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A novel disinfected Trombe wall for space heating and virus inactivation: Concept and performance investigation

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HIGHLIGHTS

• A novel concept of disinfected Trombe wall with multiple use of solar energy.
• Combination of solar heating and thermal disinfection.
• Performance analysis on space heating and virus inactivation.
• A potential way to contain the aerosol transmission of COVID-19 in closed space.

GRAPHICAL ABSTRACT

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ABSTRACT

Trombe wall is a simple and mature passive solar building design while its utilization of solar energy is limited to space heating. Aerosol transmission, as a potential transmission pathway of COVID-19, poses a serious threat to the public health especially in a closed indoor environment. The thermal disinfection of virus, which can be easily integrated into solar systems, seems to be a suitable method for controlling bioaerosols. Therefore, a novel disinfected Trombe wall for virus inactivation and space heating is proposed, providing a potential way to fight the current COVID-19 pandemic. After the proposal of the concept, its performance on space heating and virus inactivation was investigated through experimental and simulation methods. The main results were as follows: (1) The average thermal efficiency was 0.457 and the average indoor temperature was 20.7 °C, 1.9 °C higher than the ambient temperature. (2) The maximum single-pass inactivation ratio was 0.893, 0.591 and 0.893 while the total production of clean air was 112.3, 63.8 and 114.7 m³ for SARS-CoV-1, SARS-CoV-2 and MERS-CoV, respectively. (3) The increase of ambient temperature or solar irradiance may enhance the thermal efficiency while the former has little effect on the thermal disinfection process. (4) Extending the height or narrowing the thickness of the duct by 40% may contribute to an increase in total production of clean air by 510 m³ or 681 m³ per unit area during the heating seasons, but the later may cause a larger decrease (about 8%) in the heat gain of indoor air.

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1. Introduction

The development of society and the improvement in living standards speed up the consumption of fossil energy, which results in the exacerbation of the energy crisis. As a major energy consumer, buildings account for 40% of the total energy consumption, mainly for heating, ventilation and air conditioning (HVAC) [1]. The utilization of renewable energy, especially solar energy [2], instead of fossil energy to satisfy part of the demands of HVAC in buildings may alleviate the problem to some extent [3]. For this reason, various solar building designs have been proposed in the past decades, from which the Trombe wall stands out due to its simple configuration, high efficiency and zero running cost [4].

As a passive solar building design for space heating, a typical Trombe wall is composed of a glass cover, a massive wall with absorbing coating on its exterior surface, an air duct and several vents [5]. Space heating is realized by the air circulation between the duct and the indoor environment, during which period air is heated through natural convection by the absorbing coating whose temperature rises up quickly due to absorption of solar radiation. Besides, part of the heat is transferred to the massive wall, which enables the system to improve the indoor thermal comfort at night through heat convection and radiation. Although the Trombe wall has the merits mentioned above, there is still room for improvement, such as enhancement of thermal performance and extension of functionality.

In order to improve the thermal performance of a Trombe wall, efforts have been made in the modification of its structure. To overcome the shading effect, Rabani et al. [6] replaced the opaqued material with glass at both sides of the air duct, which contributed to a 16% increase in average solar irradiance. This strategy was also adopted by Dong et al. [7], in whose research selective coating was employed as well to reduce the radiant heat loss. The experimental results revealed that the average indoor temperature of the test room could be 3.5 °C higher than that of the contrast room. To increase the thermal resistance, a composite wall with a porous absorber placed between the glass cover and the massive wall was proposed by Chen et al. [8]. The porous absorber could act as a semi-thermal insulator at times lack of solar radiation, resulting in a better performance at night or on a cloudy day. To enhance the heat preservation of Trombe walls at night, Hou et al. [9] installed a panel curtain in the cavity, resulting in an increase in the average indoor temperature by 2.01 °C in the nighttime. As an effective way to improve the thermal insulation performance, enclosed air gap was also employed in some researches on Trombe wall [7,10]. Besides, the incorporation of phase change materials (PCMs) into building facades has gained popularity due to its ability to enhance the heat storage capacity and reduce the heat loss in heating seasons or lower the cooling load in non-heating seasons [11]. A PCM-encapsulated Trombe wall system was proposed by Li et al. [12] and the numerical analysis indicated that an average nighttime room temperature enhancement of 20.2% could be obtained when compared to the case without PCMs. To enhance the natural convection in the air duct, vertical and transparent partitions were interposed by Bairy et al. [13], resulting in an increase between 10.0% and 14.4% in the natural convective heat transfer according to different aspect ratios.

Apart from the improvement of thermal performance, the extension of functionality has also received considerable attention in researches on the Trombe wall. Since Ji et al. [14] proposed the concept of PV-Trombe wall with functions of both power generation and space heating, a series of studies concerning the combination of PV cells and the Trombe wall have been carried out. Jiang et al. [15] investigated the influence of PV coverage ratio on the performance of the proposed system and found that with the variation of coverage ratio, the indoor temperature difference could reach 6.8 °C while the fluctuation of electrical efficiency was less than 0.5%. The influence of PV cells on the thermal performance was attributed to the PV cells laminated on the glass cover shading the absorber from the incident solar radiation. For this reason, Hu et al. [16] proposed a novel PV blind-integrated Trombe wall system, in which the PV cells were integrated on adjustable blind slats, enabling part of the solar radiation to project on the massive wall. Compared to Trombe walls with PV cells laminated on the glass cover or attached to

### Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | area, m²    |
| c      | specific heat capacity, J/(kg·K) |
| d      | thickness, m |
| Eₐ     | activation energy, J/mol |
| G      | solar irradiance, W/m² |
| H      | height, m |
| h      | heat transfer coefficient, W/(m²·K) |
| k      | rate constant, 1/s |
| N      | viral titer, TCID₅₀/L |
| Q      | volume flow rate, m³/s |
| R      | thermal resistance, (m²·K)/W universal gas constant, J/(mol·K) |
| r      | inactivation rate, TCID₅₀/(m³·s) |
| T      | temperature, K |
| u      | air velocity, m/s |

### Subscripts

| Subscript | Description |
|-----------|-------------|
| a         | air         |
| amb       | ambience    |
| b         | back plate |
| ex        | exterior    |
| g         | glass cover |
| in        | inlet; interior |
| ins       | insulation |
| out       | outlet      |
| p         | plate       |
| r         | room        |
| s         | sky         |
| th        | thermal     |
| w         | massive wall |

### Abbreviation

| Abbreviation | Description |
|--------------|-------------|
| CADR         | clean air delivery rate |
| PV           | photovoltaic |
| RMSE         | root mean square error |
| TIMs         | transparent insulation materials |
| UV           | ultraviolet |
| IAQ          | indoor air quality |
| VOCs         | volatile organic compounds |
| HVAC         | heating, ventilation and air conditioning |
| PCM          | phase change material |

### Greeks

| Greek | Description |
|-------|-------------|
| ρ     | density, kg/m³ |
| λ     | thermal conductivity, W/(m·K) |
| σ     | Stefan-Boltzmann constant, W/(m²·K⁴) |
| ε     | emissivity |
| α     | absorptivity |
| τ     | transmissivity |
| η     | efficiency |
| β     | expansion coefficient, 1/K |
The massive wall, the proposed system is superior to the other two by a 45% increase in total energy saving [17]. Besides, considering the shading effect of the PV blind slats, a bi-directional slat control method was recommended by Hong et al. [18] to improve the performance of power generation. For further enhancement on the electrical efficiency, Xu et al. [19] proposed a hybrid BIPV/T solar wall system with PV cells laminated on the absorber plate and water pipes welded on its back, thus realizing the cooling of PV cells and the production of hot water in non-heating season.

Although the high-grade electricity can be generated by PV-Trombe wall, this is achieved at the cost of decrease in thermal efficiency [20]. Then, efforts have been devoted to novel Trombe wall designs with new functions but little adverse impact on the thermal performance. Considering the fact that indoor air quality (IAQ) has received more and more concern, the air-purification Trombe wall was proposed by Yu et al. [21], which aimed to degrade the volatile organic compounds (VOCs) contained in room air during the heating process. According to the purification principles, the air-purified Trombe wall can be divided into two types: photocatalytic-oxidation Trombe wall (PC-Trombe wall) [22] and thermal-catalytic-oxidation Trombe wall (TC-Trombe wall) [23, 24]. The contaminants (e.g. formaldehyde) in contact with the catalyst layer could be degraded into harmless substances through the corresponding catalytic oxidation reactions.

In addition to VOCs, the indoor air pollution also includes bio-aerosols which are able to transmit microbial pathogens and cause diseases in humans. As to the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) which causes the recent outbreak of the Coronavirus Disease 2019 (COVID-19), apart from the reported transmission pathway of inhalation of virus-laden droplets and contact with infected individuals or contaminated surfaces [25], aerosol transmission is assumed to be an additional, yet important pathway [26], considering the detection of SARS-CoV-2 RNA in aerosol samples, especially from areas with poor ventilation [27]. Another research on its stability reveals that SARS-CoV-2 is able to stay infectious for over 3 h in aerosols [28], which further confirms the plausibility of aerosol transmission of the pandemic. It should be noted that virus-containing aerosols can be released from infected individuals by sneezing, coughing, talking and even breathing [29]. Then, infections will occur once the inhaled viral particles reach the infectious dose, which is more likely to happen in a closed environment. In this way, ventilation seems to play an essential role in containing the aerosol transmission of SARS-CoV-2 [30]. However, for the purpose of reducing energy consumption of space heating in winter, the windows and doors are all locked up tightly to form an airtight indoor environment, thus posing a serious threat to human health. Therefore, to meet the challenge of the current COVID-19 pandemic, it is of great significance to find approaches to preventing or slowing down the accumulation of virus concentration in confined spaces with poor ventilation.

Fortunately, just like other members of Betacoronavirus genus, such as SARS-CoV-1 and Middle East respiratory syndrome coronavirus (MERS-CoV), the viability of SARS-CoV-2 is sensitive to environmental parameters, including temperature and humidity [31, 32]. For SARS-CoV-2 in virus transport medium, only a 0.57 log-unit (73%) reduction in viral titer was found at 22 °C after 12 h. However, the time for a significant reduction (greater than 4.8 log-unit, 99.998%) in viral titer was reduced to 30 min at 56 °C or 5 min at 70 °C [33]. Besides, with the incubation temperature increased to 95 °C, a 5.6 log-unit (99.9997%) reduction in viral titer could be achieved within 2.5 min [34]. Recently, Yu et al. have designed and fabricated a novel Ni-foam-based filter for inactivation of aerosolized SARS-CoV-2. The results of virus test revealed that 99.8% of the aerosolized SARS-CoV-2 could be caught and killed by a single pass through the filter which was heated up to 200 °C [35]. As to relative humidity, however, its impact seems to be mainly on aerosol deposition rather than virus inactivation. According to the experiments conducted by Dabisch et al. [36], the influence of relative humidity on virus inactivation seems to be far less important than that of temperature, especially a high temperature [32]. Then, only the impact of temperature is emphasized in the process of virus inactivation here and the higher the temperature is, the faster the inactivation process will be.

Considering that the thermal disinfection process can be easily integrated into solar systems, the concept of making use of Trombe wall to inactivate airborne viruses during the heating process was proposed. However, for the traditional Trombe wall with absorbing coating, in order to reduce the flow resistance, the thickness of air duct is usually in the range of 0.1–0.3 m [37, 38], leading to the temperature rise of air being too small to inactivate the airborne viruses within a short exposure. As a contrast, when selective coating is employed and the duct thickness is decreased, the air in the duct could be heated to a temperature as high as 80 °C at the outlet under certain circumstances [39]. Besides, the research conducted by Grinshpun et al. [40] indicated that about 90% of MS2 virions would lose infectivity during an exposure (~0.1–1 s) to temperatures of up to ~90 °C, which demonstrated the feasibility of dealing with airborne viruses through short-term exposure to high temperatures. Then, as a device which continuously exposes the indoor air to high temperature environment, such a Trombe wall seems to have the potential to play a role in curbing the aerosol transmission of SARS-CoV-2 and providing space heating simultaneously in a closed environment. Therefore, to realize the multiple utilization of the solar energy harvested by Trombe wall, the novel concept of solar building integrated thermal disinfection and heating system is firstly proposed in the article. The hybrid system with simple structure and high-efficient performance aims to provide a warmer and healthier indoor environment, and at the same time, provide a potential way to fight the current COVID-19 pandemic.

The main parts of the article involve: (1) proposal of a novel hybrid disinfect Trombe wall for virus inactivation and space heating, (2) experimental study on the thermal performance of the system, (3) establishment of heat and mass transfer model of the system, (4) performance evaluation of virus inactivation for three types of corona viruses, (5) parametric study on the impact of environmental parameters and the air duct size on the system performance.

2. Concept proposal and system description

Here, the novel concept of the disinfected Trombe wall for virus inactivation is established, whose main parts are illustrated in Fig. 1. As shown in Fig. 1, the physical concept of the disinfected Trombe wall for inactivation of COVID-19 virus and space heating. (1: Glass cover; 2: Closed air gap; 3: Absorber plate with selective coating; 4: Air duct; 5: Back plate; 6: Insulation layer; 7: Massive wall).

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**Fig. 1.** The concept of a novel hybrid disinfected Trombe wall for inactivation of COVID-19 virus and space heating. (1: Glass cover; 2: Closed air gap; 3: Absorber plate with selective coating; 4: Air duct; 5: Back plate; 6: Insulation layer; 7: Massive wall).
inactivation and space heating is proposed. The schematic diagram of the system is shown in Fig. 1. The main parts of the system consist of a glass cover, an absorber plate, a back plate, a massive wall, air vents and insulation materials. A closed air gap is formed by the glass cover and the absorber plate while an air duct connected to the indoor environment is shaped by the absorber plate and the back plate.

The fundamental running principles of the system are illustrated as follows. When the sun illustrates on the system in winter, most of the solar radiation transmits the glass cover and heats the absorber plate. Then, due to the temperature difference between the absorber plate and the air in the duct, the heat is transferred from the former to the latter by natural convection. During this period, the indoor air flows into the air duct and reaches a much higher temperature before entering the room, which makes it possible to inactivate the airborne viruses in a short exposure time. In this way, space heating and virus inactivation are realized at the same time in the system.

As mentioned above, temperature is a critical influencing factor in the process of virus inactivation: the higher the temperature is, the faster the inactivation process will be. In order to reach a high air temperature, the following measures have been taken in the design of the hybrid system. Firstly, materials with spectral selectivity are coated on the exterior surface of the absorber plate, which enables it to have high absorptivity to solar radiation but low emissivity in long wave band, thus improving the thermal performance. Secondly, there is an enclosed air gap between the glass cover and the absorber plate, aiming to reduce heat loss to the ambient environment [10]. Thirdly, an insulation layer is attached to the massive wall to decrease heat conduction into the room, thus increasing the heat gain of the air in the duct. Besides, the air duct is 0.04 m in thickness, which is much smaller than that of conventional Trombe walls. As a result, though the thermal efficiency is decreased, a much higher temperature is achieved, which enables the system to inactivate the airborne viruses during the heating process.

3. Experiment

Since air temperature in the duct plays an important role in the performance of both space heating and virus inactivation, an experiment was carried out to investigate the thermal performance in Xining, Qinghai Province. The hybrid disinfected Trombe wall was installed on the south wall of a test room (6 m long × 3 m wide × 3 m high). The Trombe wall was connected to the indoor environment through an upper vent and a lower vent, both with an area of 0.048 m². The size of the proposed system was 2 m in height and 1 m in width. Besides, the thickness and detailed thermophysical properties of each part is presented in Table 1.

The schematic diagram of the experiment rig is presented in Fig. 2, indicating that the parameters need to be measured include solar radiation intensity, temperature and air velocity. The wind speed data were obtained from the local meteorological station while other environmental parameters including the ambient air temperature and the global solar irradiance on the south wall were measured by thermocouple and pyranometer, respectively. Apart from the environmental parameters, temperatures of the glass cover, the absorber plate, the back plate, the interior surface of the massive wall, the air at the inlet and outlet and the air indoor were tested with thermocouples. As to the air velocity in the duct, a hot-wire anemometer was employed for measurement. The accuracy of the measuring instruments is presented in Table 2.

The experiment was conducted from 9:00 to 17:30 on 20th October 2015, during which time the indoor air vents were open while others were closed. Due to the high risk of infection and the lack of experiment conditions, the field test of virus inactivation by the proposed system was difficult to be conducted. Although experimental study on the disinfection performance were not conducted, the feasibility of such a system on dealing with airborne viruses can be anticipated according to the experiments conducted by Yu et al. [35] and Grinshpun et al. [40]. Besides, our group will seek cooperation with qualified laboratories to do such experiments in the future. As a result, only the thermal performance was tested in this experiment, from which the velocity and the temperature of air in the duct were derived. Based on that, the performance of heat inactivation of virus was simulated with the model for virus inactivation which will be discussed later.

| Table 1 | Detail parameters of the hybrid disinfected Trombe wall system. |
| --- | --- |
| Symbol | Explanation | Unit | Value |
| $\rho_c$ | density | kg/m$^3$ | 2500 |
| $c_p$ | specific heat capacity | J/(kg K) | 840 |
| $d_l$ | thickness | M | 0.003 |
| $\lambda_l$ | thermal conductivity | W/(m K) | 0.09 |
| $\alpha_l$ | absorptivity | – | 0.1 |
| $\varepsilon_l$ | emissivity | – | 0.6 |
| $\tau_l$ | transmissivity | – | 0.9 |
| $\rho_p$ | density | kg/m$^3$ | 2710 |
| $c_p$ | specific heat capacity | J/(kg K) | 902 |
| $d_p$ | thickness | M | 0.003 |
| $\lambda_p$ | thermal conductivity | W/(m K) | 236 |
| $\varepsilon_p$ | emissivity | – | 0.10 |
| $\alpha_p$ | absorptivity | – | 0.95 |
| $\rho_a$ | density | kg/m$^3$ | 1.18 |
| $c_a$ | specific heat capacity | J/(kg K) | 1005 |
| $d_a$ | thickness | M | 0.04 |
| $\lambda_a$ | thermal conductivity | W/(m K) | 0.026 |
| $\nu_a$ | kinematic viscosity | m$^2$/s | $1.58 \times 10^{-5}$ |
| $\rho_b$ | density | kg/m$^3$ | 2710 |
| $c_b$ | specific heat capacity | J/(kg K) | 840 |
| $d_b$ | thickness | M | 0.005 |
| $\lambda_b$ | thermal conductivity | W/(m K) | 236 |
| $\varepsilon_b$ | emissivity | – | 0.4 |
| $\rho_w$ | density | kg/m$^3$ | 1800 |
| $c_w$ | specific heat capacity | J/(kg K) | 840 |
| $d_w$ | thickness | M | 0.3 |
| $\lambda_w$ | thermal conductivity | W/(m K) | 0.814 |
| $\rho_{ins}$ | density | kg/m$^3$ | 750 |
| $c_{ins}$ | specific heat capacity | J/(kg K) | 2710 |
| $d_{ins}$ | thickness | M | 0.035 |
| $\lambda_{ins}$ | thermal conductivity | W/(m K) | 0.03 |

![Fig. 2. The schematic diagram of the experimental set-up.](image-url)
4. System model and performance evaluation

4.1. Heat and mass transfer model

To simulate the operation of the system, the heat transfer model and mass transfer model need to be set up at first. The heat transfer model can be divided into five parts, including the models of the glass cover, the absorber plate, the air in the duct, the back plate and the massive wall while the mass transfer related to thermal inactivation of virus is only considered in the air duct. In order to simplify the model, several assumptions have been made, which are as follows: (1) the thermophysical properties are assumed to be constant; (2) the temperature gradients of all parts are considered to be one dimensional, which are in the thickness direction for the massive wall while in the height direction for other parts; (3) the edges of all parts are insulated well, then the heat loss at the edges can be ignored; (4) the deposition of aerosols when travelling through the duct is negligible.

4.1.1. Heat transfer model

For the glass cover, the temperature gradient in the thickness direction can be neglected, then the energy balance equation is expressed as:

\[ \rho_g \varepsilon_g \frac{dT_g}{dt} = \frac{\partial^2 T_g}{\partial y^2} + \frac{h_{g,pb}(T_a - T_g) + h_{g,amb}(T_{amb} - T_g) + h_{g,p}(T_p - T_g) + \alpha_g G}{\rho_g c_p \varepsilon_g} \]  

(1)

where \( \rho_g \), \( \varepsilon_g \) and \( d_y \) are the density, the specific heat capacity and the thickness of the glass cover, respectively; \( \alpha_g \) is the thermal conductivity of glass; \( h_{g,pb} \) is the absorptivity of glass to solar radiation, \( T_a \) and \( T_{amb} \) refer to the temperature of the back plate and the ambient temperature, respectively. According to the literature [41], the sky temperature can be calculated by:

\[ T_s = 0.0552T_{amb}^{1.5} \]  

(2)

\( h_{amb} \) is the convective heat transfer coefficient between the glass cover and the ambient environment while \( h_i \) represents radiant heat transfer coefficient between them [42]:

\[ h_i = \varepsilon_g \sigma(T_s^4 + T_g^4)(T_s + T_g) \]  

(3)

where \( u_{amb} \) is the ambient wind velocity; \( \varepsilon_g \) is the emissivity of the glass cover.

The overall heat transfer coefficient \( h_{g,p} \) between the glass cover and the absorber plate is determined by the radiative and convective contribution to the heat transfer:

\[ h_{g,p} = \frac{\sigma(T_s^4 + T_g^4)(T_s + T_g)}{1/\varepsilon_g + 1/\varepsilon_p - 1} + \frac{Nu_{g,p}}{d_y} \]  

(5)

where \( \varepsilon_p \) is the emissivity of the absorber plate; \( d_y \) is the thickness of the closed air gap between the glass cover and the absorber plate; \( \lambda_g \) is the heat conductivity of air. The Nusselt number is calculated by [43]:

\[ Nu = 0.197(Gr_d P_r)^{1/4}(d_y/H)^{1/9} \]  

(6)

\[ Gr_d = \frac{g \beta \Delta T d_y^3}{\nu^2} \]  

(7)

where \( H \) is the height of the absorber plate; \( \beta \) is the coefficient of heat expansion of air; \( \Delta T \) refers to the temperature difference between the absorber plate and the glass cover.

For the absorber plate, similar to the glass cover, temperature gradient is only considered in the height direction. Then the governing equation can be written as:

\[ \rho_p c_p \frac{dT_p}{dt} = \frac{\partial^2 T_p}{\partial y^2} + h_{p,amb}(T_{amb} - T_p) + h_{p,p}(T_p - T_p) + \alpha_p G \]  

(8)

where \( \alpha_p \) and \( d_y \) are the transmissivity of the glass cover and the absorptivity of the absorber plate to solar radiation, respectively; \( T_a \) is the temperature of the air in the duct while \( T_{amb} \) represents the temperature of the back plate; \( h_{p,amb} \) is the radiant heat transfer coefficient between the absorber plate and the back plate, of which the calculation is similar to that of the radiative contribution in Equation (5). \( h_{p,p} \) refers to the convective heat transfer coefficient between the absorber plate and the flowing air in the duct, the value of which is given by empirical equations as follows [44]:

\[ Nu_{p,p} = 0.12(Gr_p P_r)^{1/3} \]  

(9)

\[ h_{p,p} = \frac{Nu_{p,p} \alpha_p}{d_y} \]  

(10)

where \( d_y \) is the thickness of the air duct.

With respect to the air in the duct, the temperature \( T_d \) and the velocity \( u_d \) are both averaged over the cross section perpendicular to the flow direction. Then, the energy balance equation can be expressed as:

\[ \rho_a c_a \frac{dT_a}{dt} = -\rho_a c_a u_d \frac{\partial T_a}{\partial y} + h_{a,amb}(T_{amb} - T_a) + h_{a,ex}(T_a - T_d) \]  

(11)

where the air velocity \( u_d \) is related to the temperature difference, the length of the duct, the friction at the inlet and outlet and other factors, which is calculated by the following empirical equation [38]:

\[ u_d = \sqrt{\frac{2g\beta(T_{amb} - T_{in})}{C_1(A/A_{in})^2 + C_2(A/A_{out})^2 + C_3}} \]  

(12)

where \( T_{in} \), \( T_{out} \) are the inlet air temperature and the outlet air temperature; \( A_{in} \) and \( A_{out} \) are the area of the cross section of the duct, the inlet area and the outlet area, respectively. \( C_1 \), \( C_2 \) and \( C_3 \) are constants determined by the structure of the duct.

As to the back plate, the one dimensional heat transfer equation can be written as:

\[ \rho_c c_c \frac{dT_c}{dt} = \lambda_{c,p} \frac{\partial^2 T_c}{\partial y^2} + \frac{h_{c,amb}(T_{amb} - T_c) + h_{c,b}(T_c - T_b) + \lambda_{c,amb}T_{amb} - T_c}{d_y} \]  

(13)

where \( \lambda_{c,amb} \) and \( d_y \) are the thermal conductivity and the thickness of the thermal insulation material; \( T_{amb} \) refers to the temperature of the exterior surface of the massive wall. To make sure the simulation can be conducted successfully, the heat conduction through the insulation layer is assumed to be stable. This assumption is reasonable to some extent considering its low heat capacity.

For the massive wall, temperature gradient is only considered in the thickness direction, then the transient heat conduction equation is expressed as:

\[ \rho_w c_w \frac{dT_w}{dt} = \alpha_{w,amb} \frac{\partial T_w}{\partial t} \]  

(14)

The boundary conditions at the exterior and interior surface of the massive wall can be written as:

\[ -\lambda_{w} \frac{\partial T_w}{\partial y} |_{y=0} = \lambda_{w,amb} \frac{T_w - T_{amb}}{d_y} \]  

(15)

\[ \lambda_{w} \frac{\partial T_w}{\partial y} |_{y=d_y} = h_{w}(T_w - T_{w,ext}) \]  

(16)

where \( T_w \) \& \( T_{w,ext} \) are the indoor temperature and the temperature of the interior surface of the massive wall, respectively; \( h_{w,ext} \) refers to the convective heat transfer coefficient between the massive wall and the indoor air, which can be calculated by [45]:

\[ h_{w,ext} = \frac{1}{\frac{1}{h_{w,amb}} + \frac{1}{\frac{h_{w}}{d_y}}} \]  

(17)

\[ h_{w} = \frac{h_{w,amb} + \lambda_{w,amb}d_y}{d_y} \]  

(18)
\[ h_{cr} = 2.03 \Delta T^{1.4} \]  

where \( \Delta T \) is the temperature difference between the interior surface of the massive wall and the indoor air.

### 4.1.2. Mass transfer model

To set up the mass transfer model, the model for heat inactivation of virus should be figured out in advance. Rosenberg et al. [46] reported that there was quantitative evidence for protein denaturation as the cause of thermal death of virus and bacteria. Then, virus inactivation occurs once the thermal denaturation of the proteins that comprise each virion happens. According to the literature [47], the first-order reaction kinetic model has been widely used for the analysis of protein denaturation and thermal injury of cells and tissues. Therefore, this model is employed here to describe the exponential decay of viral titer at a certain temperature:

\[ N(t) = N_0 \exp(-kt) \]  

where \( N(t) \) refers to the infectious viral titer after an exposure time \( t \) while \( N_0 \) is the initial infectious viral titer. The unit of titer is expressed as 50% tissue culture infectious dose (TCID\(_{50}\)) per liter air here, which means that the viruses collected from per liter air can still kill 50% of infected hosts even after being diluted to \( N \) times; \( k \) is the first order rate constant which is related to the exposure temperature. Equation (18) can also be written as:

\[ \log_{N_0} N(t) = -\frac{t}{D} \]  

where \( D \) is the time required for a 90% decrease of the infectious viral titer. When a linear regression analysis is made between \( \log_{N_0} N(t) \) and \( t \), the D-value can be attained easily from the slope of the fitting line. The D-value is associated with the \( k \)-value by the following equation:

\[ k = \frac{\ln(10)}{D} \]  

According to Equation (16), the inactivation rate of viruses at a certain temperature can be calculated by:

\[ r = \frac{dN(t)}{dt} = -kN_0 \exp(-kt) = -kN(t) \]  

As shown in Equation (21), the inactivation rate is proportional to the viral titer and the proportionality coefficient is the rate constant \( k \). Considering that the rate constant of protein denaturation is typically given by the Arrhenius equation [47] and that this equation has already been used for describing thermal inactivation of different kinds of viruses (including SARS-CoV-1 [48], MNV-1 [49], HAV [50] and so on), the temperature dependence of virus inactivation is then described as:

\[ k = A \exp\left(-\frac{E_a}{RT}\right) \]  

\[ \ln(k) = \ln(A) - \frac{E_a}{RT} \]  

where \( A \) is a frequency factor; \( E_a \) represents the activation energy of the virus; \( R \) is the universal gas constant; \( T \) is the absolute temperature.

With Equation (23), the association between the rate constant \( k \) and the exposure temperature \( T \) can be obtained by fitting \( \ln(k) \) versus \( 1/T \) linearly. According to the research conducted by Yap et al. [51], a linear correlation was found between \( \ln(A) \) and \( E_a \) obtained from the inactivation processes of different types of coronavirus. Such linear correlation was also reported in the process of protein denaturation [47], which further demonstrates the close relationship between virus inactivation and protein denaturation. Then, three types of coronavirus, including SARS-CoV-1, SARS-CoV-2 and MERS-CoV were chosen in this research for analysis due to their potential of aerosol transmission. The experimental data in relevant literature were fitted according to the model described above.

Take SARS-CoV-2 for example, the stability of it was measured by Chin et al. [33] at different temperatures. In their research, SARS-CoV-2 in virus transport medium was incubated for up to 14 days and then tested for its infectivity. First, with the data of viral titer \( N(t) \) at different times, the D-value or \( k \)-value under each temperature was obtained by fitting \( \log_{N_0} N(t) \) versus \( t \) linearly according to the first-order kinetic model. The fitting parameters are presented in Table 3. After that, a linear regression analysis was made between \( \ln(k) \) and \( 1/T \) on the basis of Equation (23) to figure out the dependence of rate constant on the temperature. The fitting line is shown in Fig. 3, indicating that the variation of rate constant with temperature corresponds well with the Arrhenius equation. Similarly, such linear regression analysis was repeated for SARS-CoV-1 and MERS-CoV, of which the fitting parameters are presented in Table 4.

For the heat inactivation of virus, the mass transfer taking place in the duct is assumed to be one dimensional, as shown in Fig. 4. Then, the mass transfer equation can be written as:

\[ W_d \frac{dN}{dy} = Q(N - N(y + dy) + rW_d dy \]  

where \( W, d_a \) are the width and thickness of the air duct; \( N \) is the concentration of the airborne virus with infectivity; \( Q \) denotes the volume flow rate of air; \( r \) refers to the inactivation rate of virus in per unit volume air, of which the expression is given by Equation (21). Then, the equation is rearranged into:

\[ \frac{dN}{dt} = -u_a \frac{dN}{dy} - kN \]  

with the equations mentioned above, the simulation was conducted after the discretization of each equation in MATLAB. The process of the simulation is shown in the flow chart in Fig. 5.

### 4.2. Performance evaluation

The proposed system can realize space heating and virus inactivation simultaneously in winter. Therefore, these two aspects should be taken into consideration in the criterions for performance evaluation.

With respect to the thermal efficiency, it is defined as the heat gain of the air flow travelling through the duct divided by the solar radiation received by the collector, which is presented as follows:

\[ \eta_{th} = \frac{\rho_a C_a Q_a (T_{out} - T_{in})}{GA} \]  

The average thermal efficiency can be obtained by integrating the heat gain and the solar radiation from the initial time to the final time:

\[ \eta_{th} = \frac{\int \rho_a C_a Q_a (T_{out} - T_{in}) dt}{\int G A dt} \]  

As to the process of virus inactivation, the single-pass inactivation ratio \( \epsilon \) and the clean air delivery rate \( CADR \) are employed to evaluate the performance. The single-pass inactivation ratio is defined as the proportion of the inactivated virus in a single pass while clean air delivery

| Temperature (°C) | D-value (s)   | k-value (1/s) | R²  |
|-----------------|--------------|---------------|-----|
| 4               | 2.31 × 10⁵   | 9.95 × 10⁻⁵   | 0.58|
| 22              | 1.99 × 10⁵   | 1.16 × 10⁻⁵   | 0.98|
| 37              | 2.49 × 10⁵   | 9.29 × 10⁻⁵   | 0.99|
| 56              | 1.91 × 10⁵   | 1.21 × 10⁻²    | 0.94|
| 70              | 4.11 × 10⁵   | 5.60 × 10⁻²    | 0.99|
The rate is defined as an equivalent volume flow rate assuming a total inactivation of virus at the outlet:

\[ \varepsilon = \frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}}} \quad (28) \]

\[ \text{CADR} = Q \varepsilon = Q \frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}}} \quad (29) \]

where \( N_{\text{in}} \) and \( N_{\text{out}} \) are the viral titer of the airborne virus at the inlet and the outlet of the duct. The total volume of clean air delivered during the operation time can be obtained by the time integration of the CADR value:

\[ V_{\text{total}} = \int CADR \, dt \quad (30) \]

### 5. Results and discussion

#### 5.1. The performance on space heating

The variations of ambient temperature and the total solar irradiance during the experiment are shown in Fig. 6. With respect to the solar irradiance, a sudden increase in the slope occurred at about 10:47 due to

![Fig. 6. Variations of ambient temperature and solar irradiance during the experiment.](image-url)
the orientation of the Trombe wall, which was southwest but not due south. As a result, most of the solar radiation received by the system before the turning point was diffuse but not direct. The average total solar irradiance and the ambient temperature were 638.9 W/m² and 18.8 °C, respectively. The maximum solar irradiance was over 1000 W/m², which contributed to a high outlet air temperature, thus enhancing the thermal performance of the system.

As shown in Fig. 7, the variations of both the outlet air temperature and the volume flow rate were in consistency with that of solar irradiance, reaching their maximum value at about 16:00. The outlet temperature could achieve as high as 94.8 °C on account of the intense solar irradiance and the measures taken to reduce the heat loss, especially the selective coating on the absorber plate. By contrast, the variation of the inlet air temperature was much smaller, varying from 11.2 to 23.2 °C, which was related to the indoor temperature. Fig. 8 reveals that the indoor temperature was higher than the ambient temperature by 1.9 °C in general. Since the building was towards southwest, the indoor temperature was much higher than the ambient temperature in the afternoon because of the relatively strong solar irradiance at that time. The average indoor temperature in the afternoon was 23 °C, which could satisfy the need of thermal comfort.

With the data of the inlet and outlet air temperature and the air velocity in the duct, the thermal efficiency can be derived from Equation (26). The variation of thermal efficiency with time is plotted in Fig. 9, which shows that the efficiency was always increasing even when the solar irradiance started to decrease after 16:00. This could be attributed to the heat capacity of the absorber plate, which made the decrease of heat gain a bit slower than that of solar irradiance. Generally, the thermal efficiency was in the range of 0.10 to 0.56 and the average value was 0.457. All these statistics reveal that the proposed system do have a great performance in space heating.

5.2. Model validation

To validate the heat transfer model, the comparison of the outlet air temperature between experiment and simulation is plotted in Fig. 10, which indicates that the result of simulation corresponds well with that of experiment. As a frequently used measure of the differences between values predicted by a model and the values observed in experiment, the root mean square error (RMSE) is defined as:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_{exp,i} - x_{sim,i})^2}
\]

where \(x_{exp,i}\) and \(x_{sim,i}\) represent the values obtained from the experiment and the simulation, respectively.

According to the calculation, the RMSE was 2.7 °C for air
temperature at the outlet. Since several assumptions have been made to simplify the calculation, errors between simulation and experiment are inevitable. Then, the RMSE value is acceptable.

5.3. The performance on virus inactivation

Based on the temperature and velocity field in the duct, the performance of virus inactivation is simulated with Equation (25). Three kinds of corona viruses which have the potential of aerosol transmission are selected in the simulation, including SARS-CoV-1, SARS-CoV-2 and MERS-CoV. Single-pass inactivation ratio and clean air delivery rate are employed to evaluate the performance on virus inactivation.

The plots of single-pass inactivation ratio versus time are shown in Fig. 11, which indicates that temperature plays an important role in the thermal inactivation process. Since the selected corona viruses are quite stable at low temperatures, obvious thermal inactivation of virus could not be observed until 12:00 when the outlet air temperature reached 50 °C. After that, the single-pass inactivation ratio increased quickly with the increasing temperature. It can also be inferred from the plots that SARS-CoV-2 is more stable to heat than the other two kinds of virus, since only 60% of virus was inactivated by heat when the air temperature achieved its maximum value while the ratio for SARS-CoV-1 and MERS-CoV were much higher, about 90%. Besides, the duration of the single-pass inactivation ratio maintaining above 50% was 191 min, 78 min and 196 min for SARS-CoV-1, SARS-CoV-2 and MERS-CoV, indicating a good performance of thermal disinfection for the proposed system. With respect to the clean air delivery rate, plots in Fig. 12 present a similar trend with that of single-pass inactivation ratio in Fig. 11. For the proposed system with an area of 2 m$^2$, the maximum CADR value was 24.3 m$^3$/h for SARS-CoV-2 while it was about 37.3 m$^3$/h for the other two. After integrating the CADR value over time according to Equation (30), the total volume of clean air generated by the system was 114.7, 112.3 and 63.8 m$^3$ for MERS-CoV, SARS-CoV-1 and SARS-CoV-2, respectively. Besides, the CADR can also be seen as the fresh air volume flow increased by the disinfected Trombe wall. According to the research of Dai et al. [30] on infection probability of COVID-19, for the case of both the infector and susceptible person wearing masks in a confined space, a ventilation rate of 30–90 m$^3$/h would be required to ensure an infection probability of less than 1% for 0.25 h of exposure. Then, if two such disinfected Trombe walls were installed, the total CADR would be in this range from 14:40 to 17:00, lasting for 140 min. In this way, the concept of combining virus inactivation with space heating in disinfected Trombe wall is suitable to be implemented in confined spaces with poor ventilation, especially rural houses without fresh air systems.

5.4. Parametric analysis

On the basis of the verified model and the selected virus type of SARS-CoV-2, parametric analysis has been conducted to investigate the impact of different parameters, including the solar irradiance, the ambient temperature and the size of the air duct on the performance of the system.

The impact of the solar irradiance and the ambient temperature on the thermal performance of the system is shown in Fig. 13. It is obvious that both the increases of ambient temperature and solar irradiance have a positive effect on the thermal efficiency. The higher the ambient temperature is, the less the heat loss to the ambience will be, thus increasing the thermal efficiency. As to the solar irradiance, an increase in solar irradiance will lead to a temperature rise in the absorber plate, which accordingly reinforces the heat transfer between the absorber plate and the air since temperature difference plays a dominant role in the determination of natural convection heat transfer coefficient. But this positive effect will be attenuated with the solar irradiance going up, considering the fact that heat loss by radiation also increases quickly with the temperature rise of the absorber plate. Apart from the impact on the thermal efficiency, as illustrated in Fig. 14, the ambient temperature seems to have tiny effect on the single-pass inactivation ratio while the impact of solar irradiance on that is remarkable. This can be attributed to that the exposure temperature which affects the performance of virus inactivation a lot has much stronger dependence on the solar irradiance compared to the ambient temperature. It can also be
inferred from the figure that the performance of virus inactivation is poor at a low solar irradiance level. Only about 6% of airborne virus is inactivated by heat in a single pass at a solar irradiance level of 600 W/m². Nevertheless, the situation can be improved by appropriately choosing the size of the air duct, including the height and the thickness.

Considering that meteorological conditions as good as those during the experiment won’t exist all over the heating seasons, more general weather data for Xining were exported from EnergyPlus to investigate the influence of air duct size on system performance during times with lower solar irradiance and ambient temperature.

Take the weather data on 31st December for example, the maximum solar irradiance on south facades were no more than 850 W/m² while the average solar irradiance and the ambient temperature were 555.2 W/m² and 2.3 ℃, respectively. The impact of the duct height on the average thermal efficiency and total production of clean air is presented in Fig. 15. With the increase of height, only a slight decrease occurs in the average thermal efficiency. The influence of increased duct height is reflected in two ways: on one hand, this may result in the acceleration of the air velocity according to Equation (12), thus enhancing the heat transfer process; on the other hand, an increase in duct height also means larger heat loss to the ambience and smaller temperature difference between the absorber plate and the air, which will cause a decrease in the thermal efficiency. Due to the trade-off between these two aspects, the trend of the average thermal efficiency presents only a slight decrease. With respect to the impact on the total production of clean air, the increment of duct height may lead to extended exposure time and increased exposure temperature, which will definitely give rise to an enhanced performance of virus inactivation. According to the simulation, when the height of the air duct ranges from 2 m to 2.8 m, the total production of clean air will experience a rise from 22.3 m³ to 56.8 m³ during the operation period.

Apart from extending the height, narrowing the thickness of the air duct can also improve the performance of virus inactivation. As shown in Fig. 16, with the thickness of the duct decreasing from 4 cm to 2.4 cm, the total production of clean air increases from 22.3 m³ to 47.6 m³ while the average thermal efficiency decreases from 0.397 to 0.366. The thinner the air duct is, the smaller the volume flow rate will be, which results in higher air temperature in the duct. Then, the process of virus inactivation is accelerated due to the increased exposure temperature. However, since the volume flow rate is reduced, the thermal efficiency decreases accordingly. It can also be inferred that in order to achieve the same amount of clean air, narrowing the thickness of the duct may lead to a larger decrease in thermal efficiency when compared with extending the height. But it should be noted that enlarging the height of the duct also means larger area for installation and higher cost for investment.

When the simulated operation period is extended from a single day to the heating seasons, the results for cases with the duct height increased by 40% or the duct thickness reduced by 40% are presented in Table 5. When extending the height of the duct, only a tiny decrease occurs in the heat gain of indoor air but the total production of clean air can be increased by 79%. For cases with reduced duct thickness, the increase in the total volume of clean air can be even larger (106%) while the decrease in heat gain of air is also enlarged (8%). Since there have been no such air purifiers for inactivation of SARS-CoV-2 in market up to now, it is hard to figure out the power consumption required for the production of a certain amount of clean air. Otherwise, the optimal height and thickness of the air duct can be determined from the viewpoint of total energy conservation.

\[ H \text{ and } d \text{ represent the height and the thickness of the duct; } Q_{\text{total}} \text{ is the heat gain of the air per unit area of the collector when passing through the duct while } V_{\text{total}} \text{ refers to the total volume of clean air generated by per unit area of the collector.} \]

6. Conclusions

A hybrid disinfected Trombe wall system with functions of space heating and virus inactivation is proposed. The air thermal efficiency was investigated by experiment while the performance of thermal disinfection was evaluated with the virus thermal inactivation model.
The heat and mass transfer model was established and verified, based on which the parametric analysis was conducted. The main conclusions are as follows:

(1). With the average ambient temperature being 18.8 °C and the average solar irradiance at the level of 638.9 W/m², the air temperature at the outlet of the duct was able to reach as high as 94.8 °C. As to the air heating process, the thermal efficiency was in the range of 0.10 to 0.56 and the average value was 0.457 during the experiment. Besides, due to space heating provided by the system, the average indoor temperature was 23 °C, which was 1.9 °C higher than the ambient temperature.

(2). The process of virus inactivation accords well with the first-order kinetic model and Arrhenius equation in general with the R² being 0.97 for SARS-CoV-2. Besides, the root mean square error (RMSE) for air temperature at the outlet was 2.7 °C, which is acceptable considering the assumptions made for simplification.

(3). Based on the virus thermal inactivation model, the maximum inactivation ratio in a single pass was 0.893, 0.591, 0.893 while the total generation of clean air was 112.3, 63.8, 114.7 m³ in volume for SARS-CoV-1, SARS-CoV-2 and MERS-CoV, respectively, indicating the potential of the proposed system in dealing with the airborne viruses in a closed environment.

(4). As to the impact of the environmental parameters, both the increases of ambient temperature and solar irradiance have a positive effect on the thermal efficiency. However, this effect is attenuated gradually on account of the increasing heat loss caused by the temperature rise of the absorber plate. Besides, compared with solar irradiance, the ambient temperature seems to have little effect on the thermal disinfection process considering its limited contribution to the temperature rise of air in the duct.

(5). With respect to the influence of air duct size, both extending the height and narrowing the thickness of the duct can improve the performance of virus inactivation in cases with low solar irradiance and ambient temperature due to their impact on exposure time and exposure temperature of viruses. However, the former requires larger area for installation and higher cost for investment, while the latter may result in larger decrease in thermal efficiency. Extending the height or narrowing the thickness of the duct by 40% may contribute to an increase in total production of clean air by 510 m³ or 681 m³ per unit area of collector during the heating seasons, but the latter may cause a larger decrease (about 8%) in heat gain of indoor air.

The present work firstly proposes a novel concept of building integrated thermal disinfection and heating system fully driven by solar energy. The hybrid system can realize the multiple utilization of solar thermal energy harvested by Trombe wall, thus enhancing the solar energy utilization ratio. More importantly, the work provides a new approach to utilizing solar energy passively for dealing with the aerosol transmission of SARS-CoV-2 in a closed environment. However, due to lack of experiment conditions, experimental study on virus inactivation has not been conducted. Then, we will seek cooperation with qualified laboratories to conduct experiments to verify the simulation results of virus inactivation in the future. Since this paper was just focused on the Trombe wall, we will also investigate the feasibility of implementing such concept to deal with return air in ventilation systems. Besides, a more detailed model which takes the indoor virus concentration field into consideration should be established to achieve a comprehensive understanding of the virus inactivation process happening in the indoor environment.

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