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Research paper

Novel kaolinite based coolant for hyperthermal pyrotechnic aerosol cooling

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ABSTRACT

Novel spherical pyrotechnic aerosol cooling granulates which are made of 42.8% kaolinite powder, 38.8% water, 8.1% epoxy A&B glue and 10.2% ethyl cellulose are successfully synthesized and can cool down the temperature of hot pyrotechnic aerosol from 1400 to 400 °C below with only a 1:1 mass ratio of coolant to the aerosol forming agent. The cooling system is a packing bed randomly stacked with 5 mm diameter cooling granulates. The kaolinite based cooling granulate has proper yield stress to provide the cooling bed a constant porosity in order to avoid any tunneling effect and granulate structural failure during hot aerosol cooling. Moreover, the synthesis process of current novel kaolinite based granulate coolant is simple and economic. Compared to other coolants like irregular granite gravels or ceramic intalox used for pyrotechnic aerosol cooling, the cooling performance of spherical kaolinite based cooling granulates is superior.

Nomenclature

Symbol	Definition	SI unit
D_p	equivalent diameter of the packing granulate	m
H	height	m
L	length	m
Cp_{Ae}	heat capacity of hot aerosol	J/g·K
Cp_c	heat capacity of coolant	J/g·K
Q(t)	volumetric flow rate of hot aerosol	m^3/s
R_{AB}	mass ratio of epoxy A&B binder	–
R_{KW}	mass ratio of kaolinite/water	–
R_w	mass ratio of water	–
R_K	mass ratio of kaolinite	–
T	temperature	K
V_e	superficial velocity	m/s
W_a	water activity	–
Y	kaolinite based clay yield stress	KPa
μ	fluid dynamic viscosity	Pa·s
ρ_c	density of coolant	kg/m^3
ρ_{Ae}	density of hot aerosol	kg/m^3
Φ_o	outer diameter	m
φ_i	inner diameter	m

1. Introduction

Pyrotechnic aerosol fire suppressing technology which was derived from solid rocket fuel science (Guo and Yue, 2008) was firstly introduced and developed since 1960s. As the problem of ozone depletion caused by Halon extinguishing agents which contain bromofluoroalkanes (Andrzej and Tsang, 1997), many countries joined the Montreal Protocol which announced the protective actions for ozone layer in 1987, and such act promoted the phase out movement of Halon extinguishants. Pyrotechnic aerosol extinguishing agents have a good efficiency in fire extinguishing and they do not need to be stored in a pressurized container since they do not need to be driven out by pressurized inert gases. But pyrotechnic aerosol of high temperature is produced during fire suppression and the temperature of such hot aerosol can reach 1200 K above measured near the extinguisher nozzle (Zhu et al., 2015), so the very hot pyrotechnic aerosol may bring potential risk of secondary fire. Coolants must be installed in the canister together with the aerosol forming agent (AFA). Currently, there are two typical ways to place coolants. One is to mix coolants with AFA powders (Qiao et al., 2001) and such method is barely adopted (Hu, 2003), and the other way is to place perforated metal plates, a beehive-like coolant block or coolant granulates in the space between the AFA and an extinguisher nozzle. Cooling mechanism can be either physical or chemical or both. Physical cooling is based on heat absorption by perforated metal plates, metal bars (usually copper bars) or ceramics and physical cooling efficiency is relatively low (Song, 2003). Moreover,

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Table 1
Hot aerosol extinguisher coolant.

	Physical	Chemical
Component	Metal bars, balls or perforated metal plates, ceramics	Urea, aluminum hydroxide powders, marbles, synthesized materials, etc.
Cooling mechanism	Heat capacity	Phase change and decompose
Placement	Between AFA and extinguisher nozzle	Between AFA and extinguisher nozzle or mixed with AFA
Performance	Average	Remarkable (Zhang et al., 2006)

metal coolants are unstable since they will be corroded and deteriorate with time. Chemical cooling involves the decompose and phase change of coolants, which adsorbs a large amount of heat, and those coolants can be simple natural materials like natural minerals or simple chemicals like urea or aluminum hydroxide (Qiao et al., 2001) or synthesized composites which are thermally unstable. See Table 1.

Silicate mineral like kaolinite is cheap, structurally stable and can absorb huge heat by dehydration and evaporation of its interlayer water during cooling process. Chemical formula of kaolinite is $Al_2Si_2O_5(OH)_4$ and it begins to lose absorbed (110 °C), interlayer (110– 400 °C) and constitutional water (450– 580 °C) in a wide temperature range (Yuan and Xia, 1997; Insley and Ewell, 1935).

The purpose of this study is to synthesize a cheap material based on kaolinite for hot aerosol cooling, and it is interesting and important to find a cheap and efficient material for pyrotechnic fire extinguishing aerosol cooling. So far, there has not been any kaolinite based coolant used for hot pyrotechnic aerosol cooling.

2. Materials and methods

2.1. Chemicals and materials

AFA (synthesized by authors), kaolinite powders (Jing Rui Chemical Co. Ltd., China), aluminum nitride (Gao Ye Technology Co. Ltd., China), montmorillonite powder (Thermal Fisher Scientific), epoxy P-201A and P-201B (Pengcheng Glue, China), ethyl cellulose (Essex, UK), ceramic intalox (Chen Da Chemical Packing Co. Ltd., China), granite granulates (Pyrogen Sdn Bhd, Malaysia), oven (Jing Hong Laboratory Instruments Co. Ltd., China), muffel furnace (Cotel Precision Industries Sdn Bhd, Malaysia), HK-88A pill making machine (Xu Lang Machinery Co. Ltd., China), Instron 3382 Floor Model Universal Testing System (Instron, US), water activity analyzer (Decagon Devices Inc., US), thermal resistivity and diffusivity analyzer (Decagon Devices Inc., US) and WRB-thermocouple (Feilong Instrument Technology Co. Ltd., China).

2.2. Pyrotechnic aerosol generation

The pyrotechnic aerosol is generated by an AFA which is mainly composed of strontium nitrate (Zhang et al., 2014). The AFA is weighted 100 g and it is a cylindrical block which is perforated with a hole at the central (See Table 2). During aerosol generation, the block is placed in a steel canister mounted on an iron rack and ignited by an electrical fuse inserted into the central perforated hole. The nozzle of the canister is a multiple-hole perforated steel cap and the holes are in a circular array. During aerosol generation, the probe of a WRB-thermocouple was fixed 10 mm away from the nozzle to record the aerosol temperature.

Table 2
Dimensions and mass of reaction canister and AFA block.

	Φ_o (mm)	φ_i (mm)	L (mm)	Mass (g)
Canister	63.45	59.40	123.7	277
AFA	59.40	15	30	100

The combustion formula of AFA is listed below:

$$\begin{aligned} &x\,KNO_3(s) + y\,Sr(NO_3)_2(s) + \left(\frac{5x+10y+2b-48a}{2}\right)Mg\,(s) + a\,C_{12}H_{22}O_{11}\cdot H_2O\,(s) \\ &+b\,NH_4NO_3(s) \xrightarrow{\Delta} \frac{x}{2}K_2CO_3(s) + y\,SrCO_3(s) + \left(\frac{5x+10y+2b-48a}{2}\right)MgO\,(s) \\ &+\left(\frac{x}{2}+y+b\right)N_2(g) + \left(12a-\frac{x}{2}-y\right)CO_2(g) + (12a+2b)\,H_2O\,(l) \end{aligned} \tag{1}$$

2.3. Kaolinite based coolant clay yield stress and water activity

Clays composed of kaolinite powder, water and epoxy A&B glue of different compositions were prepared by manual mixing and pressing in a ceramic mortar. Then the clays were transferred into steel canisters and put in an oven under 50 °C for 3 h solidification/drying. After solidification in the oven, Clays were taken out and subsequently cooled under room temperature for further 24 h. The yield stresses of solidified coolant composites were measured by Instron 3382 Floor Model Universal Testing System and the testing method is referred to ASTM D695-10: "Compression Testing of Composites" standard. The water activities of coolant composites were measured by a water activity analyzer. The coolant clay which gave a high yield stress and low water activity was selected for subsequent coolant conductivity study.

2.4. Kaolinite based coolant clay thermal conductivity study

Montmorillonite and aluminum nitride (aluminum nitride was pretreated under 800 °C in muffle furnace for 8 h) powders were mixed with kaolinite powder, water, epoxy A&B glue to form new clays of different compositions according to Minitab simplex centroid mixing design. The clays were transferred into steel canisters and put in an oven under 50 °C for 3 h solidification/drying later. The thermal conductivity of solidified clay was measured by a thermal conductivity and diffusivity analyzer. The clay composition which has a proper thermal conductivity was finally selected as the composition of granulate coolant. In Mini-tab simplex centroid design, kaolinite, water and epoxy AB binder were combined as one variable as mass ratio ranges from 0.65 to 1.00. The mass ratio of thermally treated aluminum nitride or montmorillonite ranges from 0 to 0.35.

2.5. Kaolinite based coolant granulates preparation

A pill maker machine was used to make coolant clay into granulates. Firstly, a bulk lump of coolant clay was flattened and then sliced by the pill maker machine (see Fig. 1), and later the slices were cut into short irregular granulates through a granulating slot. Finally, the irregular granulates were sanded into small spherical balls in a water chestnut shape roller and then the spherical coolant granulates were solidified/dried under 50 °C for 3 h in an oven and subsequently kept under room temperature for at least three days.

2.6. Kaolinite based coolant packing bed

The packing pattern of spherical kaolinite coolants inside the steel canister is a random stacking (see Fig. 2) mode. The packing bed length, packing porosity and packing coolant granulate radius were determined according to Ergun equation (see Eq. (2)) in previous research in order to maintain a pressure drop $\Delta P(t) < 2$ bar across the coolant packing bed. The combustion time of 100 g AFA is 16.5 s as recorded by a stopwatch.

$$\Delta P(t)_{in} = \frac{150\mu(1-\varepsilon)^2 V_e L}{\varepsilon^3 D_p^2} + \frac{1.75(1-\varepsilon)\rho V_e^2 L}{\varepsilon^3 D_p} \tag{2}$$