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Original Article

Improved Etching Performance Using PTC Heater: A Comparative Analysis with Traditional Heating System and Temperature Effect on Machined Geometries

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Abstract *- Positive Temperature Coefficient (PTC) heaters offer precise temperature control due to their material property, which shows high resistance to temperature. The proposed design of the etching system based on a PTC heater is compared with an ordinary resistor-based system in terms of performance. The analysis includes power consumption, temperature deviation, geometrical deviation, and machining cost. The comparative result shows that the PTC heater-based system maintains temperature with a deviation of ±0.5 °C, compared to ±1.5 °C for the conventional resistor-based system. The total power consumption was reduced in the PTC heater-based system to 0.44KWh from 1 kWh. The overall analysis shows a reduction in power consumption, which ultimately results in a cost reduction and improved product quality. This PTC heater-based system approach shows an alternative to the conventional ordinary heater-based etching system.*

Keywords *- PTC Heater, Temperature, Material Removal, Control System, Power Consumption, Geometrical Deviation.*

1. Introduction

Chemical etching plays a critical role in manufacturing industries such as electronics and aerospace components, MEMS devices, medical implants, etc., where precise manufacturing of microstructure is essential [1]. It is a commonly used machining process due to its advantage of low-cost manufacturing and is used in mass production without any mechanical stress on components, which is generally observed during the machining process and affects the material properties of components [2]. In the conventional chemical etching process, initially, light-sensitive photoresist is patterned on the substrate using the photo film. The exposed substrate is immersed in a chemical solution for further reaction and material removal by a controlled corrosion process.

The chemical solution, also called an etchant, is heated using the normal immersion heaters or coils, called ordinary heaters, as shown in Figure 1. This conventional etching process has some limitations, even though it is useful in mass production [3, 4]. The major limitation of the conventional etching process is the uneven distribution of heat, in which the chemical solution near the heater shows a higher temperature than the remaining solution, which creates localized hot spots, [3, 5]. This leads to a higher etching rate near the heater, which results in surface defects and geometrical variation due to variation in undercut [4].

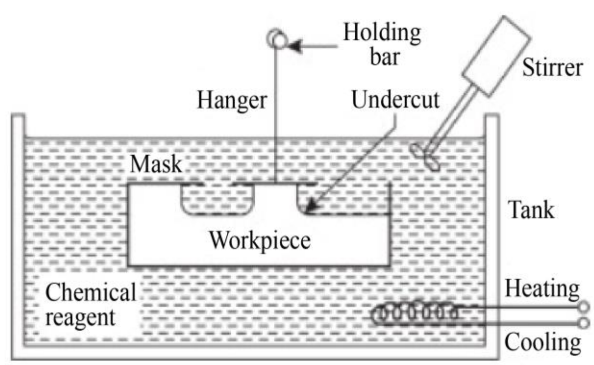


Fig. 1 Conventional etching method

The other reason behind the poor performance of the chemical etching process is due to the simple ON/OFF of the etching system and the inability to control the precise temperature of the chemical solution. The most used etching setups are built using the powder-coated SS containers, in which higher heat losses are observed [5]. These limitations impact the product quality, manufacturing cost, and change of etching solution property due to high variation in temperature. For example, uneven heating during PCB etching can cause inconsistent etching rates, leading to defects in circuit patterns and reduced device reliability. In aerospace manufacturing, temperature variations during etching can produce surface defects and compromise the structural integrity of precision components such as turbine blades and sensors.

In view of the above limitations, the solution to the precise temperature control needs to be implemented. In many industrial applications, the PTC heaters are used for precise temperature control and low power consumption. Here, in the chemical etching process, the PTC heaters can be used as the indirect heating element for maintaining thermal stability and improving the performance of the etching process [6, 7], apart from the PTC heaters, various heating and cooling systems implemented in industries such as thermostatically controlled heating systems, heat exchangers especially when very high precision in machining is required [3, 4].

M. Wang et al. demonstrated the basic working principle of PTC heaters based on the Curie point, where the material undergoes a phase transition. Beyond the curie point, the material resistance increases exponentially, which results in self-regulating the temperature [7]. This self-regulating temperature of PTC materials plays an important role in its application in industrial processes. W. Zhang et al. compared the superior temperature control accuracy of PTC heaters with ordinary resistors.

The PTC material maintained the accuracy of ±0.01°C, and a very negligible variation in temperature was observed from the pre-defined temperature when the temperature rises above the Curie point [8]. M. H. Park discussed the heating performance characteristics of high-voltage PTC heaters and how it is useful for electric vehicles [9]. C. Cho et al. also demonstrated the role of PTC heaters in reducing energy consumption in electric vehicles and low-power industrial heating systems[10].

H. S. Kang et al. did a numerical analysis of the lightweight design of PTC heaters to increase thermal efficiency by reducing material usage [11]. Y. H. Shin et al. experimented with the performance of PTC heaters used in EV heating systems, confirming their thermal response, stable output, and safety under varying voltage and current loads [12].

R. Wang et al. studied the dynamic thermal control performance of positive temperature coefficient material based on a novel heat transfer model considering internal heat transfer [13]. Advanced non-contact type etching techniques are used for machining hard, brittle, and transparent materials, such as laser, for precise and fast machining [14]. There are various etching techniques developed in the electronics domain applicable for IC packaging, where etching is a more reliable technique [15]. The literature review shows that a more cost-effective, easy-to-handle solution for etching should be provided, and the application of a based system can be tested.

The reasons behind the selection of the PTC-based etching systems are the localized hot spots and fluctuations in the etching rate, which cause the geometrical deviation and wastage of materials. The conventional etching setups used in industry, where temperatures are controlled by basic temperature sensors and a simple ON/OFF mechanism, which is not reliable.

The solution proposed in this manuscript is to use PTC heaters instead of traditional immersion heaters to eliminate the various heat losses and maintain the precise temperature throughout the chemical solution.

The literature shows that the material property of PTC material, i.e., Curie point, adds the advantage of maintaining accurate temperature by increasing the resistance. By implementing the PTC heater, the temperature can be maintained to the accuracy of $\pm 0.01^{0}$C °C, which could not be possible in a conventional etching process.

2. Design, Development, and Testing of Etching Setup

2.1. Working Principle of Etching Setup

A PTC heater designed to operate on a 12V DC supply will increase its resistance as the temperature increases and help to maintain the required temperature. It is called a self-regulating temperature device [10, 12].

The DC supply-based heater increases the safety of the system and energy efficiency. Here, the application of PTC heaters is suggested by an indirect heating mechanism where PTC heaters are installed on pipes that carry circulating water, and the chemical chamber is situated inside a water chamber.

In this indirect heating, the water is circulating through the pipe on which PTC heaters are mounted and will be continuously heated [13, 16]. The chemical solution bath is kept inside the water bath, in which the heated water transfers the heat to the chemical bath by conduction as indirect heating.

As seen in Figure 2, this arrangement guarantees even heat distribution and avoids localized overheating, which might otherwise deteriorate the etching solution and affect the quality of the final product. Air pumps are incorporated into the system for oxygenation and stirring in order to promote an effective etching process. In order to avoid sedimentation and guarantee uniform material removal, the pumps aid in agitating the solution.

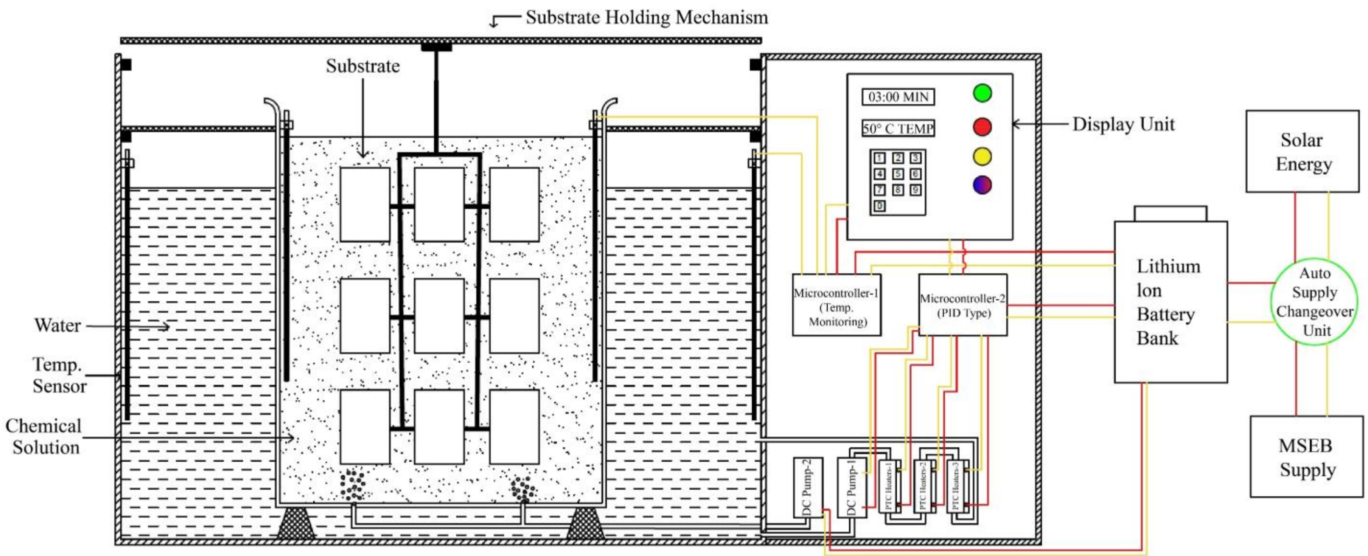


Fig. 2 Schematic diagram of the proposed chemical etching system

By promoting oxidation, oxygen accelerates the reaction and produces faster and more reliable etching. The most important parameter of the system is temperature control, for which a PID-type temperature controller is used, which dynamically modifies the heating power to maintain the desired temperature after a PT100 sensor provides accurate temperature readings [13, 16]. To monitor temperature distribution and ensure uniformity throughout the solution, K-type sensors are positioned at different points throughout the system, as seen in Figure 3 [16, 18].

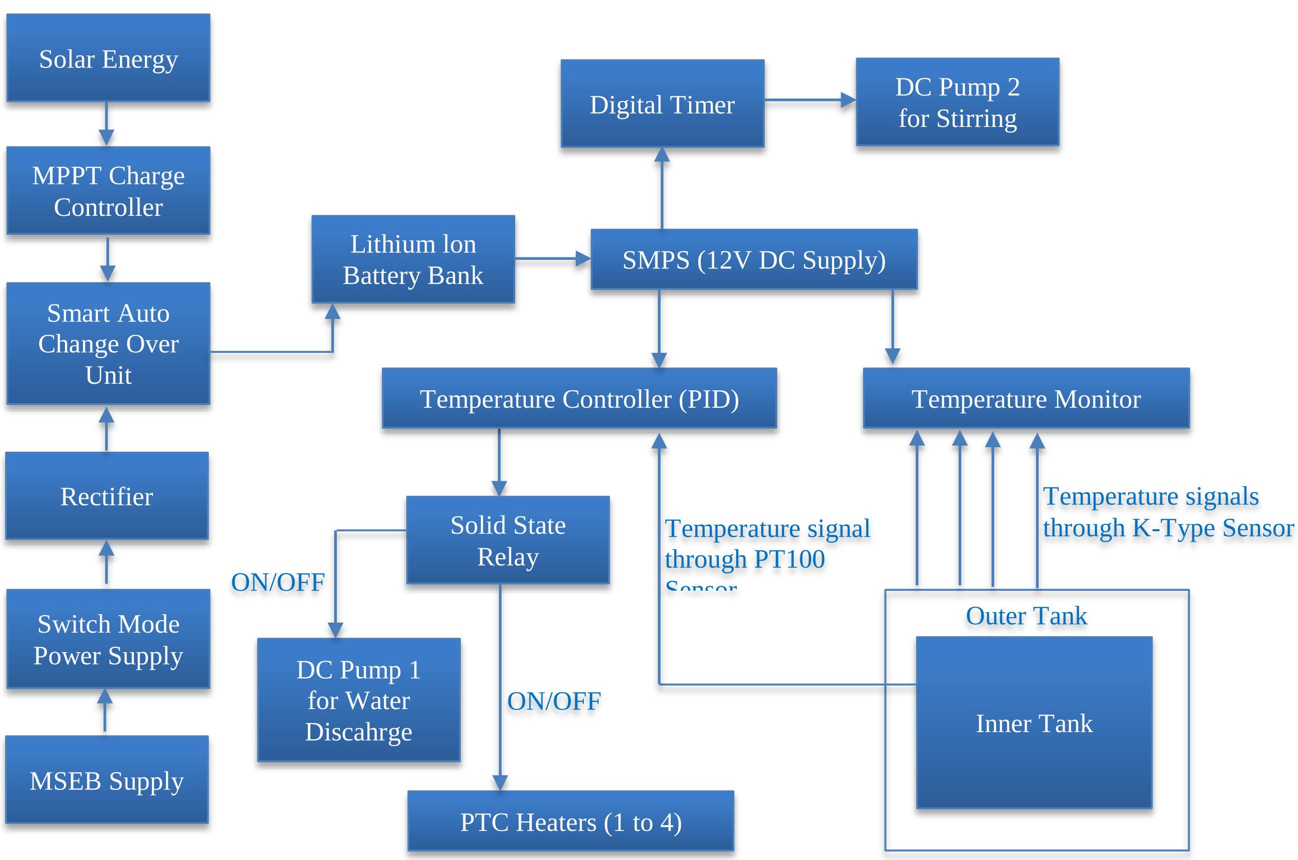


Fig. 3 Working principle of the chemical etching setup

To reduce energy losses related to AC to DC conversion, the suggested chemical etching setup is made to run exclusively on a DC power source. By using banks of lithium-ion batteries, the system ensures a dependable and efficient power source, reducing operating costs and improving dependability. To maximize energy use and encourage sustainability, the batteries will be charged using a combination of solar energy and MSEB (Maharashtra State Electricity Board) supply [17]. The system uses a programmable timing mechanism to regulate the etching process in order to increase automation and efficiency. This minimizes excessive etching and maximizes energy consumption by guaranteeing that the reaction takes place for the exact amount of time needed. Process consistency and product quality are further improved by the ability to automate the on/off cycles. Based on the specifications defined, the proposed chemical etching setup is designed for efficient indirect heating using PTC heaters, precise temperature control, low power consumption, and a higher quality of manufactured product.

2.2. Electrical Diagram of Etching System

The electrical circuit of the chemical etching setup is designed for accurate temperature measurement and control, and the whole system is powered by UPS (Uninterruptible Power Supply). All the electrical components are integrated at one location from which the whole system can be turned ON/OFF. The total of four PTC heaters, each rated at 12V and 60W, are powered by a regulated 12V DC output from 12V SMPS (Switched-Mode Power Supplies), which are used in the heating system for stable heater performance. The PTC heaters and the water pump are turned on and off by a microcontroller-based Solid State Relay (SSR) in response to real-time temperature feedback. A PT100 sensor is integrated with a PID controller (Multispan UTC114), which continuously monitors the temperature and modifies the heater's operation to maintain the appropriate thermal conditions. Dynamically controlled voltage and current ensure effective power use and avoid overheating or fluctuations that can degrade the quality of the etching.

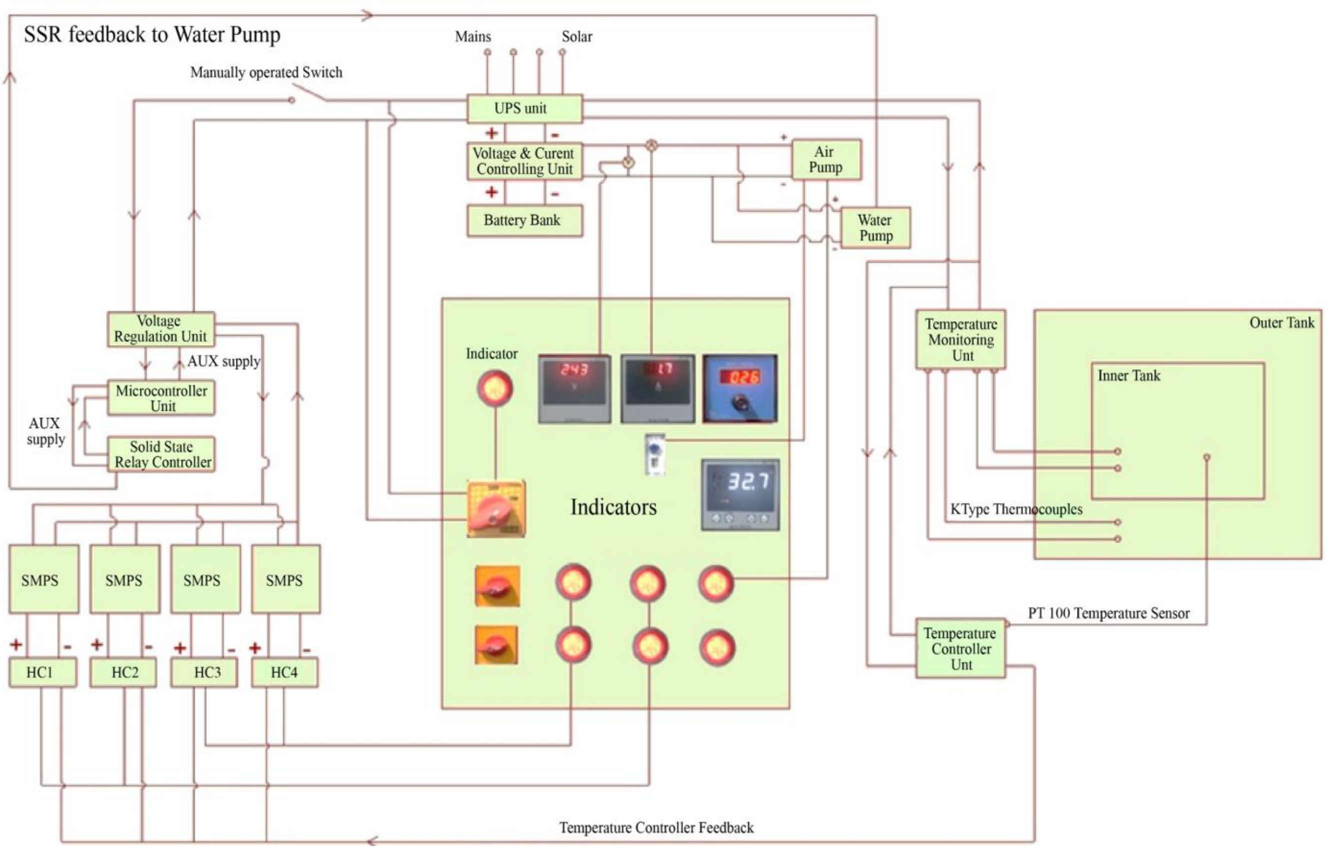


Fig. 4 Electrical diagram of chemical etching setup

A DTI 3012 12-channel temperature monitor is used to monitor the temperature connected through the K-type thermocouples, which are immersed in a chemical solution at different locations. As seen in Figure 4, this ensures uniform heat distribution throughout the solution and allows for real-time temperature monitoring.

The proposed system uses the Multispan make voltmeter and ammeter connected in parallel and series, respectively, to monitor the in-process power consumption. Also, the light indicators provided on the panel identify the working conditions of the system's devices, such as pumps, and the number of hours ON/OFF.

2.3. Design of PTC Heater

A PTC heater is designed to be mounted on a GI pipe through which water is going to pass and be heated. With a 2-inch diameter and a 6-inch length, the heater is shaped like a cylinder and is designed to transfer heat to the water flowing inside the GI pipe as efficiently as possible. To avoid heat loss, the PTC heaters are firmly fixed on the GI pipe without any air gap. The PTC material used to make the heating element has a positive temperature coefficient, which enables effective heat generation and temperature self-regulation. Cr20Ni80, a widely used alloy renowned for its exceptional resistance to heat and corrosion, is the connection wire in use as shown in Figure 5.

Milinex paper is used as an insulating material to shield the heating element and stop electrical leaks. Minilex is perfect for heating applications because it has superior electrical insulation qualities and can tolerate high temperatures. Because of its broad voltage operating range of 12-48 volts, the PTC heater can be used with a variety of power supply configurations.

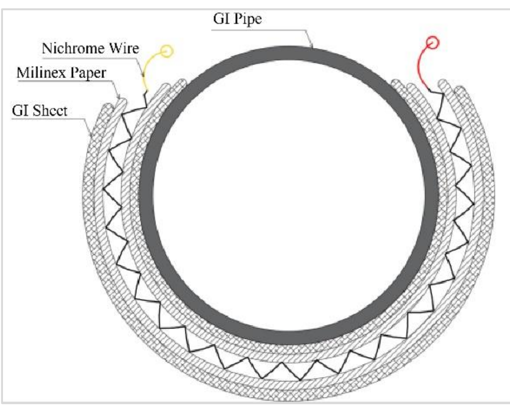


Fig. 5 Sectional view of PTC heater coil

To calculate the I (current) flowing through the heating coil based on V (Voltage) across the heating coil and R(T) is the resistance of the PTC heater coil at defined T (temperature), the following equation is considered [18, 19]:

$$\mathrm{I} = \frac{V}{R(T)} \tag{1}$$

Whereas R(T) is defined based on Tref (Reference temperature) and α (temperature coefficient of resistance), calculated by,

$$R(T) = R_{Initial} * [1 + \propto (T - T_{ref})] \tag{2}$$

P is the power dissipated by the heater coil, which can be calculated using:

$$P = I^2 * R(T) \tag{3}$$

The above equations help in understanding the electrical and thermal characteristics of the PTC heater coil, enabling efficient control and optimization of its performance in several heating applications. The details of the PTC heater coil are mentioned in Table 1.

Table 1. Specifications of DC-PTC heater coil

Shape	:	Cylindrical
Dimensions	:	Diameter of 2 inches, Length of 6 inches
Heating Element	:	Nichrome Wire of 10 Gauge and 180 Turns
Connection Wire	:	4mm Copper with Cotton Sleeve
Insulating Material	:	Milinex Paper
Voltage Range	:	12V-100V
Power Rating	:	60W
Temperature Coefficient of Resistance (α)	:	Positive (characteristic of PTC materials)
Mounting on	:	Galvanized Iron (GI) pipe for efficient heat transfer to the water passing through the pipe

2.3.1. Fabrication and Testing of PTC Heater

The experimental setup for testing the DC supply-based PTC heater coil involves several devices and a block diagram, as shown in Figure 6.

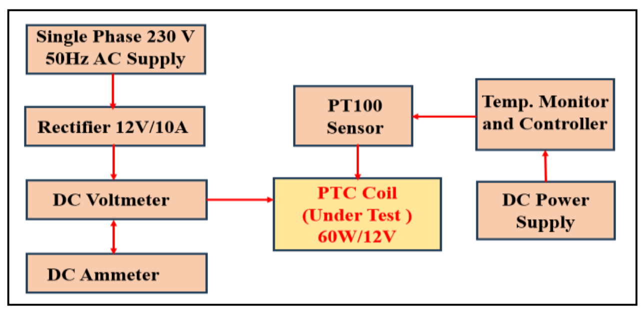


Fig. 6 Block diagram of PTC heater test coil

To validate the results, a prototype model of the PTC test coil is demonstrated in the lab. The rectifier module in this test example transforms the single-phase 230V 50Hz AC supply from an autotransformer into a 12V DC supply. The PTC test coil is then exposed to a regulated DC supply in order to evaluate different outcomes, as shown in Figure 7.

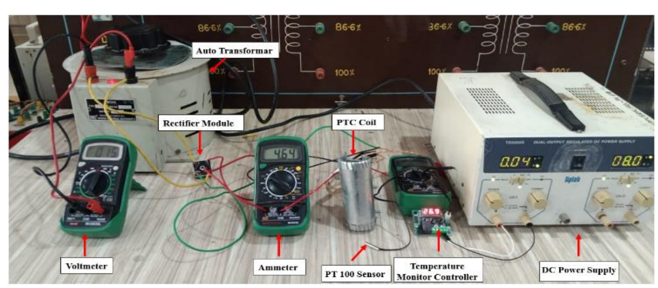


Fig. 7 Experimentation platform of PTC heater test coil

The experimental process involves progressively increasing the voltage applied to the PTC coil while obtaining corresponding voltage, current, and temperature readings. Throughout the experiment, safety measures are taken to guarantee adequate insulation and avoid electrical hazards. Following data collection, analysis was done to determine the PTC heating coil's power consumption (Wattage) and make inferences about how well it would function and behave under the necessary circumstances.

Table 2 shows the experimental readings of voltage, current, temperature, and power consumption of a single PTC heater test coil.

Table 2. Measured parameters of the DC-PTC heater

Time (Min)	Voltage (Volt)	Current (Amp)	Temp. (^{0}C)	Power (Watt)
2	12.14	4.74	81.18	58.11
4	12.14	4.73	81.09	59.80
6	12.13	4.73	82.09	59.80
8	12.14	4.73	82.04	59.74
10	12.14	4.74	82.04	58.72
12	12.13	4.74	82.04	58.79
14	12.18	4.76	82.09	58.91
16	12.14	4.73	82.10	58.94
18	12.14	4.72	82.09	59.74
20	12.13	4.74	82.09	59.78
Avg.	12.14	4.74	81.89	59.23

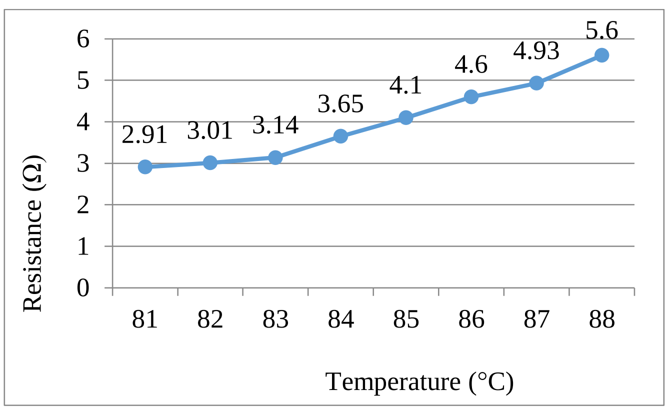


Fig. 8 Temperature Vs. Resistance of the PTC heater test coil

The tested results of the DC-PTC heater show an average voltage, current, and temperature of 12.14 volts, 4.74 amps, and 81.89 ^{0}C, respectively. Over a period of 0 to 20 minutes, measurements were taken every 2 minutes. Additionally, the power consumed by the heater is calculated to be 59.23 watts/hour. A very minimal deviation in temperature was observed during the hardware test. Figure 8 shows the relation between the temperature and resistance of the DC-PTC heater coil.

The consistency in temperature can be attributed to the inherent characteristics of PTC heaters, where their resistance increases significantly with temperature, leading to self-regulation and limiting the rise in temperature.

2.4. Modelling and Fabrication of Etching System

The CAD model of the etching system was created to better understand electrical connections and the positioning of the components. The whole etching system was fabricated based on industrial ply, which is suitable for the required application due to its non-corrosiveness, as shown in Figures 9 and 10.

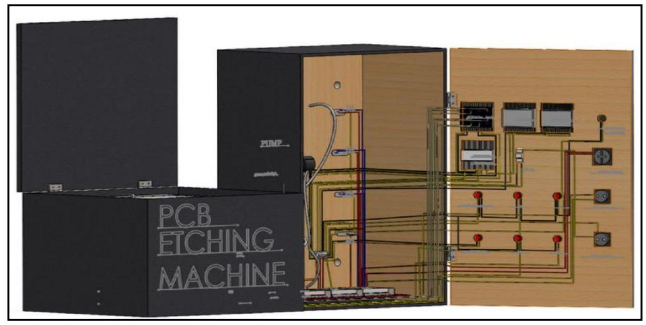


Fig. 9 CAD model of the etching system

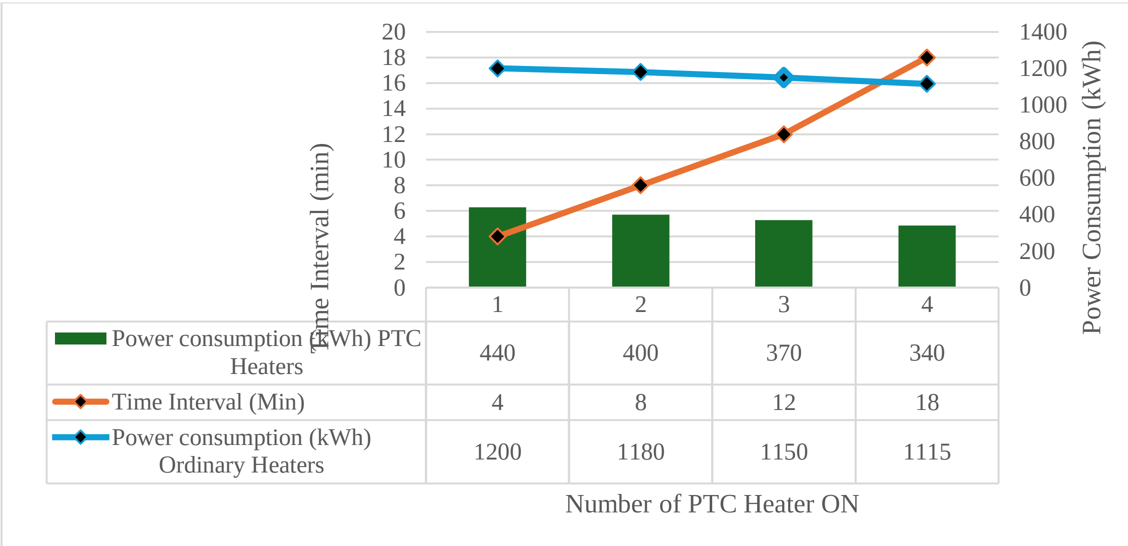
As part of the designing and fabrication of the etching system, one of the aims to reduce the cost of setup by 50% has been achieved by implementing the PTC heaters.

Fig. 10 Actual fabricated system

3. Testing of PTC Heater-Based Etching System and Comparison with Ordinary Heaters

3.1. Power Consumption

The actual prototype of the etching system has been developed, incorporating a PTC heater and DC supply as per the initial considerations. The total power consumption for the setup was calculated based on displayed values on the control panel, with a voltage (V) of 244V and a current (I) of 1.8A, resulting in a wattage (W) of 440 watts, as shown in Figure 10. This calculation reflects the scenario when all four PTC heaters, each with an approximate wattage of 60W, are operating to achieve the required temperature. Once the desired temperature of the etching solution is achieved, the system will operate only one PTC heater to maintain the temperature. This type of PTC heater controlling system has lower power consumption than an ordinary heater, where 1100 watts of continuous power consumption is observed, resulting in a lower cost of manufacturing.



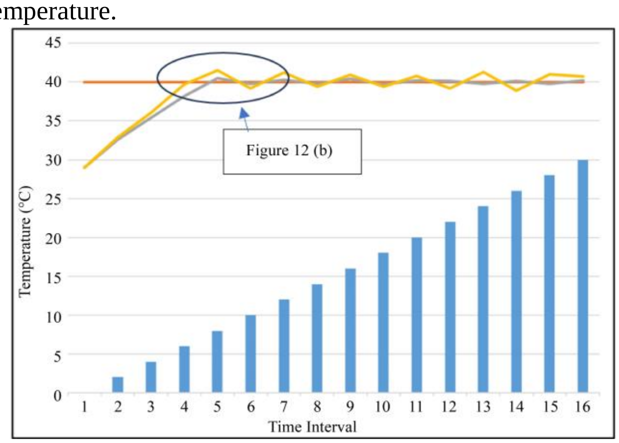
	1	2	3	4
Power consumption (kWh) PTC Heaters	440	400	370	340
Time Interval (Min)	4	8	12	18
Power consumption (kWh) Ordinary Heaters	1200	1180	1150	1115

Fig. 11 Comparison of wattage consumption of PTC heater Vs. Ordinary resistor-based etching system

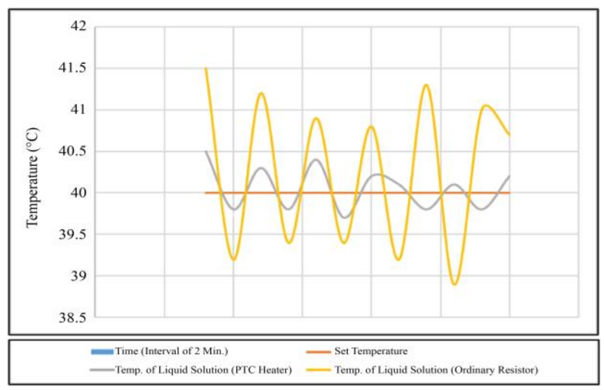
The use of a PTC heater system in PCB (printed circuit board) manufacturing (considering the most used application) leads to a reduction in costs by 10 to 15%. This cost-saving is primarily due to the lower power consumption of PTC heaters compared to conventional heaters. However, if the number of components increases, the cost will be reduced.

3.2. Temperature Deviation

The accuracy of the PTC heater in maintaining the temperature is validated through a series of tests and compared with an ordinary resistor. The testing process began by heating the liquid solution from an ambient temperature of 29°C. A set temperature of 40°C is chosen for the liquid solution. For the liquid solution, a fixed temperature of 40°C is selected. A multispan microcontroller with a temperature display is connected to a K-Type thermocouple and a PT100 sensor to measure and control the temperature. Different temperature readings were measured with a time interval of 2 minutes and plotted against the deviation. After around 8 minutes, the liquid solution reached a temperature of 40°C. Figure 12 (a) shows the temperature deviations with reference to the set temperature.



(a)



(b)

Fig. 12 (a) Comparison of measured temperature of PTC heater Vs. Ordinary heater-based etching system, and (b) Detailed deviation of temperature at the highlighted area in Figure 12 (a).

The plotted results indicated that the temperature deviations from the set point were significantly smaller in the case of the PTC heater compared to the ordinary resistor, as shown in Figure 12 (b). The range of temperature is maintained as follows;

$$\text{PTC Heater Temp. } (^0\text{C}) = 40\ ^{+0.5}_{-0.3}$$

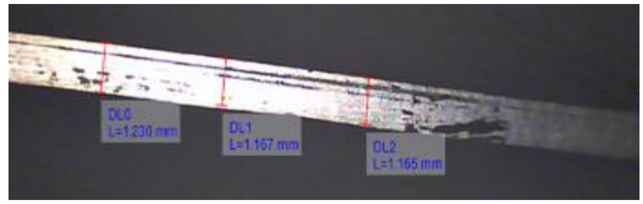
$$\text{Ordinary Resistor Temp } (^0\text{C}) = 40\ ^{+1.5}_{-1.1}$$

This demonstrates that the PTC heater provides more accurate and stable temperature control, confirming its effectiveness for precise thermal management in manufacturing.

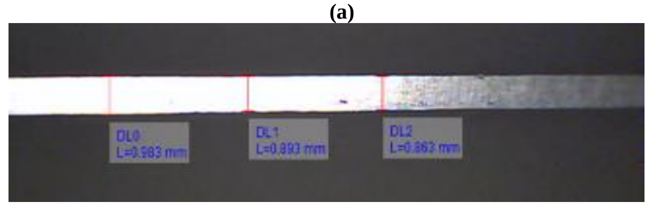
3.3. Geometrical Deviation of PCB lines and Measurement of Line Resistance

Sample PCBs (Printed Circuit Boards) were manufactured using chemical etching with two different heating methods: a PTC heater and an ordinary resistor. The initial masking of the copper-coated PCB sheet is measured to represent the PCB lines or geometry. After etching, the line width is measured for both heating methods and investigated as shown in Figures 13 (a) and (b).

Figure 13 (a) shows that PCB lines are over-etched due to non-maintenance of temperature, whereas Figure 13 (b) shows that proper etching of PCB lines is due to maintained temperature. This shows that the use of PTC heaters is more convenient for achieving accurate PCB lines. From Figure 14, it is observed that the ordinary resistor with its large temperature deviations could not maintain a consistent etching rate, resulting in varying widths and discontinuity of the PCB lines, resulting in high resistance.



(a)



(b)

Fig. 13 (a) PCB line etching based on ordinary resistor, and (b) PCB line etching based on PTC heater.

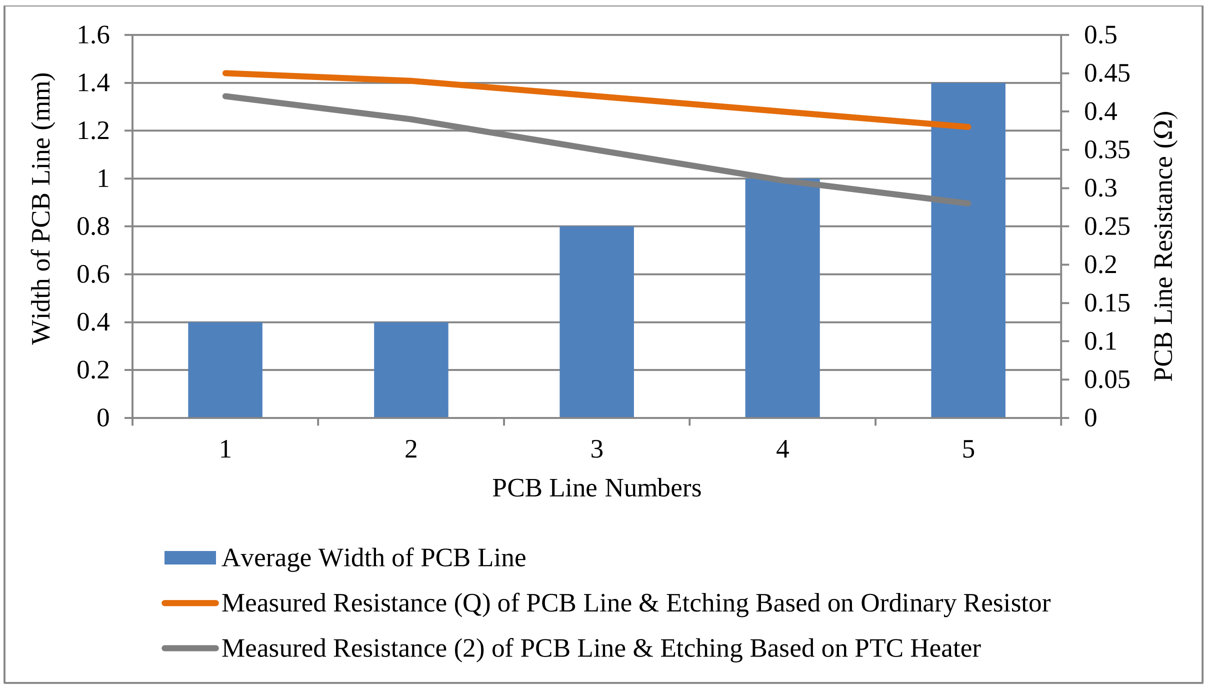


Fig. 14 Measurement of PCB line width and resistance against the etching with ordinary resistor and PTC heater

Meanwhile, the PTC heater, with its small temperature deviations, maintained a consistent etching rate, leading to uniform widths and continuity of the PCB lines and resulting in less resistance. These results show that the use of a PTC heater-based system produces higher quality PCBs with less resistance in lines, which is useful for better signal transmission.

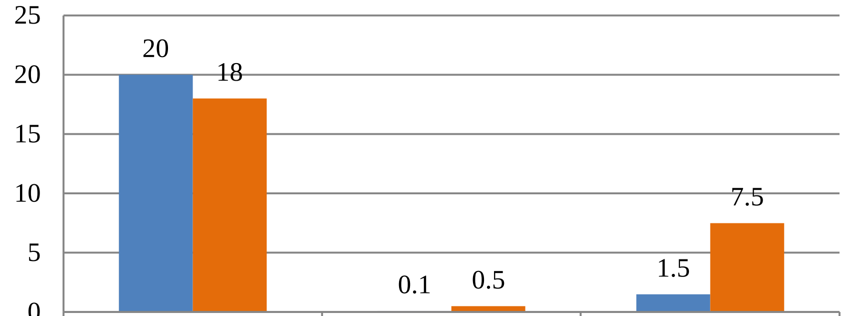
3.4. Machining Cost

The machining cost of the PCBs is based on manufacturing by ordinary resistor-based heaters and PTC heaters, and factors affecting the cost, such as PCB machining time and power consumption, are shown in Figure 15.

For a sample PCB size of 20cm*20cm, the machining time is around 18 minutes using an ordinary heater and 20 minutes with a PTC heater; the result shows no significant difference. The ordinary heater shows a lesser machining time due to an increased etching rate and faster temperature rise compared to the PTC heater-based system.

In terms of power consumption, the PTC heater system averages around 0.3 KWh, whereas the ordinary heater consumes about 1.5 kWh. For machining one PCB, the PTC heater-based system uses approximately 0.1 kWh, while the ordinary heater uses around 0.5 kWh.

As a result, the cost of machining a single PCB with the PTC heater is approximately Indian Rupees (INR) 1.5 compared to INR 7.5 with the ordinary heater system. The result shows that PCB manufacturing based on PTC heaters will be more cost-effective than ordinary heaters.



	Time (Min)	Power Consumption (kWh)	Cost of PCB Machining Per Unit in INR
PTC Heater Based Etching	20	0.1	1.5
Ordinary Heater Based Etching	18	0.5	7.5

PTC Heater Based Etching Ordinary Heater Based Etching

Fig. 15 Comparison of PCB machining time, power consumption, and cost of machining based on ordinary resistor and PTC heater

3.5. Geometrical Deviation

Figure 16 (a) shows that the etching of the component using a PTC heater-based system gives uniform etching across all four designated areas (I to IV). The consistency in material removal indicates that the PTC-based system provides precise temperature control, ensuring a stable and well-regulated etching rate. The indirect heating mechanism, coupled with efficient temperature regulation through the PID controller and PT100 sensor, ensures that the chemical reaction occurs evenly across the entire surface of the component.

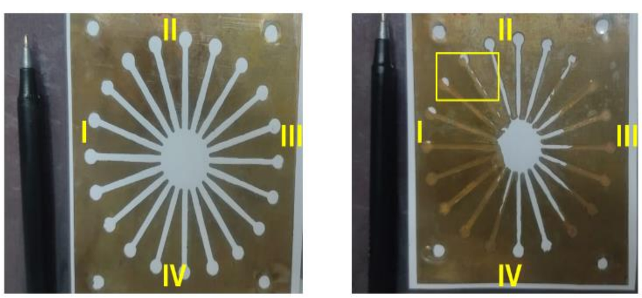


Fig. 16 Geometrical deviation of machined component based on (a) PTC heater, and (b) Ordinary resistor.

Meanwhile, the traditional etching method using the ordinary heater shows non-uniform etching across the same areas (I to IV), as shown in Figure 16 (b). The area highlighted by the rectangular box shows the non-uniform etching and variation in MRR due to temperature deviation, which results in a quality product.

The material property of the PTC heater shows better control over the temperature required for etching and produces better results compared to an ordinary heater-based system. This stability makes the etching process more accurate and repeatable by preventing localized overheating or underheating.

4. Conclusion

The results of the PTC heater-based system development and its comparison show a significant advantage over ordinary heaters. 1) The PTC heater-based system uses only 0.44 KW/h instead of 1 kW/h used by an ordinary heater-based system, which ultimately reduces the 10-15% cost of the component manufactured by the etching process. 2) The PTC heaters are self-regulating temperature types of materials that increase their resistance beyond the Curie point and maintain the desired temperature of etching. The deviation from the desired temperature in case of the PTC heart-based system is ±0.5 °C, compared to ±1.5 °C for ordinary heaters.

This result of less temperature deviation helps to regulate the etching rate and increase the quality of the product. 3) The overall calculation of the performance of the etching system shows that the PTC heater-based system consumed only 0.1 kWh of power (INR 1.5) per PCB versus 0.5 KWh of power (INR 7.5) for the ordinary heater, reducing the cost of PCB manufacturing by 80%. 4) The PTC heater provided uniform material removal, preventing defects caused by uneven heating compared to an ordinary heater-based system. 5) PTC heater-based system reduces environmental impact through lower power consumption and minimized material wastage. The PTC heater-based system proved to be a more energy-efficient, cost-effective, and reliable solution in manufacturing. This study did not systematically control certain environmental factors, such as ambient temperature and humidity, which may have a minor influence on the heating performance of the PTC system. Long-term durability testing of the PTC heating setup was not conducted within the scope of this work. Such testing would be valuable for assessing the system's sustained performance, reliability, and maintenance requirements under extended operational conditions and is suggested as a direction for future research.

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