Thermal Control Units: Development of an Analytical Model and Experimental Validation to Optimize the Voltage Input

Sudhir Kumar (Presenter), Khaled Elmadbouly, Praba Prabakaran

Kulicke & Soffa Industries Inc.
1150 North Fiesta Boulevard
Gilbert, AZ 85233-2237
Ph: 480-333-1500

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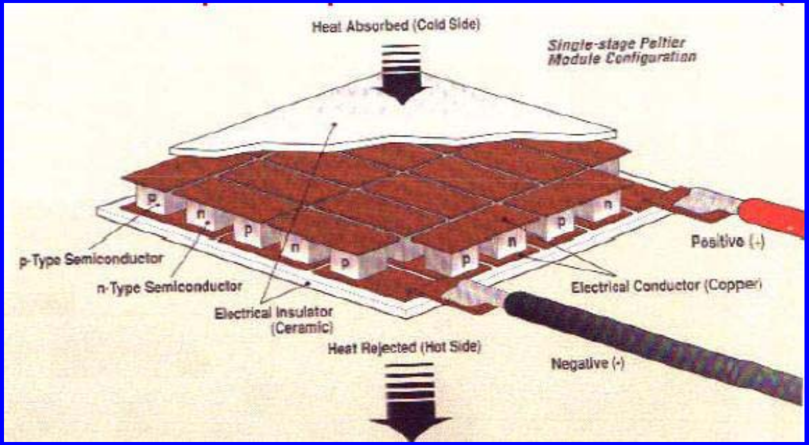
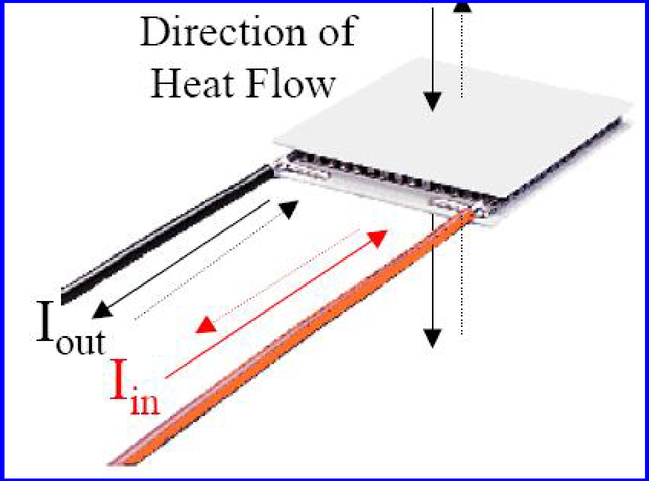
Contents

Introduction

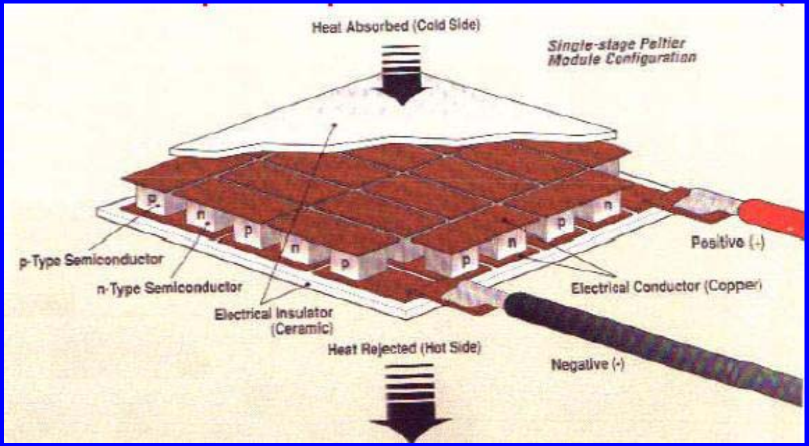
- **Thermoelectric Coolers (TECs) are solid state heat pumps working on the Peltier effect.**
- **It contains an array of p and n-type semiconductor pellets, connected electrically in series.**
- **A DC current or voltage is supplied to the device.**

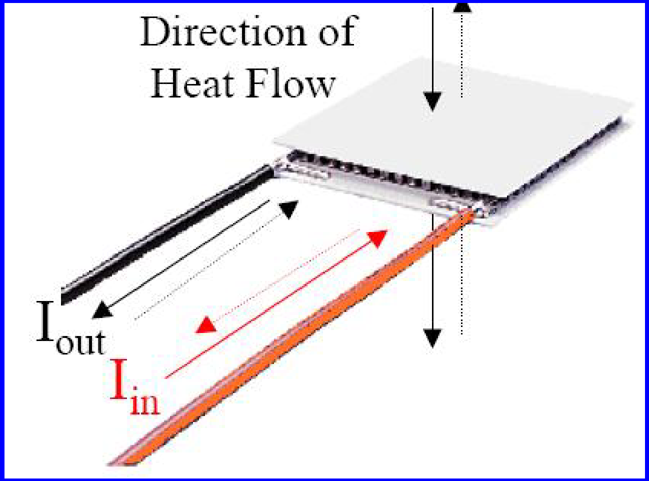




Introduction

- **Heat is transported from top to bottom face or vice versa depending on the direction of the current flow.**
- **In other words, it can work as a cooler or a heater depending on the direction of the current flow.**
- **Hence, it can be used in the applications requiring thermal control.**

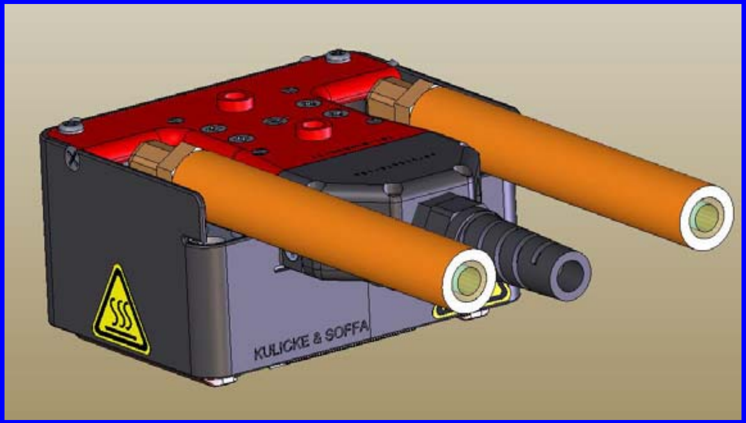


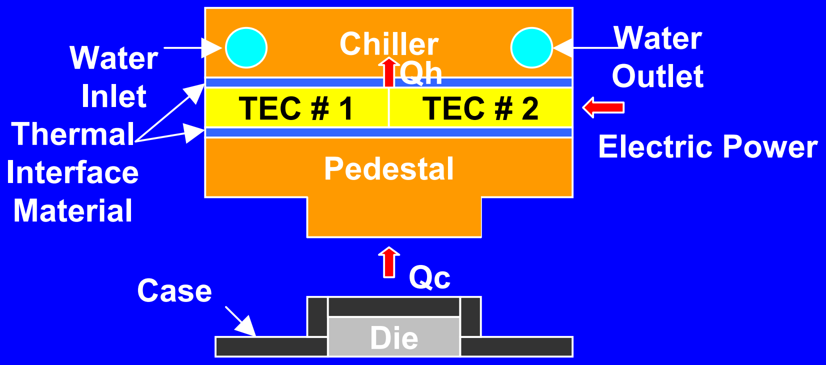


Introduction

Thermal Control Unit

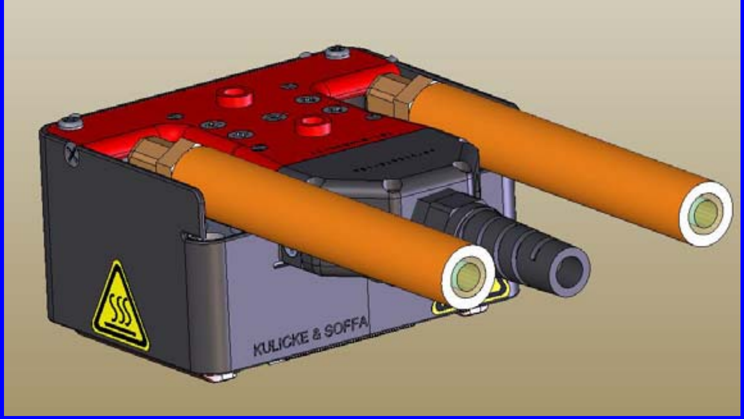
- Thermal control unit (TCU) consists of a liquid heat exchanger, contactor plate and TEC assembly and it facilitates the control of package case temperature in the IC device test sites.
- A contactor plate with a pedestal lies on the cold or the bottom side of TEC assembly and makes the contact with IC device.
- TEC assembly usually contains two TECs arranged mechanically in parallel and electrically in series configuration.

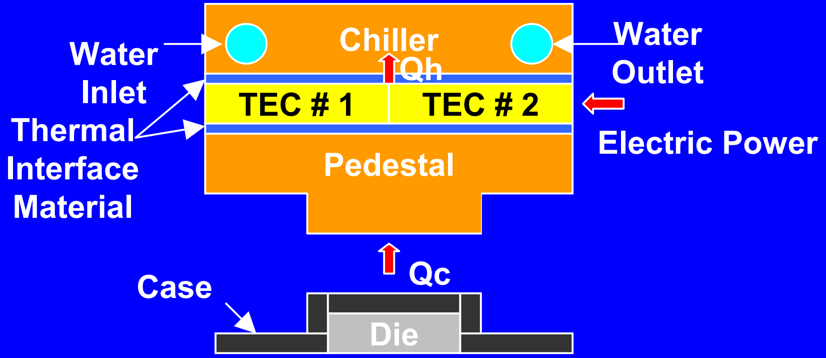




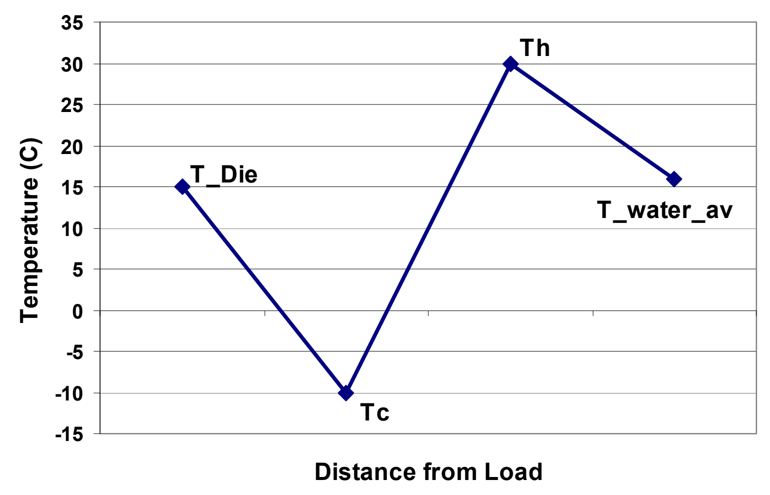
Introduction

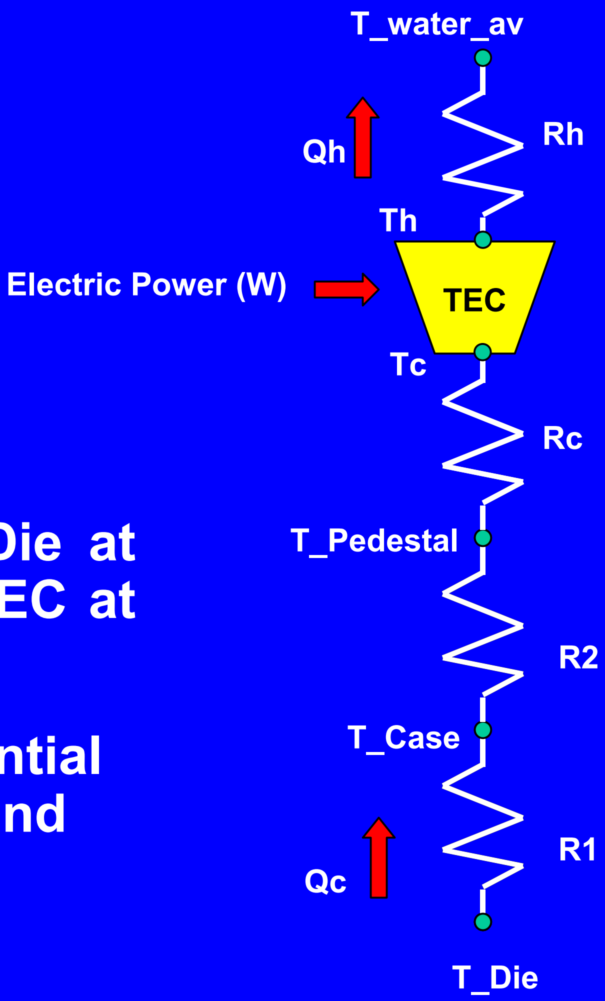
- The liquid cooled heat exchanger lies on the hot or the top side of the TEC assembly.
- The water inlet and outlet and the electric cable port are separate.
- The K&S TCU features compact size and small footprint that makes it easy to integrate with IC device test sites





Temperature Variation in a TCU





- The Heat Load Qc transfers from the Die at temperature T_Die to the cold side of TEC at temperature Tc.
- The TEC generates a temperature differential between the hot side at temperature Th and the cold side at temperature Tc at the expense of the electric power W.
- The resultant heat Qh (Qc+W) transfers from the hot side of TEC at temperature Th to the coolant water at temperature T_water_av.

Analytical Model

- KNS has developed an elaborate analytical model of the TEC developed in EES (Engineering Equation Solver) to simulate its performance for any electrical and thermal inputs.
- The driving equations are

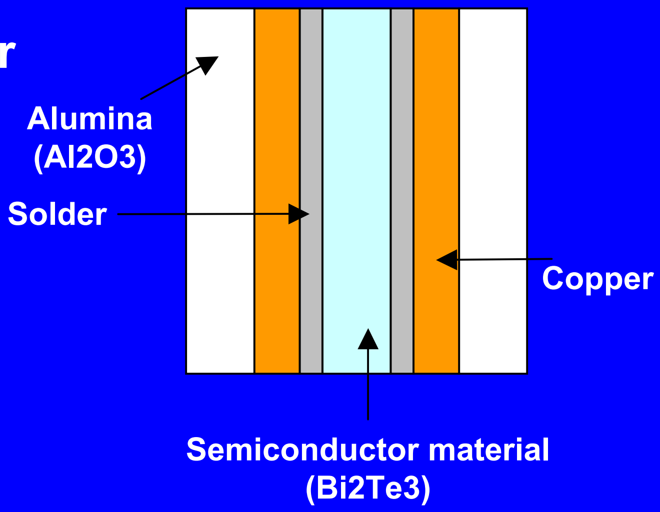
$$\frac{Q}{2*N} = Sm*I*Tc - 0.5*I^2*\rho*\gamma - \frac{\lambda}{\gamma}*(Th - Tc)$$

$$\frac{V}{2*N} = I*\rho*\gamma + Sm*(Th - Tc)$$

$$\gamma = \frac{h}{a^2}$$

- Where:

Q = Heat Load
I = Current
V = Voltage
Th = Hot Side TEC Temperature
Tc = Cold Side TEC Temperature
a = Length/Breadth of Thermoelectric Pellet
h = Thickness of Thermoelectric Pellet = 0.8 mm
γ = Geometry factor
N = Number of Thermocouples
Sm = Seeback coefficient = $2.068 *10^{-4}$ V/K
ρ = Electrical Resistivity = $1.029*10^{-5}$ Ohm-m
λ = Thermal Conductivity = 1.614 W/m-K



Material	Thickness (mm)
Alumina	0.8
Copper	0.3
Solder	0.1
Bismuth Telluride	0.8
Solder	0.1
Copper	0.3
Alumina	0.8
Total	**3.2 mm**

Layer stack-up of the TEC

Analytical Model

Sub-Assemblies Details

- Heat transfer analysis is done for the water chiller to determine the average water temperature.
- The internal thermal resistance of the TEC is also calculated and taken into account.
- One dimensional thermal resistance models of the sub-assemblies are developed and integrated with the TEC model.

$$Qh = \dot{m} * Cp * (T_{water,\ out} - T_{water,\ in})$$

$$T_{water,\ av} = \frac{T_{water,\ in} + T_{water,\ out}}{2}$$

$$R_{TEC} = R_{Alumina} + R_{Copper} + R_{Solder}$$

$$Qc = 2 * Q$$

$$P = V * I$$

$$Power = 2 * P$$

$$Qh = Qc + Power$$

$$Qc * (\frac{R_{TEC}}{2} + Rc + R_1 + R_2) = T_{Die} - Tc$$

$$Qh * (\frac{R_{TEC}}{2} + Rh) = Th - T_{water,\ av}$$

Analytical Model

Features and Capabilities

- The model simulates the Peltier effect of TECs very accurately.
- It is generic and can be used for any TEC once its geometric and material properties are known.
- It can be used to generate the characteristic performance curves of the TECs.
- It is integrated with one-dimensional thermal resistance models of the cold and hot side sub-assemblies and thus a complete system level modeling of the TCU can be done.
- It can be used to do thermal analysis and determine the temperatures at different layers.

Analytical Model

Features and Capabilities

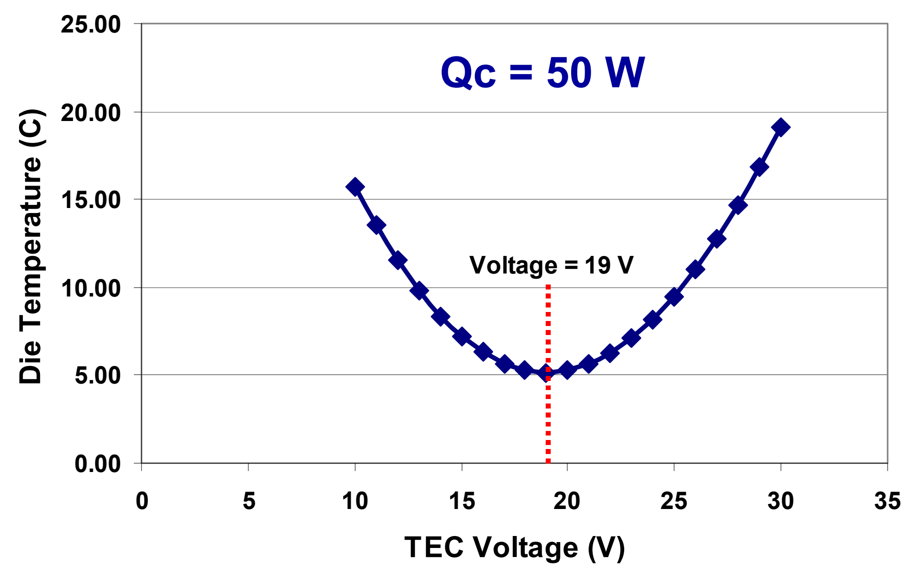
- **The model can also be used to change the dimensions of various layers and see its effect on the thermal performance. Hence, it can be used for the design and optimization purposes.**

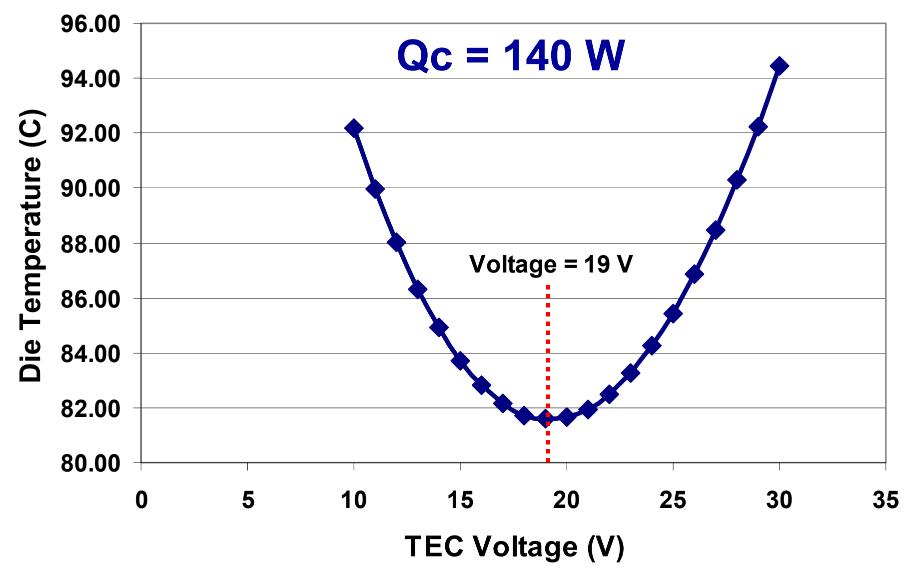
- **Besides geometric and thermal parameters, electric inputs can also be analyzed and optimized with the help of this model.**

- **The model contains non-iterative procedures and the results are obtained in a very short time.**

- **It can be used only for steady state analysis.**

Optimal Voltage Simulation





- **One of the parameters that influence the performance of TECs is the operating voltage input.**

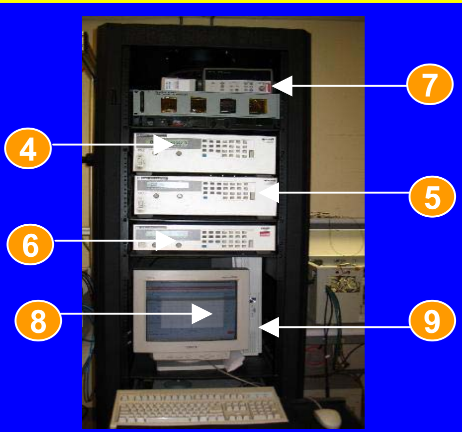
- **In this analysis, the complete system level analytical model of the TCU is used to determine the variation of the die junction temperature versus the TEC operating voltage for the heat loads of 50 W and 140 W.**

- **The optimal voltage is determined as 19 V for both the heat loads. It is observed that as the operating voltage is increased beyond the optimal voltage, internal Joule heating takes over the thermoelectric effect and the TCU thermal performance decreases.**

Experimental Validation

Testing Equipment

Chiller Tower

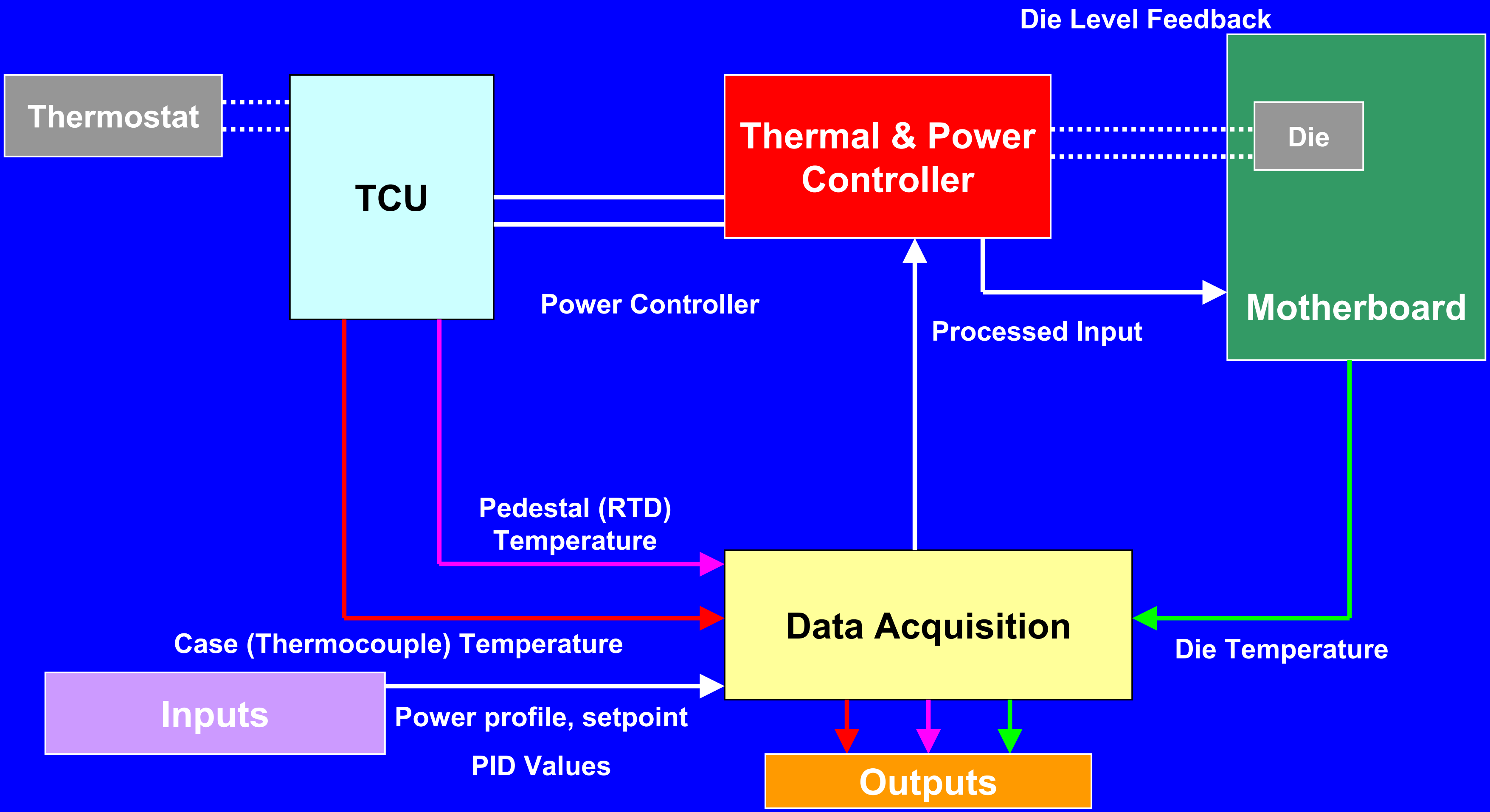


Rack containing other equipments

Ref. No.	Equipment
1	IC Device Test Site
2	Mother Board with Device
3	Thermal Controller
4	Power Supply
5	Power Supply
6	Power Supply
7	Data Acquisition Switch/Unit
8	Data Acquisition Software
9	Computer/Monitor and Accesories
10	Chiller Tower
11	TCU

- **In the second phase of the project, detailed experimental testing is done to determine the optimal voltage and validate the simulation results.**
- **The equipment used in the testing are listed and shown here.**
- **There are three different power supply units to supply power to mother board , TCU Thermal Controller and the pneumatic actuator.**

Experimental Validation *Schematic of the Experimental Setup*



Die Level Feedback

Thermostat

TCU

Thermal & Power Controller

Die

Motherboard

Power Controller

Processed Input

Pedestal (RTD) Temperature

Data Acquisition

Case (Thermocouple) Temperature

Die Temperature

Inputs

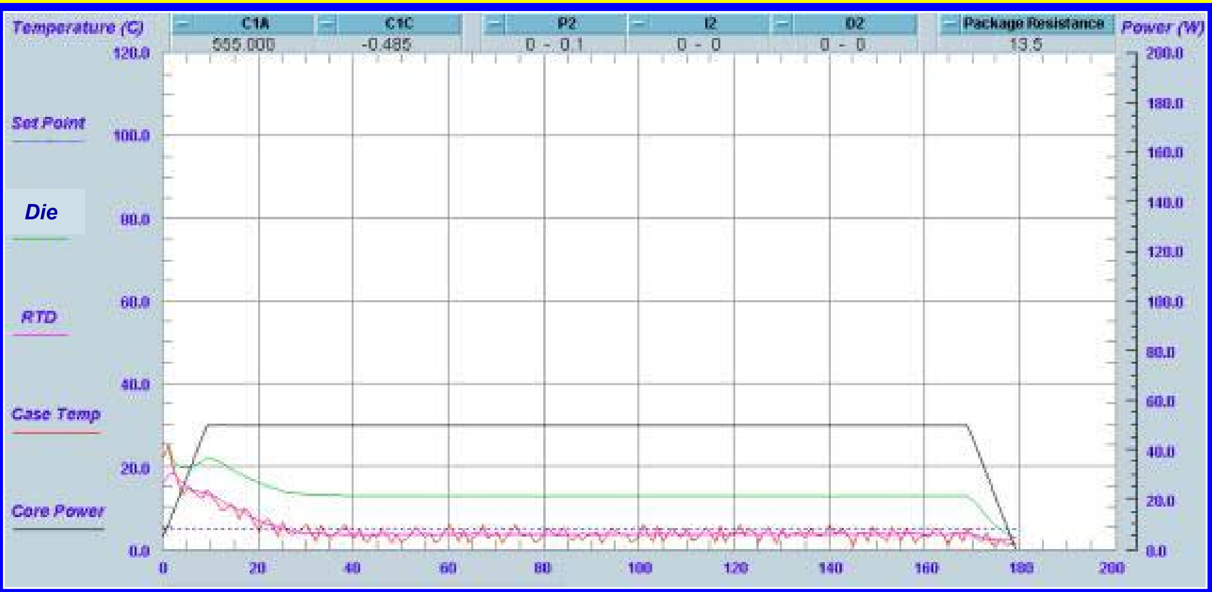
Power profile, setpoint

PID Values

Outputs

Experimental Validation

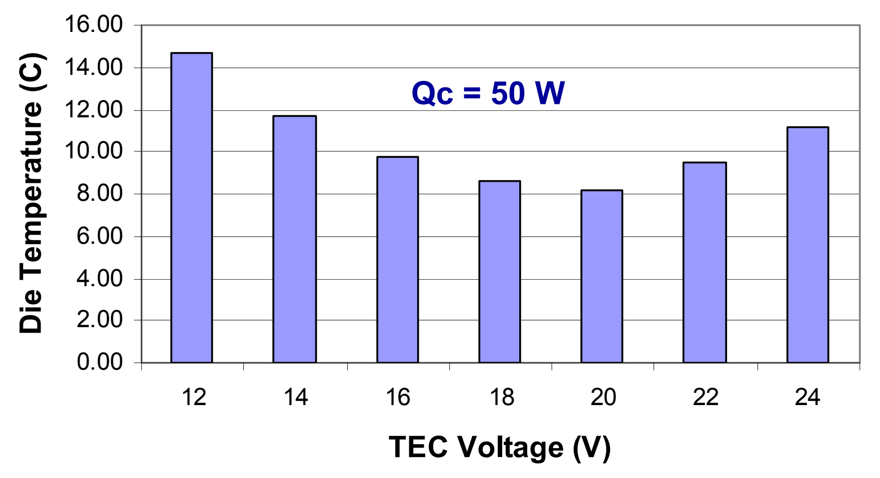
Graphic Output

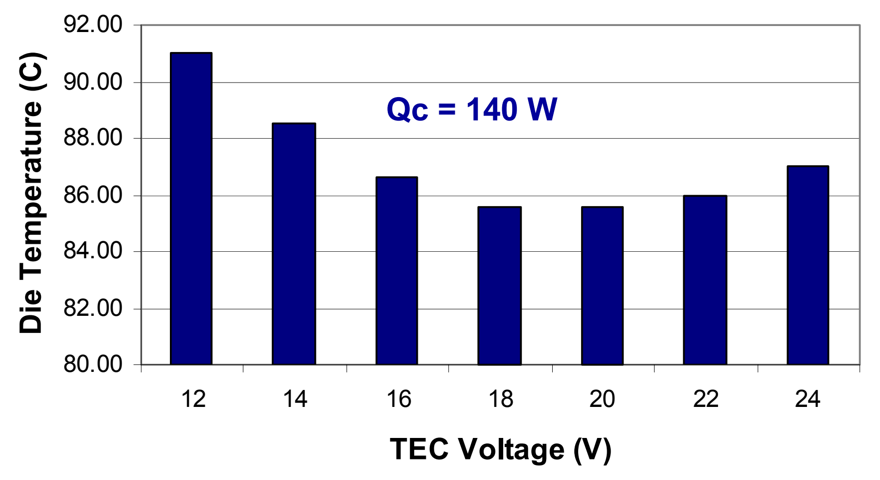


C1A 555.000
C1C -0.485
P2 0 - 0.1
I2 0 - 0
D2 0 - 0
Package Resistance 13.5

- A sample graphic output is displayed above.
- In this test,
  - Heat Load = 50 W
  - Input Voltage = 12 V per TEC or 24 V per TCU
- The test duration is 3 minutes to let the system reach steady state.
- Besides graphic output, it also saves the output to a text file. The output die temperature in this particular test was 14. 7 °C.

Experimental Validation

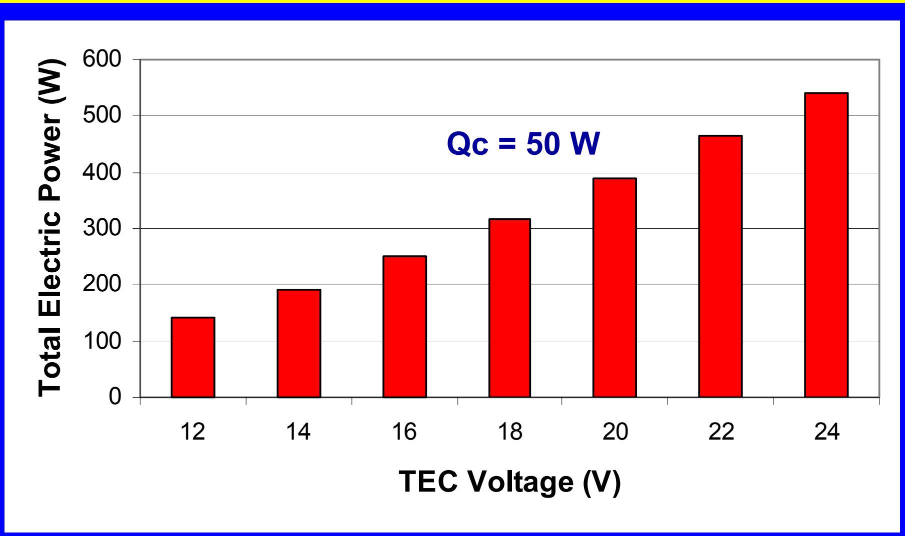


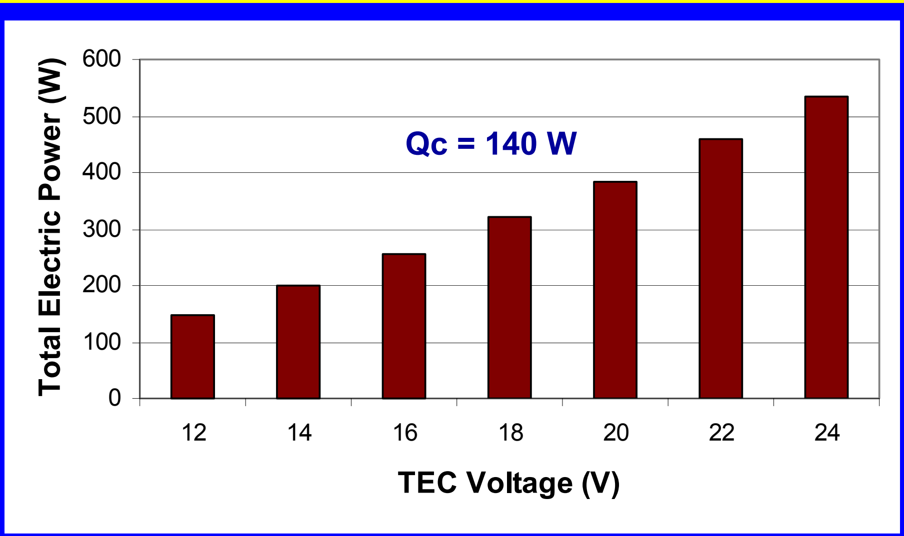


- The die temperature reading in the steady state test decreases as the TEC voltage is increased. It reaches an optimal value at voltage around 19 V.
- As the voltage is increased further internal Joule heating takes over the Peltier effect and the die temperature rather increases.
- The trend is same for Qc = 50 W and Qc = 140 W. Also the trend matches with the predicted results of the analysis.

Experimental Validation

Results

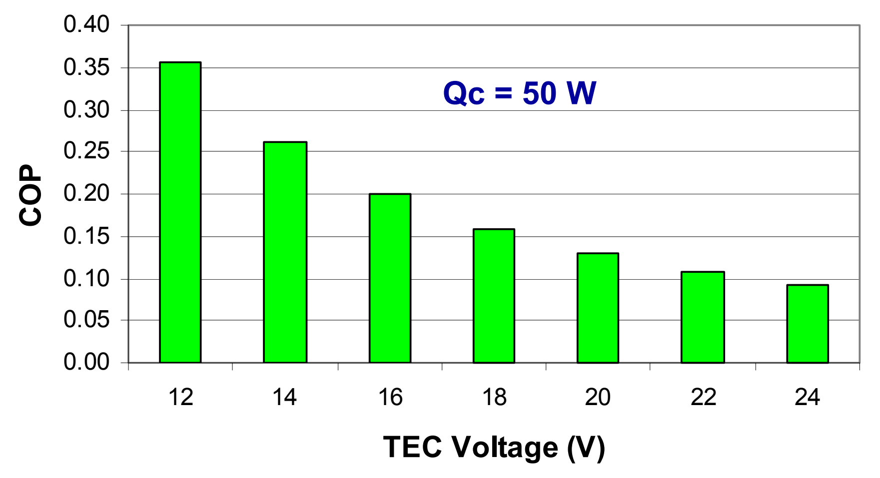


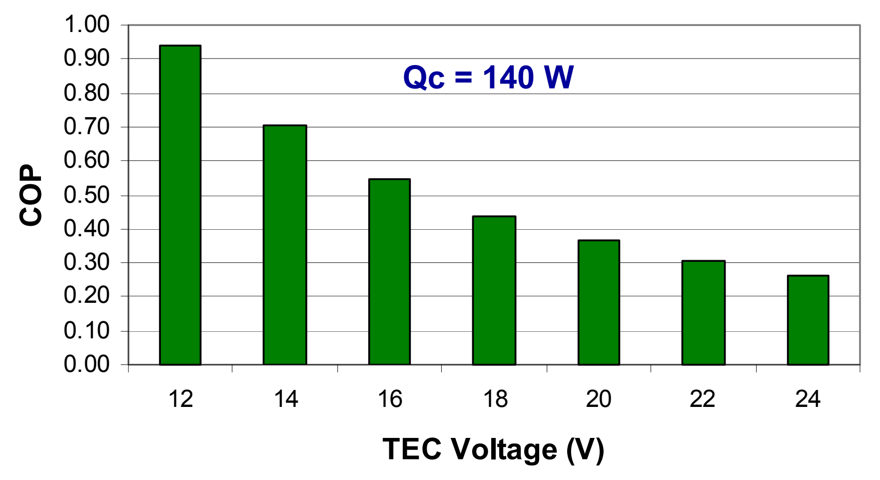


- **The total voltage and current readings were experimentally determined and multiplied to obtain the total electrical power input into the TECs.**
- **As the TEC voltage increases, the electrical power increases rapidly for both Qc = 50 W and 140 W.**
- **For 140 W, the electrical power is slightly more than corresponding figure for 50 W. For Qc = 140 W, the temperature inside the TEC is higher. As the thermoelectric material heats up, its electrical resistivity decreases. Hence, the current and power increases for the same voltage.**

Experimental Validation

Results





- **The coefficient of performance indicates the performance of a heat pump and is defined as Qc/Work. Here, the "Work" refers to the total electric power supplied to the TECs.**
- **For a given heat load, COP decreases as the TEC voltage and the electric power increases.**
- **For a given voltage, COP would be higher for the higher heat load. It can also be interpreted that as the heat load increases, temperature difference (Th-Tc) decreases and hence the performance of the heat pump increases.**

Conclusions

- TECs are solid state heat pumps working on the Peltier effect. They are very effective means of thermal management and control.
- A TCU consists of a liquid heat exchanger, a contactor plate and TEC assembly and it facilitates the control of package case temperature in the IC device test sites.
- KNS has developed an elaborate analytical model of the TEC. The model is also integrated with the one-dimensional thermal resistance models of sub-assemblies and thus a complete system level modeling of the TCU can be done.
- The model can be used for the thermal analysis and optimization with respect to geometric, thermal and electrical parameters.

Conclusions

- **The system level model of the TCU is used to determine the variation of the die junction temperature versus the TEC operating voltage for the heat loads of 50 W and 140 W. It was found that the optimal voltage input is 19 V per TEC.**
- **Subsequently, experimental validation is done and it is observed that simulation results of the model are quite accurate. The optimal voltage is found to be 19 V per TEC experimentally also.**
- **Besides die temperature, variation of other parameters like electric power, COP with respect to TEC voltage was also studied for the heat loads of 50 W and 140 W.**

References

- *Allan D. Kraus, Avram Bar-Cohen*, “Thermal Analysis and Control of Electronic Equipment,” Hemisphere Publishing Corporation, New York.
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- *Philip Yu. Takhistov*, “Using of Thermoelectric Modules for Heat Exchange Intensification,” 20th International Conference on Thermoelectrics 2001, pp 467 – 469.