Thermal environment modelling of the Chinese mono-slope solar greenhouse

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ABSTRACT The high heating cost of greenhouse production in winter sets up an obstacle for the greenhouse growers in cold regions. The padlock of most Canadian greenhouses in Prairie provinces in the coldest months is the direct proof. Fortunately, solar greenhouse, which relies on solar energy to maintain indoor temperature, seems to be the optimal solution. However, limited research has been done to quantify the supplemental heating requirement of solar greenhouses. In this study, a modified thermal simulation model was developed and verified by field data and using this validated model to simulate the thermal environment of a solar greenhouse in Saskatchewan. Indoor thermal environment parameters including temperature and RH, supplemental heating were predicted with typical meteorological year data. The results revealed that solar greenhouse is capable of producing local vegetables with relatively low energy consumption in the coldest months.

Keywords: Cold regions, meteorological year data, solar greenhouse, simulation model, validation.
INTRODUCTION The high heating cost of greenhouse production in winter continues to be a barrier for the greenhouse growers in Saskatchewan in which has 64-million-acre farmland, accounting for around 40% of the total Canadian farmland. Most traditional Canadian greenhouses in Canadian Prairies shut down in the coldest months because of the extremely low temperature. Although supplemental heating has been commonly applied in greenhouses, the high energy consumption and maintenance requirement set up a tough hurdle for vegetable production in winter. Thus, imported vegetables and fruits occupy winter food market in Saskatchewan. Chinese mono-slope solar greenhouse, due to its unique structure, does not primarily rely on supplemental heat but on solar energy to maintain indoor temperature. Fortunately, Saskatchewan is the sunniest province in Canada, which provides a favorable environmental condition for the establishment and development of mono-slope solar greenhouses, this may cut down the heating cost considerably.

Evaluation research work has been conducted using simulation model with MATLAB, CFD, evaluation model with VC++ method (Meng et al., 2009; Tong et al., 2007; Xu et al., 2013; Guo et al., 1994; Ma et al., 2010). However, some of these methods have many restrictions towards thermal environmental simulation, and some are not accurate enough through validation. Therefore, they are not suitable to simulate greenhouse indoor thermal environment in Canadian Prairies. The field experiment conducted in Elie, Manitoba by Zhang et al. (2006) showed that mono-slope solar greenhouse production is a more energy-efficient method for greenhouse production in cold regions than traditional gutter-connected greenhouse production. Nonetheless, no further study can evaluate the thermal environment condition and energy consumption in the solar greenhouse in cold regions.

To simulate the indoor thermal environment of the solar greenhouse and evaluate its energy consumption, modifications needs to be done in previous simulation research work. Dr. Ma in China developed a solar greenhouse thermal environment simulation model RGWSRHJ. However, this simulation model was not capable of simulating with Canadian conditions. The objective of this study is to modify this software, including making this model applicable in Canada, adding the polystyrene pellet insulation and the double-layer inflated front-roof cover, resetting the wind speed and simulation month limitation, adding a working condition storage function, and so on. Besides, field data were collected in a solar greenhouse in Manitoba to validate the accuracy of the modified simulation model. Afterward, solar greenhouse simulation in Saskatoon was conducted to evaluate the supplemental heat demands of a study solar greenhouse. With these results, greenhouse growers will be provided with the difference in energy consumption between traditional gutter-connected greenhouses and mono-slope solar greenhouses, thus making winter local greenhouse vegetable production economical for Canadian Prairies.

MATERIALS AND METHODS

The original model RGWSRHJ was developed by Dr. Ma in visual studio with C++ language. It intends to evaluate and optimize the design scheme of a solar greenhouse, predict its thermal environment, and provide environmental reference foundation to greenhouse growers. Before simulation, users need to input several greenhouse information. First, select simulation location and the model will calculate required weather data such as outdoor temperature, RH, and solar irradiance. Second, fill thermal and structural parameters of each construction material. Third, select plant’s density according to the estimated weight per unit area, and fill plant’s height and distance to the north wall to calculate the height of shadow on the north wall. Fourth, select covering material and aging degree of front roof to determine its thermal conductivity and transmittance. Finally, input thermal blanket cover schedule, supplemental heating rate, and ventilation rate. In the real greenhouse production, electric greenhouse heater, hot air system, and
hot water tubing heating system are normally applied for supplemental heating while opening part of the front roof for ventilation. For large greenhouses, the hot water tubing heating system is a more affordable heat distribution method. After all the sets done, it takes approximately 5 to 90 minutes to simulate the indoor environment, which depends on the simulation step size and selected accuracy. The outputs include various information, such as hourly indoor temperature and RH, supplemental heating power, heat loss from the south roof, heat released from north wall and ground, etc. Users can easily know the hourly indoor thermal condition and energy consumption through the outputs. However, the original model was not suitable for Canadian conditions and had not been validated with field data. Thus, modification and validation steps are necessary before simulation thermal environment in Canadian Prairies.

**Model Modification** This step currently includes ten major modifications. First, the simulation model was translated into English. Translation from Chinese to English enables Canadian greenhouse researchers and growers to use the model, and it is a fundamental step in this research. Second, extend the simulation location from 15°~60° NL and 0°~179° EL to the whole northern hemisphere, which makes it possible to simulate in Canadian Prairies. Third, organize the typical meteorological year data of Saskatoon in needed format because it represents ambient environment better than the previously calculated one. Fourth, although the meteorological year data has replaced the previously calculated weather data, those solar-related calculation formulas such as the solar declination and clear-sky solar radiation are modified based on ASHRAE Handbook. Fifth, reset the maximum wind speed from 10 m/s to 18 m/s according to the weather condition in Canadian Prairies. Sixth, add polystyrene-pellet insulation system and a double-layer inflated film cover option, all of which can reduce heat loss through front roof cover. Seventh, add a summer solar shading cover. Similar to the traditional greenhouses in Canadian Prairies, solar greenhouses also need knitted polyethylene fabric solar shading cover in the summertime to reduce the exorbitant sunlight at noon. Eighth, program a new function to output daily supplemental heating demand, which facilitates users to calculate whole period energy consumption. Ninth, add the internal thermal blanket option which can be used independent of the outer thermal blanket to further reduce heat loss or can be used against malfunction of the outer thermal blanket. Tenth, add a storage and call function to save and invoke the greenhouse working setting which avoids the inconvenience of each input.

The above modifications rebuild the simulation model to be more applicable, more accurate, and more reliable. After the modification step, the modified model was renamed THERMOD, and the validation process was conducted.

**Model Validation** In order to validate the accuracy of the modified simulation model, research group members collected field data in a commercial solar greenhouse in Elie, Manitoba (49° 55’ N; 97° 28’ W) for three days in March 2017. This solar greenhouse follows the classic structure of the mono-slope solar greenhouse, which makes it suitable for the thermal environment validation.

According to the measurement of the greenhouse structure, the length and width of the solar greenhouse are 28 m and 6.7 m respectively. Its north wall is 2.2 m in height and ridge is 3.3 m, and the included angle between the north roof and the horizontal plane is 34°. Its north wall consisted of 2-mm thick inside and outside sheathing of corrugated galvanized sheet steel, 152-mm of sand, 13-mm plywood, and 152-mm fiberglass insulation (Fig.1). A thermal blanket (RSI-1.2) covered the 6-mil single-layer polyethylene film front roof during the night to keep warm. While its north roof consisted of fiberglass, plywood board, and plastic film. For the ground condition, average 14cm height tomato plants (31cm interval) were raised in wet soil, and the distance between plants and north wall was 0.96m.
Figure 1. Structure of the north wall.

For the instrument setting, one pyranometer was set 0.4 m above the ground on the growing bed, two soil temperature sensors were set 2.14 m from the north wall, and south roof, two wall temperature sensors were placed 0.76 m from the top and bottom line, and air temperature and RH sensors were set at 1.22 m above the ground. Besides, outdoor temperature and RH sensors and anemometer were installed on the top of the solar greenhouse. According to the measured outdoor weather condition, it was getting warmer every day during the three-day measurement period. In the first day, the outdoor temperature was around 0 °C with a peak of 3.0 °C at 17:00, the wind was mild (average 4 m/s), and maximum solar radiation was 425.4 W/m² at 11:00. The outdoor temperature of the following day went higher with a peak of 10.8 °C at 14:00, the wind was stronger (average 5.7 m/s), and similar solar radiation intensity with a high of 420.1 W/m² at 10:00. While the third day was a windy day, average wind speed is 6.93 m/s with a peak of 10.8 m/s at 13:00. The outdoor temperature kept going higher, and its maximum value 11.4 °C occurred at 14:00, and maximum solar irradiance was 441.4 W/m² at 11:00. As for the mean outdoor RH during the whole period is 82.4%.

During the measurement period, the thermal blanket covered the front roof at 17:30 pm and uncovered at 7:00 am in the morning. There was an electrical heater with an average heating power of 3.6 kW, working from 18:00 pm to 9:00 am. However, the ventilation schedule was not recorded because growers manually opened the roof when the indoor temperature went too high. The recorded indoor data shows that temperature dropped evidently at 11:00 am and 13 am, while RH went down at 8:00 in the morning and rose at 17:00 pm. So, the following ventilation assumption was made when setting the working schedule: 0.16 m³/s from 8:00 am to 11:00 am, 0.52 m³/s from 11:00 am to 13:00 pm, 0.57 m³/s from 13:00 pm to 14:30 pm, and 0.16 m³/s from 14:30 pm to 17:00 pm.
Model Simulation

A large (100m x 12m) study solar greenhouse located in Saskatoon (52° 10’ N; 106° 43’ W) was simulated. The overall structure followed a classic Chinese design and its north wall was 4.15m in height. The north wall consisted of 2 mm sheet steel, 218 mm fiberglass, 19 mm plywood, 399 mm soil, 2 mm sheet steel from external to internal side. The ridge is 5.62 m, and the angle between the north roof and the horizontal plane is 40°. While its north roof was constructed by sheet steel, fiberglass, plywood, and plastic film from external to internal side. To reduce the heat loss, the wall foundation was built plywood with fiberglass insulation. As for the front roof, thermal blanket (RSI-1.2) covered the double-layer inflated film front roof during the night. The indoor ground was covered with mulch with tomato plants, and the distance between the north wall and plants was 1 m. The Fig. 2 shows the cross-sectional view of the study solar greenhouse in Saskatoon.

![Cross-sectional view of the solar greenhouse](image)

Figure 2. Cross-sectional plan of the assumed solar greenhouse.

As the software only simulate a maximum of 6 days, to shorten the simulation time, six days around 21st day of each month (19th to 24th) was chosen to represent the weather condition of each month. According to the typical meteorological year data, the minimum outdoor temperature between January 19th to 24th was as low as -38.1°C, and the maximum solar irradiance was 288 W/m², which means high supplemental heat and low ventilation rate are necessary. In February and March, the average outdoor temperature and RH raised to around -10°C and 80% respectively, and the solar irradiance reached up to 600 W/m², which is favor of greenhouse production. While in April, the daytime average outdoor temperature went up to over 10°C but the minimum night temperature was still below 0°C. Due to the longer sunshine duration and higher solar irradiance, the greenhouse may need no supplemental heating from May. From May to August, the highest outdoor temperature was more than 20°C, considering the high solar irradiance and sunshine duration, high ventilation rate is needed to cool the greenhouse. In September and October, the average daytime outdoor temperature dropped to below 10°C and the minimum night temperature was even lower than 0°C, which means a lower ventilation rate and supplemental heat may be needed. The weather in November and December was getting colder, the lowest outdoor
temperature declined to -30°C, and supplemental heating system needs to operate properly because the sunshine duration and solar irradiance are not favorable for greenhouse production. Table 1 shows the study greenhouse working condition for simulation.

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<tr>
<td>Thermal Blanket</td>
<td>16:40-10:10</td>
<td>17:00-10:30</td>
<td>18:00-8:30</td>
<td>19:00-7:00</td>
<td>21:00-6:30</td>
<td>24:00-6:00</td>
<td>24:00-5:30</td>
<td>18:00-7:40</td>
<td>17:00-8:30</td>
<td>16:00-10:00</td>
<td>16:00-10:30</td>
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<tr>
<td>12:00-17:00 Inner Sunshine Screen</td>
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<td>N/A</td>
<td>applied</td>
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<tr>
<td>Supplemental Heating</td>
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<td>18°C</td>
<td>18°C</td>
<td>18°C</td>
<td>N/A</td>
<td>N/A</td>
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<td>18°C</td>
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<tr>
<td>Ventilation Rate (m³/s)</td>
<td>12:00-12:00</td>
<td>11:00-12:00</td>
<td>10:00-11:00</td>
<td>8:30-9:00</td>
<td>7:30-9:30</td>
<td>7:00-9:00</td>
<td>6:30-8:00</td>
<td>7:00-9:00</td>
<td>6:30-8:00</td>
<td>7:00-9:00</td>
<td>7:00-9:00</td>
<td>9:00-10:00</td>
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### RESULTS AND DISCUSSION

**Validation Results**

The data measured from March 26th to 28th, 2017 was used for model validation. According to the measured information of the greenhouse structure and electrical heater, simulation was conducted in the modified research model THERMOD. In this validation process, the supplemental heating power and outdoor weather condition were fixed, and the ventilation rate was assumed based on real working condition, while the indoor temperature and RH were the parameters used to compare and evaluate the accuracy of the simulation model. Figure 3 gives the difference between measured and simulated air temperatures. It was apparent beforehand that a rise in air temperature would appear as solar radiation goes high in the morning. Indeed, the temperature increased to 33°C at 11:00 and then dropped gradually to 15°C in the first day, and the next two days also followed this trend. It is evident that most of these large differences appear at noon, which may because of the sudden increase in ventilation rate. For example, in the third measurement day, the indoor temperature at 11:00 was 35.3°C, while it dropped dramatically to below 25°C during the following two hours; however, the simulated result shows a gradual decline instead of a sharp one. Nevertheless, the average temperature difference is still within 10 percent (9.58%).
As for another important parameter, RH, the difference is higher than that of indoor temperature. That may be mainly because the young tomato plants were only 14 cm in height, transpiration from the plants was weak, and evaporation from wet soil dominated the moisture change. Based on the measured outdoor RH data, the average RH was 82% which was higher than indoor RH, but the outdoor humidity ratio was much lower due to low outdoor temperature. Thus, the indoor RH will decline when opening the roof for natural ventilation. As shown in Figure 4, since applying natural ventilation at 8:00, the indoor RH has turned down to approximate 50% at noon, and then rose to more than 80% after closing the roof. The overall difference in indoor RH is 13.7%.

Simulation of a Saskatoon solar greenhouse

Saskatoon typical meteorological year data and the study solar greenhouse were used for the greenhouse heating simulation in Saskatoon. Simulation of a Saskatoon solar greenhouse using the modified model THERMOD was conducted with the greenhouse working setting given in Table
1. As shown in Figure 5, the monthly average indoor temperature was below 20℃ during the coldest months (January, November, and December), even though long supplemental heating schedule and low ventilation rate were applied throughout the period. While in the summertime, the mean indoor temperature was around 25℃ when high ventilation rate and indoor solar shading screen were used. However, the average indoor RH maintained at a high level (approximate 90%) in the cold months, and it went down to below 80% in summer due to the increased ventilation rate. Most importantly, the daily energy consumption from supplemental heat rose dramatically in winter from November to February, during which most traditional gutter-connected greenhouses shut down in Canadian Prairies. In mild months (March, September, and October), the supplemental heat energy consumption was relatively low because of the higher solar irradiance. Surprisingly, the supplemental heating demand dropped to zero from May to August, which significantly cut the energy consumption of greenhouse production.

![Figure 5. Average monthly thermal condition and daily energy consumption.](image)

To illustrate the relationship between indoor and outdoor temperature and RH, results from three representative simulation months (January, July, and September) were picked out. As shown in Figure 6, the outdoor temperature of first three days in January was below -20℃ and the lowest temperature was -38.1℃, which challenged the performance of the study solar greenhouse. Heat loss during daytime was much higher than during night because the thermal conductivity of the thermal blanket was far lower than that of the front roof thermal cover. Due to this, supplemental heating energy consumption in the daytime was much higher than that in the night. Thus, the indoor temperature can be maintained around 18℃. On the other hand, the indoor RH was going down right after uncovering the thermal blanket in the morning because higher condensation occurred on interior surfaces of the front roof cover. However, it rose after the sharp decline because of the high plant transpiration and low ventilation rate.
Figure 6. Simulated indoor environmental conditions during Jan. 19th to 24th.

Figure 7 demonstrates the indoor condition in July. In contrast to the situation in January, the outdoor temperature in July was the highest, and the maximum temperature was 31.1°C. To avoid a sharp increase in indoor temperature caused by high outdoor temperature and solar irradiance, the internal solar shading screen and higher ventilation rate were applied. The solar shading screen can reduce the solar irradiance by 50% from 12:00 to 17:00, which greatly relieved the pressure on ventilation system. Thus, the indoor temperature varied in an acceptable range. Due to the high ventilation rate in the daytime, drier air from the outside replaced the indoor moist air, reducing the indoor RH significantly. However, the indoor RH kept more than 90% at night from 22:00 to 6:30 because the ventilation system was shut down.
Figure 7. Indoor environmental conditions during Jul. 19\textsuperscript{th} to 24\textsuperscript{th}.

It can be seen in Figure 8 that in September, the outdoor temperature varied from -1.7\degree C to 13.9\degree C. In addition to the carbon dioxide supply in the morning (1 m\textsuperscript{3}/s ventilation rate), ventilation rate in the afternoon was getting lower than that in July, reducing to 5.67 m\textsuperscript{3}/s. Thus, the whole period indoor temperature fluctuated from 18\degree C to 39.1\degree C. As for the RH, high condensation rate in the morning and high ventilation rate in the afternoon made the indoor RH much lower than that of the night.

Figure 8. Indoor environmental conditions during Sep. 19\textsuperscript{th} to 24\textsuperscript{th}.
CONCLUSION Theoretically, the mono-slope solar greenhouse is suitable for the cold weather in Canadian Prairies, and can make winter local greenhouse vegetable production economical. Thus, based on the weather condition in Canadian Prairies, several important modifications were done in the simulation model to make it applicable in the cold regions. To validate the accuracy of the modified simulation model, field data was measured in a commercial solar greenhouse in Elie, Manitoba. After running the model and comparing the difference between measured data and simulated data, there were 9.6% and 13.7% discrepancy in indoor temperature and RH, respectively, which prove that the modified simulation model is capable of simulating the thermal environment of the mono-slope solar greenhouse in cold regions. Then, simulation of a study solar greenhouse in Saskatoon was performed using THERMOD, and simulation in cold months was first conducted to evaluate the feasibility of winter greenhouse production in Canadian Prairies. According to the simulation results, daily energy consumption in January was 2136 kWh, and the monthly cost for supplemental heat was $ 5908 based on the commercial electrical rates in Saskatchewan, while $ 499 if using natural gas, and $ 577 using coal. Annually, $ 23712 was spent for supplemental heat with electricity, while $ 2273 with natural gas, and $ 2607 with coal.

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REFERENCES


