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Automatic air temperature control in a container with an optic-variable wall

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HIGHLIGHTS

- Automatic air temperature control is proposed for energy saving in containers.
- With OVW, air is simultaneously kept cool in summer and warm in winter.
- Adjustment of solar radiation with OVW is verified experimentally in winter.

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ABSTRACT

Solar energy is one important source of sustainable and green energy. However, solar radiation is not always demanded as heat source for building in seasons. Automatic air temperature control with an optic-variable wall is proposed in this paper to reduce the HVAC (Heating, Ventilation & Air-Conditioning) energy consumption in containers. The feasibility of an optic-variable wall (OVW) is first verified with sample-test on the color, reflectivity and absorbance with UV 3600. The reference for relectivity test is $BaSO_4$ and the reference for absorbance test is quartz. The feasibility of its performance on air temperature control inside a container is verified with preliminary experiments under natural winter conditions at a low ambient temperature. It is checked that the color of OVW varies from dark at low temperature to light at high temperature. The reflectivity of OVW is small at low temperature and high at high temperature. Then, the theoretical investigation on air temperature inside a container is conducted. It is concluded that air inside a container is simultaneously kept cool in summer and warm in winter, with the adoption of OVW. The stable air temperature rise is small under the conditions of high ambient temperature and large solar radiation, leading to the potential of less energy consumption for cooling in summer, while it is large under the conditions of low ambient temperature and small solar radiation, leading to the potential of less energy consumption for heating in winter. The variation range of the stable air temperature with OVW is also narrower. The results are helpful for green design and energy saving in containers.

1. Introduction

Energy demand in modern society increases rapidly with civilization, leading to the anxiety of sustainable development for human being. According to a recent survey [1], energy consumption of buildings, mainly in the form of HVAC (Heating, Ventilation & Air-Conditioning) for air temperature control in seasons, is reported as 857 million tce in 2015, accounting for 20% of global energy consumption in China and corresponding to 74% of potential for energy-saving in buildings by 2050 as well as 50% of contribution for energy-saving in carbon-emission peak.

Besides the heat generation in buildings, ambient temperature and solar radiation are two major factors affecting the air temperature inside and its corresponding HVAC load [2,3]. To control the air temperature inside buildings, active and passive measures are taken, e.g. air conditioning [4–6], ventilation [7–9], light-color wall-painting [10–12], large thermal mass [13,14], thermal insulation [15–20]. Comparing with the active measures, the passive measures demand less energy consumption of fossil fuels or electricity. Among these measures, utilization or reflection of solar radiation is very attractive [21–30]. Zhang et al. [21] developed perovskite solar cells for PV transition of solar energy. Wang et al. [22] adopted thermal energy storage (TES) technique to collect solar energy for PT utilization. Ma et al. [23] investigated the performance of high-temperature latent heat storage units. Si et al. [26] optimized the active solar energy system in buildings at cold places. Xaman et al. [28] discussed the performance of a

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Nomenclature

C	heat capacity, J·kg^{-1}·K^{-1}
h	convective heat transfer rate, W·m^{-2}·K^{-1}
I	solar radiation rate, W·m^{-2}
t	time, s
T	temperature, °C
u	velocity, m·s^{-1}
x	position of wall, m

Greek symbol

α	absorptivity
δ	wall thickness, m
Δ	difference
λ	thermal conductivity, W·m^{-1}·K^{-1}
ρ	density, kg·m^{-3}
σ	equivalent depth of container facing OVW, m
τ	time, s

Subscripts

air	air
ambient	ambient
in	inner wall
l	lower
out	outer wall
s1	set value 1
s2	set value 2
u	upper
w	wall

Superscripts

s	stable value

reflective roof in Mexico. Pashiardis et al. [30] conducted a statistic analysis on the solar energy utilization in Cyprus.

Solar radiation is one important source of green and sustainable energy. Nevertheless, it is not always necessary as heat source for building [31], in spite of its favorite merits as sources of illumination as well as PV utilization in all the seasons. For instance, in summer, when the ambient temperature is high, the absorption of solar radiation is not demanded, because this will increase air temperature inside buildings and correspondingly increases the cooling load [32–36] for air-conditioning or ventilation. However, in winter, when the ambient temperature is low, the absorption of solar radiation will help increase air temperature inside buildings, which is good to decrease the heating load [37–40] for room-heating. That is to say, the photo-thermal (PT) utilization of solar energy in buildings should be varying in seasons, i.e. less in summer and more in winter, which calls for the adjustment of solar radiation, instead of fixed reflectivity.

Solar radiation influences the air temperature inside buildings by two ways, i.e. transmission through windows and absorption on walls as well as roofs. However, besides the solar-shading techniques on windows [41–45], little attention has been paid to the adjustment of solar radiation [46,47] on walls or roofs to control the air temperature inside, which will definitely reduce the energy consumption of HVAC in buildings and the environment disruption as well. Goldstein et al. [46] reported that the reflection of solar radiation and the emission at certain wavelengths will generate the cooling power in hot and dry weather. This is inspiring and promising, but it only works in summer for cooling and cannot solve the heating issue in winter. Zhu et al. [47] reported a long-time period experiment on the passive house with color-change in summer and winter. The results show good performances in Dalian, a city in North China. However, the couple of the color-change mechanism with the artificial operation of shuttle-window and heavy-weight wall design are not suitable for a mobile container.

In this paper, a container with steel wall is considered for the mobile or temporary housing or cargo storage, which means that the window is not considered for installation. Moreover, the demands for device mobility as well as inner-space are intense. Therefore, the techniques such as heavy thermal mass, strong insulation layer as well as solar shading, are not considered as the first choice, although they are widely accepted in designs of domestic buildings. Instead, automatic air temperature control with an optic-variable wall is proposed to reduce the energy consumption in a container, as shown in Fig. 1, according to the relationship between the solar absorptivity and the wall-painting color [10–11,47–49]. The wall is painted with a special material, the color of which is controlled by temperature. When the wall temperature increases from a low temperature, e.g. lower than set value T_{s1}, to a high temperature, e.g. higher than set value T_{s2}, the wall-color varies from dark to light, which will be discussed in details in the next section. Therefore, less cooling power in summer and less heating power in winter are possible, due to the automatic adjustment of solar radiation reflectivity by the optic-variable wall. Comparing with the applications of heavy thermal mass or strong thermal insulation, which is utilized widely in buildings, the application of OVW has potential advantages, e.g. to control the addition of weight as well as the occupation of space within an acceptable range.

In this paper, the samples of optic-variable walls (OVW) are fabricated and the feasibility of OVW is first verified with the tests on color, reflectivity. Later, the feasibility of air temperature control with OVW is verified with preliminary experiments. Then, the influence of solar radiation and ambient temperature on the air temperature inside a container is theoretically investigated with an accepted model cited from references. The stable air temperature rise and the variation range of the stable air temperature with optic-variable and optic-fixed walls are discussed under four conditions, including high and low ambient temperatures as well as large and small solar radiations. With the sample-test results, the performances of sample-walls on air temperature control are also estimated and compared with the optic-fixed and optic-variable walls. The results verify the feasibility of OVW as well as its performance on the air temperature control inside a container. Since HVAC load is related to the deviation of the air temperature inside from its set value, the results of OVW show some potential for energy-saving in containers. The results are helpful for the green design and energy saving in buildings.

2. Heat transfer model

Typical heat transfer process between the air inside and the ambient is depicted in Fig. 2. Heat is transferred in series, as in the forms of convection between the ambient $T_{ambient}$ and the outer wall T_{out}, conduction between the outer wall and the inner wall T_{in}, and convection between the inner wall and the air inside T_{air}. The solar radiation is partly reflected on the outer wall and the rest is absorbed. The heat radiation between the exterior surface and the sky or the ground is ignored [50].

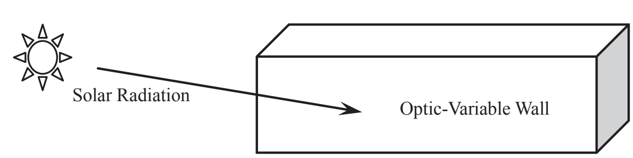

Fig. 1. Container with solar radiation.