Conceptual Design Review

Mechanical Engineering Senior Design

Team 20

Solar-Powered Phase Change Compressor

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Introduction:

The senior design team is working to address the following project need statement:

"Design a compressor for a refrigeration system that is powered by solar energy."

To define a specific, measurable, and achievable goal, it has been decided to specify a compressor that is capable of driving a vapor-compression refrigeration cycle that achieves 5,000 BTU/hr of cooling, or 1,465 W. This is the equivalent of a small window air conditioner unit.

The phrase "powered by solar energy" leads to two distinct options for design concepts: photovoltaic solar generation, and concentrated solar thermal generation. The first concept explained below will describe the use of a photovoltaic system to address the need. The following three options make use of concentrated solar thermal as the power source. Though the photovoltaic option is a simpler design, its cost is prohibitive given the resources available to the team. The solar thermal design concepts are creative in the way energy is converted, and at the initial estimation are much less expensive to develop.

Concept 1: Photovoltaic Generation

The first idea that comes to mind when considering a solar-powered device involves the use of solar panels to generate electricity. Assuming that there are sufficient photovoltaic (PV) panels to meet the power requirements of a device, the device can simply be plugged in without any major modification to the device.

The proposed system would utilize an array of photovoltaic cells to convert incident radiation from the sun to solar energy. Batteries would be needed to store energy that is generated. Also necessary is a power inverter to convert the electricity from direct current to an alternating current supply that an off-the-shelf air conditioner could be plugged in to.

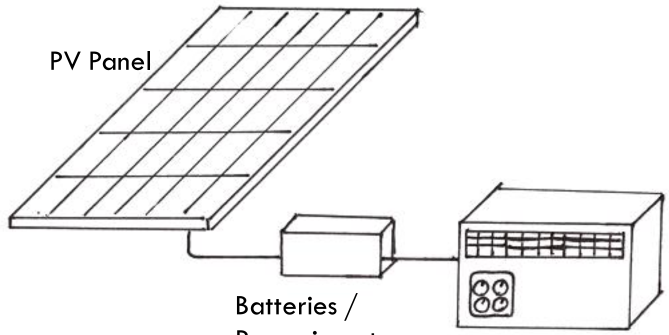

Figure 1.1: Schematic of PV system

This design presents a comparatively simple solution to the problem. Each component is commercially available, and systems such as are already used in residential applications. The major downfall of this concept is the cost involved. The power requirement of a small air conditioner which produces 5000 btu/hr of cooling is approximately 500 W. Assuming that the unit would run for 24 hours per day, the daily power consumption is 12,000 W·hr. Assuming that the generating potential of a PV panel is 70mW/in^2, and there is an average of 5 hours of direct sunlight per day, the daily generating potential is 0.35 W·hr/in^2. In order to determine the surface area required, the following calculation is applied: $\text{Surface Area } = \frac{(12{,}000\ W{\cdot}hr)}{\left(0.35\frac{W{\cdot}hr}{in^2}\right)} = 34286\text{in}^2 = 238\text{ft}^2$. At a cost of \$56 per square foot, the cost of the panels alone comes to \$13,328.[1]

Pros:

- Simplicity, every major component is available off-the-shelf.
- Low maintenance required, no moving parts in the power supply system.
- Capable of storing surplus electricity.

Cons:

- High cost. Over \$13,000 for panels.
- Requires a minimum amount of direct sunlight.
- Lacks innovation. It has already been done.

Concept 2: Concentrated Solar Thermal Energy Steam Turbine System [2]

This concept utilizes current systems that have experimental background integrated with off the shelf products. The overall system converts the direct insolation from the sun to electricity produced by a generator. The goal of this concept is to generate at least 500W in order for the 5,000 BTU A/C unit to properly function.

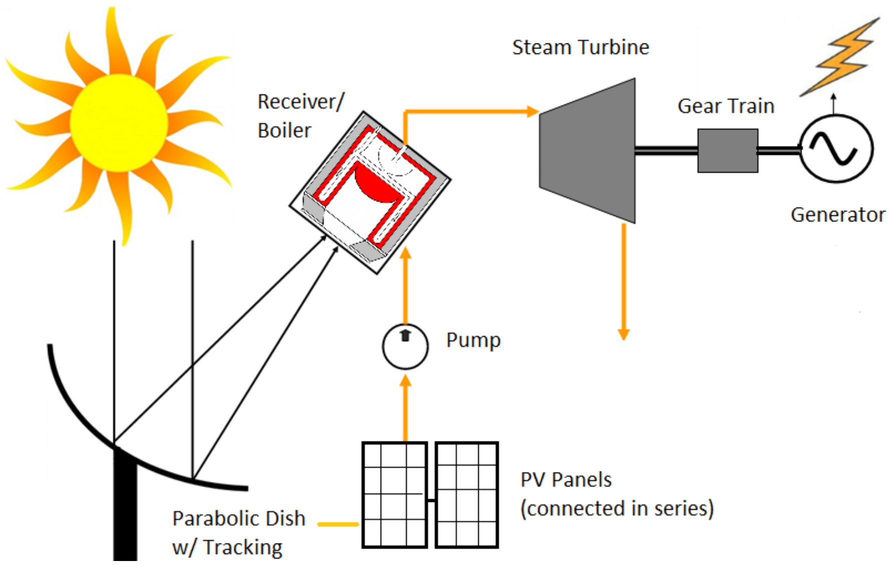

Figure 2.1: Schematic of System (Dascomb) [2]

Each component of thy system will be broke down in order to analyze the complete process of the solar thermal energy system. The diagram of the concept is shown in Figure 2.1. It begins with a parabolic dish constructed from aluminum. This dish will be coated with ReflecTech, a highly efficient, approximately 94%, reflective adhesive. This adhesive is pertinent to the longevity of the dish because it can last up to 10 years as well as survive harsh weather conditions. Another important factor that the parabolic dish must have is a tracking system in order to obtain as much sunlight as possible. The system will consist of a combination of satellite dish linear actuators and photo-sensing control units.

The receiver/boiler is attached to the dish due its function of collecting the concentrated solar energy. The most commonly used is a cavity receiver, as opposed to an external receiver, because it has an aperture which the reflected radiation passes through; absorbing a majority of the energy. The downside to the external cavity is that it has a much higher heat loss rate. Once the heat is focused inside the cavity, it absorbed by the inner walls and transferred into sodium nitrate. The molten salt is used as a heat transfer agent to the wrapped copper coils located inside the cavity. A schematic of the cavity receiver can be seen in Figure 2.2.

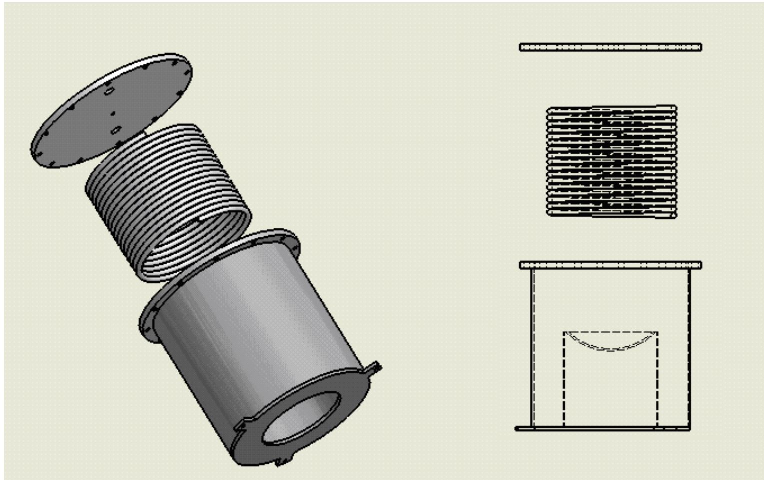

Figure 2.2: Exploded View of Receiver (Dascomb)

After the heated coils reach a certain temperature water is pumped through and heated. This heated water, due to the molten salt, is then flash boiled into steam where it can increase its volume up to 16,000 times. The generated steam is then focused through nozzles. These nozzles greatly increase its kinetic energy which causes, due to impulse, the blades on the turbine to rotate, as illustrated in Figure 2.3. This rotation causes the rotor to spin, resulting in shaft rotation.

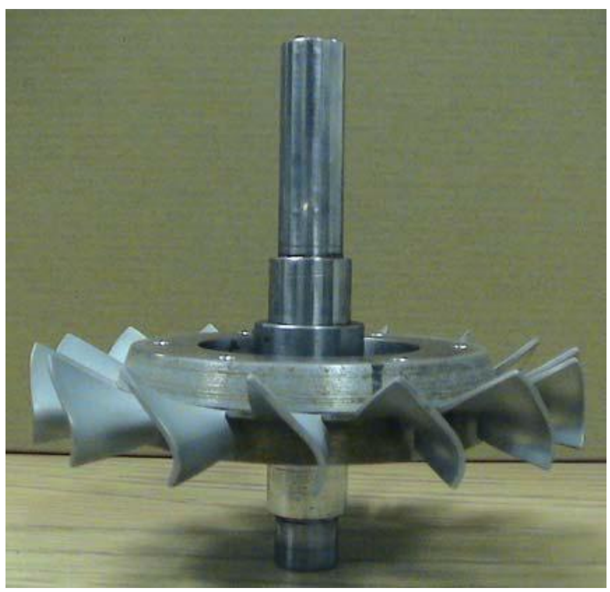

Figure 2.3: T-500 Impulsive Turbine Rotor (Newton)

The shaft rotation of small scale steam turbine produces high rotation but little work. A gear train will be implemented to help balance out the two. A moderate torque is needed in order to produce the desired mechanical energy that will result in at least 500W produced by the generator. The generator/alternator that will be coupled to the gear train is a 600W DC to AC Power Inverter. A power source must be used in order to run the tracking system and the water pump. The concept will use two 12 Volt deep cycle batteries wired in series in order to increase the voltage. The batteries will be powered by two Solar World, Inc. 15.7 Volt solar panels, also wired in series. These panels will easily generate enough wattage to power the systems.

Cost:

Mount and Frame: $800
Parabolic Dish: $600
Tracking System: $350
Receiver/Boiler: $600
T-500 Impulsive Turbine: $400
PV panels and Batteries: $300
Water Pump: $50
Gear Train: $200
Generator : $400
Total = $3700

Pros:

- Water does not have to be purified
- No modification to A/C system required (a plug is the interface between the two systems)
- Non-technical design
- Low maintenance

Cons:

- No thermal storage components
- Dependent on direct insolation
- Extended warm-up period
- Economically Inefficient

Concept 3: Concentrated Solar Thermal Energy Stirling Engine-driven Compressor [3,4,5]

The goal of this concept is to replace the compressor of a 5,000 BTU air conditioner. The solar reflector dish concentrates light/heat toward the Stirling engine canister, whose end is rounded to the same curvature as the dish. This makes the incident reflected light hit at a right angle to the tangent of the canister. The set up makes the light more focused which overall means more heat. The working fluid option options for this concept are air, helium, or hydrogen, depending on availability or knowledge of using certain mediums. On the Stirling engine wheel, there will be an even number of rods attached, with equivalent angles between them, which will all go to the pump. An even number is chosen in order to have continuous, even flow of the refrigerant. The pump is reciprocating, with as many cylindrical compartments as rods attached to the Stirling engine wheel. Each compartment has a piston (end of the rods) pumping the fluid, sealing to keep the refrigerant from leaking, and 2 outlet valves for the inlet and outlet. The schematics below show two pistons ending at the top on the left square are compressing and the two ending at the bottom are creating a vacuum.

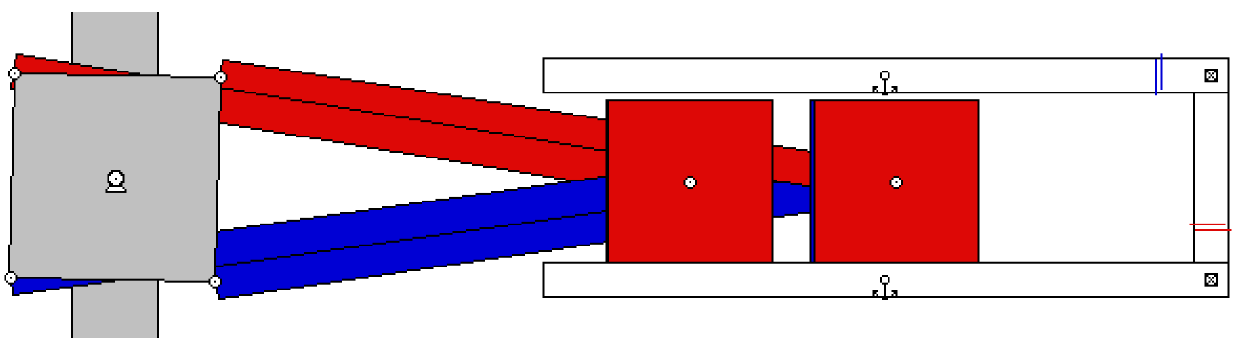

Figure 3.1 Overlap

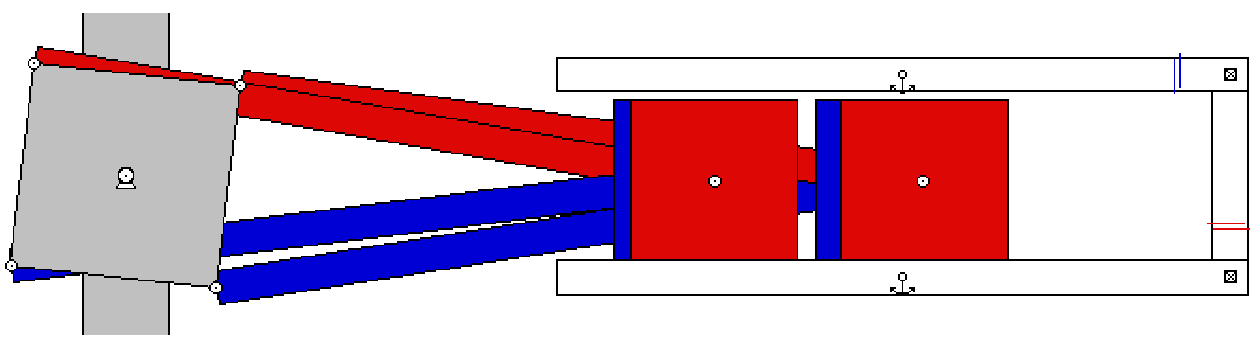

Figure 3.2 Right after overlap

This design will have some foreseen drawbacks. An example of this is that one engine may not have enough power to achieve the necessary compression in which case more than one will be put in parallel to increase our power. Also, since we want the refrigerant to stay inside the system so to prevent leaks sealing methods will have to be researched. Lighter fluids are better as engine working medium and since we will have metal moving parts, flammable gases will be potentially dangerous.

Cost:

Mount and Frame: $800
Parabolic Dish: $600
Tracking System: $350
Stirling engine: $1000
Pump: $200
Tubing: $30
Sealing: $50
Total = $3030

Pros:

- Each component is relatively simple and can be machined if purchasing proves too expensive.
- No electric components in compression (100% solar thermal compression) meaning no conversion system needed.

Cons:

- A lot of moving parts means reliability goes down.
- Since the compressor is non-electric, rewiring the A/C system may be needed.
- From an initial estimation, the price of buying the components may pass our budget.
- Not usable at night (unless other heat source is used).

Concept 4: Fluid Expansion Reciprocating Compressor

The inspiration for this design concept is from a patent owned by the project sponsor, Grant Peacock.[6] As in the previous two designs, the energy source will be thermal energy collected from the sun. As an auxiliary heat source, for times when direct sunlight is not available, a natural gas burner can be incorporated into the design. The principle of the concept is that heat will boil a fluid – we will choose water – and cause it to expand. This expansion will be used to push on an elastic membrane. As the membrane expands, it will compress the refrigerant fluid on the other side. When the pressure generated by the boiling water is released, the membrane will return to the original position and draw more fluid into the pressure vessel. If this reciprocation can be controlled and achieve a high frequency, the system can function as a useful compressor.

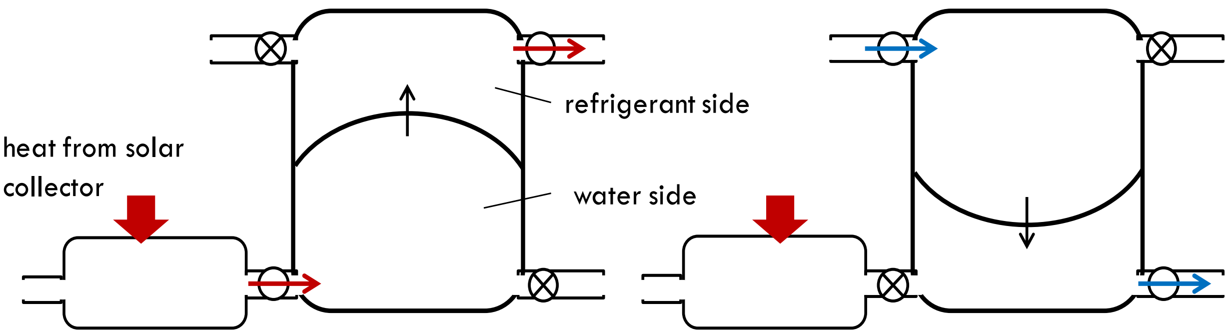

Figure 4.1: Schematic of fluid expansion reciprocating compressor

As an estimator of cost a diaphragm expansion tank, used to regulate pressure in a hydronic heating system, is considered. This off-the-shelf product incorporates the major components particular to this concept: a pressure vessel with two chambers separated by an elastic membrane. An expansion tank manufactured by Amtrol retails for $50.80.[7] As a conservative estimate, it is expected that the necessary valves and fittings will cost an additional $100. Including the estimated cost of a solar collector mount, dish, and tracking system ($1750) the total cost for this concept comes to $1900.

<u>Cost:</u>

Mount and Frame: $800
Parabolic Dish: $600
Tracking System: $350
Expansion Tank: $50
Valves and fittings: $100
Total = $1900

<u>Pros:</u>

- Low cost, since no high tech components are required.
- Simple design, few moving parts.
- Innovative approach to solving the problem.

<u>Cons:</u>

- May not be capable of producing sufficient power.
- Valve timing must be precise.
- Membrane will need to resist fatigue failure after high number of cycles.

Decision Matrix

	wt	1. PV Supply		2. Steam Turbine		3. Stirling Engine		4. Peacock Concept	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Versatility	x4	3	**12**	4	**16**	4	**16**	4	**16**
Cost	x7	1	**7**	4	**28**	2	**14**	5	**35**
Innovation	x5	1	**5**	3	**15**	4	**20**	5	**25**
Simplicity	x4	5	**20**	2	**8**	3	**12**	3	**12**
			44		**67**		**62**		**88**

The decision matrix above shows the criteria by which each design concept has been rated. For each criterion, the designs are ranked on a scale of 1 (worst) to 5 (best). There are four criteria used to evaluate each design: versatility, cost, innovation, and simplicity.

Versatility is a rating of how well the system will operate across a variety of conditions. Ideally, the sun is always shining and the system will operate at peak performance; however, due to unpredictable weather, this isn't always the case. The photovoltaic concept scored moderately in this category, since it relies only on direct sunlight. A battery system would provide reliable power at night time and during periods of cloudy weather. Nevertheless, if there is a period of several days without direct sunlight, the batteries my run out of power. The remaining three concepts, each operating on concentrated solar heat have the advantage of an alternate heat source such as a natural gas burner. For this reason, they each scored slightly higher in versatility.

Cost carried the highest weight as a criterion for evaluation. The PV system has the highest estimated cost at over $13,000; accordingly it ranked the lowest. The project sponsor's (Grant Peacock) concept for a reciprocating compressor has the lowest estimated cost, and is within the limits of the $2,000 budget.

Innovation is an important criterion, since it is a goal of the team to explore a system which is not already widely used. Using PV panels to generate electricity is common enough to be sold in do-it-yourself kits for homeowners. Conversely, Mr. Peacock's concept is both creative and novel; research conducted by the senior design team has revealed no precedent for a commercially available or prototype compressor that operates on the principle.

Simplicity is the final criteria used to rate each concept. A simple design has the advantage of a lower probability of failure, due to fewer components. In this respect, the PV system rated well. The Stirling engine concept would require extensive design and many components; thus it was rated lowest in this category. Mr. Peacock's concept rated moderately in simplicity. It does not have many components, but it will need to be custom manufactured.

The maximum possible weighted score is 100. Taking into consideration all of the criteria, the Photovoltaic system received the lowest score (44). Mr. Peacock's concept received the highest score at (88). This is the concept which the senior design team will proceed with designing.

References

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