Assessment of fire protection performance of water mist applied in exhaust ducts for semiconductor fabrication process

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SUMMARY

Fume exhaust pipes used in semiconductor facilities underwent a series of fire tests to evaluate the performance of a water mist system. The parameters considered were the amount of water that the mist nozzles used, the air flow velocity, the fire intensity and the water mist system operating pressure. In order to make a performance comparison, tests were also performed with a standard sprinkler system. The base case served as a reference and applied a single water mist nozzle (100 bar operating pressure, 7.3 l/min water volume flux and 200 μm mean droplet size) installed in the pipe (60 cm in diameter) subjected to a 350°C air flow with an average velocity of 2 m/s. In such a case, the temperature in the hot flow dropped sharply as the water mist nozzle was activated and reached a 60°C saturation point. Under the same operating conditions, four mist nozzles were applied, and made no further contribution to reducing the fire temperature compared with the case using only a single nozzle. Similar fire protection performances to that in the base case were still retained when the exhaust flow velocity increased to 3 m/s and the inlet air temperature was increased to 500°C due to a stronger input fire scenario, respectively. Changing to a water mist system produced a better performance than a standard sprinkler. With regard to the effect of operating pressure of water mist system, a higher operating pressure can have a better performance. The results above indicate that the droplet size in a water-related fire protection system plays a critical role. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: exhaust duct; water mist; fire protection; semiconductor

1. INTRODUCTION

Taiwan has approximately 1000 semiconductor facilities, with their total output value at roughly 20 billion US dollars in 2002 ranking 4th in the world. Its manufacturing procedure uses hundreds of chemicals, some of them evaporate easily and have a wide flammability range [1,2]. Some pyrophoric-like gases ignite spontaneously in air at a temperature below 54°C. The fume

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exhaust duct, used to exhaust these highly flammable gases out of workstations, can be a potential fire source as well as a way to spread fire [3]. In Taiwan two major fires occurred in 1996 and 1997, respectively. Two facilities were totally destroyed and the total loss was approximately 0.5 billion US dollars. One occurred in 1997, after workers used a hot air gun to repair the polypropylene (PP) exhaust duct. Unfortunately, the heat from the repair work ignited the powder residue inside the ducts causing a fire and it then propagated all the way up to the scrubbers, then to the clean room, causing extensive smoke and corrosion damage in the clean room. The clean room was totally ruined. Similar exhaust duct fires occurred in the following years. To reduce this fire risk and to prevent the huge property losses, fire control in exhaust systems became crucial in the fire protection design for semiconductor facilities. The NFPA 318 [4] and FM Global loss prevention data sheet 7-7 [5] suggest several methods of fire control for such ventilation systems. One method is to use a non-combustible pipe or an approved pipe to prevent fires from spreading in the ducts, the other is to use an automatic sprinkler to control the fire and the corresponding heat generation in the ducts. Sprinkler systems need a large amount of water, and it may increase the supporting load on the pipe during operation, possibly leading to huge water damage in the clean room. Nevertheless, the gas extinguishing systems are inadequate for such an open-type situation. Restated, water-based systems are still the best choice if water damage can be controlled. Intuitively, the water mist system was taken into consideration. This system consumes much less water (usually about 1/10 of that in a sprinkler system) and has a higher efficiency [6]. To evaluate the fire protection performance, several field tests were carried out using a water mist system installed in the exhaust ducts. A traditional sprinkler system was also used for comparison.

2. FIELD TEST DESCRIPTION

In the field test, a 24 m long circular exhaust duct with a 60 cm diameter was set up as shown in Figure 1. The test duct was made of polypropylene (PP). These polymeric-like material ducts are adopted by most of the semiconductor facilities [7]. As expected, they are also very common in the corresponding facilities in Taiwan. There was a hood in the inlet for collecting the fire
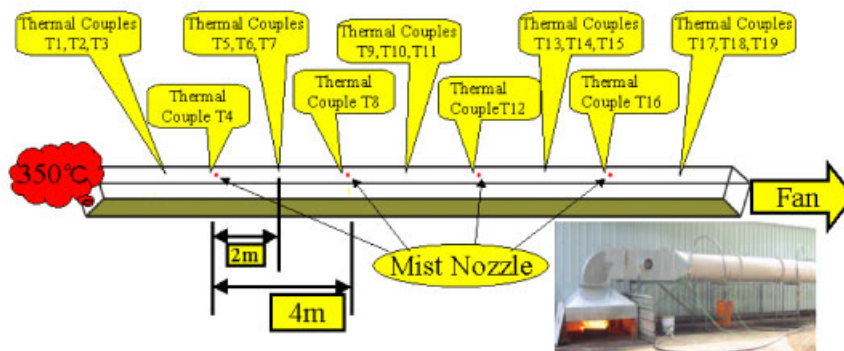

Figure 1. Locations of thermocouples and water mist heads.

generated heat from a gasoline pan. An exhaust fan was installed in the rear to produce the air flow with the velocity range 2–4 m/s, similar to the real exhaust speed adopted in the semiconductor facility. The fire scenario simulated the conditions so that the exhaust duct intake vented the hot flow from a clean room fire.

In this field test, the four mist nozzle system was used to protect the test duct. Their locations were in an arranged line parallel to the pipe's axis-symmetric line and the spacing between two consecutive nozzles was 4 m. The operating pressure for the mist nozzle was 100 bar, the water volume flow rate was 7.3 l/min and the mean droplet size was 200 μm. There were 19 thermal couples installed along the test duct. The thermal couple locations and mist nozzles are illustrated in Figure 1. The measured temperature data were collected by a data receiver every second and recorded simultaneously by a computer. A thermocouple tree, 2 m downstream of each nozzle, with three K-type thermocouples was used to measure the mist-cooled top, middle and bottom temperatures in the duct flow. The inlet temperature was controlled to around 350°C by using a 0.5 m × 0.5 m gasoline-pan fire, regarded as the worst possible case scenario in the clean room [8]. The effective combustion heat of gasoline is $\Delta H_c = 43.7$ kJ/g and the heat release rate (HRR) of a pan fire is about 115 kW [9]. The test procedure is given in Figure 2. The exhaust fan was switched on first to generate an adequate airflow speed for the test, then the pan fire was ignited just after the data receiver was turned on. As the inlet temperature reached around 300°C, i.e. higher than the PP melting temperature, the mist system was activated manually. The data collection was terminated when the fuel burned out.
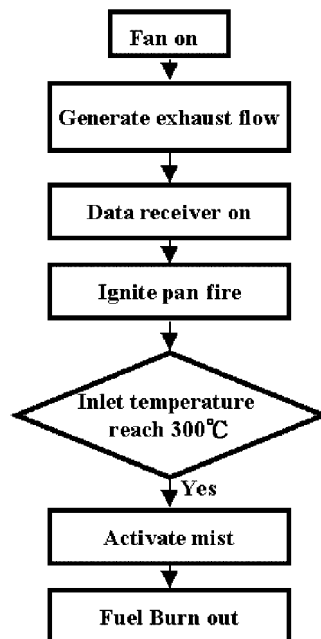
Figure 2. Test procedure.

3. RESULTS AND DISCUSSION

Figure 3 illustrates the temperature history at the inlet and at a position 2 m downstream of the mist head with only a mist nozzle operation. Figure 1 shows the locations of the temperature measurements of T1, T5, T9, T13 and T17. The heat was generated by a fire resulting from 2 l of gasoline in a 0.25 m^2 pan. The exhaust velocity was set to 2 m/s. The mist nozzle was manually activated at 90 s after ignition. After activation, the temperatures at T5, T9, T13 and T17 dropped sharply and eventually reached a constant value of about 60°C after 150 s. The temperature at T1 kept increasing until about 240 s, then, it dropped sharply because the pan fire was burned out. It was apparent that the water mist exhibited a good fire protection performance in the exhaust duct application.

As mentioned above, the effectiveness of fire control was quite satisfactory just by using a single mist nozzle so that the final temperature was kept at a constant 60°C temperature. Could the final temperature be lower than 60°C if more mist nozzles are applied? Figure 4 shows the temperature history at the same locations as those in Figure 3, but with an application of four mist nozzles. Interestingly, the final temperatures did not become lower than expected and the final temperature was still maintained at nearly the same temperature as that in a single mist nozzle operation. The explanation is that the air flow in the exhaust duct became saturated as it went through the mist cloud provided by the first nozzle, then, no further contribution could be made even if more mists were supplied by the downstream nozzles to allow the temperature to decrease further.

The next parameter concerned the flow velocity. Figure 5 shows the temperature history with a single mist operation at a specified exhaust velocity of 3 m/s. Comparing Figure 3 with Figure 5, reveals that temperature differences were not obvious. Closer examination of the two figures indicates that ahead of the mist operation the temperatures of T5, T9, T13 and T17 in Figure 5 exceeded those in Figure 3. This phenomenon is because the heat could be convected faster downstream with a higher exhaust velocity. However, the final stable temperature still
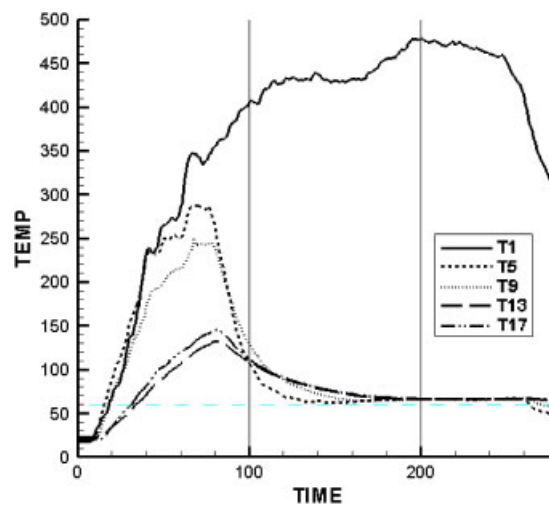

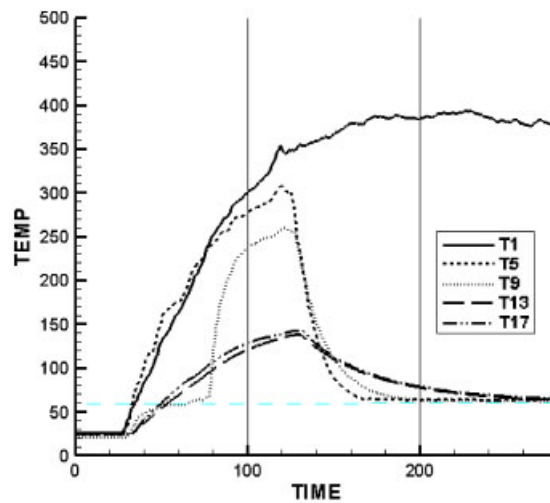Figure 3. Temperature history of single mist nozzle system.

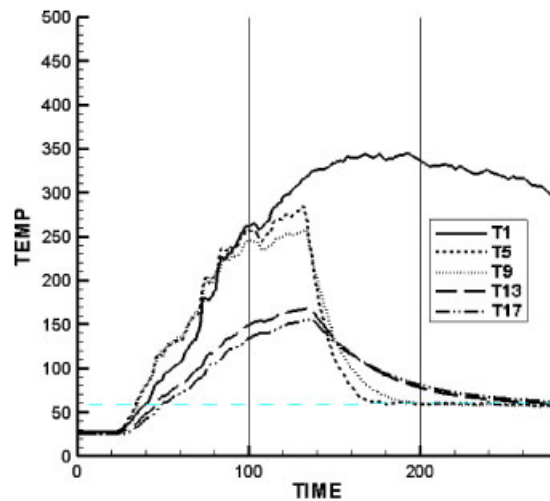Figure 4. Temperature history of four mist nozzle system.

Figure 5. Temperature history of single mist nozzle operating at 3 m/s exhaust velocity.

made no difference, implying that the mist effectiveness was still retained even with a higher exhaust velocity, such as 3 m/s.

Figure 6 shows the results under a stronger input fire, generated by a 0.5 m^2 pan together with three more 0.25 m^2 pans, which are shown on the right hand side of the figure. The total gasoline used was 3.7 l. The inlet temperature rose to 500°C. However, the temperatures still dropped substantially after the mist nozzle activation, indicating that the mist flux generated by a single mist nozzle was still sufficient to control the fire temperature even if the fire intensity was larger.

Figure 7 shows the temperature history under a single sprinkler operation. The sprinkler used was a standard one, whose operating pressure was 1 atm and water flux was 80 l/min. Comparing Figure 7 with Figure 3, revealed that the water mist system appeared to perform better than the sprinkler did. In this figure, the final temperatures for each thermocouple tree after the activation of the sprinkler were over 100°C, whereas the corresponding ones were maintained at more or less 60°C with a single mist operation. Note that the amount of water used in the latter system was only 1/10 of that used in the sprinkler. Why does a sprinkler system
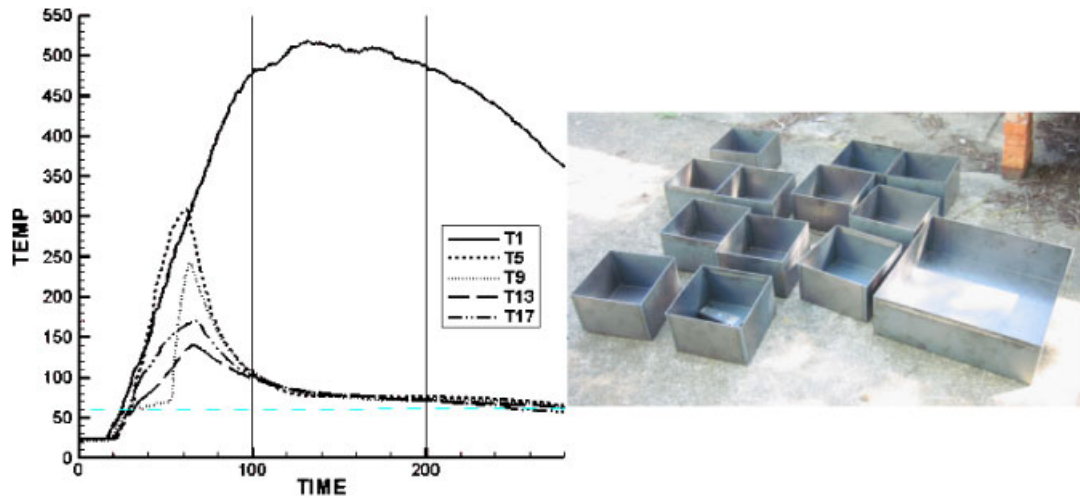

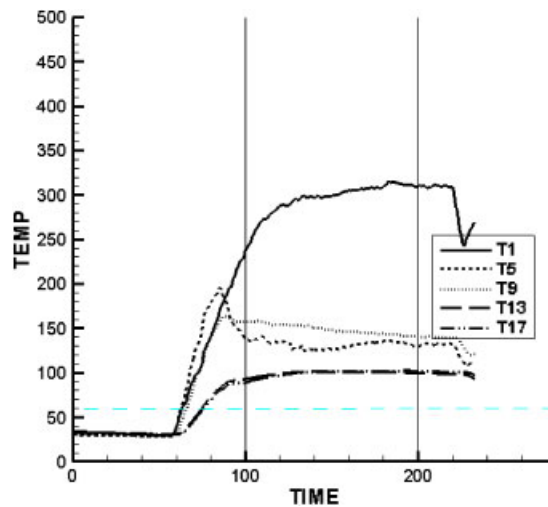Figure 6. Temperature history of single mist nozzle operating with larger fire.

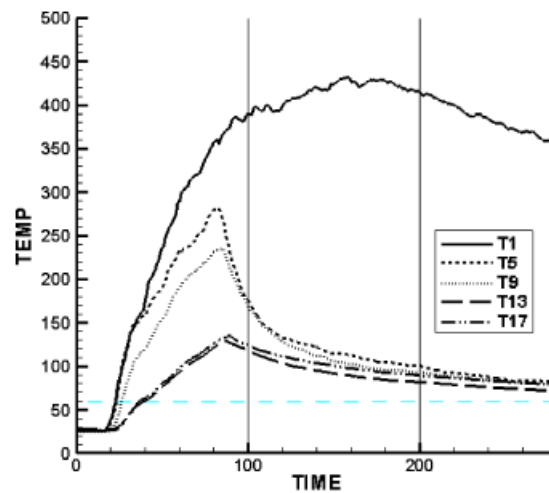Figure 7. Temperature history of single sprinkler.

Figure 8. Temperature history of single medium-pressure mist nozzle.

use more water but have a poorer performance? Of priority concern are the evaporation rate and the interaction with the fire. Inside the test pipe, the traveling distances were the same for both mist and sprinkler droplets. However, it was still too short for sprinkler droplets to evaporate in the hot environment. The sprinkler droplets will directly hit the bottom surface of the duct in about 0.1 s and accumulate to form a pool, which not only is difficult to evaporate but also does not meet the above hot flow to cool it down. The mists may hit the duct surface as well, but they are fine enough so that most of them flow with air and have enough time to evaporate and cool down the air simultaneously. In fact, the evaporating and cooling time is very short. Also, smaller mist-droplets have a much larger surface area/water volume than do sprinkler droplets greatly enhancing both evaporation and cooling rates [10].

Figure 8 illustrates the results using a single medium-pressure mist nozzle. The operating pressure was 16 bar with a water flux of 8 l/min and the mean droplet size was 350 μm. Comparing Figure 8 with Figure 3 reveals that the latter performed better from the view point of the temperature dropping rate and the final stable temperature. These two mist nozzles differ in pressure, water flux and mean droplet size. From the previous comparison with a sprinkler, it is concluded that the droplet size is the dominant factor. Such conclusions are still retained in the comparisons between the high- and medium-pressure mist nozzles. Since the mean droplet size of the medium-pressure mist nozzle is larger than that of a high-pressure nozzle, the evaporation rate is expected to be lower, as is the cooling performance.

4. CONCLUSIONS

A series of fire tests on the fume exhaust pipes used in semiconductor facilities was carried out to evaluate the fire performance of water mist systems. The pipe was 24 m long with a diameter of 0.6 m. The input fire, generated by a gasoline pan, was established in the inlet, and a fan was installed at the other end to provide the required air flow. Four thermocouple trees, each with

three thermocouples, were used to measure the temperatures. The measurements were recorded by a data receiver and a computer. The parameters considered in the fire tests were the number of water mist nozzles applied, air flow velocity, input fire intensity, and use of a standard sprinkler system and a water pressure mist system. The variables for the base case that served as the reference were a single water mist nozzle, whose operating pressure was 100 bar, water volume flux 7.3 l/min and mean droplet size 200 μm, installed inside the pipe under 2 m/s flow velocity, subjected to 350°C inlet hot flow. The experimental results indicated that the temperature in a hot flow dropped sharply as a single water mist nozzle was activated and the final temperature reached 60°C. Under the same operating conditions, the application of more mist nozzles made no further contribution compared with the single nozzle. Similar fire protection performances to the base case were still retained as the exhaust flow velocity increased to 3 m/s and the inlet temperature increased to 500°C due to a stronger input fire scenario, respectively. On changing the water mist system to a standard sprinkler, the former system showed a better performance. A higher operating pressure of the water mist system produced a better performance. From the above test results, it seems that the droplet size in a water-related fire protection system plays an important role.

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