Research on feature of thermal performance of integrated composite system

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Abstract
The aim of this study is to explore the effect of stud on the characteristics of thermal insulation and decoration composite system. Prior research conducted has primarily focused on the insulation material performance aside from the composite system. The theoretical calculation and field measurement method are adopted in this paper to compare the insulation performance for different building envelope systems. By considering the thermal transfer coefficient as the performance indicator, thermal bridge and air cavities of integrated insulation composite system as impact factors are investigated. Firstly, the high insulation performance of the composite system is determined via comparing other systems. Secondly, the thermal bridge issue of the composite system led by stud is subsequently investigated followed by the air cavity influenced element being studied via field measurement, which is caused by stud condition. Final results indicate that the thermal insulation and decoration composite system can achieve a substantial insulation performance. In this case, the corresponding optimal size of studs and air cavity is achieved. Further, scattered layout of air cavities could apparently improve the entire thermal system’s insulated performance. All these studied conclusions can contribute designers to implement this system more accurately.

Keywords: insulation; decoration; composite system; building envelope; air cavity; thermal bridge

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Received 21 December 2020; revised 25 January 2021; editorial decision 3 February 2021; accepted 3 February 2021

1. INTRODUCTION

Due to global urbanization trends, the requirement of building energy has received increased attention from scholars [1]. The concept of a building envelope is integral to decrease energy requirements, which takes up almost 50% of the energy consumption [2]. Notably, high-performance insulation for building envelope contributes to energy efficiency, particularly in cold climate regions. Further, it can also serve as an effective strategy for improving indoor thermal comfort condition [3, 4]. Different wall constructions correspond to disparate thermal features, with external thermal insulation systems being increasingly implemented because it can eliminate thermal bridges more effectively. Meanwhile, contrary to this, interior insulation systems tend to generate water vapour condensation [5], leading to structural damage as against the external system. In addition, according to Vereecken and Roels [6], establishing an impermeable system is one possibility to enable energy harvesting. Here, various material solutions were performed to improve insulation performance, such as oriented strand board plates [7], gypsum [8], façade impregnations [9] and capillary-active mineral insulation systems [10].

1.1. Thermal insulation material
Thermal insulation material is central to ensure insulation heat resistance in an enclosure capacity [13, 14]. In terms of ingredient composition, insulation materials can be bisected into two types, namely inorganic and organic. Inorganic thermal insulation materials include glass wool, mineral wool, asbestos, perlite, roseite, etc., while wood fibres, expanded polystyrene, polyisocyanurate, extruded polystyrene (XPS), polyurethane (PU), cork, wood and hemp fibres, etc. are organic materials [15]. Regarding heat transmission, although organic materials have better insulation properties than inorganic ones [4], the flammable characteristic of organic substances may spread fire and produce toxic gases [16].

For inorganic material, most researchers focus on its excellent performance of flame prevention. Zach et al. [17] performed experiments on fibre flax, while studying textile materials,
and developed new insulating materials to meet the physical, machinery and ecological requirements of buildings. Hamid and Wallenten [18] researched the positive influence of capillary active materials on internal wall insulation, while Feng and Janssen [19] observed that calcium silicate was a suitable material for internal insulation in construction by harnessing its high water diffusion coefficient and low moisture diffusion resistance. Chen et al. [20] invented a new type of low thermal conductivity nanocomposite paper using silica gel and nanowires. The thermal conductivity of ceramic fibre insulation materials was investigated by Headley et al. [21] and Yang et al. [23], who analysed the thermal and mechanical performance of a new inorganic material integrated with hollow glass microsphere.

With regard to organic materials, related research primarily centres attention on thermal insulation performance. Zach et al. [17] analysed and found the performance of wool thermal insulation material was similar to that of mineral wool insulation. A new insulating material was developed improving the flame resistance capability through graphene incorporated in PU foams and reducing the evolution of toxic gases in a small fire [22]. Troppova et al. [24] explored the thermal property of biological materials, such as wood base fibreboard, assessed under the thermal indicators of temperature and moisture.

Innovative hybrid insulation materials are a recent production, with two main changes to the traditional materials being noted:

- reduce the material types to improve thermal resistance of the material [25];
- replace traditional materials with ‘environmentally friendly’ materials to reduce the environmental impact [26].

When it comes to the material type, the hybrid use of multiple materials commonly induces a loss of control in the thermal characteristics of the envelope. Hence, researchers’ attention has progressively shifted towards the size and distribution of insulation instead of the material type. For instance, Cascone et al. [25] investigated the impact of the PCM thickness and location in the external wall on the building insulation performance proving the thermal conductivity of organic thermal insulation materials is lower than that of recycled ceramic-based inorganic ones. Be that as it may, as the fire protection of the building is not yet guaranteed, there is still a risk of fire spreading. For this reason, in accordance with fire standards [27], increasing the thickness of indoor insulation rather than increasing the type of materials and reducing the annual energy consumption is required.

Further, regarding the environmentally friendly material having advantages in the life circle aspect, this gradually became a hot topic of study. This was illustrated by Senga Kiess et al. [26], who demonstrated the environmentally friendly impact of hump straw insulation construction. In the 2018 solar decathlon competition, a similar material of straw produced by French was employed in the architecture designed by Xiamen University and achieved high insulation performance. However, despite significant advantages in the influence on the surrounding environment, its utilization is limited by the high cost and size and it remains in the development stage.

Natural fibre and aggregates are implemented in combination to produce high porosity insulation products in the expansion of bio-based isolation materials [17, 28, 29]. With regard to thermal conductivity, this kind of product can not only compete with traditional materials (~0.040 W·m⁻¹·K⁻¹) but also offer further environmental positive advantages. Hygroscopic, bio-based materials have demonstrated contributions in interior adaptation of temperature and relative humidity [30]. Carreras et al. [31] proposed a multi-objective optimization model optimizing the insulation thickness with high precision and minimizing the impact of energy consumption in the design stage, while Özel et al. [32] and Ashouri et al. [33] performed similar analyses to optimize the thickness of bio-based insulation materials to limit the energy requirements of the building. Moreover, scholars have begun to pay attention to the effect on energy harvesting by environmental and cost impact of bio-based insulation material [34, 35, 36, 38]. Notably, the determination of optimal thickness is also strongly influenced by the type of insulation material and its installation location [39]. Although the natural fibre and aggregates integrated into insulation materials have been commercially exploited in UK [29], the recycled ceramic-based inorganic thermal insulation materials and improved hygroscopicity of biomaterials are still in the development stage. However, the early prototypes from this material development such as foamed ceramic insulation board and ceramic fibre insulation material has partially enabled commercialization. Heat coefficient condition of building envelope construction made by materials has influence on the thermal performance.

1.2. Thermal transmittance

Thermal transmittance is vital for the whole building envelope. In the view of achieving optimal thermal transmittance value, the external facade of a building commonly should have an additional 20–25 cm of traditional thermal insulation materials with thermal conductivity of 0.030–0.040 W/(m·K) [11]. Additionally, vacuum insulation panels are composed of several multi-foil-clad porous cores of gas-phase silica with thermal conductivity of 0.005 W/(m·K) [12], enabling the objective of heat transmittance in a thin thickness with vacuum. It can also be formed from fumed silica and then evacuated. Construction adopting vacuum insulation distinctly results in a reduction in the wall thermal conductivity to 0.020 W/(m·K). Besides, thermal bridge is another significant factor impacting thermal transmittance condition.

1.3. Thermal bridge performance

Increasing the requirements for building energy efficiency leads to better insulation capacity [37]. Yet, since the heat flow of the thermal bridge is relatively independent of the insulation layer, heat is frequently lost via this thermal bridge section in the building envelope [40]. Modern building codes [42, 43] have introduced other manners of thermal flow in the past few decades, such as linear thermal bridge [41]. The effect of thermal bridges is
regarded as secondary under moderate insulation requirements but becomes progressively vital as the heat can be reduced by better insulation. Further, the lower heat transfer coefficient (U) cannot distinctly affect thermal bridge heat flux loss [44]. All relevant parameters that are used for the calculation of thermal insulation properties, such as heat insulation thickness or material coefficient of thermal conductivity, are considered to have a lower importance for building insulation ability than the thermal bridge [45].

As reported by the International Energy Agency, architecture accounts for 40% of the global primary energy consumption and 32% of the global whole final energy consumption [46]. Besides, the construction sector is often regarded as one of the most cost-effective areas to reduce energy use [47]. Immediate action to reduce building energy consumption was called for at the 21st convention on climate change, where from the Paris Accord framework was developed. Appropriate heat insulation design of the building structure is generally enough to cope with this challenge [48]. As a thermal barrier, building envelope could play a significant role in reducing the energy requirement so as to maintain a comfortable indoor environment [50]. Many recent policies in Europe, such as the Energy Performance of Buildings Directive [49] and the Energy Efficiency Directive [50] could also deal with this issue. Pursuant to recommendations, by 2050, the European commission is expected to cut the energy demand for cooling and heating by 17%, compared with 2005 levels [4].

On the basis of the aforementioned research observations, it can be ascertained that insulated construction primarily centred on the kind of material as well as corresponding sizes. Hybrid insulation material construction is an innovative structure developed in recent years and has not received enough attention, being able to integrate multiple materials together into one. The purpose of this study is to evaluate a hybrid construction referred to thermal insulation and decoration composite system that has been applied in construction of a high-rise building in Europe [51]. Firstly, the effective insulation performance of this composite system is demonstrated by comparing other systems with three typical insulated constructions. Subsequently, focusing on this effective composite system, the installation method may have influence on its insulation performance. Hence, an impact factor for insulation performance of installation component stud is investigated. Thirdly, as variation of stud may lead to air cavity change between them, so, as another potential influenced element, the air cavity is studied via field measurement. On-site measurements and theoretical computation approach were used to evaluate these influencing elements. The entire investigated workflow is as exhibited in Figure 1. The final results will contribute to future building envelope design in terms of improving insulation performance and filling the gap for investigations in the field of composite insulation systems.

In this paper, the integrated thermal insulation and decoration composite panel is introduced in the first part of methodology. The integrated composite system of Case 1 refers to the entire construction including installation section and using this composite panel as facing part. Follow-up on thermal bridges and air cavities investigation are all based on this model. In the result stage, the first studied part of Cases 1–3 proves that the integrated composite system has a better insulation performance than the other two decorative systems. The second part of Cases 4 and 5 presents the thermal bridge effect caused by installation method of integrated composite system. Subsequently, the stud size as a thermal bridge impact factor is investigated. Finally, as the stud sizes changing causes the air cavity condition variation between studs, the air cavity layout influencing thermal characteristics is studied in this part (Figure 2).

2. METHODOLOGY

2.1. Integrated thermal insulation and decoration composite panel

Building envelope construction usually consists of two main independent sub-functions, namely façade decoration and wall insulation. An innovative composite panel installed on the building envelope combines the insulation and facing materials into an
entire model that can be prefabricated beforehand. Meeting the requirements of energy efficiency and adornment function for architecture, such fabricated construction panel also prevents thermal flow. Presently, this composite board can be divided into multiple types of XPS, moulded polystyrene and PU pursuant to different insulation materials. At the same time, depending on different materials of finishing, it can also be classified into coloured aluminium board, PVC board, coloured steel plate, etc. As against the traditional external insulation structure, composite construction could save the manufactural time via factory assembly. There are three main manners for mounting in this integrated panel with regard to on-site installation. The first refers to as paste and anchoring that involves pasting the integrated sheet onto the wall with special bonding mortar and then fixing it with mechanical anchoring. The second is bolt hanging, in which assembled integrated panels are fixed on the corner code installed on the wall using bolts. The final one is the stud hanging solution, whereby composite board is fixed in advance on the studs being installed on the substrate. Figure 3 presents five typical types of integrated composite panels.

The aluminium composite panel comprises three parts: surface level of colour-coated aluminium board with 0.5-mm thickness, various colours and decorative pattern. The core material is made of PU rigid plastic foam (40 mm) and the inner finishing is 0.6-mm aluminium foil. Further, a 25-mm air layer also exists between the wall and the substrate, enhancing the thermal insulation performance of the entire external wall.

The unplasticized polyvinyl chloride (UPVC) panel is bisected into two parts: the surface layer is coated with UPVC resin decorative board with 2-mm thickness and the insulation level implements PU thermal insulation material with 13 mm. However, as the insulation thickness is only 13 mm, the overall insulation performance may be relatively poor and the waterproof performance of the system may be reduced as it lacks a waterproofing layer.

The metal composite panel combines fluoro-carbon paint, quality decorative materials and excellent thermal insulation materials (XPS board). The base material takes aluminium alloy or inorganic resin board as the decorative base forming a sandwich structure encasing insulated construction.

The stone composite panel consists of a foamed insulation and natural ultra-thin stone material. This kind of product embeds insulation material between two stone surface materials, whereby both organic and inorganic materials can be implemented as the insulation section, that is, XPS or foam glass board.

Similar with the aluminium board, the imitation stone composite panel regards inorganic or metal boards as a decorative surface combined with several insulation materials. Despite the surface having the appearance of stone finishing, this imitation component has better performance in terms of shaping ability, being able to meet the requirements of different building design. With regard to installation, this panel is hanged on the wall harnessing anchors or adhesives. These composite panels combine with corresponding installation components form homologous integrated composite system.

2.2. Three typical constructions of thermal insulation and decoration systems

Figure 4 exhibits three typical constructions of thermal insulation and decorative systems.

Case 1: integrated composite system (using above thermal insulation and decoration composite panel).

The integrated composite system is a product that integrates insulation materials with decorated surface materials into a whole construction via injection moulding process (Figure 4). It adopts aforementioned thermal insulation and decoration composite panel as the main construction. The surface level of the integrated sheet is coated by colour coatings with a thickness larger than 20 mm, enhancing the weather and corrosion resistance capability, thereby meeting the usage requirements.

Case 2: stone decorative system.

The stone decorative system mainly comprises three parts: substrate wall, insulation level and decorative layer. Insulation level primarily implements mineral wool and is adhered to the substrate wall as demonstrated in Figure 4. A large air cavity located behind the decorative level and in front of the insulation material, while the facing layer usually adopts marble, granite and stone, etc., supported by the bracket stud.
2.3. Thermal governing equation of envelope system

The heat transfer process of the enclosure primarily includes the following three aspects: (1) heat conduction between the skin components, (2) convective heat transfer between the skin and surrounding air and (3) radiation after absorbing the heat of envelope construction (Figure 5).

Table 1 lists the governing equations that control the entire thermal transmission courses as shown in Figure 6.

In the steady-state heat process, the temperature of each part for the building envelope does apparently not vary with time. Hence, each part in the wall is equal with others when it comes to the heat flux (Equations 1 and 2). The relationship between temperature and thickness is denoted by Equation (3). Predicated on the above equations, Equation (4) depicts the heat flux calculation method. Combining Equations (1)–(4), the heat flux could be computed as Equations (5) and (6). From the above equations, the amount of enclosure composed of multi-layer materials’ heat transfer coefficient is estimated as Equation (7). Thus, the total thermal resistance of enclosure structure composed of multi-layer materials is written as Equation (8). With no consideration of surface, the thermal transfer effect, this study principally investigates the solid bracket of the envelope structure. For this reason, in this study, the value of heat transfer coefficient of inner surface $a_i$ is chosen as $8.7 \text{ W/(m}^2\cdot\text{K)}$ and $a_e$ is $23 \text{ W/(m}^2\cdot\text{K)}$, which are always adopted in China [52]. Taking into account the thermal bridging system, Equation (9) represents the heat transfer coefficient calculation manner under an area-weighted pattern.

2.4. Different construct of thermal bridge cases

After proving the excellent thermal performance of composite systems, it is indispensable to perform an investigation for installation construction heat feature. As installation components mainly adopt metal structures such as stud, bolts, etc., it may lead...
**Table 1. Equations manipulating entire heat transfer process.**

| Equations | Parameters illustration |
|-----------|-------------------------|
| $\frac{d}{dt} = 0 \quad (1)$ | $t$ is temperature and $\tau$ represents time. $q_1$, $q_2$, $q_3$, $q_4$, $q_5$ (W/m²) represents the heat flux of each position in architecture enclosure. |
| $Q = q_1 = q_2 = q_3 = q_4 = q_5 \ldots \ldots \quad (2)$ | $t_i$ and $t_e$ are the temperature of interior and exterior of wall, respectively. |
| $\frac{dQ}{dt} = U \frac{dt}{dt} \quad (3)$ | $d$ is the thickness of the envelope construction. |
| $q = \frac{t_e - t_i}{\lambda d} \quad (4)$ | $\lambda$ is the heat conductivity coefficient. |
| $R = \frac{1}{\lambda d} \quad (5)$ | In this equation, $R$ is the material thermal resistance (m² K/W). $t_i$ and $t_e$ are the temperature of the interior and exterior of the wall, respectively. $d$ is the thickness of envelope construction. |
| $U = \frac{1}{\lambda d} + \sum_{j=1}^{n} R_{i,j} \quad (6)$ | $U_p$ is the main part of the heat transfer coefficient of the system except thermal bridging. $U_{B1}$, $U_{B2}$, $U_{B3}$ and $F_{B1}$, $F_{B2}$ and $F_{B3}$ are the heat transfer values and the area for various constructions resulting in thermal bridge effect, respectively. |
| $R = \frac{1}{U} + \sum_{j=1}^{n} R_{i,j} \quad (7)$ | $F_p$ represents these components’ whole area. This study utilizes the $U_m$ values to compare the resistance performance of different constructions. |
| $U_m = \frac{U_p \times F_p + U_{B1} \times F_{B1} + U_{B2} \times F_{B2} + U_{B3} \times F_{B3}}{F_p + F_{B1} + F_{B2} + F_{B3}} \quad (8)$ | $U_m$ is the area-weighted average of heat transfer coefficient for building envelope construction. |

The thermal conductivity condition of the entire construction is computed for the above three cases to investigate the impact of thermal bridge, which is generated by the bolts and studs.

The change of stud size leads to the variation of air cavity condition between them, which may affect whole system thermal insulation performance. With a view to determine the influence of the air interlayer on the heat transfer coefficient of the whole system, the temperature and heat flow data under followed three cases are investigated according to a field measurement method. In this study, the base wall is made of hollow brick and the insulation system employs an aluminium composite panel. Three cases are listed as follows (Figure 8).

- **Case 7:** no transverse stud partition is installed in the middle and the air interlayer is large and unsealed.
- **Case 8:** the transverse stud partition is in the middle and the gap between the stud and the wall is sealed with adhesive. Here, the air interlayer is a small air layer.
- **Case 9:** the transverse stud partition is installed in the middle and the gap between the stud and the wall is not sealed. Here, the air interlayer is a small air interlayer and not sealed, mostly being used in practical projects.

Under these three schemes, the heat transfer coefficients of the system are respectively measured via instruments. The specific parameters measured in the field measurement are wall heat flux, the inner and outer wall temperatures and the out temperature of the integrated board, etc., respectively.

### 3. VALIDATION

In the vein of validating the above theoretical analysis results, a field measurement by a heat flux metre instrument was performed. The HFM-201 field testing instrument for heat flow was implemented in this experiment as indicated in Figure 9.
Figure 4. Three typical constructions of thermal insulation and decorative systems.

this equipment, two performance indicators of temperature and heat flux in real-time were synchronously tested. The thermal conductivity for the whole system could be obtained by these two indicators. Case 4 of the stone decorative construction was regarded as the measurement wall, with Figure 9 exhibiting the measured locations of different probes of temperature and heat flow. Four heat flux and temperature probes were distributed at the same height at 1.5 m and were arranged at four surfaces, i.e. outer and inner decoration surfaces, outside surface of substrate wall and indoor surface. To maintain the experimental premise of 1D heat transfer, it was necessary for indoor and outdoor measuring points to be kept at the same horizontal line strictly perpendicular to the wall.

The measurement was performed in two typical seasons of winter and summer. In summer, measurements started on 15 June 2018, and ended on 17 June 2018, and 28 measurements were carried out. During winter, measurements were conducted from 5 January to 7 January 2019, with the instrument recording measured data every 10 minutes. All measurements were implemented under steady surrounding conditions avoiding the unpredictable weather situation. The whole day fluctuation range of temperature and heat flux was within five units. Four performance indicators were selected for calculating the thermal conductivity of the entire structure: \( T_0, T_1, F_{HF} \) and \( C_{HF} \). \( T_0 \) denotes the outdoor temperature and \( T_1 \) represents the indoor temperature condition. \( F_{HF} \) and \( C_{HF} \) refer to the field measurement and theoretical calculated heat flux value, respectively.

Figure 10 exhibits the measured heat flux for the whole system with studs in summer and winter. The thermal transfer coefficient \( U \) value is computed by the temperature difference and heat flux. Figure 10 further displays the changing situation of the internal and external temperatures and heat flow. Results indicate that the measured \( U \) value has a high agreement with the calculated one for both winter and summer. This can be observed by the fact that in winter, Figure 10 demonstrates the averaged measured \( U \) value with 1.26 W/m²·K is 1.6% larger than that calculated. Meanwhile, in summer, the measured \( U \) value is 1.25 W/m²·K. The maximum and minimum absolute deviations between measured and calculated value is \( \sim 2\% \) and 0.3\%, respectively. Thus, it can be seen that the calculated values can provide an accurate thermal transmittance coefficient.

The uncertainty regarding the measured and computed data is evaluated according to the standard deviation. Equation 10 presents the standard deviation calculated method. It can be observed that the smaller the standard deviation, the better the uncertainty. Table 2 depicts the standard deviation \( S \) outcome of \( U \) value for the measured and calculated in winter and summer. It can be ascertained that all \( S \) values were less than 1. Additionally, no matter summer or winter, the calculated results are smaller than the measured ones. This main reason is the influence of...
the outside inconsistent fluctuation weather condition. Yet, all measured data are in the range of less than 1, implying that this phenomenon proves that the uncertainty of all data and the measured time period could be accepted.

\[
S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2},
\]

where \( S \) represents the standard deviation, \( N \) is the amount of tested data and \( x_i \) refers to each data item. \( \bar{x} \) is the averaged value of all data.

4. RESULTS AND DISCUSSION

4.1. Comparison of three typical integrated thermal insulations and decoration composite systems of Cases 1–3

The thickness of the XPS material is achieved on the basis of a Chinese design standard referred to as GUOJI JIAN ZHU–BIAO ZHUN SHEJI J103–2~7 [53]. In the actual project, buildings follow this code for establishment. Therefore, these cases are investigated in accordance with this Chinese standard code.

Table 3 exhibits insulation parameters of Cases 1–3, with thermal resistance and heat conductivity being chosen as the performance indicators. Case 1 displays that the thermal...
transmittance coefficient of integrated composite system, without thermal bridge effect, are about 0.3 W/(m²·K). The substrate thermal performance is the major impact factor for the whole construction. The primary reason is that the entire construction of the building envelope is identical with each other in Case 1 except the substrate structure. As an example, the U value of the aerated concrete block is 0.25 W/(m²·K), which is smaller than concrete perforated bricks of 0.32 W/(m²·K).

As against the stone decorative system and colour steel decorative system, Case 1 has a much better insulation performance, which is due to the better insulation performance of air cavity and}

| Table 2. Uncertainty of the measured and calculated results. |
|-------------------------------------------------------------|
| Standard deviation | Measurement (W/m²·K) | Calculation (W/m²·K) |
| Summer              | 0.82                  | 0.54                  |
| Winter              | 0.97                  | 0.62                  |

facing material. With regard to the stone and colour steel system, because of the large air gap, the air cavity is unable to provide the effect of insulation. Further, the thermal resistance of the finishing material of stone and colour steel are also much weaker.
than the composite integrated panel with insulation. As exhibited in Table 3, for instance, the average U value of the integrated composite system of Case 1 is 0.31, while they are 0.85 and 1.09 for stone and colour steel systems, respectively, being much larger than integrated construction.

Predicated on the above analysis, apart from material and construction, the thermal bridge and air cavity situation also have a significant impact on the entire insulation system. For this reason, the thermal bridge air cavity effect is discussed in the next section.

4.2. The effect on integrated composite systems of Cases 4 and 5 by thermal bridge construction

In the last section, the U value for integrated composite system is calculated without consideration of thermal bridge effect. Equations (8) and (9) are implemented for computing the whole system thermal transfer coefficient after taking into account the thermal bridge effect. Tables 4 and 5 display the computed U values for different thermal bridge effects of bolt and stud. Corresponding parameters are computed following Equation (11).

4.3. Bolt (Case 4)

To investigate the thermal bridge effect, Cases 4–6 are constructed according to the concrete system. There are only 20 bolts in the entire construction in Case 4, but the thermal transmittance coefficient still achieves 0.42 W/(m²·K) (Table 4), which increased by 24% compared with the corresponding system with no thermal bridge. The central cause is that the heat transfer capacity of metals is far greater than other materials. Hence, the metal bolt would greatly weaken the insulation performance of the whole structure. In this case, it is better for other material bolts instead of metal to be employed, so as to improve the heat insulated performance of the entire building envelope.

4.4. Stud (Case 5)

As a significant thermal bridge construction, stud supports the composite insulation panel. The whole system is divided into three main parts, namely substrate, studs and composite panel. The total system thermal resistance is the sum of these three parts. However, the stud section combines two constituents of the air gap and metal studs. Thus, this part should be calculated according to
Table 3. Three typical construction insulation performances: thermal resistance (R value), thermal transmittance (U value) and thermal conductivity (λ value).

| Scenario                              | Interior surface | Thickness (m) | Substrate material | Thickness (m) | Screed-coat | Thickness Air cavity | Finish coat | Thickness (m) | R (thermal resistance), m² K/W | U (thermal transfer coefficient), W/(m² K) |
|---------------------------------------|-------------------|---------------|--------------------|---------------|-------------|----------------------|-------------|---------------|---------------------------------|---------------------------------------------|
| **Case 1: integrated composite system** | Plaster layer     | 0.02          | Concrete perforated bricks | 0.25          | Cement mortar | 0.02     | air                | 0.025 | Integrated insulation composite panel | 0.04                          | 2.75                              | 0.34                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
|                                       | Plaster layer     | 0.02          | Hollow clay tile   | 0.24          | Cement mortar | 0.02     | air                | 0.025 | Integrated insulation composite panel | 0.04                          | 3.02                              | 0.31                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
|                                       | Plaster layer     | 0.02          | Concrete perforated bricks | 0.24          | Cement mortar | 0.02     | air                | 0.025 | Integrated insulation composite panel | 0.04                          | 2.91                              | 0.32                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
|                                       | Plaster layer     | 0.02          | Aerated concrete block | 0.24          | Cement mortar | 0.02     | air                | 0.025 | Integrated insulation composite panel | 0.04                          | 3.81                              | 0.25                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
|                                       | Plaster layer     | 0.02          | Solid clay brick   | 0.24          | Cement mortar | 0.02     | air                | 0.025 | Integrated insulation composite panel | 0.04                          | 2.90                              | 0.32                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
| **Case 2: stone decorative system**   | Plaster layer     | 0.02          | Concrete perforated bricks | 0.24          | Stud         | 20       | XPS                | 0.025 | Stone                       | 0.030                         | 1.00                              | 0.86                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
| **Case 3: colour steel decorative system** | Plaster layer     | 0.02          | Concrete perforated bricks | 0.24          | Stud         | 20       | XPS                | 0.025 | Integrated colour plate | 0.025                         | 0.75                              | 1.10                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.021/λ:0.93 |             | R:1.09/λ:0.023 |             | R:1.48/λ:0.027 |                               |                                             |
|                                       | Plaster layer     | 0.02          | Neglect            | 0.02           | Stud         | 20       | XPS                | 0.025 | Integrated colour plate | 0.025                         | 0.75                              | 1.10                          |
|                                       | R:0.02/λ:0.93     |               |                    | R:0.83/λ:0.03    |             | R:0.008/λ:3.75 |             | R:0.58/λ:0.043 |                               |                                             |
Table 4. *U* values for bolt thermal bridge effect.

| Thermal conductivity | Area | Thickness | Thermal resistance (m²·K/W) |
|----------------------|------|-----------|---------------------------|
| 10.2 (W/(m²·K))     | 0.001m² | 0.08 m   | 0.005                     |
| U₁                   | FP   | U₁₁       | F₁₁ U (W/(m²-K))         |
| 0.34                 | 2.56 | 202.5     | 0.001 0.42               |

Table 5. *U* value for stud thermal bridge system.

| F(m²) | Thickness (m) | Sum F | R (m²·K/W) | R averaged (m²·K/W) | R sum (m²·K/W) | U (W/m²K) |
|-------|--------------|-------|------------|---------------------|----------------|-----------|
| Stud  | 0.0448       | 0.025 | 0.68       | 0.089               | 0.41           | 0.80      | 1.24      |
| Air   | 0.64         | 0.025 |           |                     |                |           |           |

Equation (11).

\[
\overline{R} = \left[ \frac{F_0}{R_{0,1}} + \frac{F_1}{R_{0,2}} + L + \frac{F_n}{R_{0,n}} \right] \varphi, \quad (11)
\]

where \( \overline{R} \) is the area-weighted averaged thermal resistance for entire system (m²·K/W) and \( F_0 \) is the total thermal transfer area perpendicular to the heat flow direction (m²). \( R_{0,1}, R_{0,2} \) and \( R_{0,n} \) are the thermal resistances for each component (m²·K/W), respectively, and \( F_1, F_2 \) and \( F_n \) are the corresponding ingredient areas (m²). \( R_i \) and \( R_e \) denote convective heat transfer coefficients for the internal and external faces of the building envelope (m²·K/W), while \( \varphi \) is the correction factor.

Table 5 exhibits the calculated result of Case 5. The width and length of stud are 0.028 and 1.6 m, respectively. Air cavity has a width of 0.4 m and length of 0.028 m as depicted in Figure 11. As for the formation of the thermal bridge effect, studs would significantly diminish the insulation performance of building envelope. Although air cavities are formed between the composite panel and substrate, studs connect the integrated panel with the substrate allowing heat stream to more easily flow into the interior via it. This is illustrated by Case 5 where the *U* value for the entire system with studs is 1.24 W/(m²·K), being 72% larger than the original construction without a homologous thermal bridge effect.

4.5. The impact of stud size on thermal insulation effect (Case 6)

Pursuant to the above results, studs have a non-negligible impact on the insulation performance. Be that as it may, the size of studs also potentially has an influence on the heat resistance of the entire building envelope. Thus, in Case 6, different experiments with various sizes of studs are performed to investigate the stud dimensions effect.

Figure 12 and Table 6 depict the *U* value’s condition as the stud dimension increases. The result indicates that the *U* value is positively correlated with the increase of the stud size and implies that the thermal resistance of the entire building envelope system monotonically reduces by enlarging the stud dimensions, being attributed to the enhanced thermal bridge effect. Specifically, as the cross-section area of stud improves, more heat flux flows into the substrate via the support studs. Namely, the *U* value is 0.87 and 1.93 W/m²·K for stud width with 0.002 and 0.042 m, respectively.

Conversely, the rate of increase for the *U* value with stud size is also computed as presented in Figure 13, with the growth rate trend being substantially different with that of the *U* value. This rate and the stud size demonstrate a nonlinear negative correlation pattern, and the rate progressively diminishes by enlarging the stud size. Nevertheless, the decreasing trend is impaired significantly and tends to 0 after the stud width of 0.035 m. In this way, it is predictable when the stud increases to a large size, as the *U* value and system thermal resistance would remain constant and no longer change. Hence, since a large stud would lead to high economic costs and heat losses, a small appropriate size for the support construction is recommended for a building envelope.
4.6. Impact on thermal insulation by air cavity pattern (Cases 7–9)

The change of stud size leads to a variation of air cavity condition between them, which may affect the whole system thermal insulation performance. Figure 14 exhibits the measured temperatures of the indoor and outdoor surfaces and heat flow fluctuation performances in summer and winter of Cases 7–9 to explore the insulation performance affected by studs and air cavities. The following observations are made.

The best insulation performance is demonstrated by the integrated composite system supported by stud and air cavity sealed by adhesive. By contrast, the worst insulated is the case without stud structure. The core reason is that the sealed and minor air cavity would effectively prevent heat convection effect and minimize the heat loss in Case 8. As an example, the U value 1.21 W/m²·K of Case 8 is substantially smaller than that in Cases 7 and 9, which are 1.65 and 1.25 W/m²·K, respectively.

The arrangement of the air layer has more effect on the thermal insulation in the integrated system than the thermal bridge. This can be explained by the air thermal resistance being much larger than the metal stud thermal bridge. Additionally, the cross-section areas of studs are much smaller than that of air cavities. Hence, the influence of the air layer on the insulation performance of the entire construction is significantly more than the thermal bridge. The U value of Case 7, for instance, apparently decreases as the number of studs increased. The U value of Case 7 in summer is 1.65 W/m²·K, being 26% larger than Case 8 with 1.21 W/m²·K and 32.4% larger than Case 9 with 1.25 W/m²·K.

As against the whole air layer for the composite system, the scattered layout of air cavities has a better insulation performance. This is primarily because the dispersed distribution of the air box could reduce the thermal convection effect, thereby improving the entire system insulation performance. Contrarily, the large entire air cavity would promote heat convection to decrease the insulation performance. This is illustrated by the U value of building envelopes incorporated with scattered air cavities, i.e. Cases 8 and 9, being distinctly smaller than the U value 1.65 W/m²·K of Case 7 with entire air gaps regardless of summer or winter.

| Width of stud (m) | U values (W/m²·K) | Rate of U values increased |
|-----------------|-------------------|---------------------------|
| 0.002           | 0.872926          | 0                         |
| 0.004           | 0.907362          | 0.039449                  |
| 0.006           | 0.94066           | 0.036698                  |
| 0.008           | 0.972876          | 0.034249                  |
| 0.01            | 1.004062          | 0.032056                  |
| 0.012           | 1.034267          | 0.030082                  |
| 0.014           | 1.063535          | 0.028299                  |
| 0.016           | 1.091911          | 0.026686                  |
| 0.018           | 1.119434          | 0.025206                  |
| 0.02            | 1.146142          | 0.023858                  |
| 0.022           | 1.17207           | 0.022622                  |
| 0.024           | 1.197253          | 0.021486                  |
| 0.026           | 1.221722          | 0.020438                  |
| 0.028           | 1.245507          | 0.019468                  |
| 0.03            | 1.268636          | 0.01857                   |
| 0.032           | 1.291136          | 0.017736                  |
| 0.034           | 1.313033          | 0.016959                  |
| 0.036           | 1.33435           | 0.016235                  |
| 0.038           | 1.355109          | 0.015558                  |
| 0.04            | 1.375334          | 0.014925                  |
| 0.042           | 1.395043          | 0.014331                  |

5. DISCUSSION

This study investigated the thermal performance of a composite insulation system. This state-of-the-art façade increasingly has...
been the main direction of future development that combines two functions of decoration and insulation. Comparing with other relative researches, this paper focuses on some detail information of composite system such as stud size and air cavity measure, which could be conducive to building designers make design more scientific.

In this investigation, integrated composite system is calculated to investigate the insulation performance in comparison with other constructions for building envelope. However, the studied cases are small parts of thermal insulation structure for architecture. Further investigations should be performed to compare heat performance with more typical constructions and other aspects rather than just insulation.

Thermal bridge is a significant impact factor that could influence the wall insulation performance. This study calculated the thermal transfer coefficient to investigate the thermal bridge effect of bolt and stud on composite system. However, both of these two materials are metal that may also affect the insulation characteristics. Hence, future studies are also needed to be performed to investigate the thermal bridging effect constructed by different materials.

In this research, the impact on insulation performance by air layout was investigated using filed measurement methodology. Further investigations are recommended to perform experiment to study the influence of thickness or size of air cavities on wall insulation performance.

6. CONCLUSION

This research explores the characteristics of the integrated composite system using a field measurement and calculation method. The thermal transfer coefficient of the U value is taken as the performance indicator and computes using theoretical calculation and field measurements, with the theoretical calculation being validated by field measurements. Thermal bridge and air cavities are evaluated to compare their impacts on insulation via the U value. Accordingly, the following conclusions are made.

- As against the stone decorative system and colour steel decorative system, the decorative composite system demonstrates much better insulation performance than the other constructions. This is attributed to the high insulation performance of the air cavity and the facing material.
- Metal bolt and studs forming a thermal bridge would significantly diminish the insulation ability of the whole building envelope. The U value is positively correlated with the increase of the stud size and implies that the resistance of the entire building envelope system would monotonically reduce by enlarging the stud dimensions.
- The rate of increase in the U value and the stud size present a nonlinear negative correlation, the rate diminishing gradually by enlarging the stud size. Nevertheless, this decreased trend would weaken significantly and tends to 0 after the stud width of 0.035 m. Thus, when the stud increases to a large size, the U
value would remain constant and the system thermal resistance would no longer change.

- The wall system with the best insulation performance is the composite integrated panel supported by stud and air cavity sealed by adhesive. The arrangement of the air layer has more effect on the thermal insulation than the thermal bridge. While the scattered layout of air cavities has a better insulation performance compared with the whole air layer pattern in the composite system.

**CONFLICT OF INTEREST**

None.

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