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Fabrication and Performance Evaluation of a Solar-Powered Thermoelectric (Peltier) Refrigeration System for Off-Grid Cooling

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Abstract— Vapour-compression refrigeration accounts for a large share of building electricity demand and depends on halogenated working fluids whose ozone-depletion and global-warming potentials have driven successive rounds of regulation. Thermoelectric cooling offers an alternative that uses no refrigerant, no compressor and no moving parts other than fans. This paper reports the design, fabrication and testing of a solar-powered thermoelectric refrigeration unit built around Peltier modules, a finned heat sink with forced-convection fans, a photovoltaic panel, a solar charge controller, a storage battery and an insulated expanded-polystyrene cabinet. The thermodynamic basis of the device — the Seebeck, Peltier and Thomson effects and the interaction between Peltier pumping, Joule dissipation and Fourier back-conduction that fixes the optimum operating current — is set out, and the resulting expressions for cooling capacity and coefficient of performance are given. In operation the system drove the cold-side cabinet temperature down to 9 °C while the hot-side sink reached 85 °C, the cold-side temperature being held at set point by a thermostatic controller and the battery kept within its charge window by the solar charge controller so that operation continued through periods of low irradiance. The unit is compact, silent, free of refrigerant and mechanically rugged, and is well suited to small-capacity off-grid duties such as vaccine and medicine storage, though its coefficient of performance remains below that of a comparable vapour-compression unit.
Keywords— *Thermoelectric refrigeration; Peltier module; photovoltaic; solar charge controller; coefficient of performance; off-grid cooling*

1. INTRODUCTION

Energy resources are being drawn down faster than they are replaced, and electricity and water are both limited in much of the developing world. At the same time the growth in cooling demand has made refrigeration one of the fastest-rising components of building energy use. The conventional answer to that demand — the vapour-compression cycle — carries two liabilities. It requires a compressor, a rotating machine with bearings, seals and lubricant that constitutes the principal wear item and the principal noise source in any domestic refrigerator. And it requires a halogenated working fluid, the family of substances whose ozone-depleting and greenhouse effects have made them the subject of the Montreal Protocol and its successors.

Thermoelectric refrigeration removes both liabilities at once. A thermoelectric module is a solid-state device: passing direct current through a junction of two dissimilar semiconductors transports heat from one face to the other, so that one face cools and the other heats. There is no working fluid to leak, no compressor to fail, and no greenhouse gas involved in the cooling process itself. The device is silent, it can be built far more compactly than any compressor system, it is insensitive to orientation and vibration, and its cooling output is controlled simply by varying the current — a linear and immediate control that a compressor cycle cannot match.

Pairing a thermoelectric cooler with a photovoltaic source is a natural combination, because both are direct-current devices. A photovoltaic panel produces DC; a Peltier module consumes DC; the inverter that a solar-powered vapour-compression system would need disappears, and with it the conversion losses. The system described here exploits this match. A photovoltaic panel charges a battery through a solar charge controller, the battery supplies the Peltier modules and their heat-sink fans, and a thermostatic controller regulates the cabinet temperature. The battery decouples cooling from irradiance, so the cabinet holds temperature overnight and through cloud cover.

The objective of the work was to design and fabricate such a system from commercially available components, to establish the cold-side temperature it can reach and the hot-side temperature it must reject at, and to assess its coefficient of performance and its suitability for small off-grid cooling duties.

2. THERMOELECTRIC THEORY

2.1 The three thermoelectric effects

Three related effects govern the device. The *Seebeck effect*, discovered in 1821, is the appearance of a potential difference across a junction of two dissimilar conductors held at different temperatures; the open-circuit voltage is $V = \alpha(T_1 - T_2)$, where α is the Seebeck coefficient of the pair. This is the effect exploited in thermocouples and in thermoelectric generators.

The *Peltier effect*, described by Jean Charles Athanase Peltier in 1834, is its converse: when current I is driven through such a junction, heat is absorbed at one junction and liberated at the other at a rate $Q = \pi I$, where $\pi = \alpha T$ is the Peltier coefficient. Reversing the current reverses the direction of heat transport, so a single module can cool or heat according to the polarity applied. This is the effect on which the present device depends.

The *Thomson effect* is the reversible absorption or liberation of heat when current flows along a single conductor in which a temperature gradient exists, at a rate per unit length equal to $\tau I\, dT/dx$, where τ is the Thomson coefficient. It is small compared with the Peltier term in practical modules and is normally neglected in first-order design.

2.2 Module construction

A practical module is not a single junction but an array. Pellets of heavily doped bismuth telluride — n-type, doped to give an excess of electrons, and p-type, doped to give an excess of holes — are arranged in pairs and connected electrically in series and thermally in parallel between two ceramic plates. Current passing through an n-type pellet carries heat in the direction of electron flow; through a p-type pellet it carries heat in the opposite direction relative to conventional current. By alternating n and p pellets and routing the current through them in series, every pellet pumps heat in the same direction across the module, from the cold plate to the hot plate. A typical module contains 127 such couples, operates at up to about 15 V and 6 A, and can sustain a temperature difference of the order of 60–70 K between its faces at zero load.

2.3 Cooling capacity and coefficient of performance

Three processes act simultaneously on the cold face. Peltier pumping removes heat at a rate $\alpha I T_c$. Joule dissipation in the pellets generates heat I^2R, of which approximately half flows back to the cold face. Fourier conduction through the pellets returns heat at a rate $K \Delta T$, where K is the thermal conductance of the module and $\Delta T = T_h - T_c$. The net cooling capacity is therefore

$$Q_c = \alpha I T_c - \tfrac{1}{2} I^2R - K (T_h - T_c)$$

and the electrical power drawn is

$$W = \alpha I (T_h - T_c) + I^2R$$

so that the coefficient of performance is

$$COP = Q_c / W$$

Two consequences follow directly, and both govern the design. First, because the Joule term grows as I^2 while the Peltier term grows only as I, there is an optimum current beyond which additional current heats the cold face faster than it cools it; running a module at its maximum rated current maximises cooling capacity but not COP. Second, because the Fourier term is proportional to ΔT, cooling capacity falls as the hot side gets hotter. Heat rejection is therefore the controlling design problem in any thermoelectric refrigerator: every kelvin saved on the hot side is returned directly as cooling capacity on the cold side. This is why the present system commits a finned heat sink and forced-convection fans to the hot face, and why fan power is treated as part of the system load rather than as an accessory.

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2.4 Thermoelectric materials and the figure of merit

The performance a module can reach is set by its material through the dimensionless figure of merit $ZT = \alpha^2\sigma T/k$, in which α is the Seebeck coefficient, σ the electrical conductivity, k the thermal conductivity and T the absolute temperature. A good thermoelectric material must therefore combine a large Seebeck coefficient, so that a large voltage is developed per kelvin; a high electrical conductivity, so that the Joule dissipation term stays small; and a low thermal conductivity, so that the Fourier back-conduction term stays small. The three requirements conflict, because in ordinary conductors electrical and thermal conductivity rise together, and this conflict is the reason thermoelectric coolers have improved slowly. Heavily doped semiconductors offer the best compromise. Bismuth telluride alloys, which have ZT close to unity near room temperature, remain the standard material for cooling duties; lead telluride and silicon germanium serve at higher temperatures and are used mainly in generation rather than in refrigeration.

3. SYSTEM DESCRIPTION AND FABRICATION

3.1 Components

The system was assembled from the components listed in Table 1. The Peltier modules are mounted between the cabinet wall and the hot-side heat sink, with thermal interface compound on both faces to minimise contact resistance. The heat sink is an extruded aluminium finned block; two axial fans force air through the fin stack and are powered from the same battery bus. The cabinet is an expanded-polystyrene (thermocol) box, chosen for its low thermal conductivity, low cost and low mass. The photovoltaic panel charges the battery through the solar charge controller, which prevents overcharge and deep discharge and thereby sets the useful life of the battery. A thermostatic temperature controller switches the module supply to hold the cabinet at set point.

Table 1. Principal components of the solar thermoelectric refrigeration system.

Component	Function in the system
Peltier thermoelectric module	Solid-state heat pump; transfers heat from cabinet to hot-side sink under DC excitation
Finned aluminium heat sink	Rejects hot-side heat to ambient; controls ΔT and hence cooling capacity
Heat sink fans	Force convection over the fin stack to lower hot-side temperature
Photovoltaic panel	Primary DC energy source
Solar charge controller	Regulates panel-to-battery charging; prevents overcharge and deep discharge
Storage battery	Decouples cooling from irradiance; sustains operation at night and under cloud
Temperature controller	Thermostatic control of cabinet temperature at set point
Insulated cabinet (EPS)	Refrigerated volume; limits heat ingress from ambient

3.2 Assembly

Fabrication followed a fixed sequence. The cabinet was cut and an aperture formed for the module assembly. The cold-side plate was bonded to an internal spreader so that the cooling effect is distributed over the cabinet wall rather than concentrated at the module footprint. The modules were sandwiched between the internal spreader and the external heat sink, with interface compound applied and the stack clamped to a uniform pressure — uneven clamping is the most common cause of premature module failure, since the ceramic plates crack readily under point loads. The fans were mounted to the sink and wired to the battery bus. The panel, charge controller, battery and temperature controller were then wired according to the circuit layout, with the controller in series

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with the module supply. Finally the mounting structure was fabricated to carry the panel at an appropriate tilt and to support the cabinet clear of the ground.

3.3 Circuit and control architecture

The electrical circuit is arranged as a single DC bus. The photovoltaic panel feeds the solar charge controller, which regulates the charging of the battery and presents a stabilised bus to the loads. Two loads are taken from that bus: the heat-sink fans, connected permanently so that airflow is maintained whenever the system is live, and the Peltier modules, connected through the thermostatic temperature controller. Placing the fans ahead of the thermostat rather than behind it is deliberate. When the thermostat opens at set point the modules stop pumping heat, but the sink is still hot and the cabinet wall is still cold; if the fans were to stop at the same instant the residual heat in the sink would conduct back through the unpowered modules into the cabinet, undoing part of the cooling just achieved. Keeping the fans running through the off period allows the sink to shed that stored heat to ambient instead.

The modules themselves are wired in a series–parallel arrangement matched to the bus voltage, so that each module sees a voltage close to the value at which its cooling capacity is greatest without exceeding its maximum rated current. Because cooling capacity varies non-linearly with current and passes through a maximum, running fewer modules nearer their optimum point gives more cooling for the same bus power than running more modules lightly loaded. Interface compound is applied at every ceramic-to-metal joint; contact resistance at these joints appears directly as an increase in the effective hot-side temperature and is one of the commonest causes of disappointing performance in thermoelectric assemblies.

3.4 Operating procedure

The panel is oriented for maximum incidence and the charge controller is energised first, so that the battery is under regulation before any load is applied. The fans are started before the modules; running a module with a stalled fan drives the hot side up rapidly and can exceed the module’s maximum operating temperature within minutes. The temperature controller set point is then entered and the module supply enabled. Cabinet temperature is logged against elapsed time until steady state is reached.

4. RESULTS AND DISCUSSION

4.1 Temperatures achieved

In operation the cabinet was cooled to 9 °C, measured at the cold-side plate, against a hot-side sink temperature that rose to 85 °C. The temperature difference sustained across the module in the steady state is therefore of the order of 76 K, which is close to the maximum ΔT that a single-stage bismuth telluride module can develop and confirms that the device was operating near the limit of its capability rather than in a lightly loaded regime.

The hot-side figure is the significant one for design purposes. At 85 °C the sink is running only modestly below the 90–100 °C at which the solder joints and ceramic substrates of a standard module begin to be at risk, and every kelvin of that temperature appears in the Fourier back-conduction term $K(Th - Tc)$ as lost cooling capacity. A larger heat sink, higher fan flow rate, or the substitution of a liquid-cooled cold plate would each reduce Th and would return cooling capacity and COP together. This is the single most productive avenue for improvement of the present unit.

Table 2. Summary of measured performance.

Quantity	Value	Remarks
Cold-side (cabinet) temperature	9 °C	Steady state, thermostatically held
Hot-side (sink) temperature	85 °C	Forced convection over finned sink
Temperature difference, ΔT	≈ 76 K	Near single-stage module limit
Pull-down time to set point	— (to be inserted)	From logged cooling curve
Steady-state input power	— (to be inserted)	Modules plus fans

Quantity	Value	Remarks
Cooling capacity, Qc	— (to be inserted)	From cabinet heat balance
Coefficient of performance	— (to be inserted)	Qc / W at steady state

4.2 Coefficient of performance

The coefficient of performance of a single-stage thermoelectric cooler operating at a temperature difference of this magnitude is characteristically low — well below unity, and substantially below the value a vapour-compression unit of comparable duty would achieve. That comparison, however, is not the one that decides whether the technology is appropriate. A vapour-compression system of the same cooling capacity would need a compressor, a condenser, an evaporator, a capillary or expansion device and a refrigerant charge, together with an inverter to run it from a DC source; it would be larger, heavier, noisier, orientation-sensitive and far less tolerant of vibration and of intermittent supply. Where the duty is small, the load is intermittent, the supply is a battery, and reliability with no maintenance matters more than efficiency, the thermoelectric system is the better engineering answer despite its lower COP.

4.3 Applications, advantages and limitations

The advantages that follow from the solid-state construction are substantial. The unit has no moving parts other than fans, so it is rugged and long-lived; it is silent; it can be made far more compact than any compressor system; it uses no refrigerant and therefore contributes nothing to ozone depletion or to direct greenhouse emissions; its output is continuously and instantly controllable by current; and reversing the supply polarity converts it from a cooler to a heater without any change of hardware. Set against these, the limitations are equally clear: the coefficient of performance is low, cooling capacity per module is small, the cold side cannot be driven far below ambient without multi-stage cascading, and the hot side must be provided with a heat rejection path that is generously sized and reliably ventilated.

The combination of characteristics suits particular duties rather than general refrigeration. Small-volume medical and vaccine storage in off-grid clinics, portable coolers, cooling of electronic instruments and laser diodes, laboratory sample chillers, and dehumidifiers all play to the technology's strengths. Larger domestic and commercial refrigeration remains the province of the vapour-compression cycle.

4.4 Cost and system-level considerations

The capital cost of the unit is dominated not by the thermoelectric modules, which are inexpensive in the sizes used here, but by the photovoltaic panel and the storage battery. That distribution has a design consequence. Because the panel and battery must be sized to the electrical load, and because the electrical load of a thermoelectric cooler is high relative to its cooling output, an improvement in COP propagates directly into a smaller panel and a smaller battery, and therefore into a disproportionate reduction in system cost. Every measure that lowers the hot-side temperature — a larger sink, better fan selection, shading the sink from direct insolation, mounting it where natural convection assists rather than opposes the fan flow — pays for itself twice over, once in cooling capacity and once in the size of the photovoltaic system needed to sustain it.

A second system-level point concerns the battery. The charge controller protects it from overcharge and from deep discharge, and in doing so it determines the battery's service life, which in a unit of this kind is the shortest-lived component and the main recurring cost. Operating the cooler on a duty cycle governed by the thermostat rather than continuously, and accepting a slightly wider cabinet temperature band, reduces the depth of discharge and extends that life appreciably at very little cost in stored-product temperature.

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5. CONCLUSIONS

- A solar-powered thermoelectric refrigeration unit was designed and fabricated using Peltier modules, a finned heat sink with forced-convection fans, a photovoltaic panel, a solar charge controller, a storage battery, a thermostatic controller and an expanded-polystyrene cabinet.
- The unit cooled its cabinet to 9 °C against a hot-side sink temperature of 85 °C, a sustained temperature difference of approximately 76 K, close to the practical limit of a single-stage bismuth telluride module.
- The system operates without any refrigerant and without a compressor, eliminating both the ozone-depletion and direct greenhouse contributions of the working fluid and the principal wear and noise source of the conventional cycle.
- Use of a solar charge controller allowed the battery to buffer the photovoltaic supply, so that cooling continued through periods of low irradiance and the battery was protected from overcharge and deep discharge.
- Hot-side thermal management is the controlling constraint on performance. Because cooling capacity falls in direct proportion to the hot-to-cold temperature difference, reducing the 85 °C sink temperature is the most effective single improvement available.

Future work should log the cabinet cooling curve and the steady-state electrical input so that cooling capacity and coefficient of performance can be reported quantitatively; should evaluate an enlarged or liquid-cooled hot-side sink; and should examine two-stage cascading for applications requiring cabinet temperatures below the freezing point.

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