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Research Paper

The imitation of the road surface temperature variation characteristics subjected to periodical ambient conditions

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HIGHLIGHTS

- The imitation of the road's surface temperature features was explored.
- The thermal inertial is a key factor in the imitation.
- The dimensionless thickness was defined to elucidate the findings.
- The findings are adaptive for arbitrary periodical ambient condition.
- The findings can be applied for both the concrete and asphalt roads.

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ABSTRACT

The imitation of the surface temperature variation characteristics of a road, a typical background for moving objects, is extremely important to the effective infrared camouflage and has been rarely discussed before. Therefore, one-dimensional heat transfer models for both the road and the imitative material were established to explore the influences of the latter's thermophysical properties on the surface temperature difference (STD) between them when subjected to the same periodical ambient conditions. It is elucidated that the STD is dominated by the thermal inertial of the imitative material when its dimensionless thickness is not less than 1.0. When the imitative material's dimensionless thickness is less than 1.0, the STD is influenced by both the thermal inertial and the dimensionless thickness of the imitative material. Furthermore, if the imitative material's dimensionless thickness is much less than 1.0, the STD is determined by the product of the thermal inertial and the dimensionless thickness of the imitative material. Especially, if the thermal inertial of the imitative material is the same as that of the road's surface layer, the STD approaches zero, as long as the dimensionless thicknesses of the imitative material and the surface layer are both not less than 1.0.

1. Introduction

In recent years, with the enhancement of the measurement accuracy and spectral resolution of the infrared thermometry, more attentions were paid to the infrared protection technology under different backgrounds, including sky [1,2], ocean [3,4], vegetation backgrounds [5,6], etc. However, the bare land also plays an important role in the field of infrared camouflage, and the roads (such as the concrete and the asphalt roads), as a typical land background for moving object, should be more concerned. Nevertheless, the researches about the bare land most focused on the soil, not the road, and most of the achievements were in the area of remote sensing. Watson [7] proposed a forecast model of the bare land's surface temperature based on the data from remote sensing. A few years later, Watson's model was improved by Price [8] to forecast the thermophysical properties of the bare land from its daily surface temperature fluctuation range, and vice versa, based on the semi-infinite solid assumption. The model was later widely used in the field of remote sensing for the analysis of soil moisture [9,10], or the surface materials on outer space planets like Mars [11–13]. Only a few reports were devoted to the road, mainly aimed at the exploration of the relationship between the surface temperature and the ambient conditions [14].

Here, to explore the imitation of the surface temperature variation characteristics of the roads, such as the concrete and the asphalt roads, one-dimensional heat transfer models were established for both the road and the imitative material. And the influences of the imitative material's thermo-physical properties on the surface temperature difference (STD) between the road and the imitative material were investigated subjected to the same periodical ambient con-

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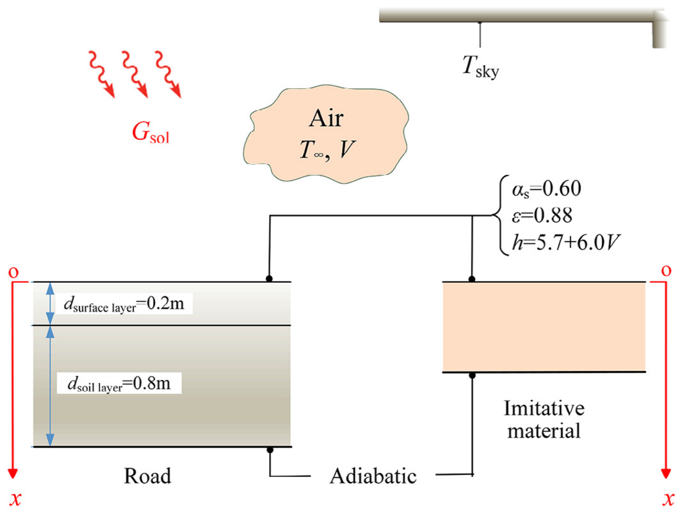

Fig. 1. Schematic diagram of the road (left) and the imitative material (right).

ditions. At the beginning, the models of the road and the imitative material were introduced, including the physical structure, the boundary conditions and the calculation condition settings, as shown in Section 2. Then, the numerical calculation results on the imitation of the concrete road surface temperature subjected to a typical daily periodical ambient condition were given as a typical case in Section 3 and the inherent rules were also explored. In the end, the numerical calculation results on the imitations of the surface temperature variation characteristics of both the concrete and asphalt roads were given to further elucidate the adaptability of the findings, subjecting to the typical annual periodical ambient conditions in different areas.

2. Model

A road consists of a surface layer and a soil layer beneath, as shown in Fig. 1. According to the Specifications for Design of Highway Cement Concrete Pavement of China and Design of Highway Asphalt Pavement of China, the thickness of the surface layer in the road is approximately 0.2 m. The thickness of the soil layer is set as 0.8 m, which is thicker than its heat penetration depth ($\delta_{p,\,soil}$) under the ambient conditions (according to Ref. 15, $\delta_{p,\,soil} = 4\sqrt{k_{soil}/(\omega\rho_{soil}c_{p,\,soil})} \approx 0.6\,\text{m}$, ω stands for the variation frequency of the ambient condition which can be calculated as $\omega = 2\pi/86{,}400\ \text{s}^{-1}$ and k_{soil}, ρ_{soil} and $c_{p,\,soil}$ represent the thermal conductivity, density and specific heat capacity of the soil, respectively, as shown in Table 1). Therefore the soil layer can be approximated as a semi-infinite solid. Thus, treating the road in Fig. 1 as a semi-infinite solid is valid. Therefore, the bottom surface of the road can be set adiabatic while its top surface is exposed to the ambient. The imitative material consists of a single material, and its top surface is exposed to the ambient and an adiabatic boundary condition is applied over its bottom due to the practical consideration. The possible application of the imitative material would be the surface cover of special equipment usually operating at a high or low temperature (relative to the ambient), which would form a strong thermal BC for the bottom of the imitative material. However, there is usually a thick thermal insulation layer around the equipment to make its operation stable. Considering the high-performance thermal insulation layer sandwiched by the equipment and the imitative material, an adiabatic boundary condition over the bottom of the imitative material can be a good approximation.

Considering that a one-dimensional heat transfer assumption is reasonable for both the road and the imitative material, their governing equations take the same form:

$$\rho c_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \tag{1}$$

where ρ, c_p and k are the density, specific heat capacity and thermal conductivity, respectively. As shown in Fig. 1, the boundary conditions of the road and the imitative material are identical. Their top boundary conditions can be similarly expressed as

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=0} = q'' = G_{abs} - Q_{rad} - Q_{conv} \tag{2}$$

and the bottom boundary conditions are both adiabatic. In Eq. (2), $q'' = G_{abs} - Q_{rad} - Q_{conv}$ is the net heat flux into the top boundary. G_{abs} is the solar irradiation absorbed by the top surface, and is equal to $\alpha_s G_{sol}$, where α_s represents the solar absorptance and G_{sol} represents the solar irradiation. Q_{rad} is the radiation heat flux between the top surface and the sky and is equal to $\varepsilon\sigma(T_s^4 - T_{sky}^4)$, where ε, σ, T_s and T_{sky} represent the infrared emissivity, the Stefan–Boltzmann constant, the top surface temperature and the effective sky temperature. Q_{conv} is the convection heat flux between the top surface and the air and is equal to $h(T_s - T_\infty)$, where h represents the convection coefficient estimated by $h = 5.7 + 6.0V$ (V is the wind speed) [16] and T_∞ represents the temperature of the air flow. The correlation used here for computing convection coefficient is selected according to the recommendation of a survey of wind convection coefficient correlations by Palyvos [16] which is commonly used to calculate the convection coefficient over a flat plate considering both the natural and force convections. And its reliability has been commonly accepted.

In the model of the road, the thermal contact resistance was neglected due to practical consideration. When a road is paved, its surface layer (such as the concrete and the asphalt) and the soil layer are usually agglutinated by a tack coat and it would be compacted. Thus, the thermal contact resistance in the road is usually assumed to be negligible [17]. This assumption was widely adopted in the studies of the pavement temperature [14,17]. Furthermore, Gui et al. stated that the neglect of the contact resistance in the road has almost no influence on the prediction of the surface temperature of the road, which was proved by his experiments [17].

The material properties are given in Table 1 and assumed to be constant. This assumption for the road was adopted because that there are few reported data on the variation of the thermal properties of the road layers to our knowledge so far. And we have found that good predictions of pavement temperature have been obtained by other authors based on constant properties [14,17] maybe due to the relative small range of temperature variation. Thus we did not consider the temperature dependencies of the related thermal properties of the road. As for the imitative material, the imitative material is not specified and there are no regular variation laws of the material's properties with temperature making it dif-

Table 1
The material properties [15].

	Solar absorptance	Infrared emissivity	Thermal conductivity (W/m·K)	Heat capacity (J/kg·K)	Density (kg/m^3)
Concrete	0.60	0.88	1.4	880	2300
Asphalt	0.90	0.90	1.5	1000	2000
Soil	–	–	1.4 (frozen soil) 2.0 (non-frozen soil)	880	1460
Imitative material	The same as that of the road		–		