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Fire Growth in an ISO 9705 Room with Different Wall Linings

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Keywords: Fire Growth, Surface Linings, Flashover, Heat Release Rate

ABSTRACT

The fire growth patterns in an ISO 9705 room decorated with different wall linings, wood-wool cement boards and plywood boards, were compared in this study. In the first experiment using cement boards, the fire source was set to produce a heat release rate of 100kW in the first 10 minutes and of 300kW in the next 10 minutes. Since the cement boards were basically nonflammable, the temperature field in the room reflected only the heat release from the gas burner flame. Except near the ceiling corner above the gas burner, the temperatures in the upper layer did not exceed 400℃, and the temperatures in the lower layer barely increased. In contrast, the plywood boards used in the second experiment were ignited in less than a minute, and the fire grew violently. The room flashed over in about 2 minutes and the temperatures in the room quickly increased uniformly to 800℃, as the wall linings in the lower region got ignited by the intensive radiant heat. The total heat release of the fire, measured from the combustion gases based on the oxygen consumption principle, was found to agree well with that calculated from the mass loss rate of the wall linings material.

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INTRODUCTION

The total heat release of a fire consists of the convective heat release carried with the fire plume and the radiation heat release emitted from the fire to the surroundings. Both convective and radiation heat release are functions of temperature. Therefore, the temperature field of a compartment fire is a direct indication of the fire growth and is of great significance to the fire protection engineers. Whether the fire will proceed to the most destructive stage, i.e., flashover, depends strongly on the temperature development. Compartment fires are often characterized by five stages: ignition, growth, flashover, fully developed fire, and decay, according to the variation of the heat release rate or the temperature in the compartment (SFPE 1995). Not all fires will evolve till flashover, but if the fire is allowed to proceed to flashover, the whole compartment will involved in intensive burning and great destruction of lives and properties would result.

A compartment fire is usually visualized as fire in a room with openings. The fire usually starts with a small ignition source, such as a cigarette butt or a match. The fire then spreads to the neighboring flammable materials. At the initial stage of the fire, the fire grows primarily as a function of the burning rate of the fuel in the direct neighborhood of the fire source. The burning of the fuel obtains full supply of air at this stage and the burning rate is said to be fuel-controlled, i.e. it depends on the arrangement and the combustion properties of the flammable materials but not on the geometry of the compartment or the opening. The fire may stay very localized and fail to spread far from the ignition source, if the burning rate is very small or the fuel is exhausted before the temperature in the room is raised to a higher level.

As the fire continues to grow, the hot combustion gases in the fire plume rise directly above the burning fuel and impinge on the ceiling. The impingement on the ceiling causes the gas flow to turn horizontally and move under the ceiling to the other parts of the room. If the ceiling is of nonflammable material, the hot gas accumulated under the ceiling, forming the so-called upper layer. The thickness of this hot upper layer grows with the entrainment of room air at the lower boundary by the fire plume but can be retarded by venting out of the room opening. In the mean time, the temperature of the upper layer rises due to the heat release of the fire (McCaffrey 1981, Foote 1986), while decreases by the conduction to the ceiling material, radiation to the surrounding surfaces, and convection by smoke flow through the openings(Delichatsios 1981, Evans 1984, Cooper 1990, Cooper 1988, Kapoor 1996). If the temperature of the upper layer gases exceeds 600ºC then the radiation heat flux from the upper layer onto the ground surface can usually be higher than 20kW/m^2. In this high radiation heat flux, flashover will occur, i.e., most of the flammable materials in the room will be ignited and the whole room will fall into a uniform burning with very intense heat release and temperature rise(Peacock 1999, Babrauskas 2003).

A more violent form of fire propagation happens when the fire is at the corner of the room and the room is furnished with flammable wall and ceiling linings (Su et. al 2008). The heat release from the fire can be greatly enhanced because of the ignition and burning of the wall linings. As the hot gases rise to the ceiling, forming the upper layer, the temperature of the upper layer will rise quickly due to the burning of the ceiling linings material. The occurrence of flashover is almost ensured if the ceiling and wall linings are easily flammable materials.

The fire load of a compartment refers to the total heat energy that can be generated for the complete burning of all the flammable materials within this compartment. It is usually expressed as the combustion heat per unit floor area. Though both the arrangement and density of the combustible influences the fire growth (Hsieh and Tsai 2008). The fire load of a compartment provides the basis for the analysis of the fire growth and spread, the temperature field, and the strategy for personal movement during a fire. The fire load is also one of the most important parameters in the establishment of fire standards. In a building compartment, the fire load is usually divided into two categories: fixed fire load and movable fire load. A fixed fire load refers to flammable materials in the ceiling, the walls, the windows, or the fixed furniture; whereas the movable furniture, books, clothes, newspapers, etc. are considered as the movable fire load. In this study, we are interested in understanding the fire growth and spread on a room decorated only with wall and ceiling linings. In this case, the fixed fire load is uniformly distributed on the surface of the whole room. The growth and spread of such a fire is influenced by interactions of wall to wall, or wall to ceiling. This basic understanding is useful for future analysis on the fire growth and spread in a fully furnished and decorated room in which contains both fixed and movable fire load.

The realization of the scenario of a room fire has revealed the correlation between the temperature distribution and the development of the fire. We, therefore, set out to compare the temperature fields associated with a standard ISO 9705 (1993) room decorated with either flammable or nonflammable wall and ceiling linings for a standard fire source. The ISO 9705 room/corner fire test is a standard test procedure to evaluate the fire characteristics of surface linings in a room fire scenario. The focus of the evaluation is usually on the heat release rate, total heat release, and smoke production rate. In the present study, the temperature distribution and its characteristics were emphasized and carefully measured. The development of the temperature field has provided us with useful insight into the effects of flammable surface linings.

EXPERIMENTAL SETUP

The experiment was carried out by following the standard procedure of the ISO 9705 room/corner fire test(1993), as shown in Figure 1. The ISO 9705 room/corner fire test facility is equipped with a standard room, an exhaust hood, a volumetric flow meter, and an $O_2/CO_2/CO$ gas analyzer. The standard room has dimensions of 3.6m depth, 2.4m width, and 2.4m height, with a door of 0.8m width and 2.0m height; and its walls and ceiling are constructed from fire-resistant materials with a thickness of 20mm and a density of 500 ~ 800kg/m^2.

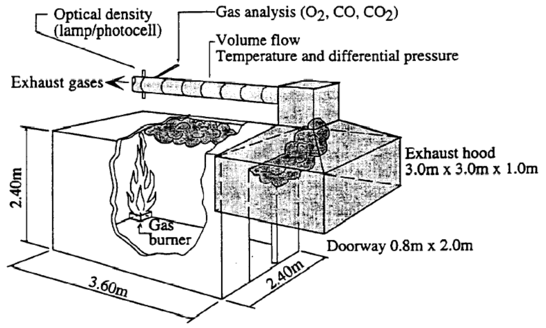


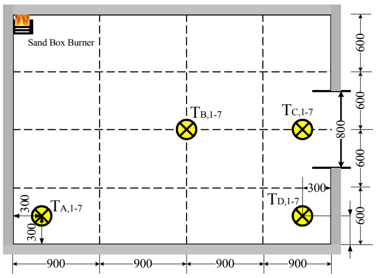
Figure 1 The ISO 9705 room/corner fire test facility

For our investigation, the interior surfaces of the room, except the floor, were covered with wall linings of wood-wool cement boards or plywood boards, for the first and the second experiment, respectively. The wall linings were nailed to wood sticks which were initially mounted on the room wall. The total area of wall linings amounted to 34.47m^2. The total length of wood sticks used for each experiment was 101.35m. In Table 1, the specific properties of cement board, plywood board and wood stick are listed. In our fire tests, the standard room contained no movable furniture; and therefore, the wall linings and the wood sticks account for all fire loads.

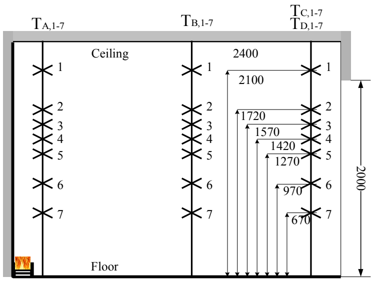
Table 1 Specific properties of cement board, plywood board and wood stick.

Material	Specific mass	Heat of combustion	Total area or length	Total mass
Wood-wool cement board (1st experiment)	16.34kg/m^2	2.56MJ/kg	34.47m^2	563.24kg
Plywood board (2nd experiment)	8.32kg/m^2	8.60MJ/kg	34.47m^2	286.79kg
Wood stick (1st or 2nd experiment)	0.49kg/m	12.95MJ/kg	101.35m	49.66kg

The temperature field of the room was measured by using four thermocouple trees, T_A, T_B, T_C, and T_D, at locations shown in Fig. 2(a). Each thermocouple tree contained seven thermocouples arranged at different distances away from the floor, as sketched in Fig. 2(b). For the measurement of ceiling jet, six thermocouples (T1 ~ T6) were fixed 100mm under the ceiling, at locations indicated in Fig. 3. All thermocouples are of K-type with a bead of 0.32mm diameter. The radiation heat flux was measured with an up-facing heat flux gage (HF) at the center of the floor, as indicated in Figure 3. The radiation heat flux was also evaluated with a paper target on the floor near the heat flux gage. In addition, the test room was placed on load cells so that the mass loss during the course of the fire can be measured.



(a) The top view



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(b) The side view

Figure 2 Arrangement of four thermocouple trees in the test room

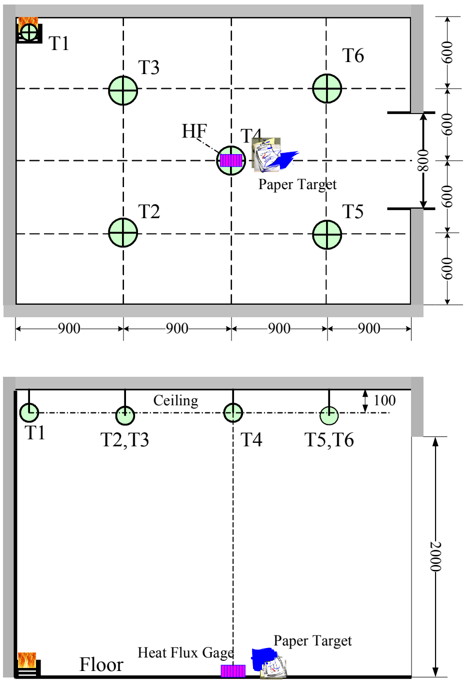

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Figure 3 Locations of ceiling thermocouples, the heat flux gage, and the burner.

The fire test was started by a sand-box propane-gas burner with an outlet area of 170mm x 170mm and 145mm high above the floor. The gas burner was located at the room corner, as shown in Fig. 3. For the first experiment, the heat release rate of the gas burner was kept at 100kW for the first 10 minutes, and increased to 300kW for the next 10 minutes. For the second experiment, the heat release rate and total burning time of the gas burner were 100kW and 400 seconds.

As the hot fire products gas flew out the door of the test room, it was collected by the square exhaust hood above the door. Through the analysis of the volumetric flow rate and the oxygen concentration of the fire products gas, the total heat release rate of the room fire can be determined by means of the principle of oxygen consumption (Janssens 1991).

RESULTS AND DISCUSSIONS

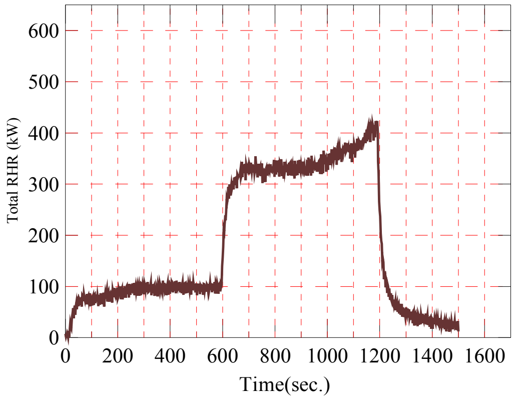
1. Burning Behaviors of the Room Decorated by Wall Linings of Wood-Wool Cement Boards

Since the wood-wool cement boards were basically nonflammable, for the first 10 minutes, the 100kW gas burner fire was not able to ignite the boards. Although the burner flame reached the ceiling, no high-temperature ceiling jet was generated. The gas burner was then turned up to 300kW for another 10 minutes, as shown in Fig. 4(a). Near the ceiling corner directly above the burner, a localized ceiling jet was observed and a small part of the board touched by the flame was slightly ignited. No other part was observed to be ignited and the ignited part did not grow after the gas burner was turned off, as shown in Fig. 4(b).

In Fig. 4(c), the measured rate of heat release was kept constant at 100kW in the first stage, which reflected simply the heat release of the gas burner. No ignition occurred on wood-wool cement boards. For the next stage, the gas burner gave off 300kW of heat while the wood-wool cement board was only slightly ignited. And we can see that, by subtracting 300kW from the total heat release rate shown in Fig. 4(c), the wood-wool cement board burning only generated at first 50kW then gradually to 100kW. As the gas burner was turned off at the end of the 20-minute period, the heat release immediately diminished due to the non-existence of fire spread.

(a) Gas burner at 300kW

(b) Gas burner turned off



(c) Measured rate of heat release

Figure 4 Burning behaviors of the room decorated by wall linings of wood-wool cement boards.

Figure 5 shows variations of the ceiling temperatures in the fire test of the room decorated by wall linings of wood-wool cement boards. The measured temperature directly above the gas burner, i.e., T1 in Fig. 5, in the first 10 minutes, stayed nearly constant around 400℃. The temperature fluctuation was caused by the dancing flame-tip of the gas burner flame. On the increase of the gas burner power up to 300kW, the T1 temperature suddenly jumped to 700℃ and gradually rose above 800℃ due to the slight burning of the wood-wool cement board near the gas burner flame. The temperature dropped suddenly as the gas burner was turned off at the 20th minute. The other temperatures, T2 through T6, basically reflected the warm air layer near the ceiling which flew towards the door. For the first 10 minutes, T2 and T3 were measured about 230℃, while T5 and T6 were 20℃ lower due to heat loss to the ceiling and ventilation from the door. For the next 10 minutes, T2 and T3 were measured near 600℃, while T5 and T6 were much lower about 400℃.

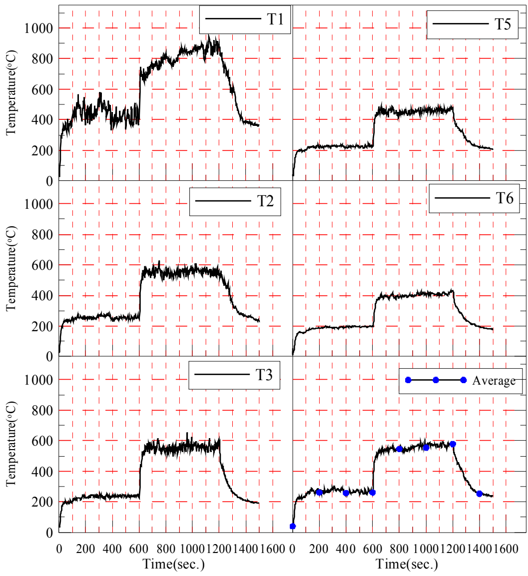


Figure 5 Variations of the ceiling temperatures in the fire test of the room decorated by wall linings of wood-wool cement boards.

As shown in Figure 6, the temperature field of the test room measured by thermocouple trees indicates that temperatures in the first 10 minutes did not exceed 200℃ in the upper layer, which was the region between 1600mm height and the ceiling. In the next 10 minutes, temperatures in the upper layer went up to 400℃, while temperatures in the lower layer never had any significant change. Flashover was impossible even if the upper layer temperature reached 600℃ because the wood-wool cement board was not flammable. The variation of the temperature field shown in Fig. 6 finally points out that without the burning of wall linings, the hot products gas generated by the gas burner flame flows upwards and spreads beneath the ceiling as a ceiling jet, and is exhausted through the door, resulting in only a hot upper layer with limited temperature increase in the room.

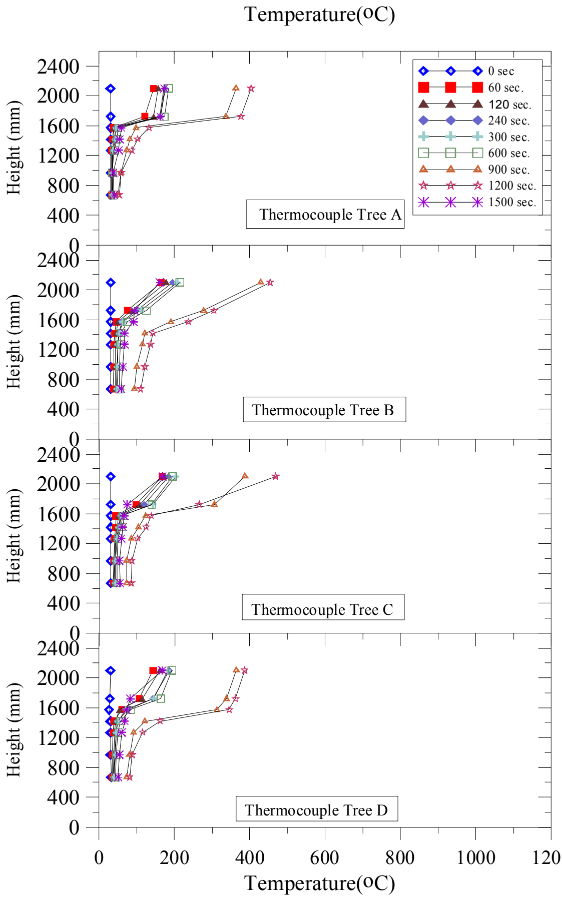


Figure 6 Variations of the temperature field in the fire test of the room decorated by wall linings of wood-wool cement boards.

2. Burning Behaviors of the Room Decorated by Wall Linings of Plywood Boards

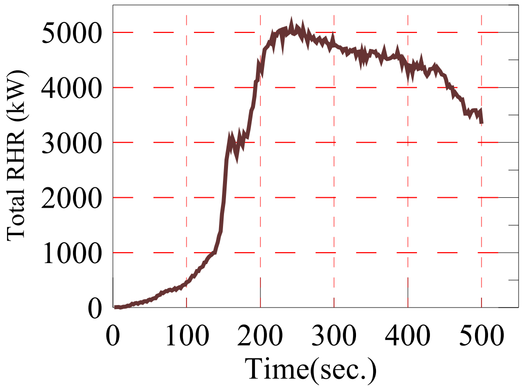
In the second experiment, burning behaviors of the test room decorated by wall linings of plywood boards are described as follows. The tip of the fire reached the ceiling 10 seconds after the ignition. At the 42nd second, the plywood board close to the gas burner was ignited and the fire started to grow. At the 58th second, as shown in Fig. 7(a), a ceiling jet was produced around the corner of the gas burner. The upper smoke layer started to move down approximately at the 88th second. The whole room was involved in intensive burning after the occurrence of flashover. The possible flashover could be identified by any of the following: the center ceiling thermocouple T4 reached 600℃ at 122s, the paper target was ignited at 154s as shown by Fig. 7(b), and the fire rushed out of the door at 145s, as shown by Fig. 7(c). The condition of flashover was determined to be between 120s and 150s.

In Fig. 7(d), the measured rate of heat release was seen to grow slowly to 1MW for the first 2 minutes. It rapidly rose to 3MW after the occurrence of flashover and reached the maximum of 5MW around 220s. The burning after flashover generated a rate of heat release higher than 4MW. Unfortunately, we had to extinguish the fire at 500s because the capacity of the facility could no longer accommodate this high rate of heat release.

(a) Ceiling corner ignited

(b) Paper target ignited

(c) Flame rushed out



(d) Measured rate of heat release

Figure 7 Burning behaviors of the room decorated by wall linings of plywood boards.

The fire spread and growth can be understood through the observation on variations of the temperature field in the test room. Figure 8 shows the measurements of thermocouples T1 through T6, indicating the temperatures at a plane 100mm beneath the ceiling in the second experiment. T1 rose the most rapidly among the six temperatures because it was right above the gas burner. As was mentioned before, the wall linings were ignited at 42s. T1 thus rose to 800℃ at t = 50s in Fig. 8. T1 remained higher than 800℃ as the burning of the plywood board at the corner continued. As the high-temperature gas flew along the ceiling to T2, T3, T4, T5, T6, it lost heat through conduction and convection to the ceiling. Therefore, the ceiling jet temperatures rose faster for locations closer to the fire source (T2, T3) than they did for locations farther from the fire source (T5, T6). T2 and T3 rose to 800℃ around 100s. As the center ceiling jet temperature T4 reached 600℃, flashover was induced and the whole room was involved in intensive burning. T4, T5, and T6 then increased to 800℃ around 300s, and the ceiling temperatures became uniform. For the time period between 300 and 400 seconds, the igniting and burning at the various parts of the wall linings made the ceiling jet temperatures jumped up and down markedly.

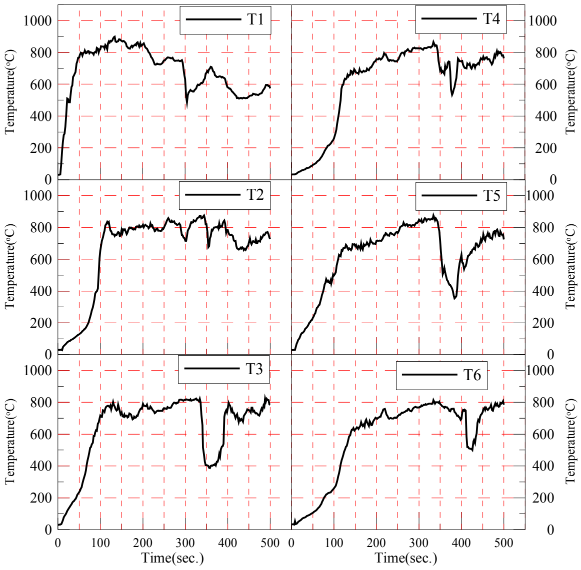


Figure 8 Variations of the ceiling temperatures in the fire test of the room decorated by wall linings of plywood boards.

To realize the extent of the upper smoke layer developed in the fire test, we can look at the vertical temperature variations indicated by the thermocouple trees, as shown in Fig. 9. In Figure 9, for the first 60 seconds, the temperatures below 1600mm remained almost no change, while above 1600mm, the temperatures rose gradually. As time proceeded up to 120s, the temperatures near the ceiling, i.e., the upper layer, rose much faster than those of the lower layer near the floor. It is noted that the temperatures of tree C and B rose slightly faster than those of tree A and D because of the direction of the gas flow. In this time, before 120s, there existed the large temperature difference between the upper layer and the lower layer. However, when flashover occurred after 120s, the temperatures at the lower layer were seen to increase quickly with the upper layer until, after 240s, the upper layer and the lower layer reached about the same temperature and rose together. In the later stage of the fire, because the upper layer near the ceiling was filled with smoke, and the ceiling linings were burned out, the temperatures at the lower layer was greater than those of the upper layer. For the time period over 420s, the temperatures gradually decreased.

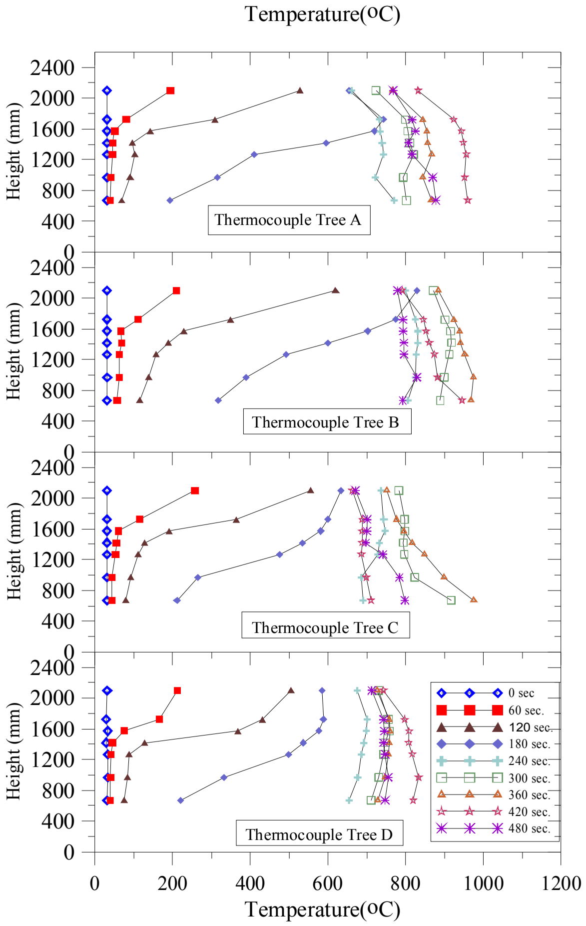


Figure 9 Variations of the temperature field in the fire test of the room decorated by wall linings of plywood boards.

In comparisons of Figs. 6 and 9, i.e., the temperature fields for burning wall linings of cement and plywood boards, it is clearly shown that in the absence of flashover, both cases existed a distinct separation between the upper and lower layer, similarly occurring at the height of 1600mm above the floor. The high-temperature upper layer showed the development of the hot ceiling jet produced by the gas burner flame. However, the burning of flammable plywood boards promoted the upper layer with higher temperatures, and finally resulted in the fire flashover, in comparison with the case of nonflammable cement boards. Shortly after flashover, the room was full of burning smoke and hot gases, and its temperature field showed a uniform high-temperature distribution.

3. Mass Loss and Total Heat Release

In the first experiment using wood-wool cement boards, the mass loss measured by load cells showed less than 5% mass reduction at the end of the 20-minute period. This small mass loss was attributed to evaporation of water content inside of cement boards and wood sticks, and very limited partial burning of cement boards in the late stage of the experiment. However, there was a significant change of mass in the second fire test using plywood wall linings, as shown in Fig. 10. The mass plotted in Fig. 10 represents the total mass of the test room, and therefore the mass loss at any instant should be obtained by subtracting the plotted data from the initial mass. The rate of mass loss is simply the slope of the curve shown in the figure. For the first 2 minutes, the fire was localized near the corner of the gas burner and the mass loss rate was small. As the flashover occurred near 120s, the whole room got into uniform burning, the time rate of mass loss went up. At this stage, the curve of the mass variation is nearly a straight line with a larger slope. The rate of mass loss stayed close to a constant until 500s, at that time the fire was extinguished due to safety reasons as explained before.

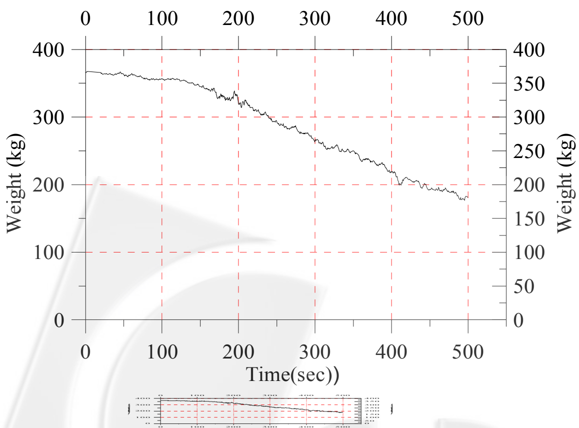


Figure 10 Mass loss of plywood boards in the fire

test.

The initial mass of the plywood boards was estimated by 286.79kg (Table 1) and the total mass loss at extinction of the fire was measured by 183.9kg (Fig. 10). The plywood boards were not burnt out in such a short burning period of 500 seconds. We noticed that wood sticks on the back of the boards might not be burned before burnt out of the boards; therefore, the heat release in the fire test was completely due to the burning of plywood boards. The effective heat of combustion per unit mass for plywood boards from the cone test was 8.60MJ/kg (Table 1); when multiplied by the total mass loss, we get a total heat release of 1581.54MJ. When compared with the experimental value of 1532.86MJ, which was calculated by the integration of the rate of heat release with a time interval of 500 seconds in Fig. 7(d), the error was found to be less than 3 per cent.

CONCLUSIONS

The fire growth and spread on a room decorated only with wall and ceiling linings was studied experimentally in an ISO 9705 room incorporated with measuring the rate of heat release by the oxygen consumption principle and the rate of mass loss by load cells. Particularly, variations of the temperature field in the room influenced by the fire were measured by four thermocouple trees and six thermocouples fixed 100mm beneath the ceiling. Two types of wall linings, wood-wool cement boards and plywood boards, were used for the first and the second experiment respectively.

For the case of nonflammable cement boards, the fire source was set to produce a heat release rate of 100kW in the first 10 minutes and of 300kW in the next 10 minutes. However, no ignition occurred on wood-wool cement boards. The variation of the temperature field showed that without the burning of wall linings, the hot products gas generated by the gas burner flame flows upwards and spreads beneath the ceiling as a ceiling jet, and is exhausted through the door, resulting in only a hot upper layer with limited temperature increase in the room.

For the case of flammable plywood boards, the gas burner flame with 100kW heat release first ignited the plywood board close to the burner at 42s, generated a ceiling jet at 58s, and then resulted in an upper smoke layer moving downward at 88s. The whole room was finally involved in intensive burning after the occurrence of flashover, between 120s and 150s. In the absence of flashover, both cases existed a distinct separation between the upper and lower layer in the room, similarly occurring at the height of 1600mm above the floor. However, the burning of flammable plywood boards promoted the upper layer with higher temperatures, and was ended up with the fire flashover. Shortly after flashover, the room was full of burning smoke and hot gases, and its temperature field showed a uniform high-temperature distribution. The total heat release of the fire, measured from the combustion gases based on the oxygen consumption principle, was found to agree well with that calculated from the mass loss rate of the wall linings material.

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不同壁裝材料在 ISO9705 標準房間內之火災成長研究

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摘　要

本研究以木絲水泥板及合板作為 ISO 9705 標準房間的壁裝材料，實驗探討不同壁裝材料的火災成長模式。使用木絲水泥板作為壁裝材料的實驗中，火源係依據標準使用丙烷燃燒器，前 10 分鐘設定使用 100kW 熱釋放率，後 10 分鐘提高至 300kW 熱釋率。由於木絲水泥板不易燃燒，燃燒過程中房間內部溫度場變化僅反映出燃燒器燃燒

火焰的影響；除了房間角落燃燒器上方天花板附近的溫度外，房間上層溫度不超過 400℃，在下層溫度則幾乎沒有增加。相對的，以合板作為壁裝材料的實驗，合板不到一分鐘即被點燃，且火勢快速成長。房間在大約 2 分鐘時產生閃燃，隨著房間火焰的影響；除了房間角落燃燒器上方天花板附近的溫度外，房間上層溫度不超過 400℃，在下層溫度則幾乎沒有增加。相對的，以合板作為壁裝材料的實驗，合板不到一分鐘即被點燃，且火勢快速成長。房間在大約 2 分鐘時產生閃燃，隨著房間下層壁裝材料被強烈輻射熱所引燃，整個房間溫度迅速均勻的提升到 800℃。利用耗氧原理經由燃燒煙氣量測計算所得的火災總熱釋放率，與以壁裝材料的質量損失率估算所得的結果具良好的一致性。