Experiments With Solar Hot Air Collectors

Ralf Seip

The solar collector installed outside the basement workshop.

I have been interested in alternative energy sources since about 1985. At that time, I was experimenting with solar-powered radios and battery chargers. Today, about 15 percent of the energy my family consumes is generated by a 240 watt photovoltaic system, with larger generating capability expected in the future. The latest addition to our solar energy system is a solar hot air collector.

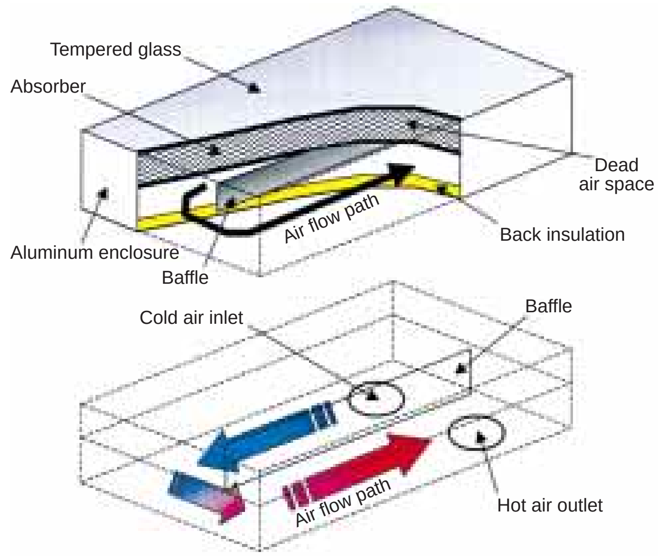
For years I have been wanting to experiment with a solar heating system to reduce winter heating bills, and a solar hot air collector seemed the right place to start. These collectors are simple because air is the heat transfer medium. This means that the glycol loops, heat exchangers, valves, and pumps commonly found in liquid collector systems are not needed.

The application of solar hot air collectors is slightly different than liquid collectors. Air collectors are typically used for space heating, while liquid collectors are typically used for water heating. Through the proper use of heat exchangers, however, either system can be used to heat water or air.

Collector Basics

Solar hot air collectors are simple and reliable. Cold air is drawn through the collector with a blower. It is heated as it comes in contact with an absorber plate exposed to the sun, and then returned as hot air for heating applications. The collector contains no moving parts, and is typically constructed of an aluminum frame, insulation on the back and sides, and tempered glass on the front. A black absorber plate is located between the glass and the back insulation.

Figure 1: Basic solar hot air collector and operation.



These collectors are of the single glazing/dead air space design, since some air is trapped between the absorber and the glazing. The absorber warms up when exposed to the sun, and some of this heat is transferred to the air between the absorber and the back insulation. Some absorber plates have dimples that create turbulence in the air, to better transfer heat to the air. Figure 1 shows a typical solar hot air collector of the single glazing/dead air space design.

System Description

The solar hot air collector system described in this article is used to warm up my basement workshop. Eventually, it will be used to warm up the living room located above the workshop through the existing forced air furnace ductwork. For the initial tests and evaluation period, I wanted to keep modifications to the house and existing ducts to a minimum.

The system consists of a 1.2 by 2.4 m (4 x 8 ft) Sun Aire solar hot air collector sold by AAA Solar, several insulated 15 cm (6 in) diameter ducts used to transport air to the collector and back to the workshop, a low-power fan to force the air through the collector, and a temperature control circuit that turns the fan on and off as required.

Collector

The collector faces south and is mounted on a simple but strong stainless steel structure, at an angle of 55 degrees. I assembled the structure out of 1.2 and 1.5 m (4 and 5 ft) lengths of slotted steel bars, available at local hardware stores. As a rule of thumb, to maximize the heating capability of the collectors in the winter months, they should be tilted to an angle equal to your location's latitude plus 15 degrees.

The structure is located close to the basement wall and is weighted down by 110 kg (243 lbs) of gravel. This temporary arrangement has survived wind gusts over 110 kilometers per hour (70+ mph). Eventually, I hope to anchor the structure properly to the concrete slab on which it now sits. The photographs show the collector and mounting structure. The collector is of the single glazing/dead air space design described previously, and its absorber plate is dimpled for higher transfer efficiency.

Fan & Ductwork

An insulated (R-4) flexible duct about 3 m (10 ft) in length transports cold basement air from the cold air inlet to the collector. I used aluminum tape on all duct joints to ensure an airtight seal. A small 14 watt AC muffin fan is able to push about 1.7 m^3 per minute (60 cf/min) of air through the collector. The collector heats the air, which returns to the basement through a similar duct and exits through the hot air outlet.

Muffin-type fans are typically not well suited for pushing large volumes of air through long ducts. Squirrel cage blowers (centrifugal blowers) are better at this task. The lowest power squirrel cage blower I found consumed 45 watts. The muffin fan seems to be adequate for this installation, as will be seen from the measured temperature increases and computed efficiencies later.

To keep house modifications to a minimum, the ducts enter and leave the basement through a window. I built a custom plywood/insulating foam/plywood panel that fits inside the open window frame and holds the ducts, fan, and circuit in place. I fastened the panel to the window frame with screws and used foam weatherstripping to prevent cold air from seeping into the house.

It is important to locate the hot air outlet above the cold air inlet, and the collector surface below both. This way, the fan is not working against the natural tendency of warm air to rise. It also transfers the colder workshop air to the collector first, and warmer workshop air does not get cooled down by the colder collector at night. The result is a more efficient system that does not require the addition of a backdraft damper to prevent nighttime cooling through the collector.

If such an arrangement of collector and duct exits is not possible (such as in rooftop mounted systems), a

Back of the solar collector showing part of the support structure, as well as insulated cold and hot air ducts.

Insulated duct adapter panel, showing the fan in front of the cold air inlet (lower right), the hot air outlet (upper left), the temperature control circuit, and the dual thermometer.

backdraft damper will be needed to prevent nighttime cooling. Notice the similarities between these guidelines and those for thermosyphon liquid-based collector systems. AAA Solar Supply's *Solar Design Catalog* has excellent installation guidelines for rooftop-mounted solar air collectors.

Temperature Control
The fan is controlled by a simple temperature control circuit. I designed and built the circuit over a weekend, and it is described in detail in the sidebar. For the circuit to operate properly, one thermistor needs to be exposed to the cold workshop temperature (close to the cold air inlet), and the second thermistor needs to be placed inside the hot air outlet.

System Cost

Item	*Cost*
4 x 8 ft solar hot air collector	$415
Shipping and crating charges	$185
Mounting structure	$80
Ducts, adaptors, and insulated panel	$40
Temperature control circuit and fan	$25
Dual-monitoring thermometer	$15
Total	$760

Warm air rising from the collector through the duct will reach the second thermistor, increasing its temperature. Once its temperature is approximately 2°C (3.6°F) warmer than that of the cold air thermistor, the fan is activated automatically and the system starts pushing warm air into the room.

To collect the temperature information presented in this article, I installed a digital thermometer capable of measuring two temperatures simultaneously. I used this thermometer to measure the workshop temperature and the temperature of the warm air coming from the collector after it had travelled through the 3 m (10 ft) return duct. The thermometer and temperature circuit can be seen in the photo to the left.

System Cost
The main components of the system and their cost are listed in the table. Notice that the total system cost is similar to that of about two typical photovoltaic modules. Sadly, crating and shipping charges are a large percentage of the overall system cost.

System Performance
To best illustrate the operation and effectiveness of the solar hot air collector, I measured typical air inlet, air outlet, and outside air temperatures for several days in intervals of 30 minutes. This allowed me to compute the power and energy produced by my system, as well as its efficiency. It also allowed me to give quantified answers to questions such as "Does the basement feel warmer now?" and "Does the system pay for itself?" It is interesting to see that solar energy does definitely impact the bottom line.

To perform these computations, it is necessary to introduce several physical constants, system-specific constants, and the underlying simple heat energy equation.

Physical Constants & Conversions
Specific heat of air (constant pressure, and 27 to 47°C):

$$c = 1.007 \text{ kJ / kg °K}$$

Density of air (at 760 mm mercury, and 40°C or 104°F):

$$d = 1.122 \text{ kg} / \text{m}^3$$

Average solar radiation S:

$$S = 1 \text{ kW} / \text{m}^2$$

Kilowatt-hour to kilojoule conversion:

$$1 \text{ kWh} = 3.6 \times 10^3 \text{ kJ}$$

System-Specific Constants

Collector area A:

$$A = 2.9 \text{ m}^2 = 31 \text{ ft}^2$$

Air volume v moved by fan:

$$v = 60 \text{ ft}^3 / \text{minute}$$
$$= 1.7 \text{ m}^3 / \text{minute}$$
$$= 51 \text{ m}^3 / 30 \text{ minute}$$
$$= 102 \text{ m}^3 / \text{hour}$$

Air mass m moved by fan:

$$m = v \times d$$
$$= 57 \text{ kg} / 30 \text{ minutes}$$
$$= 114 \text{ kg} / \text{hour}$$

Heat Equation

Heat transfer rate H (result in kilojoules per hour):

$$H = m \times c \times (T_2 - T_1)$$

Heat transfer rate H (result in kW):

$$H = m \times c \times (T_2 - T_1) \div (3.6 \times 10^3)$$

Instantaneous efficiency e:

$$e = (H_{actual} \div H_{max}) \times 100\%$$
$$= [H \div (S \times A)] \times 100\%$$

For this particular system, we use 2.9 kW for S x A, which corresponds to the area of the solar collector times the solar insolation. This is for times of maximum solar insolation only.

$$e = (H \div 2.9 \text{ kW}) \times 100\%$$

Notice that the heat flow rate H (typically expressed in joules per hour) is easily converted to kilowatts. The heat flow rate H depends on the specific heat c of the material (air in this case), the rate of mass transfer m through the collector, and the temperature difference (T_2-T_1) across the collector in degrees Kelvin (°K). Note that the calculation of H is a power (not energy) calculation.

Figure 2: Cold air inlet, hot air outlet, and ambient temperatures during a sunny winter day.

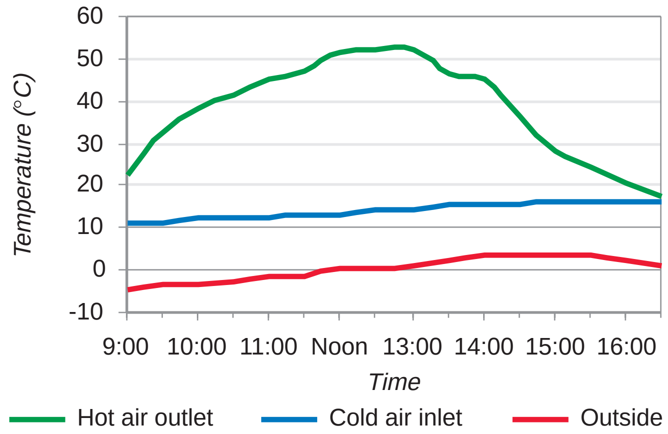
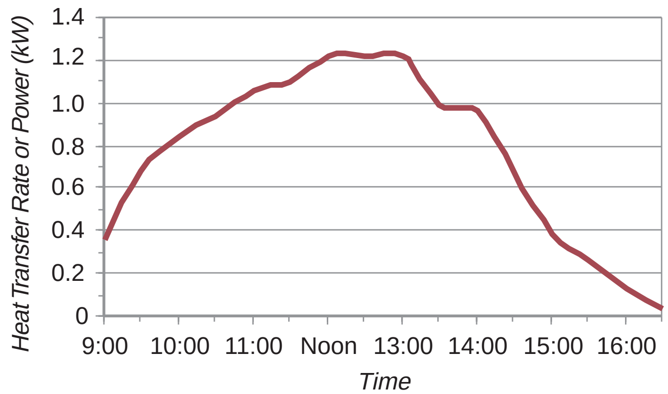


Figure 3: Energy produced during a sunny winter day.



By measuring both collector inlet air temperature (T_1) and collector outlet air temperature (T_2) and using the above equation, the instantaneous power added by the sun through the collector to the air in the basement can be computed. The energy (kWh) can then be calculated by integrating the instantaneous power (kW) over time, in hours.

Figures 2–5 show the measured temperatures and produced power for two days during the 1999 Michigan winter. Figures 2 and 3 show the measured temperatures and computed power during a nice, sunny winter day (outside temperatures of -5 to 3°C, or 23 to 37°F). The total energy produced by the solar collector during the day was approximately 6 kWh, raising the workshop temperature by about 5°C (9°F).

Figures 4 and 5 show the measured temperatures and computed power during a cloudy, overcast winter day (outside temperatures of -7 to -1°C, or 19 to 30°F). The total energy produced this day was approximately 1.9 kWh, raising the workshop temperature by about 2°C (3.6°F).

Figure 4: Cold air inlet, hot air outlet, and ambient temperatures during an overcast winter day.

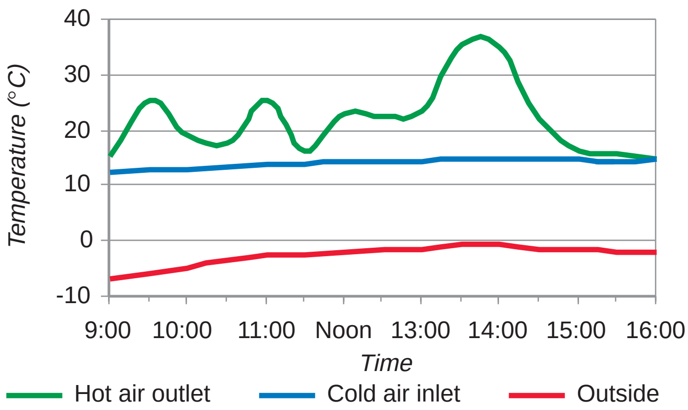
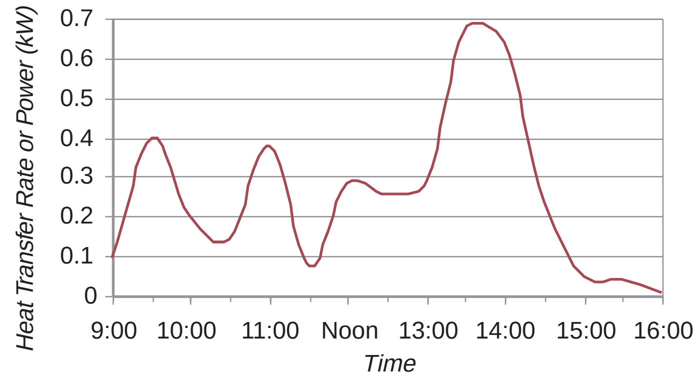


Figure 5: Energy produced during an overcast winter day.



Fan Control Circuit

Temperature control of the system is provided by a simple differential temperature sensing circuit. This circuit automatically turns the air circulation fan on when the temperature of the air at the collector output is warmer than the temperature of the air at the collector input, and leaves the fan off otherwise. The temperature difference needs to be about 2°C (3.6°F) and can be calibrated through R1 (see schematic). The fan is turned on and off through a 30 mA maximum coil current relay.

This setup ensures that the fan and collector are only used to add heat to a room, not to remove it. Two thermistors are used for this purpose: one mounted close to the cold air collector input (TR1), and the other mounted inside the collector hot air output (TR2). The schematic of this circuit is shown below. All the parts to build it can be found at stores such as Radio Shack.

The circuit consumes approximately 24 mW in the *off* mode, and 720 mW in the *on* mode, and operates at 24 V. The AC fan consumes 14 W when operating. The relay could be used to control a DC-powered fan, if available. Simply replace the AC power source and the AC fan with a corresponding DC power source (battery) and a DC-powered fan.

Calibrate the circuit by adjusting R1 until the fan turns on when a warm finger is placed on TR2. Then it will typically turn the air circulation fan on during a sunny winter day around 9:00 AM, and turn it off around 4:30 PM. The circuit also turns the fan off and back on during and after prolonged cloud covers on overcast days. This happens when the temperature of the air at the collector output drops below the temperature of the air at the collector input plus 2°C (3.6°F). This happened at around 11:30 AM on the overcast day detailed in Figure 4.

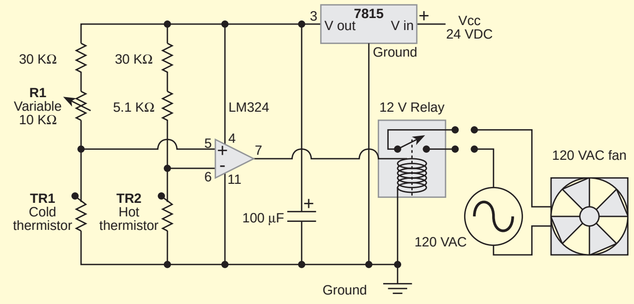
Since the hot air outlet is about 50 cm (20 in) above the cold air inlet, a large enough temperature difference is present as soon as the sun begins to warm the collector, resulting in proper and automatic circuit operation. Such circuits are commercially available for liquid-based collector systems, and are called differential controls. In those systems, a circulating pump is typically controlled by the circuit.

A possible improvement to the circuit would be to add an automatic absolute temperature switch. This switch would prevent the circuit from switching on when no heating is required because the room is already at the desired temperature. This feature would be helpful during warmer spring and summer days, when adding heat to a room would not be desirable. The present circuit needs to be manually unplugged at the beginning of spring and reconnected in the fall to achieve this operation.

Temperature Control Circuit Parts List

Qty	*Description*
1	7815 voltage regulator
1	LM324 operational amplifier
2	Thermistors (Radio Shack part number 275-248)
1	12 VDC relay, 30 mA max. coil current (Radio Shack part number 271-110)
2	30 KΩ resistors
1	5.1 KΩ resistor
1	10 KΩ adjustable potentiometer
1	100 µF capacitor
1	120 VAC muffin fan (or DC-powered, depending on the available power source)
1	Small circuit board
	Miscellaneous parts: wires, solder, connectors, etc.

Temperature Control Circuit Schematic



During the winter months, the basement workshop temperature hovers around 11°C (52°F). The installed collector is able to raise this temperature as much as 6°C (11°F) during sunny days. This results in a comfortable working temperature around 17°C (63°F).

The largest temperature difference measured to date between the air inlet and air outlet has been 45°C (81°F). This corresponds to a maximum efficiency of approximately 50 percent (114 kg/h x 1.007 kJ/kg °K x 45°K ÷ 3.6 x 10^3 kWh/J ÷ 2.9 kW x 100% = 50%). Even though this efficiency is respectable, the single glazing/dead air space collectors are supposed to be between 60 and 70 percent efficient. Currently, I am attributing the loss in efficiency to the long flexible ducts connecting the collector to the basement.

Typical temperature differences between the air inlet and air outlet are below 40°C (72°F). This seems to indicate that the fan that I am currently using in my system is pushing close to the right amount of air through the collector. But the maximum measured efficiency of this system at 50 percent is still below the 60 to 70 percent specified for these solar collectors. So I will be conducting measurements with higher-capacity fans and blowers to determine their effect on system efficiency. These experiments will have to wait until next winter.

Rewards

It is satisfying to feel the hot air streaming out of the hot air outlet during collector operation. It is also rewarding to be able to work in a warmer workshop, knowing that it is heated by the sun. I am assuming that we are lowering house heating costs indirectly by some small amount through workshop heating.

From a purely financial viewpoint, the savings are small. We currently heat our home with propane during the winter. One gallon of propane contains 90,000 BTUs, approximately 70 percent of which can be extracted in the form of heat. Furthermore, it takes approximately 3,410 BTUs to generate 1 kWh of energy. This means that 1 gallon (3.8 l) of propane can generate approximately 18 kWh of energy.

Remember that the described system generated 6 kWh during a nice sunny winter day, or the equivalent of 1/3 of a gallon (1.3 l) of propane. At current propane prices of US$0.80 per gallon, this amounts to savings of 27 cents per day in the best case! Such calculations are somewhat depressing, but it is important to keep the bigger picture in mind. This picture includes less reliance on fossil fuels, a reduction in atmospheric emissions, a positive feeling of independence, and great hands-on learning experiences!

My system is able to increase the basement workshop temperature as much as 6°C (11°F) during sunny winter days. It was easy to install, and coupled with the automatic temperature/fan control circuit, operates unattended. I measured its operating efficiency to be approximately 50 percent. While realized savings in heating fuel costs are small, I enjoyed installing this system and am happy knowing that my family has decreased its reliance on fossil fuels just a bit more. I am now tempted to explore the capabilities of solar hot air collectors for water heating, but that will have to wait!

Access

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