Developing a Calcium Silicate Prefabricated Board Ventilated Wall for Building Energy Efficiency Retrofit in Hot-Humid Areas

Xu lei Jin1**, Junsong Wang2, Qing lin Meng2

1 Guangzhou Panyu Polytechnic, Guangzhou, 511483, China
2 State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, Guangdong, 510640, China
Email: 710652805@qq.com

Abstract. Ventilated wall is considered as an effective technique for building energy efficiency retrofit in hot-humid areas, and the heat exchange inside the ventilated layer blocks the heat gain into the wall. Most current researches focus on the performance assessment of the wall system but lack the optimize design of the external board. Here we demonstrated a new type of ventilated wall, using the calcium silicate material as the cladding panel for its excellent physical properties and easy installation and maintenance. In particular, the aluminum foil was attached to the interior side of the board to further lower the emissivity for achieving a better insulation effect. Based on the field experiment in summer days, the thermal performance of the new type of ventilation wall was obtained and further compared with the conventional wall. Moreover, the equivalent thermal resistance of this novel ventilated wall was also calculated. The results revealed that: the interior wall surface temperature and energy consumption of the new ventilated wall proposed was about 3-5˚C and 39.2% lower than those of the conventional wall, respectively. The low emissivity significantly insulated the heat transfer inside the cavity. In parallel, the calculated equivalent thermal resistance of the ventilation wall (0.971m²⋅K/W) was also 2.07 higher than that of the conventional wall.

Keywords: ventilated wall; calcium silicate board; aluminum foil; thermal performance

1. Introduction

Since the 21st century, a large number of energy resources have been exploited and consumed, not only causing exhaustion of fossil energy resources but also significantly influencing the human living environment [1-3]. Among which, the building section contributes to approximately 40% of world energy consumption, mainly caused by large existing buildings with poor envelopes that could not meet the request for heating and cooling [4-6]. When explicitly considering the thermal performance of different parts of the building envelope, the external walls were especially conspicuous. Previous studies revealed that the external walls contribute to about 20% of total cooling loss in China [7]. Furthermore, this situation goes even worse when combines with the climate of southern areas in China (i.e., hot-humid climate), as these places suffer the abundant rainfall and high temperatures in summer and significantly increase the operation time of air-conditioners in buildings [8]. To reduce the heating and cooling energy demand, the energy efficiency retrofit for existing buildings is essential, especially for the retrofit of the external walls [9, 10]. Among the techniques applied, the ventilated wall is considered as an effective technique, benefiting for its thermal performance as well as simple maintenance [11-13]. Reports in [14] illustrated that the well-designed ventilated wall achieved an...
energy saving even exceeding 40% in summer.

Ventilated wall is usually constructed as double-skin facades, which consists of two solid walls and is interlayered by an air gap (figure 1) [15, 16]. The cladding panel shields the solar radiation directly on the external wall. Meanwhile, the intermediate air gap allows buoyant-driven air convection to perform passive cooling. The absorbed solar radiation of the cladding panel is partitioned into three parts, including heat convection, long-wave radiation, and heat conduction. Since the thermal conductivity and heat convection of the air in the interlayer are small, the long-wave radiation dominates the heat transfer compared to convection [17, 18]. For the absorbed energy of the wall $A_{nw}$, it could be represented as:

$$A_{nw} = \frac{\sigma (T_p^4 - T_w^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_w} - 1}$$

where $\sigma$ (W·m⁻²·K⁻⁴) is the Stefan-Boltzmann constant, $\varepsilon$ is thermal emissivity, $T$ (K) is the temperature, and subscripts of “$p$” and “$w$” represents the interior surface of the cladding panel and external wall, respectively.

![Schematic diagram of heat transfer in a ventilated wall.](image)

Figure 1. Schematic diagram of heat transfer in a ventilated wall.

However, above-mentioned analysis demonstrates that the performance of ventilated wall is influenced by many factors, such as the ambient conditions (incident solar irradiation, local wind speed and direction, and air temperature), the air gap geometrical characteristics, flow regime, boundary conditions, and building materials. As a result, these uncertainties can easily lead to the instability of the performance of the ventilated wall [16, 19]. To achieve a better thermal performance, a series of strategies were put forward in previous studies based on simulation and experiments [14, 20-22]. Among which, one strategy was to decrease the temperature of the external layer, as it was controlled mainly by the solar absorbance of the cladding panel. Using materials with a high albedo / high thermal resistance could contribute to the low temperature [14]. Another way was to increase the air layer space or velocity inside the cavity to take the heat away quickly. Studies in [14, 23] found that the energy saving increased as the air cavity width $d$ raised, and such a rise turned out to be particularly marked by $d < 0.15$ m. A report in [21] showed that a velocity between 1.0 m/s and 1.5 m/s in the air gap was suggested to facilitate the convective exchanges. The last practical strategy was to decrease the thermal emissivity of the interior surface of the cladding panel ($\varepsilon_p$) or the external wall surface ($\varepsilon_w$). Simulation in [23] revealed that using low emissivity films on both sides of the channel was favorable to reduce heat gains in summer and heat losses in winter.

Unfortunately, making the outer wall highly reflective could not effectively cut down the building heat gain from the wall in tropical regions, due to the risk of albedo degradation after construction.
While for the air cavity configuration, it was too difficult to find an optimum width/thickness to reduce building heat gain [23]. Moreover, the width of air interlayer would also further increase the construction cost. In contrast, decreasing the interior surface emissivity of the cladding panel was the most practical strategy to cut down the heat gain from the outdoor. However, although simulation revealed that the decrease of emissivity significantly contributed to the insulation effect of the ventilated wall, the practices were still limited. Moreover, few field measurements were undertaken to assess the thermal performance. To fill this gap, we introduced a novel composite ventilated wall, using calcium silicate board as the cladding panel. Moreover, the aluminum foil was pasted on the back of the board to cut down the emissivity. Its thermal performance was tested through an outdoor field experiment, comparing to the conventional ventilated wall. In addition, the equivalent thermal resistance of the novel ventilated wall was also calculated to further identify the insulation performance. This study looked forward to one new technique for building energy efficiency retrofit in the subtropical area.

2. Experimental Setup

2.1. Materials

2.1.1. Calcium Silicate Board. The calcium silicate board is an inorganic construction product primarily made of siliceous materials (i.e., quartz powder, fly ash, and diatomaceous earth), calcium materials (i.e., lime, calcium carbide mud, and cement), reinforcing fibers, and auxiliaries. After matching these materials in a certain proportion, they are processed by molding and autoclaving to further shape the board. The main physical and mechanical parameters are listed in table 1. The board not only shows the properties of high density, high strength, and low water absorption but also exhibits a high performance of cold-resistant, wind-resistant, anti-wall leakage, anti-mildew, and heat insulation. With these merits, this board could meet the request of the external wall refurbishment of old buildings well, since it successfully solves the problem of leakage of external walls and the elimination of the additional load of a wall. In this study, we collected the sample of this board with yellow color with thickness of 10 cm to investigate the thermal performance.

| Item                                  | Index            | Remarks                      |
|---------------------------------------|------------------|------------------------------|
| Density                               | ≥1.25 g/cm³      | /                            |
| Thermal conductivity                  | ≤0.3 W/(m·k)     | /                            |
| Moisture Absorption                   | ≤38%             | /                            |
| Volume moisture content               | ≤10%             | /                            |
| Albedo                                | 0.35             | yellow                       |
| Freezing resistance                   | No stratification and cracking | 25 freeze-thaw cycles       |
| Water tightness                       | No water drop formed on the bottom | 24h                        |
| Non-inflammability                    | A1               | superlative degree           |
| Asbestos content                      | 100% asbestos free | safe application             |
| Shock resistance under dryness        | No through cracks on the plate | qualified                  |
| Breaking strength                     |                   |                              |
| Dryness Crosswise                     | ≥ 16.0 Mpa       | /                            |
| Dryness Lengthways                    | ≥ 11.0 Mpa       | /                            |
| Water-saturated Crosswise             | ≥ 10.0 Mpa       | /                            |
| Water-saturated Lengthways            | ≥ 7.0 Mpa        | /                            |
2.1.2. Composite Wall Structure. By using this board, two kinds of ventilated walls were fabricated to compare their thermal performance, including the ventilated wall without aluminum (I) and ventilated wall with aluminum foil (II). Their structures were demonstrated in figure 2. Generally, both I and II were mainly composed of three major parts, including the calcium silicate board, the air layer, and the structural skeletons. The calcium silicate board was fixed to the keel skeleton by rivets or fasteners, which was made of either corrosion-resistant or galvanized steel or aluminum alloy. The cavity of both I and II was set with 110mm, considering the whole structure stability. In the opposite, the only difference between I and II was the set of aluminum foil. As mentioned before, decreasing the emissivity of both the interior surface of board and the exterior surface of the wall could significantly insulate the heat into the wall. Therefore, we installed the aluminum foil on the interior surface of the board with glue to examine its thermal performance improvement. Here we did not install the aluminum on the external surface of the wall at the same time, as it was too difficult to attach the aluminum foil stably on the rough surface of the wall. While for the board, its interior surface was much smoother than that of the wall, which made the installation much easier.

![Figure 2](image)

**Figure 2.** The cross-section structure of the ventilated wall: a) installation of the ventilated walls; b) ventilated wall without aluminum foil (I); c) ventilated wall with aluminum foil (II).

2.2. Field Experiments

An experimental laboratory with $6.0 \times 5.0 \times 3.2$ m (length × width × height) was built on the outdoor open area inside the campus of the South China University of Technology for the field experiments (figure 3). Inside this laboratory, two individual rooms were built in the west side with the same size of $1.5 \times 3.0 \times 2.8$ m (length × width × height). In particular, the three inside walls of the two small rooms were treated with heat preservation, only leaving the west wall exposed to the outdoor environment.

Since there were only two rooms for the experiment, we only installed the ventilated walls on the room 2 and left the other one as a reference. For the ventilated wall setup, firstly, the calcium board without foil (I) was installed on the room 2 and its thermal performance was tested. After that, the aluminum foil was pasted on the back of the calcium silicate board (II) to further investigate the thermal performance improvement. To ensure that the board covered all the west wall of room 2, we set the board with $2.8 \times 2.3$ m (height × length), which was a little higher than that of the room 2. Besides, we painted the west wall of room 1 into yellow to keep a consistently absorbed solar radiation with the room 2.
To monitor the thermal performance of the ventilated walls (I and II), the T-type thermocouple and heat flux meters were used in this study. All these sensors on the room 1 and 2 were set in the same place and their details were demonstrated in figure 4. A total of 48 T-type thermocouples and 12 heat flux meters were applied, which the parameters of the sensors were demonstrated in table 2. For the installation of the sensors, we pasted on the wall surface with heat conduction glue and then fixed with clamps to prevent falling off. Moreover, to make ensure the sensors, which directly exposed to the sun, absorbed the same radiation with the external surfaces, we painted them to the external surface color. Meanwhile, a weather station was set close to the laboratory to log the daily meteorological data consisting of solar radiation, air temperature, relative humidity, and wind speed. All the data were collected automatically every 10 min.

Table 2. Parameters of the instruments.

| Measurement device       | Range                  | Accuracy         |
|--------------------------|------------------------|------------------|
| T-type thermocouple      | -200-120 °C            | ±0.5 °C          |
| Heat flow meter          | 0-75°C                 | ±0.5%            |
| Data logger              | -200-400°C, -20-20mV   | ±0.05%, ±0.05%   |
| Portable weather station | 73-60°C, 10-100%, 0-175mph, 0-1500W/m² | ±0.7°C ±3%, ±5%, ±5% |

All the experiments were conducted during continuous sunny days in summer, when the outdoor weather conditions were nearly the same (figure 5). Limited by the experimental condition, the
experiments were divided into two stages. The first stage was from Aug 19 to Aug 24 with the purpose of comparing the heat insulation effect (Aug 19 to Aug 21) and air conditioning energy consumption (Aug 22 to Aug 24) of I with referenced room 1. The second stage was from Aug 26 to Sep 01, also aiming to compare the heat insulation effect (Aug 26 to Aug 28) and air conditioning energy consumption (Aug 29 to Sep 01) of II with referenced room 1. Besides, during all the experiments, all the rooms were closed with nobody inside to exclude the anthropologic heat.

![Figure 5](image.png)

**Figure 5.** Weather conditions during the experiment: a) solar radiation, b) air temperature, c) relative humidity, and d) wind speed.

3. Results and Discussions

3.1. Thermal Performance

Figure 6 illustrated the external surface temperature of the calcium board of I and II, comparing with that of the referenced conventional wall. As expected, all of them showed the same change pattern in two-days experiment cycle, due to the similar reflectivity. During the daytime, the external surface temperature of them could up to 65-75 °C. However, it was noticed that the external board surface temperature of II was slightly hotter than that of the referenced wall. A plausible reason was that the calcium board’s interior surface with low emissivity hindered heat emitting to the external wall, further retained the heat at the board, and eventually increased the temperature. While for the interior surface temperature of the wall, I was 1-2 °C lower than that the referenced wall during the daytime because of the interlayer natural ventilation (figure 7a). Moreover, after adding the foil (II), the ventilated wall exhibited a better cooling performance with the interior surface temperature decreased about 3-5 °C, comparing to the referenced wall (figure 7b). The temperature difference was great at daytime but negligible at nighttime, due to the impact of the outdoor climate condition. This indicated that lowering the emissivity of the interior surface of the board could significantly decrease the surface temperature of the interior wall.
Figure 6. The external surface temperature of different wall structures. I and II represented ventilated wall without / with aluminum foil, respectively.

Figure 7. The interior wall surface temperature of different type of wall structures. I represented ventilated wall without aluminum foil. I and II represented ventilated wall without / with aluminum foil, respectively.

The inward heat fluxes into the wall were represented in figure 8. All the heat flux of I and II were lower than those of the referenced wall. More precisely, the reduced inward heat flux of II was much higher than that of I. For instance, during Aug 20-Aug 21, I only cut down a maximum inward heat flux to 8 W/m², while for II, the reduction was up to 22 W/m². It confirmed that the board with aluminum foil attached to its back effectively stopped the heat transfer into the indoor.

Figure 8. The inward heat flux of different type of wall structures. Here we defined the heat flux from outdoor to indoor as the positive direction. I and II represented ventilated wall without / with aluminum foil, respectively.
3.2. Energy Consumption
Other than comparing the thermal performance of the three type of walls, we further analyzed the energy consumption of the rooms with air-conditioning. During the experimental time, all the air conditioning were set with 26°C. We selected the accumulated daily energy consumption of air-conditioning as the evaluation indicator, as the power consumption of air-conditioning was limited by the space of the room. Since the weather conditions were nearly the same, the daily energy consumption of the two rooms remained basically stable in three days, and the average daily power consumption of the air conditioners in the room 2 with I wall was 0.78kW·h, saving 24.74% energy compared to the room 1 with referenced wall (figure 9a). This was because that natural ventilation effectively took the heat away, and further decreased the cooling load of the experimental room, thus lowering down the energy consumption. Contributing to the aluminum foil, which acted as a thermal barrier, the room 2 revealed an even lower energy consumption with average electricity per day of 0.62kW·h, which was 39.2% lower than that of the referenced room (figure 9b), demonstrating a high energy saving potential.

![Figure 9](image)

**Figure 9.** The energy consumption of rooms with different type of wall structures. I and II represented ventilated wall without / with aluminum foil, respectively.

3.3. Equivalent Thermal Resistance
Despite the qualitative analysis of the insulation performance of the studied ventilated walls, we employed the equivalent thermal resistance $R$ (m²·K/W) as the indicator for further assessment. The $R$ was calculated by using the temperature difference between the external and internal surface of the wall structure divided by the inward heat flux into the wall, which details were followed by Eqs. (2)-(5). According to the previous studies, this indicator could accurately evaluate the thermal resistance of building structures, especially when the temperature difference between the external surface and internal of the wall was larger than 8°C [24]. Hence, we chose the experimental data under air conditioning condition to increase the diversity of the interior and external temperature of different wall structure.

The temperature difference between the outer surface of the wall and the wall at i moment could be calculated as:

$$\Delta \theta_i = \Delta \theta_{i,e} - \Delta \theta_{i,i}$$  \hspace{1cm} (2)

To avoid the calculation error, the average temperature difference in the whole period was used and calculated as:
where the average heat flux through the wall in a certain period could be represented as:

\[
\bar{q} = \frac{\sum_{i=1}^{k} \Delta q_i}{k}
\]  

(4)

then we could get the equivalent thermal resistance \( R \) by Eq. (5):

\[
R = \frac{\Delta \theta}{\bar{q}}
\]  

(5)

where \( \Delta \theta \) (°C) was the surface temperature at \( I \) moment and subscripts of “e” and “i” represented the external and interior surface of the wall, respectively; \( \Delta q_i \) (W) was the heat flux of the interior surface of the wall at \( i \) moment. \( k \) was the number of the record number in one hour, here, the value of \( k \) was 6.

The calculated results were listed in Table 3. Among which, II had the best thermal insulation performance, which was 2.07 and 4.71 times higher than that of I and the referenced wall, respectively. This result further demonstrated that lowing the interior surface emissivity of the board could effectively improve the comprehensive thermal performance of the wall.

### Table 3. Equivalent thermal resistance of walls with different structures.

| Number       | T(h) | R(m²·K/W) |
|--------------|------|-----------|
| I            | 24   | 0.468     |
| II           | 24   | 0.971     |
| Referenced wall | 24   | 0.206     |

### 4. Conclusions

Ventilated wall is widely used as a passive cooling solution to reduce heat gain of building in hot and wet area in China. Here, we showed a new retrofit calcium silicate board ventilated wall to cut down the building heat gain. The thermal performance and energy consumption were obtained and compared with the conventional wall. Our observations revealed that under the similar outdoor meteorological conditions, the ventilated wall without aluminum foil (I) showed a cooling effect with interior wall surface temperature 1-2 °C lower than that conventional wall. It illustrated that the cooling effect of ventilation wall only by natural ventilation in interlayer was not significant. However, after adding the aluminum foil (II), the cladding panel’s interior surface with low emissivity effectively hindered the heat of the outdoor into the interior wall. The further analysis of daily air conditioning electricity consumption represented that the II was 0.39 times lower than that of the I, showing greater potential for energy conservation. Meanwhile, the equivalent thermal resistance of II was 4.71 and 2.07 times higher than that of I and the referenced wall, respectively.

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