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Design of Thermal Insulation Energy-Saving Coatings for Exterior Wall

Hui Zhang[a,b], Fei Wang[a,b]*, Jinsheng Liang[a,b], Qingguo Tang[a,b], Yalei Chen[a,b]

[a]Institute of Power Source & Ecomaterials Science, Hebei University of Technology, 300130 Tianjin, China
[b]Key Laboratory of Special Functional Materials for Ecological Environment and Information, Hebei University of Technology, Ministry of Education, Tianjin 300130, China
wangphilip@yeah.net

Thermal insulation coatings can effectively prevent coatings and substrate from solar radiation under the condition of zero-energy consumption, which could improve the working conditions and reduce the energy consumption. A kind of thin layer thermal insulating energy-saving coatings with high performance was designed by synergistic effect of thermal insulation mechanisms during the process of light and heat transfer. The excellent performance of coatings had characterized with low thermal conductivity, good insulation effect, high reflectivity, and so on. Moreover, double insulation system as an optimized thermal insulation coating structural model was proposed and designed. The reflection-insulation type thermal insulation coating was used as the top-coat to form reflection-insulation layer, and the radiation-insulation type thermal insulation coating was used as the intermediate-coat to form radiation-insulation layer. The double system had advantages of good thermal insulation and convenient process, and it is also easy to rush, save energy and reduce energy consumption. Some issues of insulation coatings were explored and explained, such as coating strength, filler arrangement and coating thickness.

1. Introduction

The world's energy demand is increasing at an average annual rate of 1.2 %. According to the forecasts, until 2030, the global construction energy consumption will increase by 30 - 40 % over 2010 (Judkoff, 2008). In China, the construction energy consumption accounts for about 25 % of the total national energy consumption (Guo, 2009), and this value will rapidly increase to 30% (Wu, 2006). In addition, CO_2 emissions of buildings account for a large amount of proportion of total global greenhouse gas emissions (Dodo et al., 2015). Therefore, construction energy conservation has great importance. The development of new thermal insulation materials for the buildings construction is able to decrease wasteful consumption of energy resources (Lybimova et al., 2014) and CO_2 emissions. External thermal insulation of exterior wall has excellent advantages of saving energy and improving the using function of buildings. At present, the application of thermal insulation coatings on the construction exterior wall has been an effective way to save construction energy (Cai, 2014) and improve indoor environment comfort (Song et al., 2008).
With the consumption of zero energy, thermal insulation coatings can effectively prevent the solar radiation heat from coatings and internal substrate to improve work environment and reduce energy consumption. The heat transfer mechanism of construction is divided into radiation, convection and conduction. Moreover, thermal insulation coatings are separated into insulation-type insulation coatings, reflective-type insulation coatings and radiation-type thermal insulation coatings in accordance with the different insulation mechanism and methods. The thermal insulation effect of single type thermal insulation coating has limitation, so it is necessary to cooperate with two or more kinds of insulation mechanisms for complementary each other's advantages (Yao et al., 2015).
The current trend of research in thermal insulation coatings is to improve the structure and preparation process. Shen and Wang (2015) have designed a kind of double reflective insulation coatings structure, which was composed with a primer based on titanium dioxide and hollow glass bead and a top-coat based on inorganic colour pigment and IR radiation ceramic powder. The results showed that the structure can

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effectively improve the infrared reflectivity and stain resistance. In order to solve the defect of single colour of reflective insulation coating on the market, Ma (2016) have proposed a double-layer reflective insulation coatings which was formed by white thermal reflective bottom layer and dark surface layer. Compared with the single-layer structure, the double-layer structure had better thermal reflective properties and reduced the use of pigments. Anderson et al. (2006) have developed a kind of outdoor coatings which was prepared by two reflective materials, and biological inhibitors or self-cleaning fillers added in the second layer, so that the coatings can maintain high reflectivity over a long period of time in serious polluted or humid environment. Developing the thermal insulation coatings with high performance (Braun et al., 1992) will be the trend of thermal insulation energy-saving coatings, including nanometre size, thin layer (Ozkan and Onan, 2011), multifunction (Mei et al., 2012), water-borne (Liu et al., 2012), environmental protection and so on.

In recent years, the external insulation composite system has become one of the main research objects in the field of construction energy saving (Bouchair, 2008), which has shortcomings of complex structure, high cost, narrow construction range and inconvenient hot bridge formation. Thus, the thin-layer insulation coatings technology has been developed to replace the thick-layer insulation coatings. The scientific and technical personnel of National Aeronautics and Space Administration have developed a space refractive thermal insulation latex paint to solve the control problem of the spacecraft during heat transfer, which has characteristic of high efficiency, high reflectivity, non-toxicity and safety. The excellent thermal insulation performance of ceramic latex paint has been proven by many researches (Liang et al., 2013) and test methods (Chen et al., 2013). However, ceramic latex paint has not been widely used because of its high cost.

A kind of high-efficiency thin-layer external thermal insulation composite coating was designed and developed in this paper, which was characterized by excellent thermal conductivity, good thermal insulation effect, high reflectivity, high emissivity and simple preparation. Meanwhile, this work attempted to achieve the purpose of energy conservation and environment protection.

2. The design basis of external thermal insulation coatings

Based on a large number of theoretical studies, a coating structural model with ideal thermal insulation effect was designed and shown in Figure 1.

The design of coating structure was based on different thermal insulation principles of the three types' thermal insulation coatings, and the coating was formed by reasonable brushing order, drying and other coating processes. Thus, a small amount of solar radiation heat could only enter internal coating as a result of multiple insulation effect of coatings system, and the vast majority of heat could be limited to external coating, in order to achieve the purpose of thermal insulation.

When the sunlight irradiated on the surface of the coating, there were three kinds of action mode of heat transfer in coating, including reflection, absorption, and transmission. The relationship between the reflectance ρ, the absorptivity α and the transmittance τ was indicated in E(1).

$$\rho + \alpha + \tau = 1 \tag{1}$$

Since the following of coatings was mostly opaque material, such as cement layer or steel layer, then the transmittance could be approximated as 0. Thus, the above formula could be simplified as Eq(2).

$$\rho + \alpha = 1 \tag{2}$$

The above equation showed that the absorption of solar radiation reduced only if the reflectivity of the coatings increased. Solar energy mainly concentrated in the visible and near infrared light region in which the wavelength was 0.4 – 1.8 μm. Because of this the role of the reflective layer was to reflect visible light and near infrared light back to the atmosphere as much as possible in order to reduce the heat absorption of coatings and thin air layer on coatings surface, as a consequence, the heat could be isolated from outside coatings effectively.

When unreflecting heat was absorbed by reflective layer, the heat continued to transfer into the internal coatings. Under the vacuum conditions, heat conduction and convection could not exist without object, so heat radiation could transfer in the vacuum layer. Thus, the vacuum layer could block the heat outside the layer caused by heat conduction and convection. Then, the remaining part of the heat radiation could be absorbed into the next coating and provided a radiation condition for radiation layer. The radiation layer constantly converted the heat energy into radiant energy due to thermal excitation, and released heat radiation to outside. The band (8 -14 μm) was called "atmospheric window" because of its high permeability, hence, the heat radiation of the object on the ground could reach the outer space through it directly. The heat absorbed by coatings and coatings substrate was launched into outer space through this band in the form of infrared radiation caused by the high emissivity of coatings, but the other heat could be re-passed out. The thermal insulation effect of coatings could be realized ultimately through the effect of three-layer coatings on light and heat.

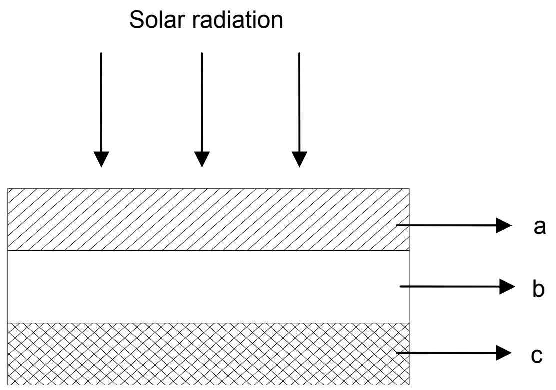

Figure1: Structural model of the perfect thermal insulation coatings (a) Reflection layer; (b) Vacuum layer; (c) Radiation layer

Up to now, the ideal vacuum layer was difficult to achieve, especially, it was hard to form a large area vacuum layer in the construction thermal insulation coatings. The pressure difference existing inside and outside coatings might lead to collapse under the effect of atmospheric pressure, and eventually resulted in adverse effect to thermal insulation. According to the research of Gesele et al. (1997) and later Marliere et al. (2001), N_2 and O_2 was the main components of air and account for 99 % of the total volume of air, and the average free path of these two gases were about 70 nm. When the diameter of hollow sphere or the pore size of hollow channel was as small as the nanometre scale (less than 50 nm), most of the air molecules in the hole could not flow freely. The air molecules in the pores were almost in a quiescent state and completely adsorbed on the pore wall, so there was a vacuum state form in the pore. An approximate vacuum layer was formed by the application of such porous materials in coatings, and the layer could not only solve the problem of coatings pressure-bearing but also ensure a good thermal insulation effect. On the above basis, a modified coating structural model with porous material instead of the vacuum layer was shown in Figure 2.

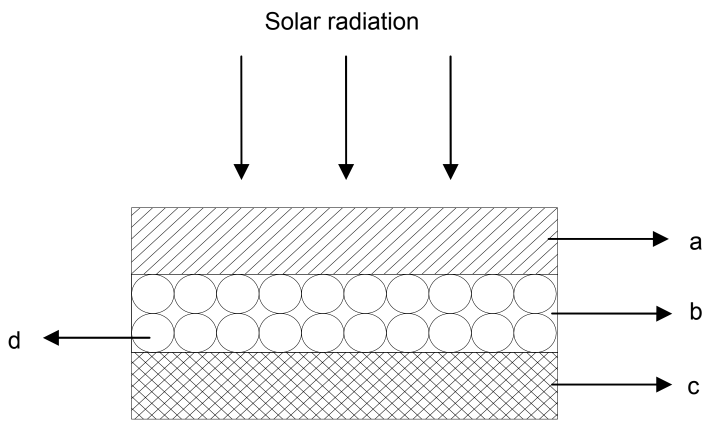

Figure 2: Improved structural model of the perfect thermal insulation coatings (a) Reflection layer; (b) Insulation layer; (c) Radiation layer; (d) Porous material

The modified structural model showed in Figure 2 was mainly to improve the vacuum layer that was formed by an insulation layer with the addition of porous material. Considering the properties, composition, porosity, water content, bending rate and other factors of porous material, the heat transfer process of the porous material could obey the following models:
(1) Heat transfer between the solid skeletons;
(2) Heat transfer and thermal convection of the fluid (between liquids, between gases, and both);
(3) Thermal convection between fluid and solid skeleton;

(4) Heat radiation between the solid skeletons and between solid skeleton and gas; In general, the heat radiation was not significant when the end-use temperature of porous materials was not very high, so that it could be ignored.

Generally, the hollow pore or hollow sphere materials with low thermal conductivity and high porosity would be used in this insulation layer, and the internal pores were mostly mesoporous (pore size less than 50nm). Due to the high porosity of mesoporous, the approximate vacuum structure occupied a high ratio in the coatings. On the one hand, the heat conduction of solid molecules and the thermal conductivity of the coatings reduced; on the other hand, since the air molecules of the pores were in a quiescent state, the convective heat conduction effect was weak. Meanwhile, such porous materials provided the number of interfaces in the insulation layer, which leaded to the increase of the reflection and scattering interface in the coatings as well as reduce the heat radiation efficiency. When the number of hollow pores or hollow spheres was sufficient, the amount of interface in the coatings tended to be infinite, so that the heat radiation efficiency was close to zero. The addition of a large amount of porous material in the insulation layer got an ideal insulation coating structure more easily and weakened the three basic forms of heat transmission, thus, most of the heat was blocked outside the coatings. The combined action of the insulation of this layer, reflection of external reflection layer on the solar radiation and radiation of heat absorbed by the internal radiation layer made the system achieve a good insulation effect.

3. The optimization of external thermal insulation coating structure

The design of above two kinds of coating structural model with ideal insulation effect was based on the heat transmission law in the coating, and was formed by three layers. Although this structural model has been well supported theoretically, the following problems still existed in the specific preparation of coatings:

(1) The metal or metal oxide with high refractive index was used as a pigment in reflective layer, so that the coating reflectivity improved significantly. However, the high thermal conductivity of pigment would lead to rapid heat transfer in the coatings;

(2) The thick coatings extended the heat transfer path in the coatings, which made the coatings tend to store more heat and cause bad effect of heat radiation;

(3) Three different kinds of thermal insulation coating had disadvantages of resource waste, high cost, as well as complex preparation process;

(4) In the preparation process of coatings, the operations must be repeated, including brushing and drying of the film. Moreover, the coating adhesion and other issues should be considered, such as the long cycle of preparation and uneven thickness of repeated coating. Besides, cracks might exist on the surface, which reduced the life of coatings.

In view of above problems, a thermal insulation coating optimization structure was designed and shown in Figure 3, which depended on the heat transfer law in the coating and the idea of ideal thermal insulation coating structural model.

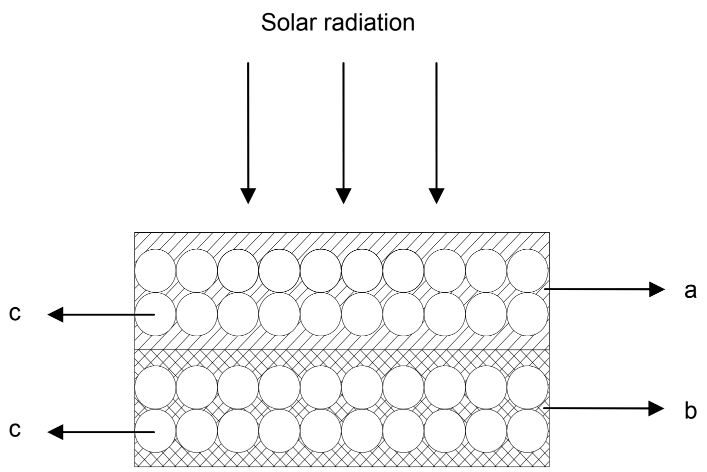

Figure 3: Optimized structural model of thermal insulation coatings (a) Reflection–Insulation layer; (b) Radiation–Insulation layer; (c) Porous material

The structural model of coating with three-layer coatings system was reduced to two-layer coatings system. In this coatings system, the porous material was added in reflected and radiation layer to form reflection-insulation layer and radiation-insulation layer instead of single insulation layer. In actual use, the reflection-insulation coating and radiation-insulation coating was used on surface and bottom.

Many studies indicated that high solar reflectance and low heat absorption was caused by the addition of pigment with high refractive index in reflection-insulation layer. However, the high thermal conductivity of this pigment would lead to the quick transfer of absorbed heat into the internal coating, and resulted in adverse effects. Through adding appropriate amount of porous material to the coating, the coating would have a large number of nanopores to prevent the rapid transfer of heat. On the one hand, it weakened the heat conduction and convection and reduced the overall thermal conductivity of the coatings. On the other hand, since the number of gas-solid interfaces in the coating tended to be infinite, the heat radiating rays would occur to reflection, absorption, transmission and re-radiation when it passed through the interface of each layer, which was equivalent to set up countless heat board in heat propagation path and slow down the heat transfer. Consequently, the reflection-insulation layer had high reflectivity and good thermal insulation effect.

Generally, the emissivity of radiation-insulation coating could reach more than 0.9 in the band of 8 ~ 14 μm caused by the addition of radiation type filler. When the coating temperature changed, the energy of radiation type filler will be released in the form of infrared radiation after being subject to thermal excitation, which could make the heat that was absorbed by coatings and coatings substrate passed through the "atmospheric window" to the outer space in the form of infrared radiation. Radiation heat transfer referred to the total effect of radiation and absorption among substances, the heat radiation on the surface still existed when the object and the environment were in thermal equilibrium, but the amount of radiation heat transfer was zero. As a result, the phenomenon could promote the internal and external coating cooling at the same rate. In order to improve the heat insulation effect of the coatings, it was also necessary to add a porous material which had hollow pores or hollow sphere to the coating. So that the coatings reduced the entrance of heat, increased the emission of heat and improved the coating insulation performance.

The double insulation system was prepared by the two coating layers with suitable thickness of the coatings and reasonable brushing method. Therefore, the top-coat and the bottom-coat had high reflectivity and high emissivity, respectively. Moreover, each layer had a good heat insulation performance. Meanwhile, the double-layer insulation system belonged to thin layer insulation coatings, which can be seen as porous materials. So that the system not only increased the proportion of the insulation layer in coating but also reduced the overall thickness of the coatings, which was conducive to radiant heat dissipation. And it also had advantages of saving raw materials, simplifying the preparation process of coating, ensuring good coating surface performance, shortening preparation cycle and facilitating construction. As a consequence, the purpose of reducing costs, saving energy and protecting environmental has been achieved through above the design.

4. Conclusions

In this paper, a kind of high performance thin double-layer system thermal insulation coatings for exterior wall was designed to reduce the high energy consumption. Two or more thermal insulation mechanisms worked together in the process of light and heat transfer, achieving the excellent thermal insulation performance of coatings. Therefore, an optimized structural model of thermal insulation coating was proposed and designed based on the heat transfer law of coatings. The model effectively solved the issues of thermal insulation coatings, including coatings thickness, thermal insulation properties, coatings strength and so on. In this design, the reflection-insulation layer composed of reflective coating and porous material was used as top-coat, and the radiation-insulation layer composed of radiation coating and porous material was used as bottom-coat. In conclusion, the double layer system could successfully insulate most of heat and was easy to brush, and it also had advantages of saving resources and reducing energy consumption.

Acknowledgments

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