Application of composite materials in mobile food truck tandoor ovens

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Introduction

Tandoor ovens are cooking utilities with long histories of development and use in various cultures around the world. They are integral in the preparation of some culinary dishes and are very relevant to the food industry today. Regardless of size, shape, or region of origin, all tandoor ovens have the same operating principles. The ovens are often made of clay, with some sort of insulating material, such as concrete or mud, on the outside. They are cylindrical in shape and often curve inward toward the top, much like a beehive or jug, to concentrate the heat within the chamber. An opening at the very top of the oven in present, to allow access and ventilation. The fire, which is built in the bottom of the chamber, heats both the walls of the oven and the air inside to upwards of 900°F. Before cooking, the fire is reduced to coals, so that the temperature remains consistent while food is cooked. Considering the high efficiency for burning little fuel and retaining a large portion of the heat, tandoors are quite beneficial. Once they are heated, they can keep their internal chamber temperature at consistently high values for many hours, using very little additional fuel. The modern, mobile food truck tandoor oven is investigated in this project. The main issues with the current mobile tandoor are: 1) it loses heat during naan baking, due to a large volume and high rate of food turnover to customers, 2) the consumption of propane throughout the day for keeping the temperature constant is quite expensive, 3) the tandoor is heavy, 4) it is hard to clean the burners below the tandoor oven and 5) given the mobile nature of the oven, it is prone to experiencing impulse loads, which can easily cause fracture and mechanical failure of the brittle materials currently used.

The goal of this feasibility study is to explore and select alternative designs and materials (composite materials) for a mobile food truck tandoor oven, which has better thermal properties, such as high specific heat capacity and moderate thermal diffusivity, along with proper durability (not too brittle for transportation) and light weight. In the following sections, some of the composite materials used for thermal insulation purposes are investigated.

Composites Used for Thermal Insulation

Materials used for thermal insulation are characterized by a low thermal conductivity (Table 1), which is mostly obtained by the use of air (a thermal insulator), as in the case of polymer foams (e.g., Styrofoam), glass fiber felts, and porous ceramics (e.g., perlite and vermiculite) [1]. Perlite is an amorphous volcanic glass that expands upon heating, due to the vaporization of the trapped water. Vermiculite is a natural clay mineral that expands upon heating. Foaming agents may be used in the fabrication of polymer and cement materials, in order to provide a large number of small air cells that are uniformly distributed. Silica fiber tiles are used as a high-temperature thermal insulation for the Space Shuttles, which face very high temperatures during re-entry through the atmosphere. Multiple glass panes that are hermetically sealed (airtight), such that the environment inside the unit is isolated from that outside the unit, are commonly used for insulated glass windows.

Figure 1. A schematic of a tandoor oven

Composite materials for thermal insulation are designed to obtain a low thermal conductivity, while the mechanical properties remain acceptable. They are mainly polymer-matrix and cement-matrix composites [1]. Either type of composite consists of a foamy or porous phase, which can be the matrix or the filler. However, such a phase is detrimental to the mechanical properties. For example, perlite and vermiculite are used as admixtures to decrease the thermal conductivity of concrete, although they decrease the strength of the concrete.

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Table 1. Thermal conductivities of various materials

Material	Thermal conductivity (W/(m K))
Diamond	2,000
Boron nitride (cubic)	1,700
Silver	429
Copper	401
Beryllium oxide (BeO)	325
Aluminum	250
Aluminum nitride	140–180
Molybdenum	138
Brass	109
Nickel	91
Iron	80
Cast iron	55
Carbon steel	54
Boron nitride (hexagonal)	33
Monel (Cu-Ni alloy)	26
Alumina	18
Zirconia (yttria stabilized)	2
Carbon	1.7
Fused silica	1.38
Window glass	0.96
Mica	0.71
Nylon 6	0.25
Paraffin wax	0.25
Machine oil	0.15
Straw insulation	0.09
Vermiculite	0.058
Paper	0.05
Rock wool insulation	0.045
Fiberglass	0.04
Styrofoam	0.033
Perlite (1 atm)	0.031
Air	0.024
Perlite (vacuum)	0.00137

Cement-Matrix Composites

In the case of a cement-matrix composite [2], methods of decreasing the thermal conductivity involve (i) the addition of a polymer (e.g., latex particles) admixture, since the thermal conductivity of a polymer is lower than that of cement, and (ii) the use of interfaces as thermal barriers. Table 2 lists the thermal conductivities of various cement pastes that utilize silica fume (fine particles), latex (a polymer), methylcellulose (molecules) and short carbon fibers as admixtures.

Carbon Fibers and Thermal Insulation

Although carbon fibers are thermally conducting, the addition of carbon fibers to cement lowers the thermal conductivity, thus allowing applications related to thermal insulation [3]. This effect of carbon fiber addition occurs due to the increase in air void content. The electrical conductivity of carbon fibers is higher than that of the cement matrix by about eight orders of magnitude, whereas the thermal conductivity of carbon fibers is higher than that of the cement matrix by only one or two orders of magnitude. As a result, the electrical conductivity increases upon carbon fiber addition in spite of the increase in air void content, but the thermal conductivity decreases upon fiber addition.

Table 2. Thermal conductivities and specific heats of cement-matrix composites

Cement paste	Thermal conductivity (W/(m K)) (± 0.03)	Specific heat (J/(g K)) (± 0.001)
Plain	0.52	0.703
+ latex (20% by mass of cement)	0.38	0.712
+ latex (25% by mass of cement	0.32	0.723
+ latex (30% by mass of cement)	0.28	0.736
+ methylcellulose (0.4% by mass of cement)	0.42	0.732
+ methylcellulose (0.6% by mass of cement)	0.38	0.737
+ methylcellulose (0.8% by mass of cement)	0.32	0.742
+ silica fume	0.36	0.765
+ silica fume + methylcellulose[a]	0.33	0.771
+ methylcellulose[a] + fibers[b] (0.5% by mass of cement)	0.44	0.761
+ methylcellulose[a] + fibers[b] (1.0% by mass of cement)	0.34	0.792
+ silica fume + methylcellulose[a] + fibers[b] (0.5% by mass of cement)	0.28	0.789

[a] 0.4% by mass of cement; [b] carbon fibers

Expanded Perlite-Fumed Silica Composites

Currently, fumed silica (FS) is widely used as the core of vacuum insulation panels (VIPs) for longer service life required for building applications. It is relatively expensive and a major contributing factor to the current high cost of VIPs. Expanded perlite-fumed silica composites were experimentally investigated as an alternative lower cost material for VIP core, using expanded perlite as a cheaper substitute of fumed silica. Perlite has been used for different construction applications such as lightweight cement aggregate, insulation and ceiling tiles due to its low density (35‑120 kg m−3), porous nature, low thermal conductivity, ease of handling and non-flammability.

A study [4] investigated the thermo- physical properties of expanded perlite-fumed silica composites. The centre of panel thermal conductivity of the core board containing expanded perlite mass proportion of 60%, was measured as 53 $mWm^{-1}K^{-1}$ at atmospheric pressure and 28 $mWm^{-1}K^{-1}$ when expanded perlite content was reduced to 30%. The center of panel thermal conductivity with 30% expanded perlite content was measured as 7.6 $mWm^{-1}K^{-1}$ at 0.5 mbar pressure.

Porous Insulation Materials

A separate study [5] investigated the effective thermal conductivity (ETC) of porous insulation materials. This was determined based on the analysis of various heat transfer mechanisms such as conduction through the solid or the gas, gas convection in pores due to air movement, and radiation between the solid surfaces. Multilayer thermal insulation for low temperature applications was measured, by using a guarded hot plate apparatus (Figure 2). The lowest thermal conductivity was achieved with an increase of additional layers in the insulation materials. The results indicated that significant correlations exist between ETC and the characteristics of the materials with decreasing temperature. The ETC decreases with reinforcement with aluminum foil at

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the same temperature or with temperature differences of 5 and 15 C. In addition, it was clearly observed that the ETC decreases sharply with decreased temperature. Consequently, reflective materials may reduce the ETC at low temperatures.

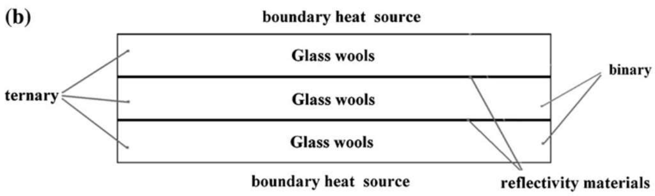

Figure 2. The structure of the ternary insulation materials reinforced with aluminum foil

Porous Polymer Materials

Most porous polymer materials are thermally insulating. Recently, various types of polymer fibers, such as polyester and polypropylene (Table 3) [6], have been developed for thermal insulation. The thermal insulating performance of the porous polymer materials is strongly dependent upon the properties of the polymer fiber. Wu et al. 2007 found that the mechanisms of thermal energy transport within porous polymer materials, and found the effects of polymer fiber characteristics on the thermal energy transport investigated, in order to understand the thermal insulating performance of such materials. It was found that decreasing fiber radius would significantly reduce the total thermal energy flux through the porous polymer materials, whereas increasing fiber emissivity or decreasing the thermal conductivity would cause a just slight reduction of the total thermal energy flux.

Table 3. Properties of Polyester and Wool Fiber

Property	Wool	polyester
Density (kg/m^3)	1310	1390
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.19	0.14
Volumetric heat capacity ($kJ\ m^{-3}\ K^{-1}$)	1600	1300
Emissivity	0.78	0.62

Next Steps and Future Work

Selection of the top candidate among the different suitable composite materials for thermal insulation tasks, falls into a materials selection/design and multi-criteria decision-making problem. The criteria consist of the price of the composites, durability of the material and its thermal insulation characteristics. The chosen composite material must satisfy the limited budget of tandoor production, while making the tandoor lighter. Finally, finite element (FEM) analysis should be done on the selected material in order to monitor the product's reaction to physical effects.

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