Electricity Free Peruvian Food Storage Design Solution

Addy and Isabelle
Professor Erica Kemmerling
ME51

Part 1:

Introduction

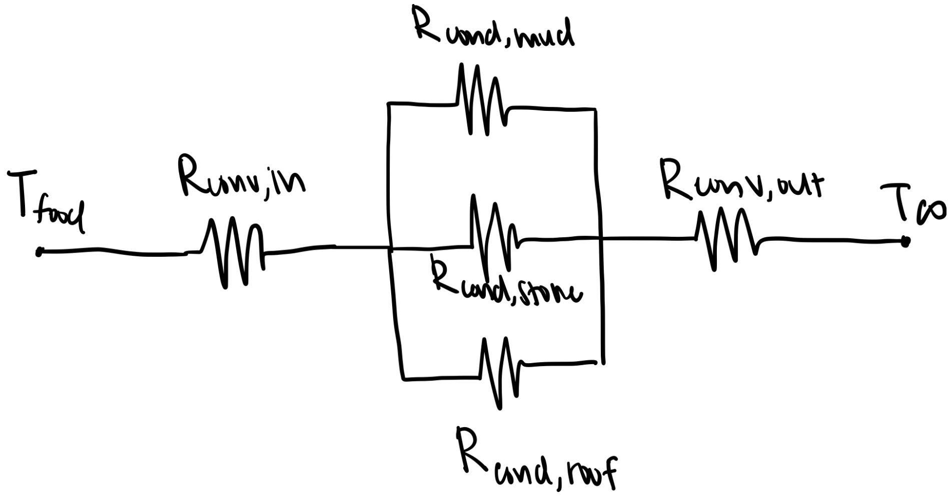
We have chosen to study the Peruvian food storage problem where we are investigating how to mitigate the effects of climate change on food insecurity. Specifically, we are studying the effectiveness of qolcas as an alternative to refrigerators/freezers. Here are the stakeholders and how they are affected:

1) Researchers who design qolcas
    a) The efficiency of the qolca is mostly dependent on the design, which someone needs to create
2) Farmers growing food stored in qolcas
    a) A more efficient qolca means less food spoilage, and therefore less food needed to be grown/food can be grown more in peak-season
3) Peruvians eating stored food
    a) A more efficient qolca means easier access to stored food and cheaper food because it can be bought in peak-season
4) People required to build qolcas/supply the materials needed
    a) The geometry of the qolcas influences the amount of labor required to construct them and collect supplies.

Analysis

Thermal Circuit

This is a thermal circuit that represents the movement of heat from the food to the freestream moving air (glacier wind). Because we assumed the qolca is not completely full (assuming it is always filled with no air gaps seems very unrealistic), the food is surrounded by the internal air. We assumed that the ground was not providing transfer of heat and can be assumed to be the same temperature as the food. The interior boundaries of the qolca are made of mortar mud and stone for the walls and Peruvian feathergrass for the roof. Once it has made it through one of these materials (assuming there are no overlapping layers), the heat reaches the convection layer directly adjacent to the qolca which then dissipates into freestream wind.



Here are some dimensions that were based on the image in the global problem sessions document and on rough approximations online:

Inner diameter of the qolca wall: 3.5 m

Outer diameter of the qolca wall: 4.7 m

Material	Thickness (m)	Area (m^2)	Height (m) (each section)	Part of qolca	R_{conv} (k/W)
Stone	0.6	79.859	0.25	Wall	0.0025
Mud	0.6	13.572	0.05	Wall	0.0034
Peruvian feathergrass (ichu grass)	0.3	36.204		Roof	0.665
Air				Inside	5.58×10^{-5}
Air				Outside	3.13×10^{-5}

Calculations for area and k values:

a. Area

$stone = 2\pi(2.5)(1.75 + 2.35) + 2\pi(2.35^2 - 1.75^2)$

$mud = 2\pi(0.5)(1.75 + 1.85) + 2\pi(1.85^2 - 1.75^2)$

$roof = \pi(2.35)(2.35 + \sqrt{1^2 + 2.35^2})$

$inner\ surface = \pi(1.75^2)(3) = 16.51\ m^2$

$outer\ surface = \pi(2.35^2)(3) = 22.17\ m^2$

We calculated these areas using the area formula for cylinders ($\pi r^2 h$) and a cone for the roof πr(r+h2+r2).

b.

i. Stones in the wall: limestone, k = 1.30 W/mK, thickness 0.5 m
ii. Mud mortar (fiber content ~3.5%), k = 1.6 W/mK, thickness 0.1 m
iii. Thatched roof: ichu grass, k = 0.047 W/mK, thickness 0.3 m

Conduction

The conduction values for all materials the qolca is made from are found above to understand material properties. From the calculations, the mud and stone have very similar thermal properties and the ichu grass has a very high resistance. This means it will allow the flow of heat much more easily than the mud and stone which oppose the flow of heat. The walls provide more insulation while the roof will allow the wind to flow in and cool off the internal air.

i. $R_{cond,\,mud} = \frac{L}{kA} = \frac{0.6m}{(1.6\ W/mk)\ (13.57\ m^2)} = 0.02764\ k/W$

ii. $R_{cond,\,stone} = \frac{L}{kA} = \frac{0.6m}{(1.3\ W/mk)\ (79.86\ m^2)} = 0.0068\ k/W$

iii. $R_{cond,\,roof} = \frac{L}{kA} = \frac{0.6m}{(0.047\ W/mk)\ (36.204\ m^2)} = 0.3526\ k/W$

iv. $R_{cond,\,total} = (\frac{1}{R_{cond,\,mud}} + \frac{1}{R_{cond,\,stone}} + \frac{1}{R_{cond,\,roof}})^{-1}$

$= (\frac{1}{0.02764} + \frac{1}{0.0068} + \frac{1}{0.352})^{-1} = 5.3741\ x\ 10^{-3}\ K/w$

Convection

The convection parameters were found by calculating the Reynolds number with two different wind speeds, one found from the weather forecast link at the bottom of the global problem session document and the other one an estimate of the inside air movement. Then the Reynolds number was used to find the value of the heat transfer coefficient, along with the value of k found from interpolating. Finally, convection can be found from using the heat transfer value and area (calculated above). The high value for convection in the inside air makes sense because it is easier for heat to flow through, while the high speed glacial wind temperature is much lower because of the strong opposition to heat flow.

v. Parameters:
   1. $K_{air} = 0.023108 \frac{W}{mK}$ (based on table value interpolation between K at 0 degrees and K at -10 degrees C)
   2. $u_{\infty} = 5.556 \frac{m}{s}$ (based of weather forecast)
   3. $Pr = 0.7\ (dimensionless)$(given)

vi. $Re_{out} = \frac{Du_{\infty}^2}{v} = \frac{(4.7\ m)(5.556 \frac{m}{s})}{(1.328\times10^{-5} \frac{m^2}{s})} = 1966355.42169$

vii. $Re_{in} = \frac{Du_{\infty}^2}{v} = \frac{(4.7\ m)(1 \frac{m}{s})}{(1.328\times10^{-5} \frac{m^2}{s})} = 353915.662651$

viii. $h_{air,\ out} = \frac{K_{air}}{D} Re_D^{0.805} Pr^{\frac{1}{3}} =$
$\frac{0.023108 \frac{W}{mK}}{4.7\ m} (1966355.42169)^{0.805} (0.7)^{\frac{1}{3}} = 508.661 W/m^2K$

ix. $h_{air,in} = \frac{K_{air}}{D} Re_D^{0.805} Pr^{\frac{1}{3}} =$
$\frac{0.023108 \frac{W}{mK}}{4.7\ m} (353915.66)^{0.805} (0.7)^{\frac{1}{3}} = 127.907 W/m^2K$

x. $R_{conv,\ in} = \frac{1}{hA} = \frac{1}{(127.907 \frac{W}{m^2K})(16.61\ m^2)} = 4.707\ x\ 10^{-4} k/W$

xi. $R_{conv,\ out} = \frac{1}{hA} = \frac{1}{(508.661 \frac{W}{m^2K})(22.17\ m^2)} = 8.868\ x\ 10^{-5} k/W$

xii. $R_{conv,\ total} = R_{conv,\ out} + R_{conv,\ in} = 4.707\ x\ 10^{-4} + 8.868\ x\ 10^{-5} = 5.5937 \times 10^{-4} k/W$

Equilibrium Temperature

Solar radiation is 1361 W/m^2 according to Nasa.

a. Find T_{crop} by using $T_{crop} = T_{\infty} + R_{total} Q''_{solar}$:
   i. Find Q''_{solar}:
      1. Grass can transmit 10.3% of light/solar radiance so
         $Q''_{solar} = 1361 \frac{W}{m^2} (0.103) = 140.183 \frac{W}{m^2}$

ii. Find R_{total}:

1. Found above by adding the total convection and conduction so $R_{total} = 0.00599 k/W$

b. $T_{crop} = T_{\infty} + R_{total} Q''_{solar} = -7°C + (0.005995 k/W)(140.183 \frac{W}{m^2}) = -6.16 °C \rightarrow 20.91 °F$

c. The crops are sufficiently frozen, which will keep them fresh for months.

d. This chart shows that at 14% moisture content (low) the food will last for a very long time and while there is a high moisture content (30%) then the food must be eaten before 60 days.

% Moisture content	Temperature (°F)					
	30	40	50	60	70	80
	days					
14					200	140
15				240	125	70
16			230	120	70	40
17		280	130	75	45	20
18		200	90	50	30	15
19		140	70	35	20	10
20		90	50	25	14	7
22	190	60	30	15	8	3
24	130	40	15	10	6	2
26	90	35	12	8	5	2
28	70	30	10	7	4	2
30	60	25	5	8	3	1

Scaling Thoughts

You would need to increase the volume inside the qolca to store more food for more people. This change would increase the surface area of the walls as well as the diameter, decreasing the conductive thermal resistances and making the food colder. If you wanted to maintain the same temperature, you could add more stone to thicken the walls to maintain the same resistance. It makes sense to continue with the cylinder shape regardless of the fact that a large one is difficult to build with mountainous terrain. This is because the circle has the best perimeter to area ratio, meaning it is the most space efficient and would require the least amount of ground flattening.

Methods

Geometry

We are using the cross section of a cone on top of a cylinder because it closely resembles the geometry from the picture. The number of stones varies between 1 and 3 stones, so we are modeling 1 stone for simplicity. It does not represent real life geometry exactly because it is not perfectly a cylinder with straight walls, but it is a reasonable estimate. The flow enters from the left side and exits via the right side.

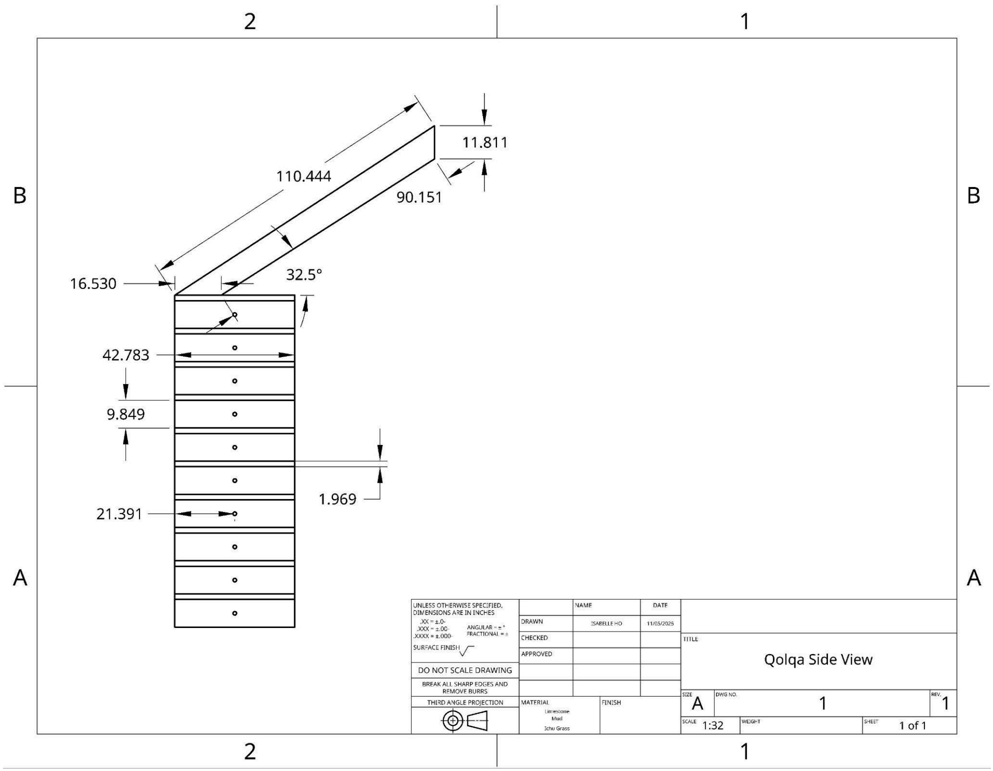


Figure 1: This shows the dimensioned technical drawing of the setup we will use in Comsol.

Model

The Reynolds number is close to 11 million, so we are well within turbulent flow. We chose the SST turbulence model because we needed a model that represents an external flow at a high Reynolds number and it excels at adverse pressure gradients and separation. Other models, including Spalart–Allmaras and k-ε, either are not as good for flow separation, are more accurate with low Reynolds numbers, or are better for internal flows. Our turbulence model, SST, is also a community standard and, while no turbulence model is 100% accurate, this has proven to be a good estimate.

Defined material sources:

	Density (kg/m^3)	Thermal Conductivity (W m−1 K−1)	Heat capacity at constant pressure (J kg−1 °k-1)
Limestone	2600	3	806
Peruvian Feathergrass	29.59	0.08	2100
Mud (dried)	1700	0.312	587.9

Boundary conditions

Location/Surface	Temperature (˚C)	Heat flux (W/m^2K)	Flow speed (m/s) and ??
Inlet on the non-mountain side of the qolca	-7		5.556
Mountain side wall	-7		Outlet
Top of qolca	-7		Outlet
Bottom of qolca	0 (daytime estimation based on insulating grass layer found in picture)		Wall
Top of Qolqa Roof		140.183	Wall

Mesh

There are 45536 elements in the mesh. We chose “finer” as a setting on Comsol to ensure we see all results of flow separations, including eddies, while having a reasonable computation time for the simulation. We also included ample air around the qolca to showcase freestream air as well as air affected by the qolca shape. The first mesh image shows the freestream and overall mesh. The second and third pictures show two examples of parts of the flow that we expect to be significant in the results as this they both show points where the freestream air will be disturbed. One allows for separation to be directed upward and the other point is where there is a boundary (the ground).

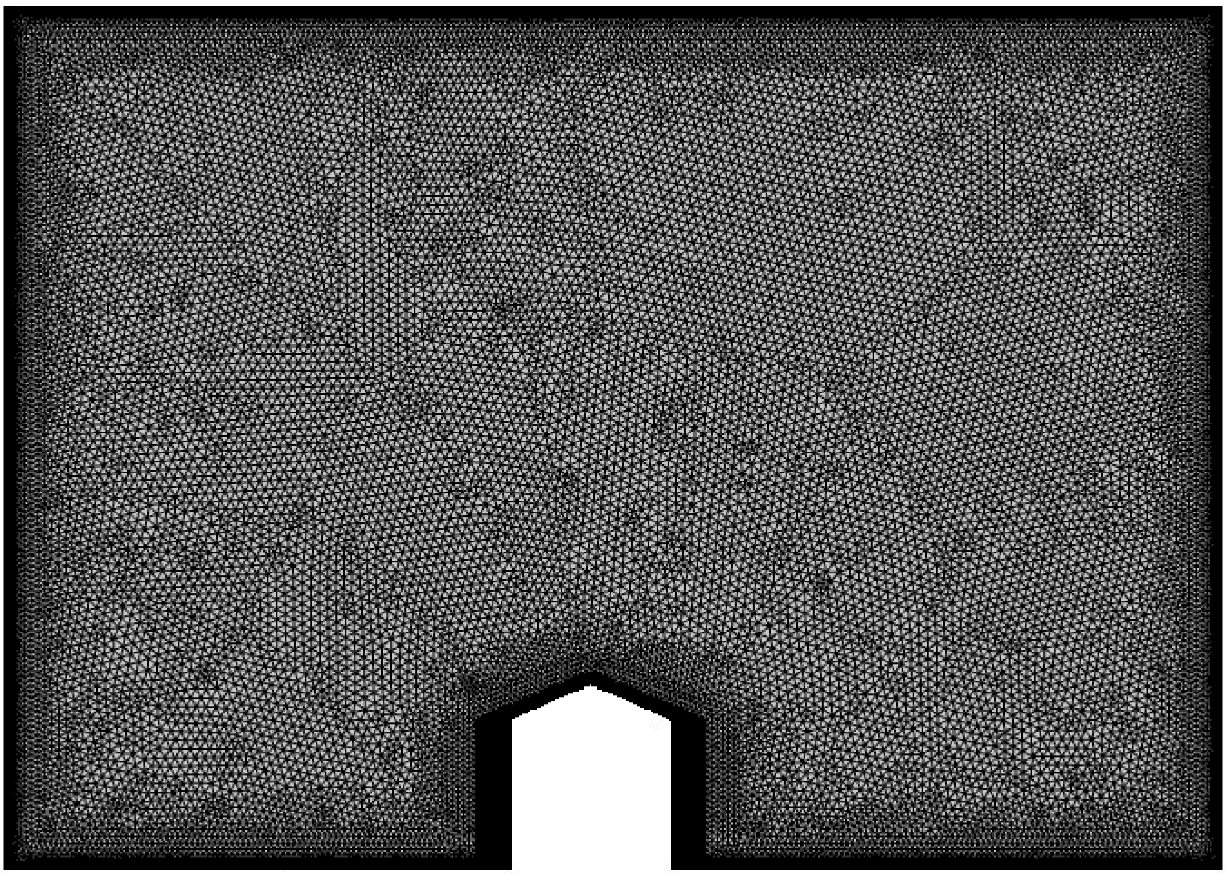


Figure 2: Full “finer” mesh showing the entire simulation

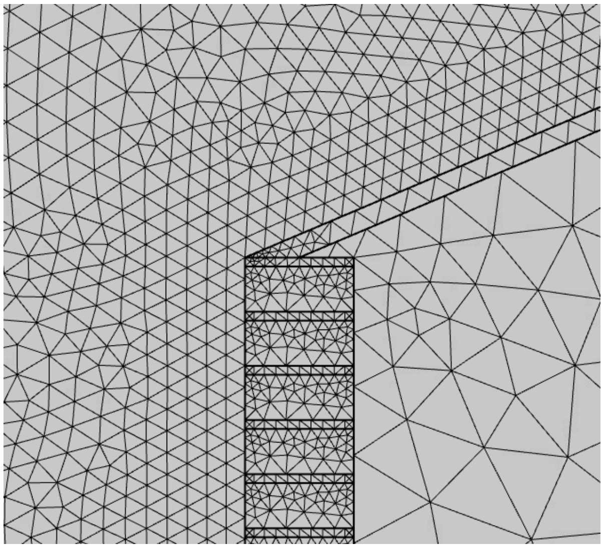


Figure 3: Top left mesh view of qolca

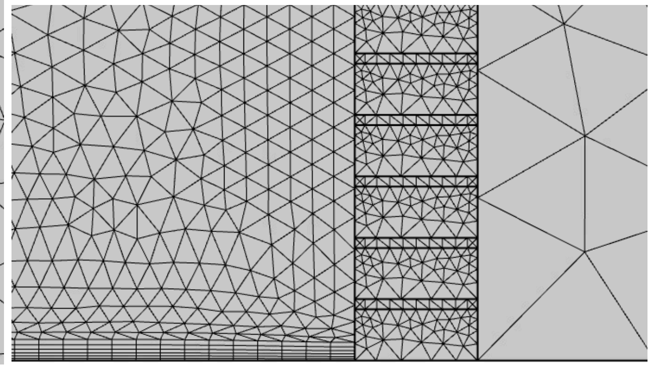
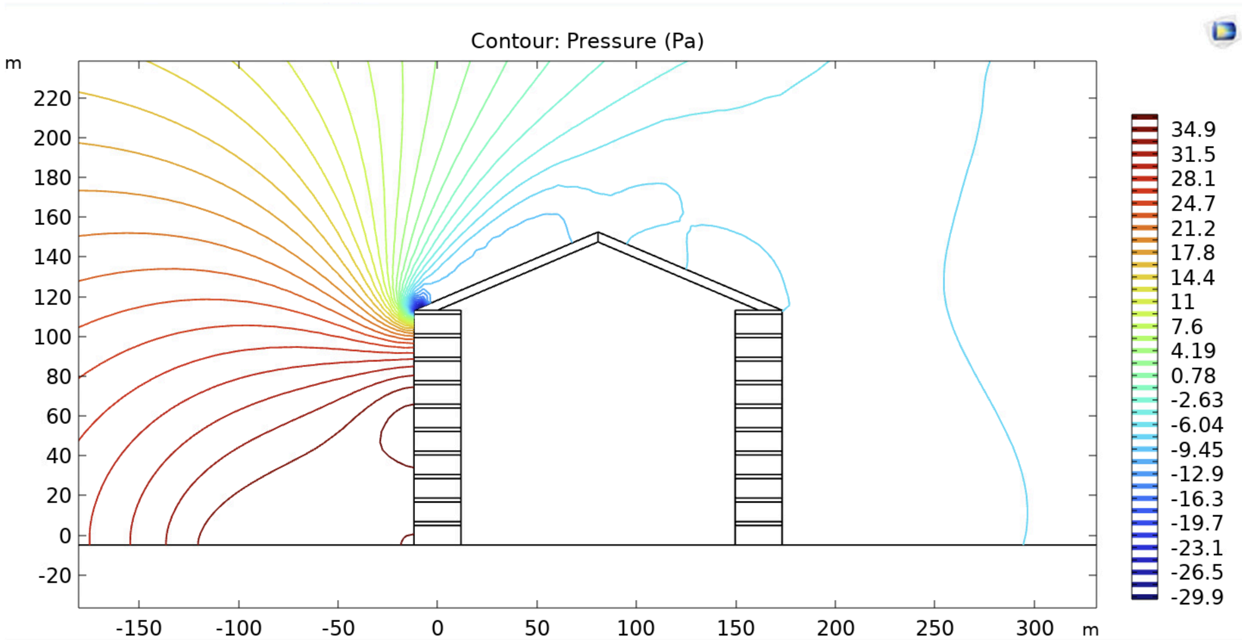


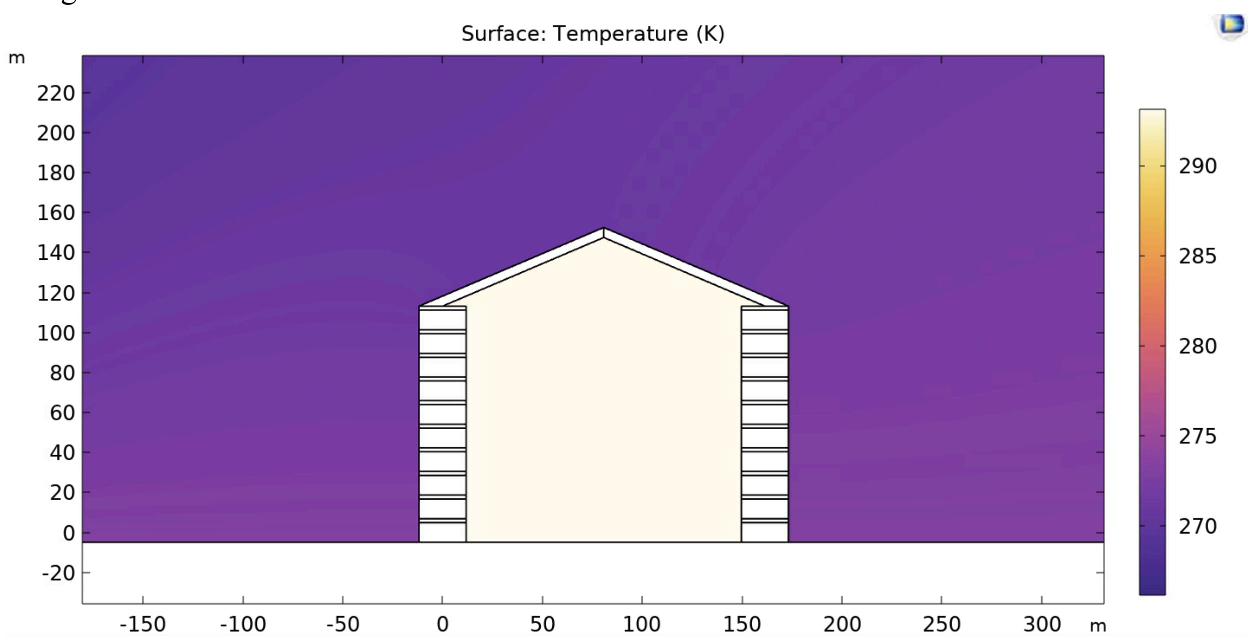
Figure 4: Bottom left mesh view of qolca

Results and Validation

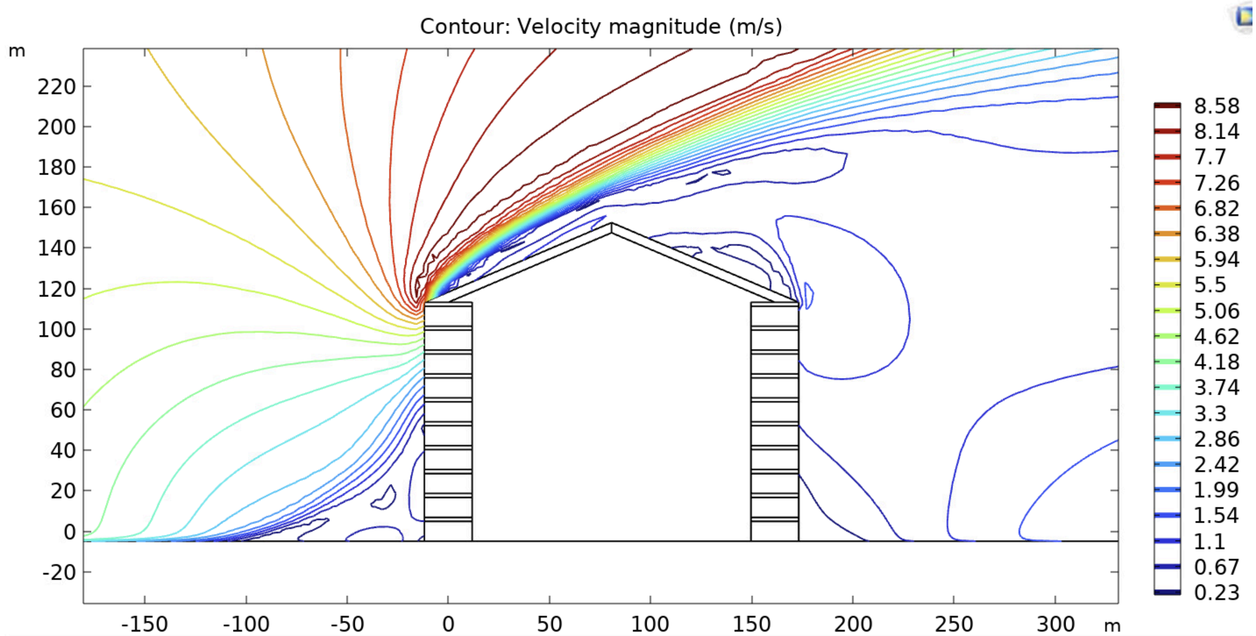
Initial Results



This is a graph of pressure in the area surrounding the qolca. Its highest at the redirection points on the flat left side of the qolca and also quite high at the corner of the roof where the velocity changes.



This is the temperature graph both outside and inside the qolca. The ground is a warmer temperature than the air, leading to an ombre effect. Inside, we estimated all temperatures to be the same due to no fluid flow, leading to the uniform color.



The velocity magnitude depends on where the fluid flow is relative to contact with the qolca. When the air gets redirected, the velocity slows down.

Validation

The velocity where the air makes contact with the left side of the qolca is 0.23 in this solution but should be 0, analytically, due to redirection of fluid flow. It is possible this difference is due to too high of a tolerance in the Comsol, or the velocity accounts for y direction velocity, which the analytical solution does not.

The interior temperature is much warmer than the analytical solution calculated with radiation and exterior temperature. The analytical solution shows the inside temperature of the qolca to be 30 ℉ where the Comsol model estimates 80℉. These clearly do not agree well as the analytical solution shows the food frozen while the Comsol solution would make the food spoil quickly. We are not precisely sure why this is a large difference, however that is something we will iterate on for the final submission.

Part 2:

Sociotechnical Analysis

1. The average temperature of food stored in the qolca according to the Comsol simulation results is 29.03 ˚F. Commonly, many people store corn, quinoa, potatoes, and supplies in qolcas and this is an appropriate temperature to store corn (source) for 60 - 190 days, quinoa indefinitely (source), and not ideal for potatoes (source). Though the storage temperature for potatoes will prevent bacteria growth, it negatively affects the plant due to its composition. The range for corn depends on its moisture content, as a higher moisture content causes faster spoilage.

2. We chose limestone because it is readily found in that area and that is traditionally what the Incan civilization used to build them. The thermal properties are appropriate because we chose them specifically as they are relevant to the problem.

3. Other common foods found in Peru include chili peppers which should be stored around 45˚F(source), salted meats which should be stored below 40˚F (source), and onions which should be stored around room temperature or above 31˚F to avoid freezing injury (source) (source, source). To create a less uniform inner temperature with regions appropriate for foods that need to be slightly warmer there will be another closed box on the qolca's back wall furthest from the wind next to the ground that is made from the same stone so that there is another layer of convection to go through. For foods that need to be colder than the qolca's original temperature, there will be a small opening in the side of the qolca next to the wind that allows direct wind to cool down the food, again contained in a separate container. This design would work well because most foods will be okay at the general qolca temperature, but this variation will allow a variety of foods to be kept here, because of the increased insulation for warmer foods and direct cold wind for colder foods.

Methods, Iteration 2:

In our initial COMSOL solution, the predicted interior temperature of the qolca was clearly unrealistic. The simulation returned a value of 293.15 K (63°F), which conflicted substantially with the analytical estimates. Addressing this discrepancy became the central focus of our second iteration.

Our first step was a systematic review of all boundary conditions and material properties. Because the materials used in the model had been created manually, we revisited each parameter and cross-checked it with verified sources. Several material values required adjustment to better reflect the physical system. We also noted that the heat flux applied at the roof boundary was unrealistically high after consulting Erica's office hours. After reviewing literature on solar transmission through grass canopies, we reduced the heat-flux magnitude by an order of magnitude. Despite these corrections, the simulation results remained unchanged.

We then pursued a series of debugging strategies, including running the model on a different computer, deleting the study, updating the solution rather than recomputing it, and temporarily altering boundary-condition values to test sensitivity. Through this process, we discovered that the temperature boundary condition was set to the COMSOL default for heat transfer in solids and fluids. Then, even after adjusting material properties, thermal conductivity, and insulation settings, the solution continued to remain inconsistent with our analytical expectations. Attempts to override the preset temperatures and insulation within continuity conditions were also unsuccessful and confirmed that these were not the source of the issue.

Finally, we identified the remaining problem: the fluid velocity was set to zero in both the turbulence model and the heat transfer in fluids initial conditions, despite previously setting inlet velocity to 5.556 m/s. After correcting this value, the simulated interior temperature dropped to 29.03°F, which is 39°F lower than the original unrealistic prediction and within one degree of our analytical result. Updating the default values for velocity and related model parameters was therefore essential for obtaining a physically meaningful solution that closely matched the calculated temperature.

Results, Iteration 2:

The plot shows the temperature around and inside the qolca. The outside temperature is set, so it is uniform. We are assuming no air flow within the qolca, so the inside temperature is also uniform. The inside temperature is around 271.5 K, -1 ˚C, or 29.03 ˚F.

Design Reflection:

For our second iteration, we focused on computing an accurate, realistic interior temperature of the qolca in the Comsol simulation. In part one, the interior temperature was predicted to be 68˚F, which is 38˚F different from the analytical solution. In part two, we were able to lower the internal temperature to get a much more realistic simulation result of 29.03 ˚F. The calculated internal temperature was 20.91˚F, so the solutions are much closer. In future iterations, we would adjust parameters and boundary conditions to try to get these values closer and indulge in further comparison to understand any remaining differences. We would include further analysis on pressure dynamics as we included a graph of those results in part one and have no calculated values or further iterations. Finally, we could look into geometry changes to increase aerodynamics and, more importantly, to vary the internal temperature so foods with different storage temperature requirements could be accounted for.

Social Reflection:

Overall, the process went fairly smoothly. We had to make some assumptions because properties were not measurable. If we could have asked questions, we would have asked specifically what stone they used (we have an educated guess, but we are not certain), specific dimensions for the qolca, and temperature and wind speeds. We eyeballed and Googled these properties, but they were not as accurate as they could have been.

References:

Our sources are linked throughout the document, as we thought it more helpful to list them where relevant. For completeness, here is the compiled list:

"Thermal Conductivity." *Engineering Toolbox*, n.d., https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

Bagheri, A., et al. "Thermal Performance of Building Materials: A Review." *Energy and Buildings*, vol. 109, 2016, pp. 1–15. ScienceDirect, https://www.sciencedirect.com/science/article/pii/S0378778815302371.

(You listed this link twice; MLA only needs it once.)

"Properties of Air at Atmospheric Pressure." *Penn State Mechanical Engineering*, n.d., https://www.me.psu.edu/cimbala/me433/Links/Table_A_9_CC_Properties_of_Air.pdf.

"Ausangate Weather Forecast (6384m)." *Mountain-Forecast*, n.d., https://www.mountain-forecast.com/peaks/Ausangate/forecasts/6384.

5. "Solar Irradiance." *NASA Earth Science Division*, n.d., https://earth.gsfc.nasa.gov/climate/projects/solar-irradiance/science.

Silva, Juan, et al. “Solar Elevation Effects on Agricultural Environments.” *Agricultural and Forest Meteorology*, 2024. ScienceDirect, https://www.sciencedirect.com/science/article/pii/S037811272400478X.

“Limestone: Properties and Uses.” *Insgeo*, n.d., https://insgeo.com.ua/en/limestone/.

Quispe, Ivan, et al. “Assessment of Ichu Fibers as Non-Expensive Thermal Insulation for the Andean Regions.” *ResearchGate*, 2015, https://www.researchgate.net/publication/282814089_Assessment_of_Ichu_fibers_as_non-expensive_thermal_insulation_system_for_the_Andean_regions.

Vásquez, Hernán, et al. “Thermal Properties of Adobe Employed in Peruvian Rural Areas.” *Construction and Building Materials*, 2017. ResearchGate, https://www.researchgate.net/publication/315442281_Thermal_properties_of_adobe_employed_in_Peruvian_rural_areas_Experimental_results_and_numerical_simulation_of_a_traditional_bio-composite_material.

“Thermal Conductivity Measurements of Weathered Limestone.” *UNF Scholar Repository*, n.d., https://scholars.unf.edu/en/publications/thermal-conductivity-measurements-of-weathered-limestone/.

“Assessment of Ichu Fibers as Non-Expensive Thermal Insulation System for the Andean Regions.” *CRIS UTEC*, n.d., https://cris.utec.edu.pe/en/publications/assessment-of-ichu-fibers-as-non-expensive-thermal-insulation-sys/.

Raj, Arul, et al. “Thermal Properties of Natural Fibers for Insulation.” *Case Studies in Thermal Engineering*, vol. 8, 2016. ScienceDirect, https://www.sciencedirect.com/science/article/pii/S2214509516300900.

“Specific Heat Capacity of Materials.” *The Engineering Mindset*, n.d., https://theengineeringmindset.com/specific-heat-capacity-of-materials/.

“Insulation Materials: Thermal Properties.” *GreenSpec*, n.d., https://www.greenspec.co.uk/building-design/insulation-materials-thermal-properties/.

“Corn Drying and Storage.” *South Dakota State University Extension*, n.d., https://extension.sdstate.edu/sites/default/files/2019-09/S-0003-53-Corn.pdf.

“Long-Term Storage of Quinoa.” *Wallaby Goods*, n.d., https://wallabygoods.com/blogs/news/long-term-storage-of-quinoa-storage-options-and-shelf-life.

“Potato Storage.” *UC IPM*, University of California Agriculture & Natural Resources, n.d., https://ipm.ucanr.edu/agriculture/potato/storage/.

“Chile Pepper: Postharvest Handling.” *UC Davis Postharvest Center*, n.d., https://postharvest.ucdavis.edu/produce-facts-sheets/chile-pepper.

“Cold Food Storage Chart.” *FoodSafety.gov*, n.d., https://www.foodsafety.gov/food-safety-charts/cold-food-storage-charts.

“Storage and Handling of Onions.” *National Onion Association*, n.d., https://www.onions-usa.org/all-about-onions/storage-and-handling/.

“Discover Peru’s Local Cuisine: Flavors to Savor.” *Peru Explorer*, n.d., https://www.peru-explorer.com/discover-perus-local-cuisine-flavors-to-savor.htm.

“The Storehouse in Machu Picchu.” *AB Expeditions*, n.d., https://abexpeditions.com/the-storehouse-in-machu-picchu/.

Not included above are the Canvas documents we used, such as the project instructions and global problem session document, as well as the group work from the in-class problem session.

AI Statement

We used AI (Chat GPT and AI Overview in Google) throughout this project. The most common usage was to troubleshoot Comsol errors, though that had dubious utility. AI was also used to find sources for material properties which we double checked by visiting the sites ourselves after, and for generating MLA citations post checking sources. After researching the different turbulence models online, ChatGPT was used to confirm we chose the best model.