SUPPRESS FLASHOVER OF GLASS-REINFORCED POLYESTER FIRE WITH WATER MIST INSIDE ISO 9705 ROOM

by

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Water mist suppression tests for glass-reinforced polyester panels were conducted in ISO 9705 room. Panels covered part of the room and a wood crib fire was used as fire source to ignite glass-reinforced polyester fire. A four-nozzle water mist suppression equipment was used inside test room on the time of flashover. Heat release rate of the combustion inside the room, room temperature, surface temperature of glass-reinforced polyester panels, total heat flux to wall, ceiling and floor in specific positions were measured. Gas concentration of O_2, CO, and CO_2 was also measured in the corner of the room at two different levels. A thermal image video was used to record the suppression procedure inside room. Test results show that the water mist system is efficient in suppressing the flashover of glass-reinforced polyester fire and cooling the room within short time.

Key words: *water mist suppression, glass-reinforced polyester panels, flashover, ISO 9705 room*

Introduction

As mentioned in some literatures [1], composites, such as glass-fiber reinforced plastics or polyester (GRP) and cored panels, are the materials of choice in some marine and flight applications. Their unique characteristics of interest are: high strength to weight ratio, durability and resistance to the marine environment, ease of maintenance and repair, toughness, particularly at low temperatures, and low thermal conductivity compared with metals. Composites can also be used for seamless construction, which minimizes leakage and eliminates many costly secondary assembly processes. The primary concerns associated with the acceptability of composite construction in high speed craft are flammability and structural

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performance under fire exposure. Fire safety [2] is an important part of overall safety concerns when use composites in ship and boat building. How composite materials behave under fire conditions was studied by many researchers with bench scale (cone calorimeter) [2, 3] and room scale (ISO 9705 Room) experiments [4]. International Maritime Organization (IMO) adopt a resolution specifying the ISO 9705 room fire test as the procedure to be used to qualify fire-restricting materials used for bulkheads and compartment linings. The ISO 9705 room test has been used to determine how the fire behavior of the lining material was affected when subjected to a standard, reproducible flame source as dictated in the ISO 9705 [5]. The bench scale test result can also be used to predict flashover in ISO 9705 room [6].

When a fire is ignited in a room with GRP lining, the material's exposed face begins producing pyrolysis gases under the incidence radiant of fire. Initial pyrolysis is usually followed by an initial delamination within the GRP skin [2]. Then melting and charring would happen on the GRP panel with increasing of incidence radiant from fire source and also from the fire of the ignited combustible pyrolysis gas of its own. At this time the fire spread rapidly and would result in a flashover. For the ordinary fire behavior tests in ISO 9705 room, the fire always suppressed by sprinkler spray in the room as a safety method preventing dangerous situation. But in our tests, a water mist suppression system was used to suppress flashover to evaluate the efficiency of water mist for future using on marine ships.

The research performed on fire suppression with water mist started nearly 60 years ago [7]. The term water mist [7] was adopted by the National Fire Protection Association Committee, NFPA 750, *Standard for Water Mist Fire Protection Systems*, 2000 edition, in the early 1990s as part of the renewed interest in efficient use of water in fire suppression systems. The interest of water mist suppression was motivated by some events, which were the aviation industry response to the Manchester air crash, the 1987 signing of the Montreal Protocol and an IMO ruling that required the installation of marine sprinklers on all existing and new passenger ships capable of carrying more than 35 passengers [7]. Numeral researches on water mist were conducted both on the mechanisms of extinguishment and engineering aspects of water mist. The mechanisms of extinguishment and suppression were described by Mawhinney [8] and these are accepted as common view of water mist for researchers and engineers. Three primary and two secondary mechanisms are associated with extinguishment of hydrocarbon fires, which are gas phase cooling, oxygen depletion and flammable vapor dilution, wetting and cooling of the fuel surface, radiation attenuation, and kinetic effects [8]. But as Mawhinney [8] described the extinguishing mechanisms apply to extinguishment of different class of fire with different importance of one mechanism over another, and typically, all mechanisms are involved to some degree in the extinguishment process. That is true for the water mist suppressing flashover of GRP fire in ISO 9705 room due to special burning procedure of GRP panels.

Experimental details

Experiment facilities

The tests of water mist suppression for GRP fire were conducted in ISO9705 [9] room. Dimensions of the room are 3400 mm long, 2400 mm wide, and with a height of 2400 mm. There is a single doorway opening to out side centered on the south wall, as shown in fig. 1, with a width of 800 mm and height 2000 mm. The doorway was opened during all the tests. Exhausted gas is collected by the hood outside the doorway. The data collected in exhaust duct enabled the heat release from the burning inside room to be determined by means of oxygen consumption calorimetric. The instrumentation in the duct met the specifications in ISO 9705. The sampling rate is 1 sample per 2.5 seconds. Other temperature, heat flux and oxygen sampling measurements inside the room were conducted by other set of instrumentation system. Locations of the test points are described in the following paragraphs and depicted in fig. 1.

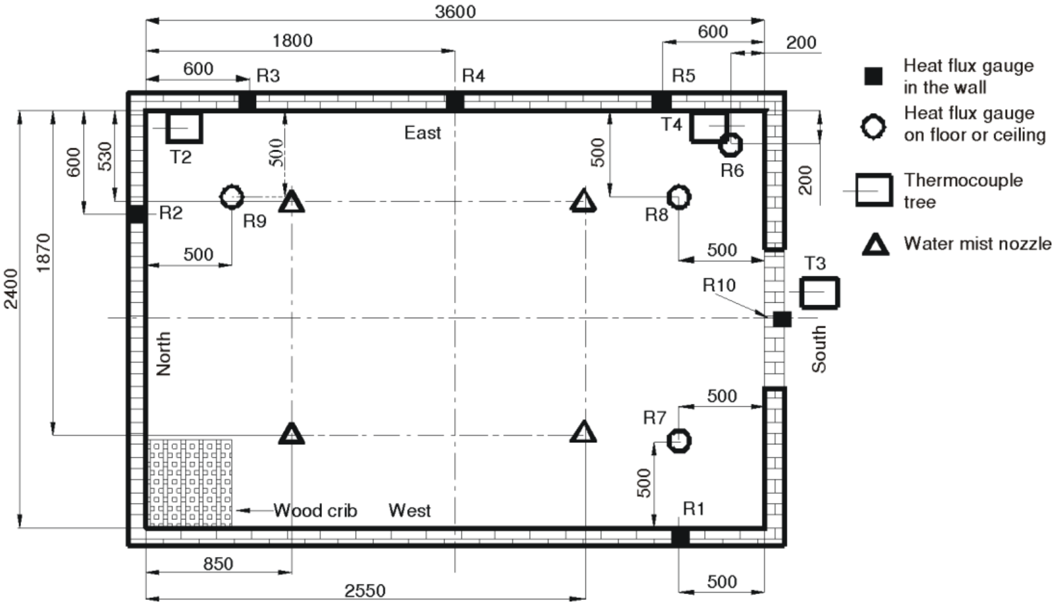

Figure 1. Diagram for room configuration and instrumentation; all dimensions are in millimeters

The water mist suppression system with four nozzles was mounted on the ceiling of the room. Nozzles are of type AM4 *AquaMist*® open nozzles donated by *tyro*® International Ltd. Company. The AM4 *AquaMist*® nozzle have been fire tested within compartmentalized areas and found effective for the extinguishment of a wide variety of exposed and shielded class B hydrocarbon pool, spray, and cascading pool fires, as well as for combinations of incidental class A and B fires [10] (data sheet from *tyco*®). Approximately 5% of the water droplets produced by AM4 nozzle are larger than 225 microns. These large droplets, which comprise about 50% of the volumetric flow rate, provide the majority of the momentum, which entrains the finer droplets and carry them into the combustion zone. Approximately the diameter of 77% of the droplets is smaller than 100 μm. These data were obtained at a pressure of 12 bar, in a plane located 1000 mm below nozzle diffuser. Water supply of single nozzle is 15 liters in 1 minute at 17.2 bar. The total water consumption in 1 minute for four nozzles was nearly 60 liters. A 1 m^3 tank was used as reservoir and a pump supplied the water to each nozzle with necessary pressure. A pressure transducer was mounted on the main water pipe to monitor water pressure. The positions of nozzle are shown in fig. 2. This type of nozzle was used by US Coast Guard Research and Development Center as one of five kinds of water mist suppression system [11]. Five water mist suppression systems were tested in small machinery spaces and spaces with combustible boundaries to evaluate the suppression efficiency.

(a) (b)

Figure 2. Inside of ISO 9705 room with panels installed and four water mist nozzles on the ceiling before test. The wood cribs can be seen in fig. (b). Also shown in photo are the thermocouple tree (north corner) and a sprinkler pipe standing vertically on the floor in case of uncontrolled fire

Three tests were conducted inside the room, which were labeled as Test1 to Test3. Wood cribs were used as ignition source for GRP panels. The crib consists of three layers of radiata pine wood sticks which are 35 × 35 × 500 millimeter (width × height × length). There are eight sticks per layer. The crib weights around 7 kg. The cribs were located at the north--west corner of the room 70 mm above the floor. The position is not under the north-west nozzle directly. The nominal fire size of wood cribs was 0.2 MW according to the heat release rate obtained from calibration burning tests under the hood of ISO 9705 room. Under the crib two aluminum foil trays filled with 0.3 liter methylated spirits each to ignite the crib fire. The tray's size is 290 × 190 × 50 millimeter (length × width × depth). The fuel inside trays was ignited by gas torch. It would take 300 seconds to reach this peak of heat release rate (HRR).

Ten Schmidt-Boelter heat flux gauges (from Medtherm Corporation), which were labeled as R1 to R10, were used in the tests. They had a range of 0-100 kW/m^2, with an 180° view angle. R1 to R5 were placed on the wall. R1 was on west wall, R2 was on back (north) wall and R3 to R5 were on east wall. All these five gauges were placed directly through the plywood and gypsum panel comprising the wall and were 1200 mm above the floor. The surface of each gauge was flush with the wall. R7 to R9 were placed on the floor facing vertically upwards. R6 was placed in the ceiling down to the south-east corner facing vertically downwards. R10 was placed in the doorway 1200 mm above the floor pointed to the fire source (wood cribs). All these gauges were water-cooled with a tube-pump system.

Three thermocouple trees were used for each test, which were labeled as T2, T3, and T4. Type K MIMS thermocouples (stainless steel sheathed, 1.5 mm diameter) were used on each tree. T2 was located at north-east corner of the room with 10 thermocouples which were labeled as T21, T22 to T210, with 200 mm increments from 300 mm above the floor to 2100 mm (which is 300 mm below the ceiling). The tip of each thermocouple on this tree was 100 mm to north wall and 150 mm to east wall. T3 was located just outside the doorway of the room with 10 thermocouples which were labeled as T31, T32 to T310, with 200 mm increments from 300 mm above the floor to 2100 mm. The tip of each thermocouple on T3 was at the center line of the doorway. T4 was located at south corner of the room also with 10 thermocouples which were labeled as T41, T42 to T410, with 200 mm increments from 300 mm above the floor to 2100 mm (which is 300 mm below the ceiling). The tip of each thermocouple on this tree was 100 mm to south wall and 150 mm to east wall.

The GRP panels cover two sidewalls (west and east), one back wall (north) and the ceiling of the room, as shown in fig. 2. GRP panels are 1000 mm wide, 1200 mm long and the thickness is from 6 mm to 8 mm. Surface temperature of GRP panel was measured by thermocouples. At the center of each GRP panel, one thermocouple was inserted through the panel walls and bent against the inner surface which is exposed to crib fire. Another thermocouple was bent against the outer surface for each GRP panel at center to measure the back temperature of the panel. These thermocouples were labeled as shown in fig. 3.

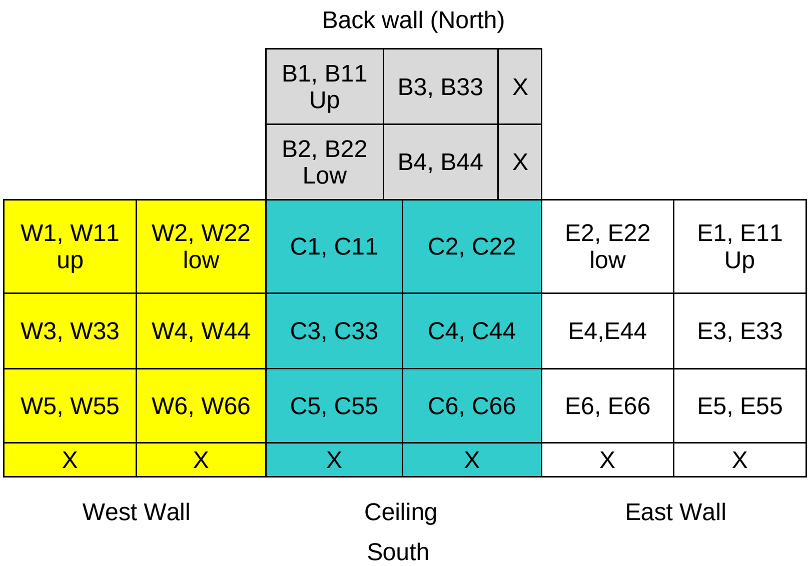

Figure 3. Temperature measurement positions on the wall (*e. g.* W1 is the thermocouple on the surface inside room on the west wall, W11 is on the back of the panel on the west wall)

Two gas sampling probes are located at north-east corner, one is 600 mm above the floor and the other is 1800 mm above the floor. The tip of each probe was 500 mm to north wall and 500 mm to east wall. Probes were connected to gas concentration analyzers which could provide concentrations of O_2, CO, and CO_2.

Cone test result of GRP

The flammability properties of GRP panel was tested by using of cone calorimeter. Cone calorimeter tests were carried out in accordance with [12]. Tests were carried out at the irradiance level of 50 kW/m^2. Five specimens were tested.

Surface material could be determined belongs to which so-called FO-categories based on statistical information from cone calorimeter [6]. Surface material belongs to which category is determined by application of the following set of rules:

* FO-category 1: products not reaching flashover during 1200 seconds of testing time,
* FO-category 2: 600 seconds ≤ t_{FO} <1200 seconds,
* FO-category 3: 120 seconds ≤ t_{FO} <600 seconds, and
* FO-category 4: t_{FO} < 120 seconds.

We used Anne Steen Hansen's method [6] which evaluated the application of multiple discriminant function analysis to deal with cone calorimeter data to predict the FO--category of surface material. The results is that this GRP panel can be determined as a member of FO-category 3, which would reach flashover in ISO room from 120 to 600 seconds.

Test procedure

The fire test procedure was as follows. The ISO 9705 system started more than 2 minutes before fire ignition and all measurement started. Wood crib fire was ignited by underneath methylated spirits which was set fire by a gas torch. When HRR reaches 1 MW which is defined as flashover in ISO 9705 room the water mist suppression is turned on manually. Water mist was discharged for 120 to 150 seconds.

Results and discussion

Observation

A serial of thermal images in fig. 4 illustrate the thermal environment change inside room during the test. Figures 4(a) to 4(f) show the fire development inside room and the smoke layer became thicker and hotter. At the time of fig. 4(g) flashover happened. Mist was discharged at the time of fig. 4(h). It is very clear in figs. 4(h) to fig. 4(l) that the hot smoke layer was pushed down and cooled by water mist. The upper layer near the ceiling was cooled by water mist as shown in fig. 4(m) to fig. 4(o). Figures 4(p) to fig. 4(t) illustrate the thermal condition inside room after the flame was extinguished. The room was cooled by water mist evenly except a triangle area near the ceiling because of the blind zone between nozzle's mist cones. But this hot area shrank as the room temperature reduced by water mist.

The fire damage to the marine composite was examined after exposure to a radiant heater in the cone calorimeter and a fuel fire [3]. A through-the-thickness cross-section of sample reveals three easily distinguishable zones. The sections include a char layer consisting of glass and residue from combustion of the resin, a discoloured zone with no visually obvious material loss, and undamaged material. The depth of charring and discolouration is dependent on the intensity and duration of the fire [3]. The surface of the post-test panel in our tests can also be divided into distinguishable zones by observation. The two photos in fig. 5 illustrate the situation in post-test ISO9705 room. The wood crib was still in its shape. The pyrolysis boundary is very clear on panel. The boundary implies the crib flame leant toward the wall. Four zones can be seen on the burnt panels. The first is the clear zone (undamaged surface) which keeps its original surface condition and color. Some soot deposited on this zone, but it can be wiped away easily. This zone is labeled as Zone1 in fig. 5(a) and (b). The second is surface pyrolysis zone which is labeled as Zone2 in fig. 5(a) and (b). The panel sur-

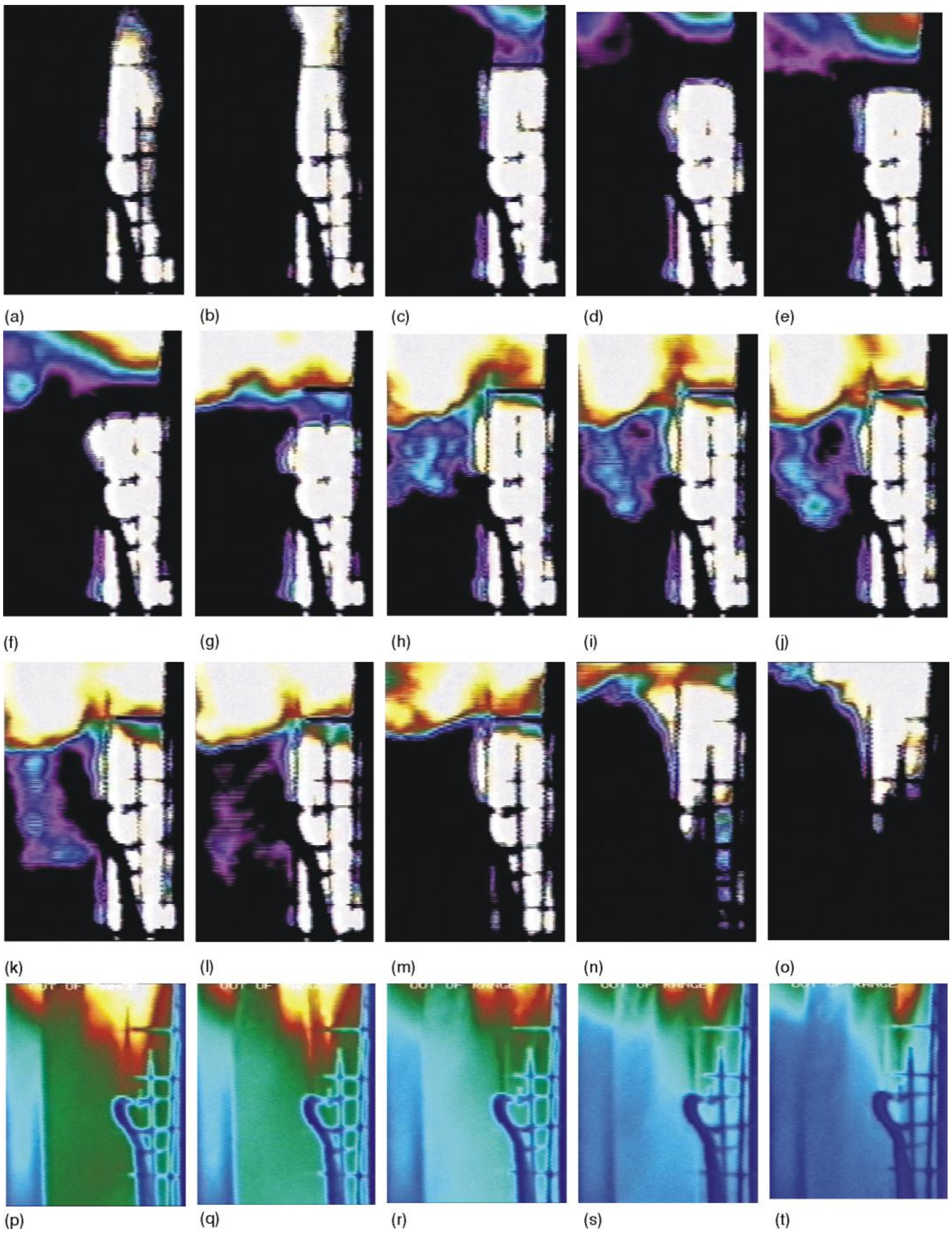

Figure 4. Thermal image serial of fire development inside room (color image see on our web site)

face began to pyrolyze within this zone, and this zone was not acted on by flame but by the hot combustion productions. The third is the deep pyrolysis zone which is labeled as Zone3 in fig. 5(a) and (b). This zone was covered by intermittent flame plume or ceiling jet. Large amount of pyrolysis occurred in this zone. The forth zone was heated by the wood crib flame directly and the GRP panel in this zone pyrolyzed at the beginning of the test. Deep charring layer formed on the surface of panel. This zone is mainly on the wall and ceiling at the corner on which the flame plume acted directly, and labeled as Zone4 in fig. 5(a). Delamination occurred on the edge of panel with Zone4 on it. The panels which have Zone2 to Zone4 on them were replaced by new ones.

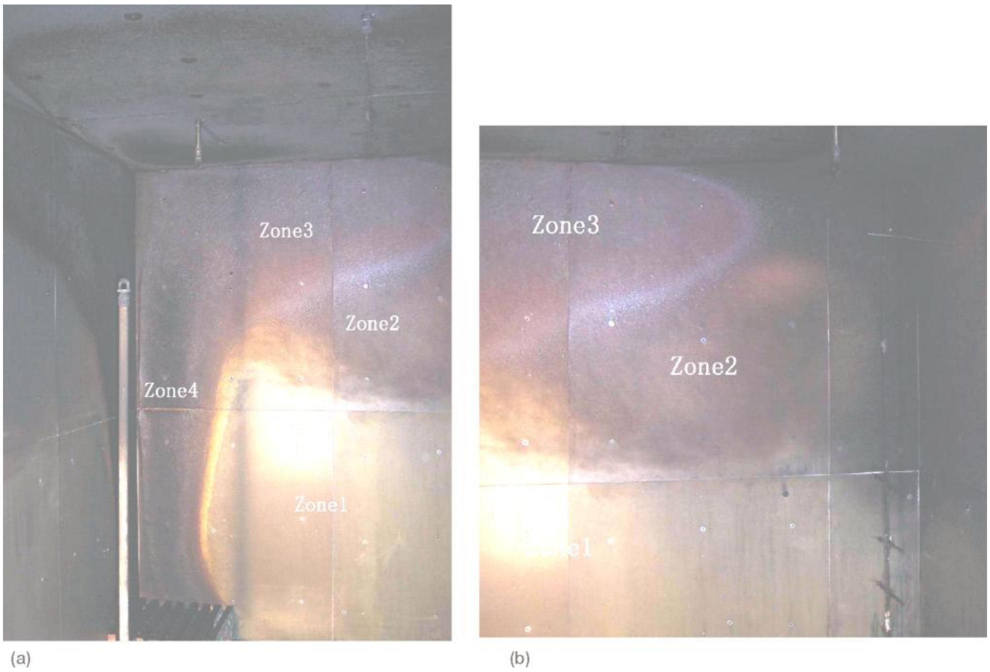

Figure 5. Inside of ISO9705 room post-test. The partly burnt wood cribs can be seen in fig. (a) (color image see on our web site)

Heat release rate

The HRR curves of these three tests are shown in fig. 6. The flashover point is 226 seconds after ignition for Test1, 217 seconds for Test2, and 193 seconds for Test3. The peak HRR is 3030 kW for Test1, 5409 kW for Test2, and 1127 kW for Test3. Mist was discharged shortly after flashover for Test3 at 196 seconds, but a bit delayed for Test1 at 240 seconds and test2 at 243 seconds. The HRR dropt abruptly and reduced to 100 kW at 264 seconds for Test1, 273 seconds for Test2, and 210 seconds for Test3. It took 24 seconds for Test1, 30 seconds for Test2, and 14 seconds for Test3 to suppress flashover in the room. This time is corresponding to the peak HRR, the higher HRR, the longer suppression time.

The burning procedure can be seen from fig. 7 in which the HRR of GRP fire tests were compared with free burning test of wood cribs. The free burning test was conducted inside ISO room without GRP panel installed. The crib had the same structure and weight as those used in GRP tests, and was located at the same place as in GRP tests. Figure 7 illustrates that the initial part of HRR curve of GRP tests was kept along with that of free burning test. But the curves diverge from the free-burning curve in the later part. The divergence point of Test1 is 187 seconds after wood crib ignited, 174 seconds for Test2, and 143 seconds for Test3. It implies that at divergence point a significant amounts of pyrolysis gases were released from the heated GRP panel and begin to burn, and the combustion of pyrolysis gases has contributed remarkably to the total HRR measured inside the room. The more test conducted, the shorter the divergence point, and the shorter time of flashover point. The reason for the tendency might be that not all GRP panels were changed after each test. Only those which were deeply burnt were changed. The unchanged panels underwent one or two times of flashover. Their surface was easier to pyrolysis than that of new panels. Thus, the accumulation of combustible pyrolysis gases has been moved up in later tests, such as Test2 and Test3, and it results in earlier divergence point and flashover in the later tests.

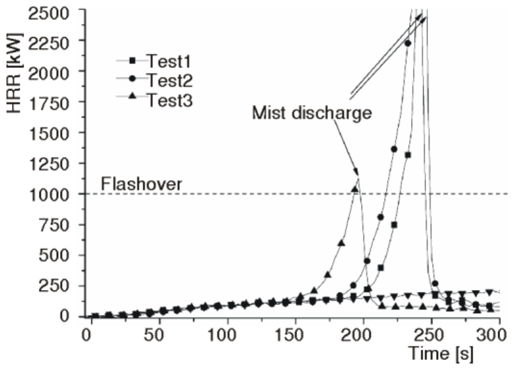

Figure 6. HRR change with water mist suppression

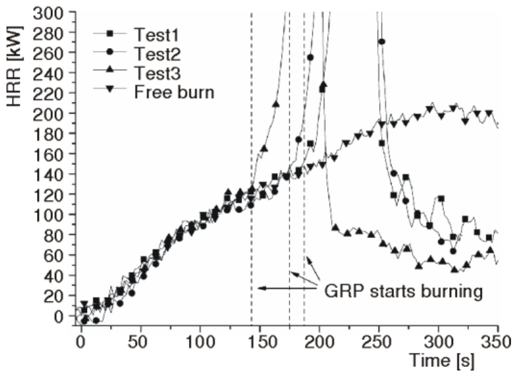

Figure 7. HRR of GRP fire compared with free burning of wood cribs

Room gas temperature

Figure 8 illustrates the change of gas temperature measured by thermocouple tree 2 at the north-east corner of room in Test1. The temperature curves show that gas temperature was divided into two zones before flashover (226 seconds after ignition), and the dividing level was at the height between 1100 mm (thermocouple T25) and 1300 mm (thermocouple T26). After the room fire reached flashover the dividing level began to drop and fall to 700 mm (thermocouple T23) when the mist was discharged. Figure 9 illustrates, in Test1, for the three thermocouple trees, the amount of temperature decrease from the temperature at which mist was discharged to the temperature at which HRR reduced to 100 kW. As shown in fig. 9, the temperature of Tree2 decreased most at the level of 1500 mm (thermocouple

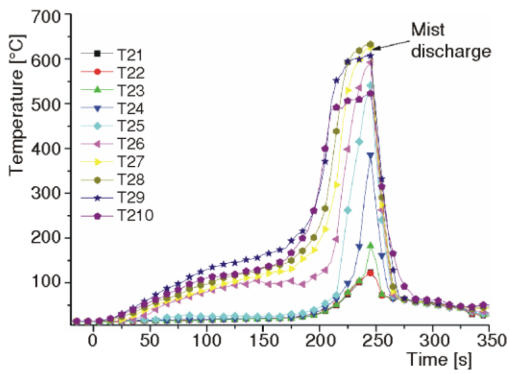

Figure 8. Typical temperature time history in Test1 from north corner thermocouple tree

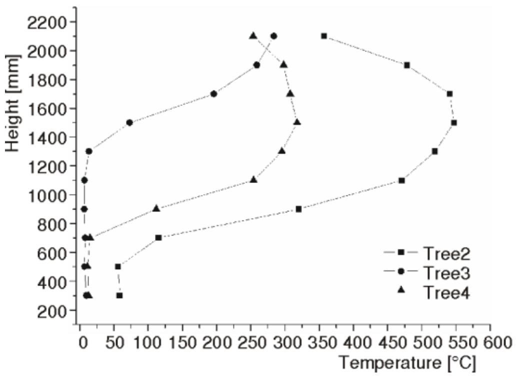

Figure 9. Temperature decrease in Test1

T27), and it is the same for Tree4. This might be caused by the nozzle's spray cone angle. The spray cone is well developed at the plane 800 mm to 1000 mm below the nozzle. Thus the gas temperature below this level decrease more quickly than the gas temperature above the level which is close to the ceiling.

Figure 10 and fig. 11 show the same situation as that in fig. 9. But for Test3, as shown in fig. 11, the mist was discharged just after the time of HRR reached flashover level (196 seconds after ignition), the peak temperatures didn't reach as high as those in Test1 and Test2. Thus the amount of temperature decrease in Test3 was lower than that in Test1 and Test2.

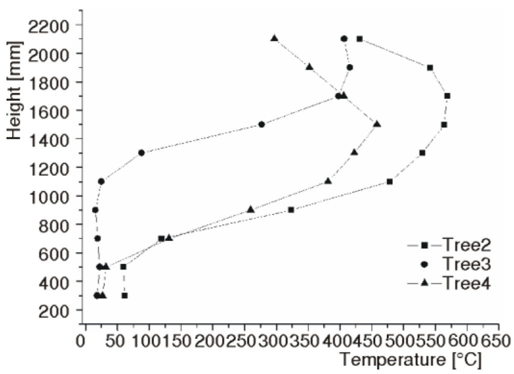

Figure 10. Temperature decrease in Test2

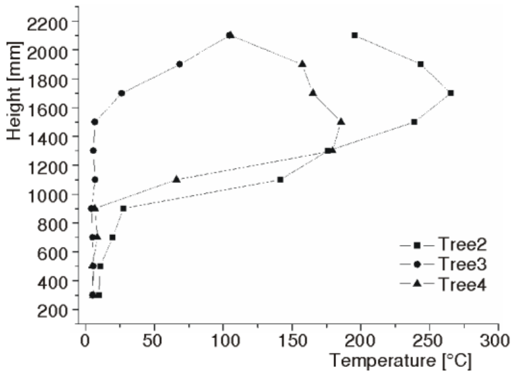

Figure 11. Temperature decrease in Test3

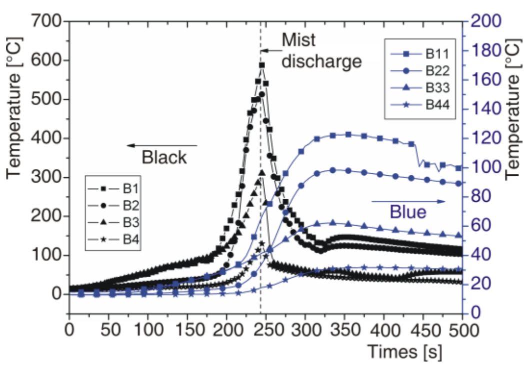

Figure 12. Back wall temperature of Test1 (color image see on our web site)

Wall temperature

Figure 12 illustrates the panel's temperature of inner and outer surface in Test1. These panels are on the back (north) wall. Water mist acted on the inner surface temperature directly and caused temperature reduced to a low level at which the pyrolysis of GRP terminated. This results in lower combustible gas concentration inside room. No more heat was generated to support flashover after mist discharged. Outer surface temperature did not change immediately after water mist discharged and it took a long time to reduce. The same situation happened in Test2 and Test3. Figure 13 illustrates the surface temperature of west wall. The surface temperature of panels on the ceiling is shown in fig. 14. The tendency of temperature development is same as that in fig. 12.

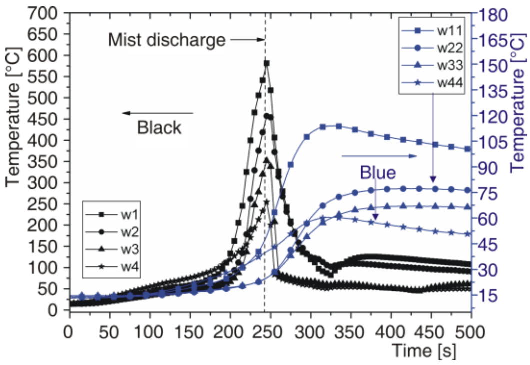

Figure 13. West wall temperature of Test1 (color image see on our web site)

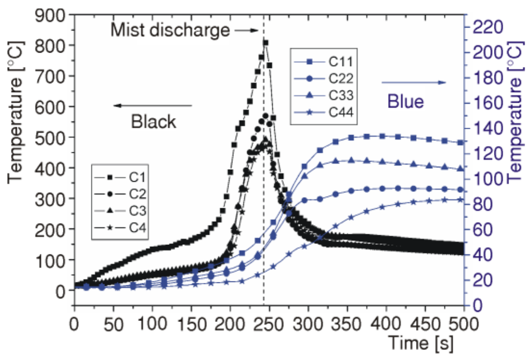

Figure14. Ceiling wall temperature of Test1 (color image see on our web site)

Total heat flux

Figure 15 shows the peak total heat flux to side walls, floor and ceiling in the three tests and the flux when HRR reduced to 100 kW after water mist discharged. R1 to R5 were on the side wall, R6 was on the ceiling, R7 to R9 were on the floor and R10 in the doorway. The figure shows that total heat flux was reduced from 25% to 50% of its peak value after activation of water mist in a very short time. But part of this reduction is caused by water mist cooling the surface of heat flux gages. The contribution of this water cooling effect is not quantified. Only the reduction on R6 could reflect the efficiency of water mist in attenuating heat flux to the ceiling.

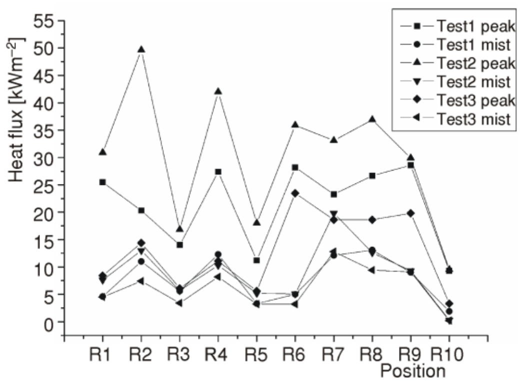

Figure 15. Total heat flux decrease of the three tests

Air concentration inside room

Figures 16, 17, and 18 illustrate oxygen concentration, carbon dioxide concentration, and carbon monoxide concentration inside room, respectively. The upper air sampling probe inserts in the ceiling jet and measures the gas concentration in ceiling jet. In the upper level of the room, for Test1, Test2, and Test3 oxygen concentration dropt to 12%, 8%, and 7.5% in flashover before mist discharge. The upper part of the ISO room was taken by black smoke at that time. But at the same time in the lower level of the room, oxygen concentration kept the normal value. After mist discharge, oxygen concentration increased rapidly in the upper level

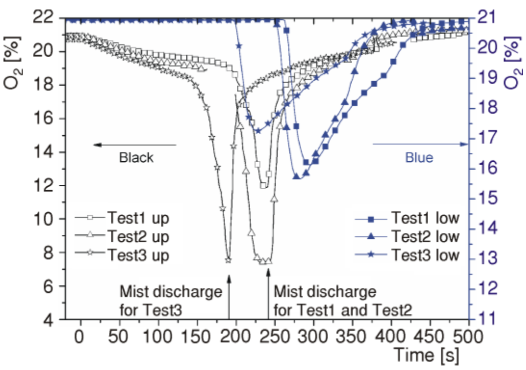

Figure 16. Oxygen concentration inside room (color image see on our web site)

within 20 seconds as the smoke was pushed away by water mist. But it recovered to normal level slowly afterwards because of the dilution effect of mist, as shown in fig. 16.

The carbon dioxide concentration reached 8.1%, 11.9%, and 13.1% in the upper level gas during Test1, Test2, and Test3 just before mist discharge. Mist expelled smoke layer by kinetic effects and mixed with combustion products. The smoke layer was broken up and forced to lower level. This results in dramatic reduction of CO_2 concentration in upper level but an increase of CO_2 concentration in lower level, as shown in fig. 17. This implies the mist can push smoke layer to a low level efficiently. Carbon monoxide concentration illustrates the same situation as carbon dioxide's, as shown in fig. 18.

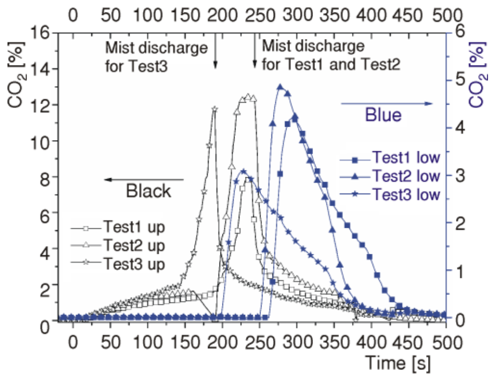

Figure 17. Carbon dioxide concentration inside room (color image see on our web site)

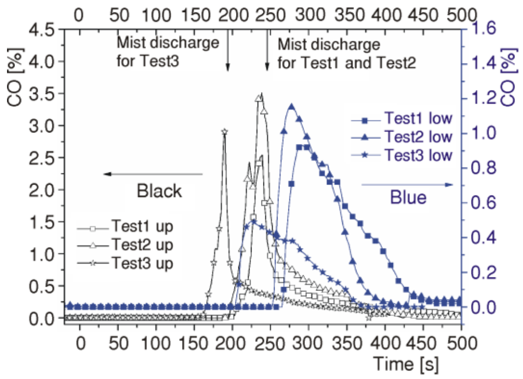

Figure 18. Carbon monoxide concentration inside room (color image see on our web site)

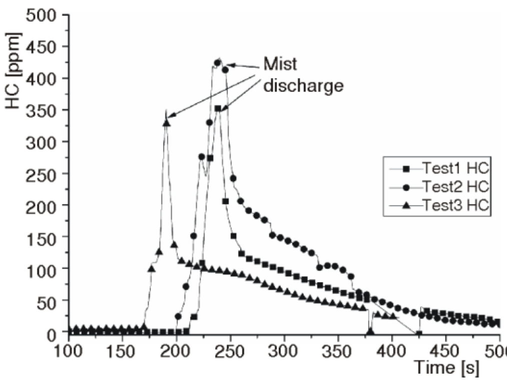

Figure 19. HC concentration inside room

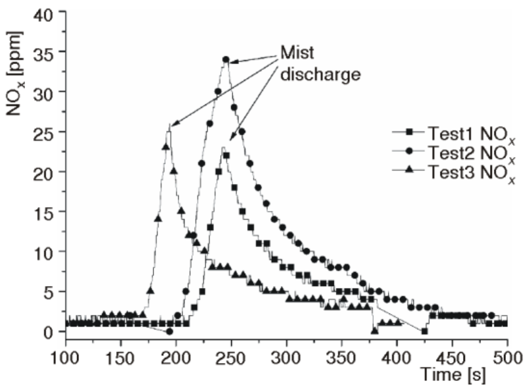

Figure 20. NO_x concentration inside room

HC and NO_x in combustion products of GRP fire are toxic. HC and NO_x concentration was measured at the upper level, as shown in figs. 19 and 20. The concentration was reduced sharply by mist suppression. The cooling of GRP panels by water mist also caused a slower pyrolysis which results in a lower concentration of these two compositions.

Conclusions

The three tests present in this paper imply that the four nozzle arrangement of water mist suppression system is efficient to suppress the flashover caused by burning of GRP panels. The GRP panels have special burning procedure which includes melting, delamination and pyrolysis. Liquid fire, gas fire and even solid fire are all involved in its combustion. Cooling the panels and cutting the heat fed back to them is the efficient way to terminate the combustion chain. Water mist is effective in cooling and combustion products dilution with very low water consumption.

All the mechanisms of water mist extinguishment were effective in the tests. Wetting and cooling of the fuel surface, flammable vapor dilution, and kinetic effects worked more important than other two mechanisms. Direct surface cooling of GRP panel caused the pyrolysis of GRP slow down and this resulted in less combustible products generated. Melting and delamination also slowed down with lower temperature. The flammable vapor generated from the pyrolysis of GRP was not only diluted by mist but also cooled and driven away by mist with rapid jet flow.

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