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# Heat exchanger based on paraffin/expanded graphite composites for breathing air cooling in fire

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**Abstract.** The enormous amount of heat in fires can push inhalation temperature to ~500 K, which is fatal to the civilians. However, conventional rescue respirators are unable to control the breathing air temperature. In this work, we utilized paraffin/expanded graphite (EG) composites to construct a heat exchanger for breathing air cooling. The material itself can be used as the mechanical support, the heat spreader and the heat absorber at the same time. The composites of 0~35 wt% EG were prepared and characterized. The results showed the paraffin was uniformly absorbed in the porous structures of EG. And the paraffin/EG composite with 25 wt% EG has better performance both in simulation and experiment. The heat exchanger constructed by this composite shows good cooling efficiency by cooling the inlet air from 500 K to a breathable 313 K and sustaining for more than 20 minutes.

## 1. Introduction

In the fires and explosion disasters, the ambient air temperature tends to be heated to an extreme level that can cause inhalation thermal injury and even death. In these situations, inhalation injury is the most fatal cause of death rather than skin burns [1-2]. However, conventional self-rescue respirators are unable to control the gas temperature. Therefore, many researchers made efforts to solve such a problem by designing different kinds of cooling modules [3-5]. For example, Hughes et al. suggested a four-level design [5], composed of a heat exchanger, a thermoelectric module, a layer of capsuled phase-change materials and a chamber vented by a fan. However, it has low efficiency due to the multi-level design and requiring an external power supply, which is inconvenient, expensive and unsafe.

Recently, we noticed the advances of phase change materials (PCMs), especially the paraffin/EG composites [6-8], which are easy to prepare, cheap and lightweight. In this work, we utilized the paraffin/EG composites to construct a heat exchanger. In these composites, the paraffin can absorb a large amount of heat in the phase transition process. The 3D porous structure of EG provides a vessel to constrain the liquid paraffin by capillary effect and also promises to form 3D networks for thermal transfer. Thus, the screen criteria for optimum compositing ratio are low phase-change leakage, sufficient thermal conductivity and high latent heat.

## 2. Methodology

### 2.1 Preparation of paraffin/EG composites.

Commercial expandable graphite powders (mesh 150, from Herita Graphite Products Co., Ltd, China) were dried in a vacuum oven at 100 °C for 24 hours. Then the dried powders were heat treated in a



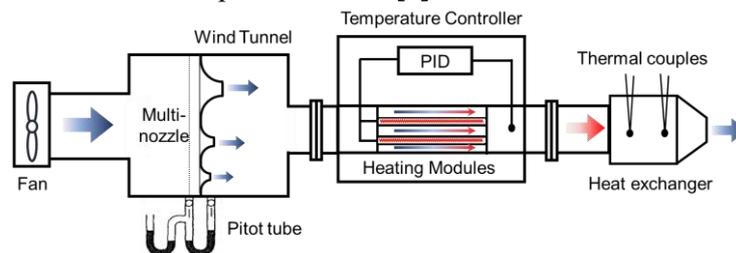
muffle furnace (900 °C, 30 seconds) for the expansion to take place. The paraffin (99.99%, Ruhrtech, China) was liquefied at 75 °C before it was impregnated into the EG powders (75 °C, 1 hour). The as-obtained paraffin/EG mixture was afterwards filtered and press moulded to a sheet at room temperature. A series of paraffin/EG composites with different EG mass fractions were prepared.

## 2.2 Characterizations of paraffin/EG composites

The microstructures of materials were observed by scanning electron microscope (SEM, ZEISS Meilin, Germany). The latent heat capacity was measured by differential scanning calorimetry (DSC, Mettler Toledo DSC3, Switzerland). The DSC measurements were performed from 20 °C to 70 °C at a heating rate of 5 °C/min in nitrogen atmosphere. The through-plane thermal conductivities were measured by LW-9389 TIM Tester (Longwin, Taiwan), while the in-plane thermal conductivities were measured by LFA 447 based on laser flash method (NETZSCH, Germany).

## 2.3 Cooling efficiency analysis of heat exchanger

The cooling efficiency of the heat exchanger was analyzed by LW-9081-60 wind tunnel (Longwin, Taiwan) equipped with a homemade heating module. The inlet air was heated to 500 K and the flux was 20 Liter per minute (LPM). Several thermal couples were embedded into different positions of the heat exchanger for real-time temperature measurement. Figure 1 gives the system schematic. Simulations on the performance of the heat exchanger was carried out by the commercial CFD solver, ANSYS-FLUENT. An adiabatic boundary condition was applied in the outside wall of the module. Other simulation details are the same as our previous work [9].



**Figure 1.** Schematic of cooling efficiency analysis system

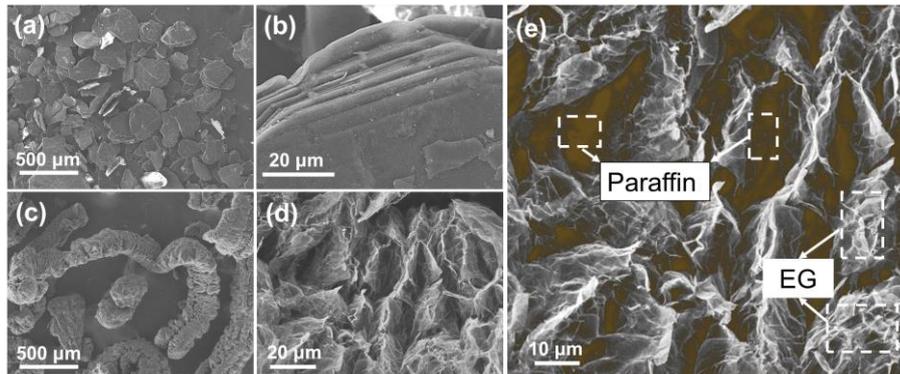
## 3. Findings

### 3.1 Characterizations of paraffin/EG composites

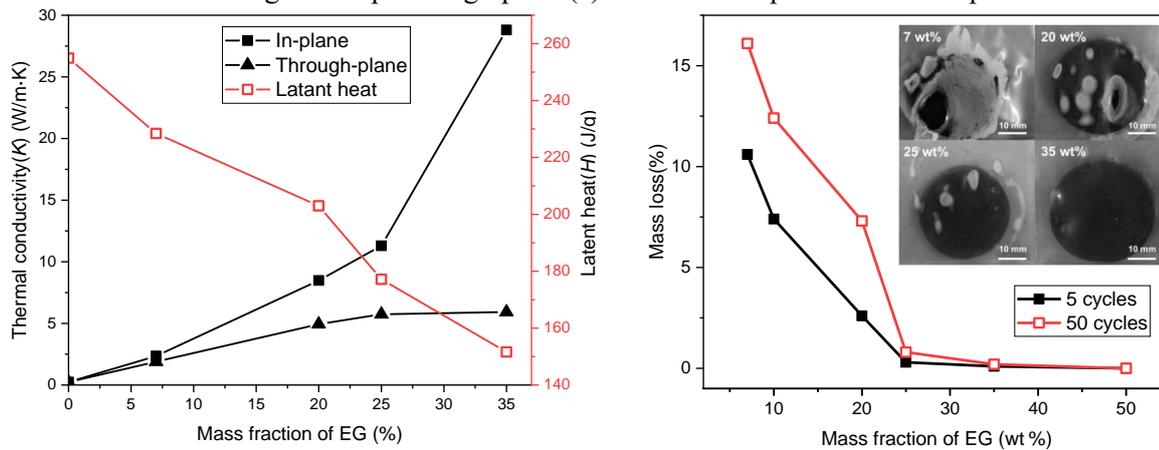
**3.1.1 Microstructure of the paraffin/EG composites.** Figure 2 a-d shows the SEM micrographs of the raw expandable graphite and expanded graphite. It can be clearly seen from Figure 2a-b that the expandable graphite powders are of flake configuration; whereas Figure 2c-d shows that the expanded graphite powders turn to a worm-like structures. In the enlarged view (Figure 2d), a wealth of porous structure can be seen clearly. This kind of porous structure can provide a vessel to constrain the liquid paraffin by capillary effect. Figure 2e shows the schematic of paraffin/EG composites: the expanded graphite (white areas) provides the supporting framework and the 3D heat transfer network, while the paraffin (dark brown areas) fills all the pores inbetween.

**3.1.2 The tradeoff between thermal conductivity and latent heat.** In practice, thermal conductivity ( $K$ ) and latent heat ( $H$ ) impact the cooling performance in a different way.  $H$  reflects the system “capacity”, while  $K$  renders the system “response rate”. Figure 3 shows that  $K$  and  $H$  are in inverse relation: In general, both in-plane and through plane  $K$  increase with the EG mass fraction, whereas the latent heat drops from 254 J/g to 153.5 J/g. This inverse relation implies the tradeoff between  $K$  and  $H$ . Since the material used in the heat exchanger is in shape of sheets, the in-plane  $K$  is more influential. Thus, in the following sections, the best in-plane  $K$  and  $H$  combination is yet to be found.

**3.1.3 Thermal stability.** We studied the material thermal stability by aging tests: 50 cycles between  $-10\text{ }^{\circ}\text{C}$  to  $60\text{ }^{\circ}\text{C}$  at a rate of  $10\text{ }^{\circ}\text{C}/\text{min}$  with the high temperature ( $60\text{ }^{\circ}\text{C}$ ) maintaining for 1 hour. The mass loss and macromorphological changes are shown in Figure 4. With the increase of EG mass fraction, the mass loss dramatically drops from 17% to about 0%. When the EG mass fraction is greater than 25 wt%, the mass loss is negligible and thus considered thermal stable. The optical images (Figure 4. inset) also verify the leakage improvement by the adding of EG, which comes from the capillary confinement effect of the porous structure in EG.



**Figure 2.** (a) (b) SEM images of raw expandable graphite (c) (d) SEM images of expanded graphite (e) Schematic of paraffin/EG composites



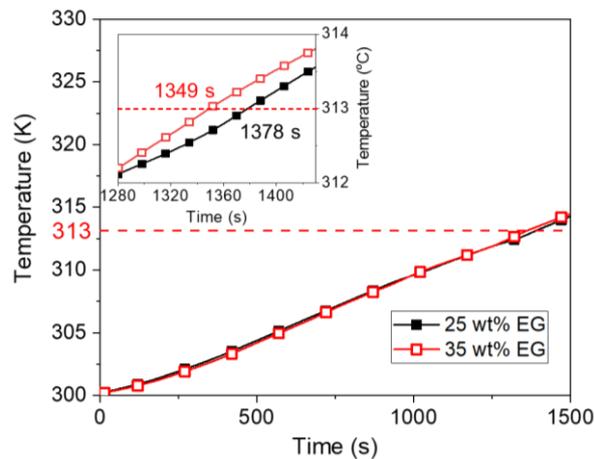
**Figure 3.** Thermal conductivity and latent heat of paraffin/EG composites versus EG mass fraction

**Figure 4.** Mass loss of paraffin/EG composites versus EG mass fraction after aging tests. The inset figures are optical images of paraffin/EG composites after 50 aging cycles

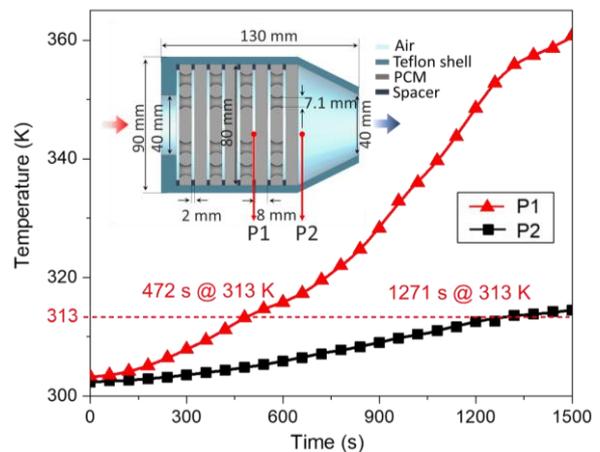
**3.1.4 The selection of optimum composites.** Simulations were used to find the optimum EG mass fraction ( $\geq 25\text{ wt}\%$  EG for thermal stability) for the as-designed heat exchanger. As shown in Figure 5, using 313 K as the control bar, the heat exchanger constructed by 25 wt% EG composite sheets with longer failure time performs slightly better than the 35 wt% one. Meanwhile, considering the cost, we prefer to choose a composite with less EG, which means the composites with 25 wt% EG is the optimum one.

### 3.2 Heat exchanger

**3.2.1 Structure.** Figure 6 (inset) presents the structure of the designed heat exchanger. It is a cylinder with a tapered outlet mouth connecting to the cannister, where the selected paraffin/EG composite (25 wt% EG, 313 g in total) sheets are placed in parallel and separated by spacers.



**Figure 5.** The simulated outlet temperature evolution of the heat exchangers. The inset is a zoom-in view of that range



**Figure 6.** Temperature evolution of the heat exchangers under test. The inset is schematic diagram of heat exchanger

**3.2.2. Efficiency.** According to the suggestion from the Burn Surgery Department of Changhai Hospital (the top burn surgery department in China), the average air temperature in fires is  $\sim 500$  K, and 20 minutes is fair enough for civilians to evacuate in the building fires. And the mean respiratory rate under normal condition is about 6–10 LPM [10]. Here we assume the mean respiratory rate for fire escaping as 20 LPM. We used the homemade analysis system (Figure 1) to test the cooling efficiency of heat exchanger. As shown in Figure 6, P1 and P2 are two different testing points. P1 is inside the heat exchanger. P2 is the outlet temperature. The constant inlet hot air (500 K, 20 LPM) flows through the heat exchanger and the temperatures are measured by thermal couples positioned at P1 and P2. At the initial stage of the test, the outlet temperature (P2) instantly dropped from 500 K to room temperature and then gradually climbed up. The inside temperature (P1) presents the similar but more drastic change. Using 313 K as the control bar, the sustainable time is about 1271 s, which is fair enough for civilians to evacuate in the building fires.

#### 4. Conclusion

In this work, the paraffin/EG composites with EG mass fractions varying from 0% to 35% were prepared and characterized. By thermal stability tests, we found the optimum EG mass fraction should be greater than 25%. With the help of simulation, 25 wt% is the finally selected. Then the as-selected material sheets were used to construct a heat exchanger, which was found can rapidly cool the inlet air from 500 K to a breathable 313 K and sustain for more than 20 minutes.

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