Applied Thermal Engineering 224 (2023) 120101

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermoelectric cooler (TEC) based thermal control system for space applications: Numerical study

V.K. Singh [a,*], S.S. Sisodia [a], Akshat Patel [b], Tirth Shah [b], Prasanta Das [a], R.N. Patel [b], R.R. Bhavsar [a]

[a] *Thermal Engineering Division, Space Applications Centre, ISRO, Ahmedabad, Gujarat 380015, India*
[b] *Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat 382481, India*

A R T I C L E I N F O

Keywords:
Thermoelectric Cooler
Thermal control system
Detector
Spacecraft Systems

A B S T R A C T

The present study devises and numerically investigates a new thermal control system for detectors of optical payloads for spacecraft systems. The system uses thermoelectric coolers (TECs) as the active element which maintains the cold finger at the required set point such that temperature of detectors is maintained within the required range throughout its operation. The system doesn't utilize any heat pipe network, but instead, uses radiators attached to the hot-side of TEC to dissipate the heat load into the ambient space environment. System level modelling using effective properties are used to model the performance of TEC without modelling any internal intricate geometry. Temperature dependent current profiles are used as input conditions for the TECs such that the TEC consume only the required amount of external power. Effect of TEC set point and geometrical parameters of the radiator is studied and it is observed that considerable reduction in power consumption or improvement in coefficient of performance is obtained by utilizing a larger set point or a radiator with larger dimensions. The system is further investigated for different heat loads and duty cycles (upto 50% for an orbit period of 100 mins) to evaluate its efficacy under varying operating conditions. The system is also investigated for successive operating cycles and it is observed that the cyclic error between successive cycles eventually diminishes to zero thus implying that the temperature control requirements are met for successive cycles throughout the life of the system.

1. Introduction

A spacecraft payload consists of several electronic subsystems and components which operate intermittently in the orbit period and generate heat load during this period, while for the remaining cycle it remains off. These subsystems and components require appropriately designed thermal control systems (TCS) so that this heat load is transported away from the source and the temperature of these subsystems are maintained within their safe limit of operations. One such component is a detector which is used for spectral measurements and astronomical observations. The operating period of a detector for space-based remote sensing is typically between 2 and 20 min in an orbit period of 100 min depending on the application. The type of detector can vary depending on the wavelength range of light it detects such as X-ray detectors, infrared detectors, etc. The detectors are calibrated at their operating temperature and thus require suitable TCS, which maintains the detector's temperature within a narrow range of the calibrated operating temperature. High temperature fluctuations or voiding the prescribed operating temperature limits would drastically affect the accuracy and efficacy of the detector and may even generate thermal stresses within the detector or its assembly which would ultimately reduce its life [1,2].

The traditional method for temperature control of a detector usually consists of several components such as cold-fingers, heat pipes and radiators. On a typical optical payload, there may be several such detectors, all which may have the same or different temperature requirements. Detectors may not be always physically accessible to be directly attached to the miniature heat pipes because of space or assembly constraints. Instead, cold fingers of highly conductive metals are attached to the detectors. These cold fingers perform the function of an intermediate link which provides area for heat pipes to be attached and also transports the heat from the detector to these miniature heat pipes. Depending on the total number of detectors and their arrangement within the payload, miniature heat pipes from the different detector may transfer their heat to a common dual-core heat pipe which then further

* Corresponding author.
E-mail addresses: singhvivek84@gmail.com, singhvivek@sac.isro.gov.in (V.K. Singh).

https://doi.org/10.1016/j.applthermaleng.2023.120101
Received 29 June 2022; Received in revised form 9 January 2023; Accepted 19 January 2023
Available online 23 January 2023
1359-4311/

Nomenclature

A	Area (m^2)
C_P	Specific Heat (J/kg.K)
G	Geometric Factor (mm)
I	Current (A)
k	Thermal conductivity (W/m.K)
k_{mo}	Module thermal conductivity (W/K)
L	Length (m)
N	No of thermocouples
n	Unit vector normal to surface
Q	Heat load (W)
Q_c	Cold Side heat load of TEC (W)
r	Resistivity (Ω.m)
T	Temperature (K)
t	Time (s)
t_D	Detector Thickness (mm)
t_{CF}	Cold Finger Thickness (mm)
L_R	Edge length of radiator (mm)
t_R	Radiator thickness (mm)
V	Voltage (V)
Vo	Volume (m^3)

Greek Symbols

α	Seebeck Coefficient (V/K)
α_{mo}	Module Seebeck Coefficient (V/K)
ρ	Density (kg/m^3)
ρ_{mo}	Module resistivity (Ω)
σ	Stefan-Boltzmann Constant (W/m^2K^4)
ε	Emissivity

Subscripts

Al	Aluminium
a	Ambient
Cr	Ceramic
c	Cold
h	Hot
int	Initial
Lu	Lumped
max	Maximum
rad	Radiator
set	Set Point

Abbreviations

COP	Coefficient of Performance
CVM	Control Volume Method
TEC	Thermoelectric System
TE	Thermoelectric
TCS	Thermal Control System

transports it to external radiators. These radiators then radiate the heat to ambient space environment. Utilizing such common heat pipes instead of individual heat pipes reduces the complexity of the system and also the volume occupied by the system within the spacecraft. A typical thermal control system catering to the heat loads of multiple detectors is shown in Fig. 1.

However, using such a thermal control system has several limitations also. As there is a network of heat pipes which is employed for temperature control, there will also be several interfaces all of which will contribute to the thermal resistance of the heat path. Further, heat pipes also maintain a temperature difference across their ends, and thus using such network of heat pipe will significantly increase the temperature gradient across the entire network and this eventually increases the radiator sizing as it is to be now maintained at colder temperatures to accommodate the large temperature gradient across the network. Also, because of vibrations and thermal stresses, a flexure may be required which can handle different vibrations and stresses but at the cost of an increase in the thermal resistance of the network. This further increases the thermal gradient across the network which in turn further increases the radiator size. Another disadvantage is that due to the use of common heat pipes and radiators, the detectors are interlinked and thus operating or testing a single detector isn't possible as the system is designed for the combined load of all detectors. Thus, the traditional approach may be very cumbersome and complex to implement for the sophisticated payloads of future which may have more stringent requirements due to an increase in the processing power of such devices and rapid miniaturization of such devices. Thus, a new design for the thermal control system of such detectors and devices is needed to cater the needs of future and to simplify the existing system by eradicating the various disadvantages associated with it.

Thermoelectric coolers (TEC) also known as Peltier coolers are progressively gaining popularity as an active component that can be readily integrated into the existing thermal control setup. TECs operate on the principle of the Peltier effect and transfer thermal energy from its cold side to its hot side by utilizing external electrical energy and subsequently also maintaining the temperature difference across the hot and cold side. TECs have no moving parts, occupy less space & are lightweight, are easy to operate & regulate and have high reliability throughout their life making them highly suitable for the thermal management of spacecraft subsystems and components. TECs have been extensively used in several terrestrial applications. Zhu et al. [3] devised an TEC based heat exchanger for electronics system cooling and analytically analysed the system to optimize the system in terms of various parameters such as heat transfer area, maximum cold side heat flux and minimum cold side temperature. Shen et al. [4] investigated a miniature thermoelectric module for the cooling of a pulsed laser. The study employed a step-change cooling method to regulate the current supplied to TEC and utilized supercooling to cool the pulsed laser. Lorenzi et al. [5] utilized thermoelectric devices to improve the coefficient of performance of photovoltaic systems upto 3.05 % by utilizing residual thermal energy to generate electrical energy. Caroff et al. [6] employed a multi-objective optimization approach to devise a peltier cooler based cooling system for thermal management of avionics. However, utilizing TECs in such cooling system usually involves employing a heat sink on the hot side of TEC in order to dissipate the heat load into the ambient atmosphere through convection. Such heat sinks cannot be used for space applications as external convection is absent. Instead, conductive or radiative heat transfer is to be utilized to dissipate the heat load into the space.

Morales et al. [7] utilized TECs to conductively maintain the temperature of detector, a bolometer model UL04171 manufactured by ULIS, aboard the Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO) at 30 °C and also to ensure that the temperature of focal plane array is also simultaneously stabilized. Semena et al. [8] employed TECs to thermally stabilize semiconductor X-ray stripped and multimodule detectors being planned under the Russian-German project "Spectrum-RG". The thermal system comprised of a network of heat pipes which transported the thermal load to external radiators which then dissipated the thermal load into the ambient space environment at 4 K. Serbinov et al. [9] also utilized a similar thermal control setup based on TEC, heat pipes and 2 external radiators to maintain 4 CdTe detectors, used to measure cosmic X-ray background, at −30 °C ± 2 °C under fluctuating external conditions of ISS such as direct sun irradiance which varied from 0 W/m^2 to 1400 W/