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Cool black roof impacts into the cooling and heating load demand of a residential building in various climates

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ABSTRACT

This paper describes the impacts of different cool black paints on cooling and heating load demand of a residential building in different climates. Cool paints with dark appearance and high reflectance in near infrared portion of sunlight are of great interest by the owners of homes to satisfy both desired visual and energy saving aspects. Three copper oxide (CuO) powders, different in pigment size, and a chromium–iron oxide (Cr_2O_3–Fe_2O_3) powder, as a commercial cool black pigment, are used to make the black paints. The samples are made on both conventional black and cool white base coats. The spectral reflectance of all samples in solar range (0.3–2.5 μm) and infrared region (2.5–25 μm) is measured. The thermal emittance of the samples is estimated using the spectral reflectance measurement and validated by the measurement of infrared camera. A typical residential single-stage single-family home in three different climates of Iran is considered and the impacts of applying the different black paints on cooling and heating load demand are discussed. The results show that the peak and annual cooling load demand decrease by 0.4–1.4 kW (6–13%) and 405–2202 kWh (6–14%), respectively, depends on the type of pigmented coating and climate conditions.

1. Introduction

A clean, smooth, and solar-opaque white cool surface that strongly reflects both visible (VIS, 0.4–0.7 μm) and near infrared (NIR, 0.7–2.5 μm) portions of sunlight, achieving a solar reflectance of about 85% [1], improves the thermal comfort for residents and the building energy efficiency but at the same time produces high brightness and glare that is offensive to the human eye. In addition, white surfaces easily become dirty and lose their appearance. On the other hand, cool black paints with dark appearance, high reflectance in near infrared portion of sunlight, and high thermal emittance are of great interest by the owners of homes to satisfy both visual and energy saving aspects in cooling dominated regions.

Levinson et al. [1] described methods for creating cool non-white surfaces. The suitability of a pigment for inclusion in cool paints was studied by Levinson et al. [2,3]. Rosado et al. discussed the effect of cool tile roof on temperature, heat flow and energy use of a single-family home in California [4]. Single layer and multiple layers of cool white coatings and their effect on energy efficiency of buildings were investigated by Song et al. [5]. Reduction of heat transmission through the roof by applying thermal insulation coating (TIC) formulated using titanium dioxide pigment on the roof was investigated by Yew et al [6]. Several passive roof designs were investigated in [7] and their performances were compared by determining the temperature of roof, attic and ceiling. Al-Obaidi et al [8] designed an innovative roofing system (IRS) to reduced heat gain effect for tropical residential buildings. Xue et al. [9] described the method for creating cool gray coatings by mixing titanium dioxide rutile and black pigments. The effects of mixing five different black colorants with commercial paints on their NIR properties have been investigated by Cozza et al. [10]. Qin et al. [11,12] discussed the methods of creating black coatings pigmented with different black colorants and their optical properties and cooling energy savings. Dias et al. [13] studied the impact of using cool paints and/or thermal insulation on the energy demand of a residential building. The authors proposed controlling the pigment size, volume concentration of pigments, and coating thickness to optimize the optical and thermal properties of cool pigmented coatings [14,15]. The effects of applying TiO_2 pigmented coatings on temperature and brightness of a coated black substrate was studied in Ref. [16]. Baneshi et al. [17] theoretically compared the optimum spectral behavior of white titanium dioxide and black copper oxide (CuO) cool paints. Gonome et al. [18] experimentally investigated the radiative properties of various CuO pigmented coatings on different

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substrates. Following the previous works, this paper aims first to compare the optical and thermal properties of various black paints made on laboratory scale, second to estimate the impacts of using these paints on cooling and heating load demand, thermal comfort, and potential of energy saving of a residential building, and third to investigate the suitability of these paints for various climates.

Three CuO black powders different in pigment size and one commercial cool black pigment named chromium–iron oxide (Cr_2O_3–Fe_2O_3) were used. The paints were made in laboratory scale. The pigmented coating samples were built on both typical black and cool white base coats. The spectral reflectance of all samples in solar range (0.3–2.5 μm) and infrared region (2.5–25 μm) and the thermal emittance were measured. A conventional residential single-stage single-family home in three different climates of Iran including hot dry desert, Mediterranean, and cold mountain climates was considered and the impacts of applying the different black paints on cooling and heating load demand, thermal comfort, and potential of energy saving were estimated.

2. Experimental

The spectral reflectance and thermal emittance of paint samples are required in calculating the heating and cooling load demand of a building. These data are measured experimentally as discussed in this section.

2.1. Preparation of black paints and pigmented coating samples

Three different CuO black powders with mean pigment size of 0.05, 0.9, and 3 μm (from Wako Pure Chemical Industries, Ltd. and Kojundo Chemical Laboratory Co., Ltd.) and a commercial cool black pigment named Cr_2O_3–Fe_2O_3 (from Tokan Material Technology Co., Ltd.), with no catalog data available for the mean pigment size and the ratio of Cr_2O_3 to Fe_2O_3, were used. Appropriate amounts of the black pigment, polymer resin, and thinner were mixed in a high performance super mixer (THINKY CORP., AR-100) to make the paint with desired volume concentration of pigments. The mixer also removed the air bubbles and the paints were then shaken in an ultrasonic shaker for a few minutes.

Conventional black base coat and cool white base coat (introduced by Japan Industrial Standards) were used as substrates of pigmented coating samples. To coat the substrate a motorized film applicator (Elcometer 4330) equipped with spiral bar coaters (Elcometer 4360) were used. Table 1 shows the characteristic of selected samples.

Table 1
Characteristics of selected pigmented coating samples.

Base coat	Pigment type	Pigment size (μm)	Volume concentration (%)	Coating thickness (μm)
Black base coat	CuO	0.9	5	40
		3	3	60
		0.05	3	45
	Cr_2O_3–Fe_2O_3	–	5	40
White base coat	CuO	0.9	5	10
		0.9	5	40
		3	3	60
		0.05	3	20
	Cr_2O_3–Fe_2O_3	–	5	10
		–	5	40

2.2. Spectral reflectance and thermal emittance measurement

Spectral reflectance in the wavelength range of 0.3–0.85 μm was measured using UV-VIS spectrometer (Shimadzu UV-2450) equipped with a $BaSO_4$ coated integrating sphere (Shimadzu ISR-2200). In the wavelength range of 0.85–2.5 μm an infrared (IR) spectrometer (Shimadzu IR Prestige-21) which is utilizing a gold coated integrating sphere (Shimadzu Integrat IR-A) was used. In infrared (IR) region, 2.5–25 μm, an IR spectrometer (Shimadzu IR Prestige-21) which has extra equipment (Shimadzu SRM-8000A) to measure the reflectance was used. The IR spectral reflectance was used to estimate the spectral emittance and finally total emittance of samples. An infrared camera (NEC/Avio, TVS-500EX) was used to directly measure the thermal emittance of the black pigmented coating samples. More details of experimental setup can be found in [15,18].

3. Cooling and heating load demand calculation

A conventional single-stage single-family, flat roof house directed south with total area of 108 m^2 and height of 3 m was studied. The U-value of external walls, internal walls, and non-insulated roof is 2.4, 2.1, and 1.9 W/m^2 K, respectively. The U-value of the roof when 1 in. and 2 in. thick insulation, with thermal conductivity of 0.012 W/mK, is used can be reduced to 0.88 and 0.33 W/ m^2K, respectively. The weight of external walls, internal walls, and roof is 385.7 and 214.8, 336.9 kg/m^2, respectively. The conventional house has six 1.2×1 m^2 double glazing windows, four on south wall, one on east wall, and one on west wall with U-value of 3.7 W/m^2 K. There is also one 1.2×2.2 m^2 entrance door with U-value of 4.25 W/m^2 K on south wall.

Table 2
Selected meteorological data of three different locations in Iran.

Location	Climate	Dry bulb temperature (°C) (Month Day: Hour)		Average relative humidity (%)	Average wind speed (m/s)	Daily average global horizontal solar irradiation (Wh/m^2)
		Max	Min			
Yazd {N 31° 52′} {E 54° 16′}	Hot dry desert	42.3 (Aug 16/16)	−7 (Jan 3:07)	29	2.4	5562
Shiraz {N 29° 19′} {E 52° 21′}	Mediterranean	39.8 (July 29/15)	−4.9 (Dec 22:06)	38	2.2	5431
Tabriz {N 38° 2′} {E 46° 10′}	Cold mountain	37 (July 14/16)	−15 (Jan 25:06)	53	3	3788