AIAC-2019-032

SELECTION OF THE CONDUCTION AND/OR RADIATION COOLED TRAVELLING WAVE TUBE ACCORDING TO SATELLITE THERMAL CONTROL AT GEOSTATIONARY ORBIT

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ABSTRACT

The travelling wave tube is a critical electronic equipment for satellite data transmission and one of the highest dissipative equipment in the satellite. The travelling wave tubes generate approximately 70% of payload waste heat at geostationary earth orbit satellite. Therefore, thermal management of travelling wave tube is one of the key aspects for satellite applications. The demand for higher power travelling wave tubes and limitations in satellite thermal design led to choose between the conduction and/or radiation cooled travelling wave tube. The aim of this study is to make a selection of the conduction and/or radiation cooled travelling wave tube.

INTRODUCTION

Heat dissipation has become a significant challenge for satellite manufacturers. Therefore, managing waste heat generated from the satellite becomes one of the critical issues at the early stage of the satellite project. For geostationary orbit satellites, most of the waste is generated by the payload which includes in TWTs. Travelling wave tube (TWT) is a broadband vacuum microwave devices used as a high power microwave amplifier in satellite for communication [Mistry, et al. 2018]. Satellite waste heat ie rejected to space by radiators which are covered by optical solar reflector (OSR). OSR are attched to external surfaces of the satellite. OSR is a mirror of second surface with low absorptivity/emmisivity ratio [Boato et al., 2017].

At preliminary design (PDR) and critical design review (CDR) phases, radiative areas (radiators) are designed for end-of-life (EOL). Radiative areas receives the highest heat flux from the Sun because of OSR degradation. OSR absorptivity value increases with time.

In this study, radiative areas are studied based on the conduction and/or radiation cooled travelling wave tube heat dissipation.

TRAVELLING WAVE TUBE

TWT is one of the most critical components of the satellite transponder and is the hottest component of the satelite. TWT is a cylindical structure which contains an electron gun from a cathode tube, a slow wave structure (SWS), a magnetic focusing system, RF input and output couplers, a collector. RF input is sent to one end of the helix and the output is drawn the other end of the helix. Figure 1 shows pyhsical construction of TWT. Approximately 70% of the total consumed power is converted into RF energy, and the remaining 30% is converted to waste heat [Lohmeyer, 2016]. Passive thermal control including heat pipes and surfaces of high emissivity is used to dissipate the concentrated heat in the payload [Murthy et al., 2011]. TWTs use heat pipes and raditors as passive thermal control. TWTs also use heaters as active thermal control.

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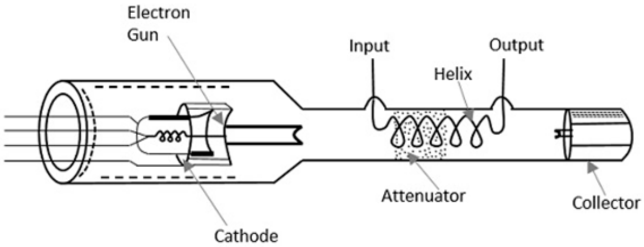


Figure 1: Pyhsical construction of TWT

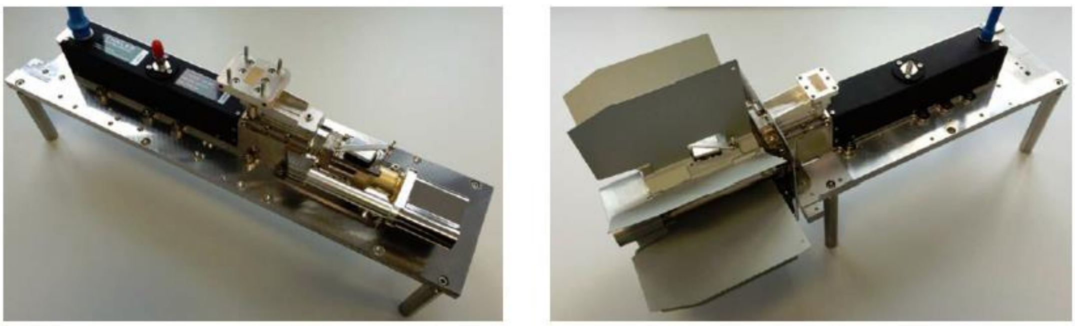
TWT principle was invented by Kompner in 1943. TWT was mathematically characterized by Pierce in 1950 [Pierce, 1950]. Kompfner recounted his early work on the TWT published in 1964 [Kompfner, 1964]. Comparison of TWT's is shown in Table 1.

Table 1: Comparison of TWT's [Kornfeld and Bosch, 2001; Bosch and Fleury, 2004]

Program	**First TWT in Use TV-Ground Link**	**First Space TWT Telstar 1**	**First European Space TWT Symphonie**	**C-band**
Manufacturer	STC	Bell Lab	AEG	Thales
Year	1952	1962	1973	2002
Frequency	3.6-4.4 GHz	3.7-4.2 GHz	3.7-4.2 GHz	3.6-4.2 GHz
Output Power	2 W	2 W	13 W	115 W
Gain	25 dB	40 dB	46 dB	50 dB
Efficiency	=1%	<10 %	34%	70%
Nonlinear Phase	?	50^o	50^o	50^o
Mass	>5000 g	>1000 g	640 g	790 g
Collector	1 stage	1 stage	1 stage depressed	4 stage depressed
Focusing System	Solenoid	PPM PtCo	PPM PtCo	PPM CoSm
Cathode	Oxide	Oxide	Oxide	Mixmetall

The first operational TWT built as TV relay tube by STC in 1952. The first communication satellite Telstar 1 was equipped in 1962 with an 8 W C-band TWT from Bell Lab. The first European satellite TWT built by AEG and launched 1973 on board of the French/German Symphonie Satellite. From the first European built and successful operated space amplifier in the Symphonie program until today, C-band TWTs have been improved in mass from 49 g/W to avout 6 g/W and in efficiency from 34 % to 70 % (time period 1972 to 2002) [Bosch and Fluery, 2004].

Helix TWT are most commonly used an amplifier for the satellite communications. A space TWT may be conduction cooled or radiation cooled. Figure 2 shows conduction cooled and radiation cooled TWT [Hanika et al., 2015].



(a) (b)

Figure 2: (a) conduction cooled TWT (b) radiation cooled TWT [Hanika et al., 2015]

For radiation cooled TWT, the collector is cooled by radiation. The demand of higher power transponders and limitation in satellite thermal design led to the development and widespread use of radiation-cooled TWTs in the mid-1990s [Kaliski, 2003]. In the radiation cooled TWT design, a radiating structure is installed over the collector electrodes and located outside of the satellite to allow the high percentage of the collector heat dissipation to radiate directly to space. The remaining heat dissipation is conducted to the satellite via the collector support structure. Key attiributes of TWT in used space applications include long life (mission life greater than 20 years), high reliability, lower power consumption (high efficiency). The majority of all TWTs in space have been manufactured by Thales (France) or L-3 Electron Technologies Inc. (US; for formely Boeing/hughes) with developments progressing CEERI (India) [Coaker and Challis, 2008]. TWTs used VHF, UHF, L, S, C, X, Ku, Ka, and EHF frequency band. TWTs most commonly used Ku and C frequency band [Menniger et al 2005].

ANALYTICAL SOLUTION OF SATELLITE HEAT REJECTION

Most of the satellites at GEO are called three-axis stabilized satellites. The thermal control system used in geostationary satellites rely on North and South panels which are used to reject waste heat from the satellite and the solar panels are mounted on North and South panels [Bulut, 2007; Bulut and Sozbir, 2017]. Radiators placing on the north-south sides experience consistent thermal loading from day to day with respect to the sun. Figure 3 shows three-axis stabilized GEO communication satellite.

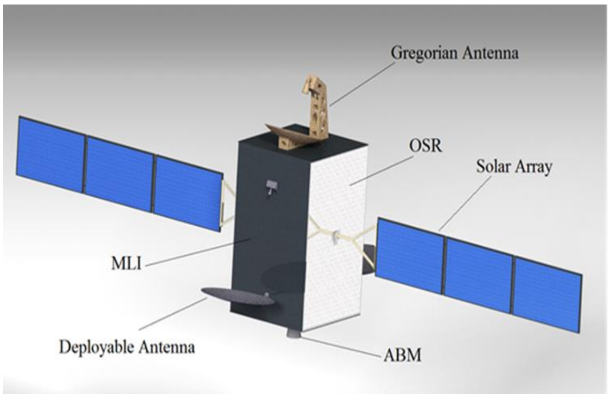


Figure 3: Three- axis GEO communication satellite [Bulut and Sozbir]

The thermal control is to balance the thermal energy of the satellite to ensure all the components remain within their acceptable temperature limits during the worst hot and cold cases. Energy balance requires that generated heat in the satellite plus absorbed heat from outside equals heat rejected to space.

The steady-state temperatures uses a basic energy balance. The equilibrium temperature is obtained from condition Q_{in}=Q_{out}. The effects includes in the calculation are internal dissipation *(Q_i^d)*, Solar radiation *(Q_{Sun})*, Albedo *(Q_{albedo})*, Earth radiation *($Q_{EarthIR}$)* and radiation from the body to space.

The heat balance equation for node i coupled with nodes j though n is [Czernik, 2004]

$$(Mc)_i \frac{dT_i}{dt} = Q_i^{\,d} + (\dot{Q}_{Sun} + \dot{Q}_{albedo} + \dot{Q}_{EarthIR})_i - \sum_j \Im_{ij} A_i^r (\sigma T_i^4 - \sigma T_{jr}^4) - \sum_j K_{ij}(T_i - T_{jk}) \quad (1)$$

When there are no interactions with other surfaces in the space and the equation written

$$Q^d + \alpha^s q^s A^s + \alpha^s q^A A^A + \varepsilon q^E A^E = A^r \varepsilon \sigma T^4 \quad (2)$$

after IR emission (Earth flux q^E, W/m^2) and reflected sun (Albedo q^A, W/m^2) are neglected at GEO and then heat rejection capability at given radiator temperature with radiation to deep space gives

$$A^r = \frac{Q^d - Q_{loss}}{\varepsilon\sigma T^4 - \alpha^S(q^S + q^A) + \varepsilon q^E} \quad (3)$$

Q_{loss} is heat loss or gained by the attached and surrounding structure. In a hot case analysis, this quantity is frequently assumed zero when the interacting structure can have the same or lower temperature, and negative when this temperature is higher [Karam, 1998].

The values in Table 2 were used for the calculation. During the calculation EOL of ε and α are used to estimate the radiative areas. Hot case always happened EOL. Values of begin-of-life (BOL) are used during cold case to estimate the heating power.

Table 2: Properties of materials

Description		Values	Unit
q^S	summer	1326	W/m^2
q^S	winter	1418	W/m^2
θ	elevation angle	23.5	deg
T	OSR temperature	40	^{o}C
σ	Stefan-Boltzman	5.67E-08	W/m^{2}K^4
OSR			
α	BOL	0.11	
α	EOL	0.27	
ε	BOL	0.84	
ε	EOL	0.84	

Five different TWTs are listed in Table 3. Ku band TWT-1 represents 100 % conduction. Ku band TWT-5 represents 30 % conduction and 70 % radiation.

Table 3: List of TWTs

				Conduction	Radiation
		Conduction	Radiation	Dissipation	
	Type	%	%	W	W
Ku band TWT-1	Conduction	100	0	60	60
Ku band TWT-2	Conduction+Radiation	60	40	36	24
Ku band TWT-3	Conduction+Radiation	50	50	30	30
Ku band TWT-4	Conduction+Radiation	40	60	24	36
Ku band TWT-5	Conduction+Radiation	30	70	18	42

Table 4 shows nine different cases for the analytical calculation. Case 1 is 100 % conduction. From Case 2 to Case 9 is a combination of different TWTs. 50 % of TWTs is located on North panel and the rest of TWTs is located on South panel.

Table 4: Calculation cases

				North		South	
				# TWT		# TWT	
Case		%		Conduction	Radiation	Conduction	Radiation
Case 1	Conduction	100	Ku band TWT-1	12		12	
Case 2	Conduction+Radiation	50+50	Ku band TWT-1 + Ku band TWT-2	6	6	6	6
Case 3	Radiation	100	Ku band TWT-2		12		12
Case 4	Conduction+Radiation	50+50	Ku band TWT-1 + Ku band TWT-3	6	6	6	6
Case 5	Radiation	100	Ku band TWT-3		12		12
Case 6	Conduction+Radiation	50+50	Ku band TWT-1 + Ku band TWT-4	6	6	6	6
Case 7	Radiation	100	Ku band TWT-4		12		12
Case 8	Conduction+Radiation	50+50	Ku band TWT-1 + Ku band TWT-5	6	6	6	6
Case 9	Radiation	100	Ku band TWT-5		12		12

ANALYTICAL RESULTS AND DISCUSSION

In order to understand how conduction or/and radiation cooled TWTs affected the radiative areas, 9 cases with different configurations studied. The analytical results of radiative areas of different configurations are shown in Table 4. For Case 1, all of TWTs is conduction cooled TWTs Radiative area is 4.61 m^2 for Case 1 that has the highest radiative areas. For case 9, all of TWTs is radiation cooled TWTs Radiative area is 1.38 m^2 for Case 9 that has the lowest radiative areas. There is 3.23 m^2 between Case 1 and Case 9. Case 1 (conduction) and Case 9 (radiation) differ factor of 3.34.

Table 5: Calculated radiative areas

		North	South	North	South	Total
		Dissipation		Radiative area		
		W	W	m^2	m^2	m^2
Case 1	Conduction	720	720	2.27	2.34	4.61
Case 2	Conduction+Radiation	576	576	1.81	1.87	3.68
Case 3	Radiation	432	432	1.36	1.4	2.76
Case 4	Conduction+Radiation	540	540	1.7	1.75	3.45
Case 5	Radiation	360	360	1.13	1.17	2.3
Case 6	Conduction+Radiation	504	504	1.59	1.64	3.23
Case 7	Radiation	288	288	0.91	0.94	1.85
Case 8	Conduction+Radiation	468	468	1.47	1.52	2.99
Case 9	Radiation	216	216	0.68	0.7	1.38

CONCLUSION

In this study, mid-size GEO three- axis stabilized satellite is give an example. Total number of TWTS is 24. 12 conduction and/or radiation cooled TWTs are located at north panel. 12 conduction and/or radiation cooled TWTs are located at south panel. Conduction cooled TWTs (4.61 m^2-total area) and radiation cooled TWTs (1.38 m^2- total area) differ a factor of 3.3. The results showed that conduction cooled TWTs needed more radiative areas than radiation cooled TWTs. It means that the satellite with radiation cooled TWTs carries more TWTs than the satellite with conduction cooled TWTs.

A selection of the conduction and/or radiation cooled TWT is one of the critical decisions at the early phase of the satellite project. There are main three important issues in the decision stage are cost, available place and thermal. In this study, the thermal issue was focused on.

For space applications, determining radiative areas are one of the critical parameters of the thermal control system and have to be calculated at the beginning of the program. Optimized radiative areas are also needed to determine by the thermal engineers. This study will be beneficial for the satellite thermal engineers to conduct the analytical investigation in order to search out the radiative areas of the satellite properly. Results of present study can be used as a practical approach.

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