

An Aerosol Generator for Fire Depression - Design Considerations and Experimental Study

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Abstract

A new lightweight gas-particle mixture generator for fire-extinguishing purposes is designed such as to keep the generator and aerosol temperatures low by including a Phase Change Materials (PCM) component. The new generator performances have been studied experimentally and compared to the corresponding performances of a traditional design. The temperature evolution profiles of this gas-particle mixture generator, operating pressure, mass flow rate and the total discharge weight, were characterized experimentally. The re-design, resulted in 30% decrease in the total weight, a significant decrease of the wall operation temperature and also a decrease of the generated aerosol temperature. Therefore, this concept shows a promising alternative.

Keywords: polymer combustion, extinguishing mixture, weight minimization, Phase Change Materials (PCM)

1. Introduction

Gas-particle mixture generators for fire-extinguishing purposes have significant advantages over their counterparts in a wide variety of applications, e.g., in domestics, offices, public places, industrial, transportation and military uses. In a gas-particle mixture generator, the generated mixture is the products of the combustion process of a specific polymer that takes place inside the unit. The combustion is triggered on real time, when the extinguishing mixture is needed. The polymer is energized by an external source, ignites, combusts and generates the gas-particle mixture. As compared to pressurized extinguishing agent, in this method, a pressurized container is not required thus extending shelf-life, reducing container weight, minimizing leakage and safety issues and reducing maintenance routines.

Prior to its activation by an energy input source, the polymer is a stable inert and non-toxic solid. The gas-particle mixture that is generated during its combustion is composed of aerosol of chemical particles and inert gases. The chemical particles suppress the fire by scavenging the hydrogen atoms, oxygen atoms and hydroxide radicals, while the inert gases dilute the oxygen whilst absorbing heat that cools down the media.

Different types of polymers have been developed to enhance the fire suppression effectiveness, polymer stability and to increase water absorption resistance. Among them are the HEAE materials (Highly Effective

Aerosol fire Extinguishing agents) that are composed of oxidizers, fuels and catalyst ingredients. In order to shorten the fire extinguishing time (Z. Yongfeng *et al*, 2006) studied the effect of the initial temperature, density, and the granularity on the burning, thus aerosol generating, rate. They found that the initial temperature has a negligible effect, while lower density and lower raw material granularity (smaller particles) shorten the required extinguishing time. The behavior of fire suppression by using a combined mixture of mist and double-based solid propellant gas generator (A.I. Karpov *et al*, 2013) was studied. The burning products of the solid fuel formed a supersonic flow injected through the nozzle into the diffuser chamber having input for the water component ejected from the storage. High values of temperature and pressure at stagnation point imparted the substantial kinetic energy to the flow, which provided the atomization of water droplets into mist spray. Since the water evaporation occurs already in the diffuser chamber due to the high temperature of input gas flow, the droplet size is gradually decreased to the lower limit value that could ever exist. The presence of vapor phase enlarged the volume of fire extinguishing jet allowing it to operate as a flooding agent (along with the effect of heat consumption due to water evaporation) at the very beginning of fire suppression process, much before the water droplets evaporation by the flame itself. Proposed technique of the water mist production has showed noticeable fire suppression capability through the series of testing application to the gasoline and wood model fire sources. A new type of fire suppressant additive consisting of

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NaHCO₃ nano-particles and solid zeolite particles (X. Ni *et al*, 2009) was developed. The NaHCO₃ nano-particles covered the zeolite matrix with the shell of about 10nm. Their new system showed a superior performance in fire suppression to that of the common dry powders by decreasing the extinguishing time and the amount of the powder consumed. Such an improvement of fire suppression performance could be ascribed to the synergetic effect of solid sodium bicarbonate nano-particles and porous zeolite homogenously that are believed to capture the flame free radicals while keeping the same extinguisher design.

Another gas–solid composite particles generator (X. Ni *et al*, 2011) suitable for extinguishing cooking oil fires has been developed. This powder product was composed of zeolite 13X particles of diameter 1–2 mm and absorbed 2-bromo-3,3,3- trifluoropropene. The performance and possible mechanism in extinguishing cooking oil fires have been investigated with full-scale burning tests. Their extinguisher was compared to some different dry powder designs. Results indicated that the new composite particles have better performance in extinguishing cooking oil fires. Relatively shorter extinguishing time was achieved with smaller amount of agents without any re-ignition. They concluded that the new composite particles give better performance because of highly efficient free flame radical scavengers, improved cooling capacity, and their hydrophobic and oleophobic surface.

Examination of the minimum extinguishing concentrations (O.P. Korobeinichev *et al*, 2012) of mixtures of organo-phosphorus and iodine-containing compounds and inert diluents was experimentally studied. The tests demonstrated that short-term action of an aerosol cloud of an aqueous solution of potassium ferrocyanide K₃[Fe(CN)₆] on the flame front of a surface forest fire led to suppression of gas-phase combustion, and in the case of wood burning, to complete flame extinction. The minimum extinguishing mass concentration of K₃[Fe(CN)₆] in these experiments was 4.5g/m³. In fire suppression by the aerosol, the volumetric flow rate of this fire suppressant was found to be 30 times lower than the standard flow rate of pure water from a fire hose.

Most of the work done in this area investigates the change in ingredients components of the polymer or the extraction method to the fire area, producing smaller particle or droplets with higher surface area to the fire media. The influence of these parameters upon the fire suppression capability and efficiency has been investigated. To the best of our knowledge almost no work has been published on the design and operating characteristics of the generator itself. The present paper addresses the in-extinguisher design in an attempt to reduce its weight by using Phase-Change-Materials.

2. Experimental

A typical commercial unit is shown in figure 1. It comprises case, combustion chamber, flame arrestors to avoid downstream flame spread, heat exchanger to cool down the aerosol to the required temperature, and a

discharge orifice. Since the burning rate of the polymer depends solely on the pressure (which is practically constant during the entire combustion process), the mass flow rate of the generated fire extinguishing agent depends solely on the burning surface area. The total surface area of the polymer ensures that 200 g of the solid fuel (polymer) will burn completely in 30 s. The polymer geometry has been designed by the manufacturer such that the surface area during a wide time interval of its burning process is fairly constant, and therefore the mass flow rate of the combustion products (the fire extinguishing agent) is constant in time. Trial and error studies have led to a fine tuning of the design. The discharged mass of the polymer is thus proportional to the time elapsed from the process initiation. Temperatures at some discrete locations (shown in figure 1) were recorded vs. time, from which the mixture temperature profile and the unit walls temperature are estimated.

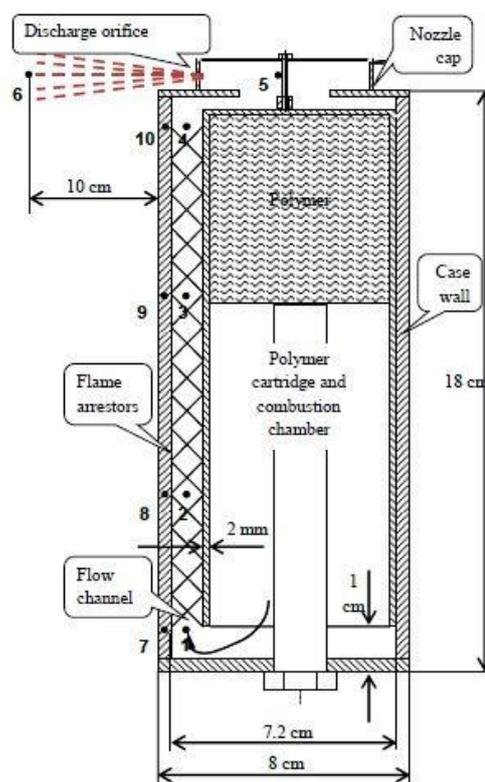


Fig 1: Cross-section of the unit and thermocouples locations

Ten K-type thermocouples compatible up to 1,250 °C were used (1-10). Four of them (1-4) in the flow channel center, 5mm from each wall, each at the same level as the corresponding wall thermocouple (7-10), i.e., at the heat-exchanger entrance (combustion output), heat-exchanger 1/3 and 2/3 way downstream, and at the heat-exchanger uppermost location. The wall thermocouples were located at the wall mid-width, 2 mm deep. The fifth thermocouple (5) was located prior to the discharge orifice, and the sixth one (6) outside the unit to measure the products temperature at 10 cm downstream. Figure 2 shows a snapshot of the unit installed with the thermocouples.



Fig 2: The unit installed with the thermocouples and pressure transducer

The thermocouples were made by butt welding 0.25 mm diameter wires and were calibrated and connected to bench-link data logger. According to the thermocouples manufacturer ("Omega") the response time is 0.2 s. The pressure was measured with a "Kistler" pressure transducer with 4 bar maximum pressure range. At the end of the process, a standard water-bath calorimeter was used to estimate the heat absorbed by the unit walls during the entire process. The experiment was repeated several times to validate the results, the process repeatability and the results reliability.

The design of the Phase Change Material (PCM) generator is based on the same construction as shown in figure 1, while the case walls are replaced by double thin walls that enclose the desired amount of the PCM material. A top-view cross section is shown in figure 3. Crystalline powder (white crystalline solid) of hydrated-salt magnesium sulfate ($MgSO_4$) has been selected as the PCM material for its suitable adjustable melting temperature, melting heat capacity, and for its nonflammable and non-toxic properties [6-9]. The specific salt hydration degree yielded the specific properties as summarized in table 1.

In the present device 200 g polymer is used. According to the polymer data, during combustion it releases 568 kJ. In order to reduce the generator weight while keeping a similar temperature for the generated mixture, we used the same design for the internal combustion compartment, flame arrestors locations, discharge orifice and total flow path, while replacing the outer shell of the case by two thin walls separated by a gap (Fig. 3). The formed compartment has been filled with 300 g PCM. In this arrangement we kept the same internal structure design while ensuring a minimal wall thickness for safety reasons. We notice that the time required for the thermal wave to propagate through the gap width is $\Delta t \approx \frac{\delta^2}{4\alpha} \sim 30$ s, which is roughly the complete burning time of the solid fuel (polymer) [9-10]. Here, t , δ and α denotes for time, penetration depth and thermal diffusivity, accordingly.

Since we used the same internal structure design we should expect similar operation time and internal pressure. Similar to the tests with the traditional can, the temperature of the discharged products 10 cm downstream (point #6 at figure 1) and the external wall temperature at the hottest spot (point #8 at figure 1) were measured.

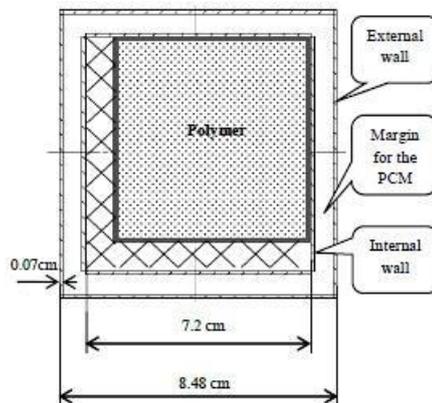


Fig 3: The PCM generator top-view cross section

Table 1: Properties of the PCM and the metal case

PCM		
Melting Temperature	106	°C
Heat of Fusion	220	kJ/kg
Specific Heat	2.1	kJ/kg-K
Density	1,500	kg/m ³
Thermal Diffusivity	$0.22 \cdot 10^{-6}$	m ² /s
Total Mass	0.3	kg
Carbon Steel Case		
Specific Heat	0.45	kJ/kg-K
Density	7,600	kg/m ³
Total Mass (PCM Generator)	1.7	kg
Total Mass (Traditional Generator)	2.85	kg

3. Results

3.1 Traditional Design

In the current unit, the gas-particles mixture (the combustion products of the polymer) flows through a duct that is located between the combustion chamber and the case carbon steel walls. While flowing, the hot gas-particles mixture (the polymer products of combustion) exchanges heat with the cold steel walls. The total mass of steel is 2.85 kg such that its total heat capacity is sufficient to absorb the required amount of thermal energy (maintaining an average aerosol temperature below 200 °C) whilst keeping the steel raising temperature during the discharge process below 400 °C. Figure 4 shows the temperature evolution of the gas-particles mixture at six points, #1-#6 as indicated in the scheme shown in figure 1.

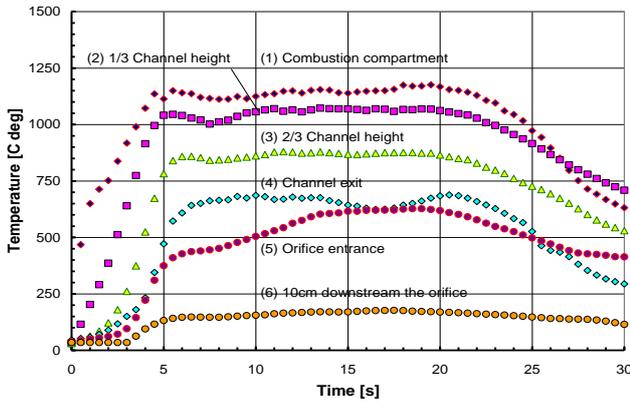


Fig 4: Temperature evolution of the gas-particle mixture

It shows that when leaving the combustion compartment (#1), the temperature of the gas-particle mixture is rather above 1,100 °C for the first 23 s, and then it gradually declines till quenching. While flowing through the duct, the gas-particle mixture loses its thermal energy to the duct walls such that the temperature prior to discharging (#5) is around 600 °C and as a result of mixing with the free surrounding air, it leaves the unit (#6) at a temperature fairly below 200 °C.

Figure 5 shows the temperature recordings of the unit walls at four downstream locations as indicated in figure 1. It seems that for the highest temperature measured, at the unit's 1/3 channel height (#8), the steel temperature is well kept below 400 °C. Figure 6 shows the pressure recording inside the combustion compartment during the whole process. It shows that except for the first 6 s, the pressure inside the unit remains fairly constant at a value of 101 kPa (1 kPa above the atmospheric pressure).

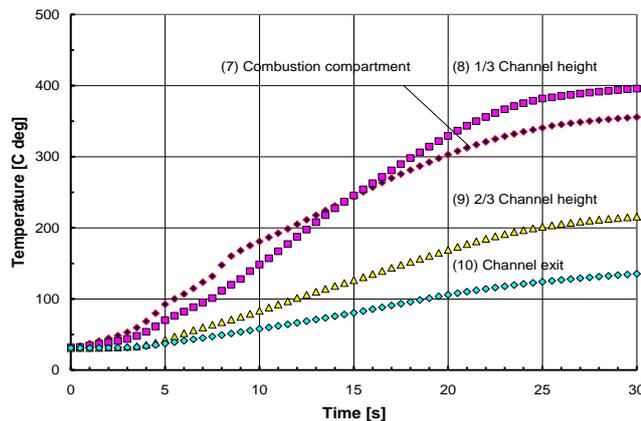


Fig 5: Temperature evolution of the unit walls

During combustion, the polymer releases 568 kJ. Calorimetric measurements at the end of the process show that the total absorbed energy in the unit is 472 kJ, suggesting that the thermal energy of the particle gas mixture is 96 kJ.

3.2 PCM Design

Figure 7 compares the temperature evolution profiles at points #6 and #8. Similar to the traditional design, the

thermocouples were located at the wall mid-width in this case, 0.3mm deep.

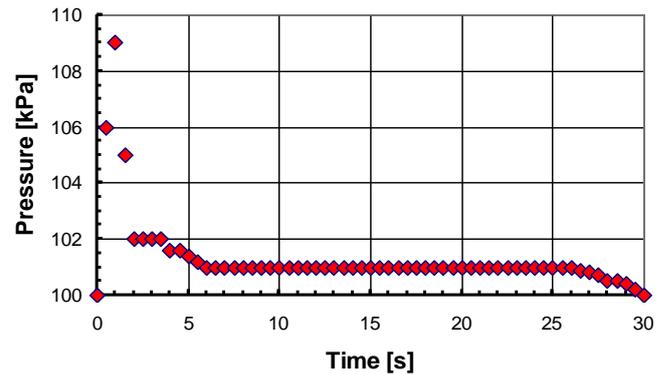


Fig 6: Pressure variation inside the unit

The effect of the new design is rather impressive; the wall maximum temperature at point #6 has been drastically reduced from about 400 °C to below 100 °C, while the aerosol temperature 10 cm downstream the orifice has been reduced from 170 °C to 120 °C. These were achieved along with a significant weight reduction of the complete gas-particle mixture generator from 3,050 g (2,850 g of the carbon steel case + 200 g of the polymer) down to 2,200 g (1,700 g of the carbon steel case + 300 g PCM + 200 g of the polymer).

4. Conclusions and Final Remarks

A new lightweight gas-particle mixture generator for fire-extinguishing purposes has been designed. The unit incorporates a Phase Change Materials (PCM) component to keep the generator and aerosol temperatures low. The new generator performances have been studied experimentally and compared to the corresponding performances of a traditional design. It is expected to have a positive effect on the fire suppression capability due to the temperature decrease of the generated extinguishing mixture. A significant weight reduction of the complete gas-particle mixture generator from 3,050 g down to 2,200 g has been achieved.

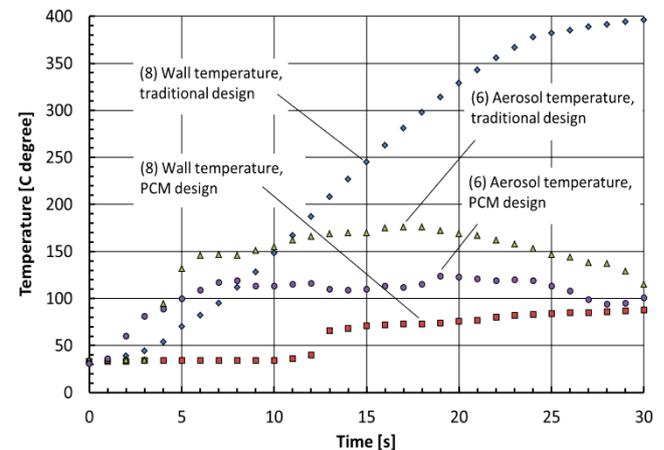


Fig 7: Wall and aerosol temperatures for the traditional and PCM designs

Acknowledgments

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