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Operability of Solar Chimneys in Cold Environments

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Abstract:

The objective of this experimental project was to determine the beneficial extent of a solar chimney in Washington State. A scaled down model chimney was constructed and tested for temperature and airflow. Minor adjustments to the design were implemented throughout the testing phase to determine how best to optimize the airflow effectiveness within the chimney. Differing small amounts of airflow were measured within the chimney.

Introduction:

I. MOTIVATION AND SIGNIFICANCE

The need for cheap, clean renewable energy is inescapable as climate change is more evident now than ever. A solar chimney possesses all of these qualities, with economic appraisals based on both experience and knowledge suggesting that warm weather large scale solar towers (Chimney generates ≥ 100 MW) are fully able to produce energy at costs comparable with conventional power plants (Badenwerk and EVS, 1997).

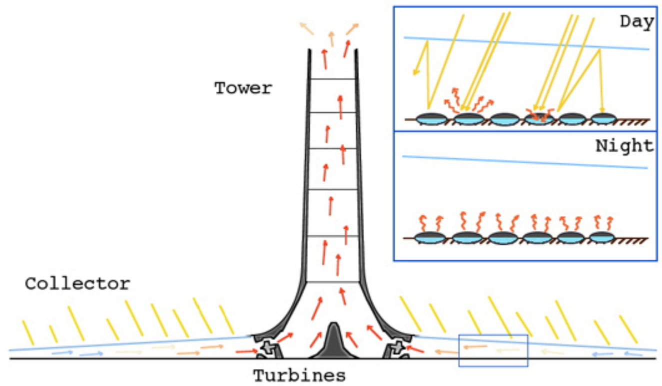
Previous tests have been limited to climates with warm temperatures. If this technology can be practically used to produce electricity in colder climates then the viability of the technology will be greatly increased. If proven that the technology is useful in cold weather climates we believe that there will be an explosion of interest that is likely to greatly impact the future of green technology.

II. OVERVIEW

II A. Introduction to Solar Chimney Technology

Solar chimneys produce energy by cleverly combining three basic technologies greenhouses, turbines, and chimney ventilation/suction. The basic layout of a chimney energy plant is extremely simple with only a few simple requirements. The ground must be relatively flat, large quantities of solar radiation must be available and stable ground to support the large tower. Air is heated by solar radiation under a large circular roof that gradually ascends into a central collector in the center; this and the ground below it form a hot air collector. In the very center of the glass roof is a vertical chimney that collets and funnels the warmed air upwards. The connection between the roof and the chimney is built to minimize air restriction and maximize air flow into the base of the chimney. Because of the density difference the air that has been heated by the green house effect produced by the roof rises up the tower. Suction is produced which brings in more heated air form the collector which draws unheated air from the perimeter of the roof.

In many instances bags filled with a mixture of propylene glycol and water with a depth of 5 to 20cm are placed under the roof to absorb solar radiation at peek hours of the day to allow for the release of energy in the night hours that permits production of electricity 24 hours a day (Jörg Schlaich, Wolfgang Schiel, 2000 p 1, 2). The quantity of electricity yielded by a solar chimney is proportional to the intensity of global solar radiation, collector area, and chimney height (Jörg Schlaich, Wolfgang Schiel, 2000 p3). The collector is a large roof that is most often made form plastic or glass that is raised 2-6m above the ground with a constantly increasing height as it nears its center giving a peak temperature difference of 30-35 ^oK. The materials are critical for this covering as they must let short wave solar radiation through and retaining long wave heat radiation while being resistant to ultraviolet degradation. The chimney is an extremely tall concrete structure that is essentially a giant heat engine. The velocity of air moving in the tower can reach speeds of 15 m/s and volume is controlled by the size of the greenhouse collector. The height of the chimney is the most critical because it partially determines the thermal efficiency of the heat motor (Jörg Schlaich, Wolfgang Schiel, 2000 p2, 3).



II B. Objectives

The objective of this experiment was to compare the energy production capabilities of solar chimney power in cold temperature climates such as Washington's. The variables for the tests will be the temperature of the ambient air surrounding the tower and the collector area. The results of this test will determine the fitness of solar chimneys for use in Washington State.

III. BASIC THEORIES

To compare the amount of power the solar chimney received in this experiment to the amount of power it could receive during the day one must look at the difference in energy input. The average solar intake from the sun is 1378 W/m^2 ($P_{average}$) (Wolfson p. 253). The power of the average solar intake varies throughout the zero to ninety degree range across the Earth. At 45^0 latitude this power is exactly at its average. Washington not quite at this average but rather 47^0 latitude. The Earth is tilted at a 23^0 angle relative to the sun. The maximum power received by the sun is at the equator (P_{max}).

The amount of power received at our experimental site can now be determined based on what is known above. The average solar intake is equal to the maximum power multiplied by the respective angle of interest, so $P_{average} = P_{max} \cos(45^0 + 23^0)$. The newly adjusted power (given our testing latitude) P_{new} can be related to the power at the equator in approximately the same way, so $P_{new} = P_{max} \cos(47^0 + 23^0)$. Notice the two degree difference in latitude used. Now to solve for P_{new} we must eliminate one of the unknown variables. This can be done through setting each equation equal to P_{max} and then substituting.

$$P_{new} / \cos(47^0 + 23^0) = P_{max} = P_{average} / \cos(45^0 + 23^0)$$

Multiplying the equation by $\cos(47^0 + 23^0)$ give us P_{new}.

$$P_{new} = P_{average} * [\cos(47^0 + 23^0) / \cos(45^0 + 23^0)]$$

The portion of the equation in brackets shows the percent of change given the fact that Washington is not exactly at 45^0 latitude. This equates to 0.91 or 91% of the average solar intake.

We now know that $P_{new} = 1368 \text{ W/m}^2 * 0.91 = 1245 \text{ W/m}^2$

Now the amount of power reaching the surface of our collector can be determined in a given model. The amount of power that our solar chimney would likely intake is theoretically 10,532 Watts given the following conditions.

- The incoming solar intensity is 1245 W/m^2
- The atmosphere reflects six percent of incident sunlight (workshop global energy balance by Kump, Kasten and Crane, 2nd Ed of Fundamentals of physics).
- There are no clouds present over the chimney site.

When the light reaches the atmosphere six percent is reflect out back into space.

$$1245 \text{ W/m}^2 * 0.06 = 74.4 \text{ W/m}^2$$

$1245 \text{ W/m}^2 - 74.4 \text{ W/m}^2 = 1170 \text{ W/m}^2$ penetrating through the atmosphere

The collector area is three meters by three meters so the total energy intake will be greater then the 1170 W/m^2 value.

$1170\ W/m^2 * 9m^2 = 10{,}532$ Watts encountering the surface area of the chimney collector.

IV. IDEAL LOCATIONS OF IMPLUMENTATION

Eastern Washington is ideal for this type of solar energy production due to its very flat cheap open land. The solar intensity in the summer months also adds to the viability of the site. In addition, we are currently experiencing issues with the hydroelectric system being used. The current hydroelectric dams are in need of replacement, retrofitting, and are damaging environmental resources resulting in the search for alternative solutions. Solar chimneys have the potential to be a large source of cheap clean energy in Washington State if they can operate in such cold temperatures.

The conundrum is that the winter months in Washington State often reach extremely low temperatures. These extreme temperature variants may render the plan inoperable during the winter months making this type of solar technology unfeasible for use in Washington State. This is with the consideration of current available technology only. Prior to this project there was no data that thoroughly discussed the operability of Solar Chimneys in cold weather. Further investigation has the potential to expand the usability of this technology to areas of the world that would otherwise invest in fossil fuel energy production.

The tests were performed in western Washington's climate. Its applicability to eastern Washington is limited because of the differences in air humidity, and temperature. Operability under cold temperatures and high humidity will be the conditions tested and not cold temperatures with relatively low humidity as is eastern Washington's climate during the winter months. Low humidity and low temperature data is already available from the towers built in Spain and Australia.

Cloud cover, and precipitation remain a significant concern. We attempted to take both into account by averaging a significant quantity of measurements over several days. This process is thought to have yielded a better estimate of the chimney's productivity in western Washington's rapidly shifting weather patterns. Further details on the measurements can be seen in the results section.

Research Questions – Hypothesis:

1. Will air velocity remain the same despite shifts in overall ambient temperature?
2. Will a solar chimney produce enough airflow to meet the US minimum standard for large scale wind production facilities?
3. Will the possible addition of a green house atmosphere over the heated area and or ice at the top of the chimney affect air flow rate?
4. What is the correlation between the rate of energy intake (watts) and the airflow through the chimney?

Hypothesis: A change in the ambient temperature will not change the internal velocity.

Alternative Hypothesis: A change in the ambient temperature will change the internal velocity.

Null Hypothesis: Solar chimneys will not work at all in cold temperatures.

Note: For question two the minimum standard can be found in the discussion section. It was chosen as a reference because of the similarities between the wind technology in the tower and more traditional wind turbine technology.

Construction Methodology:

I. MATERIALS LIST

Item	Provider	Role
$25m^2$ of polyethylene as cover	Home Depo	Function as the green house cover
3.3m by 10.2cm PVC pipe	Home Depo	Function as the Chimney
3 digital thermometers	Lab Stores	Record Temperature
Anomometer	Lab Stores	Measure air flow and temperature
Welded base stand for tower	Personal Shop	Direct airflow upward
Extension chords for thermometers	Lab Stores	Assist measurement
Night lamps	Personal Shop	Provide exact lighting in Watts
Nitrous Oxide (possible item use)	Personal Shop	Was not implemented
Ice (possible item use)	Personal Shop	Was not implemented
Tin foil flooring above cardboard	Home Depo	Active as reflective surface

II. DESIGN IMMAGES

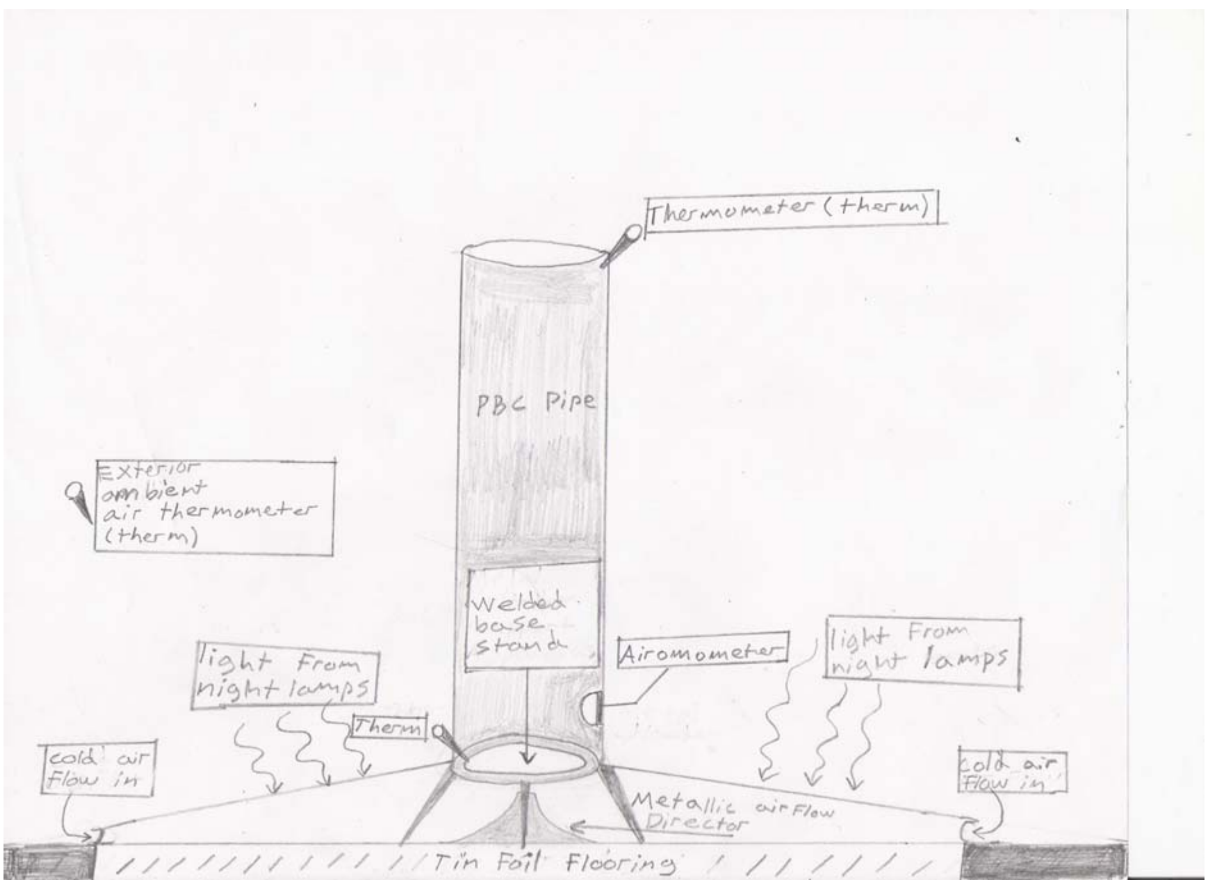


Figure 1 By Garion Bienn

Figure 2 Photo taken of actual chimney

III. METHODOLOGY

We began by welding the circular base that held up the tower. It stood 25cm above the ground. We then submerged 1/4th of its length it into the dirt for stability. Next we submerged several wooden stakes around the circular base. We used a water leveler to ensure that each of the stakes was of equal height above the ground and to ensure that the perimeter of the collector was completely level. We then connected each of the stakes to each other and the center base with thin ropes. We covered the area between the stakes and the center with polyethylene. Staples were used as a means to secure the polyethylene. The area covered by the polyethylene was $9m^2$. We then cut a circular hole atop the polyethylene for the pipe to fit over. We then erected and firmly lodged the pipe into place by attaching ropes at the top and using friction between it and the circular base at the bottom.

Right before we attached the PVC pipe we constructed a wood siding shown in figure 2. This siding can be seen 3/5ths up from the base of the tower. At the horizontal base of the siding we drilled a small hole to take air flow and temperature measurements at with the anemometer. We also drilled small holes in the top of the tower to tie the ropes upon. We set up three 500 Watt lights during the evening measurements. No daytime measurements were taken.

A few weeks later we temporarily dismantled the chimney. We removed the birds' nest that resided within. We then restored the chimney back to its upright position. After which point we proceeded to obtain the rest of our measurements.

Results:

I. GRAPHICAL DATA

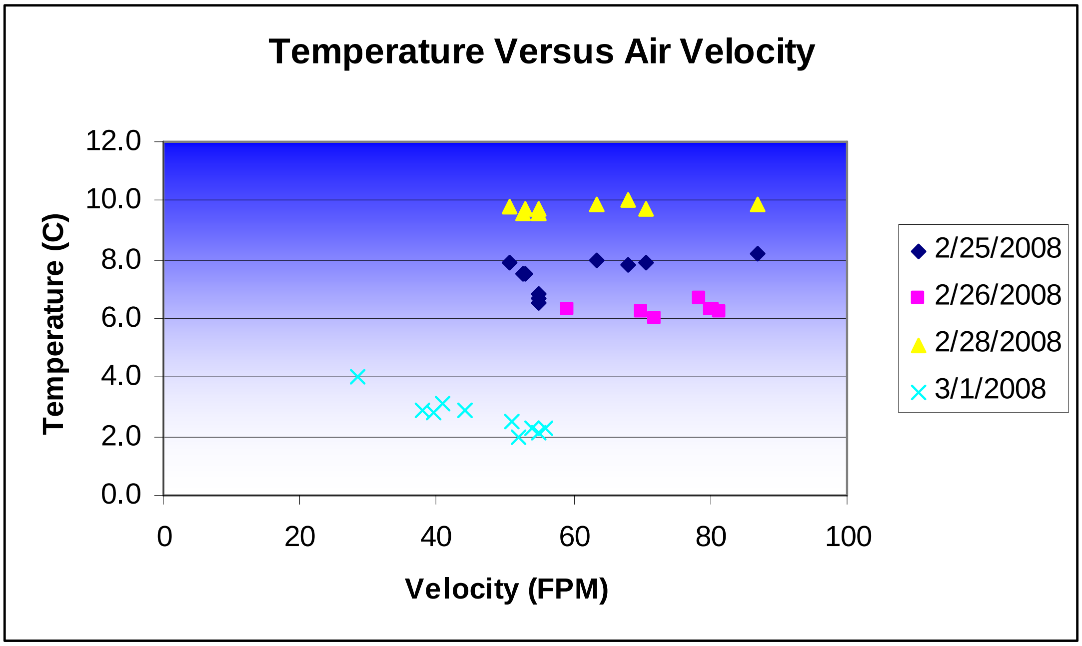


Figure 3 shows the degree of correlation between air velocity and temperature

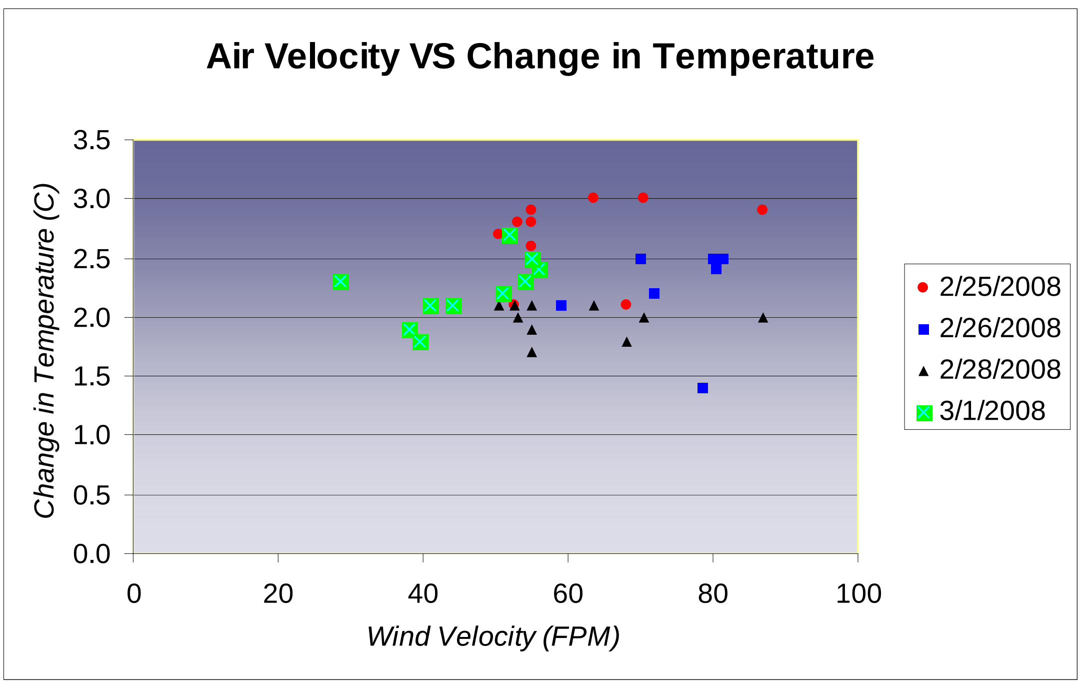


Figure 4 Shows the degree of correlation between the changing air temperature and air velocity through the chimney

II. RAW DATA

Date	2/25/2008					
Time	Ambient Temp.		Base Temp	Chimney Velocity Ft/Min		
HH:MM	*T1(C°)*	*T2(F°)*	*T4(C°)*	*Min.*	*Max*	*Average V*
7:15 PM	7.8	45.3	9.9	54	82	68
7:20 PM	8.0	46.4	11.0	47	80	63.5
7:25 PM	8.2	45.0	11.1	67	107	87
7:30 PM	7.9	45.6	10.9	51	90	70.5
7:35 PM	7.9	44.0	10.6	41	60	50.5
7:40 PM	7.5	43.5	10.3	46	60	53
7:45 PM	7.5	43.6	9.6	45	60	52.5
7:50 PM	6.8	42.2	9.7	42	68	55
7:55 PM	6.7	41.7	9.3	47	63	55
8:00 PM	6.5	47.5	9.3	46	64	55

Date	2/26/2008					
Time	Ambient Temp.		Base Temp	Chimney Velocity Ft/Min		
HH:MM	*T1(C°)*	*T2(F°)*	*T4(C°)*	*Min.*	*Max*	*Average V*
7:20 PM	7.1	44.7	9.1	17	21	19
7:25 PM	6.3	42.7	8.6	17	24	20.5
7:30 PM	6.3	42.7	8.6	16	20	18
7:35 PM	6.0	42.7	8.2	69	75	72
7:40 PM	6.2	42.5	8.7	66	74	70
7:45 PM	6.2	42.5	8.7	78	85	81.5
7:50 PM	6.3	42.6	8.4	45	73	59
7:55 PM	6.7	43.6	8.1	75	82	78.5
8:00 PM	6.3	42.5	8.8	77	83	80
8:05 PM	6.3	42.5	8.7	73	88	80.5

Note: The yellow cells above are outlier data points omitted from the graphs on page 7.

Date	2/28/2008					
Time	Ambient Temp.		Base Temp	Chimney Velocity Ft/Min		
HH:MM	*T1(C°)*	*T2(F°)*	*T4(C°)*	*Min.*	*Max*	*Average V*
9:00 PM	10.0	49.0	11.8	54	82	68
9:05 PM	9.9	49.0	12.0	47	80	63.5
9:10 PM	9.9	48.4	11.9	67	107	87
9:15 PM	9.7	48.1	11.7	51	90	70.5
9:20 PM	9.8	48.3	11.9	41	60	50.5
9:25 PM	9.7	47.9	11.7	46	60	53
9:30 PM	9.6	47.8	11.7	45	60	52.5
9:35 PM	9.6	47.8	11.5	42	68	55
9:40 PM	9.6	47.9	11.7	47	63	55
9:45 PM	9.7	47.7	11.4	46	64	55

Date	3/1/2008					
Time	Ambient Temp.		Base Temp	Chimney Velocity Ft/Min		
HH:MM	*T1(C°)*	*T2(F°)*	*T4(C°)*	*Min.*	*Max*	*Average V*
11:30 PM	4.0	37.7	6.3	27	30	28.5
11:35 PM	3.1	35.8	5.2	37	45	41
11:40 PM	2.9	35.7	5.0	41	47	44
11:45 PM	2.9	35.8	4.8	35	41	38
11:50 PM	2.8	35.8	4.6	37	42	39.5
11:55 PM	2.5	35.6	4.7	45	57	51
12:00 AM	2.3	35.3	4.7	49	63	56
12:05 AM	2.3	35.3	4.6	46	62	54
12:10 AM	2.1	34.7	4.6	47	63	55
12:15 AM	2.0	34.5	4.7	46	58	52

Discussion:

I. RESEARCH QUESTION ANSWERS

1. The range in air velocity remained nearly unchanged despite the changing ambient air temperature.
2. The US minimum standard for large scale wind power construction is 6.4 to 7.0 meters per second (approximately 1260 to 1378 feet per minute, FPM). Our measured airflow was significantly below this value on all collected data. The standard was therefore not met given the following parameters of our model: 1500 total Watts applied to a nine square meter area, scaled down chimney size, no green house gas addition, and significant wet absorbent soil underneath the collector. Please note that the 1500W/ 9m^2 is 1/9th the global average solar input of 1500W/ 1m^2.
3. Inconclusive, insufficient time for data collection.
4. Given a 1500W input the observed air velocity ranged from forty to ninety FPM.

Hypotheses confirmation: The differing ambient air temperature did not significantly affect the air flow within the chimney. Further test trials on the matter are recommended for greater quantities of reproducible data.

II. DATA ANAYSIS

Despite the variations in Ambient air temperature the fluctuation between three to ten degrees Celsius of air velocities within the chimney remained relatively constant as shown in Fig. 3. In order to make stronger conclusions more tests at additional higher and lower temperatures are necessary. In order to produce more definitive data more accurate thermometer equipment and solid lodging for measurement equipment is necessary.

Figure four does not show any definitive correlation between the changing ambient air temperature and air velocity up the chimney. Between a 1.4 and a 3.0 degree change there was only a 30 to 90 FPM range in air velocity. With the exclusion of outlier data the velocity ranged between 40 and 60 FPM on average within this 0.6 ^{o}C temperature range.

The time of year at which this data was taken should be acknowledged. February is traditionally the colder part of winter. Warmer months may have yielded faster airflows but a comparison during which the worst possible temperature conditions were present was the goal of this project in order to show whether or not a solar chimney can work in extremely harsh cold weather climates such as Washington's climate.

It is interesting to note that when the anemometer was used, it measured differing air velocities when it was inserted at a perpendicular angle to the tower. More specifically the outer edges of the tower were the only locations that any air flow was measured. The middle of the tower did not yield any air flow. The distance from the edges of the tower at which any airflow was measured was approximately half an inch compared to the total four inch diameter of the chimney. The data results show only data taken within this half and inch margin.

The cause of the air flowing only along the sides of the tower is thought to have been caused by the fact that rising air does not travel horizontally when the colder air at the top of the chimney is in a vertical direction. There must have been insufficient hot air built up to fill the entire chimney, just enough to cover that half an inch. Most wind turbines are spun horizontally through the solar chimney anyways so the fact that the only air flow occurred on the sides is not a major problem. In either case a greater rate of hot air buildup would likely result in the entire tower being filled with rising hot air. Increasing the cover area at the base of the tower would do well to accomplish this. This is the hypothesis/explanation of our research group.

It is the opinion of our research group that profitable construction of solar chimneys in Washington State on a large scale is still a potentially viable option. Further experimental tests would be preferable to definitively prove the air velocity and in turn the degree power producing potential of solar chimney technology in Washington State's cold weather climate.

IV. PROJECT LIMITATIONS

Limitations on the project:

-The weather and moisture were an uncontrollable factor that was not quantitatively measured and incorporated as part of the project data. Alterations in either factor for chimneys built in other locations could have unaccounted for effects on air flow velocity. This uncertainty persists in many other coastal regions.

-Our location and setup gave us relatively repeatable conditions but things like humidity were not taken into account.
-The anemometer was fixed in place upon the wooden siding but was periodically removed when measurements were not being taken and then re-fixated back to its original location. Slight changes in orientation of its position each time is though to have had a significant effect on the results. Even though attempts were made to minimize this hazard.
-Thermometers where placed in consistent locations and were placed in the same locations every day. They were however designed to measure water and not air temperature and a thermometer that is designed to measure air temperature would be better for more accurate results.

Future Work (optional):

It is recommended to future researchers that careful consideration is made when selecting an anemometer. Particularly a fixed un-removed unit with data logging capabilities would be preferable so as to eliminate variation due to unwanted movement of instruments. Similarly the thermometers would be placed at fixed locations on the perimeter, base of tower, and tower peak again possessing data logging capabilities. Further more polyethylene did not perform well under windy conditions. The use of glass is recommended for permanent installations in locations were high winds are prevalent.

The rain did not impede our results once the polyethylene cover was made sufficiently taunt. Most of the water simply ran off the sides of the polyethylene. Small puddles forming at the base of the tower were an issue however. Construction upon high ground with a near by downward slope for run off is recommended for future researchers.

Future experimental tests should include the addition of an actual turbine and electric generator to the model, temperature measurements at the top of the chimney, and possibly the addition of a double layer green house chamber. This chamber would be composed of a sealed compartment made of either polyethylene or glass. It would also act as the cover collector for the chimney. Within the two layered space would be a chosen green house gas such as nitrous oxide. The addition of the gas is theorized to have the same effect on the air underneath the cover as natural green house gasses have on the Earth (a warming effect). Such an effect would theoretically produce a greater temperature gradient and in turn higher wind speeds up the tower.

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