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THERMOELECTRIC COOLING FOR THE CONSTRUCTION OF SOLID-STATE AIR CONDITIONER IN LIFT

RESEARCH SUMMARY

Construction Industry Council
Thermoelectric Cooling for the Construction of Solid-State Air Conditioner in Lift
Research Summary

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FOREWORD

Climate change was one of the biggest challenges facing mankind. The HKSAR Government was embarking upon a series of measures to reduce greenhouse gas (GHG) emissions and proposed a target of reducing 50% to 60% Carbon Intensity by 2020 on the 2005 basis. In 2015, the total GHG emissions in HK was about 41.6 million tonnes of carbon dioxide equivalent and about 66% were released from electricity generation so promoting wider use of renewable energy became essential to meet the reduction target.

With the vision of developing low or zero carbon high-rise buildings, the CIC initiated the research by engaging a research team from the City University of Hong Kong to develop an air-cooling system consisting of thermoelectric modules (TEM) to cool the passenger lift cabin.

The research work presented in this report was funded by the CIC Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

The research work described in the report was carried out by a research team led by Dr Roy VELLAISAMY from the City University of Hong Kong. The project cannot succeed without the dedicated effort of the research team. I would like to thank to all who took part in this valuable work.

Ir Albert CHENG
Executive Director
Construction Industry Council

PREFACE

The work described in this report was supported by the research funding from the Construction Industry Council (CIC) of the Hong Kong Special Administrative Region, China for the project "Thermoelectric Cooling for the Construction of Solid-State Air Conditioner in Lift", CityU Project Number (9231225). In addition, we would also like to take this opportunity to give our sincere appreciation to Mr HO Kwok Cheung, Filed Operation Director of HOLAKE Hong Kong Lifts Limited, for collating their support and supplying the research team a full-scale passenger lift unit for conducting tests and the patience for providing the valuable technical information and data for passenger lifts used for Hong Kong.

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RESEARCH HIGHLIGHTS

In the challenge for solutions against energy crisis, there are many research works into alternative ways to produce more energy as to satisfy the increasing demand for fulfilling the comfort in our daily life. However, over the years, the development of modern electrical appliances is tending to have greater energy dependent, where in term research works were directed to look into alternative ways to produce energy with less reliant on fossil fuel. Through recent studies, research for energy saving solutions should be equally important to the research studies for energy production. According to data published by the HKSAR Electrical and Mechanical Services Department (EMSD), "Space Conditioning" for residential and commercial sectors consumes about 4342 GW and 8837 GW respectively.

Moreover, Hong Kong is a city renowned with high density of high-rise buildings for place of work and home, Elevator lift is possibly one of the space that must visit during the day. Statistical data revealed that a total of 64,930 units of elevator lifts were installed in Hong Kong, with a staggering of 33,231 units (over 51%) of the lifts are over 20 years old. As older lift units are tending to be of smaller physical dimensions, and many are without additional ventilation system due to limited footprint on the lift-top. The limitation of effective ventilation is prone for health concern as contagious diseases like common flu and others can easily spread in a confined space. With the above complicated concerns, CityU Research Teams were stimulated to explore innovative solutions for an environmentally clean air-conditioning system that could optimize the issues of energy consumption and promote better thermal-comfort for confined spaces that current systems may not be possible for older type passenger lifts.

In this research project, TE modules were used as the cooling source to demonstrate its feasibility as an air conditioner. Copper and aluminum heatsinks were used to act as cooling coil on the cold side, while copper and aluminum heatsinks were also used for heat dissipation. The system performance was studied under mock-up testing condition or actual field testing. We found that with the lower range of input power (0 – 9V), the peltier devices show a linear relationship of temperature change on both hot and cold sides. With this we are able to achieve a steady stream of cool air of 5^{o}C below the ambient temperature (21^{o}C). We have constructed system model consisting of Uni-block and Multi-block modules for increasing the COP of the system. Finally, we have achieved a cooling capacity of 550 Watts or 0.8 hp. On further improvement on the system design and modules performance the efficiency can be further adjusted.

CONTENTS

1 INTRODUCTION

Minimizing the environmental "footprint" today has become a decisive factor in many decisions. For the design of passenger lift ("the lift"), it would be quite a challenge to fit all key electrical and mechanical (E&M) components within the limited space on the lift-top, and even greater challenge for the installation of an optional ventilation system for thermal-comfort. At present, compressor type air-conditioner system is often installed on the lift-top. It is not the best solution as it is noisy, heavy with large physical dimensions and also prone to add more environmental problems such as water condensation and exhibit environmental pollution as the cooling appliance is still much reliant on chemical materials as coolant and refrigerant for the heat exchange process.

1.1 Background

Thermoelectric effect denotes direct conversion of the temperature difference into voltage which refers to phenomena with the current flows through the P and N legs of a TE module. Thermoelectric effect is generated due to transport of the charge carriers (free electrons and holes) in metals and semiconductors while carrying energy and electric charge. In this case, the electric effects are accompanied by thermal effects and vice versa. The thermoelectric effects are Peltier effect, Thomson effect and Seebeck effect. Peltier coefficient (π) is defined as the amount of heat developed or absorbed at a junction P and N legs when a current of one ampere passes through this junction for one second. Peltier coefficient π is positive for heat absorbed and negative for heat dissipated. The peltier coefficient controls a cooling outcome when the current drifts from the N-type semiconductor material to a P-type semiconductor material and a heating effect when the current drifts from the P-type semiconductor material to an N-type semiconductor material.

In this project, we planned to construct a solid-state air-conditioner (air-cooling system) consisting of thermoelectric modules (TEM) to cool the passenger lift cabin. Commercial TEM were not available until the 1960s, after the first important discovery relating to thermoelectricity dated back to 1821 by a German scientist, Thomas Seebeck, and later discovered by Jean Peltier in 1834. The physical properties of thermoelectric (TE) materials in converting electrical energy directly into thermal energy or vice versa, offering promising solutions for Clean energy applications. Peltier cooler or Thermoelectric Coolers (TEC), is a semiconductor-based Thermoelectric Module (TEM) that functions as a small heat pump when power is connected to it. During the cooling process, TEM device produced no noise. Its rapid cooling process with outstanding cooling temperature range makes it ideal for wide range of applicable uses. The unit size of commercially available TEM is of small footprint, typically from $1cm^2$ to $36cm^2$, and of thickness 3mm to 5mm, allowing the overall TEC system to be of compact footprint. Most importantly, TEC system does not use chemical refrigerant or liquid coolant, it is environmentally green and makes it unique that the system can be installed at any orientations on the lift-top's limited space.

Internal structure of the Peltier element comprises semiconductor pellets fabricated from N-type and P-type Bismuth Telluride materials. The array of pellets is electrically connected in series, but thermally arranged in parallel to maximize thermal transfer between the hot and cold ceramic surfaces of the module (Fig-1). Thermoelectric cooling takes advantage of the Peltier effect, which is observed as heat being either absorbed or emitted between the junctions of two dissimilar conductors when a current is passed. A thermoelectric module comprising a Peltier element sandwiched between two ceramic plates of high thermal conductivity, with a power source, is effectively able to pump heat across the device from one ceramic plate to the other. Moreover, the direction of heat flow can be changed simply by reversing the direction of current flow. Applying a DC voltage causes the positive and negative charge carriers to absorb heat from one substrate surface and transfer and release it to the substrate on the opposite side. Therefore, the surface where energy is absorbed becomes cold and the opposite surface, where the energy is released, becomes hot.

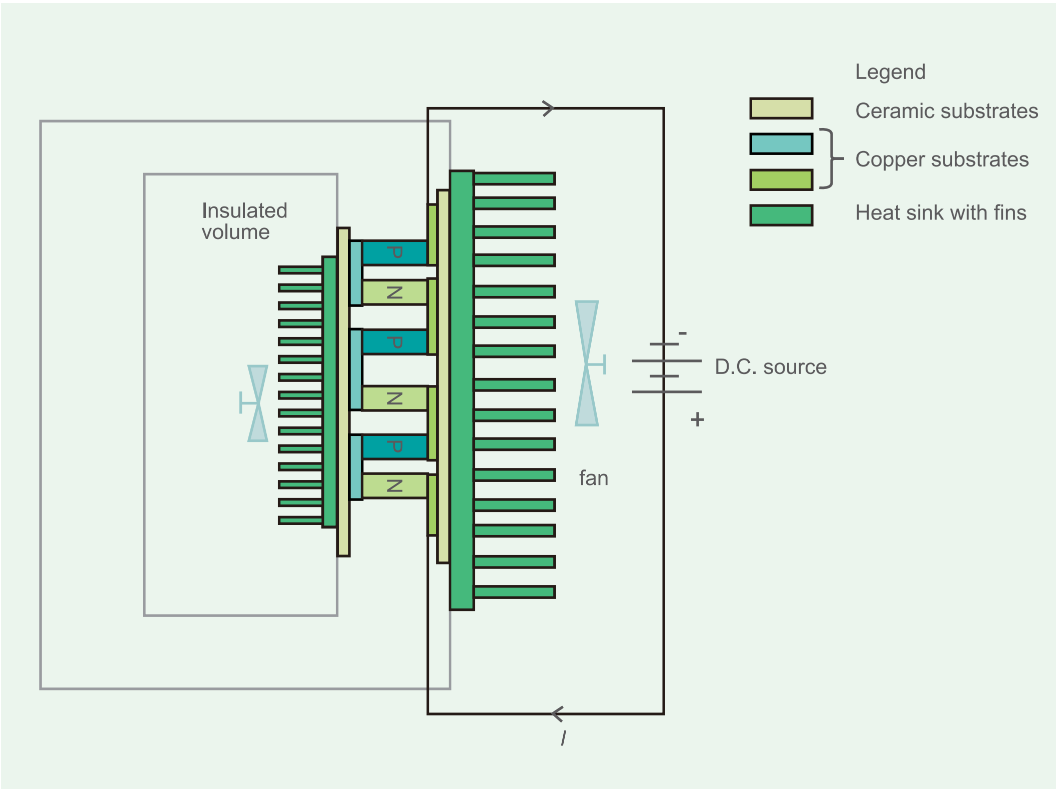


Fig-(1) Illustration of Energy Flow through a TEM and TE-Cooler

In a practical thermoelectric cooling unit, the Peltier module is built into a system that comprises a metal heat sink of high thermal conductivity, such as an aluminum or copper alloy. The heat sink is attached to the hot side of the Peltier device, to extracted heat into the ambient environment. A thin layer of thermal grease, or other thermal interface material, is applied to minimize thermal resistance. Temperature sensors are used to monitor the hot and cold plates. The maximum temperature difference and maximum current should also be considered, to ensure the chosen Peltier module can maintain the desired temperature difference when operating at a suitable current. Some approaches to improve the TEC performance are:

- Developing high performing thermoelectric materials
- TEC design
- Thermal transfer design
- Optimization of the internal temperature controller of cooling compartment (using PID)

A thermoelectric cooler unit works with COP typically >0.5 due to the limited cooling temperature. Coolers with thermoelectric modules with materials based on alloys of Bi_2Te_3 have a COP about 1, which is low when compared to the vapor-compression systems with COP = 2 - 4. However, the low COP values of TECs are not considered as a drawback. These cooling systems are more suitable for a niche market sector (below 25W) such as military and medical industries, in applications such as temperature stabilization of semiconductor lasers and vaccine cooling. Furthermore, they are also suitable for the civil market (e.g., transportable refrigeration,automobile cooler). For these applications, the thermoelectric elements have the advantages that do not suffer vibrations and shocks.

1.2 Aims and Objectives

- To construct a solid state air-conditioner (solid state air-cooling system) consisting of TEM to cool the passenger lift cabin.
- To demonstrate the rapid cooling process by using Peltier modules, achieving thermal comfort in elevators.
- To demonstrate the precise control of temperature in car cabinet by using PID temperature controller to control current passing through the Peltier modules.
- To establish Peltier modules with a long life exceeding 100,000 hours.

1.3 Scope

Stage 1

Evaluate and Estimate for the Proposed Cooling System

- Proof of concept for the feasibilty of using TEM for air-cooling for lift;
- Evaluate testing components to build a single TEM cooling unit for testing;
- Functional testing;
- Observe the optimum controlled test conditions.

Stage 2

Prototype Testing (Single TEM Unit)

- Design and set up the scaled size cooling chamber;
- Cooling improvements for the TEM Cooling unit;
- Tests to observe the optimal working conditions at target temperture settings;
- Determination of supply power, heat transfer, energy harvesting, insulation.

Stage 3

System Improvements

- Experiments to optimize the performance factors (e.g. cooling COP);
- Improve ease of control and use.

Stage 4

Full-Scale Experiment Under Live Size (1:1) Scale Lift Cabin

- Set up for the live size testing eironment;
- Tuning experiments to optimize controlled conditions.

Fig-(2) Summary of the Test Scope in each Phase

Air conditioning systems are one of the high profile targets when considering reducing energy usage in buildings and indeed are a crucial factor, as reviewed in the 2014 HKSAR End-users Energy Consumption report, “Space Conditioning”, (cooling) in residential sector is 36% while in commercial sector is 31%. The traditional compressor type air conditioning system that ventilates the elevator is not the best solutions because of its large footprint and associated nuisance such as noise and water condensation. Based on our foregoing research and preliminary results exposed, it is clear that the refrigeration process using Peltier modules is feasible alternate source for cooling, and it is a better choice if installation is subject to limited space. Research and studies are constantly made in improving a building’s efficiency by means of renewable resources, and so the application of Peltier modules is a sought-after area of research that would arouse the interest of the government and industries to utilize this technology. It is noteworthy that it is possible to achieve zero energy loss if a Peltier-based refrigeration system is implemented in large scale. It is known today that the application of these TE modules often ties into the use of energy generation by capturing waste heat. In the future, the buildings with zero energy consumption in Hong Kong can be achieved if the technology of thermoelectricity generation and thermoelectric cooling are adopted.

2 RESEARCH METHODOLOGY

In this research project, TE modules were used as the cooling source to demonstrate its feasibility as an air conditioner. Copper and aluminium heatsinks were used to act as cooling coil on the cold side, while copper and aluminium heatsinks were also used for heat dissipation. A large block of graphite coated on the hot side for heat dissipation would be demonstrated to observe the improvement factor. The cooling capacity and COP of this Peltier-based air conditioner was continuously evaluated on the experimental uni-block systems as well as on the final full-scale prototype system. With the full-scale prototype test data, we evaluate the performance key values and compare them with the commercially available compressor type air-conditioner. Based on the lab-tested results, further development in design and scale of the Peltier-based solid state cooling device was continuously built for conditions that are normally powered by the compressor-type air cooler. The system performance was studied under mock-up testing condition or actual field testing.

2.1 Systematic Design

The prototype TE-cooling system in this research was designed through the studies of specification requirements which were initially analysed mathematically in order to attain the required components needed. A "bench-test" prototype was then built to go through an all dimensions testing to ascertain the prototype design has the performance that was feasible to further develop into a larger version to be used for lift cabin. A schematic illustration of the design process for the TE-cooling system is illustrated below:

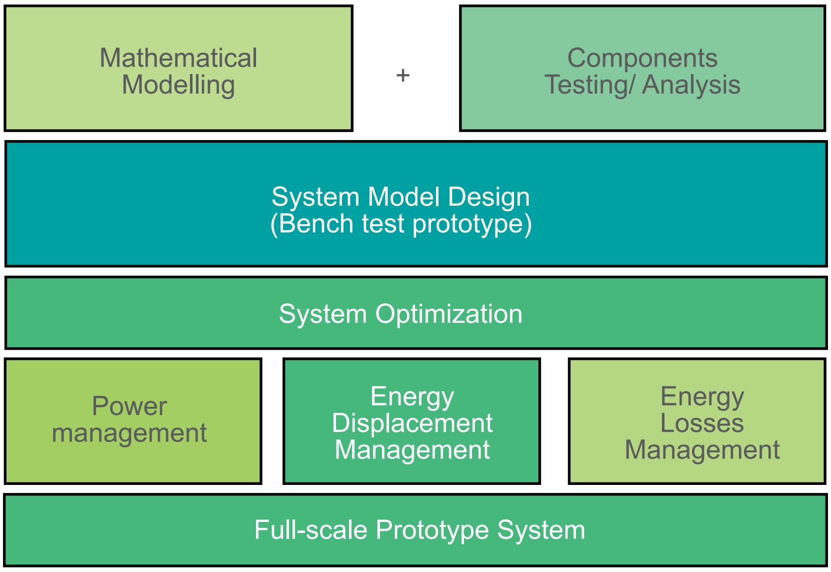


Fig-(3) Design Process for TE-Cooler system

2.2 Mathematical Model

The following system parameters were estimated and formed the benchmarks threshold level that the TE-cooler need to attain.

Estimation for System Energy Capacity (for TE module)

Assumptions:

- Initial Ambient temperature and humidity = 30^{o}C & 80%
- Target temperature = 25^{o}C
- Target time = 5 minutes (300 seconds)
- Volume of Lift Cabin = 3.30 m^3

Estimated Heat Load to remove from cabin (size 3.30m^3)

- Energy to remove = 42146.32J (or 140.4877J/s or 140.49W)
- Experimentally with system buffer of 30%, heat removed is 182.63W

Experimental experience shown that TE in cooling mode is approximately 30% effective,

- estimated TE Total Heat Dissipation = (assumed 3x times cooling) = 3 x 182.63W
- Total heat dissipation for the constructed TE cooling system = 547.90W

Estimation for Air Flow System (for Cold Side)

Assume 5 cycles to attained target temperature in 5 minutes:

- Air exchange rate = 1 cycle/min
- Total air displacement to target temperature = 3.30 m^3 x 5 cycles (in 5 mins) =0.055m^3/s

Assume air duct cross section area: 100 mm x 100 mm =0.01m^2

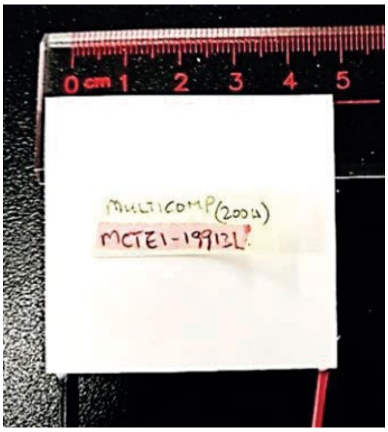
- Estimated minimum air flow rate to lift cabin cooling = 5.5 m/s

Estimated COP of the TE-module				
Input Current (A)	Rate Q-power (W)	Input Voltage (V)	Input Power (W)	COP (estimated)
2	N/A	N/A	N/A	N/A
3	25	6.1	18.3	1.37
4	42	9.1	36.4	1.15
5	60	10.2	51.0	1.18
6	70	12.1	72.6	0.96
7	80	15.5	108.5	0.74
8	100	17.8	142.4	0.70

2.3 System Components and Apparatus

TE Module

The TE-cooler systems in experiment were decided to use commercial TEM throughout this project, as the fabrication of a specialized TEM has a long lead time and is very costly if produced in small quantity. Moreover, commercial TEMs are already controlled-tested at factory under ideal conditions, such information is useful to serve as benchmark reference for our prototype systems performance prediction.



Data (provided by manufacturer)	TEC-19913L (200W) @ ref temp (300K)
I(max)	13A
V(max)	24.1V
Internal Resistance	1Ω ± 10%
Q(max)	200W
ΔT(max)	68°C
Physical Dimension	(50x50)mm, (H)3.5mm

Fig-(4) TE Module and its Specifications

2.4 Apparatus & Measuring Instruments

For consistency of measuring the testing results, the same apparatus and measuring instrument were used throughout the research project.

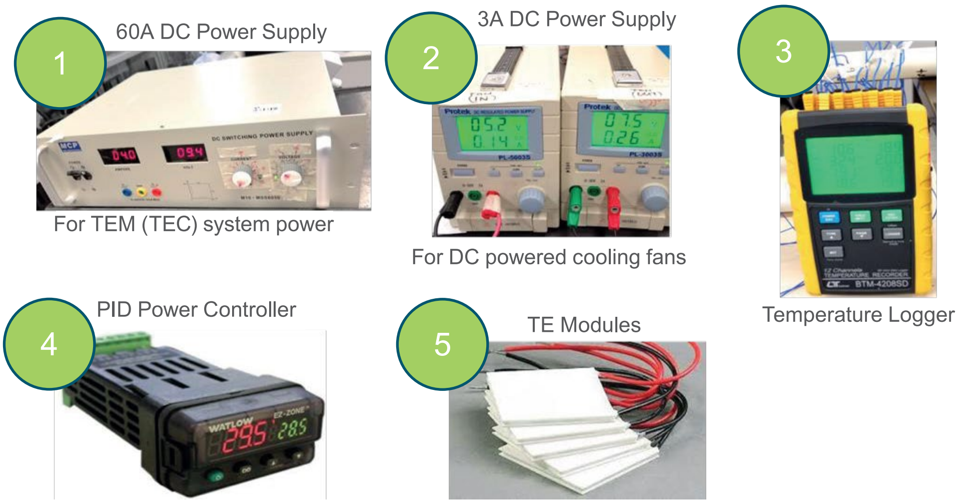


Fig-(5) Equipment's used for the bench testing

2.5 Uni-block TE-cooler (for Bench-test)

The uni-block TE-cooler as shown in Fig-(6), is a construction of one TE module sandwiched in the center between two heatsinks of same physical dimensions. The objective of using identical heatsinks on both Hot-side and Cold-side provided us an initial analysis of system performance under a controlled test condition for heat dissipation, thereby we could make further refinements on components and controllable variables such as, input power (for Cooling Power Generation Optimization), and ventilation (for Energy Transfer Optimization).

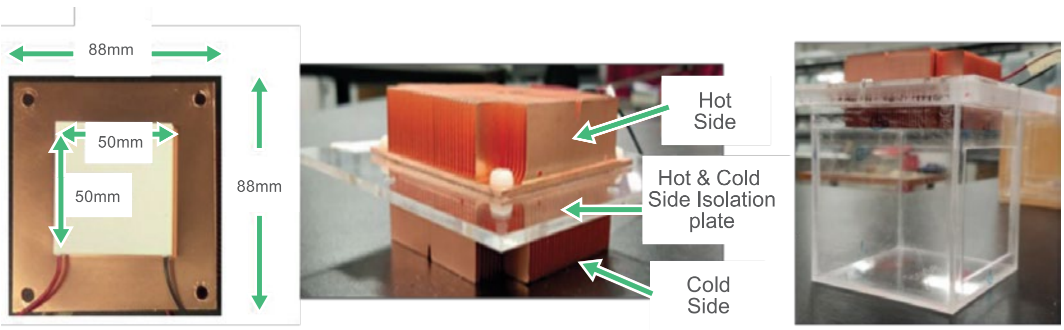


Fig-(6) Bench-test Prototype TE-Cooler

2.6 Multiple block TE-cooler (for Bench-test)

The cooling chamber was redesigned to accommodate multiple uni-block TE cooler as shown in Fig-(7). The air deflectors inside the cooling chamber help to direct the airflow with maximum contact with the TE-cooler heatsinks, ultimately increasing more energy being displaced from the heatsinks. Tests were made with variables of Input power and air-flow speed.

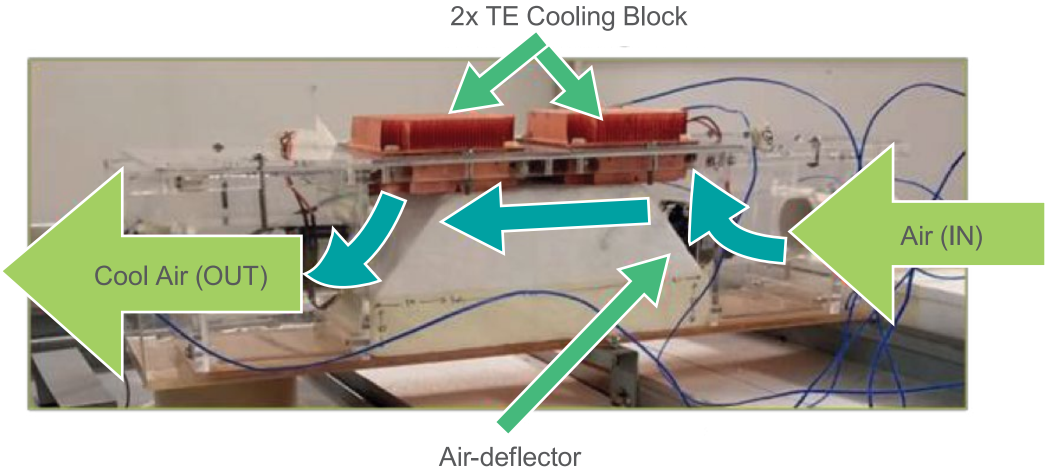


Fig-(7) Multiple Connection of TE-Cooler in Testing

2.7 Full-scale Prototype TE-Cooler (for Lift Cabin Testing)

The full-scale prototype uni-block TE-cooler, Fig-(8), is a larger version of the bench-test version with similar construction by assembling the TEM with the heatsinks. However, there were many refinements to the final design for the full-scale prototype TE-cooler as summarized follow:

Refinements	Objectives
Larger heatsinks used for both Hot and Cold side heatsinks	Better heat dissipation for the TE module to the heatsinks
2x TE modules for each uni-block TE cooler	Higher power and for the uni-block in cooling
4x uni-block TE coolers aligned in series with slight misalignment between each block	Optimize airflow contact with the heatsinks for better energy transfer/displacement from the TE-cooler. Optimize better energy throughput.
Fully enclosed casing for cold side chamber	Minimize energy losses during cooling generation and transfer

The full-scale prototype developed for TE cooling system, the uni-block TE cooler consist of a single TE module attached with the aluminum heat sinks where the power input and temperature output were analyzed to expand the system to a multi-block TE cooler with provided extended cooling. Scalable TE-cooler shown in fig-(8) with multiple blocks allows the air to cool down continuously as it passes through each block with which we will be able to attain a higher cooling rate. The Full-scale prototype uses two TE module in each block. The system was continuously monitored and tested under no load and full load conditions.

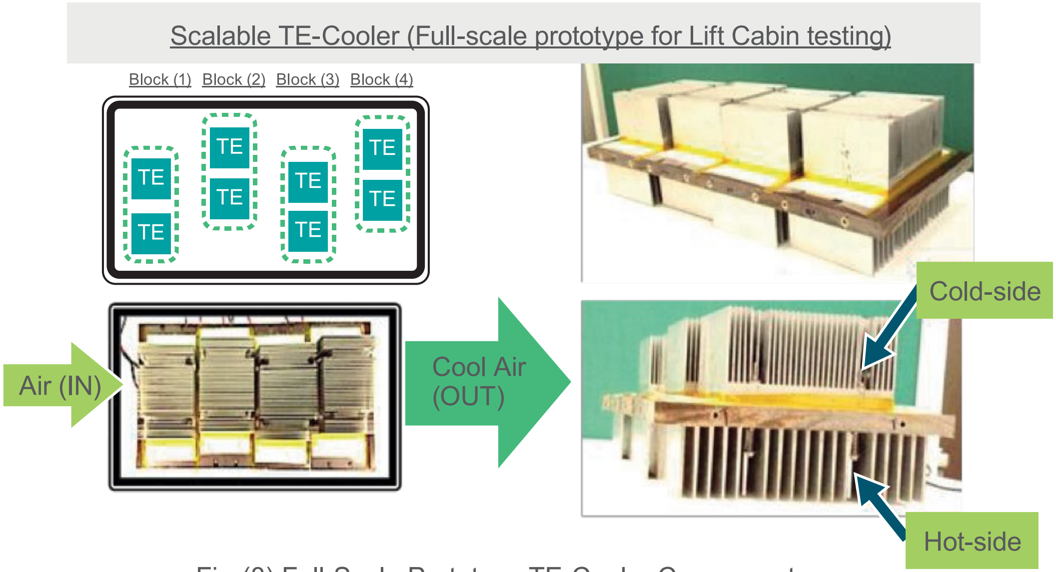


Fig-(8) Full-Scale Prototype TE-Cooler Components

2.8 Heatsinks Used

Various size and types of the following heatsinks were tested in different configuration (see table below) to sandwich the TEM. Based on the tested results, solid block copper heatsinks for both HOT and COLD sides were chosen for the ongoing experiments.

Trial Test on Heat sink property

Testing Conditions

TEC 12708

No heat paste applied between components

3A @4.6V

Ambient (℃) 21.5

Input energy turn on for (5 mins)

Fan on HOT side only (5V@1A approx 6m/s)

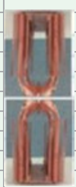
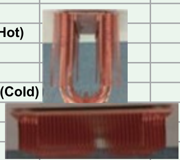
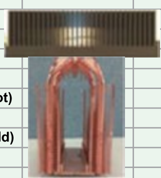
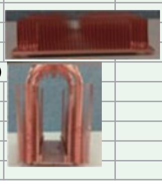
	Temp Point (°C)	No Fan	Fan	ΔT(Fan)	ΔT(HotvsCold) No Fan	ΔT(HotvsCold) Fan	ΔT(%Amb) No Fan	ΔT(%Amb) Fan	ΔT(%Joint) No Fan	ΔT(%Joint) Fan
										
CU pipe(Hot)	Hot Sink Fin Tip	38.0	22.4	15.60		(2.6)	16.5	0.9	(2.4)	-
	Hot Side Joint	40.4	22.4	18.00			18.9	0.9	(1.5)	(2.6)
	Hot Side Plate	41.9	25.0	16.90			20.4	3.5		
					22.3	9.8				
	Cold Side Plate	19.6	15.2	4.40			(1.9)	(6.3)		
CU pipe(Hot)	Cold Side Joint	21.0	20.2	0.80			(0.5)	(1.3)	1.40	5.00
	Cold Sink Fin tip	21.5	20.2	1.30		5.0	-	(1.3)	0.50	-
	Temp Point (°C)	No Fan	Fan	ΔT(Fan)			No Fan	Fan	No Fan	Fan
CU pipe(Hot)	Hot Sink Fin tip	38.0	23.2	14.80		(2.8)	16.5	1.7	(2.40)	1.20
	Hot Side Joint	40.4	22.0	18.40			18.9	0.5	(1.50)	(4.00)
	Hot Side Plate	41.9	28.0	15.90			20.4	4.5		
CU block(Cold)					22.7	10.5				
	Cold Side Plate	19.2	15.5	3.70			(2.3)	(6.0)		
	Cold Side Joint	19.5	15.5	4.00			(2.0)	(6.0)	0.30	-
	Cold Sink Fin tip	20.5	19.0	1.50		3.5	(1.0)	(2.5)	1.00	3.50
	Temp Point (°C)	No Fan	Fan	ΔT(Fan)			No Fan	Fan	No Fan	Fan
	Hot Sink Fin tip	33.8	26.2	7.60		(2.2)	12.3	4.7	(5.80)	0.60
	Hot Side Joint	39.6	25.6	14.00			18.1	4.1	(1.80)	(2.80)
AL block(Hot)	Hot Side Plate	41.4	29.4	13.00			19.9	6.9		
					21.8	10.2				
CU pipe(Cold)	Cold Side Plate	19.6	18.2	1.40			(1.9)	(3.3)		
	Cold Side Joint	21.0	20.8	0.20			(0.5)	(0.7)	1.40	2.60
	Cold Sink Fin tip	21.5	21.3	0.20		3.1	-	(0.2)	0.50	0.50
	Temp Point (°C)	No Fan	Fan	ΔT(Fan)			No Fan	Fan	No Fan	Fan
	Hot Sink Fin tip	55.2	22.6	32.60		0.1	33.7	1.1	(1.30)	(1.40)
	Hot Side Joint	56.5	24.0	32.50			35.0	2.5	(1.10)	1.50
CU block(HOT)	Hot Side Plate	57.6	22.5	35.10			36.1	1.0		
					40.0	6.6				
CU pipe(Cold)	Cold Side Plate	17.6	15.9	1.70			(3.9)	(5.6)		
	Cold Side Joint	19.0	20.4	(1.40)			(2.5)	(1.1)	1.40	4.50
	Cold Sink Fin tip	19.7	20.1	(0.40)		4.2	(1.8)	(1.4)	0.70	(0.30)

Table-(1) Performance of heat transfer using different heat sinks.

2.9 Development of TE Cooler

The following illustrates the development of the uni-block TE-Cooler (for bench testing) and full-scale prototype (for lift cabin testing) constructed for the research.

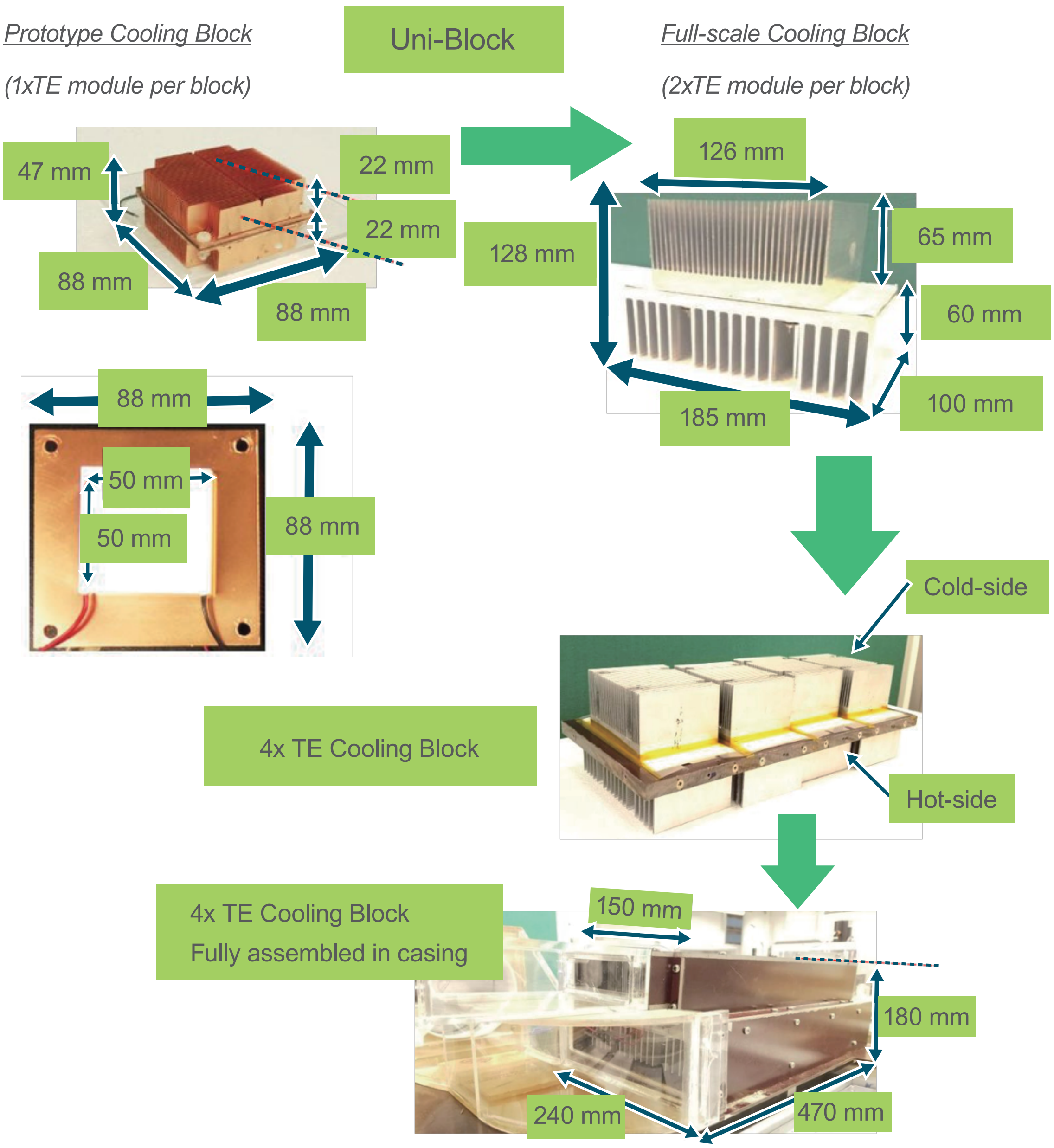


Fig-(9) Construction of Uni-block TE Cooler and Full-Scale Prototype

2.10 Full-scale prototype cooling system on Lift Cabin

The following illustrates the full-scale prototype cooling system (4x TE cooling block) on a mock up lift cabin.

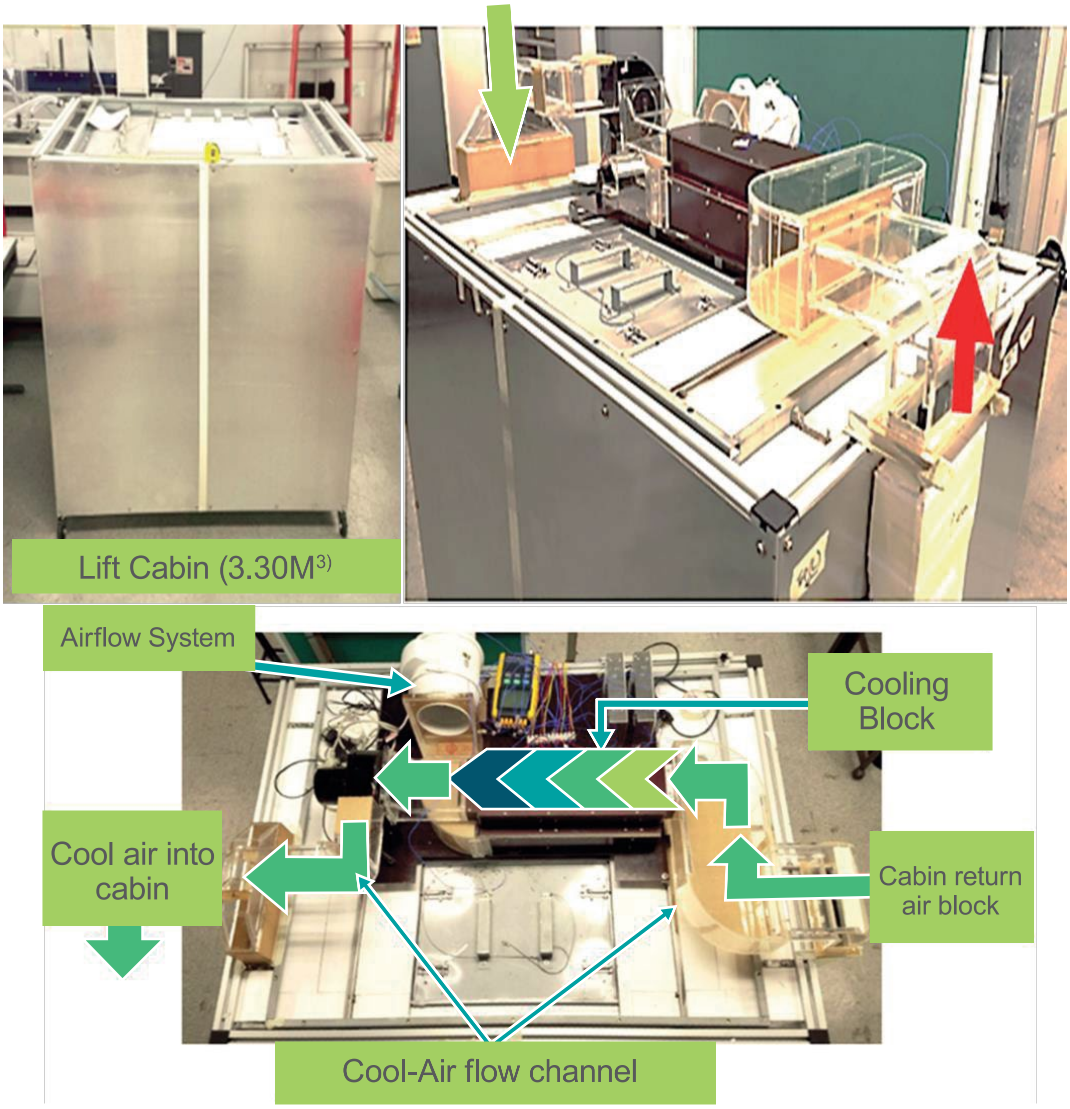


Fig-(10) Full-Scale Implementation of TE Cooling System on the Lift Cabin

3 RESEARCH FINDINGS AND DISCUSSION

The testing results for each stage of this research project as to illustrate the development from proofing of concept to the implementation with the prototype units. The uni-block TE cooler that lead to the analysis of the feasibility of applying TE as a source for cooling and its fundamental indicators for system control refinements as well as to proof the prototype TE-cooler design are presented. The uni-block TE-cooler, formed the basic design that lead to the development of the full-scale prototype design. The performance stability of the full-scale prototype TE-cooler tested under the mock-up lift cabin is presented in detail.

3.1 Uni-Block TE Cooler (Bench–test)

No Load (no ventilation on both heatsinks)

Theoretically, an ideal linear relationship of ΔT against the input power, and the same ΔT on both sides of the TE would indicate perfect heat dissipation within the system. The results enable a prediction of the TE-cooler characteristic in energy transfer, hence its energy efficiency and limitations.

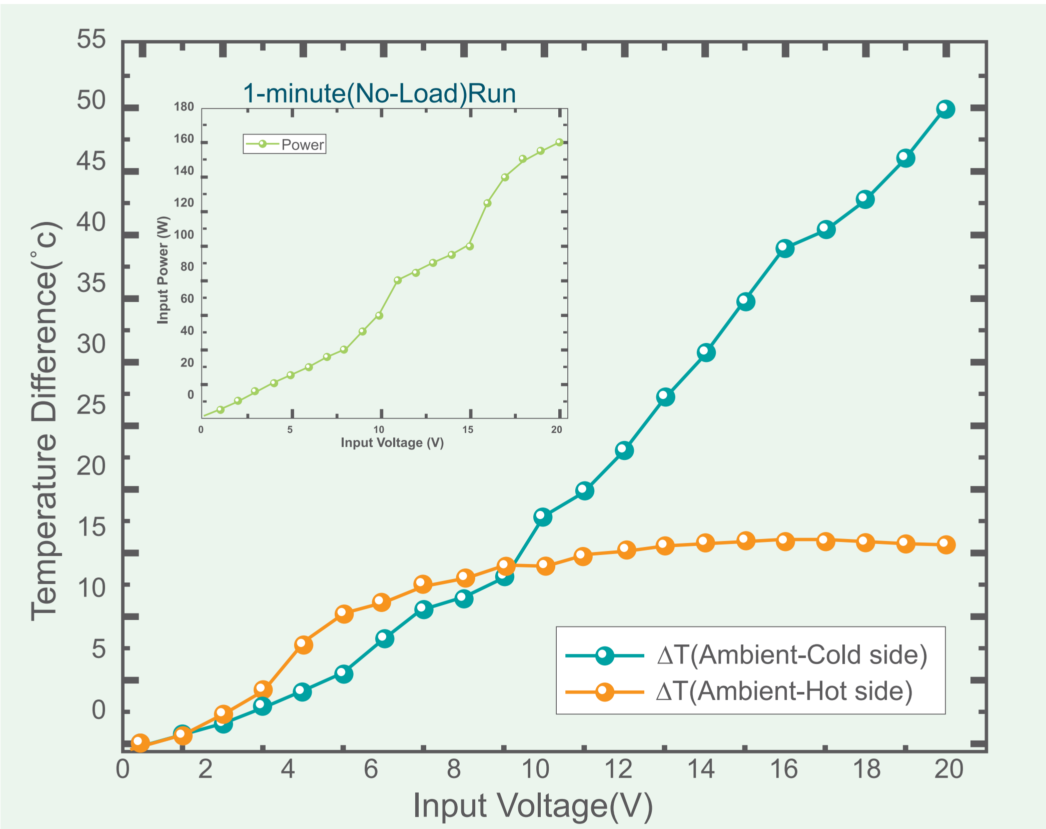


Fig-(11) Energy Output of TE Cooler against Electrical Input Power

Findings/Outcomes:

- In the lower range of Input Power, (0~9V), the TE-cooler shows a linear relationship of temperature change on both HOT and COLD sides.
- Beyond Input Power of 9V, the hot side heatsink is roughly maintaining a linear relationship with input power,
- Cold side is trending into a saturation situation with Input Voltage greater than (10V).

Importance:

The above results suggest better energy management for the TE-cooler as follow:

- Optimal operating conditions with input power below 9V.
- Refinements are needed beyond operating input of 9V, as an attempt to expand the operating range of the system to provide more versatility and usefulness of the cooling system.

3.2 Forced-Air Displacement on Heatsinks

This test was an investigation of the refinements extended from the results observed in uni-block model. The intended objective was to create forced-air displacement from the heatsinks, aiding energy transfer from the heatsinks to the environment and moving airflow. The testing variable was to switch on electrical fans at both sides of heatsink after 1-minute of switching on TE-cooler and then leave system to run for 5 minutes.

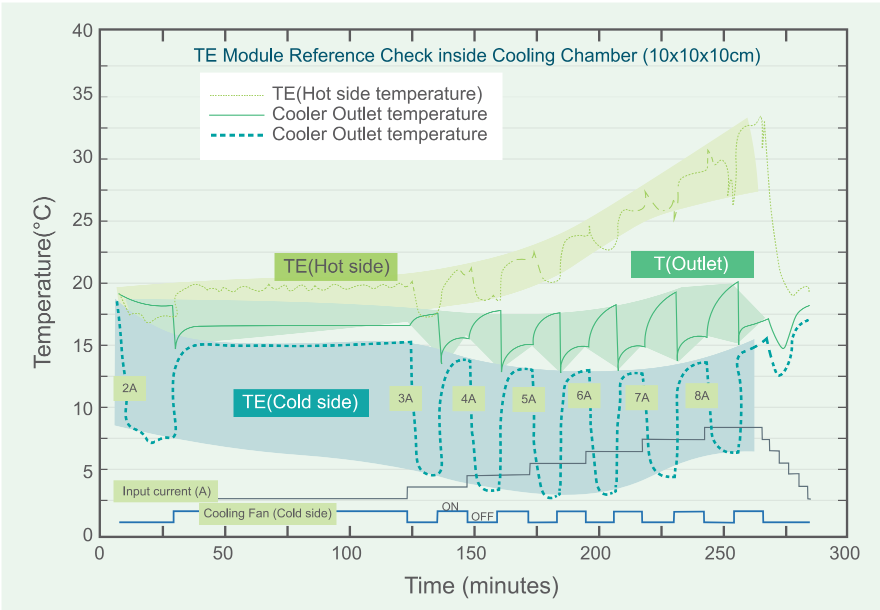


Fig-(12) Energy Output of TE-Cooler with steady airflow on heatsinks

Forced-air cooling test case shown in fig-(12) explains the performance of the TE cooling system with the assistance of external fan to forcefully suck out the temperature from the heat sink. The plots in fig-(12) shows the deflections in the lift cabin temperature with ON/OFF of the fan. The plot also explains the change in temperature with different input current. The outcome of the experiment shows that when forced air cooling (Fan on) is used to remove the temperature stagnated on heat sink the system temperature climbs up and falls down to lowest (Fan off) owing to extra load applied. However, the output temperature into the lift cabin shows a consistent result at varied current input and fan assisted cooling as well. The lift cabin temperature was maintained at 15°C at every change in current and fan on/off.

Findings/Outcomes:

With input power of (9V 4A):

- Able to displace a steady stream of cool air, T(outlet) of temperature 15°C under ambient temperature of 21°C, hence ΔT is 6°C.
- Noticeable improvements of ΔT on both heatsinks when cooling fan was switched on.
  - HOT heatsink temperature @ 23°C, ΔT was down from no-load 13°C to 2°C
  - COLD heatsink temperature @13°C, ΔT changed from no-load 13°C to 8°C

Importance:

Although it would be impossible to attain the ideal perfect condition for which a linear relationship of temperature change, ∆T on both side of the heatsinks. However, we observed a noticeable decrease of ∆T on hot-side which indicates a wider versatility for improving the TE efficiency and performance further.

- The TE-cooler was observed to maintain at a steady temperature below the ambient temperature, of ∆T (6°C), which had exceeded of target of ∆T (5°C).
- The results indicate the TE-cooler of its primitive design is feasible as a cooler unit.

3.3 Variable-mode of Air Displacement on Heatsinks

The test was a refinement investigation extended from the results observed in forced air displacement on heatsink. Forced-air was directed to the cold side heatsink, while the variable was the mode of switching on the fan. This experiment would also allow us to measure the rate of the TE-cooler to reach to a steady state which would also enable a comparison of the lowest attainable steady temperature.

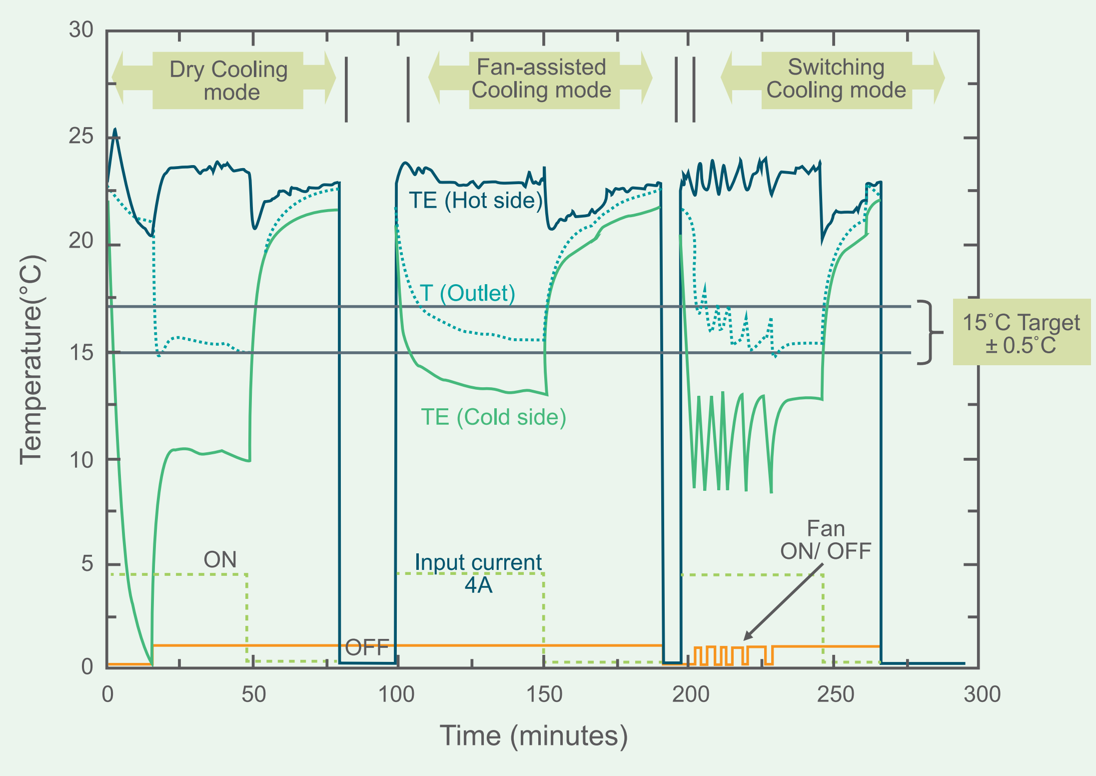


Fig-(13) Energy Output of TE-Cooler with variable airflow on heatsinks

Parameters		Dry-Cooling mode	Fan-Assist mode	Switching mode
TEC Input Power @ (4A, 9.1V)	(W)	36.4	36.4	36.4
Q(power) @ steady	(W)	33.63	31.79	33.72
Estimated COP @ steady		0.92	0.87	0.93
Outlet Temp @ steady	(ºC)	14.13	14.77	14.37
∆T (outlet) @ steady	(ºC)	7.02	6.63	7.04
∆T (TE) @ steady	(ºC)	12.92	9.32	10.30
Time to steady	(mins)	9.63	10.02	5.77

Fig-(13) Energy Output of TE-Cooler with variable airflow on heatsinks

Findings/Outcomes:

with input power at (4A 9.1):

- Best system COP performance attained (0.87 ~ 0.93) @ steady state.
- Best time of reaching the steady state was 5.77 minutes.
- Best Q(power) @steady was in the range (31.79W ~ 33.72W).
- Best ∆T (outlet) @ steady was 7.04 ºC

Importance:

- The best achievement of COP was (0.93). On comparison with the manufacturer data (ref. Appendix-1), projected COP is of 1.15 at input power of (4A), hence the prototype system was about 84.5% against the manufacturer's performance, which indicates the prototype system design is a viable construction.
- Also observed the temperature difference at the cold outlet, ∆T (outlet) at steady was 7.04ºC, which had exceeded the original target of ∆T 5ºC.

3.4 Temperature Gradient

This test was a refinement investigation extended from the results in previous case, to observe how quickly the TE-cooler could lower the space temperature (i.e. cool-air displacement), through various mode of air forced into the cooling chamber. Fig-(14) explains a 30-minutes view of the system performance under dry case which is just the TE modules performance. The steady state performance explains the performance of the cooling system under perfect test conditions with fan on throughout the operating time. In the case of switching the fan on/off time is controlled in regular intervals so that the stagnated temperature is release instantly which produces higher cooling effect as shown in the plot.

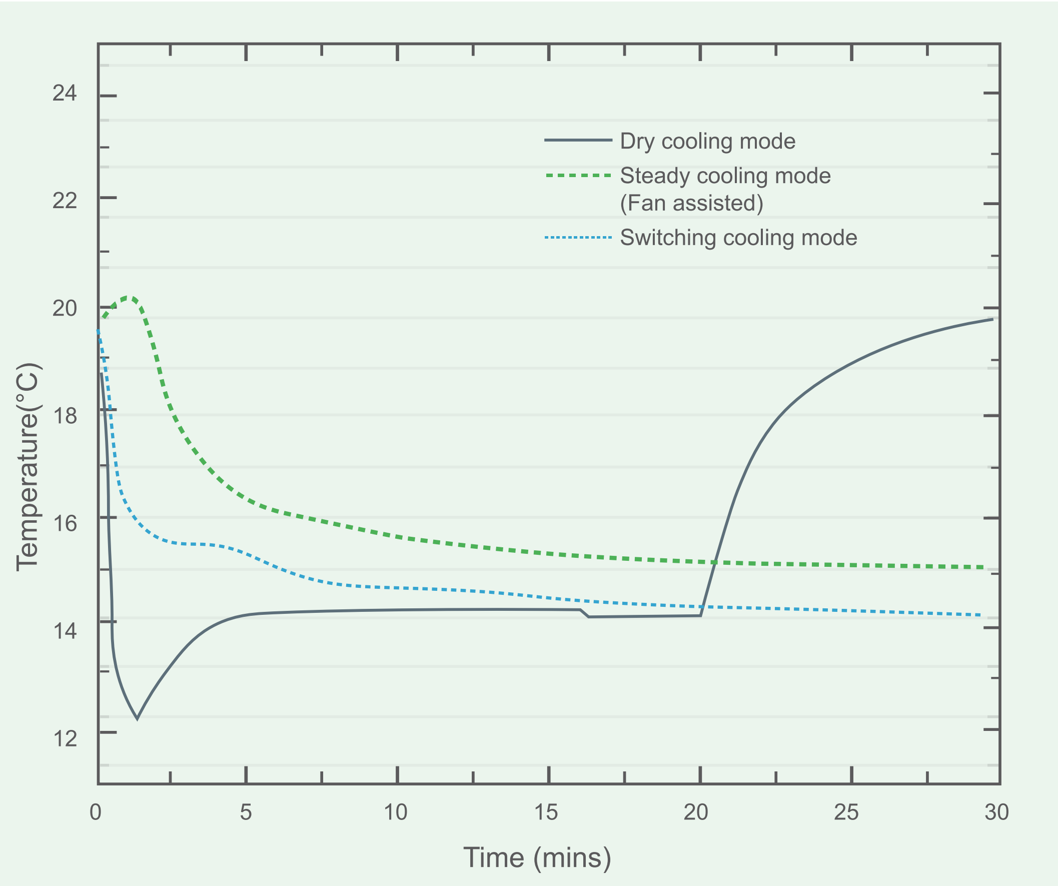


Fig-(14) Temperature Gradient of TE-Cooler on cold-side

Findings/Outcomes:
<u>With input power of (4A 9.1V):</u>

- Temperature between (14ºC~16.3ºC) were observed for the space inside the cooling chamber, after 5-minutes of switching on the fan on COLD-side.
- This temperature change translates as ∆T of (5.8 ºC ~ 7.1 ºC), which have all exceeded the original proposed design of 5ºC difference from ambient.

Importance:

- The prototype TE-Cooler design had achieved the proposed design indicators i.e. ∆T of (5 ºC) or more within 5 minutes.

3.5 Cascading Arrangement of Uni-block TE Cooler

An innovative feature of this TE-cooling system is the "scalability". From the test results in the previous sections. We have observed the best attainable Q(energy) from the prototype TE-cooler was 33.72W.

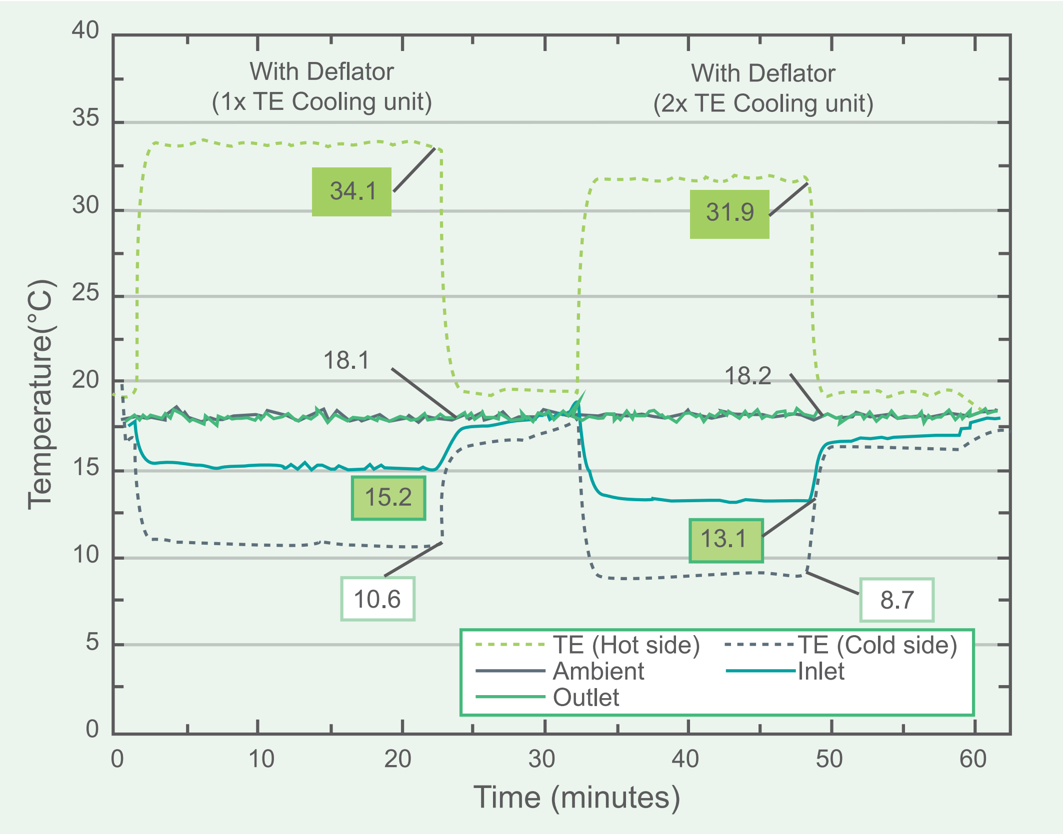


Fig-(15) Energy Output comparison with multiple TE-Cooler in cascade arrangement

Findings/Outcomes:
With input power of (9V 4A):

- A linear change in temperature (ΔT of around 2 ºC) was observed at all points after cascading 2 TE-cooler in series.
  - Hot side : temperature dropped (34.1 ºC) to (31.9 ºC), ΔT of (2.2 ºC)
  - Cold side: temperature dropped (10.6 ºC) to (8.7 ºC), ΔT of (1.9 ºC)
  - Outlet : temperature dropped (15.2 ºC) to (13.1 ºC), ΔT of (2.1 ºC)
- Q(output) observed:
  - 1xTE cooler system: Q(output) 13.9W
  - 2xTE cooler in cascade: Q(output) 24.6W (76% increment)

Importance:

- The most noticeable change is observed on HOT-side and COLD-side and the OUTLET, where the temperature changed were quite proportional, i.e. ΔT of around 2 ºC.
- The ability to bring the temperature down is crucial as to enable the system with a wider operating range.
- The cascading arrangement of TE-coolers is a good design for a greater output performance and a system of wider operating range.

3.6 Full-scale Prototype TE-Cooler

This test was a refinement investigation extended from the results observed in previous trails. The intended objectives Construct a full-scale prototype cooling system, which is 8 TE modules cooler system in the arrangement as 4 uni-blocks cascaded together, Fig- (8). Tests were carried out that confined with the following refinement considerations:

Airflow Management:	Vary the direction and speed of air-stream into cooling system.
Power Management:	Vary different input power and mode of input power into cooling system.
Energy Losses Management:	Refinements to system components, components assembly and insulation.

The graph below illustrates the test result of different test trail cases conducted with the full-scale prototype TE-cooler (13 cases). Results are consolidated in graphical format were intended for easy comparison of the Energy Conversion performance of the TE-cooling system for all cases tested.

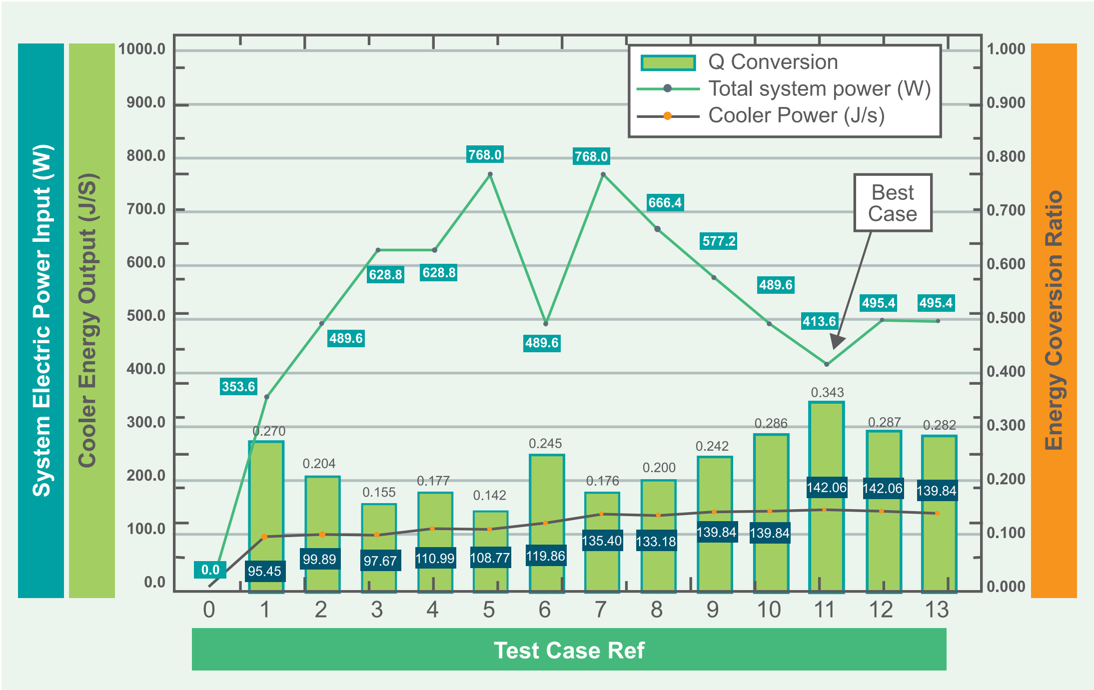


Fig-(16) Performance comparison of the full-scale prototype under different operating

Findings/Outcomes:

- A total of 13 test cases were designed and executed.
- Best performance under case (Test 11), with energy output of 142.06W.
- Cabin temperature could reach to steady temperature within 5-minutes.
- Within the pre-defined testing time period of 5 minutes, the best ΔT(Cabin), cabin temperature change attained was 4.5ºC.

Importance

- The construction design of the full-scale prototype cooling system was capable to cool the lift cabin space (3.3 m^3) to the predefined specification of temperature difference -5ºC against ambient, and within the time period of 5minutes.

3.7 System Performance

Energy Conversion

The following table selected the top 3 test cases executed in section with the best energy conversion from the full-scale prototype TE-cooler.

Table 8 TE-Cooler Performance Comparison for the best 3 operating modes

Performance Category		Top 3 performance test cases		
		1st (case #11)	2nd (case #12)	3rd (case #10)
Q-Energy	J/s	142.1	142.1	139.8
Horse Power (@1hp = 746 J/s)	hp	0.191	0.191	0.187
System Electrical Power Consumption	W	413.6	495.4	489.6
Q-conversion Ratio (q-energy / Electrical consumption)		0.343	0.287	0.286
∆T(cabin), cabin temperature change	ºC	4.5	4.6	4.5
∆T(cooler), TE-cooler IN/OUT temperature difference	ºC	2.7	2.7	2.7
∆T(outlet), TE-Cooler outlet vs Ambient	ºC	6.4	6.4	6.3

From the Q-energy data alone, (i.e. 142.1 J/S or 142.1W), the performance is falling short of the original aim of (550W). However, it is worth to note that this rate of Q-energy had already exceeded our original mathematic model (Appendix-II), of (140.4877 J/s) needed to displace an air space of ($3.3m^3$) inside the lift within 5 minutes.

In a close inspection of the operating limits of the components and apparatus used in the full- scale prototype TE-cooler, better performance could be achieved.

TE module:
the TE device used is rated at 24V(200W@13A), however, in the best performance cases, the TE-cooler was working in the range of 11V~13V (approx. 50% of the operation range). There are refinement opportunities of increasing the Q-energy output by increasing the operating voltage.

Mode of Input Power:
In section (3.2), in the cascade arrangement, it is observed a consistent change of temperature between the uni-block TE-cooler. In fact, refinement could be done by varying different input power for each block, we would expect significant saving on system power consumption and still achieve the cooling power (target temperature) needed.

Airflow system:
commercial electrical fans of single speed were chosen in the tests, possible refinements to be made with variable speed fans as to compensate the energy losses absorbed by fan.

Insulation:
for our convenience of making system refinements during the exhaustive testing cycle, we have excluded insulation to the cooling system which is a prime source of energy losses.

3.8 Lifetime Study of the TE-cooling System

Peltier cooling modules are highly reliable components due to their solid-state construction model. They will provide long, trouble-free service. There are examples where TE modules are being used continuously for 20 or more years and the lifetime of a module often exceeds the lifetime of its associated accessories. Steady-state cooling where DC power is applied to the module on more-or-less continuous and uniform basis, thermoelectric module reliability is extremely high. Mean Time Between Failures (MTBFs) in excess of 100,000 hours are not uncommon in such cases and this MTBF value generally is considered to be production standard.

During the test period, relevant module parameters are continuously recorded. Parameters that are a good indicator of overall module performance is the maximum temperature difference (ΔT) and cabin temperature. These parameters were tracked for over 1000 hours with the average value being shown the graph of Fig-(18). From the results we see no degradation in the system performance.

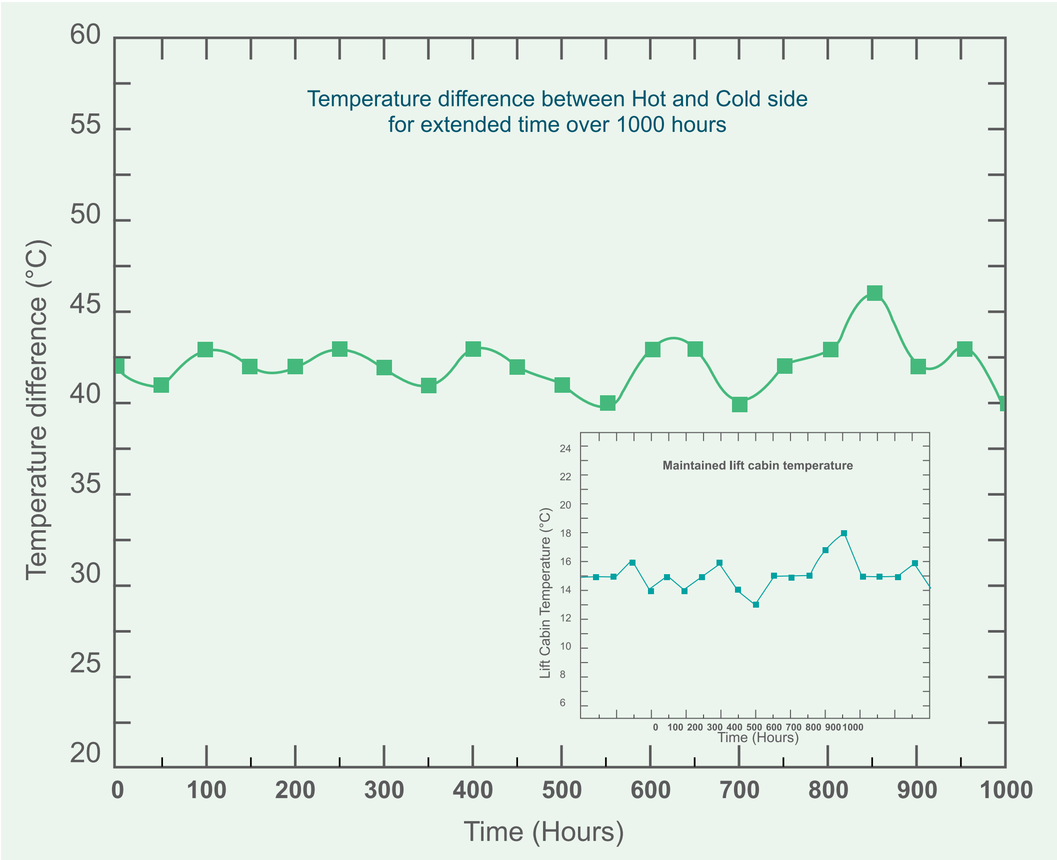


Fig-(18) Performance of the TE-Cooling System for over 1000 hours

3.9 PID Power Controller Settings

In order to effectively control the temperature of the lift car cabin, we have installed a Watlow TC 3400 PID power controller. The PID controller always monitors the lift car cabin's temperature and adjusts itself with an algorithm which allows them to control the power required to alter the temperature. The set point of the PID temperature sensor is always 5°C below the ambient temperature. An on/off controller is the simple PID temperature control device. The output from the controller is either on or off pulse, with no middle state. An on/off controller will switch the output only when the temperature crosses the setpoint. When the temperature crosses the setpoint to change the output state, the process temperature will be cycling continually, going from below setpoint to above, and back below.

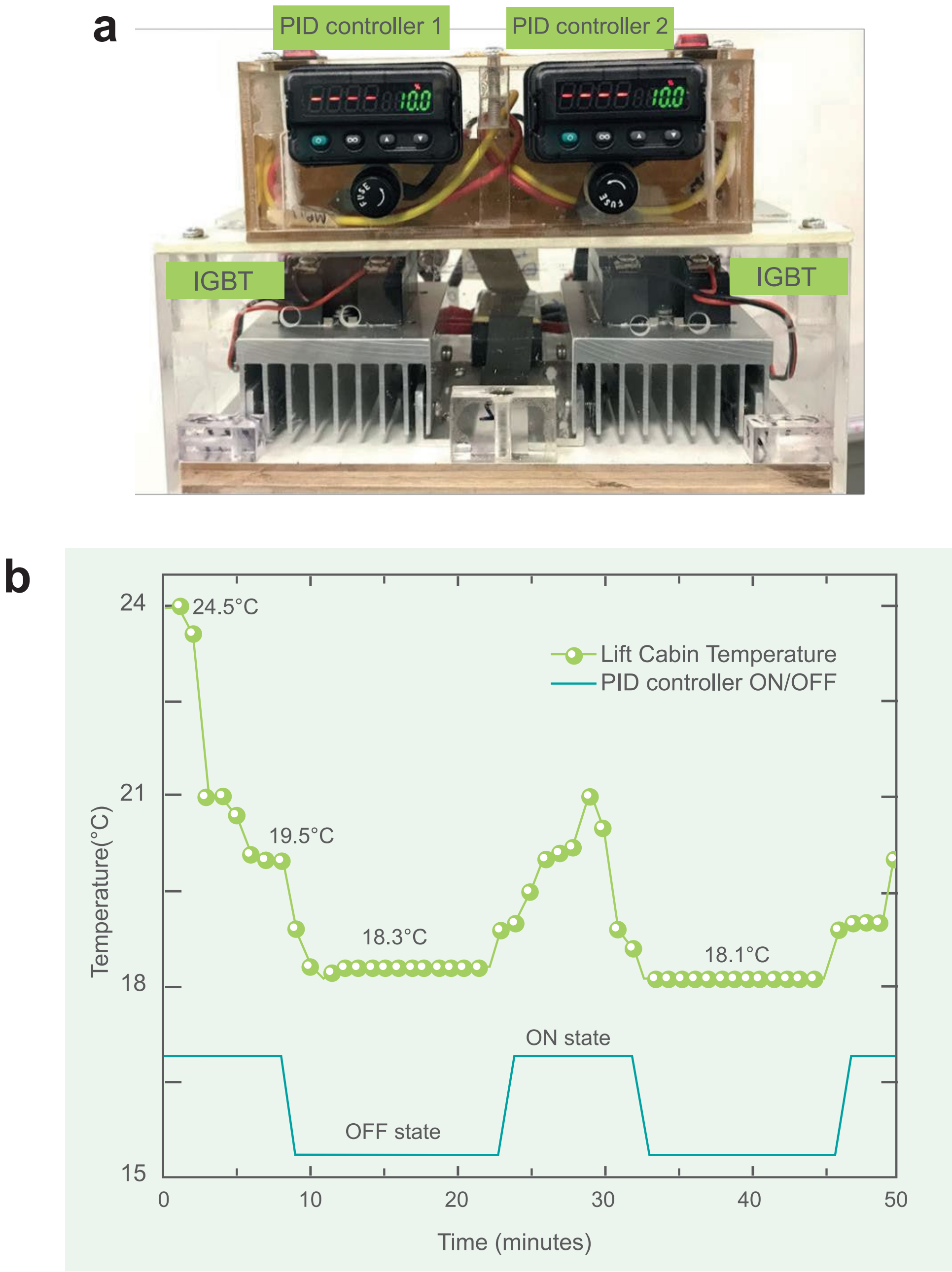


Fig-(15) (a) Setup arrangement of the PID temperature controller
(b) shows the working performance of PID controller in Lift cabin

In the above fig-(15), the setup for the PID controller is shown, where we use two stage of PID controller. PID controller 1 and PID controller 2 are connected to four TE modules each, this arrangement provides a wide control over the lift cabin temperature. PID controller 1 is operated as power switch which on sensing the cabin temperature 5°C below ambient atmosphere switches off one set of TE(four) modules for power conservation. Whereas, the PID controller 2 always monitors the cabin temperature with other set of TE modules. The plot in fig-(15b) demonstrates the working of PID controller with respect to cabin temperature. As the cabin temperature increase, the PID controller 1 automatically powers ON the TE modules for full load cooling. Our setup helps in maintaining a comfortable temperature inside the lift cabin with high precision PID controllers.

3.10 Comparison with Compressor-type Air-con

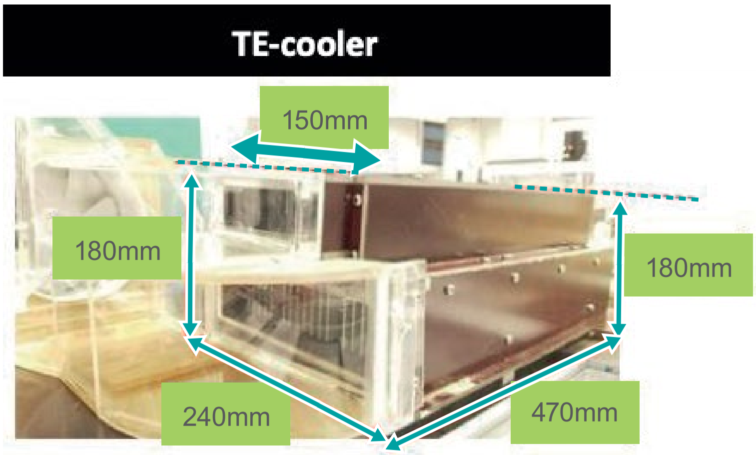


Table-(9) Performance Comparison against Commercially available compressor type air-con

	TE-Cooler CityU prototype (8TE-2018)	Compressor-type Air-con Panasonic (CW-XV715JA)
Physical measurements (mm)	(L) 470mm (H) 180mm (D) 240mm	(L) 450mm (H) 346mm (D) 590mm
Weigh (Kg)	10Kg	29Kg
Power Source	DC	AC
Rated output (hp)	0.191hp	0.75hp
Power Consumption (W)	413W	690W
Cost (HK$)	HK$ 3000	HK$ 4380

The full-scale prototype TE-cooler system reviewed a number of area that is better than the more traditional compressor type air-conditioning, especially in the physical dimensions of it size and weight which are critical decision factors for installation on the limited footprint and restricted space of the lift-top. Being powered by DC, makes the system versatile in operation by all type of power source, DC converters or batteries, making the TE-cooler possible to provide ventilation in the event of power outage. Although the side-by-side comparison see the rated output (hp) for the TE-cooler less favorable. However, as we have observed in Chapter-3 in the development of this TE-cooler prototype, by cascading TE-cooler together, the output energy and operating limits (temperature range) would be proportionally increased. So this versatility nature will be most suited for solving the current problems for installing air-conditioning unit to older lifts (20+ age) which accounts for more than 51% of the total lift installed in HK.

4 CONCLUSIONS

Thermoelectric generators have long been relegated to use in space-based or other niche applications. Such applications have proven that TEG provides long and reliable operating life for the device under continuous operation. Such good nature of TE materials has extended more research into thermoelectric coolers for solid state cooling systems.

Section (4.3) reviewed a number of areas that TEC is better than the traditional compressor type air-conditioning unit, especially in the physical dimensions of it size and weight which are critical decision factors for installation on lifts.

Although the current research results show TEC may not be as efficient. Comparing to traditional heat pumps and refrigerators, TEC is superior in its high reliability, low maintenance, no moving parts that cause vibration, no refrigerants, and also converting energy directly. The cooling temperature can be controlled easily by changing the input electrical current, so that the operation of TEC is highly adjustable. Moreover, one main characteristic of the TEC is that the performance is almost independent of its capacity, so it is good to be a cooler for confined space.

Because the TEC system contains no liquid form components, the system can therefore be mounted in any orientation, which is a distinct difference and advantage for the choice to install TE-cooler at restricted space of the lift-top.

In terms of cost, as the prototype TE-cooler were entirely built with commercial components, the high cost for the TE-cooler unit being the price paid for the TE modules, which are specialized version. With mass-production of TE module, the overall cost for the TE-cooling unit will be much less, would foresee to be under HK$1500 for the current prototype version. By then, TE-cooler system would become a choice in term of cost-effectiveness.

The Way Forward

System efficiency will always be a prime concern in electrical system design. For this TE-Cooling system, continuous refinements will be studied with focus in the following area to further develop the existing prototype to be a production version:

- Power Management
- Energy Displacement Management
- Energy Losses Management

TE Module

The power output of the TEC system is very much dependent on TE module efficiency. Continuous research studies are in progress for more advanced TE materials, such as Graphene. If similar material of high power factor is made commercialize, we would expect radical changes and improvement in the TE applications and solutions.

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