Solar Energy 237 (2022) 231–238

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Regression equation for estimating the maximum cooling load of a greenhouse

Ali Pakari [*], Saud Ghani

Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar

A R T I C L E I N F O

Keywords:
Greenhouse
Central composite design
EnergyPlus
Building energy simulation
Experiments
Statistical model

A B S T R A C T

Cooling is essential for greenhouse crop cultivation in hot areas. The selection of a suitable cooling system size for greenhouses is challenging since various environmental and structural factors are involved. In this study, a regression model was developed that relate input factors, including ambient air temperature (30–44 °C), ambient relative humidity (0.15–0.5), greenhouse air temperature (20–35 °C), cover transmission (0.3–0.9), cover U value (1–6 W/m^{2}K), and ground soil thermal conductivity (0.1–1.5 W/m K), to a response, the maximum cooling load of a greenhouse (W/m^2). The model was developed using a central composite design and the maximum cooling load was calculated using EnergyPlus. The EnergyPlus results were validated against measured cooling loads of eight experimental greenhouses. The cooling loads predicted by EnergyPlus matched the calculated cooling loads from the experimental measurements within 12.4%. While the regression equation's predictions matched the experimental measurements within 13.1%. The results showed that the effect of the factors on the cooling load in order of significance from high to low were as follows, soil thermal conductivity, cover transmission, greenhouse air temperature, ambient air temperature, cover U value, and ambient air relative humidity. The developed regression equation provides a straightforward means to predict the cooling system size for greenhouses.

1. Introduction

Crops can be grown in greenhouses all year round and their yields can be tenfold of open field crops (Vadiee and Martin, 2014), nonetheless, large amounts of energy are required to obtain high yields (Pakari and Ghani, 2019a). In hot climates, most of this energy is used for cooling the greenhouse to provide a suitable environment for the growth of crops.

A number of tools are commonly used to model greenhouses, for example, computational fluid dynamics (CFD) models. Even though these models are computationally expensive and time consuming, they are more economical than building a physical prototype. These models are usually used when the objective is determining the temperature, airflow, or solar distribution inside a greenhouse (Boulard et al., 2017; Fatnassi et al., 2015; Kim et al., 2021; Pakari and Ghani, 2019b). There are building energy simulation tools, like EnergyPlus that are based on the energy balance method and can be used to predict the energy loads of buildings. Tools like EnergyPlus are considerably less computationally intensive than CFD models, however, no spatial variation in temperature is considered and the air is assumed to be well mixed (Crawley et al., 2000).

A number of studies have been conducted to determine the effect of various parameters on the thermal performance of greenhouses. The effect of cover transmission and *U* value have been studied by using different levels of shades and color shade nets (Adams et al., 2001; Ahemd et al., 2016; El-Gizawy et al., 1993; Ilić et al., 2012; Kittas et al., 2009). The crop yield, heating load, and cooling load of a greenhouse is directly influenced by the amount of solar radiation transmitted through its cover (Chen et al., 2018, 2020; Cossu et al., 2014; Sethi, 2009; Stanciu et al., 2016).

Depending on the properties of the greenhouse topsoil, it can act as a heat sink and dissipate a portion of the absorbed heat from the inside of the greenhouse to the ground. However, as pointed out by Al-Helal & Abdel-Ghany (2011) the heat conduction to the ground soil in modeling greenhouses is often neglected.

In hot climates, evaporative cooling is the preferred cooling method used in greenhouses. However, conventional evaporative cooling systems are incapable of providing a suitable environment, in terms of air temperature and humidity, for the growth of crops during the summer months. Therefore, for greenhouses to be productive, vapor compression air conditioning systems can be used in combination with evaporative

* Corresponding author.
E-mail addresses: alipakari@outlook.com, ali.pakari@qu.edu.qa (A. Pakari), s.ghani@qu.edu.qa (S. Ghani).

https://doi.org/10.1016/j.solener.2022.04.006
Received 30 September 2020; Received in revised form 21 November 2021; Accepted 3 April 2022
Available online 8 April 2022

Nomenclature

C_p	specific heat, J kg^{-1} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
RH	relative humidity
t	greenhouse cover transmission
T	temperature, °C
U	greenhouse cover U value, W m^{-2} K^{-1}
v	air velocity, m/s

Subscripts

a	ambient air
ex	exhaust air
g	greenhouse air
s	supply air

a central composite design (CCD), the number of the experimental runs was determined. Then, the experiments were conducted using EnergyPlus to calculate the maximum cooling load of the greenhouse. Then, using regression analysis, a second-order model was fitted to the maximum cooling load response. Using the regression model, the relative effect of the selected factors on the greenhouse cooling load was determined. In order to validate the EnergyPlus simulations, the cooling loads of a number of greenhouses were calculated using experimental field measurements. The main stages of this study are shown in the form of a flowchart in Fig. 1

The remainder of this paper is structured as follows. In Section 2, the experimental methods and the methods used to develop the regression model are described. In Section 3, the results are presented and discussed. Finally, Section 4 concludes this paper.

2. Methods

2.1. Experimental setup

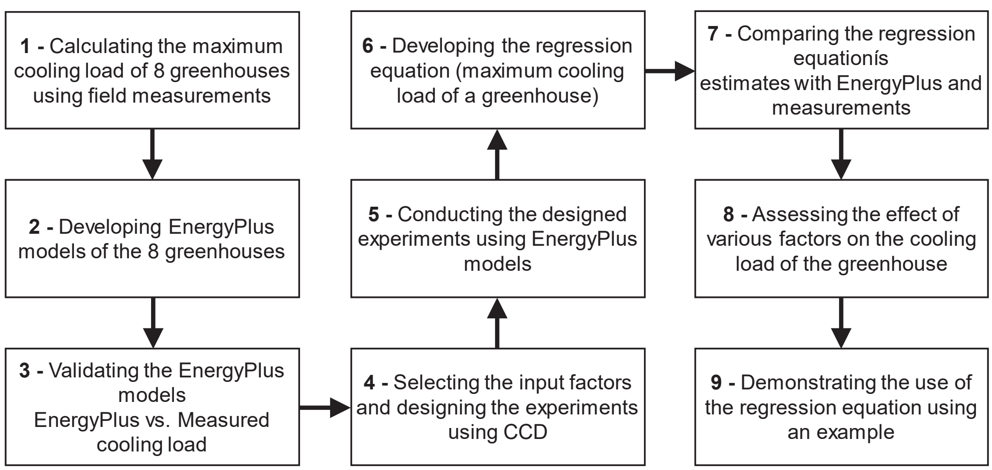

Fig. 1. Flow chart of the main stages of the study.

cooling systems.

The objective of this study is to develop a regression model to predict the maximum cooling load of a greenhouse, which can aid in the appropriate sizing of the cooling system of a greenhouse and subsequently provide a suitable environment for the growth of crops. The regression model is a mathematical expression that relate input factors, including ambient conditions and greenhouse specifications, to a response, the maximum cooling load of the greenhouse. The considered ambient factors are air temperature and relative humidity. The greenhouse specifications are greenhouse air temperature, cover transmission, cover *U* value and ground soil thermal conductivity. First, using

In order to validate the EnergyPlus model and the regression equation, the maximum cooling load of eight greenhouses was calculated using experimental field measurements. The greenhouses were located in Leatooriya district (25.5179° N, 51.2091° E). The measurements were carried out on July 20th and August 12th, 2020 around noon so the solar radiation was maximum (approximately 1000 W/m^2). All eight greenhouses had a round arched tunnel shape. A schematic of the greenhouse is shown in Fig. 2 (a). The greenhouse is 21 m long and 9 m wide with a north–south orientation, the surface area of the walls is about 310 m^2. Fig. 2 (b) shows a picture of the inside of the greenhouse. No crops were planted in the greenhouses at the time of measurements. The cooling

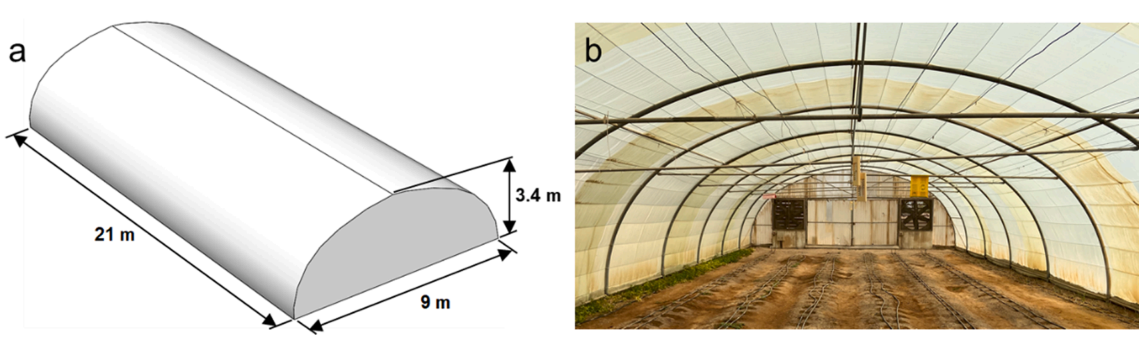

Fig. 2. (a) Schematic of the experimental greenhouse showing its dimensions and (b) picture of the inside of the greenhouse.

Table 1
The measured and calculated factors of the eight experimental greenhouses. T_a = ambient air temperature, RH_a = ambient air relative humidity, T_g = greenhouse air temperature, t = cover transmission, U = cover U value, k = ground thermal conductivity.

Greenhouse no.	T_s °C	T_{ex} °C	v m/s	T_a °C	RH_a	T_g °C	t	U W/m^2 K	k W/m K	cooling load W/m^2	flow rate m^3/h/m^2
1	30.0	34.5	1.4	42.0	0.40	34.0	0.62	5.1	0.35	275.0	183.2
2	31.0	34.5	1.3	42.0	0.40	34.0	0.48	5.7	0.35	254.1	217.7
3	31.0	34.5	1.4	42.0	0.40	34.0	0.58	5.6	0.24	273.6	234.4
4	30.0	34.5	1.3	42.0	0.40	34.0	0.77	5.2	0.40	326.7	217.7
5	29.5	31.7	1.7	42.0	0.29	31.6	0.49	1.7	0.12	312.9	426.5
6	31.0	33.2	1.8	42.0	0.29	32.8	0.49	4.0	0.12	331.3	451.5
7	30.7	37.0	0.6	42.0	0.29	35.0	0.35	3.9	0.12	250.5	119.2
8	27.3	34.8	2.7	42.0	0.29	34.7	0.35	4.0	0.12	243.1	97.2

load was calculated using the ANSI/ASAE EP406.4 JAN03 standard, which includes measuring the supply air temperature, supply air flow rate, and the exhaust air temperature. The cooling load was calculated using the following equation:

$$Coolingload = \dot{m}C_p(T_{ex} - T_s) \tag{1}$$

where $\dot{m}$ (kg/s) is the supply air mass flow rate, C_p (kJ/kg °C) is specific heat of air, T_{ex} (°C) is the exhaust air temperature, and T_s (°C) is the supply air temperature.

The measured and calculated factors of the eight experimental greenhouses are shown in Table 1. The air velocity, temperature, and relative humidity measurements were performed with Kestrel Meter 5400 Heat Stress Tracker. The supply air measurements were carried out at multiple locations right after the evaporative cooling pads. Similarly, the exhaust air measurements were carried out right before the meshed screen of the exhaust fans. At each location, the measurements lasted for about 5 min and the time-averaged values were used in the cooling load calculations. The uncertainties of the air velocity, temperature, and relative humidity measurements were ±0.1 m/s, ±0.5 °C, and ±0.02, respectively. The transmission of the covers was estimated by measuring the incident solar radiation inside and outside the greenhouse. The measurements were performed using a full-spectrum quantum meter (MQ 500, Apogee instruments). The uncertainty in the measured solar radiation was about 5%. The cover U value is a material property provided by the manufacturer. The soil of all eight greenhouses was a mixture of sand and compost. The soil thermal conductivity was estimated using data of the thermal conductivity of sandy soil at different moisture contents presented by Farouki (1981), therefore, the thermal conductivity of the greenhouses soil was estimated by measuring the soil moisture content. The measurements were performed using a soil moisture meter (Extech soil moisture meter, model MO750), the uncertainty of the measurements was about ±5%.

The uncertainty in the calculated cooling load was estimated based on the uncertainties in the experimental measurements using equation (2) as presented by Kline and McClintock (1953) and according to the procedure described by Moffat (1988):

$$\delta R = \left(\sum_{i=1}^{N} \left(\frac{\partial R}{\partial X_i} \delta X_i \right)^2 \right)^{\frac{1}{2}} \tag{2}$$

where δR is the uncertainty in the calculated result and δX_i represents the uncertainties in the experimental measurements, T_s, T_{ex}, and supply air velocity, v (m/s).

2.2. Building energy simulations

The building energy simulations were performed using EnergyPlus, which is an open-source whole building energy simulation program. It is commonly used for modeling greenhouse energy consumption (Graamans et al., 2018; Nadal et al., 2017; Pakari and Ghani, 2019a). EnrgyPlus consists of three main modules. The first module is the simulation manager that represents the outermost level of the program controlling all the simulation levels. The second module is the heat and mass balance simulation, which includes the surface heat balance module and the air mass balance module. The surface heat balance module deals with the heat transfer through outside and inside surfaces while the air mass balance module deals with infiltration, exhaust air, and ventilation air. The heat balance method is used to calculate the cooling load with the assumption that the air in the thermal zone is well mixed with no spatial variations in temperature (Crawley et al., 2000). The third module is the building systems simulation which controls the simulation of HVAC equipment. The same dimensions and orientation of the experimental greenhouses were used in the simulations. The greenhouse consisted of one zone and similar to the experimental conditions, the presence of plants was not considered in the simulations.

2.3. Regression model

The appropriate selection of an experimental design facilitates the fitting and analysis of a response that is affected by several factors. A central composite design (CCD) was used to determine the effect of a number of factors on the maximum cooling load of a greenhouse. The considered factors were ambient air temperature, T_a, ambient relative humidity, RH_a, greenhouse air temperature, T_g, the transmission of the greenhouse cover, t, the U value of the greenhouse cover, and the thermal conductivity of the greenhouse ground soil, k. The selected response was the maximum cooling load of the greenhouse. The CCD is a very efficient and the most popular class of designs for fitting a second order model. The distance of the axial points from the center in the CCD was selected as 2 (Pakari and Ghani, 2019c). Table 2 lists the factors and their levels in the CCD. The 90-run design containing 64 factorial points, 14 center points, and 12 axial points is shown in Table 3, along with the corresponding maximum cooling load response calculated using

Table 2
The factors and their corresponding levels in the central composite design.

Factor	Description	Units	Levels				
T_a	Ambient temperature	°C	30	33.5	37	40.5	44
RH_a	Ambient relative humidity	–	0.15	0.2375	0.325	0.4125	0.5
T_g	Greenhouse temperature	°C	20	23.75	27.5	31.25	35
t	Cover transmission	–	0.3	0.45	0.6	0.75	0.9
U	Cover U value	W/m^2 K	1	2.25	3.5	4.75	6
k	Ground thermal conductivity	W/m K	0.1	0.45	0.8	1.15	1.5

Table 3
The central composite design matrix along with the calculated cooling loads using EnergyPlus.

	Factors						Response
Run	T_a (°C)	RH_a	T_g (°C)	t	U (W/m^2 K)	k (W/m K)	Cooling load (W/m^2)
1	40.5	0.2375	31.25	0.75	2.25	0.45	324.4
2	40.5	0.2375	23.75	0.45	2.25	0.45	240.4
3	37	0.325	27.5	0.6	3.5	0.8	216.4
4	37	0.325	27.5	0.6	3.5	0.8	216.4
5	33.5	0.4125	31.25	0.45	4.75	0.45	213.5
6	40.5	0.4125	23.75	0.45	4.75	1.15	235.0
7	40.5	0.2375	23.75	0.75	2.25	1.15	257.0
8	33.5	0.2375	31.25	0.75	2.25	1.15	192.3
9	40.5	0.4125	23.75	0.75	2.25	0.45	367.1
10	40.5	0.2375	23.75	0.75	2.25	0.45	364.6
11	40.5	0.2375	31.25	0.75	2.25	1.15	208.8
12	40.5	0.4125	31.25	0.45	4.75	0.45	246.0
13	40.5	0.4125	31.25	0.45	2.25	0.45	204.4
14	40.5	0.4125	23.75	0.75	2.25	1.15	259.2
15	40.5	0.2375	23.75	0.45	4.75	0.45	295.3
16	30	0.325	27.5	0.6	3.5	0.8	192.8
17	40.5	0.4125	31.25	0.75	4.75	0.45	314.8
18	40.5	0.4125	23.75	0.75	4.75	1.15	272.0
19	40.5	0.2375	23.75	0.75	4.75	1.15	268.7
20	37	0.325	27.5	0.6	3.5	0.8	216.4
21	37	0.325	27.5	0.6	3.5	0.8	216.4
22	37	0.325	27.5	0.6	3.5	1.5	151.2
23	33.5	0.4125	31.25	0.45	2.25	1.15	109.4
24	33.5	0.2375	23.75	0.75	4.75	0.45	332.2
25	37	0.325	27.5	0.6	6	0.8	267.4
26	33.5	0.2375	23.75	0.45	4.75	1.15	203.6
27	40.5	0.2375	31.25	0.45	4.75	1.15	174.7
28	37	0.325	27.5	0.9	3.5	0.8	320.7
29	33.5	0.2375	31.25	0.75	4.75	0.45	279.1
30	37	0.325	27.5	0.6	3.5	0.8	216.4
31	33.5	0.4125	31.25	0.45	2.25	0.45	184.7
32	40.5	0.4125	31.25	0.75	2.25	1.15	210.9
33	33.5	0.4125	31.25	0.75	4.75	0.45	282.2
34	37	0.325	27.5	0.6	3.5	0.8	216.4
35	33.5	0.2375	23.75	0.45	4.75	0.45	262.7
36	37	0.15	27.5	0.6	3.5	0.8	212.7
37	40.5	0.2375	23.75	0.45	4.75	1.15	231.9
38	40.5	0.4125	23.75	0.45	2.25	0.45	242.9
39	40.5	0.4125	31.25	0.45	2.25	1.15	125.4
40	40.5	0.4125	31.25	0.75	2.25	0.45	326.9
41	37	0.325	35	0.6	3.5	0.8	167.4
42	33.5	0.4125	31.25	0.75	4.75	1.15	185.5
43	33.5	0.4125	23.75	0.45	2.25	1.15	154.3
44	37	0.325	27.5	0.6	3.5	0.8	216.4
45	37	0.325	27.5	0.6	3.5	0.8	216.4
46	33.5	0.2375	31.25	0.45	2.25	0.45	182.5
47	37	0.325	27.5	0.6	3.5	0.8	216.4
48	37	0.325	27.5	0.6	3.5	0.1	339.8
49	37	0.325	27.5	0.6	3.5	0.8	216.4
50	33.5	0.2375	23.75	0.45	2.25	1.15	152.4
51	33.5	0.2375	31.25	0.45	2.25	1.15	107.6
52	40.5	0.2375	31.25	0.75	4.75	0.45	311.3
53	40.5	0.4125	31.25	0.45	4.75	1.15	177.7
54	33.5	0.4125	23.75	0.45	4.75	0.45	265.8
55	33.5	0.4125	31.25	0.75	2.25	0.45	306.6
56	33.5	0.2375	31.25	0.75	2.25	0.45	304.4
57	40.5	0.2375	23.75	0.45	2.25	1.15	168.7
58	33.5	0.4125	23.75	0.75	2.25	0.45	346.9
59	33.5	0.4125	23.75	0.45	2.25	0.45	223.2
60	33.5	0.2375	23.75	0.75	4.75	1.15	240.4
61	44	0.325	27.5	0.6	3.5	0.8	240.6
62	37	0.325	27.5	0.3	3.5	0.8	123.8
63	40.5	0.2375	31.25	0.75	4.75	1.15	210.2
64	37	0.325	27.5	0.6	3.5	0.8	216.4
65	40.5	0.2375	31.25	0.45	4.75	0.45	242.6
66	37	0.325	27.5	0.6	1	0.8	220.9
67	37	0.5	27.5	0.6	3.5	0.8	218.6
68	40.5	0.4125	23.75	0.45	2.25	1.15	170.8
69	40.5	0.2375	31.25	0.45	2.25	1.15	123.3
70	37	0.325	20	0.6	3.5	0.8	266.2
71	33.5	0.4125	23.75	0.75	4.75	1.15	243.3
72	33.5	0.4125	31.25	0.75	2.25	1.15	194.1
73	40.5	0.2375	31.25	0.45	2.25	0.45	201.9
74	40.5	0.2375	23.75	0.75	4.75	0.45	364.9
75	33.5	0.4125	23.75	0.75	2.25	1.15	242.1
76	33.5	0.4125	23.75	0.45	4.75	1.15	206.3
77	33.5	0.2375	31.25	0.45	4.75	1.15	147.5
78	40.5	0.4125	23.75	0.75	4.75	0.45	368.6
79	40.5	0.4125	31.25	0.75	4.75	1.15	213.3
80	33.5	0.2375	23.75	0.45	2.25	0.45	221.0
81	33.5	0.2375	31.25	0.45	4.75	0.45	210.6
82	33.5	0.4125	31.25	0.45	4.75	1.15	150.0
83	40.5	0.4125	23.75	0.45	4.75	0.45	298.9
84	33.5	0.2375	23.75	0.75	2.25	1.15	240.2
85	33.5	0.2375	31.25	0.75	4.75	1.15	182.8
86	37	0.325	27.5	0.6	3.5	0.8	216.4
87	33.5	0.4125	23.75	0.75	4.75	0.45	335.5
88	37	0.325	27.5	0.6	3.5	0.8	216.4
89	33.5	0.2375	23.75	0.75	2.25	0.45	344.7
90	37	0.325	27.5	0.6	3.5	0.8	216.4

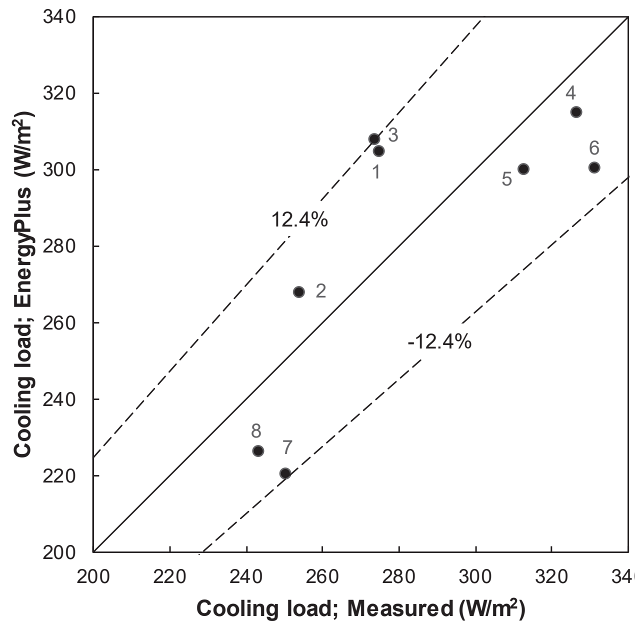

Fig. 3. Comparison between the predicted cooling loads by the EnergyPlus model and the calculated cooling loads using the experimental measurements. The data points are labeled with the greenhouse numbers from Table 1.

EnergyPlus.

3. Results and discussion

3.1. EnergyPlus model validation

Fig. 3 compares the EnergyPlus models' predictions of the maximum cooling loads of the experimental greenhouses and the calculated cooling loads using the experimental measurements. The data points in the figure are labeled according to the greenhouse numbers listed in Table 1. The cooling loads predicted by the EnergyPlus model match the calculated cooling loads from the experimental measurements within 12.4%. The average discrepancy between the predicted and measured cooling loads is about 8.1%. Overall, a good agreement between the predictions and the measurements was obtained, therefore, the EnergyPlus model was used to predict the maximum greenhouse cooling loads at the

Table 4
Analysis of variance for the prediction model of greenhouse cooling load.

Source	coded coefficients	DF	Adj SS	Adj MS	F-Value	P-Value
Model		27	341,717	12,656	753.14	0
Linear		6	315,969	52,661	3133.75	0
T_a	12.1	1	10,542	10,542	627.34	0
RH_a	1.336	1	128	128	7.65	0.007
T_g	−24.571	1	43,469	43,469	2586.71	0
t	40.468	1	117,911	117,911	7016.6	0
U	10.513	1	7957	7957	473.5	0
k	−43.455	1	135,961	135,961	8090.7	0
Square		6	8091	1348	80.24	0
T_a^2	1.262	1	56	56	3.34	0.072
RH_a^2	0.997	1	35	35	2.08	0.154
T_g^2	1.282	1	58	58	3.44	0.068
t^2	2.656	1	248	248	14.77	0
U^2	8.123	1	2323	2323	138.21	0
k^2	8.468	1	2524	2524	150.2	0
2-Way Interaction		15	17,658	1177	70.05	0
T_aRH_a	0.091	1	1	1	0.03	0.859
T_aT_g	−0.124	1	1	1	0.06	0.809
T_at	0.09	1	1	1	0.03	0.862
T_aU	3.04	1	592	592	35.21	0
T_ak	−0.989	1	63	63	3.72	0.058
RH_aT_g	−0.03	1	0	0	0	0.954
RH_at	0.018	1	0	0	0	0.972
RH_aU	0.236	1	4	4	0.21	0.647
RH_ak	−0.095	1	1	1	0.03	0.854
T_gt	−0.45	1	13	13	0.77	0.384
T_gU	−3.049	1	595	595	35.4	0
T_gk	−1.468	1	138	138	8.21	0.006
tU	−13.036	1	10,876	10,876	647.18	0
tk	−8.675	1	4816	4816	286.61	0
Uk	2.957	1	560	560	33.31	0
Error		62	1042	17		
Total		89	342,759			

different factors levels listed in Table 3.

3.2. Regression analysis

The results of fitting a second-order model to the maximum cooling load response is summarized in Table 4. In the table, DF is the degrees of freedom, Adj SS is the adjusted sum of squares, which measures the amount of variation for different parts of the model, and Adj MS is the adjusted mean sum of squares, obtained by dividing the adjusted sum of squares by the degrees of freedom.

In scientific and engineering practice, in most situations, a significance level of 0.05 is used. Therefore, a significance level of 0.05 was selected to assess the significance of the terms of the model. According to Table 4, all the six main factors were significant since their P-values were less than 0.05. The P-values for the square terms in the table indicate that the square terms of the ambient temperature, ambient humidity, and greenhouse temperature were not significant. While for the interaction terms, only six of the 15 terms were significant. The significant terms were T_aU, T_gU, T_gk, tU, tk, and Uk.

The relative effect of each term on the response can be determined from their coded coefficients listed in Table 4. Given that the coded coefficients are dimensionless; they are directly comparable. Whether the relationship between a term and the response is direct or inverse is indicated by the sign of the coded coefficient. Therefore, it can be seen that the effect of T_g is almost two times the effect of T_a on the response. However, T_g is inversely proportional to the response while T_a is directly proportional to the response. The effect of t is almost four times the effect of U. From all the factors, the most significant factor is k and the least significant is RH_a. It should be noted that depending on the growth stage of a crop in a greenhouse, the amount of incident solar radiation that is absorbed by the ground would be different since a portion would be absorbed by the crop. Therefore, in future studies, the effect of the crop and its growth stage should be considered.

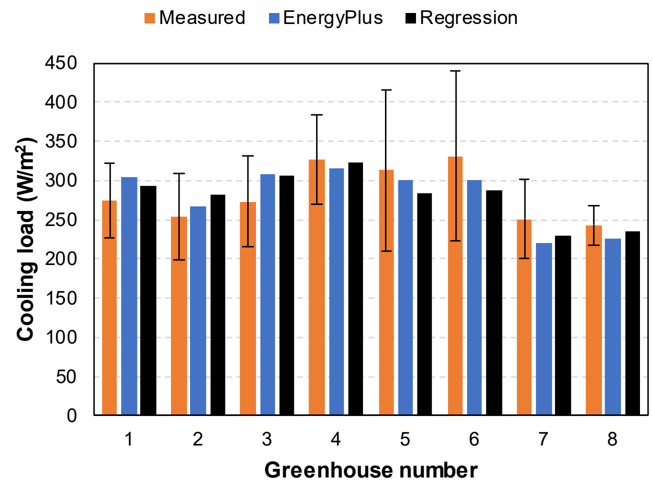

Fig. 4. Comparison between the predicted cooling load of the eight greenhouses by the regression equation, EnergyPlus model, and the experimental measurements. The vertical bars represent the uncertainty in the calculated cooling loads using the measured values.

After excluding the terms with a P-value less than 0.05, a reduced model for the greenhouse maximum cooling load (GMCL) response was obtained. The model's coefficient of determination, R^2, is 0.996; that is, about 99.6 percent of the variability in the response is explained by the model. The obtained regression model is:

$$\begin{aligned} GMCL = {} & 132.1 + 1.025T_a + 15.27RH_a - 3.381T_g + 480.1t - 1.48U \\ & - 134.3k + 137.7t^2 + 5.482U^2 + 72.74k^2 + 0.695T_aU - 0.650T_gU \\ & - 1.118T_gk - 69.52tU - 165.2tk + 6.76Uk \end{aligned} \quad (3)$$

3.3. Comparison between the regression model, EnergyPlus model, and experiments

To assess the obtained regression equation, its predictions of the maximum cooling load of the eight experimental greenhouses are compared to the EnergyPlus model and the experimental measurements (Fig. 4). The vertical bars in the figure represent the uncertainty in the calculated cooling loads using the measured values. The predicted cooling loads of the greenhouses by the regression equation and the EnergyPlus model match within 5.5%, with an average difference of about 3.8%. While the predictions by the regression equation match the experimental measurements within 13.1%. The average difference between the regression equation' predictions and the experimental measurements is about 8.1%.

3.4. Effect of the factors on the cooling load of the greenhouse

The effect of varying the factors in the significant interaction terms on the greenhouse cooling load was investigated by constructing contour plots of the response surface. Contour plots of the greenhouse cooling load as functions of the factors in the interaction terms obtained from the regression model are shown in Fig. 5. The unvaried factors, which are shown in the figure, are held at their mean levels as listed in Table 2.

Fig. 5 (a) is a contour plot of the greenhouse cooling load as a function of ambient air temperature, T_a, and greenhouse cover U value. When considering the main effect of T_a and U, they are both directly proportional to the cooling load, the lower the ambient temperature and U, the lower the cooling load. However, it can be seen from the figure that at the lowest ambient temperature, the cooling load is minimum when the U value is between 2 and 4 W/m^2 K. Fig. 5 (b) presents a contour plot of the greenhouse cooling load as a function of greenhouse temperature, T_g, and greenhouse cover U value. The cooling load

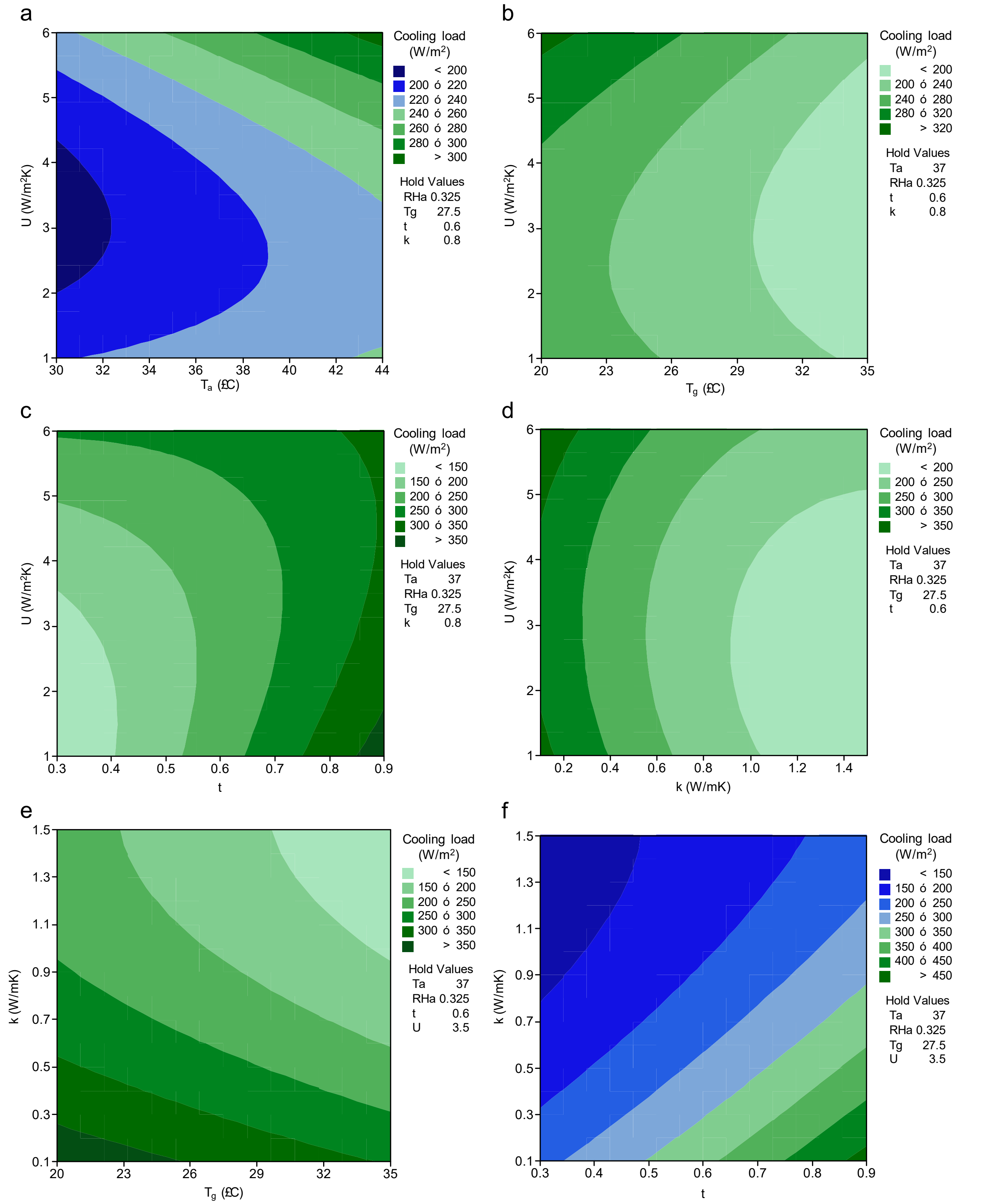

Fig. 5. Contour plots of greenhouse cooling load as functions of (a) ambient air temperature and greenhouse cover *U* value, (b) greenhouse temperature and greenhouse cover *U* value, (c) cover transmission and cover *U* value, (d) ground thermal conductivity and cover *U* value, (e) greenhouse temperature and ground thermal conductivity, and (f) cover transmission and ground thermal conductivity.

decreases as T_g increases and cover U value decreases. The lower the U value, the higher the thermal resistance of the greenhouse cover and the lower the conduction heat gain through it, leading to lower cooling loads. The contour plot of the greenhouse cooling load as a function of cover transmission, t, and cover U value is shown in Fig. 5 (c). The greenhouse cooling load decreases as cover transmission and cover U value decrease. Fig. 5 (d) shows a contour plot of the greenhouse cooling load as a function of ground thermal conductivity and cover U value. By examining the plot, we see that the cooling load decreases as ground thermal conductivity increases and cover U value decreases.

Fig. 5 (e) shows a contour plot of the greenhouse cooling load as a function of greenhouse air temperature and ground thermal conductivity. By examining the plot, we see that the cooling load decreases as both greenhouse air temperature and ground thermal conductivity increase. Fig. 5 (f) shows a contour plot of the greenhouse cooling load as a function of greenhouse cover transmission and ground thermal conductivity. It can be seen that the cooling load decreases as cover transmission decreases and ground thermal conductivity increases. The lower the greenhouse cover transmission the lower the admitted solar radiation and the higher the ground thermal conductivity the higher the amount of heat absorbed and transferred by the ground, leading to lower cooling loads of the greenhouse.

3.5. Example of using the regression equation

In this section, an example of using the regression equation to estimate the cooling system size of a greenhouse is presented. The selected greenhouse size is the same as the one shown in Fig. 2, with a floor area of about 189 m^2. For the weather conditions, the ASHRAE annual cooling design conditions for Doha, Qatar was selected. The 1% dry bulb temperature is 42.9 °C and the coincident wet bulb temperature is 22.4 °C, equivalent to a relative humidity of 0.16. The target greenhouse air temperature is 28 °C, which is a suitable temperature for the growth of tomatoes (Yildirim and Bilir, 2017). The greenhouse cover transmission and U value are 0.35 and 1.6 W/m^2 K, respectively, and the ground thermal conductivity is 0.4 W/m K. Substituting these values into equation (3), the size of the greenhouse cooling system is estimated to be about 35.3 kW, which is about 10 tons of refrigeration. Suitable temperatures for the growth of lettuce and cucumber are 23 °C and 35 °C (Yildirim and Bilir, 2017), respectively. Therefore, using equation (3), the cooling system size for growing lettuce is estimated to be about 39.9 kW (11.3 tons of refrigeration) and for growing cucumber is about 28.8 kW (8.2 tons of refrigeration).

The regression equation developed in this study can be used within the range of the input factors listed in Table 2. Moreover, the regression equation can be used for greenhouses with various length to width ratios, arch shapes, and cooling systems. It should be noted that the regression equation was developed considering a maximum incident solar radiation of about 1000 W/m^2. Therefore, in regions where the maximum incident solar radiation is lower, the regression equation can be used by adjusting the transmission of the greenhouse cover. For example, for a location where the maximum incident solar radiation is 700 W/m^2, the transmission of the greenhouse cover should be adjusted by multiplying it by 0.7, which is the ratio of the incident radiations (700 W/m^2 over 1000 W/m^2).

4. Conclusions

This paper described the development of a method to estimate the maximum cooling load of greenhouses. Regression analysis was used to develop a second order equation for the maximum cooling load of a greenhouse as a function of ambient air temperature, ambient relative humidity, greenhouse air temperature, cover transmission, cover U value, and ground soil thermal conductivity. Therefore, using the central composite design a number of experimental trials were designed and were conducted using the building energy simulation tool EnergyPlus. To validate the simulations, the cooling load of eight experimental greenhouses were measured and compared to the EnergyPlus and regression equation predictions, which matched within 12.4% and 13.1%, respectively. Using the regression analysis, the relative effect of the selected factors on the maximum cooling load of a greenhouse was determined. The results showed that the effect of the factors on the cooling load in order of significance from high to low were as follows, soil thermal conductivity, cover transmission, greenhouse air temperature, ambient air temperature, cover U value, and ambient air relative humidity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by a grant from the Qatar National Research Fund under its National Priorities Research Program [award number NPRP11S-0114-180295]. The contents of this work are solely the responsibility of the authors and do not necessarily represent the official views of the Qatar National Research Fund.

References

Adams, S.R., Valdeés, V.M., Cave, C.R.J., Fenlon, J.S., 2001. The impact of changing light levels and fruit load on the pattern of tomato yields. J. Hortic. Sci. Biotechnol. 76 (3), 368–373. https://doi.org/10.1080/14620316.2001.11511379.

Ahemd, H.A., Al-Faraj, A.A., Abdel-Ghany, A.M., 2016. Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. Sci. Hortic. (Amsterdam) 201, 36–45. https://doi.org/10.1016/j.scienta.2016.01.030.

Al-Helal, I.M., Abdel-Ghany, A.M., 2011. Energy partition and conversion of solar and thermal radiation into sensible and latent heat in a greenhouse under arid conditions. Energy Build. 43 (7), 1740–1747. https://doi.org/10.1016/j.enbuild.2011.03.017.

Boulard, T., Roy, J.C., Pouillard, J.B., Fatnassi, H., Grisey, A., 2017. Modelling of micrometeorology, canopy transpiration and photosynthesis in a closed greenhouse using computational fluid dynamics. Biosyst. Eng. 158, 110–133. https://doi.org/10.1016/j.biosystemseng.2017.04.001.

Chen, C., Li, Y., Li, N., Wei, S., Yang, F., Ling, H., Yu, N., Han, F., 2018. A computational model to determine the optimal orientation for solar greenhouses located at different latitudes in China. Sol. Energy 165, 19–26. https://doi.org/10.1016/j.solener.2018.02.022.

Chen, J., Ma, Y., Pang, Z., 2020. A mathematical model of global solar radiation to select the optimal shape and orientation of the greenhouses in southern China. Sol. Energy 205, 380–389. https://doi.org/10.1016/j.solener.2020.05.055.

Cossu, M., Murgia, L., Ledda, L., Deligios, P.A., Sirigu, A., Chessa, F., Pazzona, A., 2014. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. Appl. Energy 133, 89–100. https://doi.org/10.1016/j.apenergy.2014.07.070.

D.B. Crawley, L.K. Lawrie, C.O. Pedersen, F.C.W., 2000. EnergyPlus: energy simulation program. ASHRAE 42, 4.

El-Gizawy, A.M., Abdallah, M.M.F., Gomaa, H.M., Mohamed, S.S., 1993. Effect of different shading levels on tomato plants. 2. Yield and fruit quality. Acta Hort (323), 349–354. https://doi.org/10.17660/ActaHortic.1993.323.32.

Farouki, O.T., 1981. Thermal Properties of Soils. Mater. Sci. https://apps.dtic.mil/sti/citations/ADA111734.

Fatnassi, H., Poncet, C., Bazzano, M.M., Brun, R., Bertin, N., 2015. A numerical simulation of the photovoltaic greenhouse microclimate. Sol. Energy 120, 575–584. https://doi.org/10.1016/j.solener.2015.07.019.

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., Stanghellini, C., 2018. Plant factories versus greenhouses: Comparison of resource use efficiency. Agric. Syst. 160, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003.

Ilić, Z.S., Milenković, L., Stanojević, L., Cvetković, D., Fallik, E., 2012. Effects of the modification of light intensity by color shade nets on yield and quality of tomato fruits. Sci. Hortic. (Amsterdam) 139, 90–95. https://doi.org/10.1016/j.scienta.2012.03.009.

Kim, R., Kim, J., Lee, I., Yeo, U., Lee, S., Decano-Valentin, C., 2021. Development of three-dimensional visualisation technology of the aerodynamic environment in a greenhouse using CFD and VR technology, part 1: Development of VR a database using CFD. Biosyst. Eng. 207, 33–58. https://doi.org/10.1016/j.biosystemseng.2021.02.017.

Kittas, C., Rigakis, N., Katsoulas, N., Bartzanas, T., 2009. Influence of shading screens on microclimate, growth and productivity of tomato. Acta Hortic. (807), 97–102. https://doi.org/10.17660/ActaHortic.2009.807.10.

Kline, S.J., McClintock, F.A., 1953. Describing uncertainties in single-sample experiments. Mech. Eng.

Moffat, R.J., 1988. Describing the Uncertainties in Experimental Results. Exp. Therm. Fluid Sci. 1 (1), 3–17.

Nadal, A., Llorach-Massana, P., Cuerva, E., Lopez-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017. Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. Appl. Energy 187, 338–351. https://doi.org/10.1016/j.apenergy.2016.11.051.

Pakari, A., Ghani, S., 2019a. Evaluation of a novel greenhouse design for reduced cooling loads during the hot season in subtropical regions. Sol. Energy 181, 234–242. https://doi.org/10.1016/j.solener.2019.02.006.

Pakari, A., Ghani, S., 2019b. Airflow assessment in a naturally ventilated greenhouse equipped with wind towers: numerical simulation and wind tunnel experiments. Energy Build. 199, 1–11. https://doi.org/10.1016/j.enbuild.2019.06.033.

Pakari, A., Ghani, S., 2019c. Regression models for performance prediction of counter flow dew point evaporative cooling systems. Energy Convers. Manag. 185, 562–573. https://doi.org/10.1016/j.enconman.2019.02.025.

Sethi, V.P., 2009. On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. Sol. Energy 83 (1), 21–38. https://doi.org/10.1016/j.solener.2008.05.018.

Stanciu, C., Stanciu, D., Dobrovicescu, A., 2016. Effect of Greenhouse Orientation with Respect to E-W Axis on its Required Heating and Cooling Loads. Energy Procedia 85, 498–504. https://doi.org/10.1016/j.egypro.2015.12.234.

Vadiee, A., Martin, V., 2014. Energy management strategies for commercial greenhouses. Appl. Energy 114, 880–888. https://doi.org/10.1016/j.apenergy.2013.08.089.

Yildirim, N., Bilir, L., 2017. Evaluation of a hybrid system for a nearly zero energy greenhouse. Energy Convers. Manag. 148, 1278–1290. https://doi.org/10.1016/j.enconman.2017.06.068.