Analysis of materials used for Greenhouse roof covering - structure using CFD

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Abstract: Greenhouse is widely used to create a suitable environment for the growth of plant. During summer, high temperatures cause harm to the plant. This work calculates characteristics required to optimize the above-mentioned parameters using different roof structure covering materials for the greenhouse. Moreover, this work also presents a simulation of the cooling and heating system. In addition, a computer model based on Ansys Fluent has been using to predict the temperature profiles inside the greenhouse. Greenhouse roof structure shading may have a time-dependent effect the production, water and nutrient uptake in plants. An experiment was conducted in the emirate of Dubai in United Arab Emirates to discover the impact of different materials in order to have an optimal plant growth zone and yield production. These structures were poly ethylene and poly carbonate sheets of 2 different configurations. Results showed that poly carbonate sheets configuration of optimal thickness has given a high result in terms of yield production. Therefore, there is a need for appropriate material selection of greenhouse roof structure in this area of UAE. Major parameters and properties need to be considered while selecting a greenhouse roof structure are the resistance to solar radiation, weathering, thermal as well as mechanical properties and good abrasion resistance. In the present study, an experiment has been conducted to find out the material suitability of the greenhouse roof structure in terms of developing proper ambient conditions especially to minimize the energy lose by reducing the HVAC and lighting expenses. The configuration verified using the CFD, so it has been concluded that polycarbonate can be safely used in the greenhouse than other roof structure material having white or green colour.

Keywords. Poly-carbonate, Poly-ethylene, HVAC, Photo synthetically Active Radiation (PAR), ultraviolet (UV), infrared (IR) and far infrared (FIR).

1. Introduction:

The use of greenhouses for the vegetable cultivation relates to the limitations of lights affecting the plant growth. Greenhouses or shade houses promote plant growth by avoiding the direct sunlight interventions to the plant. In this scenario the shade structure materials are providing a vital role in the effectiveness of greenhouses. In hot climates the greenhouses can maintain a good fruit quality by maintaining the inhouse temperatures. However in the areas with cold climatic conditions, only a properly designed structure of the greenhouse can maintain proper indoor conditions even without the continuous HVAC systems and
additional lighting. Light is considered as one of the vital parameters in greenhouse cultivation[1]. Cucumber is one of the high yield vegetables in greenhouse methodology. Cucumbers grown in commercial greenhouses produced larger commercial yield and lower percentages of defective growth than the one grown in open field.

2. Identifying the challenges

The Challenges need to be identified in order to improve the effectiveness of the greenhouse through proper selection of shade structure material. Identifying the drawbacks of the existing greenhouse covering structure is one of the important stages in up-gradation of the green house structure. The major technical challenge is the selection of the shade structure components [2]. This involves the detailed analysis of material properties of the existing poly ethylene and the proposed poly carbonate sheet and the identification of the key indicators which need reorientation to improve the energy performance. This can affect the control of the temperature and diffusion in an optimum level in summer and winter. Logging and control of these variables are the vital part to get the desired PAR (Photosynthetically Active Radiation) for the plant growth [4].

3. Experiment:

3.1 Description of the study

The study was conducted in the ABB farm land in the Al Khawneej district in the emirate of Dubai around 32 Km from the main land of Dubai. Existing greenhouses in the farm land was made up from poly ethylene sheets as the roof structure and cucumbers were cultivating inside [3]. Test set up has been carried out in 3 different greenhouses in the farm with one as an existing poly-ethylene and the other two with polycarbonate of different thickness; 2mm as well as 4mm. Forty plastic houses were installed over the farm area in total three were used for the present test under detailed observational scenario. All the three have been cultivated with the cucumbers from the same growth pattern. Three different shade structures were conducted in a randomized complete block design with three replicates. All data obtained were analyzed spectrometrically and the same has been verified by CFD (Computational fluid dynamics) simulations.

Figure 1(a) Polyethylene sheet  Figure 1(b) 2mm Poly carbonate sheet
3.2 Experimental Design

Experimental set up comprises of mainly three different greenhouses and with first one having an existing poly ethylene covering structure, second one with polycarbonate of 2mm thickness and the third was for the same polycarbonate sheet with 2 layers in operation. Realtime cultivations have been carried out for one cycle of cucumber in three different greenhouses. Spectrometric analysis has been carried out using the field devices such as PAR [4] meters and temperatures sensors. A detailed CFD simulation of the entire set up has been comprehended in a structured way and the real time data has been verified. The study were conducted in the three identical green houses with a floor area of 265m2 with a ridge height of 6m and a gable height of 4m covered one with polyethylene and the other two with poly carbonate sheet of 2mm thickness of single and multilayer configurations[5].

Green houses were oriented in some N-S directions in the Al Khawanej Farm in the emirate of Dubai in United Arab Emirates. Each greenhouse is ventilated using the individual evaporative coolers of 285m3 as a combined capacity Methodology of this study has been outlined in the below flowchart shown in Figure 4.
Spectro metrical analysis using the licor -LI190 R sensors [7] has been carried out and the following initial results has been obtained to conclude the selection of polycarbonate sheet as the ideal material for the high yield in this climatic condition [6].

**Table 1- Spectro metrical Analysis results**

| Material                                      | Range     | Wavelength [nm] | Transmittance [%] | Reflectance [%] | Absorptance [%] |
|-----------------------------------------------|-----------|-----------------|-------------------|-----------------|-----------------|
| 2mm Double wall polys ethylene sheet          | PAR       | 400-700         | 90                | 66              | 13.4            | 7.2             |
| 2mm poly carbonate sheet                      | PAR       | 400-700         | 63                | 41              | 23.4            | 14.2            |
| 2mm Double wall poly carbonate sheet          | PAR       | 400-700         | 27.2              | 11.8            | 56.1            | 87.2            |

The greenhouse base model was created in 3D software with the dimensions scaled in comparison to real size, with one extraction fan positioned centrally in Figure.03. Scaled parameters have been tabulated in Table 2.

**Table 2- Greenhouse scaled parameters summary**

| Parameter          | Value   |
|--------------------|---------|
| Height             | 6 meters|
| Length             | 10 meters|
| Width              | 5 meters|
| Volume             | 285 m³  |
| Base Surface Area  | 265 m²  |
3.3 CFD Simulation setup

Mesh Parameters

The 3d CFD model was designed based on the provided 2d CAD plan view & sectional drawings details of the greenhouse such as supply air diffusers & grills, return air diffusers & grills. The prepared 3d model & mesh in different views are shown in the below sections. The mesh for the base model was generated as an unstructured mesh with advanced size function on curvature and the details have been tabulated in Table 3.

Table 3- Greenhouse scaled parameters summary

| Maximum Face Size | Number of Elements | Number of Nodes |
|-------------------|--------------------|-----------------|
| 185mm             | 173392             | 33206           |

Figure .4 - 3D Mesh view of “Green House”
Simulation Setup Parameters

Simulations were run on ANSYS FLUENT for 3 configurations as tabled in Table 4 in order to draw a comparison between the varied roof structure as well as thickness. Solar Loading was taken into consideration in order to capture the effect of the sun’s radiation.

| Name            | Cover Material | Cover Thickness (mm) | Density (g/cm³) | Specific Heat Capacity (kJ per kg K) | Thermal Conductivity (W/m per °C) |
|-----------------|----------------|----------------------|-----------------|-------------------------------------|----------------------------------|
| Configuration 1 | Polyethylene   | 2                    | 975             | 1.9                                 | 0.4                              |
| Configuration 2 | Polycarbonate  | 2                    | 1200            | 1.2                                 | 0.19                             |
| Configuration 3 | Polycarbonate  | 4                    | 1200            | 1.2                                 | 0.19                             |

The boundary conditions calculations that are used for the CFD simulations are shown in below table:

| Solver Setup |
|--------------|
| Solver Type  | Steady, Pressure -Based |
| Models Solved | • Energy  
• Viscous – Realizable k-e, with Scalable wall functions  
• Radiation, Surface to Surface with Solar Loading. |
| Boundary Conditions | Zone  
Cover Fan Inlet  
Outlet |
| BC Type | Wall  
Velocity-inlet, fan velocity = 2m/s  
Pressure-outlet |
| Free-stream conditions | Temperature : 300 K  
Pressure : 101325 Pa  
Density : 1.225 kg/m³ |
| Solution Methods | SIMPLE, Second Order Spatial Discretization |
| Solar Load Parameters | • Sun Direction Vectors  
X: -.11  
Y: -0.66  
Z: -0.74 |
|                | • Global Position  
Latitude : 25°  
Longitude : 55° |
|                | • Date and Time : 1st February, 1pm |
4 Results and discussion:

Temperature distributions, velocity profiles, temperature volume rendering images were captured from the results of the simulations and observations were made from figures.05

![Figure 5(a) Temperature distribution for 2mm Polycarbonate @ 1.00 PM](image)

![Figure 5(b) Velocity Streamlines for 2mm Polycarbonate @ 1.00 PM](image)

![Figure 5(c) Temperature Volume Renderings for 2mm Polycarbonate @ 1.00 PM](image)

Figure 5- CFD simulation results for the temperature, velocity & temperature volume renderings

4.1 Temperature Distribution on the greenhouse covering surface:

It is observed that the appropriate temperature distribution was captured on the covering surface for all configurations. The effect of the Sun at 1pm has caused a temperature spike region on the covering surface. It can be seen that for both the polycarbonate configurations (2mm and 4mm thickness) similar patterns have developed as shown in figure.06 &07. However, the maximum temperature at the surface of the 4mm configuration is 329.6 °K and the maximum temperature at the surface of the 2mm configuration is 328.7 °K, which indicates that the 4mm cover has absorbed more of the Sun’s radiation causing it to heat up 1°K more than the 2mm cover. This is in compliance with the real experiment.
As for the Polyethylene configuration it is seen that the pattern for temperature distribution is similar although the maximum temperature observed on the surface is $326.3 \text{ } ^\circ K$. That shows a difference of 2.4
°K compared to the corresponding 2mm configuration for polycarbonate. This can be attributed to the weaker solar radiation absorption properties of polythene and the CFD simulation has been summarized as below in figure .08

![Figure 8: 2mm polyethylene sheet temperature contour at 1.00 PM](image)

**Figure 8** - 2mm polyethylene sheet temperature contour at 1.00 PM

4.2 Temperature Distribution on an imaginary planar surface positioned 10mm below the covering surface:

From these distributions figures 09, 10 & 11, it is observed that the appropriate temperature distribution was captured on the imaginary plane for all configurations. This planar surface was selected in order to capture the effect of solar radiation being transmitted beneath the covering material. The maximum transmitted temperature from all the three configurations can be found in the polycarbonate 4mm covering. It can be seen that the 2mm polycarbonate material transmits air at a temperature approximately 2°K higher than polyethylene. This observation is also in compliance with the real experiment conducted.
Figure 9 - 2mm polyethylene sheet temperature contour at 1.00 PM

Figure 10 - 2mm polycarbonate sheet temperature contour
4.3 Temperature Distribution through Volume rendering

Temperature distribution patterns are also visualized using Volume rendering in figure.12 and demonstrate similar patterns as discussed above. Variations in temperature can be observed up to approximately 100mm below the cover due to heat transfer effects.
4.4 Velocity streamlines.

Velocity streamlines for each configuration have been captured and observed in figure 13. The streamlines follow the expected pattern due to the 2 m/s air velocity supplied from the fan. Air from the greenhouse is seen to escape from the outlet passage as expected.
5 Conclusion:

In conclusion spectro-radiometrical analysis & CFD simulation have been carried out for the selection of appropriate roof structure covering material for the commercial greenhouses. Analysis was done for the existing poly ethylene and polycarbonate sheets of different configurations in Al Khawaneej Farm @ the emirate of Dubai, UAE. The plants in the existing green house was facing a tip burn in the summer and stem and cutting damages for the leaves in the winter. Detailed analysis concluded the fact that the damages in different seasons occurred due to improper lighting distribution which is reducing the PAR regions for the plant growth to create the wavelengths ranges from 400nm to 600nm. Spectro-radiometrical as well as CFD analysis presented the fact that the lighting distribution has been affected due to the improper greenhouse structure. Green house structure made up from polycarbonate sheet was provided an ideal scenario for the crop growth in this study the crop used was cucumber. Polycarbonates sheets of different configurations have been applied in the two green houses on test basis and the results has been improved with a reduction in HVAC power consumption and green house electrical lighting energy with a high yield. And at the same time the light intensity effect was maximized during winter with a reduction of the radiations during summer. The entire test setup has been analyzed using the CFD simulation and the real data has been comprehended resulting in an effective reduction in OPEX (20 to 30%) only in terms energy savings as well high yield in crop.

Future work

- Obtain methods to demonstrate humidity variations within the CFD model
- Obtain more pronounced heat transfer effects through improved CFD model and mesh.

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NOMENCLATURE

- PAR Photosynthetically Active Radiation
- HVAC Heating, Ventilation and Air Conditioning
- CFD-Computational fluid dynamics
- DLI daily light integral

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