Finding India's place in the Sun – Prospects for harnessing solar thermal energy

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Abstract | In this article, we describe our ongoing efforts in addressing the environment and energy challenges facing the world today. Tapping solar thermal energy seems to be the right choice for a country like India. We look at three solar-thermal technologies in the laboratory — water purification/distillation, Stirling engine, and air-conditioning/refrigeration.

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1. Introduction

The Earth faces an environmental crisis that is almost certainly caused by human action — through population growth, staggering increases in per-capita consumption, and rampant pollution. In particular, increases in average global temperatures have been linked to human emissions of greenhouse gases. To put this in perspective, even a 2 °C rise in average temperature will cause an appreciable rise in sea levels, the impact of which will be severe even under the lowest estimates of sea level increase. About 10% of the world's population lives in low-elevation coastal zones that will likely be flooded. Possible loss of life, coastal erosion and inundation, destruction of marine habitats, increased flood risk, and ground water deterioration are some of its certain consequences. We fully expect that reduction of emissions from coal-fired plants and fossil-fuel automobiles will soon become a mandate across the globe.

It is in this context that solar energy emerges as a sustainable source of renewable energy for the future. It is an obvious choice for India [1]. The country is blessed with plentiful sunshine, while large swaths of its population are still mired in energy poverty which hinders their economic growth. India's growth and stature in increasingly tied to its economic development that, in turn, is intimately tied to energy independence. Solar energy will keep the country independent of oil cartels, nuclear supplier groups, and other fickle political groupings. Just as developing countries by-passed landlines for mobile phone networks over the last decade, we expect that developing countries hungry for energy will forgo the massive incremental costs of extending a national grid in favour of renewable *decentralized* sources, which are not subject to massive centralized investments and inevitable transmission losses.

One well-established way of tapping solar energy is through photovoltaic (PV) technology, where the incoming solar light energy is directly converted to electricity using a semiconductor material. The main advantage of this technique is that it has no moving parts and the PV panels can be mounted on the rooftop at some suitable angle so that they face the sun throughout the year. The most common commercial PV devices use silicon as the semiconductor material. It is important to note that the environmental cost of processing silicon is not figured into the final cost of the device, which, in recent years, has fallen to less than Rs 100 per watt. Furthermore, India does not have a reliable supply of high-quality silicon to make it a viable alternative for the future. PV also has the disadvantage that it uses mainly the visible part of the solar spectrum and not the infrared heat. This can be a problem particularly when using solar concentrators (in order to get more mileage out of the same amount of semiconductor material) because the unwanted heat has to be rejected efficiently.

For all these reasons, we believe that solar thermal devices (and not PV) have a better future in India. Solar thermal is a general term that covers any method of using *heat energy* from the sun. One well-known example is the ubiquitous solar water heater that adorns many rooftops in our cities. These heaters use the thermal energy from the sun to heat water to about 80 °C, and then supply it to the bathroom. Running an electric geyser, the most power-hungry device in the household, with unreliably delivered power from a coal-fired plant hardly makes sense any longer. Not surprisingly, the initial investment in a solar water heater (about Rs 18,000 for a 100 liter unit) pays for itself in less than 5 years, even without any government subsidies. There are now several companies that make and sell solar heaters, so there is no reason why the government should not mandate their use and force geyser manufacturers out of business!

But water heating is just one application of solar thermal technology. Another example is a solar-powered Stirling engine, which may make the conversion of solar power to electricity much more cost-effective. One major advantage of this method is its hybridizability. In other words, since the Stirling engine needs only an external heat source to run it, one can easily imagine a hybrid solution where the device works on solar power during the day and some other fuel source (such as biogas) during the night. This addresses one of the primary disadvantages of solar PV technology, which is that it works only when the sun is shining. Moreover, since heat is the energy source for Stirling engines, using concentrators will help improve their efficiency by increasing the heat input per unit area.

There are several other applications of solar thermal technology such as ice making, air conditioning, refrigeration, and water distillation. In this article, a few of these examples, which are currently being investigated in our laboratory at the Indian Institute of Science, will be considered in detail.

2. Water purifier/distiller

One of the simplest uses of solar thermal energy is a water distiller. This is not technology-intensive as it uses solar heat to evaporate water, and has a cold zone where the vapor condenses to form pure liquid. Many applications come to mind immediately – making brackish water potable, reusing waste water from washing and bathing, or desalinating salt water from the sea. The collected water is distilled and hence does not need to be treated further for organic or inorganic contaminants that might pass through other water purification methods such as reverse osmosis.

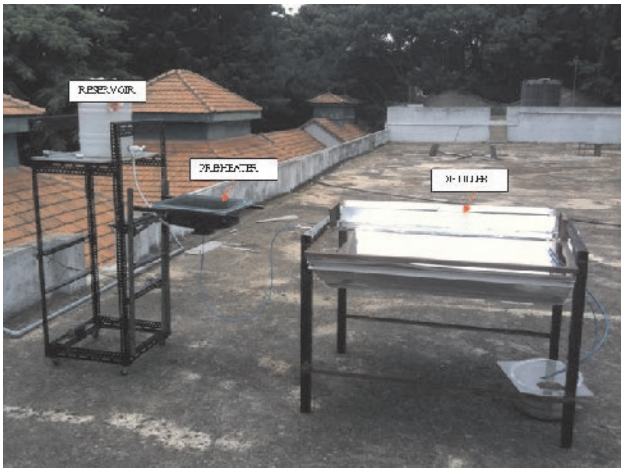
A typical solar-water distiller developed in our laboratory is shown in Fig. 1. The collector is a parabolic trough of area 0.9 m^2, and about 500 W of solar thermal power is collected. This is concentrated on to a 50-mm diameter semi-circular tube which contains impure water. The impure water evaporates and the vapor condenses along the sides of an aluminium hat covering the tube, which is kept cold using a water jacket. The pure water is collected on both sides of the central tube. The system produces about 3 liters of distilled water in 4 hours of operation. A large reservoir constantly supplies the impure water into the tube so there is no manual intervention necessary. Between the reservoir and the distiller assembly is a small tank that maintains the water level and serves as a pre-heater. The collector parabola is oriented in an east-west direction, so it does not need to track the sun. The only adjustment necessary is for seasonal variation of the sun along the north-south axis, which needs to be done once a week. The total cost of the laboratory prototype, at retail market rates for the components, is less than Rs 5,000. Mass-production methods will reduce this cost significantly.

3. Stirling engine

The Stirling engine is a simple external-combustion engine that can achieve efficiencies close to the ideal Carnot engine [2]. Though the idea of Stirling engines is more than 200 years old, they have started receiving renewed interest in recent times because the energy source can be renewable and quite flexible — solar, geothermal, biogas, etc.

The basic design of the Stirling engine is a heat engine that works a power piston by moving gas from a hot region (causing the piston to expand) to a cold region (causing the piston to contract). Heat energy is transported in and out of the engine through the sealed chamber walls, so that the working gas inside remains as a single fluid. One of the advantages of Stirling engines over other external-combustion engines (e.g., steam engines) is that the lower working pressure leads to fewer failures (such as cylinder bursts in steam engines). The contribution of Rev. Stirling to the design of these engines, and the reason for associating his name with them, is the addition of a *regenerator* inside the main chamber where the heat to be lost

Figure 1: Photograph of a home-built solar water distiller set up on the roof of the Physics department building.

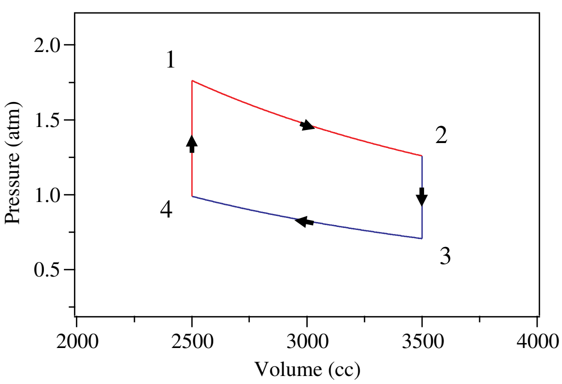


by the gas during its movement to the cold region is temporarily stored and regained when the air comes back to the hot region. In other words, the regenerator acts as an internal capacitor which reduces the heat that has to be lost on the cold side, and thereby increases the overall efficiency of the engine.

The ideal Stirling cycle is shown in pressure-volume space in Fig. 2. It consists of the following four thermodynamic processes:

1. *Isothermal expansion, 1 to 2*. The working gas is mainly in contact with the hot surface (expansion space), and is maintained at a high temperature so that it undergoes near-isothermal expansion by absorbing heat from the hot source.
2. *Isovolumetric or Isochoric (constant volume) heat removal, 2 to 3*. The gas is passed through the regenerator, where it cools by transferring heat to the regenerator for use in the next cycle.
3. *Isothermal Compression, 3 to 4*. The gas is mainly in contact with the cold surface (compression space), and is maintained at a low temperature so that it undergoes near-isothermal compression by rejecting heat to the cold sink.
4. *Isovolumetric or Isochoric (constant volume) heat addition, 4 to 1*. The gas passes back through the regenerator where it recovers much of the heat transferred in step 2, heating up on its way to the expansion space.

Figure 2: The ideal Stirling cycle in pressure–volume space. The 4 processes in the cycle are explained in the text.

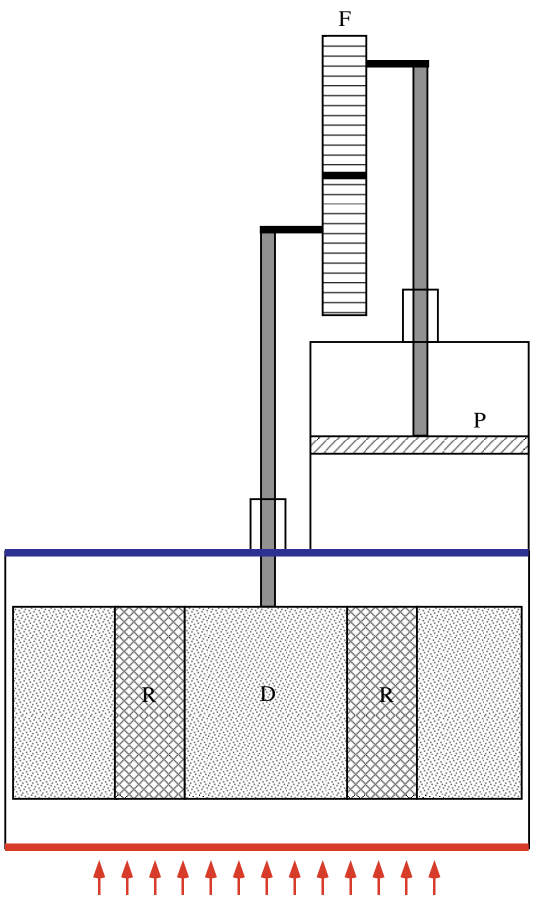


The thermal efficiency of the ideal Stirling engine equals that of the hypothetical Carnot cycle, i.e. the highest efficiency attainable by any heat engine. However, real-world issues due to limitations of convective heat transfer and viscous flow (friction) reduce the efficiency of actual engines. There are also practical limitations imposed by the non-ideal nature of the working gas and its finite thermal conductivity. Ideally, the regenerator should be infinitely efficient at transferring heat and should add no extra "dead" volume, both of which are not realizable in practice. Thus, a good rule of thumb is that the real Stirling engine will operate at about 50% of the Carnot efficiency. Though the overall efficiency can be improved by going to a higher hot-side temperature (implying higher Carnot efficiency), the materials used in the construction of the engine should be able to handle this higher temperature.

There are three basic designs for the Stirling engine – Alpha, Beta, and Gamma. The *alpha* engine has two power pistons, one on the hot side and one on the cold side. There is a tube connecting these two regions, with the regenerator inside. The two pistons are 90° out-of-phase, so that, at any given instant of time, the greater part of the gas is either in contact with the hot surface or with the cold surface. The main problem with this design is the requirement of a hot moving seal for the power piston on the hot side. The *beta* design avoids this problem by having a single power piston on the cold side. A loose-fitting *displacer* piston acts to shuttle the gas between the hot and cold regions, but does not extract any work. This design has a single engine chamber housing both the displacer and the power pistons, with the regenerator placed between the hot and cold regions. The displacer piston is slaved to the power piston with a 90° phase lag. The third design is the *gamma* engine. This is just a beta engine modified to have a separate chamber for the power piston, but in a way that allows the gas to flow freely between the two chambers. This is mechanically a simpler design since the power piston chamber can be designed and optimized independently. We have therefore chosen this design for our studies.

The gamma engine designed in our laboratory is shown schematically in Fig. 3. It consists of a main stainless steel chamber with 300 mm diameter and 170 mm height. The hot surface is on the bottom. For testing purposes, the bottom is heated on a gas burner, but in actual use the energy source will be solar power or biogas. The hot surface is heated to a temperature of about 300 °C. The cold side is a water-cooled aluminium plate mounted on top of the main chamber. The cold surface temperature is about 50 °C. The displacer is made of rock-wool insulation and has a clearance of a few mm from the chamber wall. The regenerator is made of aluminium wire mesh and designed to be part of the displacer, as shown in the figure. The power piston sits in a separate cylinder of diameter 125 mm placed on top of the cold plate. The linear motions of the piston and the displacer are converted to rotary motion using crank mechanisms. They are both connected to a flywheel that helps in keeping the motion uniform over the entire cycle. With a 40 mm stroke of the displacer and an 80 mm stroke of the piston, the flywheel rotates (with no external load) at 300 rpm. The mechanical power measured by braking the shaft is 4 W.

Figure 3: Schematic of the gamma-type Stirling engine designed in our laboratory. The hot side on the bottom is heated on a gas burner and the cold side on top is water cooled. Figure key: D – displacer, R – regenerator, P – power piston, F – flywheel.



We are in the process of improving our engine design to increase the output power to about 100 W. The standard ways to increase power are (i) to pressurize the engine to several times atmospheric pressure, thereby using a larger amount of gas to do the work, or (ii) to use a gas such as helium, which has 5 times the thermal conductivity of air. But we believe that a 100 W engine with air at 1 atm pressure can be designed with some effort. A 300 W, 1 atm, air engine was developed at Saitama University in Japan more than a decade ago [3]. While 100 W is not a large enough figure for an on-grid supply of electricity, we feel that this is enough for many useful off-grid applications such as lighting for rural households.

The Stirling engine has several advantages over the more common internal combustion engines. In particular, it is less complex because it does not require valves and timing. It is also less susceptible to wear and tear because the fuel/combustion is external to the engine chamber. However, there are no standardized designs to facilitate mass production, and heat transfer to the fluid in the engine is a difficult design parameter. Therefore commercially available Stirling engines have been expensive. Our goal is to build low-cost systems through creative selection of indigenous materials and components. We believe that this approach will result in innovative, yet economically viable systems, appropriate for developing countries like India.

4. Air Conditioning and Refrigeration

Air conditioning (AC) is one of the major consumers of electrical energy in many parts of the world. In the developed world, more than 40% of the electrical energy used by the domestic sector is for air conditioning, and in many developing countries this number is higher than 30%. The trend is only increasing. Most air conditioning systems in use today are vapor-compression systems that draw on grid electricity. This impacts the environment in two ways. First, many of the common methods of electricity generation have some kind of negative impact, by emissions of carbon-, sulphur- or nitrogen-dioxide (fossil-fuel plants), radioactive waste (nuclear plants), or polluted rivers and destroyed waterfalls (hydropower). Second, the refrigerants used in vapor-compression systems also have a negative impact on the environment. CFC and HCFC gases (known under the trade name Freon) are patently harmful to the ozone layer. These and HFC refrigerants are also well-known greenhouse gases.

Solar air conditioning [4] offers great promise in reducing the demand for electricity and the stress on the environment, while catering to the burgeoning demand for air conditioning in the developing world. Using heat to produce cooling might sound like an oxymoron, but the following sections will help illustrate the science behind it.

4.1. *Vapor-absorption chilling*

Absorption chillers differ from the more prevalent vapor-compression chillers in that the cooling effect is driven by thermal energy rather than mechanical energy. Both kinds of systems use a low-temperature refrigerant that takes away heat when it evaporates, thus providing a cooling effect. To complete the cycle, this gas must be condensed back into a liquid, and this is where the systems differ. Rather than rely on an electrically-driven *compressor* to increase the pressure of the gas before condensing it into the liquid phase, vapor-absorption systems use a *generator* to thermally increase the gas pressure before condensing it into liquid form. A solar AC is one that uses solar energy to supply heat to the generator through a solar-collector assembly that captures the energy.

The absorption cycle is shown in Fig. 4. The system uses two fluids: one a refrigerant (usually water) and the other an absorbent (usually ammonia NH_3, or lithium bromide LiBr). The high affinity of the refrigerant for the absorbent causes the refrigerant to boil at a lower temperature and pressure than it otherwise would, thus making the cycle work. LiBr–water systems are used for larger tonnage in process applications, while NH_3–water systems are more common in lower tonnage applications and for lower temperature requirements. Either cycle would require electrical energy for "parasitic" needs such as pumps, fans, and controls.

The LiBr-water cycle is described below.

1. *Generator:* The dilute LiBr solution (which might be pre-heated) is moved into the generator where heat from hot water or steam is transferred into the solution, causing it to boil off (desorb); the refrigerant (water) vapor is sent into the condenser, leaving behind a concentrated LiBr solution.
2. *Condenser:* The refrigerant vapor condenses into a high pressure liquid at the bottom of the condenser and rejects heat to the surrounding water.
3. *Evaporator:* The liquid refrigerant is throttled by an expansion valve onto an evaporator tube bundle. Here it evaporates in the extreme low pressure environment, creating the desired cooling effect that chills the water carried through the evaporator tube bundle. (The hygroscopic action of the LiBr in the absorber, which is connected to the evaporator, creates a near vacuum allowing the refrigerant to evaporate at a very low temperature).
4. *Absorber:* As the refrigerant vapor migrates to the absorber, the strong LiBr solution from the generator is sprayed on top of the absorber tube bundle. The LiBr draws out the refrigerant into a solution that collects at the bottom of the absorber. This process also creates the vacuum in the evaporator and generates heat, which is removed by water circulating through the absorber tube bundle. The dilute LiBr-water solution is pumped back by the solution pump to the generator (and pre-heated using reject heat from the system) to restart the cycle.

Absorption systems may be *direct-fired* (e.g., using gas) or *indirect-fired* (e.g., using waste or reject heat that is a byproduct of another industrial process), and may employ a *single-effect* or *multiple-effect* cycle. A single-effect system rejects to the environment the heat that is generated in the absorption process. Multiple-effect absorption systems capture some of this energy to generate more refrigerant vapor, by using additional generators that are paired with a single

Figure 4: Schematic of a vapor-absorption chiller.

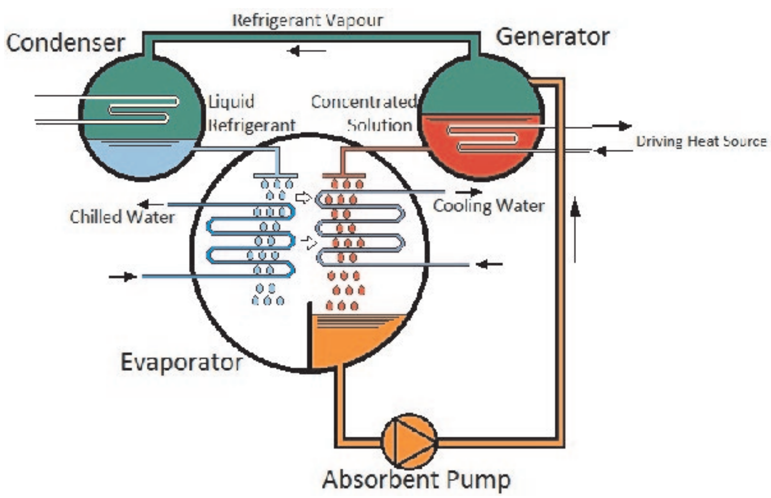
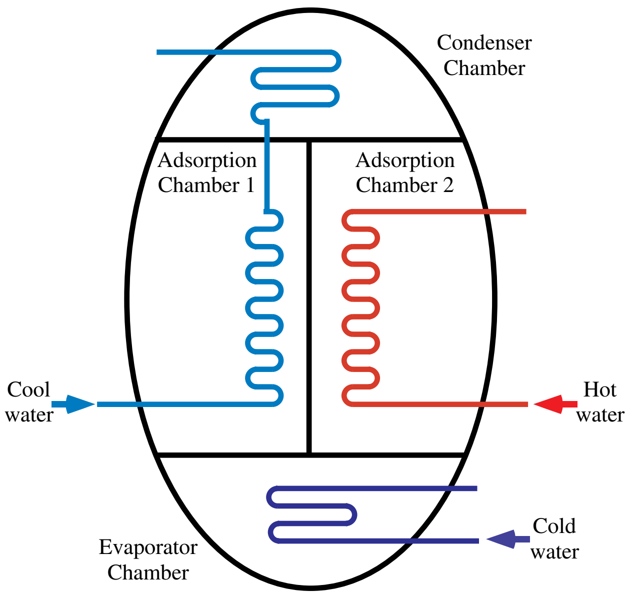


Figure 5: Schematic of an adsorption chiller.



condenser, absorber, and evaporator. For example, a double-effect system uses the external heat source to power a high temperature generator, while the heat of condensation of the vapor from the high temperature generator is recycled to power the low temperature generator – with the goal of extracting as much vapor as possible from the solution. The more vapor generated per unit of heat input, the greater the cooling effect, and the higher the overall operating efficiency.

The efficiencies of absorption chillers are described in terms of coefficient of performance (COP), which is defined as the ratio between the refrigeration effect and the net heat input, taken in comparable terms. Single-effect absorption chillers have a COP between 0.6 and 0.8, out of an ideal of 1.0. A direct comparison with electric vapor-compression systems may show them as less efficient, but this masks the losses in generation and transmission of electricity. This does not apply to absorption systems that run on waste heat or renewable energy. The term "Resource COP" accounts for this source-to-site loss factor, and when this is factored in, absorption systems have comparable or even superior efficiencies.

4.2. *Adsorption Chiller*

Adsorption systems use solid sorption materials instead of liquid solutions. One is a refrigerant (often water) and the other a sorbent, usually silica-gel. Zeolith/water is another combination. They are similar to absorption systems in that they also use heat energy, rather than mechanical energy, to achieve compression of the refrigerant. Heat energy is supplied through hot water that could come off a solar thermal installation, or through industrial waste heat.

A schematic of an adsorption system is shown in Fig. 5. It has two adsorption chambers flanked by a condenser and evaporator at either end. All four chambers operate at nearly full vacuum to allow for evaporation at low temperatures. The refrigerant (water) vaporizes in the evaporator under low pressure, creating the desired cooling effect upon the surrounding water jacket. The water vapor enters adsorption chamber 1 where it is adsorbed into the silica gel. This heat generating process is cooled by an external water-cooled jacket. The fully adsorbed silica gel is desorbed, or forced to lose water, through heat exchange with hot water (solar heated) circulated through adsorption chamber 2. This vapor moves up into the condenser where it gives off heat and condenses into liquid that is returned to the evaporator.

Some of the disadvantages of adsorption systems are the long adsorption–desorption times and small cooling capacity per unit mass of adsorbent. Continuous adsorption cycles can address the issues of intermittent operation cycles, where cooling and heating can be simultaneous using more than one adsorber bed. Designing better adsorber beds and better treatment of adsorbents to improve adsorption capacity are some areas of ongoing research and improvement. Many solar-adsorption systems also reject to the environment the heat from the condenser and adsorption beds. Recycling this wasted energy for pre-heating and other purposes, like hot water generation, will further improve the overall efficiency. Dual-purpose solar continuous-adsorption systems, for refrigeration and hot-water generation, appear to be one of the promising avenues ahead. In addition, an intermittent cycle system can be used as an ice-maker, with the heating part of the cycle taking place during the day and the cooling part during the night. The ice can be harvested the next morning for use in ice-pack refrigerators.

4.3. *Hybrid systems*

There are two types of hybrid systems designed to reduce the electrical load of conventional air conditioners. The first is an absorption system that is installed in parallel with an electric vapor-compression system. Such systems are usually deployed to take advantage of differing electricity rates, based on time-of-use. The electric chiller runs during the off-peak hours of lowest cost, while the absorption system works during the hours of peak rates. The idea is to eliminate the high incremental costs of peak-hour electricity imposed by many utilities worldwide.

Another type of hybrid system is a solar-assisted air conditioning system that uses solar energy to assist a compressor by using thermal compression in conjunction with vapor compression. In this case, a specialized solar collector is placed between the compressor and the condenser coils. The collector superheats the refrigerant above what the compressor would be able to achieve under electric power. This increases the ability of the gas to change back into a liquid more quickly and reduces the energy requirement on the compressor. The gas condenses more easily, in an earlier stage of the condenser than otherwise, and is almost a liquid (rather than a saturated gas) by the time it reaches the expansion device in the evaporator. This allows the liquid refrigerant to be more efficient at absorbing heat, thereby improving cooling. The system is often similar to a common split-AC design, where the compressor and condenser are located in an outdoor unit and the evaporator is situated in an indoor unit that can be electronically controlled and adjusted. The addition is a solar thermal collector mounted on the roof.

5. Conclusion

In conclusion, we have seen that tapping solar thermal energy might provide a cost-effective solution to the present environmental crisis faced by our planet. We have described in detail the three technologies that we are working on in the laboratory. We have selected these based on their appropriateness for the needs of developing countries like India. The first is a solar-powered water distiller, which is both easy to build and has a low cost. It will help address the issue of providing safe drinking water in an environmentally-friendly manner. The second is a solar-powered Stirling engine, which may prove to be an efficient way of converting solar energy to electricity (e.g., to charge a battery) or to motion (e.g., to drive a pump or a fan). The battery can then provide much needed lighting during the night in rural off-the-grid households. The third application is solar-powered or solar-assisted cooling. Both absorption and adsorption chillers may help in addressing the energy-intensive air conditioning and refrigeration needs of the world. In addition, an adsorption-cycle ice maker can provide simple refrigeration without any need for electricity by producing ice over a one-day cycle.

Acknowledgments

The authors gratefully acknowledge the help of Akhilesh, Chetan, Harish, Hemanth, Raghuveer, Sharief, and Siddharth, with the experiments. The authors also thank Dr. R. R. Sonde of Thermax, India, for useful discussions.

Received 25 October 2010.

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