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A Review on Heating and Cooling system using Thermo electric Modules

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Abstract: *Conventional heating systems use either fuels or electricity as a source of thermal energy. Conventional cooling systems use either air or liquids or the pressurized refrigerants to absorb thermal energy from the air.These conventional methods of heating and cooling release greenhouse gases and leads to global warming when they leak into the environment. The thermal ramp rates for heated air techniques, whilst faster, are still limited, in this case by the low thermal mass and Conductivity of air. The response time of heating and cooling with Air or liquid is slow due to the inertia of the air or liquid movement. Conventional methods require an adjunct cooling/heating method for thermal cycling. These problems can be overcome by alternative forms of heating and cooling are being developed using Thermoelectric cooling and heating system and their by protectiong the environment.*

Keywords: *Peltier Effect, Polymearase Chain Reaction, Thermoelectric Module, Thermalcycling.*

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I. Introduction

Though the Thermoelctric concept was discovered more than 100 years ago, thermoelectric coolers have only been applied commercially during recent decades. The thermoelectric cooling (TEC) system, known as an active cooling method, is considered to be one of the alternative technologies with light and compact size, free from long-term maintenance, quiet and vibration-free operation, and operation with DC voltage. The thermoelectric module is widely used in military, medical, industrial, scientific/laboratory, electro-optic and telecommunications areas for cooling, heating, and power generation and many products also using TECs including laser diode, blood analysers, Charge coupled device Cameras, microprocessors. They are also used in the applications where temperature cycling,temperature stabilization, or cooling below ambient are required.

The French watchmaker Jean Peltier (1785–1845) discovered in 1834, the effect of heating or cooling at the junctions of two different conductors exposed to the current. When an electric current flows through the junction of two dissimilar conductors, besides Joule heat, additional heat known as Peltier heat is either produced or absorbed, depending the direction of the current or of the temperature gradient called thermoelectric phenomena or peltier effect and the device is called Thermo-Electric Cooler (TEC).

Peltier modules act as heat pumps can generate and remove the heat means transfer heat from one side of the device to the other, with consumption of electrical energy, depending on the direction of the current. Thermoelectric cooler(TEC) can be used either for cooling or heating. Thermoelectric modules have been used for energy conversion and electricity generation from waste heat sources, solid state refrigeration.The heat flows via the semiconductor elements from one face to the other by applying a low-voltage DC power source to a TEC. The electric current cools one side and simultaneously heats the opposite side.Consequently, a given side of the device can be used for heating or cooling by reversing the polarity of the applied current. The characteristics of TECs make them highly suitable for precise temperature control applications and where reliability and space limitations are paramount or refrigerants are not required.

A typical TEC module consists of two ceramic plates with p-type and n-type semiconductor materials (bismuth telluride alloys) between the ceramic plates. An array of these material comprises a single-stage module. The elements of semiconductor materials are connected thermally in parallel and electrically in series. When a positive DC voltage is applied as shown, electrons pass from the p-type to the n-type material, and the cold-side temperature decreases as the electron current absorbs heat, till equilibrium is reached. The heat absorption means cooling is proportional to the number of thermoelectric couples and the current.. This heat is transferred to the hot side of the cooler, where it is dissipated into surrounding environment.

II. System Design

The thermoelectric module is made up of two ceramic plates with a series of P and N doped bismuth-telluride semiconductor material sandwiched between ceramic plates. The ceramic plates on both sides of thethermoelectric provides the necessary electrical insulation and rigidity and . The the P type material has a deficit of electrons, while N type material has an excess of electrons . The thermoelectric couples are thermally in parallel and electrically in series. A thermoelectric module can contain one to several number of couples.The elements are vibration-free, solid-state, noise-free heat pumps, which move heat from one side to another when a direct current (DC) voltage is applied on it.

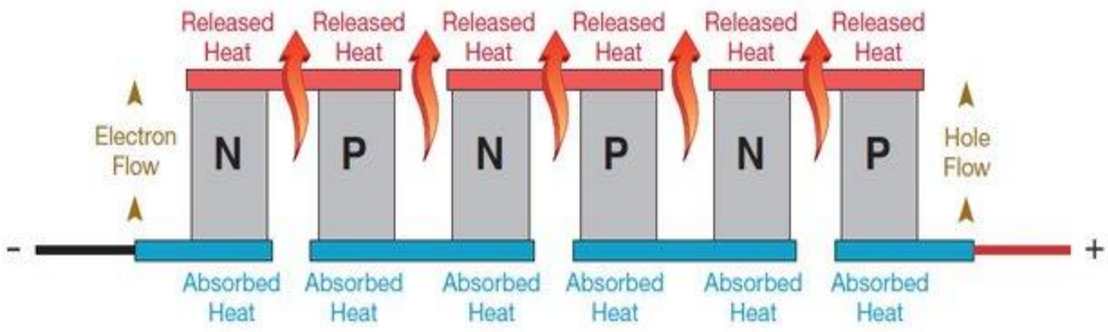

Fig1: Heat flow in TEC module

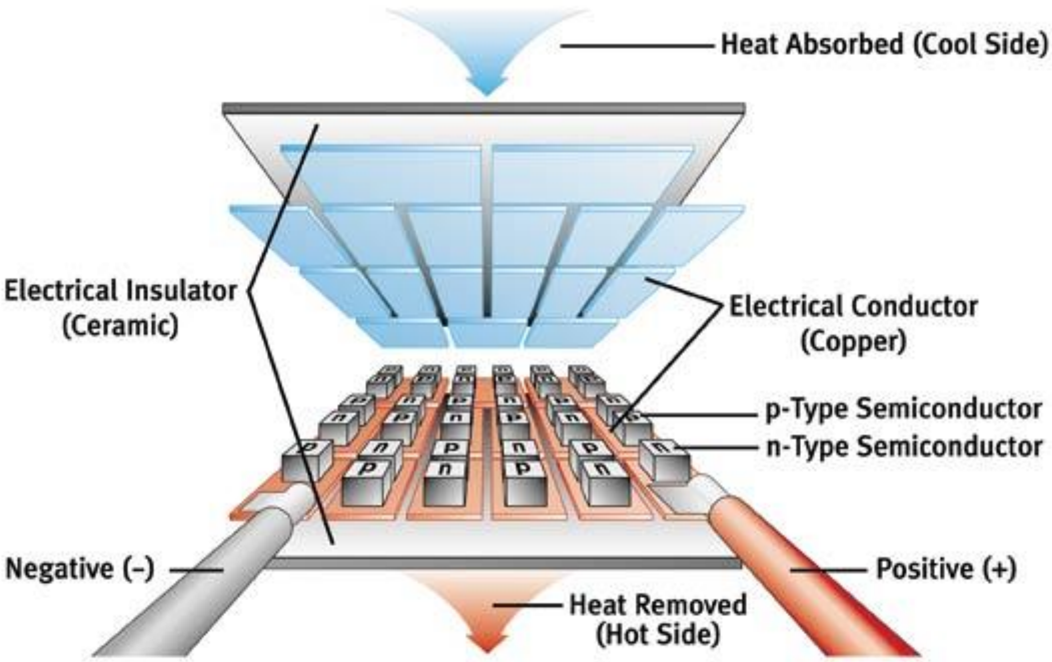

Fig.2 TEC construction

A large temperature difference across the TE module is required for power generation, and this temperature difference leads to significant thermal stress. The performance of Thermoelectric modules degrades with thermal cycling as the constituent materials and interfaces are exposed to large temperature gradients.

III. Governing Equations

As the electrons move from the P type material to the N type material through an electrical connector, the electrons jump to a higher energy state absorbing thermal energy (cold side). Continuing through the lattice of material, the electrons flow from the N type material to the P type material through an electrical connector, dropping to a lower energy state and releasing energy as heat to the heat sink (hot side).

Thermoelectrics can be used to heat and to cool, depending on the direction of the current. In an application requiring both heating and cooling, the design should focus on the cooling mode. Using a thermoelectric in the heating mode is very efficient because all the internal heating (Joulian heat) and the load from the cold side is pumped to the hot side. This reduces the power needed to achieve the desired heating.

The appropriate thermoelectric for an application, depends on at least three parameters. These parameters are the hot surface temperature (Th),the cold surface temperature (Tc), and the heat load to be absorbed at the cold surface (Qc).

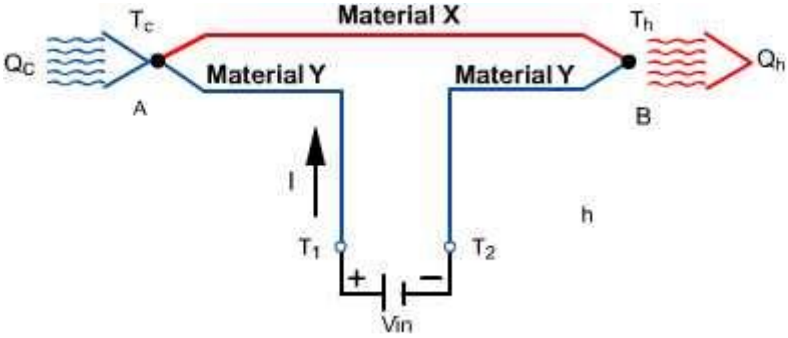

Fig.3 Peltier Effect

The hot side of the thermoelectric is the side where heat is released when DC power is applied. This side is attached to the heat sink. When using an air cooled heat sink (natural or forced convection), the hot side temperature can be found by using Equations 1 and 2.

$$Th = Tamb + (O)\ (Qh) \qquad (1)$$

Th = The hot side temperature (°C).
Tamb = The ambient temperature (°C).
O = Thermal resistance of heat exchanger (°C/watt).

$$Qh = Qc + Pin \qquad (2)$$

Qh = the heat released to the hot side of the thermoelectric(watts).
Qc = the heat absorbed from the cold side (watts).
Pin = the electrical input power to the thermoelectric (watts).

The thermal resistance of the heat sink causes a temperature rise above ambient. If the thermal resistance of the heat sink is unknown, then estimates of acceptable temperature rise above ambient are:
Natural Convection : 20°C to 40°C
Forced Convection : 10°C to 15°C
Liquid Cooling : 2°C to 5°C (rise above the liquid coolant temperature)

The heat sink is a key component in the assembly. A heat sink that is too small means that the desired cold side temperature may not be obtained.The cold side of the thermoelectric is the side that gets cold when DC power is applied. This side may need to be colder than the desired temperature of the cooled object. This is especially true when the cold side is not in direct contact with the object, such as when cooling an enclosure.
The temperature difference across the thermoelectric (ΔT) relates to Th and Tc according to Equation 3.

$$\Delta T = Th - Tc \qquad (3)$$

Estimating Qc, the heat load in watts absorbed from the cold side is difficult, because all thermal loads in the design must be considered. Among these thermal loads are:
a. Active: I2R heat load from the electronic devices
Any load generated by a chemical reaction
b. Passive: Radiation (heat loss between two close objects with different temperatures)
Convection (heat loss through the air, where the air has a different temperature than the object)
Insulation Losses Conduction Losses (heat loss through leads, screws, etc.)
Transient Load (time required to change the temperature of an object)

1. Powering the Thermoelectric Module:

All thermoelectrics are rated for Imax, Vmax, Qmax,and ΔTmax, at aspecific value of Th. Operating at or near the maximum power is relatively inefficient due to internal heating (Joulian heat) at high power. Therefore, thermoelectrics generally operate within 25% to 80% of the maximum current. The input power to the thermoelectric determines the hot side temperature and cooling capability at a given load.

As the thermoelectric operates, the current flowing through it has two effects: (1) the Peltier Effect (cooling) and (2) the Joulian Effect (heating). The Joulian Effect is proportional to the square of the current. Therefore, asthe current increases, the Joule heating dominates the Peltier cooling and causes a loss in net cooling. This cut-off defines Imax for thethermoelectric.

For each device, Qmax is the maximum heat load that can beabsorbed by the cold side of the thermoelectric. This maximum occurs at Imax, Vmax, and with ΔT= 0°C. The Tmax value is the maximum temperature difference across the thermoelectric. This maximum occurs at Imax, Vmax and with no load (Qc= 0 watts).

2. Features of Thermoelctric Modules

Some of the significant features of thermoelectric modules are:

a) No moving parts: - A thermoelectric module works electrically without any moving parts so they are virtually maintenance free.
b) Small size and weight: - The overall thermoelectric cooling system is much smaller and lighter than a comparable mechanical system. In addition, a variety of standard and special sizes and configurations are available to meet strict application requirements.
c) Ability to cool below ambient: - Unlike a conventional heat sink whose temperature necessarily must rise above ambient, a thermoelectric system attached to that same heat sink has the ability to reduce the temperature below the ambient value.
d) Precise temperature control: - With an appropriate closed-loop temperature control circuit, thermoelectric module can control temperatures to better than +/-0.1˚C.
e) High Reliability: - Thermoelectric modules exhibit very high reliability due to their solid state construction. Although reliability is somewhat application dependent, the life of typical thermoelectric system is greater than 200,000 hours.
f) Electrically Quite Operation: - unlike a mechanical refrigeration system, thermoelectric modules generate virtually no electric noise and can be used in conjunction with sensitive electronic sensors. They are also acoustically silent.
g) Operation in any Orientation: - Thermoelectric modules can be used in any orientation and in zero gravity environments. Thus they are popular in many aerospace applications.
h) Convenient Power Supply: - Thermoelectric modules operate directly from a DC power source.
i) Spot Cooling: - With a thermoelectric module it is possible to cool one specific component or area only, thereby often making it necessary to cool an entire package or enclosure.
j) Ability to Generate Electric Power: - When used „in reverse" by applying a temperature differential across the faces of a thermoelectric refrigeration system, it is responsible to generate a small amount of DC power.
k) Environmental Friendly: - Conventional refrigeration system cannot be fabricated without using chlorofluorocarbons or other chemicals that may be harmful to environment. Thermoelectric devices do not use or generate gases of any kind. Another benefit to thermoelectric devices is that they convert thermal energy directly into electricity, or vice-versa. Direct conversion eliminates losses associated with multiple energy conversion processes. Direct conversion also means there is no need for additional equipment or materials, making for a simplified device. Thermoelectric energy conversion is done in the solid state. As such, the devices have no moving parts that can wear out.

IV. Application of Thermoelctric module as Thermal Cycling System

The polymerase chain reaction (PCR) is a revolutionary laboratory technique used in molecular biology research worldwide. PCR technology was developed by Kary Mullis at the Cetus Corporation in 1983. The Thermal Cycler is a laboratory apparatus used to amplify segments of DNA via the Polymerase Chain Reaction (PCR). PCR is a three-step process that is carried out in repeated cycles. The initial step is the denaturation, or separation, of the two strands of the DNA molecule. This is accomplished by heating the starting material to temperatures of about 95 °C (203 °F) and will be heated for 20–30 s to separate the DNA double strands. Each strand is a template on which a new strand is built. In the second step the temperature is reduced to about 55 °C (131 °F) depending on the primer length and percent guanine and cytosine content) and will be kept at this temperature for 20–40 s so that the primers can anneal to the single stranded DNA template through Brownian motion in the solution and subsequent hydrogen-bonding. In the third step the temperature is raised to about 72 °C (162 °F), and the DNA polymerase begins adding nucleotides onto the ends of the annealed primers. At the end of the cycle, which lasts about five minutes, the temperature is raised and the process begins again. The number of copies doubles after each cycle. Usually 25 to 30 cycles produce a sufficient amount of DNA. Because different steps of the reaction take place at different temperatures hence it is called thermal cycler.

PCR is an enzymatic process in which a specific region of DNA is replicated over and over again to yield many copies of a particular sequence. This molecular xeroxing process involves heating and cooling samples in a precise thermal cycling pattern over 30 cycles. During each cycle, a copy of the target DNA sequence is generated for every molecule containing the target sequence.In the ideal reaction with 100% amplification efficiency, approximately a billion copies of the target region on the DNA template have been generated after 32 cycles. However, a reduction in amplification efficiency through PCR inhibition or poor primer annealing leads to lower quantities of PCR product being produced.

The equation for the number of target molecules produced, which incorporates the amplification efficiency, is

$$=Xo(1+E)(N-2)$$

where Xn is the predicted number of target molecules created, Xo is the number of starting molecules, E is the efficiency of the reaction (between 0% and 100% or 0 to 1), and N is the number of cycles. The N-2 takes into account that for the first two cycles the specific double-stranded target is not yet created.

At the inception of the technology in the early 1980s, DNA amplification by PCR was a time-consuming and laborious process. Thermal cycling steps were performed manually, involving repeated transfers of DNA samples among three large water baths set at different temperatures for denaturation, annealing, and extension.

1. Liquid handling system:

In the early development of thermal cyclers, the cooling system relied on a bulky plumbing compressor, which made it impossible to have a small-footprint instrument. The cooling system of the early PCR machine was comprised of a refrigerator compressor, and included plumbing within the aluminum sample block. Early-stage heater elements were used. Next stage of the PCR machinery consists of a liquid handling arm that slides up and down and a drawer portion. The system has solenoid valves on the top of the machine.

The Process requiring a few chemicals, it is incredibly time-consuming to perform by hand. scientists performing the reaction were required to stand at the lab bench for several hours, moving the sample back and forth between water baths of different temperatures. While they loved the technique, scientists were eager for an automated machine that could perform the reaction for them. The tray on the front held the sample and could slide back and forth. When slid to the front, the sample tray would rest in a water bath. The black hoses brought water from baths of different temperatures as necessary. When slid to the back, the sample could be injected with new enzyme, a chemical used to speed up the reaction, that had to be added once during a cycle. These two features water baths and the need to add enzyme during each cycle would be phased out in new prototypes in research. The water baths were replaced first with Peltier devices for thermoelectric heating and cooling.

2. Joule Heating Designs:

Resistive heating can be monolithically integrated in many lab-on-chip fabrication processes and is power-efficient compared to Peltier designs, it requires an adjunct cooling method when used for thermal cycling. The literature describes a large number of basic flow-through Joule-heated designs. Poser et al. presented an early silicon micromachined device offering nominal ramp rates as high as 80°C/s with fan cooling at 40°C/s and typical cycling power of 2.5 W per 5–10 μL reactor. Using platinum heater and resistive temperature detector (RTD) elements in a silicon and glass device, Yoon et al. demonstrated 36°C/s heating and 22°C/s cooling of a 3.6 μL sample while drawing 0.6 to 1.8 W steady-state during dwells.

The Researchers started to look into inventing an all-in-one instrument (thermal cycler) that would help automate the PCR process. In 1987 the first commercial thermal cycler, became available with the ability to program heating and cooling of samples using a metal block. This paved the way for applications of PCR in a wide range of scientific fields, as well as innovations in thermal cyclers that revolutionized molecular biology research. In the present day, solid-state Peltier blocks are utilized in thermal cyclers to both heat and cool by controlling the direction of an electrical current. Advanced Peltier systems can heat and cool the block at a fast rate, enabling fast PCR, to complete more PCR runs in a day. The device has a thermal block with holes where tubes holding the PCR reaction mixtures can be inserted. The cycler then raises and lowers the temperature of the block in discrete, pre-programmed steps.

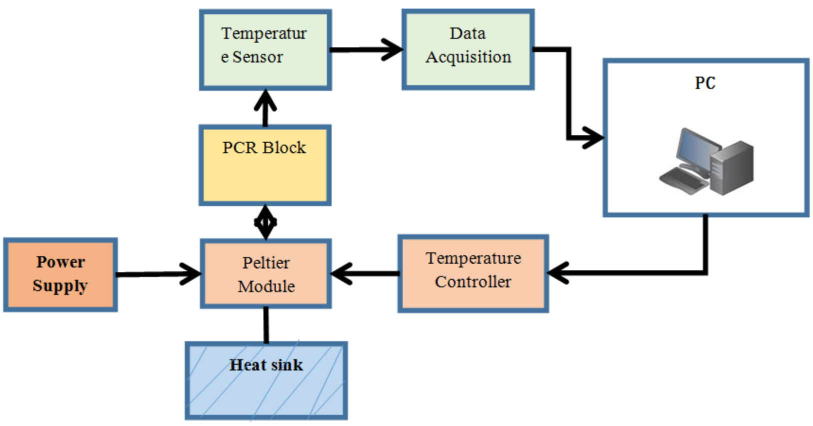

Fig.4 Block diagram of Thermal Cycler using Peltier Module

PCR temperature cycling profile for five stages. Each stages has specific heating temperature and period.

Stages	Temperature (°C)	Period (minutes)
Pre-heat	95	15
Denaturation	95	1
Annealing	55	1
Extension	72	1
Final Extension	72	10

Table.1 Thermal cycling Steps

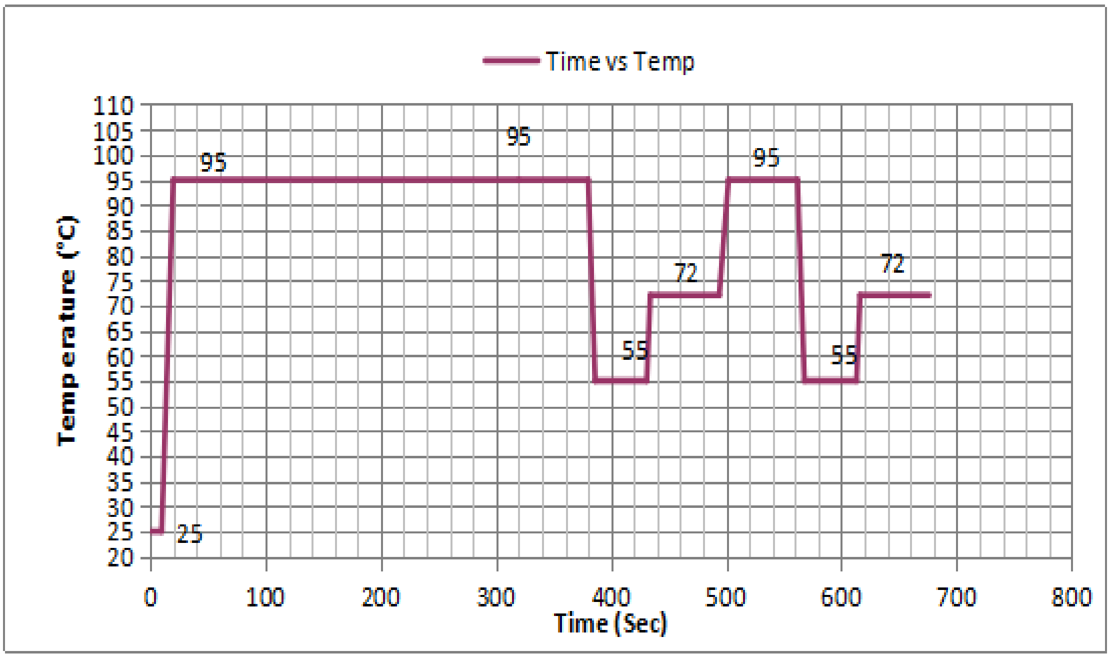

Fig.2 Temperature Profile of Thermal Cycler

3.Bench-top PCR Instruments:

Most commercial PCR systems are rely on Peltier thermoelectric (TE) heater/cooler elements to modulate the temperature of a sample-bearing thermal block, a power-intensive approach (typically 200–1000 W) primarily suited to operation in high-resource laboratories. Typified by instruments like the Agilent SureCycler 8800, Bio-Rad C1000, Eppendorf Mastercycler Pro, Life Technologies GeneAmp 9700, Roche LightCycler 96, and Thermo Scientific Arktik, vendor literature indicates maximum temperature ramp rates in the 1.5 to 5°C/sec range, sample to sample temperature uniformity of +/- 0.1 to 0.5°C, and temperature accuracy of +/- 0.25°C for sample volumes typical of standard 0.1, 0.2, and 0.5 mL centrifuge tubes and 96- or 384-well plates. Some companies have worked to improve ramp rates by optimizing thermal block design (Bio-Rad S1000: 2.5–6°C/s, 700 W), selecting high conductivity but low thermal mass block materials like silver (Eppendorf Mastercycler Pro S: 4.5–6°C/s, 950 W), scaling down system and reaction volumes (Thermo Scientific Piko: 4.5–5°C/s, 180 W [39]), reducing block size and sample count (Chai Biotechnologies OpenPCR, 1°C/s, 180 W), or reconfiguring the surface-to-volume ratio of the PCR tubes themselves (Cepheid SmartCycler: 2.5–10°C/s, 350 W [41]; Streck Philisa: 12–15°C/s [42]). Even the pioneering Idaho Technology LightCycler convective cycling design [43,44], embodied today by the Roche LightCycler 2.0 and Qiagen Rotor-GeneQ systems (15–20°C/s nominal, 1.9–3.6°C/s in-capillary, 800 W), achieves speed at the expense of power and portability.

S.No.	1	2	3	4	5	6	7	8
Parameter	ABS 7500	ABS 7500 Fast	RocheLightcycler 480	Biorad Opticon2	Thermoscientific Piko	Eppendorf Master cycler	Illumina Eco	Straragene Mx3000p
Heating/Cooling Element	Peltier	Peltier	Peltier block (Therma- Base technology)	DNA Engine peltier element	Peltier	Peltier	Peltier	Peltier
Temperature Range(°C)	4- 110	4- 110	4- 110	4- 110	4- 110	4- 110	4- 110	4- 110
Time (40 cycles)	130	30-37	<40	<40	<15	30	<40	110

(min.)								
Ramp rates (°C/Sec)	1.5/1.5	5.5/3.5	4.8/2.5	3.0/2.0	5/4.5	6 & 4.5	5.5/5.5	2.5/2.5
Uniformity (oC)	±0.5	±0.5	±0.2	±0.4	±0.3	±0.3	±0.1	±0.25
Accuracy (oC)	±0.25	±0.25	±0.2	±0.4	±0.2	±0.20	-	±0.25
Reaction Format (Wells)	96x0.2ml Aluminum	96x0.2ml Aluminu m	96x0.2ml Aluminum	96x0.2ml Aluminu m	24x0.2ml/ 96x0.05ml Aluminum	96x0.2ml Aluminum	48x0.2ml Silver	96x.2ml Aluminum

Table 2: Benchmark Instruments features comparison

From the above comparison tables, observed that the majority of the manufacturers are using the Peltier heating/cooling technique as it is an advanced technique as well as it overcomes the limitations of the conventional techniques.

4.Literature Revirew:

In the initial PCR systems, heated water baths were used to achieve the necessary temperature cycles. Presently, one method for conventional PCR machines to control the temperature in the micro-centrifuge reaction tubes is by utilizing Peltier elements, which are mounted on a metal block. Cycling is achieved by heating and cooling the massive metal block with a maximum temperature ramp of 1– 6 C/s. In fact, to ensure temperature homogeneity across the whole plate, a large value of thermal capacitance of the system is required, resulting in slow PCR cycles. In these machines, every cycle usually takes 4 min and it takes around 2 h to perform the full PCR process. These machines accommodate a number of parallel reactions with typical volumes of 10–100 lL [29]. Excessive reaction volume, high power consumption and low efficiency are some of the barriers in the application of PCR [30].

Utilizing smaller instruments and reduced reaction volumes can result in faster cycles. The miniaturized DNA reaction chambers have advantages in integration, process speed, efficiency, and decrease in the consumption of expensive reaction materials. The first miniaturized PCR appeared in 1993 [32] with simple micro-machined chemical reactors with integrated heaters for PCR in Lawrence Livermore National Lab [29]. Swerdlow et al. [33] studied PCR in thin fluidic capillary tubes and used air forced convection for thermal management. They reported that they could decrease the PCR cycle time from 1 to 4 h (which is in conventional machines) to 20 min. Huhmer and Landers [34] studied the PCR for the sample in thin glass capillary tube using Tungsten lamp for heating and utilized air forced convection for cooling thermal management. They reported 65 C/s and 20 C/s for heating and cooling, respectively. Lee et al. [31] used infrared (IR) heating and water impingement cooling technique for PCR in thin glass capillary tubes. They reported a temperature rate of 65 C/s and 80 C/s for heating and cooling processes. They also studied two other cooling methods, natural convection and air forced convection, which performed 2 C/s and 6 C/s temperature ramps, respectively.

Khandurina et al. [35] utilized a compact thermal cycling assembly based on dual Peltier thermoelectric elements coupled with a microchip gel electrophoresis platform for a PCR microchip. They reported temperature ramps of 2 C/s for heating and 3–4 C/s for cooling. Lagally et al. [36] used an integrated microfluidic device which consists of submicroliter PCR chambers etched into a glass substrate. They used nitrogen flowing over the top of the chip for cooling and thin film heaters and reported cooling/heating rates of around 10 C/s. A similar thermal management is used in Ref. [37]. In another study by Lagally et al. [38], the authors improved the heating/cooling temperature ramps to 20 C/s utilizing an integrated PCR-CE device including micro-fabricated heaters and resistance temperature detectors (RTDs) within the PCR chambers. Niu et al. [30] used a PDMS-glass hybrid micro PCR chip and zigzag shaped Pt heater for heating and a fan for forced convection cooling. They reported 10 C/s and 4.6 C/s as heating and cooling temperature ramps of the sample. For DNA amplification, a PDMS-silicon chip was designed and optimized by Bhattacharya et al. [39]. The thermal management is done by a current controller with a power MOSFET serving as a pulse width modulation device by varying the duty cycle of the gate voltage as a switch. The heating and cooling temperate ramps are reduced by a factor of ten from the conventional thermal cycling machines.

V. Conclusion

A Thermoelectric cooling & heating system is used in Thermal cycling application. The literature exploits Single TEC to upto 6 TECs are used for achieving the cooling and heating with a DC power supply. Termoelectric cooler based devices provide the design simplicity of both heating and cooling given a suitable heat-sink. The solid-state Peltier blocks are utilized in thermal cyclers to both heat and cool by controlling the direction of an electrical current. Advanced Peltier systems can heat and cool the block at a fast rate, enabling fast PCR, to complete more PCR runs in a day. Conventional Techniques are Complex in design, requires an adjunct cooling/heating method when used for thermal cycling.The literature regarding the investigation of Thermoelectric cooling and heating using different modules has been thoroughly reviewed. From the review of the pertinent literature presented above, it can be inferred that thermoelectric technology using different modules used for cooling as well as heating application has considerable attention. Thermoelectric coolers to be practical and competitive with more traditional forms of technology, the thermoelectric devices must reach a comparable level of efficiency at converting between thermal and electric energy.

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