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Thermal-Fluids Laboratory Project: First and Second Law Analysis of a Thermoelectric Cooler*

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A thermal engineering laboratory/design project is presented. The objective of the project was to construct an experiment to measure the performance of a heat pump based on first and second law principles. A thermoelectric device drove the heat pump. A student lab group selected, analyzed, designed, planned, built, instrumented, and tested this experiment. The students calculated the coefficient of performance of the system and compared it to the Carnot COP. In addition they calculated a second law efficiency based on entropy generation. The aim of this senior level laboratory project was not only to strengthen their understanding of principles, but also to initiate critical thinking on their own. The experiment was a success, because they applied knowledge from their undergraduate education: thermodynamics, heat transfer, fluid mechanics, electric circuits, instrumentation and design principles.

NOMENCLATURE

COP	coefficient of performance
L	length
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate, (kW)
Re	Reynolds number
$\dot{S}$	entropy transfer rate, (kW/K)
T	temperature, (K)
$\dot{W}$	work transfer rate, (kJ)

Subscripts

gen	generation
H	high
L	low
net	net

INTRODUCTION

EDUCATORS in mechanical engineering have investigated the notion that lab-based teaching places large demands on department resources, i.e. time, space, equipment and faculty, with small added value to the students learning [1, 2]. These authors identify the problem as the lack of critical thinking in lab-based learning. Their suggestion for the success of lab-based teaching is to provide challenging open-ended projects. This author agrees with their suggestion and has developed a course which provides a framework for critical thinking.

The course ME 378 at The University of Michigan-Dearborn, is a senior level required mechanical engineering course. In this course the students review thermodynamic, fluid mechanics and heat transfer principles by performing a variety of thermal-fluid lab experiments. During the last part of the course, the lab groups are to demonstrate a principle through planning, designing, constructing and testing an experiment. Afterwards the students present the project to the class.

This paper presents one project performed in this course. The students chose to demonstrate the thermal performance of a heat pump. With the suggestion of the instructor the students chose to demonstrate the heat pump performance through the use of a thermoelectric cooler (TEC). In addition the instructor suggested that not only should they investigate the first law efficiency, but also a second law efficiency. This experiment was an excellent lab project for the students since it was relatively easy to construct, it demonstrated a thermodynamic principle, and most importantly required critical thinking by the students.

In the following sections, this paper develops the theory that the students used. Afterwards their design is presented with the results. Finally a conclusion of the experiment's impact is provided.

THEORY

The thermoelectric cooler is a heat pump or can be considered as an entropy pump. Figure 1 shows the schematic of the heat pump and entropy pump.

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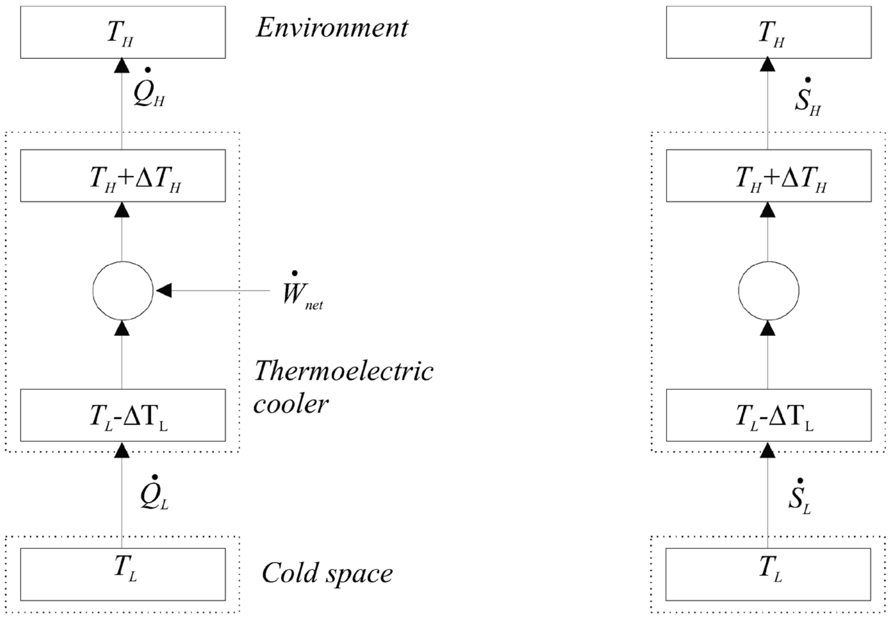

(1a) (1b)

Fig. 1. Schematic of (a) heat pump and (b) entropy pump.

The cycle energy balance on the heat pump is:

$$0 = \dot{Q}_L + \dot{W}_{net} - \dot{Q}_H \quad (1)$$

where $\dot{Q}_L$ is the refrigeration capacity, $\dot{W}_{net}$ is the net power input, and $\dot{Q}_H$ is the heat rejection. Introducing the first law efficiency of the heat pump in cooling mode, the coefficient of performance (COP), is:

$$COP = \frac{\dot{Q}_L}{\dot{W}_{net}} \quad (2)$$

An entropy balance on the entropy pump for the cycle is:

$$0 = \dot{S}_L + \dot{S}_{gen} - \dot{S}_H \quad (3)$$

where $\dot{S}_L$ is the entropic capacity, $\dot{S}_{gen}$ is the entropy generated, and $\dot{S}_H$ is the entropy rejection.

The entropic capacity and the entropy rejection are related to the heat transfers by:

$$\dot{S}_L + \frac{\dot{Q}_L}{T_L} \text{ and } \dot{S}_H = \frac{\dot{Q}_H}{T_H} \quad (4)$$

respectively. It can be shown that the entropy generation is related to the COP. Combining equations (1) to (4) the entropy generation is:

$$\frac{\dot{S}_{gen}}{\dot{S}_L} = \left(\frac{1}{COP} + 1\right)\frac{T_L}{T_H} - 1 \geq 0 \quad (5)$$

Note the second law constraint was added. The entropy generation ratio must be greater than or equal to zero. The entropy ratio is a second law efficiency parameter. It approaches zero as the performance improves. The COP for the given temperature reservoirs T_L and T_H is a maximum when the entropy generation is zero. Letting the entropy generation equal zero, the maximum COP is:

$$COP = \frac{T_L}{T_H - T_L} \quad (6)$$

that is known as the Carnot COP.

STUDENT DESIGN

In this section, a brief description of the design is given. They identified the heat pump's design constraints as the high and low temperatures that it operates between and the refrigeration capacity. They identified the room temperature, 20°C, as their high temperature reservoir. The low temperature reservoir was arbitrarily chosen to be the ice point of water, 0°C. Based upon an average TEC's capacity, the refrigeration capacity of 9 W was selected. With these design constraints, the students identified that the maximum COP, equation (6), was 13.7 and the minimum power requirement was 0.7 W.

The students learned about the thermoelectric device through a web search [3] as well as through the manufacturer's device selection literature [4]. The students had to determine the thermal resistances, ΔT_H and ΔT_L shown in Fig. 1, between the thermal reservoirs and the hot and cold faces of the TEC. The students selected equal temperature differences of 15°C. The TEC would have to

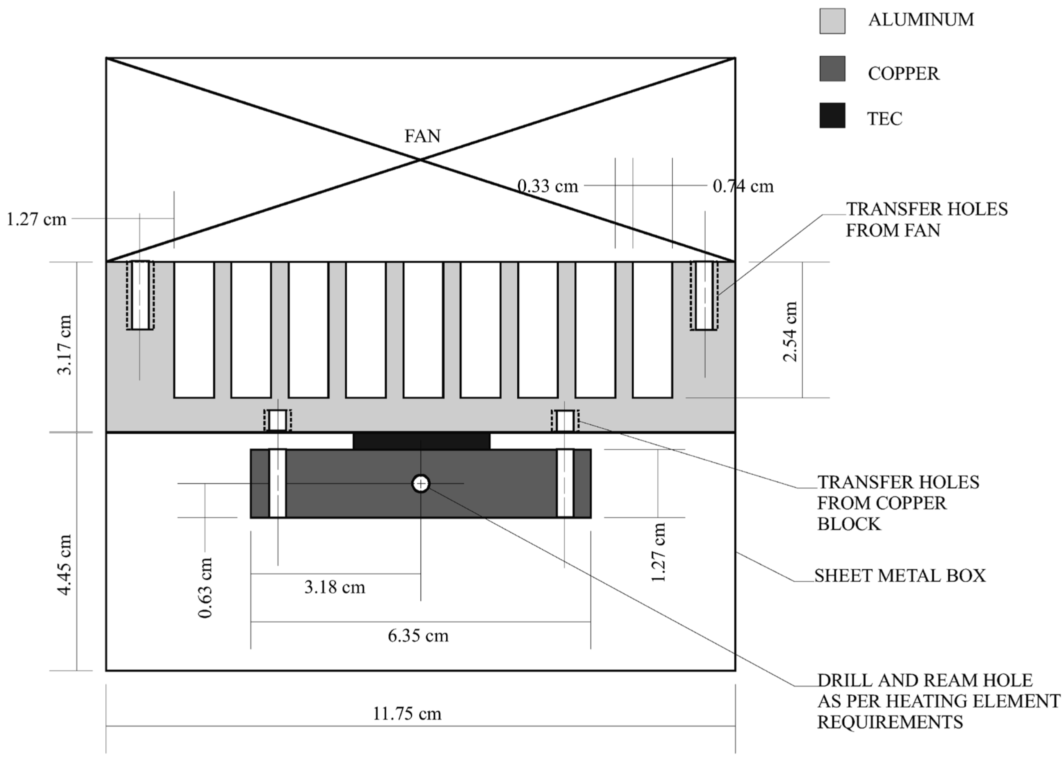

Fig. 2. Drawing of experimental apparatus.

provide 9 W of cooling with a temperature difference across the TEC of 50°C. Selecting a design between optimum (higher TEC cost and lower input power) and maximum (lower TEC cost and higher input power) operating conditions, the chosen TEC (catalogue number: CP 0.8-127-06L) required a voltage, current and power input of 14 V, 1.8 A, and 25.2 W. Based on the manufacturer's specifications, the predicted COP was expected to be 0.36, which is only 2.6% of Carnot. In this simple analysis the students' realized the thermal efficiency of the device. Originally the students had praised the device because of the simplicity and compactness, but now are aware of its low thermodynamic efficiency.

The next step in the design of the experiment was to determine the method to reject the thermal energy to the environment. They considered alternative cooling methods, and chose forced-air cooling because of the infinite supply and the availability of electricity. The heat exchanger was required to meet their design criterion of a maximum temperature difference of 15°C at the warm end of the device and reject 34.2 W of thermal energy. The students assumed a log mean temperature difference of 12°C to ultimately identify a flowrate of 0.003 kg/s. The thermal resistance was 0.4 K/W.

Estimation of the forced air convection heat transfer coefficient was made using an impingement correlation [5]:

$$Nu_L = 0.228 Re_L^{0.731} Pr^{1/3} \tag{7}$$

where $4000 < Re_L < 15000$, Nu is the Nusselt number, Re is the Reynolds number, L is the characteristic length of the plate, and Pr is the Prandtl number. The students determined that the required heat transfer surface area was 0.069 m^2. Based on this value, the heat exchanger design is shown in Fig. 2. In addition the rest of the apparatus is shown.

EXPERIMENTAL APPARATUS

Table 1 is a list of the equipment for constructing the apparatus in Fig. 2 and also to perform the experiment. There are associated costs with some of the equipment that most probably would be purchased even for a well-equipped lab. The other needed equipment is mostly likely to be found in a machine shop and laboratory. The copper block is the cold space to be cooled. The material was chosen because of its high thermal conductivity to insure uniform temperature. It was large enough to mate with the TEC and also to be fastened to the heat exchanger above. A small long hole was drilled in the block to insert a cartridge heater. The cartridge heater supplied the thermal heat load. A box made of sheet metal enclosed the copper block and TEC. The box was relatively airtight to reduce internal condensation. Fiberglass insulation was used inside to reduce heat losses to the surroundings.

As seen in Fig. 1 the TEC is sandwiched between the copper block and the aluminum heat exchanger. It is important to use thermal grease to obtain

Table 1. Equipment list

	Equipment	Cost [$]
1	Thermoelectric cooler Melcor cat. no. CP 0.8-127-06L	25
1	Cartridge heater Omega cat. no. CSS-01115/120V 15 W at 120V	27
1	AC axial fan 51 cfm; 5 in × 5 in	25
	Other needed equipment:	
1	Copper block $2\frac{1}{2}$ in × $2\frac{1}{2}$ in × $\frac{1}{2}$ in copper block	
1	Aluminum block $1\frac{1}{4}$ in × $4\frac{5}{8}$ in × $4\frac{5}{8}$ in aluminum block	
	Thin sheet metal	
	Thermal grease	
	Thermocouple wire	
1	DC power supply 0-30 V; 0-2 A	
2	Variac power supply 120 V	
1	16 Channel thermocouple meter	
1	Multimeter	
	Fiberglass insulation	

a good thermal contact between the TEC and the other surfaces. The sheet metal box is fastened to the bottom of the heat exchanger. The heat exchanger was tapped with four holes on the top to fasten the axial fan. The entire experiment was instrumented with thermocouples to measure copper block, aluminum and air temperatures. The DC power supplied to the TEC and the AC power supplied to the fan were measured to determine the net power input. The AC power supplied to the cartridge heater was measured to determine the refrigeration heat load. With these three measurements the COP of the device was calculated by equation (2). Measuring air and copper block temperatures allowed the students to calculate the Carnot COP, equation (6). The two Variacs were used to control the fan speed and the cartridge heater's power dissipation.

RESULTS

Given in Table 2 are the results of the steady-state operation based on the students' design and on the students' measurements. The design was originally supposed to provide 9 W of cooling with an electrical input, which includes the fan power as well as the TEC power of 43.2 W. The COP of the design was 0.21. Note the original COP design was 0.36, but that did include the additional power to supply the fan. The COP is only 1.5% of Carnot. Including the fan power makes the performance of the heat pump even less efficient. The measured capacity of the actual device provided only 5 W of cooling, a decrease in 44%. Its COP was 0.10 which was only 0.8% of Carnot COP. The reduction in the actual performance was initially surprising. The students investigated why it was less than expected. They finally attributed the loss in capacity to the conduction heat leak through the steel screws connecting the aluminum heat exchanger to the copper block. An estimate of the conduction heat transfer through the screws was 4.5 W, which was the correct order of magnitude.

The second law efficiencies were calculated for the design and the actual device. The design had a value of 4.4 and the actual device was approximately 9.7 assuming the conduction heat load of 4.5 W.

CONCLUSIONS

The lab experiment was a success because of the value it added to strengthening their understanding of learned principles, applying their engineering knowledge to understand new systems (the operation of the TEC), and the opportunity to practice their engineering skills.

The experiment was adequate for teaching purposes. The experiment was small and easy to construct in the limited amount of time the students had in a semester while taking a full load of senior level engineering courses. It was simple and clearly demonstrated the fundamental principle of a heat pump.

The construction of the experiment gave the students a sense of accomplishment. Much enjoyment was realized in the cooling of the system. Much amazement was expressed when they calculated the actual efficiency of the device and compared it to the ideal efficiency.

The instructor found the experiment to help reach the goal of lab-based teaching. The experiment definitely required critical thinking by the students.

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Table 2. Comparison of data with expected results

	Air Temp. [C]	Copper Temp. [C]	TEC Input Power [W]	Cartridge Input Power [W]	Fan Input Power [W]	COP	COP/COP_{Carnot} [%]	S_{gen}/S_L
Design	20	0	25.2	9	18	0.21	1.5	4.4
Experiment	21.8	1.6	25.2	5	23	0.10	0.8	9.7

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