Transparent dynamic insulation: a novel system combining ventilation and insulation for sustainable greenhouse applications

A.J.H. Frijns, L.A. van Schaijk

Eindhoven University of Technology, PO Box 513, 5600MB Eindhoven, the Netherlands,
email addresses: a.j.h.frijns@tue.nl; l.a.v.schaijk@tue.nl

Abstract. Greenhouse horticulture cultivates vegetables, fruits, and flowers in protected glass houses. Approximately 65%-85% of the total energy in greenhouses is used for heating. To reach the climate goals energy reduction is needed. Energy savings cannot only be achieved by improving the insulation value of the greenhouse covers since also the relative humidity of indoor air needs to stay below a critical humidity level to avoid fungus growth. Therefore ventilation is required with an average air change rate (ACH) of 2.5/h. This is often realized by (partly) opening and closing the glass greenhouse cover thereby losing part of the heat. In this paper, we focus on a novel method that improves the thermal insulation of transparent top covers and/or walls while ensuring sufficient ventilation: transparent dynamic insulation (TDI). TDI is based on a concept called Dynamic Insulation, also known as a "breathing wall": infiltrating air flows through the multi-layer insulation panel. While doing this, the incoming air takes up part of the heat and uses this for pre-heating. Thereby it reduces the overall heat transfer value (U-value) and provides pre-warmed, fresh air flow into the greenhouse. The main difference compared to "traditional" dynamic insulation is that its design is transparent for solar irradiation and therefore can be used for greenhouses. In this paper, we show experimental results on a TDI prototype panel using a hot box apparatus with an ACH=2.5/h and prescribed temperature differences between indoor and outdoor of $\Delta T=10^oC$ and $\Delta T=20^oC$. It is shown that the measured overall U-value for the TDI panel is about 19% lower than for double glass and more than a factor 2 lower than single-layered Hortiplus glass. Therefore it is concluded that TDI is a promising approach to reducing energy consumption in greenhouse horticulture while ensuring sufficient air refreshment for moisture control.

Keywords. Dynamic thermal insulation, ventilation, greenhouses, energy savings
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1. Introduction

In greenhouse horticulture, vegetables, fruit, and flowers are grown in protected glass houses. In the Netherlands, in 2018, the annual energy consumption attributed to greenhouses was 100.5 PJ [1]. Hereof, about 77% comprises energy for heating and 23% for electricity. Worldwide these numbers are similar: about 65%-85% of the total energy in greenhouses is used for heating [2]. To reduce the energy consumption, the electricity and heating demand should be reduced. Insulation can be improved by using for example double glazing or, poly-ethylene, polycarbonate, or PMMA covers: energy savings up to 60% compared to single-layer glass covers are reported [2]. Also, additional electricity can be generated in a sustainable way, e.g. by integrated PV panels [3]. In this paper, we focus on the heating demand.

Energy savings can be achieved by improving the insulation value of the greenhouse covers, however also the relative humidity of indoor air needs to stay below a critical RH level of 80% to avoid fungus growth. Therefore also a minimum ventilation rate is required: an average air change rate (ACH) of 2.5/h is needed, which is often realized by (partly) opening and closing the glass greenhouse covers thereby losing also part of the heat. Here we introduce a novel system that improves the thermal insulation of transparent top covers and/or walls of greenhouses while ensuring sufficient ventilation: transparent dynamic insulation (TDI).

2. Transparent Dynamic Insulation

2.1 Dynamic Insulation

Transparent Dynamic Insulation (TDI) is based on a concept called Dynamic Insulation, also known as a "breathing wall" [4]. In such a system infiltrating air flows through a porous insulation panel that is enclosed between two impermeable walls (Figure 1). While doing this, the incoming air takes up part of the heat (indicated by energy flow C) and uses this for pre-heating the supply air from the outdoor temperature $T_{outdoor}$ to a higher inlet temperature T_{inlet}. Thereby it reduces the overall transmission heat loss (indicated by energy flow D) and improves the overall heat transfer value U [4]. This effective U-value is defined as

$$U = \frac{D}{A\,\Delta T} \qquad (1)$$

where D is the overall heat loss, A the effective surface area, and $\Delta T = T_{indoor} - T_{outdoor}$ is the temperature difference between the indoor and outdoor air. Without the additional airflow through the insulation layer, the heat loss would be larger and thereby the U-values as well. Another advantage is that it provides pre-warmed, fresh airflow into the building.

The required heat input to keep the indoor air at a constant is described by:

$$Q_{req} = D + \dot{m}\,(T_{indoor} - T_{inlet}) \qquad (2)$$

where $\dot{m}$ is the mass flow rate of the incoming air. The second term on the right hand side of equation (2) indicates the amount of heat that is required to heat the incoming air (with temperature T_{inlet}) to the required indoor air temperature T_{indoor}.

Since heat loss D is lowered (lower overall U-value) and T_{inlet} is increased (preheating of the incoming air) less energy is required to keep the indoor space at the same temperature.

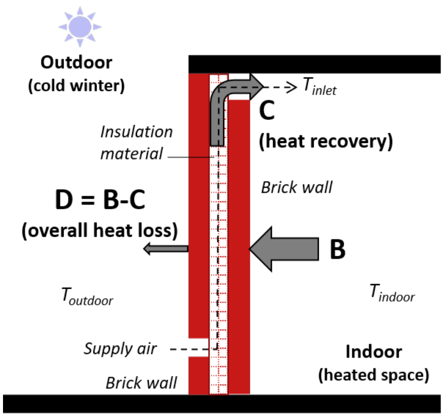

Fig. 1 - Principle of "traditional" dynamic insulation. The heat fluxes are indicated by the arrows. Arrow B indicates the heat loss from the indoor environment. Part of this heat will be taken up by the airflow through the porous insulation material between the inner and outer brick walls (indicated by arrow C), resulting in a lower overall heat loss D. *Picture based on* [4].

2.2 Transparent Dynamic Insulation

For greenhouses solar irradiation is essential. Therefore the material needs to be transparent. That limits the application of wall materials but also prohibits the use of traditional porous insulation materials like glass wool. To achieve a similar insulation effect, an additional transparent plate is added (figure 2). In this way also the path over which the incoming fresh air can take up the heat is prolonged and the temperature rise of the pre-heated incoming air will be larger. The main difference compared to "traditional" dynamic insulation is that its design is transparent for solar irradiation and therefore can be used for greenhouses. In figure 2 a horizontal cover plate is shown, but the panel can also be placed in a vertical orientation, i.e. it can also be used as a wall element.

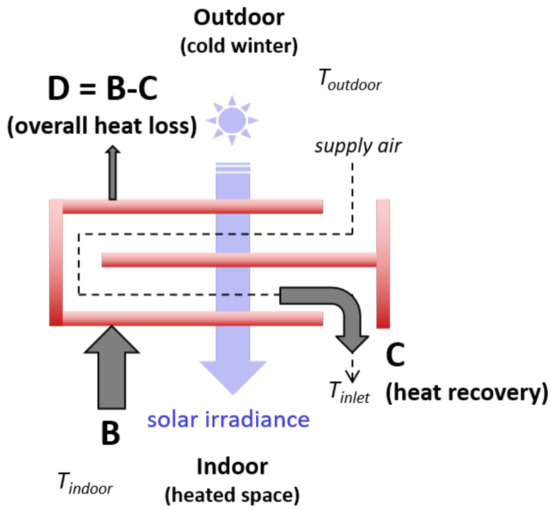

Fig. 2 - Principle of transparent dynamic insulation (TDI) roof cover. The panel walls are made of a transparent material (red lines). Incoming fresh air flows through a double curved channel (dotted line) in between the 3 layered structure while taking up the heat (C) that counterflows from the indoor to the outdoor environment. The overall heat loss (D) is thereby lowered.

2.3 Greenhouse application

In the Netherlands, the most common type of greenhouses is the Venlo-type (Figure 3).

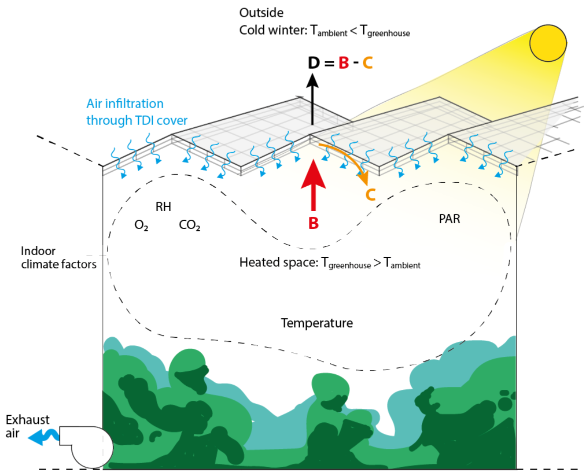

Fig. 3 - Schematic representation of the TDI greenhouse application (Venlo-type). Fresh air is drawn into the TDI cover, offering ventilation needs. The ventilated air regulates RH levels, CO_2 and O_2 concentration levels, and the disposal of moist-laden air. Material transparency allows solar radiation (PAR) to enter the greenhouse. Heat loss to the atmosphere **B** is partly recovered by heat exchange as a result of counterflow with infiltrating air **C**, such that the final heat loss **D** is reduced.

Glass is the most used cover material due to its favourable material properties. Clear, single-layered float glass is most commonly used due to its excellent chemical stability, stable light transmission, and its resistance to weather circumstances. Besides, float glass is easy to clean and relatively cheap. Disadvantages are the relatively high reflective losses, poor thermal performance (high U-values), fragility, and poor tensile strength. Alternative glass and plastic cover materials have entered the greenhouse horticulture market to cover up for the inferior properties of single float glass [5].

In greenhouses, transparency is crucial for the growth of crops. This is quantified by PAR (Photosynthetically Active Radiation). PAR defines a spectral range from 400-700 nm that is used by plants for photosynthesis. The greenhouse cover should be transparent for this spectral range. In table 1 the direct and hemispherical light transmittance within the PAR range (τ_{dir} and τ_{hem}) for the most common cover materials is shown.

Table 1 - glass and polymeric cover material properties, *adapted from* [5].

	Material	τ_{dir} [%]	τ_{hem} [%]	U-value [W/m^2K]
Glass	Float glass	89-91	82	5.8
	Hortiplus	84	69	5.8
	Double glass	81-82	-	2.7
Plastics	Polycarbonate	80/89*	61	3.5/5.8*
	PMMA	89/92*	76	2.8/5.8*

*Single layered panel material
Note that indicated values may differ per manufacturer

The ultimate goal is to design a TDI panel that has better effective insulation properties than horticulture glass at the required ventilation rates, while its transparency is similar.

3. TDI panel

A TDI-prototype panel is designed to study the potential energy savings that can be reached when applying it to a greenhouse. The TDI prototype is made out of PMMA material because of its good transmittance properties and ease of manufacturing. Its thermal properties will be determined at relevant ventilation rates and temperature differences that are representative of typical winter conditions in the Netherlands. An air change rate of ACH=2.5/h is prescribed. Furthermore, temperature differences between indoor and outdoor temperatures of $\Delta T=10^0C$ and $\Delta T=20^0C$ are used. Finally, a maximum pressure difference over the TDI-element of $\Delta p = 10$ Pa is allowed. This pressure difference was chosen such that the maximum force to open a door does not exceed 67 N for exterior hinged doors, and 22 N for interior hinged doors. These values are found in architectural regulations and were set so the elderly and children can also still open doors [6].

Next a TDI-prototype panel was constructed (Figure 4). It was built out of several TDI-unit elements and has a total panel size of LxWxH = 84.5 x 88.2 x 4.2cm.

The direct and TDI prototype PAR transparencies of the TDI-prototype are measured and are found to be $\tau_{dir} = 0.72$ and $\tau_{hem} = 0.59$. This is a bit lower than for Hortiplus glass (table 1) but is not yet optimized. It is expected that it can be improved and can come close to the values of the Hortiplus glass since the basis material is PMMA which has transmittance values that are higher than Hortiplus glass. For example, by decreasing the thickness of the PMMA plates, it is therefore expected that these transparency factors can come closer to those of the Hortiplus glass.

Fig. 4 – PMMA-based TDI-panel prototype of 42mm thickness.

4. Hot Box Experiments

4.1 Set-up

To determine the dynamic U-value of the TDI panel, a hot box apparatus has been used (Figure 5). It is a thermally insulated box that contains 25 temperature sensors, a humidity sensor, a differential pressure sensor, and two heating plates. The averaged indoor air temperature T_{indoor}, the outdoor air temperature $T_{outdoor}$ and the (pre-heated) air entering the climate box T_{inlet} are measured. The walls and bottom of the box are insulated and the TDI panel is placed on top of the setup. Via a pump at the bottom the air change rate (ACH) can be prescribed. The fresh air can enter the climate box via the TDI panel on top (indicated by the blue arrows) or via an inlet tube at the top right side in case it is covered with an airtight test panel (e.g. a double glazed panel).

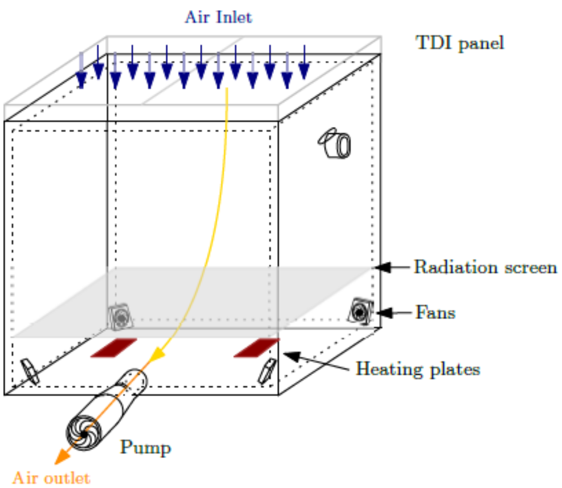

Fig. 5 – Hot box apparatus. The TDI panel is placed at the top of the box. Via heating plates (at the bottom) a temperature difference between the indoor and outdoor air is created. The air change rate (ACH) can be adjusted via the pump at the bottom.

The overall energy balance under steady state conditions is described by:

$$Q_{heaters} = Q_{loss} + Q_{TDI} + Q_{ACH} \qquad (3)$$

Where $Q_{heaters}$ is the power that is delivered by the two heating plates, Q_{loss} is the heat that is lost via the sidewalls and bottom of the hot box, Q_{TDI} *is* the heat flow through the TDI panel (or double glass panel), and Q_{ACH} is the power that is required to heat the incoming pre-heated fresh air with temperature T_{inlet} to the required indoor temperature T_{indoor}:

$$Q_{ACH} = \dot{m}c_p(T_{indoor} - T_{inlet}) \qquad (4)$$

The mass flow $\dot{m}$ is measured via a Testo 410i Vane Anemometer located at the air outlet.

The dynamic U-value of the TDI panel is defined as:

$$U_{TDI} = Q_{TDI}/A(T_{indoor} - T_{outdoor}) \quad (5)$$

where $Q_{TDI} = Q_{heaters} - Q_{loss} - Q_{ACH}$.

4.2 Results and Discussion

The experiments are performed with a double glass panel (as a reference case) and with a TDI panel. In both cases, an air change rate of ACH=2.5/h is prescribed. For comparison with the literature, in the double glass panel, the insulation value under static conditions (ACH=0) is measured as well. Temperature differences of 10^{0}C and 20^{0}C are prescribed. The results of the experiments are shown in Table 2.

It is seen that the U-values for the measurements with double glass are in the range of 2.5-3.1[W/m^{2}K]. The static U-value is lower than the dynamic value. This is to be expected since the air velocity at the bottom of the panel is increased for the dynamic case and therefore also the convective heat transfer coefficient. Also, additional heat is required to heat the incoming fresh air to room temperature.

Table 2 - Experimental measured dynamic U-values for double glass (reference case) and TDI-panels

	ΔT=10^{0}C	ΔT=20^{0}C
Static U-value double glass (ACH=0) [W/m^{2}K]	2.5	2.8
Dynamic U-value double glass (ACH=2.5/h) [W/m^{2}K]	2.7	3.1
Dynamic U-value TDI (ACH=2.5/h) [W/m^{2}K]	2.2	2.5

The U-value for double glass from the manufacturer is 2.7 [W/m^{2}K] [7]. The measured static U-value is close to the value given by the manufacturer, showing the accuracy of our set-up.

The same setup is used for our TDI prototype. We only considered the dynamic case (ACH=2.5/h) since that is the condition which it is designed for. As can be seen the dynamic U-value for the TDI-panel is about 19% lower than for double glass and more than a factor 2 lower compared to horticulture glass (table 1). This indicates that the thermal insulation of the TDI panel is better than double-glazed windows and single-layer Hortiplus glass. However, it is expected that the thermal performance of the TDI prototype can be further improved: the present prototype is designed such that the sidewalls can be clicked onto the bottom and top plates. No glue is used. The advantage is the ease of manufacturing, while the drawback is that some small gaps are present between the sidewalls and the bottom and top plates. Therefore some shortcuts for the airflow can be present, resulting in a small increase in the U-value. In addition, the walls of the TDI cells can also act as so-called thermal bridges. By making the PMMA walls thinner, as was already proposed to increase transparency, the thermal resistance will increase and thus further decrease the effect of the thermal bridges.

Finally, the TDI panel can also be used with a reversed airflow. Hereby the overall heat transfer value (U-value) will increase. This has a positive effect to prevent overheating of the greenhouses during summertime.

5. Conclusions

In this paper, we introduced the concept of transparent dynamic insulation (TDI) that can be applied to reduce the energy consumption of Dutch greenhouses. We showed that the measured heat transfer value (U-value) for the TDI panel is about 19% lower than for double glass and more than a factor 2 lower compared to the commonly used single-layered horticulture glass. This indicates the saving potential of the transparent dynamic insulation (TDI) concept. Further research is needed to further optimize the TDI design.

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