Imperial Journal of Interdisciplinary Research (IJIR)
Vol-2, Issue-11, 2016
ISSN: 2454-1362, http://www.onlinejournal.in
Proceedings of RAASA'16" Chemnokrat-16"

Construction and Evaluation of Performance of Liquid Cooled Peltier Effect Refrigerator

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Abstract: *Temperature controlled environments are very crucial in many fields like biomedical laboratories, medical institutes, industrial environments and research and development. A thermoelectric cooler with an interior cooling volume of 0.01296m^3 (27cm x 20cm x 24cm) has been fabricated. The thermo electric cooler was equipped with on/off control which was found to be adequate to meet the required precision of +/- 0.25 degrees Celsius.*

Experiments were conducted with the hot side of the Peltier element being cooled by passing liquid over the surface. A temperature sensor with a GUI obtained from an open source installed inside in the cooling volume has been used to measure the variation of temperature within the test volume which in turn is used to evaluate the COP and efficiency of the Thermoelectric refrigerator device. The maximum cooling temperature under a given load and without load has been measured experimentally. The maximum performance of the Peltier Cooling device has been obtained experimentally in cooling volume which is down to 6.63 ^{0}C from an ambient temperature of 30 ^{0}C. A temperature control has been designed and tested for different set points.

Keywords: *Arduino, Liquid cooling, QtCreator, Peltier effect, Thermo electric module.*

INTRODUCTION

Temperature controlled environments are crucial in biomedical research laboratories and medical institutes. Especially cooler environments of constant temperature are required to carry out different experiments in a host of applications [1]. Storing, preparing, analysing samples, or culturing bacteria needs precisely controlled temperature environments.

It has been observed during the last two decades that the O_3 layer is slowly destroyed because of the refrigerant (CFC and HFC) used for the refrigeration and air- conditioning purposes. The common refrigerant used is HFC's which are leaked and slowly ascend into the atmosphere. When they reach to O_3 layer they act on O_3 molecules and the layer of O_3 is destroyed. The effect of 100 g of HFC can destroy 0.5 tons of O_3 molecules. The O_3 layer once destroyed, it takes hundreds of years to regain its original thickness as it is formed by complex reactions. The capacity of HFCs to increase in earth temperature 10% is contributed by HFC's only. In recent years, with the increased awareness towards environmental degradation due to the production, use and disposal of CFCs and HCFCs as heat carrier fluids, the use of conventional refrigeration and air conditioning systems has become a subject of great concern and resulted in extensive research and development of novel refrigeration and space conditioning technologies. Thermoelectric cooling provides a promising alternative technology due to its distinct advantages.

The Peltier effect was discovered in 1834 by a French watchmaker and part time physicist Jean Charles Athanase Peltier. Peltier found that the application of a current at an interface between two dissimilar materials results in the absorption/release of heat. Thermo Electric Modules (TEMs) are effectively heat pumps that transfer heat from one side of the module to the other when a current is applied. This phenomenon is called the Peltier effect. [2] The present paper deals with the development of a thermoelectric cooler (TEC) wherein cooling is achieved by process fluid for obtaining enhanced performance in cooling a desired space volume.

A thermoelectric cooler has been designed, fabricated and the device has been tested to cool a specific volume to a desired constant temperature in the range of 6°C to +30°C. This eliminates the need for the experimental specimen to be placed in a well-sealed container before the commencement of the experiment. This device can be used as laboratory equipment and it control the temperature very accurately and keeps the temperature of the bath around the desired low temperatures. The final device also has to be free of vibrations to avoid any disturbances to the samples which may be put in the temperature controlled environment. It is equipped with serial communication with computer interfacing and a dedicated graphical user interface is also developed for visual observation of the recorded temperatures and real time plotting of the different temperatures. This is made possible by the combined usage of Arduino Uno development board and QtCreator which is an open source GUI developer with C++compiler. The same Peltier cooled constant temperature air bath can be used to do different other experiments which will be discussed.

PELTIER COOLING

Thermoelectric coolers operate by the Peltier effect (which also goes by the more general name thermoelectric effect) [3]. The device has two sides and when DC current flows through the device, it brings heat from one side to the other, so that one side gets cooler while the other gets hotter. The "hot" side is attached to a heat sink so that it remains at ambient temperature, while the cool side goes below room temperature. In some applications, multiple coolers can be cascaded together for lower temperature. Two unique semiconductors, one n-type and one p-type, are used because they need to have different electron densities. The semiconductors are placed thermally in parallel to each other and electrically in series and then joined with a thermally conducting plate on each side. When a voltage is applied to the free ends of the two semiconductors there is a flow of DC current across the junction of the semiconductors causing a temperature difference. The side with the cooling plate absorbs heat which is then moved to the other side of the device where the heat sink is [4]. TECs are typically connected side by side and sandwiched between two ceramic plates [5]. The cooling ability of the total unit is then proportional to the number of TECs in it.

CONSTRUCTION OF EXPERIMENTAL SETUP AND METHODOLOGY

This investigation employed a mini refrigerator which is used as the cooling chamber. The chamber of the refrigerator has been modified to obtain a volume of $0.01296m^3$ with dimensions *(27cm x 20cm x 24cm).* The insulated chamber alone is taken after removing all the parts from the chamber. Plywood pieces are attached to the backside and top of the chamber. Plywood at the top is used for installing the controller, switches, displays etc. At the backside provisions is given to install the power supply, radiator, coolant tank, pump etc.

The cooling unit is made by stacking the components one over the other. The cold side of the Peltier element made of Bi_2Te_3 is attached to a heat sink of metal volume $9.345\times10^{-5}\ m^3$ to increase the heat transfer area at the cold side and is placed inside the insulated chamber. The hot side of the Peltier element is attached to a hollow aluminium block. Coolant can be pumped through the block. Two such arrangement are used inside the cooling chamber. The coolant is pumped from the coolant tank using a mini centrifugal pump and is passed through the aluminium block. The coolant carries away the heat generated at the hot side of the Peltier element and is pumped to the miniature radiator placed outside the insulated chamber. The radiator cools the coolant liquid with the help of a separate fan by which the heat is transferred to the atmosphere. The coolant is then pumped back to the coolant tank. This process continues and as a result more heat is transferred from the insulated chamber to the atmosphere.

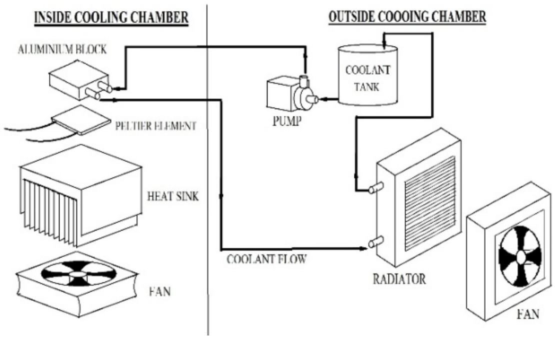

Figure 1 - Cooling mechanism

The instrumentation part for the setup is made using open source programmable circuit board called Arduino. The sensor used for measuring temperature is DS18B20. There are three of these were included in the setup. In which one measure bath temperature, other measure coolant temperature and the final one measure either atmospheric temperature or sample temperature based on the arrangement of testing. The reading rom the sensors are directly communicated to the GUI via serial communication.

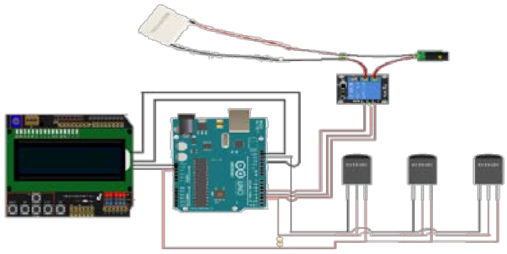

Figure 2- Schematic of instrumentation

A Constant DC source is used as the power supply for the experiment. The output of the power supply unit is of two types, the first one which provides a 6V, 1.5A DC for the operation of three fans and a pump and the other one provides a constant 12V, 5A DC for the operation of two Peltier elements.

Figure 3 - Final setup (Front/Rear)

DEVELOPMENT OF GRAPHICAL USER INTERFACE

The graphical user interface for the experimental unit has been developed in an open source GUI developer called QtCreator. Qt Creator is a cross-platform C++, JavaScript and QML integrated development environment which is part of the SDK for the Qt GUI application development framework. It includes a visual debugger and an integrated GUI layout and forms designer. The editor's features include syntax highlighting and auto-completion, Qt Creator uses the C++ compiler from the GNU Compiler Collection on Linux and FreeBSD. On Windows it can use MinGW or MSVC with the default install and can also use Microsoft Console Debugger when compiled from source code. Qt Creator includes a code editor and integrates Qt Designer for designing and building graphical user interfaces (GUIs) from Qt widgets. The code editor in Qt Creator supports syntax highlighting for various languages. In addition to that, the code editor can parse code in C++ and QML languages and as a result, code completion, context-sensitive help, semantic navigation are provided. Qt Designer is a tool for designing and building graphical user interfaces (GUIs) from Qt widgets. It is possible to compose and customize the widgets or dialogs and test those using different styles and resolutions directly in the editor. Widgets and forms created with Qt Designer are integrated with programmed code, using the Qt signals and slots mechanism. Qt Quick Designer is a tool for developing animations by using a declarative programming language QML.

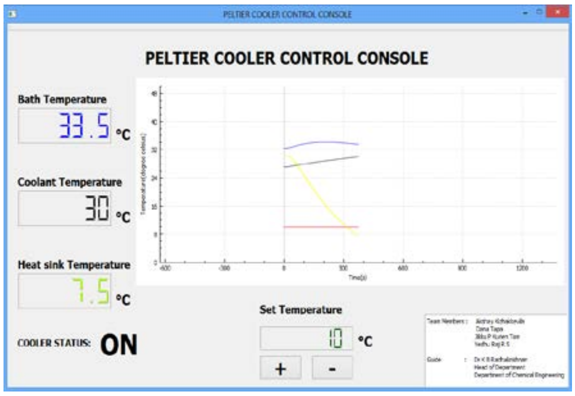

Figure 4- Graphical user interface

DEVICE TESTING AND RESULTS & DISCUSSION

MAXIMUM COOLING

This test is done to find out how low the bath temperature can be reduced by continuous operation of the setup. The setup is operated with a constant input source of 12V, 5A DC to the Peltier elements. The variables measured are bath temperature, heat sink temperature and coolant temperature. Whenever the coolant temperature increases beyond the atmospheric temperature, the coolant is replaced with a fresh batch of coolant. This is shown by the dip in the coolant temperature curve shown below. This helps to maintain the maximum possible heat transfer rate. The observation is that the bath temperature is reduced to 6.63^{0}C in 2500 seconds (approximately 42 minutes).

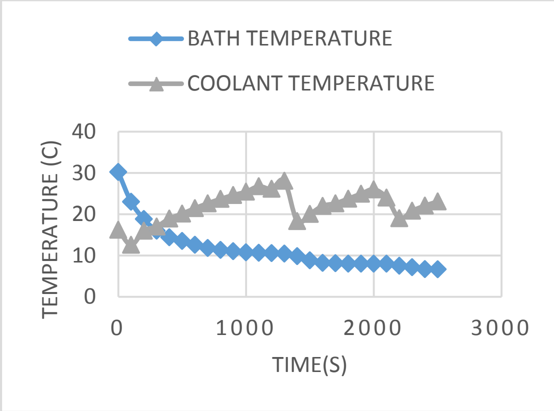

Figure 5- Maximum cooling test result

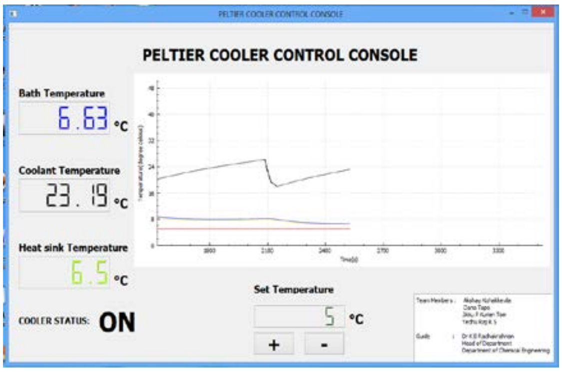

Figure 6- Maximum cooling test results on GUI

COOLING WITH LOAD

This test is done to find out the COP of the refrigerator. About 120 ml of water is taken in container and kept in the chamber. Provision for continuously measuring the temperature of sample was made available in the unit. Then the cooler is switched on and the maximum constant input is given to the Peltier elements and the auxiliaries such as fans and pumps. Here also the maximum possible heat transfer rate is maintained. The variables measured are the bath temperature, heat sink temperature and sample temperature. The readings from this test are used to find the sensible heat changes of bath, sample and heat sink. The observation is that the sample is cooled down from 33.6^{0}C to 16.9^{0}C in 2400s.

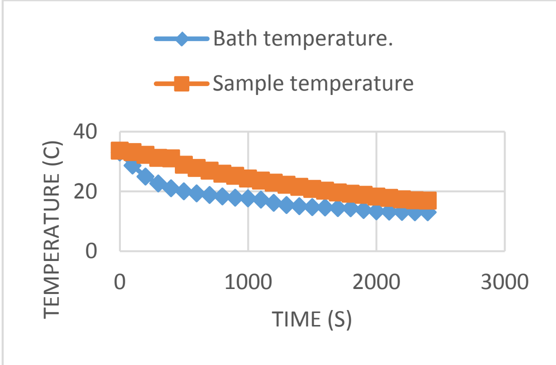

Figure 7- Results of cooling with load

FREE CONVECTION TEST

This test is done to find out the heat pumping efficiency of the Peltier element. This test is carried with the internal fans under switched off condition. As a result only free convection takes place inside the chamber which can be neglected. So that it can be assumed that the heat transfer takes place only from the heat sink and not from the air bath. The observation is that the heat sink temperature is reduced from 30.2^{0}C to -3.25^{0}C and coolant temperature is increased from 27^{0}C to 34.2^{0}C within a time period of 1200 seconds.

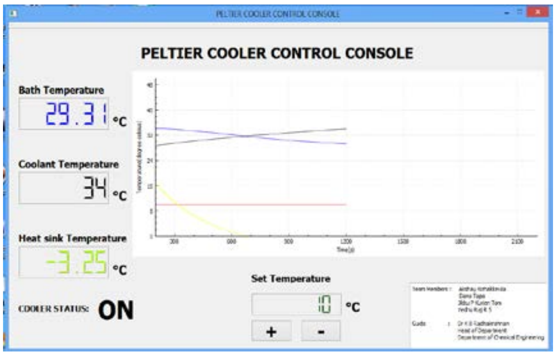

Figure 8 - Free convection test result on GUI

RADIATOR CAPACITY

This test is done to find out the heat transfer capacity of the radiator, which is required for the calculation of the efficiency of the Peltier element.

The basic idea is to operate the setup with radiator and without radiator and not down the sensible heat change of coolant. The difference in the sensible heat will give the rate heat transfer through the radiator. This test is done by operating the setup with and without radiator for same period of time. The initial and final temperature of the coolant is noted for both setup. From the difference in increase in temperature the amount of heat dissipated by the radiator can be obtained for the specific time. From these data the radiator capacity is calculated. This result is further incorporated in calculation of Peltier element efficiency.

With radiator		
Initial temperature (^{0}C)	Final temperature (^{0}C)	Time (s)
26.87	30.37	600

Without radiator		
Initial temperature (^{0}C)	Final temperature (^{0}C)	Time(s)
26.87	31	600

Table 1 Radiator capacity test results

EVALUATION OF COEFFICIENT OF PERFORMANCE (COP)

For calculation of coefficient of performance, results from the test for cooling with load are used. All the sensible heat change of bath, sink and sample is calculated by equation 1.

$$Q = V\rho \; Cp \left(T_1 - T_2\right) \qquad (1)$$

Where Q is the sensible heat change, V is the volume, ρ is the density, C_P is the specific heat, T_1 and T_2 is the initial and final temperature respectively. The energy spent (input) for heat transfer is calculated by the equation 2.

$$E = P \times t \qquad (2)$$

Where E is the energy spent, P is the Power rating of the device and t is the time spent.

The COP of the device is calculated using the equation 3 given below.

$$COP = \frac{Q_c}{E} \qquad (3)$$

Where Q_C is the heat transferred from the cold side which include heat transferred from air bath (Q_1), heat transferred from heat sink (Q_2) and heat transferred from sample of water (Q_3). The values of densities and specific heats different materials have been obtained from standard references.

The values of the above parameters respectively for Q_1, Q_2 *and* Q_3 obtained from the experimental data on temperatures are 313.89 J, 8191.50 J and 8372.71J.

$$Q_c = Q_1 + Q_2 + Q_3 \qquad (4)$$

Therefore Q_C is obtained as 16878.1 J

The rating of the Peltier element is 12V and 5A. Since two Peltier elements are used in the setup, the total power input, $P_{Peltier}$ (without considering auxiliaries) is evaluated as below.

$P_{Peltier} = 2\times12\times5 = 120$ W

Therefore energy input to the Peltier elements ($E_{Peltier}$) for 2400 seconds of usage is obtained using equation 5 and is obtained as 288000 J.

$$E_{Peltier} = P_{Peltier} \times Time \qquad (5)$$

The COP of the constructed refrigerator (without considering the auxiliaries) has been obtained as 5.86%

The above equations have been used to estimate the COP of the device with auxiliaries and the value of Q_C will be same as in the case without auxiliaries.

The power rating of each fan and pump used was 6V and 1.5A for each unit. Since three fans and one pump were used in the experiments the total power input of the auxiliaries ($P_{Auxiliaries)}$ has been evaluated to be 36 W and the energy input to the auxiliaries ($E_{Auxiliaries)}$ for maximum cooling period of 2400 seconds has been obtained using equation 6 and is 86400 Joules.

$$E_{A\,uxiliaries} = P_{auxiliaries} \times Time \qquad (6)$$

The total energy input to the setup for duration of 2400 seconds (E_{Total}) has been obtained using equation 7 and is 374400 J.

$$E_{Total} = E_{Peltier} + E_{Auxiliaries} \qquad (7)$$

The COP of the constructed refrigerator considering the auxiliaries has been obtained as 4.5%.

PELTIER ELEMENT EFFICIENCY

The heat pumping efficiency (η) of the Peltier element is obtained from the following equation 8.

$$\eta = \frac{Q_{Delivered}}{Q_{Absorbed} + Energy\ Supplied} \qquad (8)$$

$Q_{Delivered}$ is the heat rejected from the refrigerator device which is the sum of heat transferred through the radiator (Q_R) and the sensible heat change of the coolant ($Q_{coolant}$).

Radiator capacity test has been conducted for cooling of a constant volume of the coolant (4 litre)s. and the resultant data is used to find the heat transferred through the radiator.

Let Q_1 and Q_2 be the sensible heat changes of coolant without radiator and with radiator respectively and C_R be the radiator capacity.

From the experiment results it clear that without radiator the coolant temperature has increased from 26.87^0C to 31.0^0C in 600 seconds and with radiator it has increased from 26.87^0C to 30.37^0C in 600 seconds.

So the values of Q_1 and Q_2 are obtained as 69020.56 J and 58492.0 J respectively.

Therefore the heat transfer rate through the radiator is obtained from the equation 10 given below and is it comes to 17.54 W,

$$Q_R = \frac{Q_1 - Q_2}{Time} \qquad (10)$$

So the value of Q_R is obtained for an operating time of 1200 seconds (From the free convection test) and obtained using the equation 11.

$$Q_R = C_R \times time \qquad (11)$$

Thus Q_R is estimated to be 21048 J

Sensible heat change of the coolant ($Q_{coolant}$) is obtained from the temperature of the coolant in the free convection test results. From the values of initial and final temperature of coolant the value of $Q_{coolant}$ is obtained as 120326.4J.

Therefore the value of $Q_{Delivered}$ is 141374.4 J.

$Q_{Absorbed}$ is also obtained from the temperature values of the heat sink in the free convection test results. From the values of initial and final temperature of heat sink, the value of $Q_{Absorbed}$ is obtained as 15163.5 J.

Energy supplied is obtained by multiplying the total power rating and time of operation

$$E_{Supplied} = 2\times12\times5\times1200$$
$$= 144000 \text{ J}$$

Therefore heat pumping efficiency of the Peltier element is obtained as $\eta = 88.82$ %

CONCLUSION

A thermoelectric refrigerator using the principle of Pelier effect has been fabricated and subjected to experimental investigation to study the rate of cooling in a given volume. A temperature control along with a computer interface was installed using a GUI from an open source and this has been used for the control and measurement and recording of temperature in the given volume. The coefficient of Performance and efficiency of the Peltier elements were evaluated. The COP value for the cooler is obtained respectively as *4.5%* and *5.86%* with and without considering the auxiliaries devices. This value of COP is considerably higher than the COP value reported by Onoroh Francis et al, [6] which is 1.3% for an air cooled Peltier cooler. The efficiency of the Peltier element is obtained as 88.82% which is also very encouraging.

NOMENCLATURE

CFC : Chloro Fluro Carbon
GUI : Graphical User Interface
HCFC : Hydo Chloro Fluro Carbon
QML : Qt Modeling Language
MinGW : Minimalist GNU for Windows
MSVC : Microsoft Visual Studio
SDK : Software Development Kit

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