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Development of a Coupled Thermal-Electrical Circuit Model for Peltier device in heat pump application for desalination systems

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ABSTRACT

Incorporating Peltier heat pump techniques into existing energy systems and designing new large-scale applications require an understanding of the modelling and analysis of the Peltier module at the system level. Developing a specific application model for the energy conversion process is crucial for understanding and predicting the performance of Peltier-based systems. From the point of view that the thermal domain of desalination system can be easily translated to electrical network system for heat transfer analysis. In the present research work a thermal and electrical submodel of Peltier module is developed from the fundamental physics principles with circuit perspective based on the governing of the operation of the Peltier modules. The two submodels are interconnected, reflecting the bidirectional coupling between the thermal and electrical aspects of the Peltier module. In particular, the development and explanation of thermal capacitance associated with the heat capacity of material of the Peltier element is also described. Further, the model is extended for the application in heat pump in desalination system. The verification of the developed model simulation is carried out with the Peltier module, mounted on a heat sink and cold thermal mass, functions to actively pump the heat produced from the heat source in cyclic manner. A Proportional-Integral-Derivative (PID) controller is incorporated to the developed model for the Peltier module for the further verification of system temperature control within 1°C range for the set point temperature. The Experimental arrangement is designed and developed for the desalination system with the Peltier module for the validation of model.

Keywords: Peltier module, heat pump, thermal model, circuit analysis, seebeck effect, desalination system

1. INTRODUCTION

Due to the escalating global challenges such as freshwater scarcity and climate change, innovative and sustainable technologies and solutions are imperative for energy efficient system. Conventional desalination methods often consume significant amounts of energy, primarily from fossil fuels sources, leads to increasing carbon emissions. Non-conventional desalination system with advanced thermal management technologies, such as heat pump, are developing to mitigate the environmental impact and enhance the energy efficiency of desalination systems. [1][2]

Despite the potential advantages of integrating Peltier modules into heat pump-based desalination systems, there is need for comprehensive modelling and analysis to optimize their performance and ensure efficient operation.

1.1 Motivation

In the realm of Peltier device modelling, the network method of electrothermal analogy has been a prevalent approach in the literature [3][4]. Some models explain dealing with analogous method in the SPICE circuit simulator using analog behavior modelling [5][6]. While numerous models leveraging the network method and SPICE simulation can be found in literature [5,6]. There exists a significant gap concerning the development and clarification of thermal capacitance in Peltier module models. Specifically, many existing network thermal models do not consider the thermal capacitance associated with material of the Peltier element.

Presently the work is in progress on the design and development of a hybrid source thermal desalination unit based on Peltier effect with the latent heat recovery in the system [1]. We use Peltier module as a heat pump for latent heat recovery in close loop operation of energy transfer between the evaporation chamber and

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condensation chamber in the desalination unit. In this hybrid source thermal desalination unit, we require zero or minimum temperature between the condensation and evaporation whereas the Peltier module is sandwiched between these chambers for latent heat recovery working at their best coefficient of performance. Therefore, we need to have stability of minimum temperature difference with the variation of current applied to the Peltier module for performance in the latent heat recovery within the system.

From the point of view that the thermal domain of desalination system can be easily translated to electrical network system for heat transfer analysis, a model is developed with circuit perspective based on the physics of operation for the Peltier module. In this research work, thermal and electrical network of the Peltier module based on three port energy system is developed from the fundamental principle. Specifically, the development and explanation of thermal capacitance associated with the heat capacity of material of the Peltier element is analysed and described. The system is developed and simulated on the MATLAB environment incorporating the PID controller for set point control of temperature for the heat source. However, the developed model of the Peltier module can be further integrated in the practical desalination system.

2. PHYSICAL PHENOMENON

The operation of the Peltier module is based on the five fundamental physical phenomena like seebeck effect, peltier effect, joules' heating, Thomson effect, and thermal conduction. Figure 1 shows the cooling operation of the Peltier module when dc source is applied to the Peltier module. The dotted square represents the single semiconductor column soldered to electrically conducting material like plated copper on each side is connected to a dc source where the Peltier effect is happening at the junction absorbing energy ($\alpha I T_c$) and transferring energy ($\alpha I T_h$) at the other junction. The joules' heating effect is happening throughout element and shown as half of it (I^2R) is moving to both side of the junction. Similar to the joules heating effect, Thomson effect (Ʈ$I\Delta T/2$) is happening throughout the peltier element. There is thermal conduction due to internal temperature difference (T_h - T_c) between the cold junction and hot junction. The plated copper is sintered to ceramic substrate through thermal interface material where thermal conduction is happening due to external temperature difference (T_H -T_C) at the ceramic surface of the peltier module shown outside the dotted box in the figure.

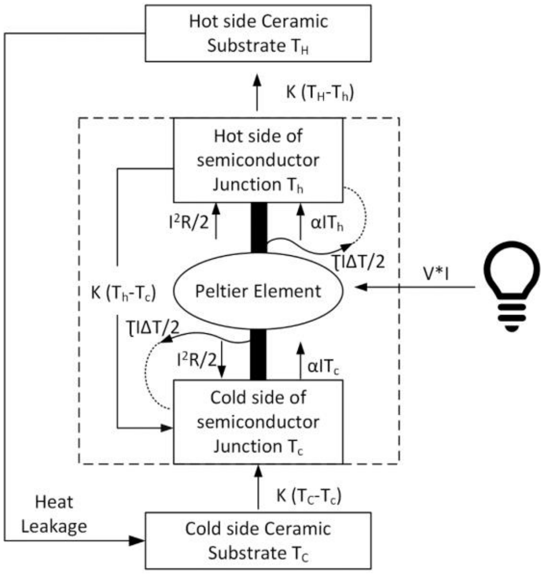

Fig 1: schematic of physical phenomena in the Peltier module

2.1 Electric current flow: Seebeck effect

Electrons should diffuse from the hot end to the cold end when there is a temperature difference between the two ends of the material. When the electrons diffuse from hot side to the cold side then a positive voltage must be developed to stop the flow of electrons. The open circuit voltage developed due to the temperature difference is the Seebeck voltage. This will be the case when the n-type material is used. Similarly, if p-type material is used, a negative open circuit voltage will be observed.

2.2 Heat current flow: Peltier effect

Consider a n type thermoelectric pellet plated with coper at both the ends of the pellet and it is isothermal with an electric current forced in top contacts. After the applied potential, the electrons flow with an average" drift velocity" from bottom to top. The Peltier effect leads to a redistribution of energy. If heat is absorbed at the junction, the average energy of the electrons increases. This increase in average energy means that the electrons have higher kinetic energy, which could potentially lead to random thermal velocity to electrons which finally an effective increase in the average energy at which current flows across the junction.

3. CIRCUIT PERSPECTIVE

From the physical phenomena we understand that we must have two sub model for the Peltier module to represent the thermal part and electrical part and that sub model should be interrelated and be able to indicate the multiphysics effect of the energy conversion happening in the Peltier module.

3.1 Thermal Submodel

The thermal submodel of the Peltier module should focus on the heat transfer aspects considering the special and temporal temperature distribution within the device, thermal gradients, and the impact of external environmental factors affecting the thermal boundary conditions. For this we must find the heat source term, thermal resistance, thermal capacitance and thermal sink and convert them into equivalent electrical network based on the electrothermal analogy. The heat source term will be acting as current source or voltage source depending on the effort and flow parameters for the network. Thermal resistance and thermal capacitance will be passive elements similar to resistor and capacitor in the electrical network. The thermal sink will define the reference for the thermal network similar to ground in the electrical network.

If we start from the outer ceramic substrate to inside the Peltier module at x=0 or at x=L, the interface between the plated copper and semiconductor material will provide the most important heat source term as explained in the previous due to flow of heat current. Depending on the direction of flow of current due to applied potential heat will release at one junction and absorbed at another junction. Therefore, heat source term due to the Peltier effect happening at x=0 and at x=L represents controlled current source as shown in the figure 2. Here, the internal temperature at the junctions T_h and T_c will be a controlled input voltage to the current source developed due to Peltier effect. However, these internal temperatures can also act as a node voltage if we have infinite thermal reservoir or source as in thermal desalination unit in our future experiment.

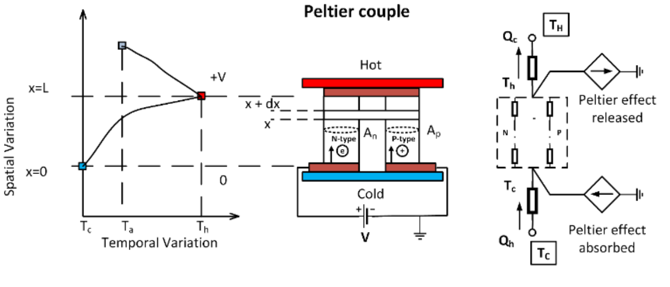

Fig 2: schematic of Peltier element with spatial and temporal variation with Peltier heat source

If we further go inside the junction into the material of the Peltier module, other two steady heat source term are there due to the flow current and temperature gradient. In the control volume at x and x + dx , controlled current source term due to the flow of current through the material of the Peltier element acting as a resistance for the flow of current representing the joule heating phenomenon in the Peltier module. Due to the inhomogeneous materials or segmented material and the temperature dependent seebeck coefficient, flowing current will give rise to heat source term due to Thomson effect and can be represented as controlled current source term. These current controlled current sources are connected to central point so that a change in the seebeck coefficient value can be visualized in the control volume. However, with the temporal variation or in the transient, the heat flux in the control volume will be affected by the change in the stored energy. Therefore, the heat capacity due to the material of the Peltier element is incorporated as the transient term as shown in the figure 3.

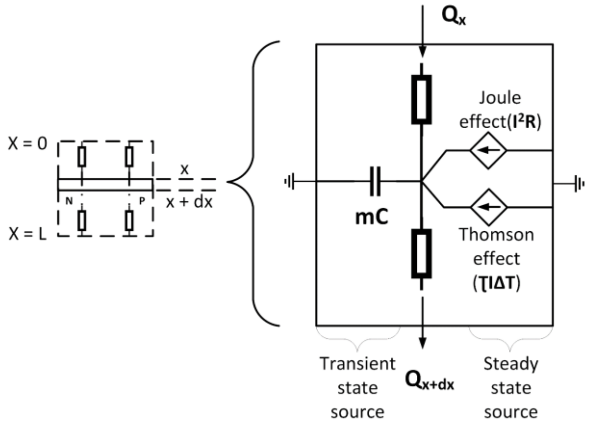

Fig 3: Elemental cross section of the Peltier element

Further,, to visualize the steady state source term and transient state source term in the figure 3, we can make a direct comparison of equivalence of heat transfer in the control volume by formulating differential equation below where symbols have their usual meaning.

$$dQ = Q_{(x+dx)} - Q_x \tag{1}$$

$$dQ = mC_P \frac{dT(x)}{dt} + I^2 \frac{\rho\big(T(x)\big)}{\alpha} dx + d\alpha\big(T(x)\big)T(x)I \tag{2}$$

$$I_{th} = C_{\text{th}} \frac{dv_{\text{th}}}{dt} \tag{3}$$

$$c_{th} = mC_p \tag{4}$$

Now, consider the temperature gradient in each microelement is negligible in 1-D, we can develop an equivalent thermal model through lumped parameters analogy. However, we need to find out the Biot number for the distributed or lumped parameters for electro analogy. Here, for adiabatic leg condition of the Peltier element lumped material is considered to further develop the model as shown in the figure 4 The Peltier material is lumped as one thermal resistance whereas the controlled current source due to joules heating and

Thomson effect are considered to distributed evenly owing to symmetrical structure at both the junction. Similarly, thermal capacitance is divided into two parts dedicated to cold side $mC_c/2$ and hot side $mC_h/2$ in the space varying from x=0 to x=L of the Peltier element.

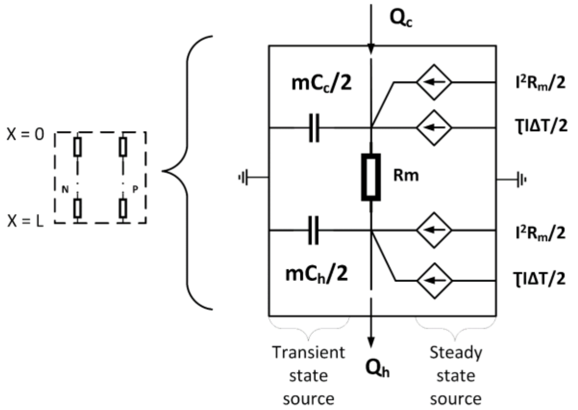

Fig 4: Spatial thermal circuit of the Peltier element

The value of Thomson coefficient compared to other Peltier parameters is very much low such that we can ignore the current source term offered due to the Thomson effect. In the case of desalination system the temperature difference across the Peltier module is minimum, therefore we can easily neglect the heat source term due to this effect. Also, the value of heat capacity offered by the Peltier element can be considered as equal.

The reference for the steady and transient heat source terms are same that is zero kelvin. However, we can also consider the ambient as a reference temperature, but it will give bipolar nature of voltage for heating and cooling application in electrical domain. The final thermal sub model of the Peltier module is shown in figure 5 excluding the ceramic substrate.

3.2 Electrical Submodel

The electrical submodel should focuses on the electrical characteristics of the Peltier module, considering the voltage, current and load for the power generation. Similar to the thermal model where we identified the heat source term here we have to identifies the electrical source term. As discussed in the previous section of physical interpretation of electric current flow in the Peltier module, potential is developed due to the temperature difference where the temperature is acting as a voltage node for the Peltier module. The material of the Peltier element will offer the resistance for the flow of electrons through the cross section of the material. Therefore, the source term in this model will be the voltage-controlled voltage source connected to an electrical resistance whose value will depends on the thermal submodel is shown in figure 6. The current from the Peltier module will depend on the load connected across it for power generation.

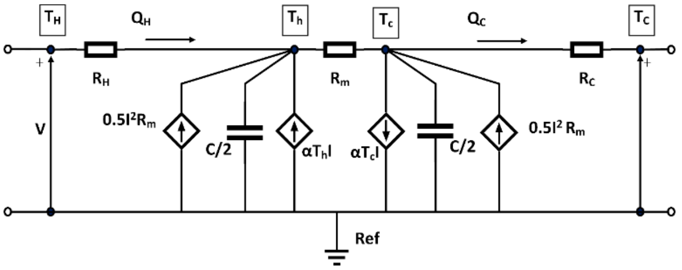

Fig 5: Complete thermal network of Peltier element

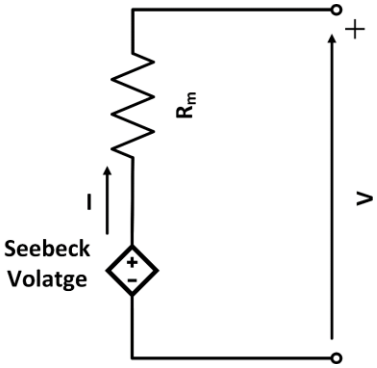

Fig 6: Electrical submodel of the Peltier element

3.3 Coupling between thermal and Electrical Submodel

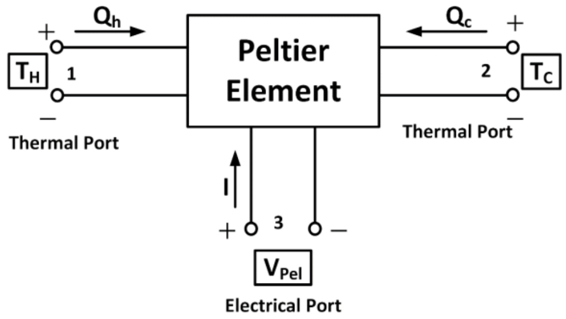

Fig 7 Three port netwrok for the Pelteir module

The two submodels are interconnected, reflecting the bidirectional coupling between the thermal and electrical aspects of the Peltier module. The temperature distribution from the thermal submodel influences the DC voltage source and, consequently, the electrical performance. Simultaneously, the current flowing through the electrical submodel influences the thermal aspects by affecting the Peltier heat at the junction and joule heat generation throughout the Peltier element. Voltage developed due to temperature difference and heating and cooling at the ceramic substrate due to the potential applied are the outputs pertaining to the applied inputs. Therefore, we can develop the model as a three-port network based on the energy flow due to the inputs and outputs as shown in figure 7.

The thermal submodel must sense the current flowing through the device. This information is crucial for determining major heat source terms and understanding the overall behavior of the Peltier module. Sensing the current involves a feedback loop between the electrical and the thermal submodels. The complete model of the Peltier module excluding the ceramic substrate can be represented as in figure 8.

For specific application of above model for the heat pump or temperature control in our system, we need to take into account the electrical input power (P_{elec}) and the heat flow absorbed at the cold surface. The ceramic substrate will at cold end will have thermal resistance R_{Ccer} and heat capacity C_c and at the hot end will have thermal resistance R_{Hcer} and heat capacity C_h as described in figure 9. The dotted square box in the figure 10 represents complete model of the Peltier module for heat pump applications.

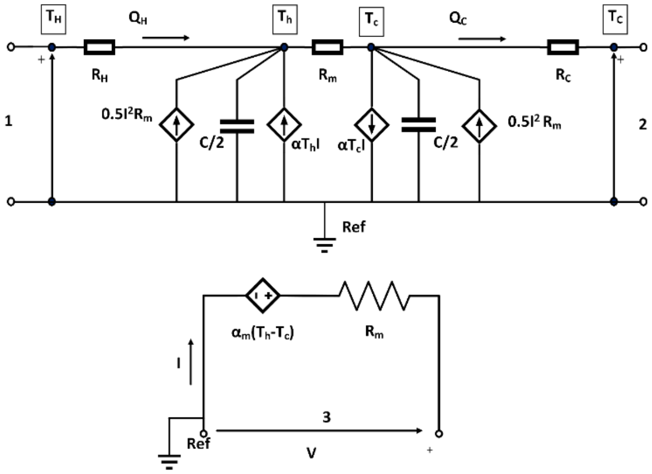

Fig 8: Coupled network model of the Peltier element

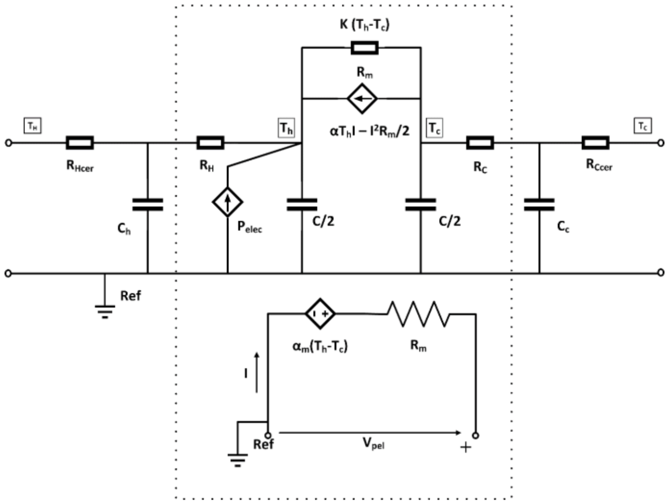

Fig 9: Coupled network model for the Peltier module

4. SIMULATION RESULTS

The schematic for the implementation of developed model of the Peltier module is shown in the figure 10.The Peltier module is mounted on a heat sink and cold thermal mass, functions to actively pump the heat produced from the heat source in cyclic manner as in figure 11(a). Thermistor is used for the sensing the temperature at the cold surface acting as feedback for the current applied through controller to the current source for the heat pumping as in figure11. The simulation results are shown in figure 11. The Ambient variation is also incorporated as an input in figure 11(c) for robust control verification. As the order of system can be reduced to two [7] a PID controller is incorporated for current close loop control input for the current source and the tracking of temperature for cold surface for the set temperature within in 1 ^{O}C range can be seen in the results figure 11(b) and 11(d).

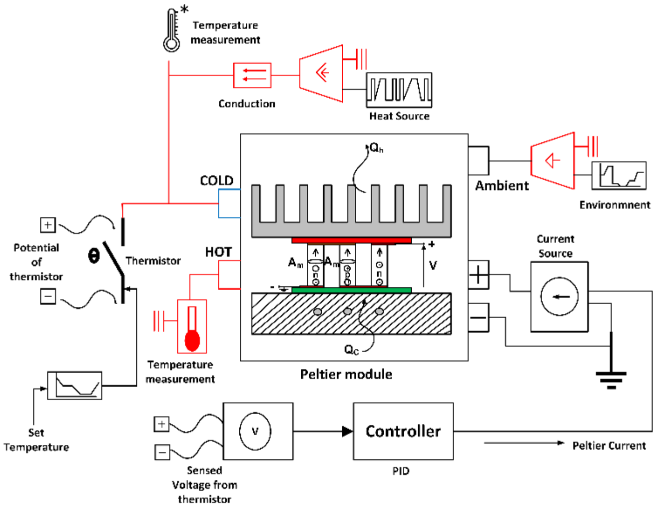

Fig 10: Schematic for the implementation of the developed model

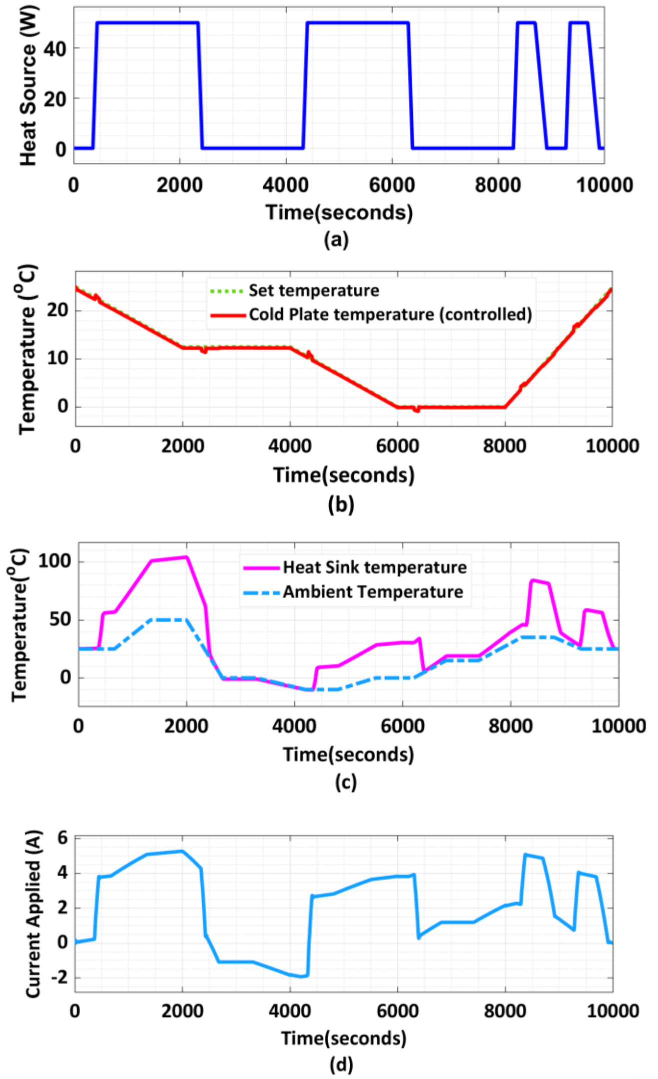

Fig 11: Simulation Results (a) cyclic heat source at the cold surface (b) set temperature for the thermistor and the controlled temperature measured at cold surface (c) Heat sink temperature at hot side and ambient variation applied (d) Current applied by current source to the Peltier module controlled by the controller

5. CONCLUSIONS AND FUTURE OUTLOOK

The thermal submodel and electrical submodel is developed for the Peltier module from the fundamental physics, specifically focusing on the developing and explaining the thermal capacitance attributed by the material of the Peltier element. Further the developed model is simulated and verified for the temperature control within 1 °C range for the set point temperature.

Experimental setup for the verification of the model for desalination system is also developed as shown in figure 12. The evaluation of the experiment and the detailed description of design of the controller will be presented in the future work.

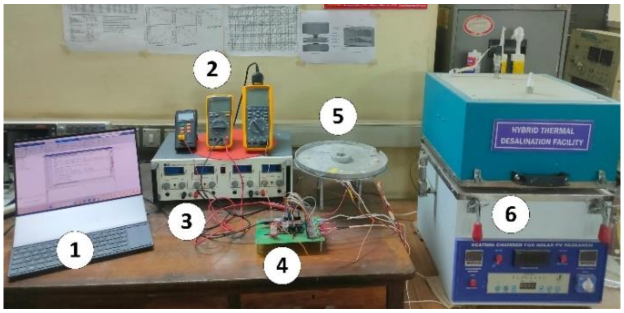

Fig 12: Experimental setup (1) logging (2) measuring instrument (3)dc power supply (4)developed temperature sensor board (5) Peltier setup (6)Desalination unit

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