2006

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Potential Benefits of Thermoelectric Elements used with Air-Cooled Heat Exchangers

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ABSTRACT

This paper investigates the application of thermoelectric devices to enhance the performance of conventional vapor compression based air conditioning systems. Thermoelectric devices are capable of converting electrical energy into thermal heat-pumping at a very high efficiency. In this paper, a validated air-cooled heat exchanger simulation tool is used to study the effect of adding thermoelectric devices between the fins and tubes to enhance heat transfer. Further, a validated system simulation tool is used to study the effect of using a thermoelectric device to increase the refrigerant subcooling at the outlet of a condenser. The study is conducted for several refrigeration and air-conditioning applications with various refrigerants.

1. INTRODUCTION

Recent advances in thermoelectric technology have fostered their usage in a wide range of applications such as telecommunications devices, home appliances, photonics and defense and space. Thermoelectric (TE) devices are solid-state devices i.e. they have no moving parts thus providing quiet operation and enhanced reliability. TE devices or modules are based on the phenomenon of conversion of thermal energy (temperature gradient) into electrical energy, referred to as Seebeck effect and the reverse effect i.e. conversion of electrical energy into thermal energy or temperature gradient referred to as the Peltier effect. It is seen from literature that the process of converting electrical energy into a temperature gradient is very efficient. For example, the coefficient of performance to acquire a 5K temperature lift is approximately 7. This paper investigates the potential applications of TE modules in air-cooled heat exchanger design wherein the TE modules can be used to enhance part of the coils to compensate for air flow maldistribution and/or the temperature difference between the fin and the air. A numerical simulation is performed to investigate the improvements and conclusions drawn.

2. THERMOELECTRICS

This section provides an introduction to the thermoelectric phenomenon followed by an overview of applications from literature that are relevant to the refrigeration and air-conditioning technology.

2.1 Thermoelectric Phenomenon

The thermoelectric phenomenon can be classified mainly into three types viz. the Seebeck effect (discovered in 1821), the Peltier effect (discovered in 1834), and the Thompson (Lord Kelvin) effect (discovered in 1854). Consider two junctions A and B connecting two dissimilar conductors (M_a and M_b) as shown in Figure 1a. Suppose that the two junctions A and B are maintained at different temperatures, i.e. one junction is cooled and the other is heated, then there is an electric potential generated between points C and D. This is the Seebeck effect. The reverse is also possible. Suppose that the two junctions A and B are brought to the same
temperature and then an electric potential is applied between points C and D by means of a battery (some current will flow around the circuit), then cooling effect is produced at one junction and heating effect is produced at the other junction. This effect is the Peltier effect. The heating and cooling effect can be reversed with respect to the junctions by reversing the direction of the current. It is to be noted that this heating effect is distinct from the Joule resistance heating which is a function of dimensions. If a temperature difference exists between any two points of a current carrying conductor, then heat is either evolved or absorbed depending upon the material. This is the Thomson effect. Furthermore, the direction of this heat transfer can be reversed if the direction of the current is reversed. The Peltier and the Thomson effect are dependent upon the flow of the current through the circuit thus formed. The three thermoelectric phenomena are related by the Kelvin relationships (Goldsmid, 1964) which are assumed to be valid for all thermoelectric materials.

![Diagram of electric circuit and thermoelectric refrigerator](image)

A simple thermoelectric refrigerator (Goldsmid, 1964) is shown in Figure 1b. When an electric potential is applied at the two junctions in the figure a temperature differential is developed between the ‘hot’ and the ‘cold’ junctions. Typically a thermoelectric cooling system is developed by assembly of several thermoelectric modules. A thermoelectric module consists of a number of pieces of thermoelectric material referred to as elements that are alternately connected to form an electrical circuit of n-type and p-type materials. This module typically is a rigid assembly of conductors sandwiched between ceramic plates.

2.2 TE Applications

Several applications of TE devices can be found in the literature. The greatest application of the Seebeck effect is thermocouples. Peltier effect application includes thermoelectric devices for refrigeration and power generation. Rowe (1995) provides a comprehensive overview of the TE phenomenon, devices, material properties and applications. Thermoelectric devices have been used for power generation as well as refrigeration applications. Applications include weather stations, navigational aids, sub-sea operations. Fossil-fueled thermoelectric generators have also been used. The application of TE modules for refrigeration (Rowe, 1995) include the following: (a) cooling of electronic components such as infrared detectors, laser diodes, charge-couple devices etc. (b) small refrigerators for boats, mobile homes, portable coolers etc. (c) Instruments such as dew point sensors, 0°C reference source, blood coagulators etc.
The heat load for single stage thermoelectric modules can range from a few milli-Watt to 100W depending upon the operating temperatures. Example temperature differential for single stage modules is -34°C cold/27°C hot and that for multistage modules is -139°C cold/ 53°C hot (Rowe, 1995).

2.3 TE Refrigeration Considerations
Some of the advantages of TE modules are: (a) they are off-the-shelf components (b) no moving parts (c) quite operation (d) reliable (e) better temperature control and (f) they do not use any refrigerant fluids. For capacities under 25W conventional mechanical refrigeration systems cannot compete with TE modules. But for large scale cooling the efficiency of vapor compression systems is hard to match up. Other practical considerations for thermoelectric refrigeration include (a) thermal - operating temperatures as TE module performance can degrade when continuously operated at high temperatures (b) environmental issues such as moisture, mechanical stresses and (c) installation challenges. Interestingly, the most reliable environment to operate a TE module is vacuum.

While much of the research (Goldsmid, 1999) focuses on inventing new materials, improving efficiency of thermoelectric devices, improvement of existing materials, in this paper we investigate the use of thermoelectric devices for improving the performance and efficiency of conventional refrigeration and air-conditioning devices. Two applications are discussed in the following sections, in which a TE module can be used to assist in improving the capacity and efficiency of conventional refrigeration systems. The modeling used in this study is greatly simplified, since the objective is to obtain a first-order estimate of capacity improvements, but all the significant parameters have been accounted for.

3. AIR-COOLED HEAT EXCHANGER ENHANCEMENT

3.1 Application
In this application, the effect of using a TE device to enhance the heat transfer in a air-cooled heat exchanger is studied. While it is possible to build an air-cooled heat exchanger that exclusively uses TE devices or elements, the focus of this study is to use a TE device in a part of a coil to investigate the improvement potential. A schematic of a TE enhanced air-cooled heat exchanger is shown in Figure 2. A half cross section of a tube-fin heat exchanger is shown in Figure 2 along with a TE element placed between the fins and the tube. The power supply connections for the TE element are not shown for simplicity.

![Figure 2: Schematic of a TE enhanced tube-fin heat exchanger](image)

3.2 Simulation & Discussion
A heat-transfer between air and a single fin-tube structure with a thermoelectric element in between is modeled and simulated using ANSYS. A fixed value for heat transfer coefficient is used on the tube side. The results are shown in Figure 3. The details of the simulation are not discussed for conciseness. Figure 3a shows the performance of the TE element in terms of power input to the lifted fin temperature.

From Figure 3 it can be seen that with relatively low power consumption the TE element is able to provide temperature lifts of more than 10K. Comparing the heat transferred per fin with the power consumption, it is possible to calculate a coefficient of performance for the TE device. From Figures 3a and 3b, an optimal value of temperature lift can be chosen for a given application.

Based on the results shown in Figure 3, the following possible enhancements to an existing air-cooled (tube-fin evaporator or condenser coil for example) heat exchanger can be foreseen:
Multiple TE devices can be installed on a number of tubes in a given coil. This will lead to enhanced heat load for the coil thereby resulting in size reduction. A qualitative comparison of such cost savings with the cost of installing a TE device is not yet performed.

Consider the case when there is significant air-maldistribution on the coil face. This can be due to placement of the fan with respect to coil or due to other geometry or mounting restrictions. Simulating such conditions using modeling tools (Jiang et al., 2002) shows that there can be a reduction of more than 10% in the heat capacity, when the velocity profile is changed from uniform to a proportional (to coil height). For such applications, optimal placement of TE enhanced tubes in the coil can compensate for the air-maldistribution effects.

A low capacity TE cooler or heater can be used to assist in improving the heat duty of a conventional air-cooled heat exchanger. This concept is further explored at the system level in the next section.

Figure 3: Simulation results - effect of TE device power consumption

4. SYSTEM ENHANCEMENT

4.1 Application
A second possible enhancement is discussed in this section. It is accepted that a thermoelectric system at full power cannot have an efficiency that approaches the one of a compression system, but a thermoelectric system has much more flexible cooling power than a vapor compression cycle and the TE system can have an adjustable power supply. Instead of building a full-fledged TE cooling system, we explore the possibility of using a TE to assist in improving the performance of an existing vapor compression system.

The underlying concept is to make use of the TE elements temperature lift capability to enhance the outlet subcooling of a condenser. Based on a simple analysis of a vapor compression cycle, it can be seen that increasing the condenser outlet sub-cooling can result in increased cooling capacity and hence increased coefficient of performance (COP). A CO₂ system is chosen for comparison. The baseline system is modeled using an in-house vapor compression system model (Richardson et al., 2002). The baseline system was modeled as a conventional four component vapor compression system, which corresponds to the case with no temperature lift through the TE cooler.

4.2 Case Study 1: Simulation & Discussion
The system simulation is performed using VapCyc (Richardson et al., 2002, 2004). VapCyc is a component based simulation tool for modeling vapor compression systems. Each component in the system is modeled independently and the system is ‘assembled’ in VapCyc. The heat exchanger models used in the current simulation were simple three-zone moving-boundary models available in VapCyc. The TE device is modeled as an additional component.
that provides a given temperature lift. The known temperature lift is applied to the refrigerant at the condenser outlet. In other words, the refrigerant outlet temperature from the TE device is equal to the refrigerant temperature at condenser outlet plus the applied temperature lift (negative in this case). This approach gives the theoretical maximum performance of the TE enhanced vapor compression system. The refrigerant inlet state into the TE device is assumed to be single phase. For a CO₂ cycle, this is insured since the refrigerant at the condenser outlet is supercritical.

The TE cooler was subdivided into multiple segments to obtain the average TE COP. The total temperature lift of the TE cooler was distributed over 100 segments and varied linearly from the inlet to the outlet. Since the power consumption of a TE-enhanced fin increases with temperature lift, this approach allowed for the total power consumption of the TE cooler to be more precisely modeled. Since the temperature of the refrigerant is changing as it flows through the TE cooler, the segment close to the inlet will require the lowest temperature lift and the last segment will require the highest temperature lift.

The baseline case was the one in which there was 0°C temperature lift in the TE subcooler. The optimum discharge pressure was determined for the cycle and was held constant for the all other simulations. The evaporating pressure was adjusted to maintain a constant superheat. The parametric study was performed with different values of temperature lift across the TE device. The results are shown in Figures 5a and 5b.

It can be observed from Figures 5a and 5b that a theoretical maximum improvement of 16.2% in COP and a corresponding increase of 20% in capacity can be achieved. At a temperature lift of 22K, the power consumption of TE cooler compensates the additional capacity, resulting in a COP equal to the baseline case. However, from this plot we can see that the capacity has increased by approximately 35% without having to increase the size of the heat exchangers in the system.
4.3 Case Study 2 – Simulation & Discussion
In this case study the cycle with the TE cooler was optimized. The optimization was carried out as follows: the optimum discharge pressure for each value of temperature lift was determined and for each run, the evaporating pressure was adjusted to maintain a constant superheat. The corresponding vapor compression cycles for Case Studies 1 and 2 are shown in a P-h chart in Figure 7. Corresponding to the optimal discharge pressure, the COP can be increased by a maximum of 38% while the corresponding capacity increase is in the range of 20%.

![Figure 6: System simulation results for Case Study 2](image1)

![Figure 7: Cycles on P-h chart for (a) Case Study-1 and (b) Case Study-2](image2)

4.4 Case Study 3
In this study, the effect of using a TE subcooler at the condenser outlet for different cooling applications was evaluated. Three different refrigerants viz. R134a, R410A and R404A, were evaluated for air-conditioning application (Tevap = 4.4°C, Tcond = 46.1°C) . Two refrigerants viz. R410A and R404A were evaluated for low temperature refrigeration (Tevap = -23°C, Tcond = 46.1°C) application.

This case study was analyzed prior to determining the TE power consumption as a function a temperature lift, and thus the TE power consumption was neglected. For each system modeled in Case Study -3, the optimum system
subcooling (at the condenser outlet) was determined for each TE subcooler temperature lift and was used in determining the maximum theoretical benefit of the TE subcooler.

The results of Case Study -3 are shown in Figure 8. For comparison purposes, the results from Case Study -1 for CO₂ are also shown in Figure 8. A steady improvement in COP is observed as the temperature lift in the TE subcooler is increased, however, the transcritical CO₂ system has the highest performance increase despite the fact that the TE power consumption was included.

![Figure 8: Effect of using TE subcooler for different applications](image)

5. CONCLUSIONS

A first order analysis of the performance benefits of using a TE module with a conventional vapor compression cycle is conducted. It can be seen from the numerical simulation, that a significant potential exists for thermoelectric devices to assist in improving the performance and the efficiency of conventional refrigeration and air-conditioning devices. The experiments show that when a TE device is used as a dedicated subcooler at the condenser outlet, a 16.2% increase in system COP and over 20% increase in cooling capacity can be achieved. This also means when designing a system for a given capacity and application, it is possible to significantly reduce the cost of the system. In order to solidify the predictions from these calculations, the heat exchanger models need to account for the TE temperature list and the actual TE effectiveness, followed by an experimental evaluation. The economic aspects of coupling a thermoelectric device with a conventional vapor compression system remain to be discussed.

NOMENCLATURE

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<td>COP</td>
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<td>TE</td>
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International Refrigeration and Air Conditioning Conference at Purdue, July 17-20, 2006
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