



# Development of a model to calculate the overall heat transfer coefficient of greenhouse covers

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## Abstract

A Building Energy Simulation (BES) model based on TRNSYS, was developed to investigate the overall heat transfer coefficient (U-value) of greenhouse covers including polyethylene (PE), polycarbonate (PC), polyvinyl chloride (PVC), and horticultural glass (HG). This was used to determine the influences of inside-to-outside temperature difference, wind speed, and night sky radiation on the U-values of these materials. The model was calibrated using published values of the inside and outside convective heat transfer coefficients. Validation of the model was demonstrated by the agreement between the computed and experimental results for a single-layer PE film. The results from the BES model showed significant changes in U-value in response to variations in weather parameters and the use of single or double layer greenhouse covers. It was found that the U-value of PC, PVC, and HG was 9%, 4%, and 15% lower, respectively, than that for PE. In addition, by using double glazing a 34% reduction in heat loss was noted. For the given temperature U-value increases as wind speed increases. The slopes at the temperature differences of 20, 30, 40, and 50 °C, were approximately 0.3, 0.5, 0.7, and 0.9, respectively. The results agree with those put forward by other researchers. Hence, the presented model is reliable and can play a valuable role in future work on greenhouse energy modelling.

**Additional keywords:** hot box; heat transfer; night sky radiation; polyethylene; TRNSYS.

**Abbreviations used:** BES (Building Energy Simulation); HG (Horticulture glass); PC (Polycarbonate); PE (Polyethylene); PVC (Polyvinyl chloride); TRNSYS (TRaNsient SYstem Simulation); U-value (Overall heat transfer coefficient).

**Authors' contributions:** Conceived and planned the experiments, read and approved the final manuscript: AR, HWL and JWL. Carried out laboratory experiment: HWL and JWL. Planned and carried out simulations: AR and HWL. Analysed the data and wrote the manuscript with input of all the authors: AR. Supervised the whole project: HWL.

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## Introduction

Energy management of greenhouses is one of the most significant challenges to greenhouse farming. The cost of heating has increased to 49% of the total production cost because of continually increasing fossil fuel prices (Yang *et al.*, 2012). In addition to using different energy supply techniques, energy saving measures need to be considered to reduce the energy demand of greenhouses and improve the economics of greenhouse crop production. The estimation of heat loss through greenhouse-covering materials is a significant component of energy management when designing a greenhouse according to the local weather conditions. Reduction of the energy consumption by the building

sector is a way of reducing the environmental impact of the buildings (Mahapatra, 2015). A greenhouse-covering material should possess good heat insulation properties by allowing shortwave radiation into the greenhouse, yet being opaque to infrared radiation. To manage greenhouse energy effectively, it is important to understand the thermal behavior of the glazing materials (Al-Mahdouri *et al.*, 2013). The amount of energy required for heating depends on the thermal efficiency of the building and it is likely to be higher under severe climate conditions. Hence, the annual operating cost associated with energy increases.

Designers can help to reduce the annual operating cost with their predesign decisions (Abu Bakar *et al.*, 2015). In the literature, researchers rarely discuss heat

flow through building envelopes; thus methods for heat loss calculations are needed in order to make decisions for future energy-efficient buildings (Pulselli *et al.*, 2009). Calculation of heat loss is the first step before selecting a suitable heating system for a greenhouse (Esen & Yuksel, 2013). Overall energy loss occurs due to convection, conduction, and thermal radiation. These losses are influenced by outside weather conditions, for which the difference between the inside and outside temperatures, wind speed, and long wave radiation are the most important. The inside and outside environmental effects are the two main aspects related to buildings (Zhang & Lei, 2012). Among the other factors influencing the energy demand of a building, the construction materials used is one of the most important (Zhou & Zhao, 2013).

Ozturk (2005) conducted a numerical study to estimate the overall heat loss of a greenhouse covered with polyethylene (PE), based on heat convection and conduction, thickness of the material, and inner and outer surface temperatures. The American Society of Testing Material (ASTM, 1993), in a report, proposed standards for a laboratory hot box for the calculation of the U-values of the materials. A hot box method is used to measure the thermal resistance of materials by estimating the temperature difference between both sides of the component. The test material is placed between two rooms maintained at different temperatures (so-called hot and cold chambers), the external envelopes of the chambers should be well insulated to reduce heat loss. The thermal resistance of the test films could be calculated by the power needed to maintain the hot chamber at constant temperature as well as to maintain a temperature difference between the hot and cold chambers (Buratti *et al.*, 2016). There are two methods for the laboratory measurement of overall heat transfer coefficient: guarded and calibrated hot box methods. The guarded hot box is built by placing a metering box (heating box) inside the guard chamber, since the guard chamber and the metering box are kept at same temperature. On the other hand, in the calibrated hot box method the entire apparatus is placed in a known surrounding ambient temperature generally different from the metering (hot) chamber. Gao *et al.* (2004), Asdrubali & Baldinelli (2011), and Kus *et al.* (2013) used an experimental hot box to study the rigid construction wall materials. These methods were originally established for measuring rigid material but they also allow measurement of thin materials like greenhouse covers. Geola *et al.* (2009) designed a laboratory guarded hot box to investigate the U-values of greenhouse covers in dry and wet conditions as a function of inside-to-outside temperature difference and wind speed. On the other hand, Fadel *et al.* (2016) prepared a laboratory hot box

to study the heat and light transmittance of different greenhouse covers by considering the temperature and light only. Diop *et al.* (2012) developed a laboratory hot box to study the effect of weather parameters including, inside-to-outside temperature difference, wind speed and sky temperature on U-value of different commercially used greenhouse covers. Feuilloley & Issanchou (1996) developed a method to for measuring U-values of single layers of greenhouse cover using outdoor hot box experiments where cover films were tested under natural conditions of temperature, winds speed, and sky radiation. All the above studies used the hot box method to investigate greenhouse cover thermal behavior experimentally under different conditions. Presence of building energy simulation (BES) tools for energy analysis of different buildings allows for complete environment for BES modelling. Compared with the experimental setup, the important advantages of BES modelling are its cost effectiveness and easy handling in terms of experiment apparatus designing and operation. Many BES models have been developed worldwide and successful validation allows adoption of these models for particular analyses.

BES tools provide the opportunity to examine the thermal behavior of buildings by considering all realistic conditions. TRNSYS (TRaNsient SYstem Simulation) program is a BES program, a hybrid simulator, which allows dynamic simulation of simple as well as complex buildings and energy systems (Klein, 2012). TRNSYS is a versatile, component based and extensible energy simulation tool. This program was designed by University of Wisconsin's Solar energy lab and has been commercially available since 1975, since then program has been under continuous development (Rasheed *et al.*, 2015). The simulations can be made using particular-purposed conditions.

In this study, TRNSYS 17 was used to prepare a BES model of an existing laboratory hot box. The BES model was calibrated using published values for inside and outside convective heat transfer coefficients and it was validated using the results from laboratory experiments. The BES model was used to examine the thermal behavior of greenhouse covers, in particular, on how the U-value was influenced by outside weather conditions and by the number of layers in the greenhouse cover.

## Material and methods

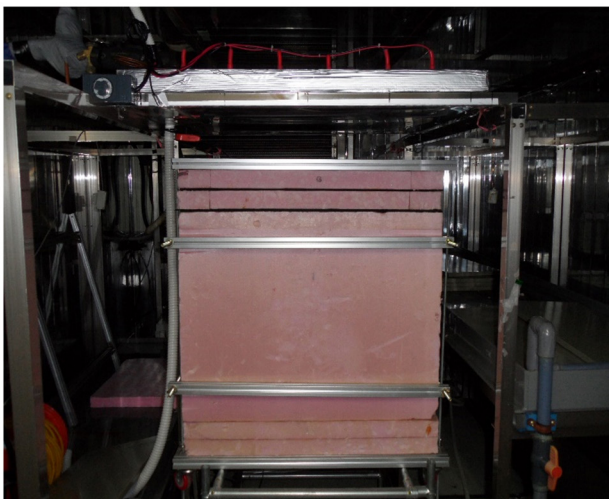
### Experimental hot box

Laboratory experiments regarding the investigation of U-values of different greenhouse covers related to outside weather parameters were conducted using a

calibrated hot box, as designed in our previous study (Diop *et al.*, 2014), according to the ASTM standards C 236-89 (ASTM, 1993). Fig. 1 shows the picture of the laboratory hot box. The experimental setup is outlined in the current paper, and the reader can find detailed information in the cited reference. Fig. 2 shows a schematic diagram of the hot box constructed in the laboratory and replicated in the BES model. The hot box had a cross section of  $800 \times 800$  mm with a height of 900 mm. The sidewalls and base were made of 100-mm thick polystyrene insulation, a heating device was placed on the bottom to maintain the required inside temperature. The heating power was 500 W and a wattmeter (Power Manager, STC, Korea) was used to measure the input power. To investigate the temperature effect, different inside temperatures were obtained by changing the heat input. The test materials were inserted through the top of the hot box, which was exposed to outside weather conditions. The hot box was placed into a cold chamber to control outside weather conditions. A cooler was installed inside of the cold chamber enabling to control temperature to  $0^\circ\text{C}$ .

The wind speed effect was created using a fan and wind speed was measured with a Kestrel 4500 wind gauge (Nielsen-Kellerman, USA). A night-sky radiation simulator, a unit to implement simulated sky radiation, was placed above the top surface of the hot box to simulate radiative heat loss to the sky. This unit is made of stainless steel covered with aluminum foil with copper pipes laid into the unit, through which coolant R22 is injected. All experiments were made for nighttime conditions. The following equation was used to calculate the U-values of the test materials:

$$U = \frac{q}{A(T_i - T_o)} \quad (1)$$



**Figure 1.** Laboratory experimental hot box setup.

where  $U$  is overall heat transfer coefficient ( $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ),  $Q$  is the heat loss through the tested material (W);  $A$  is the area of the test sample ( $\text{m}^2$ ); and  $T_i$  and  $T_o$  are the inside and outside air temperatures ( $^\circ\text{C}$ ), respectively.

In order to determine the heat loss through the tested materials the heat losses through sidewalls were subtracted from the total heat input.

$$Q = Q_r - Q_w \quad (2)$$

where  $Q_r$  is the heating power of heater (watts), and  $Q_w$  is the heat loss through walls (watts), the heat loss through the wall is

$$Q_w = \frac{\lambda S_w (T_s - T_u)}{L} \quad (3)$$

where  $\lambda$  is thermal conductivity coefficient of polystyrene ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ),  $S_w$  is wall surface area ( $\text{m}^2$ ),  $L$  is the thickness of the hot box wall (m),  $T_s$  and  $T_u$  are surface temperatures ( $^\circ\text{C}$ ) of inner and outer walls, respectively.

The inside and outside of the hot box air temperatures at various locations were measured using HOBO air temperature sensors (Onset, USA) and internal and external surface temperatures of the hot box walls were measured using UE-1530 (USEEM, Korea) surface temperature sensors. The surface temperature sensors were attached with the surface by using silicon oil compound (YG6111, Japan), a metal oxide-filled silicon oil compound which provide homogeneous super thermal conductivity.

## BES model

### Model creation

We created a model of the hot box, with the same conditions and specifications used in the laboratory hot box, using the TRNSYS program. Table 1 gives all the test conditions we applied to the selected materials. The temperature outside of the hot box was fixed at  $0^\circ\text{C}$  during all simulations. By changing the temperature inside the hot box, the sky temperature, and the wind speed, we investigated the U-values of the selected materials.

TRNSYS consists of a series of programs and add-ons used to carry out user-defined simulations. For this study, we used TRNSYS Simulation Studio, TRNBuild, Trnsys3d, with Windows 7.4 software. Fig. 3 shows a flow diagram for the hot box model using TRNSYS. We used Windows 7.4 software to create a DOE-2 file (readable by TRNBuild) for each covering material. Fig 4 shows a sample of a DOE-2 file for a double-layer of PE film with an air gap of 50 mm. This file was

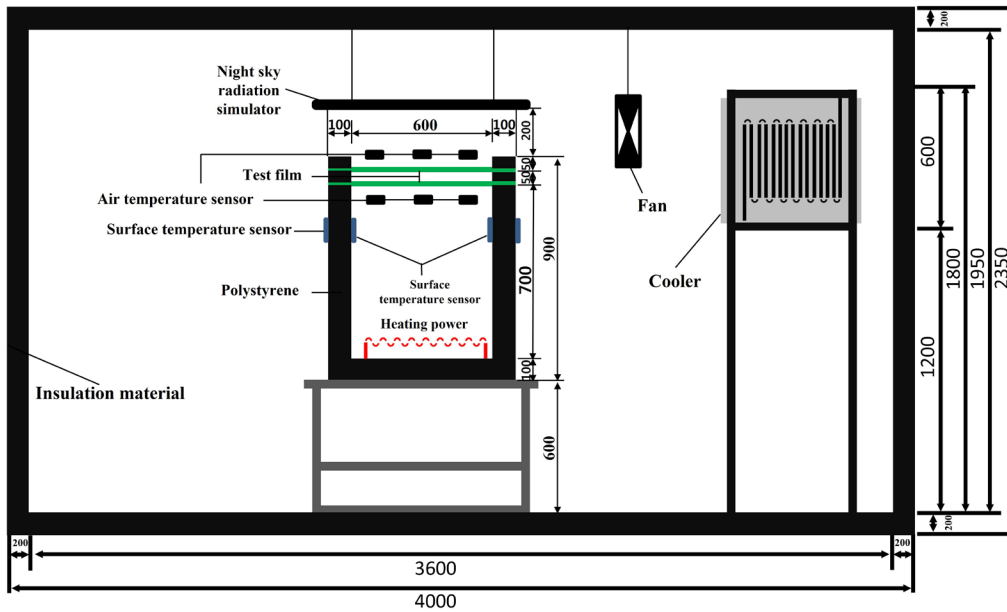


Figure 2. Schematic diagram of the hot box (units: mm)

Table 1. Test matrix.

Cover material	Cover	Test conditions		
		Inside-to-outside temp. difference (°C)	Wind speed (m·s <sup>-1</sup> )	Sky radiation
PE, PC, PVC, HG	Single	*	0	No
PE, PC, PVC, HG	Double	*	0	No
PE, PC, PVC, HG	Single	*	0	Yes
PE, PC, PVC, HG	Double	*	0	Yes
PE	Single	20	0	Yes
PE	Single	20	0~15	Yes
PE	Single	20	0~15	No
PE	Single	20~50	0~6	Yes

\*: Measured at inside-to-outside temperature differences of 2, 4, 6, 8, 10, 20, 30, 40, and 50 °C. ~ indicates the range of values, for wind speed 0 to 15 with the 1 m·s<sup>-1</sup> step and temperature range from 20 to 50 °C with 10 °C step. PE, polyethylene; PC, polycarbonate; PVC, polyvinyl chloride; HG, horticulture glass.

imported into TRNBuild to create our hot box 3-D model (shown in Fig. 5), using Trnsys3d, a plugin for Google SketchUp™ software. TRNBuild was used for the basic project description by entering the following inputs: the desired heating temperature; heat power; inside convective heat transfer coefficient ( $h_i$ ) and outside convective heat transfer coefficient ( $h_e$ ). The desired outputs needed to run simulation were the inside air and surface temperatures of the tested materials which were further used as input in TRNBuild for the calculation of  $h_i$  and  $h_e$ . The heat loss through the test material is the desired model result. TRNBuild reads and processes the input data for a specific project and makes it available to the Simulation Studio. Then, in the Simulation Studio, which is the main interface of the TRNSYS program,

all the components are linked to allow information sharing. In the Simulation Studio, the “Multizone building” model known as “TYPE 56”, a TRNSYS component, was used, which interconnects with TRNBuild, containing all the defined information of the hot box project. “TYPE 56” requires a weather-data file. For our specific study, instead of using a weather data file containing time varying weather parameters, we used fixed values of weather parameters by setting them in the Simulation Studio using an equation component.

#### Model calibration

In building simulation research, error, or the difference between simulated and experimental

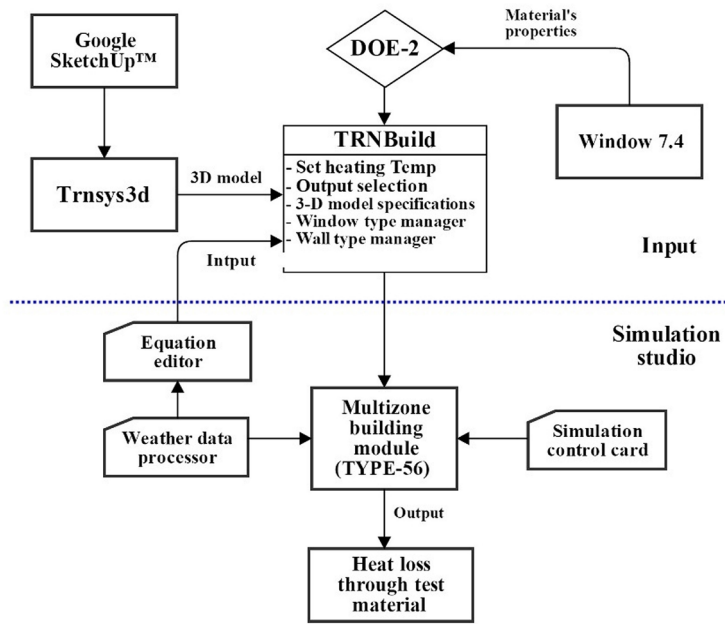


Figure 3. Flow chart of the BES procedure.

BERKELEY LAB WINDOW v7.4.6.0 DOE-2 Data File : Multi Band Calculation

Unit System : SI  
 Name : DOE-2 WINDOW LIB  
 Desc : Double\_PE  
 Window ID : 9999  
 Tilt : 90.0  
 Glazings : 2  
 Frame : 4 Vinyl 1.700  
 Spacer : 1 Class1 2.330 -0.010 0.138  
 Total Height: 1500.0 mm  
 Total Width : 1200.0 mm  
 Glass Height: 1360.3 mm  
 Glass Width : 1060.3 mm  
 Mullion : None

Gap	Thick	Cond	dCond	Vis	dVis	Dens	dDens	Pr	dPr
1 Air	50.0	0.02407	7.760	1.722	4.940	1.292	-0.0046	0.720	-0.0002
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Thermal properties gap air

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.747	0.747	0.745	0.740	0.728	0.699	0.632	0.489	0.244	0.000	0.650
Abs1	0.044	0.044	0.044	0.046	0.048	0.050	0.054	0.058	0.063	0.000	0.050
Abs2	0.035	0.035	0.035	0.036	0.037	0.038	0.038	0.035	0.028	0.000	0.036
Abs3	0	0	0	0	0	0	0	0	0	0	0
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0
Rfsol	0.175	0.175	0.175	0.178	0.187	0.213	0.277	0.417	0.664	1.000	0.254
Rbsol	0.175	0.175	0.175	0.178	0.187	0.213	0.277	0.417	0.664	1.000	0.254
Tvis	0.747	0.747	0.745	0.740	0.728	0.699	0.632	0.489	0.244	0.000	0.650
Rfvis	0.175	0.175	0.175	0.178	0.187	0.213	0.277	0.417	0.664	1.000	0.254
Rbvis	0.175	0.175	0.175	0.178	0.187	0.213	0.277	0.417	0.664	1.000	0.254
SHGC	0.775	0.774	0.774	0.774	0.774	0.774	0.774	0.774	0.774	0.764	0.764
SC:	0.74										

Optical data of material

Layer ID#	60009	60009	0	0	0	0
Tir	0.180	0.180	0	0	0	0
Emis F	0.790	0.790	0	0	0	0
Emis B	0.790	0.790	0	0	0	0
Thickness(mm)	0.1	0.1	0	0	0	0
Cond(W/m2-K)	3300.0	3300.0	0	0	0	0
Spectral File	None	None	None	None	None	None

Thermal properties of glazing

Figure 4. Sample DOE-2 file for the double-layer PE material.

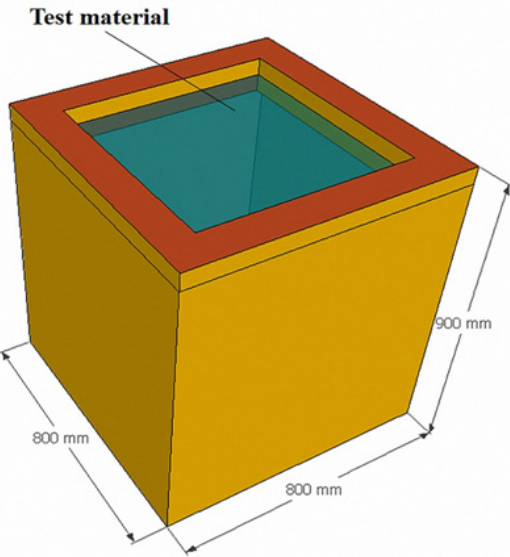


Figure 5. 3-D model of the hot box.

results, often occurs because of variation in the input parameters. To remove uncertainties, calibration of the BES model is needed, which involves modifying inputs to check their effect on outputs (Calleja Rodríguez *et al.*, 2013). Regarding this aspect, in the very first step, we needed to define the required materials, because TRNSYS does not contain greenhouse cover materials. For this purpose, the properties of the corresponding materials were entered into the Windows 7.4 software and a DOE-2 file was created (Table 2) using optical and thermal properties of each material (Valera Martinez *et al.*, 2008). Moreover, TRNBuild uses constant values of inside ( $h_i$ ) and outside ( $h_e$ ) convective heat transfer coefficients as input. We needed to adjust these input values in TRNBuild for detailed observation of the material’s thermal behavior related to weather parameters. The convective heat transfer coefficient depends on surface temperature, air temperature, and

wind speed. As building energy analyses are very sensitive to the convective heat transfer coefficient, many researchers conduct sensitivity analysis and report that, according to the choice of the convective heat transfer coefficient, energy demand can vary from 20% to 40% (Emmel *et al.*, 2007). Many researchers have proposed different relationships between the convective heat transfer coefficient and weather parameters. In our previous study, we incorporated these relationships, commonly used for thin layers such as greenhouse cover materials. The following equations show the different relationships proposed for  $h_i$  and  $h_e$  (Hwang *et al.*, 2013).

— Garzoli & Blackwell (1981)

$$h_i = 7.2 \tag{4}$$

$$h_e = 7.2 + 3.8W \tag{5}$$

— McAdams (1954)

$$h_i = 1.38(T_a - T_s)^{1/3} \tag{6}$$

$$h_e = 5.62 + 2.8W \tag{7}$$

— Watmuff *et al.* (1977)

$$h_i = 1.247(T_a - T_s)^{1/3} \tag{8}$$

$$h_e = 2.8 + 3.0W \tag{9}$$

where  $W$  is the wind speed,  $T_a$  the inside air temperature, and  $T_s$  the inside surface temperature.

These equations for internal and external convective heat transfer coefficients were analyzed for the calibration of our model for which results are shown in Fig. 6. Garzoli’s  $h_e$  and Watmuff’s  $h_i$  calculations (Eqs. 5 and 8, respectively) were adopted, as the calculated values agreed well with experimental results.

**Model validation**

To validate our model, the BES-computed results for a single-layer PE were compared to experimental results. Fig. 7 presents a comparison between the measured and simulated U-values at various inside-to-outside temperature differences, when ambient temperature was fixed at 0 °C, and sky temperature was the same as ambient temperature 0 °C considering

Table 2. Greenhouse cover material characteristics.

Cover characteristics	Greenhouse covers			
	PE	PVC	PC	HG
Solar transmittance	0.86	0.91	0.78	0.89
Solar reflectance	0.10	0.07	0.14	0.08
Visible radiation transmittance	0.89	0.92	0.75	0.91
Visible radiation reflectance	0.08	0.07	0.15	0.08
Thermal radiation transmittance	0.18	0.06	0.02	0.00
Thermal radiation emission	0.79	0.62	0.89	0.90
Conductivity ( $W \cdot m^{-1} \cdot K^{-1}$ )	0.33	0.13	0.19	0.76
Thickness (mm)	0.10	0.10	4.00	4.00

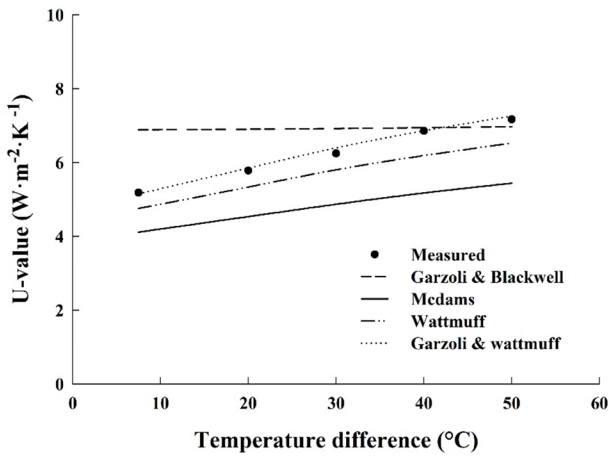


Figure 6. Variation in U-value with different values of  $h_1$  and  $h_c$ .

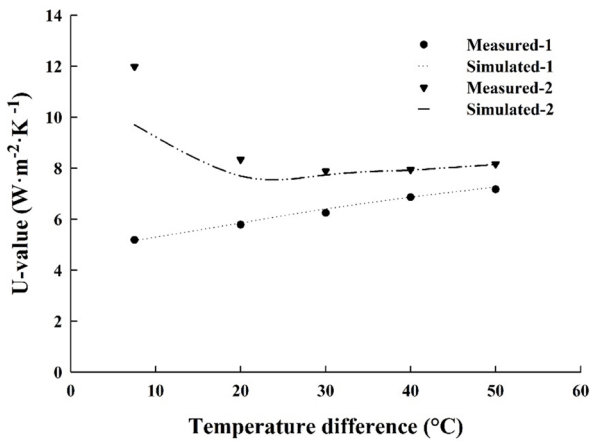


Figure 7. Experimental and simulated results at low wind speed. 1, “with night sky radiation”; 2, “without night sky radiation”.

no radiative heat loss to the sky (absence of night sky radiation), at a low wind speed of  $0.5 \text{ m}\cdot\text{s}^{-1}$ . Furthermore, the experiment was repeated with a sky temperature of  $-20 \text{ }^\circ\text{C}$  (presence of night sky radiation), while all other conditions were the same as previous. The experimental and simulated U-values agreed well in the absences of night sky radiation as the minimum error was 0% and the maximum error was only 1.3%. In the presence of night sky radiation, the experimental U-value was a little higher than that of the BES computed at lower inside-to-outside temperature differences, and the minimum error was 0.3% and the maximum was 23%. This difference occurred because during the laboratory experiments the sky temperature was not constant. The target night sky temperature was  $-20 \text{ }^\circ\text{C}$  but the distribution of night sky temperature on tested covers were ranged from  $-18$  to  $-22 \text{ }^\circ\text{C}$ , on the other hand, by using BES the sky temperature was well controlled by fixing it exactly to  $-20 \text{ }^\circ\text{C}$ . In addition, the absolute

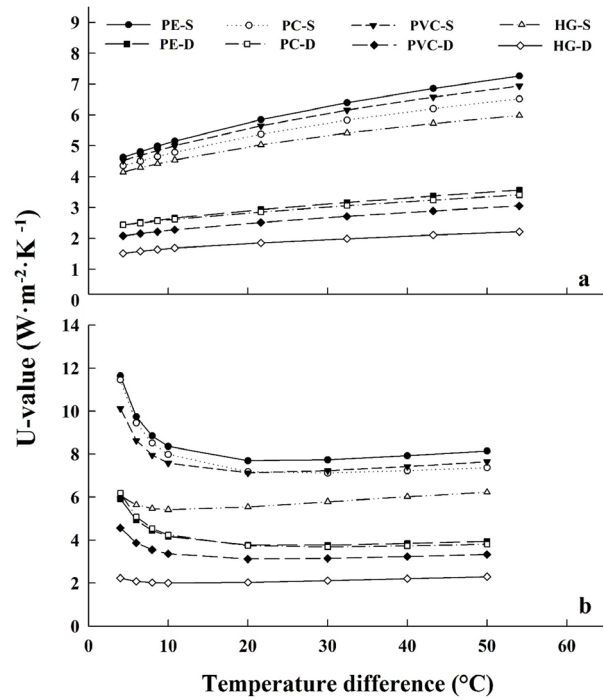


Figure 8. U-values of greenhouse covers according to the inside-to-outside temperature difference (a) in absence of night sky radiation; (b) in presence of night sky radiation. S, single-layer; D, double-layer.

radiative heat loss difference between experimental and BES computed was same for all the inside-to-outside temperature differences, but the difference between experimental and BES computed U-value increased as the inside-to-outside temperature differences decreased. This is because the U-value is inversely proportional to the temperature difference, as shown in Eq. (1).

## Results and discussion

After the successful calibration and validation of our BES model, further analyses were performed to investigate the U-values of other greenhouse covers including polycarbonate (PC), polyvinyl chloride (PVC), and horticultural glass (HG), with single and double layers, by applying the test conditions listed in Table 1. Moreover, the influence of weather parameters (including wind speed, inside-to-outside temperature difference, and night sky radiation) on U-value was analyzed.

The BES model was used to calculate the U-values of different greenhouse covering materials with both single and double layers. The simulations carried out in the absence of night sky radiation at a wind speed of  $0 \text{ m}\cdot\text{s}^{-1}$ , and over the range (0 to  $50 \text{ }^\circ\text{C}$ ) of inside-to-outside temperature differences shown in Fig. 8a. An

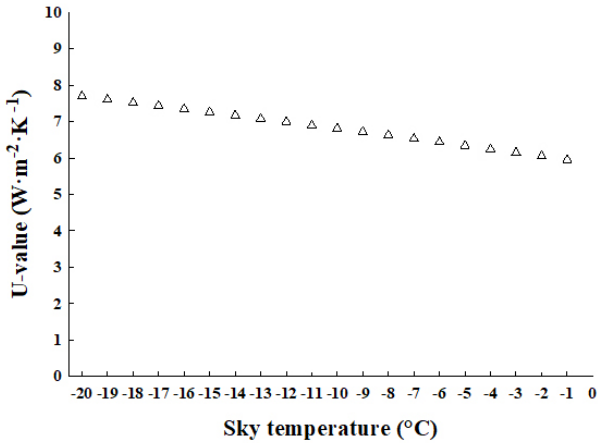


Figure 9. Relationship between U-value and sky temperature for a single-layer PE cover.

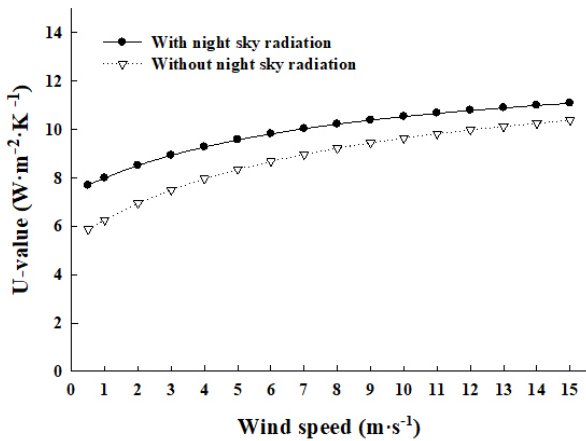


Figure 10. U-value dependence on wind speed for single-layer PE with and without night sky radiation.

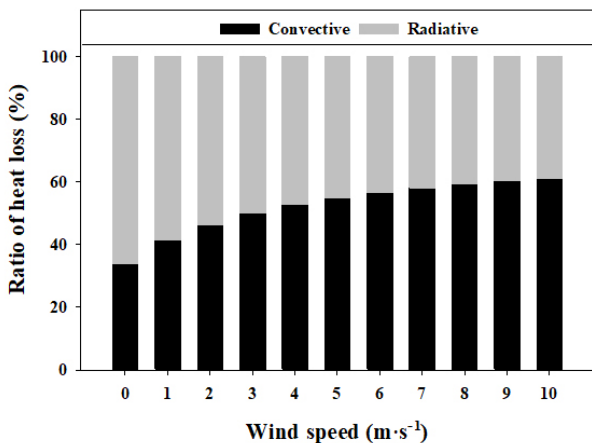


Figure 11. Ratio of convective to radiative heat loss based on wind speed.

increase in the U-value was observed as the inside-to-outside temperature difference increased. This occurred because, as the temperature difference increased, the surface temperature of the material also increased,

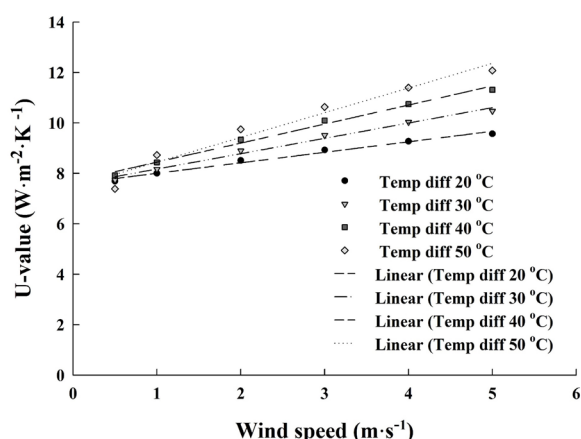
which caused more convective heat loss. This almost linear increase in U-value followed the same trend reported by Geoola *et al.* (2009), and Lee *et al.* (2015). Moreover, the U-value of double-layer PE was 34% lower than it was for single PE, which means that the heat requirement could be decreased significantly by using a double layer. The other materials showed the same trend of decreasing U-value using a double layer. PE had the highest U-value and HG the lowest among the tested materials, which indicates that HG performed better thermally. The U-value of PC, PVC, and HG was 9%, 4%, and 15% lower, respectively, than it was for PE.

Fig. 8b shows the variation in the U-value when simulations were carried out to investigate the influence of inside-outside temperature difference with night sky radiation. These were made by running the simulations with a night sky temperature  $-20\text{ }^{\circ}\text{C}$ , inside-outside temperature difference ranges (0 to  $50\text{ }^{\circ}\text{C}$ ), wind speed of  $0\text{ m}\cdot\text{s}^{-1}$ . It was found that, at the lowest temperature difference of  $2\text{ }^{\circ}\text{C}$ , the U-values of all materials were very high, and they decreased significantly as the temperature difference increased, becoming almost constant at differences above  $20\text{ }^{\circ}\text{C}$ . This is because, at low temperature difference, there is only radiative heat loss, and as the inside-to-outside temperature difference of the hot box increases, the effect of convective heat loss is added and U-value became constant. The U-value was a little higher than it was in the “without night sky radiation” results, because of the addition of radiative heat loss. The trend of these results can also be found in the study of Feuilloley & Issanchou (1996).

Fig. 9 shows the effect of sky temperature on the U-value of a single-layer PE film. Simulations were made with the following preset conditions:  $20\text{ }^{\circ}\text{C}$  inside-to-outside temperature difference,  $0\text{ m}\cdot\text{s}^{-1}$  of wind speed, and sky temperature varying from  $-20$  to  $0\text{ }^{\circ}\text{C}$ . It can be seen from the results that increasing the sky temperature from  $-20$  to  $0\text{ }^{\circ}\text{C}$  resulted in a reduction in the U-value.

Fig. 10 shows the variability in U-value according to wind speed ranges from 0 to  $15\text{ m}\cdot\text{s}^{-1}$ , for a single-layer PE film, with ( $-20\text{ }^{\circ}\text{C}$ ) and without ( $0\text{ }^{\circ}\text{C}$ ) night sky radiation, and with an inside-to-outside temperature difference of  $20\text{ }^{\circ}\text{C}$ . The results show that both with and without night sky radiation, the U-value increased with increasing wind speed. This is because wind speed is a function of the outside surface convective heat transfer coefficient, and by increasing wind speed, only convective heat loss increase. The contribution of radiative heat loss to the total cover heat loss was greater than that of convective heat loss, which is also confirmed in a previous study conducted on the night energy balance of a PE-covered greenhouse (Baile





**Figure 12.** Variation in the U-value of single-layer PE, according to the inside-to-outside temperature difference of the hot box and wind speed.

**Table 3.** Regression equations of U-value based on wind speed.

Inside-to-outside temp. difference (°C)	Equation	R <sup>2</sup>
20	$U = 0.3W + 7.2974$	0.9930
30	$U = 0.5W + 7.1433$	0.9941
40	$U = 0.7W + 7.1708$	0.9948
50	$U = 0.9W + 6.7552$	0.9848

*et al.*, 2006). Fig. 11 shows the ratio of convective to radiative heat loss based on wind speed, when inside-to-outside temperature difference was 20 °C, and sky temperature was -20 °C. Forced convection due to wind speed causes an increase in convective heat loss, a trend confirmed experimentally by Nijsskens *et al.* (1984).

Fig. 12 shows the variation in the U-value of single-layer PE, according to inside-to-outside temperature difference range from 20 to 50 °C, wind speed ranges from 0 to 6 m·s<sup>-1</sup>, and at sky temperature of -20 °C. The U-values exhibited linear increases with increasing wind speed and with temperature difference. The influence of wind speed was higher when the temperature difference was greater. Table 3 shows the linear regressions of U-value on wind speed for different inside-to-outside temperature differences. The R<sup>2</sup> values for the gradients show there is a very strong linear relationship.

In summary, a BES hot box simulation model, based on TRNSYS, was developed to investigate the U-values of greenhouse-covering materials. The BES model was calibrated using published values of the inside and outside heat transfer coefficients and validated by comparison with results measured using a physical hot box model in the laboratory. The BES model was used to calculate the U-values of covers made from single and

double layers of PE, PC, PVC, and HG. It was found that the U-value is influenced significantly by inside-to-outside temperature difference, wind speed and sky temperature. The U-value increased as the inside-to-outside temperature difference of increased, and, for any selected temperature difference, as the wind speed increased. The U-values exhibited linear relationships with wind speed and inside-to-outside temperature difference. The radiative heat loss increased as the sky temperature was reduced. During the nighttime, the radiative heat loss was higher than the convective heat loss, so different strategies should be adopted to reduce radiative loss. The convective heat loss was about 20% of the total heat loss at wind speed of 0 m·s<sup>-1</sup> which increased to 50% when wind speed was 5 m·s<sup>-1</sup> and more than 50% as wind speed increased. The U-value of PC, PVC, and HG was 9%, 4%, and 15% lower, respectively, than that for PE. In addition, by using a double layer a 34% reduction in heat loss was obtained.

The BES model allows for the analysis of glazing with different materials to observe the behavior of materials against outside weather conditions, which can assist in decision-making when applying energy conservation techniques to greenhouses. In conclusion, TRNSYS shows extreme flexibility in user-defined modelling. This work contributes to the expansion of future work on greenhouse modelling, as energy management of greenhouses requires a better understanding of the thermal behavior of the materials used along with the energy supplying techniques. Our future research will include analyses of design parameters of the greenhouse from an energy conservation point of view.

## References

- Abu Bakar NN, Hassan MY, Abdullah H, Rahman HA, Abdullah MP, Hussin F, Bandi M, 2015. Energy efficiency index as an indicator for measuring building energy performance: A review. *Renew Sust Energ Rev* 44: 1-11. <https://doi.org/10.1016/j.rser.2014.12.018>
- Al-Mahdouri A, Baneshi M, Gonome H, Okajima J, Maruyama S, 2013. Evaluation of optical properties and thermal performances of different greenhouse covering materials. *Solar Energy* 96: 21-32. <https://doi.org/10.1016/j.solener.2013.06.029>
- Asdrubali F, Baldinelli G, 2011. Thermal transmittance measurements with the hot box method: Calibration, experimental procedures, and uncertainty analyses of three different approaches. *Energ Build* 43: 1618-1626. <https://doi.org/10.1016/j.enbuild.2011.03.005>
- ASTM, 1993. Standard test method for steady-state thermal performance of building assemblies by means of a guarded hot box. *ASTM standards C236-89*: 52-62.

- Baille A, López JC, Bonachela S, González-Real MM, Montero JI, 2006. Night energy balance in a heated low-cost plastic greenhouse. *Agr Forest Meteorol* 137: 107-118. <https://doi.org/10.1016/j.agrformet.2006.03.008>
- Buratti C, Belloni E, Lunghi L, Barbanera M, 2016. Thermal conductivity measurements by means of a new 'small hot-box' apparatus: Manufacturing, calibration and preliminary experimental tests on different materials. *Int J Thermophys* 37: 47. <https://doi.org/10.1007/s10765-016-2052-2>
- Calleja Rodríguez G, Carrillo Andrés A, Domínguez Muñoz F, Cejudo López JM, Zhang Y, 2013. Uncertainties and sensitivity analysis in building energy simulation using macroparameters. *Energ Build* 67: 79-87. <https://doi.org/10.1016/j.enbuild.2013.08.009>
- Diop S, Lee JW, Na WH, Lee HW, 2012. Overall heat transfer coefficient measurement of covering materials with thermal screens for greenhouse using the hot box method. *J Kor Soc Agr Eng* 54: 1-7. <https://doi.org/10.5389/KSAE.2012.54.5.001>
- Diop S, Lee JW, Lee HW, 2014. Measurement and comparison of overall heat transfer coefficients for greenhouse covering materials with thermal screens. *J Kor Soc Agr Eng* 56: 41-51. <https://doi.org/10.5389/KSAE.2014.56.4.041>
- Emmel MG, Abadie MO, Mendes N, 2007. New external convective heat transfer coefficient correlations for isolated low-rise buildings. *Energ Build* 39: 335-342. <https://doi.org/10.1016/j.enbuild.2006.08.001>
- Esen M, Yuksel T, 2013. Experimental evaluation of using various renewable energy sources for heating a greenhouse. *Energ Build* 65: 340-351. <https://doi.org/10.1016/j.enbuild.2013.06.018>
- Fadel MA, Hammad BAB, Alhosany F, Iwaimer O, 2016. Greenhouses covering materials: A comparative study. *Agr Eng Int: CIGR J* 18: 48-57.
- Feuilloley P, Issanchou G, 1996. Greenhouse covering materials measurement and modelling of thermal properties using the hot box method, and condensation effects. *J Agric Eng Res* 65: 129-142. <https://doi.org/10.1006/jaer.1996.0085>
- Gao Y, Roux JJ, Teodosiu C, Zhao LH, 2004. Reduced linear state model of hollow blocks walls, validation using hot box measurements. *Energ Build* 36: 1107-1115. <https://doi.org/10.1016/j.enbuild.2004.03.008>
- Garzoli K, Blackwell J, 1981. An analysis of the nocturnal heat loss from a single skin plastic greenhouse. *J Agric Eng Res* 26: 203-214. [https://doi.org/10.1016/0021-8634\(81\)90105-0](https://doi.org/10.1016/0021-8634(81)90105-0)
- Geoola F, Kashti Y, Levi A, Brickman R, 2009. A study of the overall heat transfer coefficient of greenhouse cladding materials with thermal screens using the hot box method. *Polymer Testing* 28: 470-474. <https://doi.org/10.1016/j.polymertesting.2009.02.006>
- Hwang YY, Lee JW, Lee HW, 2013. Estimation of overall heat transfer coefficient for single layer covering in greenhouse. *Prot Hortic Plant Factor* 22: 108-115. [in Korean]. <https://doi.org/10.12791/KSBEC.2013.22.2.108>
- Klein S, 2012. *Trnsys 17 manual: A transient system simulation program*. Solar Energy Laboratory. University of Wisconsin, Madison: WI, USA.
- Kus H, Özkan E, Göcer Ö, Edis E, 2013. Hot box measurements of pumice aggregate concrete hollow block walls. *Construct Build Mat* 38: 837-845. <https://doi.org/10.1016/j.conbuildmat.2012.09.053>
- Lee JW, Kim DK, Lee HW, 2015. A numerical study for calculation of overall heat transfer coefficient of double layers covering and insulation material for greenhouse. *Curr Res Agric Life Sci* 33: 41-47.
- Mahapatra K, 2015. Energy use and CO<sub>2</sub> emission of new residential buildings built under specific requirements – the case of Växjö municipality, Sweden. *Appl Energ* 152: 31-38. <https://doi.org/10.1016/j.apenergy.2015.04.089>
- McAdams WH, 1954. *Heat Transmission*, 3<sup>rd</sup> edn. McGrawHill, NY.
- Nijskens J, Deltour J, Coutisse S, Nisen A, 1984. Heat transfer through covering materials of greenhouses. *Agr Forest Meteorol* 33: 193-214. [https://doi.org/10.1016/0168-1923\(84\)90070-4](https://doi.org/10.1016/0168-1923(84)90070-4)
- Öztürk HH, 2005. Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating. *Energ Convers Manag* 46: 1523-1542. <https://doi.org/10.1016/j.enconman.2004.07.001>
- Pulselli RM, Simoncini E, Marchettini N, 2009. Energy and energy based cost-benefit evaluation of building envelopes relative to geographical location and climate. *Build Environ* 44: 920-928. <https://doi.org/10.1016/j.buildenv.2008.06.009>
- Rasheed A, Lee JW, Lee HW, 2015. A review of greenhouse energy management by using building energy simulation. *Prot Hortic Plant Factor* 24: 317-325. <https://doi.org/10.12791/KSBEC.2015.24.4.317>
- Valera Martinez D, Molina Aiz F, Martinez A, 2008. Protocolo de auditoría energética en invernaderos. Auditoría energética de un invernadero para cultivo de flor cortada en mendigorria, Instituto para la Diversificación y Ahorro de la Energía, Madrid [in Spanish].
- Watmuff J, Charters W, Proctor D, 1977. Solar and wind induced external coefficients-solar collectors. *Coop Mediterr Energ Sol* 1: 56.
- Yang SH, Lee CG, Lee WK, Ashtiani AA, Kim JY, Lee SD, Rhee JY, 2012. Heating and cooling system for utilization of surplus air thermal energy in greenhouse and its control logic. *J Biosyst Eng* 37: 19-27. <https://doi.org/10.5307/JBE.2012.37.1.019>
- Zhang H, Lei SL, 2012. An assessment framework for the renovation of existing residential buildings regarding environmental efficiency. *Procedia - Social and Behavioral Sciences* 68: 549-563. <https://doi.org/10.1016/j.sbspro.2012.12.248>

Zhou S, Zhao J, 2013. Optimum combinations of building envelop energy-saving technologies for office buildings in different climatic regions of china. *Energ Build* 57: 103-109. <https://doi.org/10.1016/j.enbuild.2012.11.019>