AC 2008-1301: THE DEVELOPMENT OF A WATER PURIFICATION SYSTEM FOR USE IN WEST AFRICA

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The Development of a Water Purification System for use in West Africa

Abstract

In this paper, we describe the results of a project in which undergraduate engineering students developed and deployed a water purification system for use in rural Africa. The location of the project is a small village of 392 people in rural Ghana named Famanye, which is approximately a 40-minute drive from Accra, the capital. The only water sources in the village are brackish water from a pump and a very small, terribly polluted runoff-fed pond. The water from the pump is too salty for consumption, and the residents are forced to use the water from the pond, since the nearest fresh water source is two kilometers away. To address this problem, a team of students in the multidisciplinary engineering program on the Polytechnic campus of Arizona State University are developing a water purification system based on a unique, patented heat recovery scheme in which heat transferred from the clean water condensation process is used to evaporate the contaminated water. The result is that the needed heat input to the system is greatly reduced; the system is simplified; and the units can be reliably deployed in undeveloped rural areas. The system has been designed to be low cost, easy to produce and to require little maintenance, enabling the village to manufacture and sell the units to neighboring villages.

The project described in this paper is part of a larger interdisciplinary initiative at ASU known as GlobalResolve, in which sustainable entrepreneurial models for economic progress in developing countries are pursued. This leads to unique design constraints on projects that result in very rewarding experiences for the students involved.

Introduction

Clean water is essential to all people on earth. However, ninety-nine percent of water on Earth is unsafe or unavailable to drink and 1.2 billion people lack safe water to consume while 2.6 billion do not have access to adequate sanitation. Just to emphasize the comparison between the haves and have-nots: "Just one flush of a toilet in the West uses more water than most Africans have to perform an entire day's washing, cleaning, cooking and drinking.[1]" Waterborne illnesses from polluted water kill more than 1.6 million young children each year, according to UNICEF.

Many organizations have targeted clean water as a priority goal. Rotary International, whose past focus on eradicating polio in the world has been wildly successful is moving its emphasis to clean water. Rotary's 'Safe Water Saves Lives, Solar Water Purifier' project, now in its sixth year, has provided more than 200 solar water purifying units to poor communities in the Solomon Islands, Sri Lanka, Nigeria and other developing areas[2]. The United Nations Millennium Development Goals include a proposal to cut in half, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. In sub-Saharan Africa, home to Ghana, that proportion was reduced from 52 percent to 44 percent between 1990 and 2004. The target is 26 percent[3].

This paper describes a student project as a part of the GlobalResolve program conducted at ASU which has two combined goals: provide a village in Ghana with a sustainable way to generate clean water from polluted sources and create a sustainable model of entrepreneurship that can improve the village economy.

Global Resolve at ASU

Figure 1: Village Meeting in Fawomanye, Ghana

The water purification project is part of an interdisciplinary intercultural initiative at ASU called GlobalResolve[4]. GlobalResolve was established in 2006 as a social entrepreneurship program designed to enhance the educational experience for interested and qualified students by involving them in projects that directly improve the lives of underprivileged people, and/or those in developing nations throughout the world. Through GlobalResolve, students and faculty collaborate with international universities, residents of rural villages, local governments, financial institutions, and non-governmental organizations (NGOs) to develop and disseminate "no-tech", "low-tech", and "high-tech" solutions that address pressing public health or environmental needs of a developing-world population. Because solutions developed by GlobalResolve are designed to be replicable locally, regionally, and internationally, the solutions also create the potential for profitable new business ventures that generate sustainable income streams for impacted populations.

The method of operation of GlobalResolve emphasizes global student teaming to solve local problems. Candidate villages are identified, local needs are surveyed, and technological solutions are developed that can form the basis of new entrepreneurial ventures within the village. This requires a collaborative effort on the part of ASU, the rural village, local universities near the village, local government and financial institutions, and NGOs. Since its inception, GlobalResolve initiatives have included: the development of a gelled fuel generator and stoves in Domeabra, Ghana; the development of biodiesel crops near the village of Biemso, Ghana; the development of a neurosurgical medical device for healthcare in South Africa; and the assessment of wind energy on the Hopi Reservation in northern Arizona.

Figure 2 Drainage Pond as Water Source

The genesis for a new partnership emerged in

September 2006 when GlobalResolve visited Kwame Nkrumah University of Science and Technology in Kumasi, Ghana, and the village of Famanye, Ghana, as the first village-focus for GlobalResolve. During a village meeting under the acacia trees, the chief said the two things his village needed most are clean water and electricity (Figure 1). Water is important because the village has a salty well and a polluted drainage pond as their only local sources with the closest clean well 2 km from the village. Assuming a population of 400 in Famanye and a minimum of 4 gallons of water per day per person, it became apparent that transporting 1600 gallons 2 kms by foot every day with no vehicle was prohibitive. In fact, the villagers get most of their water from the drainage pond shown in Figure 2. Consequently, people are sick and infected with parasites. Upon returning to ASU, the authors who are professors of engineering and 8 juniors in the multidisciplinary engineering curriculum took on the project of designing a water purification system for the village that was sustainable, energy-efficient, inexpensive to operate and had the potential to create a village venture to sell both pure water and one which could be fabricated, marketed and sold in nearby communities. This model creates long term employment opportunities and revenue streams for the village. The remainder of this paper describes the project steps, the resulting prototype and plans to solve the water problem in Famanye.

Product Development Process

A conventional engineering product development process was used for this project including problem definition, identification of customer needs, development of target specifications, concept generation, concept selection and prototyping and testing the chosen concept. Implementation in the village is currently being pursued as is funding to deliver and install the purifier.

For the purpose of this project, the customer is defined as an average family in the village of Famanye. This family customer is chosen over the customer “the village” in order to minimize social and political concerns relating to the maintenance and ownership of the device and the purified water it produces. The average family in Famanye consists of seven members, typically two adults and five or six children. The families live in homes built from available resources such as concrete block & corrugated metal sheets. Basic schools and secondary institutions exist in the region along with farming and some minor industry. From these observations, it is reasonable to assume that the people have some basic mechanical skills or can be easily taught. Only basic hardware is available for any necessary repairs or maintenance. Typical family income is less than \$400 per year. Common assets for trade include poultry, livestock, and pork in addition to charcoal, selling for approximately \$4.00 per bag (8 cubic feet). We assume that the people are physically active, requiring an average level of water intake.

Famanye is located in a tropical environment. The local temperature ranges from 70˚-95˚ F with a relative humidity from 60%-90%. Ghana receives 30”-80” of rainfall per year and Famanye is in the higher rainfall region in the south.

Criteria & Constraints

Several assumptions have been made to match the water purifier to the village conditions. The goal includes making the water purification a sustainable process with little or no maintenance and able to operate without electric power from the grid, although other forms of electricity such as solar panels can be considered. Constraints are limits that must be met while criteria are goals that allow multiple concepts to be evaluated for optimal suitability.

Constraints
- The device must not be grid powered
- The device must be able to purify water from a salty well
- The prototype must cost less than $200 (a somewhat arbitrary value, but certainly the purifier must be inexpensive given the economics of the village)

Design Evaluation Criteria
- Minimal moving parts
- Durable (minimal maintenance)
- Efficient (energy input vs. gallons purified)
- Maximal use of free energy available in the village
- Desalination capacity
- Minimize fouling
- Low negative impact to environment
- Safe
- Low cost (production & shipping)
- Scalability (for larger sizes for a village)
- Minimal human capital required

Specifications and Metrics

From these criteria and constraints, a set of specifications was developed. They are a direct logical result of the needs of the customer and were derived by assigning measurable quantities to the constraints and criteria defined by the team during critical thinking sessions. Figure 3 and Table 1 show the range for a given score for each metric and metric definitions.

Score	Moving Parts [n]	Durability (%)	Cost [USD]	Scalability (%)	Human Power [Cal/day]	Energy needed per Kg water [rank]	Free Energy	Time commitment [hrs/day]	Desalinization	Fouling Avoidance	Environmental Effect	Risk Factor [rf]
0	> 50	<50	>200	50-59	>500	6	0	24	No	No	(-)	>4
1	41-50	50-60	151-200	60-69	401-500	5		12-23				4
2	31-40	61-70	101-150	70-79	301-400	4	some	6-11			(nuetral)	3
3	21-30	71-80	51-100	80-89	201-300	3		3-5				2
4	11-20	81-90	1-50	90-99	101-200	2		1-2				1
5	0-10	> 90	0	100	0-100	1	all	<1	Yes	Yes	(+)	0

Figure 3: A Chart Showing the Score for Ranges of Values for Each Metric

Table 1 Product Specification Definitions

Moving Parts	Estimated number of moving parts to reduce failure and product cost.
Durability	Estimated percent downtime based on complexity. [%]
Cost	Approximation of required material, production and shipping costs. [$].
Scalability	Ratio between thermal efficiency before scaling and thermal efficiency after scaling. [%]
Human Power	Ratio of work input to water produced/day to minimize the amount of work required by the customer. [Cal/day].
Efficiency	Ratio between the required energy and the output of clean water. The units of this metric are [rank].
Desalination	Binary metric indicating ability to remove salt from the water source.
Fouling	A binary metric indicating ability to avoid accumulation of unwanted material during operation.
Environment	Environmental impact such as byproducts and sustainability issues.
Risk Factor	Estimated number of failure modes, which could result in customer injury.

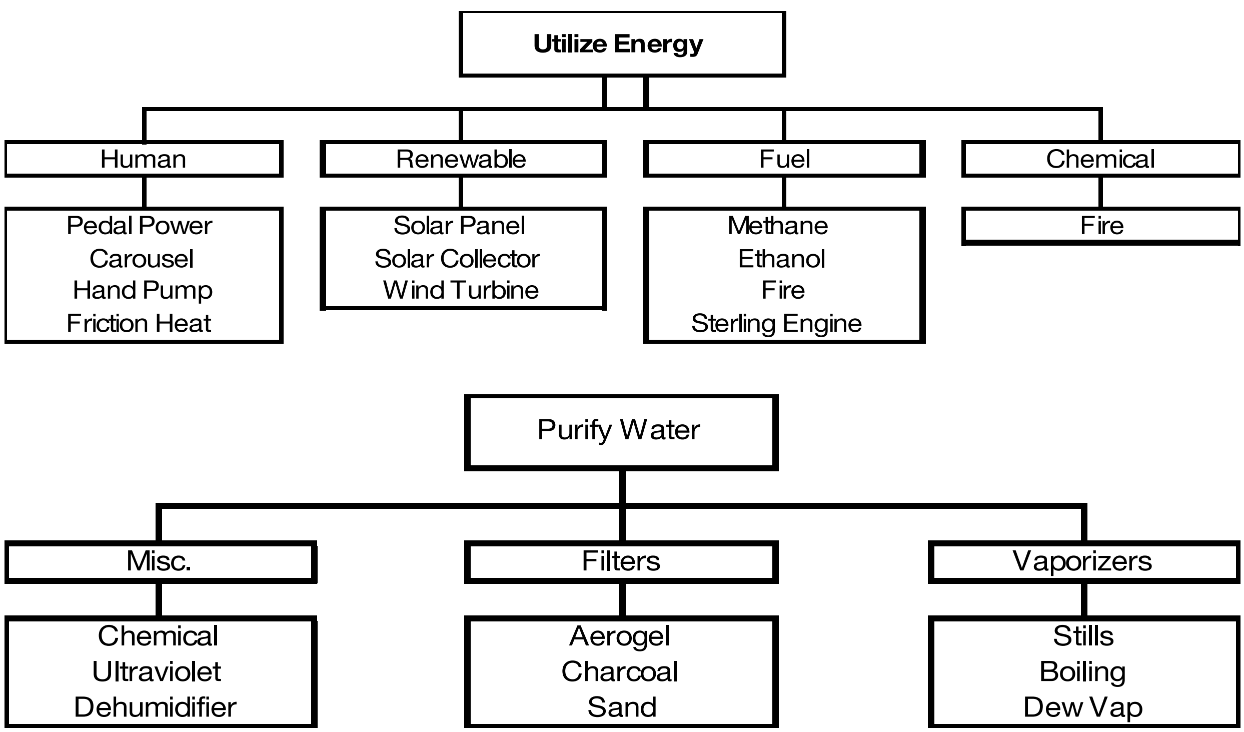

Figure 4 Function Decomposition and Solution Tree

Concept Generation

Concept generation was performed by pairing various energy generation methods with various water purification methods. Figure 4 shows possible solutions for these functions.

Concept Combination Table

The concept combination is a table that links the different energy sources with purification processes that were found in research on purification methods (Table 2). If a process and a power source can be combined into a sensible design, an X was placed in the box. If not, the box is left blank. This resulted in several different combinations that could be used to purify water. These processes will be narrowed using a screening matrix.

Table 2 Possible Water Purification Concepts

		Purification Processes					
		Filtration	Distillation	Boiling	Chemical	Ultraviolet	Dehumidification
Power Sources	Solar Panel		X			X	
	Solar Collector		X	X			X
	Fire		X	X			
	Frictional Heat		X	X			
	Pedal Power		X	X			X
	Carousel		X				
	Methane		X	X			
	Wind Turbine						X
	Hand Pump	X					
	Stirling Engine						X

Screening Matrix

The concepts were scored in a concept screening matrix (Figure 5). In the left column the concept are organized by base process: distillation, dehumidification, and the filter with the metrics listed along the top. Scores were selected based on subjective judgments by the team with input from faculty and research. The top three rated concepts were a combination Evaporation/Dew Formation (DewVap) system, the Solar Still in second place, and the Pot Still in third. The selection process up to this point has been based entirely on subjective estimates and judgments, but the final selection requires a more exhaustive analysis.

Processes	Moving Parts	Durability	Commitment Time	Cost	Scalability	Desalinization	Risk Factor	Free Energy	Fouling	Environment Effects	Total
Distillation:											
Solar Still	5	3	3	1	3	5	5	5	0	5	37
DewVap	4	4	5	4	4	5	4	0	5	5	40
Pot Still	5	5	1	2	3	5	3	0	0	3	27
Self Cleaning Solar Still	3	3	1	1	3	5	5	3	5	5	34
Dehumidification	3	0	0	0	1	5	3	0	0	0	15
Filter	4	4	3	4	3	0	5	0	0	5	28

Selection Metrics

Figure 5: Completed Selection Matrix

Modeling

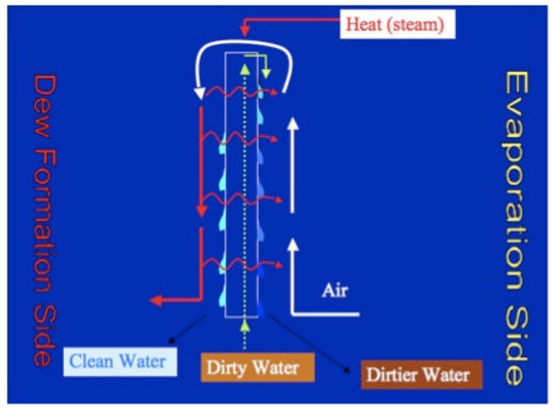

Figure 6 DewVap Schematic[5]

In the interest of space, only the DewVap system modeling will be described. A major reason for selecting the DewVap as the best design is because of its low energy consumption and a contributing factor is that ASU holds a patent on the device, making it available to use in the Ghana village[5]. The device operation and theory is covered in Hamieh[6]. Altela, Inc.[7] holds an exclusive worldwide license for the technology from ASU. and manufactures and markets water purifiers to the oil industry, where the units are utilized to clean the oily water emitted from oil wells during drilling, allowing the clean water to be dumped into the ground while the separated impurities are transported for disposal or refined.

The DewVap System

The DewVap concept (named for the innovative coupling of heat rejected in the dew formation (condensation) process with heat required in the evaporation processes) is not complicated in principle, yet results in a water purification system that requires a fraction of the energy input of traditional systems. A schematic is shown in Figure 6. Incoming polluted water is pumped up the center of a duct and allowed to drip over the side (shown as dark blue droplets on the Evaporation side) and run down a surface evaporating into incoming ambient air. As the now humid air passes over the top of the duct to the dew formation side, a small amount of steam is injected to saturate and warm the humid air. As the saturated air flows over the dew formation surface condensation occurs on the subcooled surface, releasing heat, which is transferred to drive the adjacent evaporation process occurring on the opposite side of the wall. This maintains a temperature gradient from bottom to top to help warm the incoming air and maximize evaporation, while the decreasing temperature gradient on the condensation side ensures dew formation along the length of the surface. Moisture formed on this surface drains by gravity into a clean water receptacle. The dirty water that is not evaporated now has a higher concentration of impurities because of the clean water evaporation and drips into a “dirtier water” receptacle to be recycled with the incoming water.

This process is suitable for an African village because it requires very little energy input (small pump, small fan and small amount of steam) and is physically simple to construct and maintain with few moving parts. The thermodynamics and combined heat and mass transfer model is somewhat complex, especially for junior level engineering students, but is an excellent reinforcement of principles when coupled with construction and operation of a prototype unit. Altela manufactures standard size units that are 2 feet square by 8 feet high and can produce 10 gallons of clean water per hour. The mass of water which can be purified depends on the difference between the absolute humidities at the inlet and outlet, and absolute humidity at saturation that increases exponentially with increasing temperature. The result is that the axial temperature difference along the surface is a critical performance factor for the system. However, heat and mass fluxes are limited by the physics of the processes, so that achieving this optimum axial temperature difference requires increasing the height of the unit. Hence, Altela produces the tall, narrow aspect ratio for the units.

The engineering analysis model includes heat and mass transfer, thermodynamics and fluid mechanics. The system is comprised of two basic open systems. The first is a cross-flow heat exchanger. The second is a mixing chamber. One side of the heat exchanger feeds the mixing chamber, which combines that input with steam. The resulting output feeds the other side of the heat exchanger.

Thermodynamic Modeling

The DewVap system modeled as a whole is simply an adiabatic heat exchanger, with the result that in steady operation the total rate of enthalpy carried by the incoming streams is equal to that carried out by the exiting streams. However, for the purposes of design it is necessary to consider three coupled processes. The first analysis is the evaporative side, in which dirty water is evaporated in non-saturated air, which is receiving heat from the condensation side of the unit which results in increases in temperature along the flow direction, thus maintaining a non-saturated condition even as the absolute humidity increases. The second analysis is an adiabatic mixing process in which saturated steam is injected in to the air at the top of the column to both increase the temperature saturate the air. By doing this condensation begins immediately on the clean water side, and heat will be transferred across to the evaporation side because of the higher temperature. Finally, the condensation process is modeled, in which clean water is condensed out of the humid air, and heat is transferred through the surface to supply energy needed for evaporation, resulting in a decreasing air temperature along the surface. Supplementing the thermodynamic model with a mass balance results in predictions of the clean water condensation rate and the needed steam injection rate.

The clean water flow rate divided by the steam injection rate is a critical parameter when considering the deployment of this technology to an African village, because the steam must be produced by an external energy source. For example, in this case it has been proposed that waste heat from the charcoal production fires in the village may be used to produce this steam. However, if the required steam rate is too high, the technology will not be competitive. Using observed operating conditions theoretical calculations of this ratio are approximately 9:1, or nine kg of water for every kg of steam supplied to the unit. However, in practice this ratio has not been achieved. Consequently, in subsequent semesters additional undergraduate students will be enlisted to build test apparatus and carry out designed experiments to determine how to explain this discrepancy and improve the technology.

Prototype Testing and Results

The prototype unit built during the fall of 2007 was tested near the end of the semester to demonstrate proof of concept and to obtain preliminary results on which to base subsequent designs. Because of time limitations, the unit was run only three times, the first two experiments serving to ensure proper operation of all equipment and to identify and repair leaks. In the final test, performance measurements were taken, and are given in Table 3. As these results demonstrate, the prototype unit is cleaning the water, and the DewVap process is operational since the clean water produced (1.92 kg) is greater than the 1.48 kg of steam added through the boiler. However, the prototype unit was not producing the mass or purity of water that is predicted by the theoretical model.

Salt was added to the incoming water to simulate the village well. The fact that salt was present in the clean water stream shows that the leaks were not eliminated in the prototype system, which affected not only the purity of the clean water, but the energy efficiency as well. The leaks were primarily due to perforations in the thin aluminum used in the heat exchanger.

Table 3 Prototype Test Data

Testing (2 hours)			
	Boiler	Dirty Water	Clean Water
Water before test (kg)	3	6	0
Water after test (kg)	1.52	5.6	1.92
Salt after test (PPM)	850	854	256

Future Plans and Conclusion

The prototype model built and tested in the Fall semester of 2007 demonstrated that the DewVap process is operational, and that the technology holds promise for minimal energy input water purification systems for use at the village level in the developing world. Problems that have been identified with the first prototype will be addressed during the spring semester of 2008 in the construction of a test apparatus on which designed experiments can be conducted.

The application of this technology at the village level remains a formidable problem. For example, since Famanye has no electricity and no running water, the problem of delivering energy to the water purifier remains. At the same time, there are several possible solutions that make use of resources existing in the village. For example, the village has a charcoal production business (Figure 8), which can be harnessed to power the purifier by constructing a flue over the fire and using the rising gases to turn a small fan. The heat can be used to create steam and possibly power a small pump. Finding solutions and building prototypes for these particular facets of the project are also important next steps on the development agenda for this project.

The goal is to deliver a working prototype to the village in August 2008. Rotary International has expressed interest in funding this project and proposals are underway seeking this support, which will cover additional prototyping costs as well as travel and training in the village of Famanye.

GlobalResolve will use the results of this project to create a replicable model of providing a sustainable solution to water purification in other villages with similar conditions to Famanye. The larger goal of GlobalResolve is to instantiate these solutions around the region, country, continent and wherever clean water is needed and where the conditions support this solution. Furthermore, GlobalResolve will evaluate helping the village establish an entrepreneurial business venture in providing clean water as well as building and selling the water purifiers to other villages. Income from this venture can provide a mean of sustainable economic development. Developing a venture involves more than just engineering and will include students and faculty from business, sociology and global studies.

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