster Management Department, 2010). Of these, 5.55% of the fires originated in the bedroom, highlighting the risk posed by bed mattresses catching fire. Currently, Appendix

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29 (Clause 7.3.7) of the Korean Safety Quality (Korean Agency for Technology and Standards, 2012) is applied to assess the fire safety performance of a 1:10 scale mattress based on cigarette ignitability and the extent of observed damaged area according to the KS G ISO 8191-1 Standard (Korean Agency for Technology and Standards, 2012). However, this method only explains the first stage of fire growth. As such, most mattresses already conform to Appendix 29, making it ineffective for evaluating the fire safety performance of bed mattresses. For a more realistic evaluation of the fire risk of a bed mattress, therefore, a full-scale test such as ISO 12949 (ISO, 2011) is more appropriate. Toward this end, it is important to accumulate information about the fire characteristics of full-scale bed mattresses in order to reduce the fire hazard.

In this study, a series of full-scale bed mattress tests were conducted according to ISO 12949. The results were analyzed in terms of factors such as the HRR, flame spread rate, flame height, and temperature, and flame spread by a mattress was summarized via a comparison with a calculation method.

1.2 Purpose
The FIGRA (Sundstrom, 2007) based on maximum HRR over the elapsed time is considered a necessary parameter to predict FO in a room. As mentioned before, as a burning room reaches FO, it becomes untenable, preventing escape from the fire. Furthermore, the temperature of the smoke layer in the upper space in the FO room increases to such an extent as to pyrolyze most of the combustible materials in the room.

It is necessary to understand the flame spread characteristics of combustible materials, which strongly influences the HRR and FIGRA. Flame spread is influenced by the burning radius and flame height. Specifically, flame height from the burning of combustible materials is considered to dominate heat transfer at the burning boundary because the higher the flame height, the more rapidly the combustion proceeds.

This study aims to determine the parameters influencing the flame spread of a bed mattress and to propose a burning mechanism by comparing the measured and the calculated results of the horizontal flame-spread rate on a solid surface as suggested by Quintiere et al. (2006).

2. Experiment Outline
Fire tests were performed three times on a normal bed mattress (without retardant components) according to ISO 12949 under a 3 MW open calorimeter with a rectangular hood of 5 m × 5 m based on the oxygen-consumption rate principle (Barbrauskas and Grayson, 1992).

2.1 Ignition Source
A gas burner was used as an ignition source. The burner system consists of three parts: two pilot burners with manually operated igniters, adjustable steel frame, and a mass-flow controller. This system was based on ISO 12949 and 16 CFR Part 1633 (US Federal Register, 2006). The burner is designed to provide propane gas automatically using the mass-flow controller, as described in Table 1. The test continues for 30 min or until a significant threat to the safety of the test personnel/test equipment/test facility.

| Position of | Flow (L/min) | HRR from | Operating Time from Ignition |
|-------------|--------------|----------|-----------------------------|
| Top         | 12.9         | 18 kW    | 70 s                        |
| Side        | 6.6          | 9 kW     | 50 s                        |

2.2 Mattress Specimen in Test
A pocket-spring-type mattress, which has become increasingly popular in Korea, was chosen as a specimen. A "super single size" mattress has dimensions of 1,100 mm (width) × 2,000 mm (length) × 280 mm (thickness) and has no retardant treatment with the components as following drawing.

![Fig.2. Mattress Components(a), Position of Thermocouples and Burners(b)](image)

a) Components of Mattress Specimen,

b) Position of thermocouples and burners (There are 10 thermocouples on the top surface and bottom surface, respectively [unit: mm],

2.3 Measurement Item
In this test, the HRR, total heat release (THR), temperature, and flame height were measured.
Specifically, temperatures were measured using thermocouples for specimen Nos. 1 and 2 to analyze the heat transfer effect between the top surface of the mattress and the bottom surface (10 thermocouples on both the top surface and the bottom surface of the mattress, respectively). In specimen No. 3, the flame height is recorded by using a video camera and measured using a ruler. Measurement of HRR and THR was done by 3MW open-calorimeter hood (5 m × 5 m) based on the oxygen-consumption rate principle. Flame height was recorded by using a video camera and checked by a ruler and the observation of photographs from a computer with a precision of 30 fps(frame per second).

3. Experimental Results

3.1 HRR and THR

HRR data for 600 s was selected for analysis, as shown in Table 3 and Fig.3. Entire specimens showed the peak HRR within 300 s of starting the test.

![Fig.3. HRR with Time (Nos. 1–3)](image)

Specimen Nos. 1, 2, and 3 show a peak HRR of more than 3,000 kW, and these specimens show a peak HRR of 3,399.8 kW (standard deviation: 183.2 kW) on average among three peak HRRs. The respective specimens also show FIGRA (peak HRR divided by elapsed time) values of 12.5, 12.2, and 16.4 kW/s, where the heat release speed is considered rapid and exceeds 10 kW/s (average FIGRA: 13.7 kW/s, standard deviation 2.3 kW/s). The THR was measured to exceed 350 MJ, with the average THR being 362.1 MJ (standard deviation: 8.6 MJ). Especially, specimen No. 3 showed comparatively more smoke and flame than other specimen Nos. 1 and 2. It is assumed that this resulted in the fact that the peak HRR of specimen No. 3 was faster than others.

3.2 Temperature Distribution on Top and Bottom Surface of Mattress in Specimen Nos. 1 and 2

Ten thermocouples were installed on both the top and the bottom surfaces of the mattress in specimen Nos. 1 and 2. According to Fig.4., the top surface temperature varies regularly from 600 to 1,000 °C at around 300 s. Comparatively, the bottom surface shows an unstable distribution over the elapsed time. Increase in temperature of thermocouples on the surface of the mattress indicates expansion of burning area. While temperatures on the top surface of the mattress showed a steep increase over time due to the direct contact with the flame, the bottom surface of the mattress with the indirect flame had some unstable distribution of temperatures.

![Fig.4. Surface Temperature](image)
3.3 Observation of Flame Spread

The flame-spread rate on the top surface is observed mainly in the short side direction (1,100 mm) by video recording data (Table 4. and Fig.5.). The result of specimen Nos. 1, 2, and 3 shows an average flame spread of 5.2 mm/s over the top surface.

| Specimen No. | Distance [mm] | Elapsed time [min:s] | Speed [mm/s] |
|--------------|---------------|----------------------|-------------|
| No. 1        | 1 100         | 3:42                 | 4.9         |
| No. 2        | 1 100         | 3:38                 | 5.0         |
| No. 3        | 1 100         | 3:12                 | 5.7         |

The peak HRR is ordered as No. 3 > No. 2 > No.1 as is the flame-spread rate. Therefore, the tendency of peak HRR could be identified from the flame-spread rate.

4. Analysis of Experimental Data
4.1 Flame Height

Zukoski's (1980/1981), Heskestad's (1983), and McCaffrey's formulas are generally used for calculating or predicting the average flame height. In this study, the measured values of the flame height are compared with the results calculated by Zukoski's formula, where both the HRR and the burning representative length of burning area are required to obtain Zukoski's flame height (2). Even though the surface of the mattress is not flat, it was assumed that its surface may appear to be almost flat so that Zukoski's formula could be adopted.

4.1.1 Measured Flame Height

At the beginning of the test, the origin of calculated flame height was on the top surface of the mattress. However, with flame spread continuing, the position of this origin changed into the ground level due to the convection of melted materials from the flame droplets of the mattress. The result (Fig.6.) was obtained by measuring the flame height at 20-s intervals (t = 40 - 400 s) based on video recording data for specimen No. 3 (Peak HRR = 3,610.5 kW, T_{max} = 220 s).

Fig.6. shows plots of the average flame height from the mattress top surface and from the ground (Fig.7.).

The gap between the top surface of the mattress and the ground level until 200 s is 595 mm (bed thickness: 280 mm + mattress installation height: 315 mm), and after around 260 s, the gap becomes almost zero.
As the flame concentrically spreads at the assumed center, the part in the half-circle has a burning radius r of a burning area and the part in the rectangle has a burning area with a long side of 2r and a short side of 150 mm. The total area of the half-circle plus the rectangle is considered the total burning area on the top surface of the mattress.

After calculating the diameter (D) of the given circle by using the same area as the burning area, the dimensionless HRR (\(Q^*\)) and the average flame height (\(L_0\)) were obtained from (1) and (2) (\(\gamma = 3.3\) was adopted) (Zukoski, Kubota, and Cetegen, 1980/1981). Fig.9. shows the calculation result of the average flame height and the measured result of the flame height.

\[
Q' = Q / c_p \rho_0 \sigma \sqrt{\frac{2r}{\pi}} = \frac{Q}{1116D^{5/2}} \\
L_0 / D = \gamma \begin{cases} Q'^{2/3} (Q' < 1) \\ Q'^{2/5} (Q' \geq 1) \end{cases}
\]

After the two burners are turned off at 70 s, the calculated flame height shows very good agreement with the measured height until around 140 s. But after around \(t = 160\) s, the calculated flame height shows a greatly different value from the measured one for the following reasons: At around \(t = 160\) s, the flame height measured went over the height of the hood to capture the smoke and flame. The measurement of flame height is of approximate data and it is hard to obtain exact data because the measured height of flame after \(t = 160\) s has great uncertainty due to heavy smoke.

**4.2 Horizontal Flame-Spread Rate**

**4.2.1 Flame-Spread Rate Based on Thermocouple's Temperature**

The horizontal flame-spread rate is derived from the ignition temperature of urethane foam (a combustible material in the mattress) as checked using the thermocouples on the mattress surface. The natural firing temperature and igniting temperature of normal soft urethane foam is known to be approximately 410 and 290 °C, respectively. Urethane foam is assumed to be ignited when the thermocouple temperature exceeds 300 °C. Finally, the flame-spread rate is obtained by checking the time required for the foam to ignite.

When \(T_{iq, n}\) and \(T_{iq, m}\) are considered the ignition time at thermocouple Nos. \(n\) and \(m\), respectively (\(n\) and \(m\) are integral numbers from 1 to 10), the flame-spread rate of the flame between the two thermocouples can be given by (3), and the flame spread results are shown in Table 5.

\[
(T_{iq, n} - T_{iq, m}) / (T_{iq, n} - T_{iq, m})
\]

In Table 5., in the long-side direction, the speed from thermocouple No. 4 to No. 1, No. 4 to No. 7, and No. 7 to No. 10 is 3.03, 3.24, and 6.61 mm/s, respectively. In the short-side direction, the speed from thermocouple No. 4 to No. 5 and No. 5 to No. 6 is 2.91 and 6.75 mm/s, respectively. The speed increases upon going further from thermocouple No. 4. This result suggests that as the burning area becomes larger, the flame height from the mattress surface and the heat flux coming into the unburned part also increase. Fig.12. shows the flame-spread rate. The ignition time and distance from the beginning of the test to thermocouple No. 4 are 20s and 37.5 mm, respectively.

**4.2.2 Calculating Result of Flame-Spread Rate**

For spread over solid surfaces, it has been shown that the most significant heat transfer rate is at the surface over a preheating length \(\delta\) as shown in Fig.13.
The surface heat transfer from the flames may only penetrate to a certain depth. This heating in depth takes place during the time to heat the surface from its original temperature $T_\infty$ to the ignition temperature $T_{ig}$. This heating time is the ignition time caused by the heat flux of the spreading flame.

For a thick solid, the flame-spread rate ($v$) is calculated as suggested by Quintiere et al. as above.

\[
v = \frac{4\delta}{\pi kpc(T_{ig} - T_\infty)^2} q_f^2 \tag{4}
\]

\[
t_{ig} = \frac{4}{\pi} kpc \left[\frac{T_{ig} - T_\infty}{q_f}\right]^2 \tag{4.1}
\]

\[
v = \frac{\delta}{t_{ig}} \tag{4.2}
\]

This heating time is the ignition time caused by the heat flux of the spreading flame. For a thick solid, the flame-spread rate ($v$) is calculated as suggested by Quintiere et al. as above.

This equation is normally applied to the solid surface considering a semi-infinite solid.

The equation for the radiation heat flux is as (8).

\[
q_f = q_{radiation} + q_{convection} \tag{7}
\]

\[
q_{radiation} = F \varepsilon \sigma T_f^4 \tag{8}
\]

Here, configuration factor $F$ is set to 1. And the average travel length $L_m = 0.66D$ [m] (assuming the sphere shape) is calculated by using the emissivity of the surface at the sphere shape with the representative diameter $D$ of the fire source (Fig.14.).

The emissivity ($\varepsilon$) is given as follows:

\[
\varepsilon = 1 - \exp(-kL_m) \tag{9}
\]

The flame temperature ($T_f$) is set to 1,073 K, absorption coefficient ($k$) is 2.0 m$^{-1}$, and the Stefan-
Boltzmann constant ($\sigma$) is $5.67 \times 10^{-11} \text{[kW/m}^2\text{K}^4]\text{].}

Next, the convection heat flux as shown in Fig.13.(b) is expressed as follows:

$$ q_{\text{convection}} = h(T_f - T_{\text{surface}}) \quad (10) $$

The calculation is performed considering the heat flux due to this convection(Fig.13.(b)) at the flame as forced convection flow along the flat plate(vertial part of the mattress section which is exposed to flame from the ground) because the fluid has already accelerated to become a forced convection until the flame approaches from the ground to the bottom of the bed mattress, and not by the lifting force between two objects with different temperatures.

Furthermore, from $t = 80$ s after the ignition of the mattress, many flame droplets out of the mattress started to drop down to the ground and these droplets generated some flames under the mattress considered to be convective heat. $q_{\text{convection}} = 0$ for $t \leq 80$ s, whereas $q_{\text{convention}} = h(T_f - T_{\text{surface}})$ for $t > 80$ s ($T_f = 800 \, ^\circ\text{C}$ and $T_{\text{surface}} = 25 \, ^\circ\text{C}$).

The convective heat transfer coefficient is given as follows:

$$ h = \frac{\lambda N_u}{L} \quad (11) $$

At this time, the representative length $L$ is set to 50 mm of urethane thickness inside the bed mattress.

Furthermore, the thermal conductivity $\lambda$ is calculated as follows:

$$ \lambda = 3.7 \times 10^{-7}T^{3/4} \quad (12) $$

($T$: Gas temp. = 1,073 K)

This equation can be used to obtain the average Nusselt number (Arvind Atreya, 2001) when induced by the forced convection-laminar flow or turbulent flow-flat plate as follows: (Heat flow from the melted materials on the ground goes up along the vertical face of the mattress and the effective characteristic length for convection could be assumed to the length able to be combusted which is the depth of the mattress's urethane form.)

$$ N_u = 0.664R_e^{1/2}P_r^{1/3} \quad (13) $$

$$ N_{uL} = 0.037R_e^{1/5}P_r^{1/3} \quad (14) $$

Whether a flow is laminar or turbulent depends on the Reynolds number. A flow is laminar for $Re < 3 \times 10^7$ and turbulent at higher values.

The Reynolds number is calculated as follows:

$$ Re = \frac{u_{\infty}L}{\nu} \quad (15) $$

The kinematic viscosity $\nu$ can be obtained from the temperature as follows:

$$ \nu = 7.2 \times 10^{-10}T^{7/4} \quad (16) $$

Furthermore, the fluid velocity $u_{\infty}$ replaces the gas velocity at the flame axis($w_m$). $w_m$ at the flame axis as suggested by McCaffrey is used at the height $H=595$ mm (see Fig.7.).

The height of the virtual ignition source is obtained as follows:

$$ \Delta Z = 1.02 - 0.083Q^{2/5} \quad (17) $$

$u_e$ at the $z' = \Delta Z$ axis is obtained by the equation in Table 6. At this time, each factor of $A$ and $m$ is substituted as shown in Table 6.

Table 6. Factors of $A$ and $m$ as Substituted According to McCaffrey

| $u_e = w_m$ | 0 $< z' < 0.08$ | 0.08 $< z' < 0.20$ | 0.20 $< z'$ |
|------------|-----------------|-----------------|-----------|
| $m = 1/2$  | $m = 0$         | $m = -1/3$      |

McCaffrey $A = 6.84$ $A = 1.93$ $A = 1.12$

The Prandtl number is the value of air at $T = 797 \, ^\circ\text{C}$. (Pr = 0.72 is applied)

The length of a flat plate as the representative length is the thickness of the urethane foam in the mattress. $d$ is set as 50 mm.

Accordingly, the horizontal flame spread rate is calculated as follows:

$$ q_f = q_{\text{radiation}} + q_{\text{convection}} \quad (7) $$

$$ \nu = \left[ \frac{4\delta}{\pi kpc(T_g - T_{\infty})^2} q_f^2 \right] \quad (4) $$

The result obtained by measuring the diameter of the fire source at $t = 80$ s or longer (considered as the remaining part from the fire) and that obtained by calculating the diameter of the fire source at $t = 80$ s or longer from the flame-spread rate measured by the above equation are as shown in Fig.14.

![Fig.14. Horizontal Flame-Spread Rate Considering Both Radiation and Convection Heat Flux](image)

### 5. Summary and Discussion

This paper has conducted tests, and attempted to confirm the fire behavior of the mattresses and its mechanism on the flame spread, and presents the following conclusions.

1. A normal bed mattress without fire retardant treatment has a peak HRR of more than 3 MW before around 300 s.

2. The flame heights measured by analyzing a video were compared with the mean flame height estimated from the dimensionless HRR calculated using the burning area measured in experiment No. 3 of a non
fire retardant bed mattress. The calculation results agreed rather well with the experiment results up to around 140 s, as shown in Fig.9. However, after an elapse of around 160 s, the calculation results were quite larger than the experimental ones because the flame tip protruded outside the video frame with increasing HRR or the fire flame became invisible with the existence of thick black smoke around it.

3) The calculated horizontal flame-spread rate considering both of the radiative heat flux and the convective heat flux was well consistent with the mean flame-spread rate interpolated from the measured temperature data. Therefore, it is decided that the heat flux $q_f$ proposed in (7) is able to logically reflect the mechanism of the flame spread on mattress in fire.

Furthermore, the mechanism on the flame-spread rate on the bed mattress is summarized as shown in Fig.15.

4) As shown in Fig.13.(b), it is not easy to calculate the plume's velocity at the point receiving 'convection + radiation' at the same time. Furthermore, there are not any good equations and formula for obtaining this velocity in the current theory of FSE. However there would be a possibility to be involved in axial centerline velocity with the plume's velocity. Due to this relation, (17) was adopted in spite of the limitation. Future work; it is expected to find a method to apply the plumes' velocity at the heat flux of both convection and radiation.

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