MMAE 433 Design of Thermal Systems

Final Report UFarm Greenhouse Project

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Summary

The project outlined below sought to create a greenhouse to be constructed at the IIT UFarm which could operate even during the coldest months of the year. The timing for such a project could not be better, as the org has secured mass funding from WISER, a sponsor of the farm.

The major constraints of the design was the amount of power generated via the solar paneling and the water collected through rainwater harvesting on site. Additionally, the dimensions of the base of the greenhouse were set to the shape of the prior greenhouse. This means that the envelope of the greenhouse and the modeling of the thermodynamics of the greenhouse were all in question. To start, a 2D steady heat transfer model which incorporated convective, conductive, evaporative, radiative, and plant transpiration-based heat transfer was created.

Then, this model was used to determine the optimal envelope for the greenhouse. Next, heating solutions were implemented. These solutions included a rollable blanket that would be automatically spread over the greenhouse once a certain solar heat addition was reached that would signify night time, the water for the plants was stored in black containers in the greenhouse, wherein the water would be heated and cooled in 3 hour intervals to create a heat source. Another similar heat source was created in the form of an indoor composting regime. This composting method allows for an additional 45 degree celsius heat source to be maintained for about 4-5 days at a time before additional compost needs to be added or compost mixing needs to be performed. A wind breaking tarp was employed on the perimeter of the greenhouse to lower the surrounding wind speed, thereby reducing the heat loss from forced convection.

It was discovered that 12 V of power put into transient water heating, an area equating to 20 percent of the greenhouse area in compost, and the use of the wind breaking tarp provided 5.45 kW, 1.63 kW, and 10.51 kW of added heat respectively. The remaining deficit, which only occurs for wind speeds over 16.42 mph, can define a P controller for additional gas heating.

Considering a rough budget of $5,000 dollars from the UFarm student org, the greenhouse project currently falls well under budget and is economically viable for the org to undertake. All Chicago building codes and legal requirements have been met with current designs. Future expansions such as the addition of pollinating bee colonies have also been considered. The future community development and marketing of the greenhouse and UFarm as a whole will be overseen by the students orgs marketing team.

Background

The Illinois Institute of Technology UFarm student org is currently undergoing a massive rebuilding period. This site presents a unique intersection between community, education and agriculture. Several scientific projects have been launched there to study an array of agricultural topics, but these studies have always needed to be inactive during the cold season, which is a significant portion of the academic year.

This issue outlines the goals of this project, to create a greenhouse that can operate all year long using pragmatic heating solutions and academically sound thermodynamic modeling. The site within which the greenhouse will be constructed contains city-independent solar power collection and water collection, which was used as a constraint for the heating solutions implemented.

Concept

In determining the optimal geometry for the greenhouse, a 2011 study conducted by Panwar et al. was used as a basis for identifying plausible envelopes that would ensure that the smallest amount of heat would need to be added to the greenhouse over the cold season.

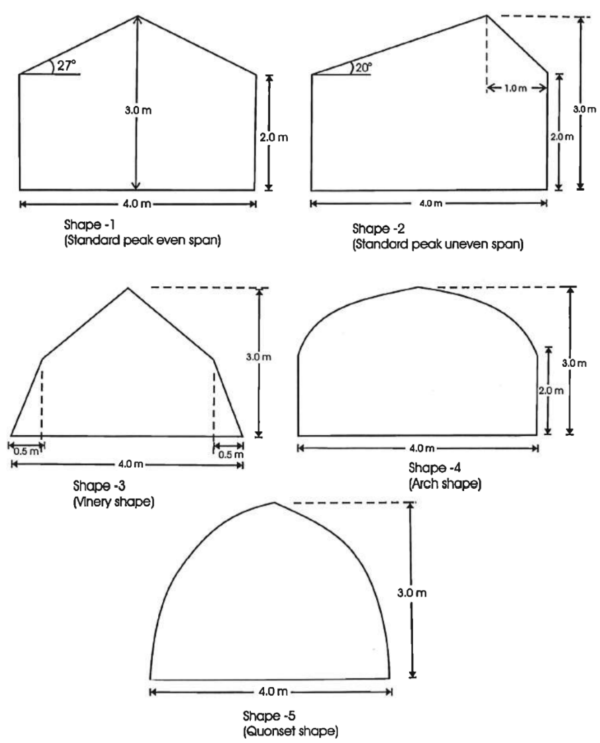

Fig. 1 The geometries considered for the design

Their findings suggested that shape 5 and shape 2 (see Fig. 1) would require the smallest heat additions to operate during the cold season, so these two geometries were modeled first; note that the images shown in figure 1 are cross sections of a cylindrical geometry.

As for the issues of the dimensionality of the problem, a transient 3D model for the heat transfer in a cylinder was adopted at first, and then the dimensionality of the model was gradually reduced and the transience was discretized on the basis of the statistical stationarity of the solar heat addition.
The heat addition was modeled by the implementation of a rollable nightly covering to reduce heat loss at night,

the use of the on site solar power to heat the water before it would be delivered to the plants so that it can serve as a heat source, the use of indoor composting to serve as an additional heat source, the modeling of evaporative heat transfer, the use of a wind breaking tarp to reduce the convective heat transfer, and finally the modeling of the plant transpiration.

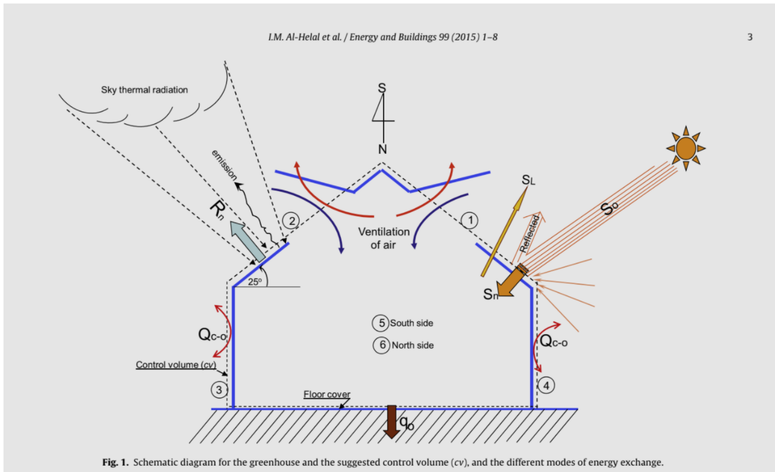

Fig. 2 Summary model of envelope heat transfer conditions (I.M. Al-Helal et al. 2015).

The use of the on site power combined with the pragmatic heat solutions, which require very little additional equipment, lead to the development of a robust thermodynamic model that can sustain the temperature of the greenhouse up to a factor of safety defined by 2 standard deviations from the mean of the local wind speed.

Analysis

Unit Settings: SI C kPa kJ mass deg

$A = 113.1$ [m^2]	$ab = 0.8$	$\alpha = 0.000109$ [m^2/s]	$A_{compost} = 24.66$ [m^2]
$A_{water} = 7.069$ [m^2]	$\beta_{air,gap} = 0.003501$ [1/K]	$\beta_{compost} = 0.003143$ [1/K]	$\beta_{in} = 0.003411$ [1/K]
$\beta_{out} = 0.0038$ [1/K]	$\beta_{water} = 0.002992$ [1/K]	$c_p = 1465$ [J/kg*K]	$c_{v,soil} = 1.9$ [MJ/m^3-C]
$D = 6$ [m]	$\delta = 0.1195$ [kPa/C]	$\delta_{time} = 10800$ [s]	$\varepsilon = 0.8$
$ET_o = 5415$ [W]	$g = 9.81$ [m/s^2]	$gam = 0.000665$ [kPa/C]	$G_{soil} = 0.000855$ [MW]
$h_{air,gap} = 29.91$ [W/m^2*K]	$h_{compost} = 4.414$ [W/m^2*K]	$h_{in} = 7.155$ [W/m^2*K]	$h_{out} = 44.02$ [W/m^2*K]
$h_{plate} = 2.226$ [W/m^2*K]	$h_{rad,plate} = 4.931$ [W/m^2*K]	$h_{water} = 5.349$ [W/m^2*K]	$k = 0.19$ [W/m*K]
$\kappa_{soil} = 5.000E-07$ [m^2/s]	$k_{plate} = 0.4$ [W/m*K]	$k_{soil} = 0.02772$ [W/m*K]	$k_{water} = 0.02888$ [W/m*K]
$l = 12$ [m]	$L_c = 2$ [m]	$L_{c,air,gap} = 0.00635$ [m]	$L_{c,compost} = 1.2$ [m]
$L_{c,water} = 1$ [m]	$m_{water} = 70$ [kg]	$Nusselt_{air,gap} = 0.9996$	$Nusselt_{compost} = 191.1$
$Nusselt_{in} = 225.9$	$Nusselt_{out} = 1390$	$Nusselt_{plate} = 11.13$	$Nusselt_{water} = 185.2$
$\nu_{gap} = 0.00001449$ [m^2/s]	$\nu_{in} = 0.00001542$ [m^2/s]	$\nu_{out} = 0.000013$ [m^2/s]	$P = 1.44$ [kW]
$P_1 = 101.3$ [kPa]	$\dot{Q}_{compost} = 2721$ [W]	$\dot{Q}_{cond} = 64.8$ [W]	$\dot{Q}_{conv,in} = 4046$ [W]
$\dot{Q}_{conv,out} = 49783$ [W]	$\dot{Q}_{conv,plate} = 1603$ [W]	$\dot{Q}_{cover} = 22.38$ [W]	$\dot{Q}_{rad,plate} = 14202$ [W]
$\dot{q}_{solar} = 500$ [W/m^2]	$\dot{Q}_{sun} = 28800$ [W]	$\dot{Q}_{total} = -0.2483$ [W]	$\dot{Q}_{water} = 4381$ [W]
$r = 3$ [m]	$raito_{dim} = 0.5$	$Ra_{in} = 2.150E+10$	$Ra_{L,air,gap} = 766$
$Ra_{L,bottom} = 126618$	$Ra_{L,compost} = 4.085E+09$	$Ra_{L,water} = 3.698E+09$	$Res = 100$ [(V^2)/kW]
$Re_{out} = 1.660E+06$	$\rho = 1.19$ [kg/m^3]	$\rho_{gap} = 1.235$ [kg/m^3]	$\rho_{in} = 1.184$ [kg/m^3]
$\rho_{out} = 1.292$ [kg/m^3]	$R_{cover,total} = 1.117$ [C/W]	$S = 6.48$ [m]	$\sigma = 5.670E-08$ [W/m^2-K^4]
$t = 0.0127$ [m]	$T_{air,gap} = 12.5$ [C]	$T_{compost} = 45$ [C]	$T_{ground} = 5$ [C]
$T_{in} = 25$ [C]	$T_{inf,in} = 20$ [C]	$T_{inf,out} = -10$ [C]	$T_{out} = 0$ [C]
$T_{plate} = 30$ [C]	$T_{water,high} = 61.08$ [C]	$T_{water,low} = 8$ [C]	$u = 3.599$ [m/s]
$V = 12$ [V]	$w = 6$ [m]		

Fig. 3 Summary model output on high wind day.

The ground area was constrained to 12 meters by 6 meters, but shape 5 was discovered to require lower heat additions than shape 2, so this geometry was adopted for the design of the greenhouse. This was determined by the different models used for the Rayleigh number, where the symmetric model fared better in a cross breeze model. The maximum radius of the greenhouse was 3 meters.

The initial 3D model, which was framed in a cylindrical coordinate system, was reduced to a 2D model on the basis that there was little circumferential variation in the temperature profile compared to the radial variation, which was the primary dimension that the mechanisms of heat transfer acted along. The axial direction of the greenhouse was modeled by a simple leadage model alongside a natural convection problem, leading to a slight axial dependence on the greenhouse thermodynamics. Ultimately, though, the radial direction was the dimension that captured the brunt of the convective, evaporative, and transpiration based heat transfer mechanisms.

The optimum temperature for the water to be heated over the course of a low wind speed day was 61.11 degrees celsius over 3 hour intervals of heating and cooling. The optimum voltage supplied over this time was found to be 12 V, though 24 V were available. The compost was found to be able to maintain a temperature of 45 degrees celsius over a five day period before needing more compost addition or mixing. The wind breaking tarp was found to reduce the peak wind speeds by about 30 percent, greatly reducing the forced convection. It should be noted that the water temperature was kept far away from the boiling temperature of the water, as using the added heat to produce a phase change instead of heat the greenhouse is suboptimal and wasteful.

The basis for the evaporative heat transfer was the Penman-Monteith equation with turf grass used as the contained plant life. This equation will be outlined in full as it is outside of the subject matter of the IIT's MMAE thermodynamics.

$$ET_o = \frac{.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + .34u_2)}$$

Where ET_o is the reference evapotranspiration, R_n is the net radiation at the crop surface, G is the soil heat flux density, T is the freestream temperature, u_2 is the freestream velocity, e_s saturation vapour pressure, e_a actual vapour pressure Δslope vapour pressure curve and $\gamma$is psychrometric constant. There is also the rich issue of humidity stratification in the greenhouse and that stratification's interaction with the heat transfer from the plant transpiration. The greenhouse was taken to be large enough that the humid air would not "pool" near the plants and significantly impact their heat transfer. This is recognized as a deficit in the modeling; however, future teams that work on this project may take on this issue via a data driven modeling problem, perhaps.

The basic procedure for modeling the convective heat transfer was the following set of equations:

$$Ra_{L,air,gap} = \frac{g \cdot \beta_{air,gap} \cdot (T_{in} - T_{out}) \cdot L_{c,air,gap}^3}{\nu_{gap}^2} \cdot \mathbf{Pr}(\mathrm{Air}, T = T_{air,gap})$$

$$Nusselt_{air,gap} = 0.19 \cdot Ra_{L,air,gap}^{0.25} \qquad Nusselt_{out} = 0.635 \cdot Re_{out}^{0.537}$$

$$h_{air,gap} = k \cdot \frac{Nusselt_{air,gap}}{L_{c,air,gap}}$$

The above are the formatted EES equations that were used to develop the heat transfer coefficients for the boundaries of the greenhouse. For instance, the equations shown above define the heat transfer coefficient within the air gap of the greenhouse covering. Similarly elementary relationships were used in the modeling of the radial conduction and radiation heat transfer models.

For high wind speeds the wind breaking tarp can save as much as 10 kW of heat loss, though for wind speeds above 16.42 mph, additional gas heating will have to be used. For the time being, a simple P controller would be advisable for monitoring the building heat flux against the model provided here.

Optimized design

The following CAD materials were developed based on the current area available at the UFarm site on IIT's campus. Note that this design can be adjusted in response to practical obstacles encountered during implementation down the line on the UFarm. This design is a good general structure for the greenhouse to be predicated on.

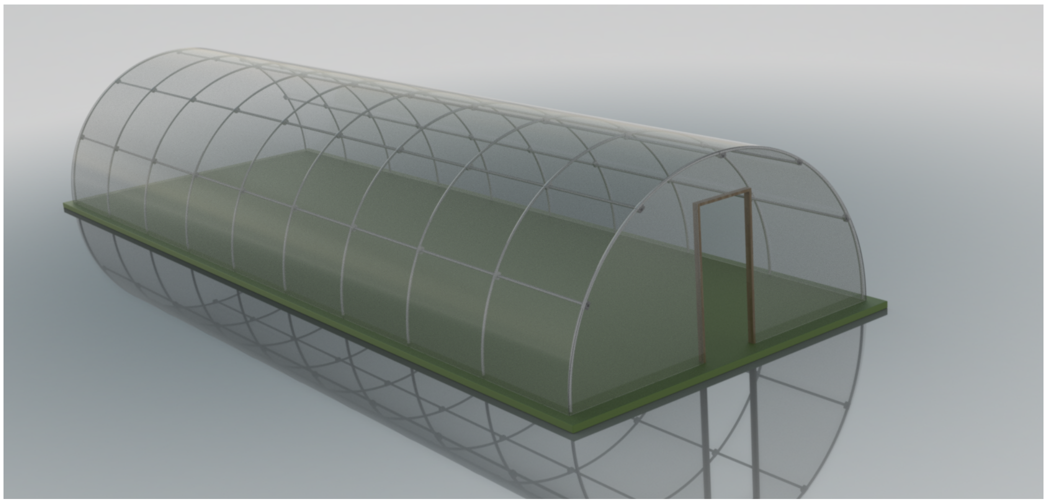

Fig. 4 Greenhouse assembly artistic render.

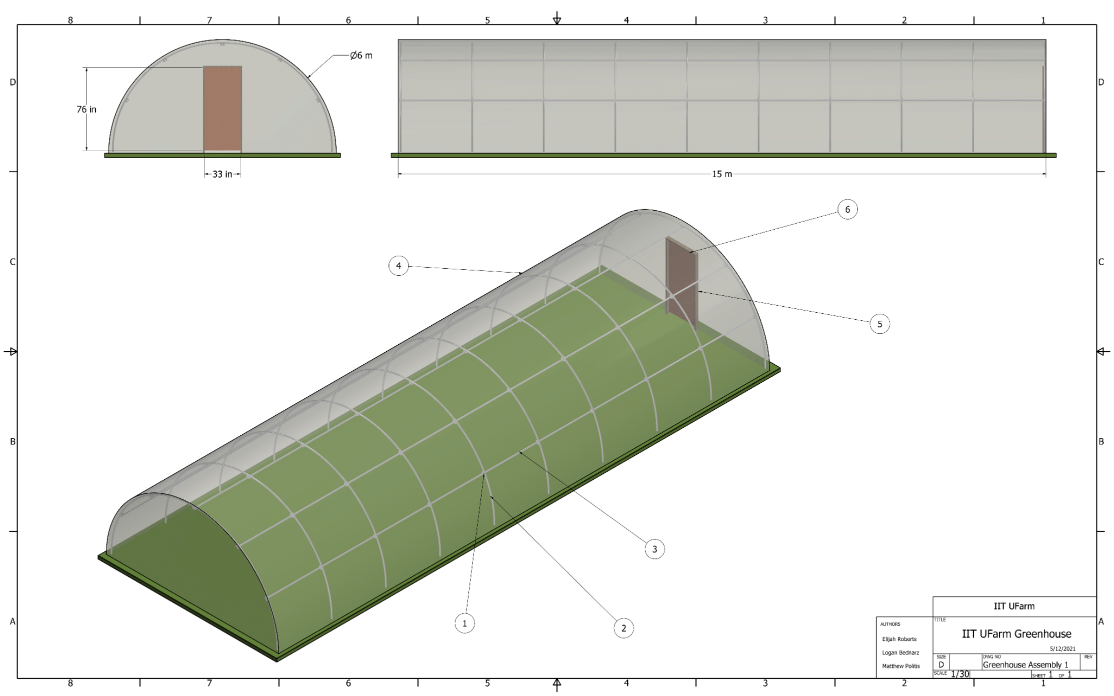

Fig. 5 Greenhouse assembly drawing.

Item	Part	QTY	Unit Cost	Total Cost
1	Pipe Joint	50	$15.70	$785.00
2	30 deg Pipe Arch 1.6 m	60	$45.50	$2,730.00
3	Steel Pipe 3 m	15	$35.50	$532.50
4	Greenhouse Polycarbonate Cover 170 m^2	1	$275.00	$275.00
5	2x4" Stud	16	$1.90	$30.40
6	Storm Door	1	$120.00	$120.00
7	Misc Small Items		$250.00	$250.00
			Project Cost:	$4,722.90

Table 1 Greenhouse assembly bill of materials.

Added Item	Quantity
Water containers to be heated	2
Compost	24.66 m^2
Wind Breaking Perimeter Tarp	1
Rollable Blanket Covering	113.10 m^2

Table 2 Added heating solutions.

Testing/Simulation

Since this project did not have access to any experimental data, a simple fluid simulation was carried out to understand the flow patterns of air within the greenhouse. As was mentioned in the analysis, the humidity stratification was not considered in the model, and the general flow pattern models displayed here could be highly informative in understanding the impact of the humidity mixing in the greenhouse.

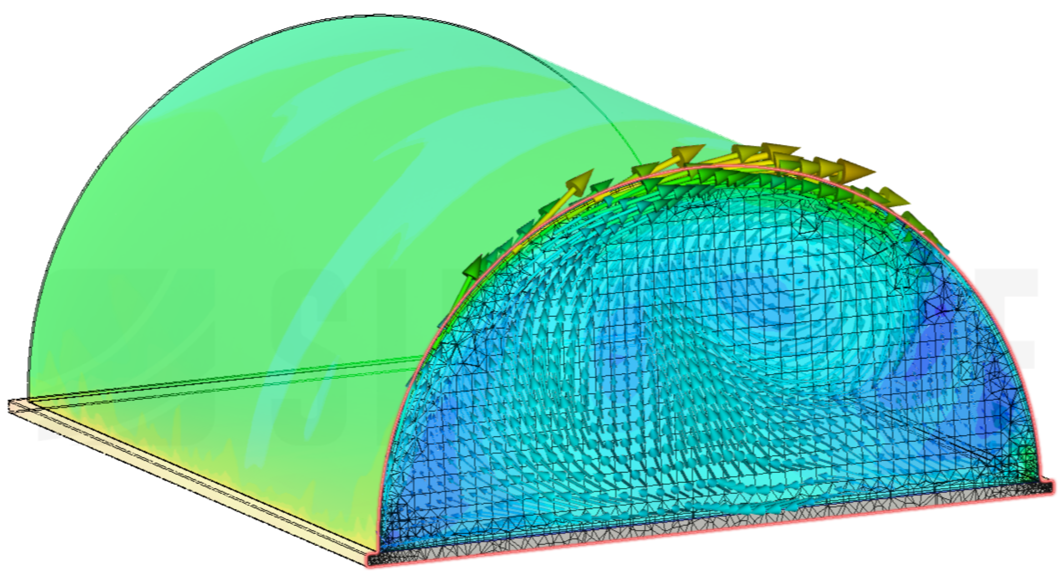

Fig. 5 Simplified greenhouse fluid simulation. Interior cross section including temperature color mapping with air velocity vector arrow magnitudes.

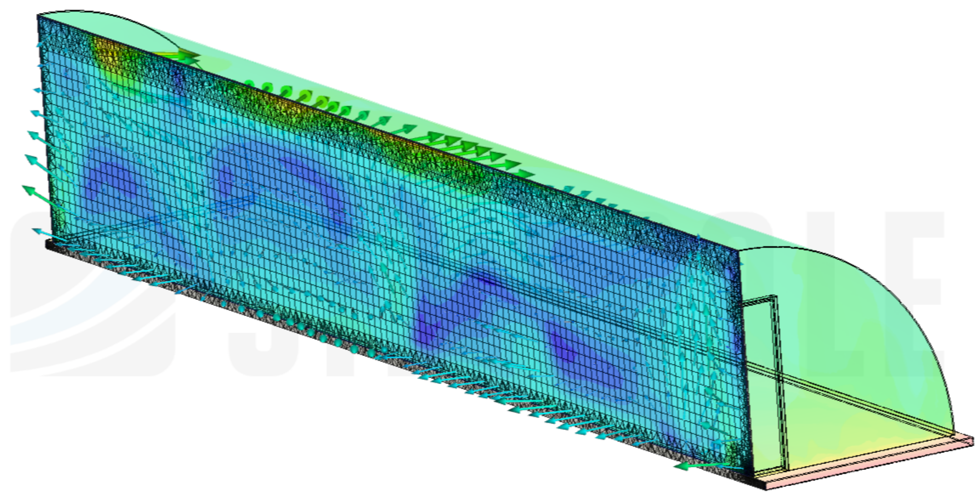

Fig. 6 Simplified greenhouse fluid simulation. Lengthwise cross section including temperature color mapping with air velocity vector arrow magnitudes.

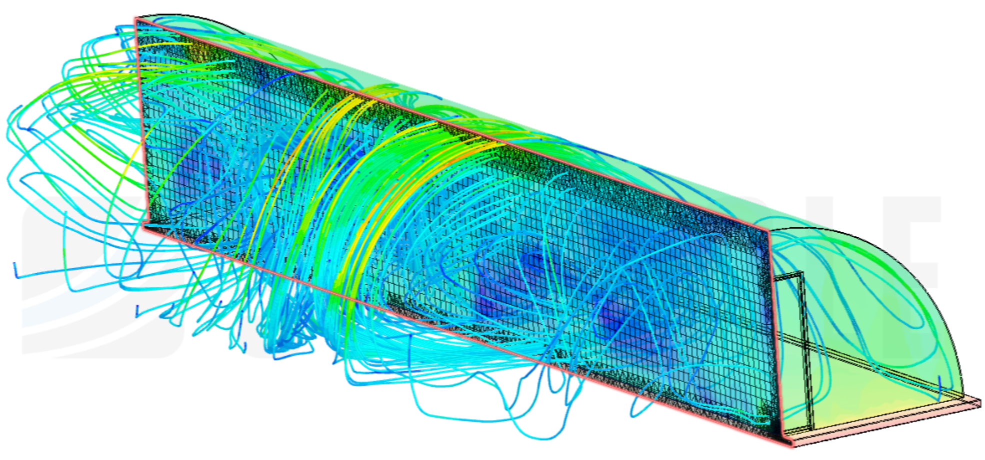

Fig. 7 Simplified greenhouse fluid simulation. Lengthwise cross section including temperature color mapping with particle path and velocity mapping.

Economic

Currently the UFarm Student Org has allotted roughly $5,000 of their budget to the construction of the greenhouse. The overall funding of the UFarm is made possible by IIT and WISER. Based on our CAD design and our own cost research the bill of materials shows an estimated total cost of $4,722.90. These prices are estimated from similar parts found on McMaster-Carr's website. Alternatively there are entire greenhouse kits available for purchase. Of these kits a similar design was found at a cost of $2,465 on the web at Greenhouse Megastore. It may be financially beneficial to consider the purchase of this kit to then retro fit the materials to our specifications. As far as construction and labor is concerned, since this is a student lead project the organizations members would provide physical labor. This means labor costs are essentially zero. Also of note is that the site has on it the remains of the previous greenhouse. These parts have been left in disrepair however so the possible cost savings from these materials are tentative. With that in mind, current designs all fall under budget and are economically viable.

Legal/Environmental

In regards to possible legal restrictions due to Chicago building codes and environmental concerns our research has found the following.

According to Section 3101 of the Chicago Building Code the size of community gardens is restricted to a size of 25,000 square feet. Within these gardens a greenhouse of the design described in our report would be limited to 575 square feet in size. Both of these size restrictions would have no effect on the greenhouse and garden as it would be constructed with current designs at IIT's UFarm.

While IIT's UFarm does not currently anticipate selling produce grown in the greenhouse, according to the city of Chicago a community garden is allowed to sell surplus produce that was grown on site if the sales are accessory or subordinate to the garden's primary purpose. This would be true for our greenhouse as the primary purpose is to give students and members of our community opportunities to use the garden for personal and educational purposes.

In compliance with both federal law and IIT's Drug Free School Policy the growth of illegal substances including marijuana would be prohibited by the school in the UFarm greenhouse and community garden.

As for the use of composting in the garden and greenhouse the amount of compost material generated or used cannot exceed 25 cubic yards at any given time according to the standards in

7-28-715 of the City's Municipal Code. Any amount of compost a garden our size would use is considerably lower than the 25 cubic yard limit.

When it comes to the use of bees for pollination the city of Chicago allows for up to five hives or colonies of honey bees to be kept as an accessory use. However, beekeepers must register with the Illinois Department of Agriculture. The UFarm does not currently have plans to keep bees so the registration with the Department of Agriculture is good to be aware of but will not restrict current design plans.

Social/Marketing/Political

The UFarm has a dedicated marketing team outside of our greenhouse development project. Along with the other members of the UFarm student organization they will be tasked with the upkeep and maintenance of the greenhouse's use in regards to the community's involvement. They will also handle advertising and outreach for the school and beyond. They have developed a stakeholders map for the UFarm as can be seen below.

Fig. 8 Stakeholder map IIT UFarm.

Credit

Logan Bednarz: Thermal modeling, evaporation heat transfer modeling, report preparation

Matthew Politis: Thermal modeling, forced convective heat transfer model, report preparation

Elijah Roberts: CAD and fluid dynamic modeling, leakage model development, economic, legal, environmental and marketing research.

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