AC 2010-1130: STUDENT PROJECT TO DESIGN A SMALL-SCALE SOLAR CHIMNEY FOR SUSTAINABLE POWER

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Student Project to Design a Small-Scale Solar Chimney for Sustainable Power

ABSTRACT

Access to energy sources is a major limitation in many areas of the world. This is particularly true for developing economies which have limited resources to devote to traditional power generation. This student project proposed to design and test a small-scale solar chimney for use as a renewable energy source. The basic design process with competing constraints for local (Minnesota) use and use in Ghana, as well as the final design and construction, will be discussed. This includes the testing of a 40 foot tall chimney in Minnesota that was able to generate a 22 degree Fahrenheit temperature difference during winter months. However, the paper will focus on the student learning experiences during the project.

1. Background

With some exceptions electricity is available to less than one quarter of the population in African countries "with supply being limited almost entirely to urban areas" [1]. The majority of this electricity is supplied by non-renewable and environmentally polluting sources such as coal and natural gas[2]. Rural locations can also be limited by a growing scarcity of firewood. In developing countries 70% of the population makes use of firewood as an energy source[3]. Power sector development and the creation of a widespread rural electrification program via a grid-based approach is a challenging and long-term endeavor. The immediate solution involves focusing on "self-contained, stand-alone systems of generation" [1]. Rather than basing these stand-alone systems on conventional fuels such as diesel, solar energy can be an attractive energy resource. It is a renewable, cheap, and non-polluting resource readily available for many areas, such as African nations. Small-scale solar installations based in rural communities are not only viable but have the potential to make substantial improvements the quality of life[4].

Photovoltaic (PV) solar panels are a common option employed. However, in terms of rural areas in developing nations there are drawbacks to PV power sources. Direct purchase of the system is financially limiting. The technology involved is often not well understood by the local population making maintenance and repair difficult, if not impossible. If the system breaks down it may never be repaired or replaced. It could, literally, be thrown into a ditch. An attractive alternative method of converting solar energy to electricity in these situations is with a solar chimney. Solar chimneys have been in existence for several decades. The operation and principles behind these devices are straightforward and can be broken up into three processes or components (Figure 1). Solar radiation is "trapped" inside a ground based collector similar in function to a greenhouse. Air is heated in this collector creating a buoyant force that causes the air to rise. At the center of the collector the air is funneled into a chimney where it continues to rise. Cooler fresh air is pulled in from the outside edge of the collector. The resulting flow of air up the chimney drives a wind turbine which produces electricity.

Several solar chimneys have been constructed for demonstration and evaluation purposes. Perhaps the best known example is the Manzanares, Spain chimney built in 1981. This device was 195 m high, had a 10 meter chimney diameter, and a 240 meter collector diameter. It generated 50 kW with a 95 % reliability[5]. Larger chimneys with outputs of up to 200 MW are currently being developed[6]. Overall solar chimneys have a low thermal efficiency. To date smaller solar chimneys have not been attractive due to their relatively low power output. They therefore have received little design attention. However, from the perspective of many rural areas large amounts of power are not needed to have a high impact. The power required for low wattage lights, refrigerators to store medicine and vaccines, or even to power a simple computer is modest and achievable with smaller solar chimneys. Since the majority of design work with solar chimneys has been on constructing chimney heights of several hundred to over a thousand meters much of the work has been with reinforced concrete towers. Relatively little work has been done in constructing small solar chimneys or ones made with different materials and manufacturing processes for less demanding design criteria.

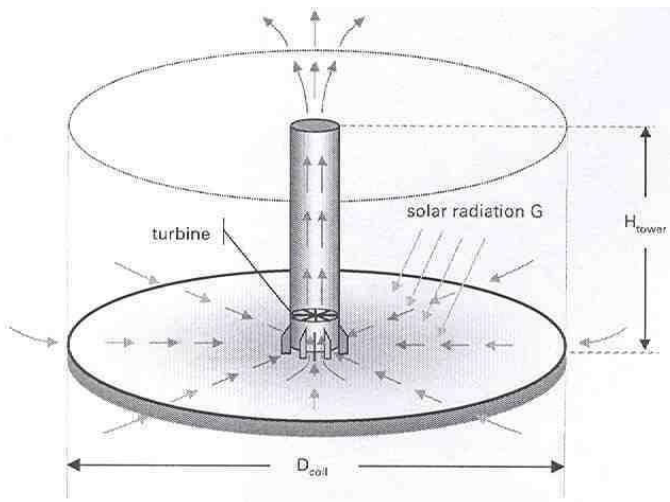

Figure 1: Principles of a solar chimney [6].

The primary purpose of this project was to promote energy independence while not promoting dependence on fossil fuels. The scope of the project was to design, manufacture and test a small prototype solar chimney. A chimney capable of powering a small city or industry was not being sought. Rather a simple yet rugged design was desired which can supply electricity to niche applications with large potential to impact the quality of life. The solar chimney should maximize use of local materials and should be manufacturable with methods available in a typical rural community or village. Potential target locations of Ghana and Botswana were identified. The major objectives of the project were to evaluate materials for the greenhouse cover and chimney tube, evaluate possible manufacturing methods, design and build a prototype solar chimney, and collect performance data.

The prototype solar chimney was intended to have an output in the range of 20-50 W. The chimney height was to be approximately 30 feet with a collector surface area of approximately 4800 ft^2. These proposed values were determined based on test results from previous researchers. The specified solar chimney could recharge a 12 volt car battery during 9 hours of operation. This would allow a laptop to be used for about three hours or ten LED light bulbs for over 10 hours during the following night or day. For the purposes of testing the prototype was to be instrumented with sensors to record temperatures, air humidity, velocities, and power output.

2. People, Prosperity, and the Planet (P3)

The original proposal for this project was developed by a faculty advisor and a team of students during the Fall semester of their junior year (at the same time as their thermodynamics course). The proposal was submitted to the EPA People, Prosperity, and the Planet (P3) Student Design Competition for Sustainability. This is an annual competition "focused on benefiting people, promoting prosperity, and protecting the planet through innovative designs to address challenges to sustainability in both the developed and developing world." [7]. The proposal was successful resulting in seed funding for materials and travel to the annual P3 competition. The student team also conducted follow-up fund raising resulting is a small grant from the Rochester section of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to allow additional instrumentation to be purchased for performance monitoring.

As part of the P3 award the students were required to make presentations at the National Sustainable Design Expo held during the Earth Day celebrations on the National Mall in Washington, DC (Figure 2). This involved a poster and oral presentation to two sets of judges, as well as answering questions from public visitors during the two and one half day event. For several students this was their first time in the nation's capital. It was an excellent experience in communication for them.

Figure 2: Student team and advisor at the National Sustainable Design Expo, Washington DC.

3. Student Design Process

This project proved to have several constraints that needed to be assessed before a test model could be created. Similar to the design of larger solar chimneys, the three key components of the design were; the solar collector, the chimney, and the turbine. The most constraining dimensions of the project were the size of the solar collector and the height of the chimney. As a starting point, a ratio of chimney height to collector area was created using previous chimneys in Manzaneres [5] and Botswana [8]. From this it was found that the height of the chimney should be nearly the diameter of the collector field. While the eventual goal of the project was a design which could be constructed in Ghana, a prototype needed to be constructed locally (i.e. on the MSU campus) for study purposes. Based on local transportation, construction requirements, and space limitations for construction on campus, the design sizes were narrowed down to a chimney diameter of approximately three feet, height of forty feet, and a collector area of 1600 square feet. This was approximately 1/3 the originally proposed collector area. Preliminary calculations were done to determine possible air flow rates using referenced equations that took into account the buoyancy effect. The impact of time of year and latitude on the angle of the sun was also examined prior to construction of the test chimney.

Collector Design:

Many of the traditional solar chimney collector designs are circular in shape. This is a difficult shape to construct in comparison to other shapes. Therefore, three small scale models were built to test the effects the shape of the collector had on the temperature difference between ambient air and moving air at the base of the chimney. The first two models used a manual thermocouple reader and several J-type thermocouples to record temperatures. The thermocouples were placed at specified locations in the collector and up the chimney. The first test model used a "three-sided" rectangle collector shape (Figure 3). The rectangular collector was 25 feet long by 15 feet wide. The second model used an elongated rectangle collector (Figure 4) to simulate a solar collector tube instead of a flat collector. This design came off the idea that if it could be long and narrow it might fit into some locations easier than the original size collector. Both test setups seemed to yield the same temperature difference between the ambient air temperature and the bottom of the tube.

The third model used a complete square design (Figure 5). For this design the manual thermocouples were replaced with miniature data loggers. A total of 8 data loggers were used to monitor the temperatures being achieved during testing in different areas of the solar chimney. The sensors were located at the top and bottom of the chimney, and in all 4 corners of the solar collector. This unit withstood a week in harsh rains and winds with minimal materials used to build and support it.

A similar maximum temperature difference was observed for all three cases, approximately 28 F in Fall. This was taken to imply that the shape of the collector was not as important as the total area. In order to select the final shape of the collector a design matrix was formulated with collector options of; square, rectangle, triangle, circle, oval, "3-sided" rectangle, and tepee shaped. Assembly, quantity of parts, complexity of parts, and manufacturability were found to be the most important criteria and were considered for each shape based on a scale of 1 to 5; 1 being worst for the design and 5 being most beneficial to the design. Each aspect was decided to have equal weight in the decision of which shape to choose. The square and rectangle were chosen to be the best for manufacturability because of the low complexity of individual parts. The square was determined to be the best in terms of number of parts and ease of assembly due to its symmetry (with a total relative rating of 20 out of 20) and was therefore selected for our design.

Figure 3: “Three sided” rectangle (25ft by 15ft) collector design.

Figure 4: Elongated rectangle collector design.

Figure 5: Square collector design.

Next the material to construct the solar collector had to be selected. There were several options considered for the design; including plastic sheeting, fiberglass panels, plexi-glass, and glass panels. Cost, manufacturability with the material, durability, availability, and resulting complexity were considered as criteria in the design matrix. The cost was a large restriction due to the massive quantity of material needed for the production of the design. Since the chimney is being designed for long term use, durability was also a crucial factor in the design.

Using a similar design matrix approach as for the collector shape, plastic sheeting was chosen (with a total relative rating of 22 out of 25). This was based not only on its durability, but because it is easy to acquire, has relatively low cost, and is easy to manufacture into the custom shapes that were required. While researchers have shown that glass would give better performance [15] it was not selected due to its high cost and low durability. For our assessment, plastic sheeting was used as a broad term used to encompass all plastic sheeting that is flexible and of 6 mil thickness. For the test model there were two specific material options, polyethylene construction and UV-rated greenhouse plastic. The estimated time of delivery of the greenhouse plastic was determined to be upwards of 6 months which would exceed the deadline of the project and was, therefore, not chosen.

Chimney Design:

The estimated size of the chimney made it difficult to find materials that would fit the criterion necessary. It needed to be weather resistant, structurally sound, lightweight for assembly, and withstand loading conditions from wind and weight. A design matrix was established with criteria of durability, cost, availability, manufacturability with the material, and complexity of the resulting design.

Since the test chimney was intended to be 40 feet tall, we needed a chimney that was both durable and strong. Several materials, such as fiberglass, concrete forming Sono Tubes, and PVC were explored. However, metal HVAC ducting was the only feasible test material for use in the Minnesota climate that was both under cost and available at short notice (with a total relative design matrix rating of 22 out of 25). This would not be a feasible option for most developing countries but was chosen as the best option for prototyping purposes. To ensure the structural integrity of the model as a whole, given the large weight of the ductwork, it was determined that the chimney would be supported with a wooden sub-frame. To support the chimney from lateral loads, guide wires were also used. Calculations were established to find the size of cabling needed to support the structure based on estimated weight and average wind. Safety considerations were double checked with the campus Safety Office prior to and during construction.

Turbine Design:

The only moving parts of the Solar Chimney are the turbine assembly and power generation unit. In the prototype chimney an average air velocity of approximately 2 m/s was created in the chimney. The low wind velocity complicated the turbine design.

The first design that was applied was to make homemade wind turbine blades out of PVC piping. A simple bearing was constructed out of washers, lithium grease, and an eye hook. Unfortunately the bearing caused too much friction for the low wind velocities to get the blades moving. The second design change made was implementing a nozzle. A nozzle was used to increase velocity by reducing the outlet area over a length and was constructed out of cheap and re-usable materials such as foam board, pine 1" x 2" s and a HVAC galvanized pipe flashing. After the nozzle was built it was about 15" tall and went from 36" diameter to 10" in diameter. In theory it was supposed to increase the air velocity by nearly 13 times. However, when placed in the chimney an increase of about 1.2 to 2 m/s total was seen.

The final turbine design constructed was to implement the initial PVC blades, but with them directly connected to a small PC computer fan. Not only was the PVC material durable but it was lightweight. Preliminary testing outside of the chimney showed that just a slight wind from a person blowing would spin the blades. The setup was then mounted and placed into the bottom of the chimney. With around 2 m/s wind velocity, it was determined that the turbine was producing around 0.35V and could light several LED's on the fan. The blades rotated easily inside of the chimney due to the low spinning resistance of the computer fan and its use of ball bearings. Unfortunately time constraints did not permit further study or optimization of the turbine/generator apparatus.

Design Iterations for Minnesota Weather:

During testing several challenges arose that required redesigns of certain items. The majority of these issues arose due to the environmental constraints of testing the chimney during a Minnesota winter (specifically high winds and snow accumulation on the collector).

Specialized UV resistant tape, purchased from a greenhouse supply store, was originally used to connect the plastic sheeting for the collector. The plastic collector did not show any problems until the second week of testing. It was noticed that the tape was separating and the plastic was not sealed in the corners. The solution was to clamp the corners together the same way as the plastic was attached to the rest of the collector structure. 1.5" PVC piping was purchased and strung on the already existing cabling in the corners, and then the plastic sheeting was "clamped" in between the PVC pipe and clamp. This was a much stronger way to attach two sheets of plastic together and held up until later changes were required.

After several nice days of weather it turned very cold and windy. When the wind would gust (above 20 mph) it would grab each sheet of plastic with a good deal of force. Rope was bought to make a "netting" of 5' x 5' squares which was attached to the outer ring and run criss-cross over the collector. This helped to reduce movement in the collector surface. However, the next problem encountered was the plastic collector sides pulling so hard due to the wind that the PVC ring it was attached to was shearing off the mounting screws. On one day the entire west side of the collector edge was pulled off of the spacing blocks. When the screws did hold, the wind instead pulled 12" and 18" landscaping spikes out of the ground.

It was decided that a more rigid structure for the collector was needed. An elaborate system was designed that allowed the collector to be constructed out of connected panels. Two types of collector panels were tested. New 4' x 4' panels (seen on the left of Figure 6) easily fit to the existing dimensions of the solar collector. They allowed the plastic to be very taught, providing the best wind and weather resistance. The panels were easily repairable because each panel was independent of the next one. Since the collector was now modular it could also be easily be expanded over time. While the panels were easy to manufacturer they were time consuming, so 8' x 8' panels (on the right of Figure 6) were also explored. These panels took much less time to construct but did not keep the plastic as taught as the 4' x 4' panels.

4. The Global Aspect – Testing in Ghana

Obviously many factors affecting construction and use in Ghana would not be the same as in Minnesota. Originally it was intended that the MSU students would work closely with counterparts in Ghana. However, due to communication difficulties and academic schedule differences this quickly became problematic. As an alternative the design group reported periodically to a Visiting Professor in Mechanical Engineering from Ghana (Dr. Jerome Antonio) and began communications with course instructors in Ghana. A visit was arranged for several MSU P3 students to visit Ghana to gather first hand data on material and construction methods available, to work with Ghanaian students, and to test a small scale solar chimney (Figure 7).

The chimney tested was intended to closely reproduce one of the early scale models (Figure 5). Given the difference in climate, due to Ghana's proximity to the equator, a much greater potential was demonstrated by the chimney. Temperature differences between ambient and the base of the chimney reached daily maximums over 50 degrees Fahrenheit. With the assistance of visiting faculty from the MSU Urban Planning Institute (who were also working in Ghana at the time) the students were also able to learn a great deal about material and manufacturing methods available in the local villages for future constructions.

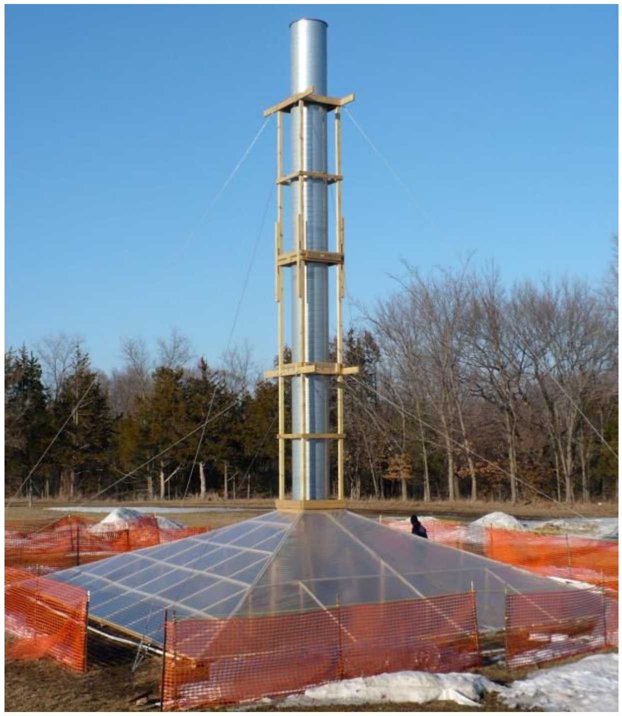

Figure 6: Completed prototype solar chimney

Figure 7: Small scale solar chimney in Ghana.

Figure 8: Taking test data with a Ghanaian student.

5. Conclusions

Overall the project was largely successful. A prototype small scale solar chimney was designed and produced in Minnesota. The chimney was made to withstand Minnesota weather and demonstrated average maximum temperature differences of over 30° F during testing in February. In fact, the temperature under the collector was near 60° F with green grass while the chimney was surrounded by snow. A prototype turbine made from recycled parts was demonstrated but was not optimized or fully tested. However, using the measured temperatures, calculations from previous researchers[9], and an assumed turbine efficiency of 80% it was determined that this chimney (in winter) could produce 1.8 W of power. While this represents much less power than the goal of 20-50 W the students were optimistic about the possibilities of improving performance with higher solar irradiance in Ghana, optimization of the turbine, enlarging the solar collector, and making use of a thermal storage media (i.e. rock) under the collector.

The best outcome of this project, however, was not the working solar chimney. The design experience, exposure to other cultures, exposure to concepts of sustainability, and presentation experience in Washington DC made this project an outstanding success.

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