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DESIGN OPTIMIZATION OF TWO-STAGE RADIATOR WITH VARIABLE EMITTANCE: ANALYSIS OF CONCEPT FEASIBILITY

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Abstract. *A new concept of a Space radiator using variable emissivity coatings, for using in thermal control of satellites is proposed. Called VESPAR, this new space radiator has two stages:an internal stage receives heat dissipated from equipment, and an external stage rejects it to space. Heat exchange between the two stages is carried out through radiation between two finned surfaces covered with variable emittance coatings. Under cold conditions the radiative heat link between these surfaces is minimal, preventing the decrease of the equipment temperature to a level below the minimal required. On the other hand, during hot conditions, the thermal coupling is increased and the heat dissipated from equipment is transferred to the upper stage and rejected to Space. It is envisioned that the utilization of such radiators in micro-satellites will lead to considerable electric power savings for safe heaters and can contribute to a longer satellite life. To verify the feasibility of the proposed concept, a mathematical model describing the radiator operating in steady-state condition has been developed. This model is coupled to an optimization algorithm and a design optimization procedure performed. Two criteria of optimization are employed: minimize the radiator mass and the power consumption of heaters. The optimal design variables are the main dimensions of the radiator. The Generalized Extremal Optimization algorithm is used as the optimization tool.*

Keywords*. space radiator, variable emittance coating, optimal design, Generalized Extremal Optimization*

Nomenclature

Symbol	Description
A	Area (m^2)
B	Width
G	Thermal conductance (W/K)
H	Height of radiator fins
k	Thermal conductivity (W/K/m) or rank
L	Length
M	Mass (kg)
N	Number of fins in radiator bottom plate
Q	Heat load (W)
q	Heat flux density (W/m2)
T	Temperature (K)
w	Distance between fins of each plate (m)
	Greeks
α	Solar absortivity
δ	Thickness
ε	Emissivity
η	Effectiveness
λ	Relative importance criteria factor

ρ	Density (kg/m^3)
σ	Stephan-Boltzmann constant (W/m^2/K^4)
χ(.)	Heaviside Step-function
	Subscripts
0	Convention radiator
1	Internal stage
12	Between two stages
2	External stage
A	Area
eff	Effective
eq	Equipment
f	fin
h	Heater
IR	Infra-red
m	Mass
r	Radiator
s	Solar
w	Wall
v	Of variable emittance

1. Introduction

From the point of view of energetic balance, a satellite is a thermodynamic system that stays in energetic balance with internal and external heat fluxes. The levels of temperatures of each element of the satellite are defined completely by the equilibrium of these fluxes. External incident heat fluxes can vary within a very wide range ($q_{max}/q_{min} \cong$ 20..100), depending on the satellite attitude and orbit parameters. Internal heat fluxes dissipated by equipment and instruments usually also varied within a wide range depending on their operational modes (typically $Q_{max}/Q_{min} \cong$ 2..4, or switched-on – switched off cycles). In such conditions the equilibrium temperature of a non-dissipating element in the external part of the satellite can vary within ~–150C to +150 ^oC. Adding variable heat dissipation to the element shifts this temperature range to higher temperatures and may increases the amplitude.

However the equipment and satellite structure temperatures must be maintained within a nominal range, typically from about -10 to +40 ^oC. Therefore, a common design approach in satellite thermal control is to thermally insulate most of its external surfaces, while allowing certain areas (radiate windows or radiators) to exchange heat with the external environment, so that excess heat generated inside the satellite can be rejected to space. Depending on the satellite size, and heat densities, the internal heat can be transferred to these radiators by conduction or through other special thermal transfer devices such as heat pipes.

The usual approch in designning a space radiator is to firstly size it to accommodate a combination of maximum internal heat loads and external fluxes, known as the hot case. Then it is verified if this design can also accomodade the cold case, when the satellite is subjected to the lowest external heat flux and equipment dissipation. If the radiator designed to the hot case leads to a temperature in the equipment below the minimum required by specification in the cold case, heaters are usually used to warm up the equipment in this condition. Although being a simple and efficient solution to overcome low temperatures in the cold case, heaters consume electrical power, a limited resource in any spacecraft. In fact, they can consume from 10 to 40 % of the total electrical power budget for maintain low-limit temperatures of equipment when the satellite is in cold case conditions.

Although using heaters to warm equipment in cold conditions means that part of the spacecraft power buget has to be dedicated to the thermal control subsystem, they are frequently used because they are simple-to-apply, very low-cost and low-mass devices. Nevertheless, in cases where the power buget is very limited, other types of thermal control devices can be used instead, such as thermal louvers (variable heat rejection ability), variable conductance heat pipes or thermal diodes (variable heat transport ability), as described, for example by Gilmore (1994) . These devices would save power consuption but will add weight to the sattelite. Hence, there is a trade-off between power consuption, mass an reliability, that must be take into account when selecting a thermal control device for a given satellite.

.One type of thermal control device used in order to avoid heaters is the thermal louver (Karam, 1998; Parisoto et al, 1996, Muraoka et al, 2001). It is a mechanical device that when opened expose the radiator to space, allowing internal heat from the satellite be rejected, while when closed reduces significantly the heat lost by the radiator and then protect the equipment during the cold case. The thermal louver makes the emmitance and absorptance of the radiator effectively variable. Thermal louvers are effective devices and have been used in various satellite applications (Gilmore 1994), but the presence of moving parts on it makes it less reliable than heaters. .

Recently, a new solid state technology device (Smart Radiation Device – SRD) that changes its surface emmitance as a function of temperature was developed (Tachikawa, 2000). The prototype is a ceramic thin plate with 3x3 cm area, thickness between 70 to 200 μm and an specific mass in the range 0.5 to 1.2 kg/m2. The principle of varying the emmitance is based on the ferromagnetic metal-insulator transition effect. The published emmitance characteristics of these devices are similar to the effective emittances obtained in radiators with thermal louvers, but it has the advantage of having no moving parts. On the other hand, they present a high absortivity (over 0.80), what is an undesirable characteristic for a radiator.

In this paper we propose a new concept for a space radiator we call VESPAR (Variable Emmitance SPAce Radiator). It takes the advantage of the variable emissivity of the SRD, while keeping a low absortance for the entire assembly. This is done by separating the radiator in two parts (stages): internal and external. The internal radiator part receives through conduction heat dissipated from equipment or payloads, and the external one rejects heat to space. While the external radiator part has its outter surface covered with a solar-reflective coating, as is usual to conventional space radiators (Gilmore, 1994), heat exchange between the internal and external parts is done through radiation between two surfaces covered with variable emissivity coatings. Therefore, under cold conditions the radiative heat link between these surfaces is minimal, preventing the temperature of equipment or payload decrease to a level below the minimal required. On the other hand, during hot conditions, the thermal coupling is increased between the variable emittance surfaces and the temperature of the equipment or payload is kept below their maximum value limit.

A solid-state radiator with variable emittance characteristics would be very suitable for applications in micro-satelites, where electric power consumption of heaters at contingency modes is a critical design item. It is envisioned that the utilization of such radiators will lead to considerable electric power savings and can contribute to a longer satellite life.

To verify the feasibility of the proposed concept, a mathematical model describing the radiator operating in steady-state condition has been developed. This model is coupled to an optimization algorithm and a design optimization procedure performed. Two criteria of optimization are employed: minimize the radiator mass and the power consumption of heaters. The dimensions of the radiator are the design variables.

The Generalized Extremal Optimization (GEO) [Sousa et al., 2003] is used as the optimization algorithm. GEO is a recently proposed evolutionary algorithm devised to be applied to complex optimization problems and has been used susccessfuly in aerospace applications.

The performance of the radiator concept proposed here is compared to a traditional design, for the same operational conditions.

2. Two-stage radiator design concept

The radiator consists of two similar finned plates made from Al alloy as shown in Figure 1. The upper plate is the external stage of the radiator, which has the outter surface covered with a coating commonly used in space radiators, which have a high emissivity and low solar absortivity. The bottom plate is the internal stage of the radiator and receives heat dissipated from equipment by direct contact or through a structural panel. The finned surfaces of both stages are covered with the SRD.

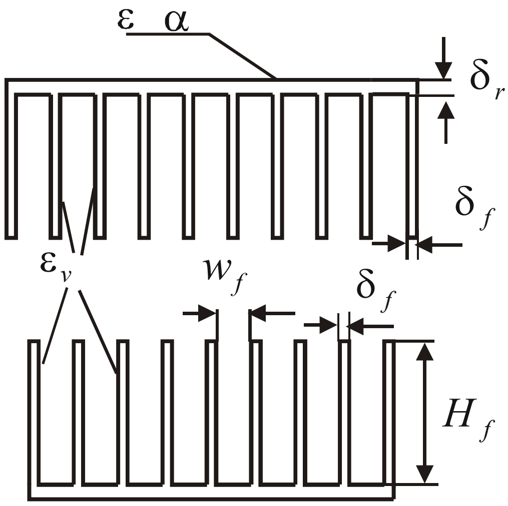

Figure 1. Parameters of radiator stages.

The stages are assembled in such a way that direct thermal contact by conduction is avoided or minimized (for example, by the use of insulation washers) and they exchange heat primarily by radiation..

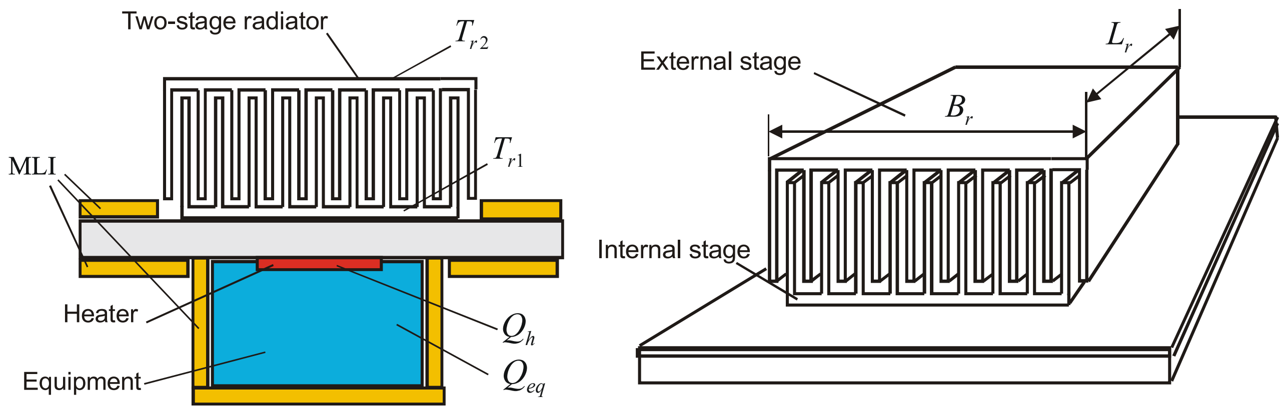

Figure 2. Two stage radiator assembly.

The SRD emittance varies non-linearly with the temperature of the radiator in a direct fashion, see Fig. (4). Hence, under cold conditions the radiative heat link between the inner surfaces of the stages is minimal, and during hot conditions, the thermal coupling is increased . With such a two-stage conception, the intrinsic high solar absortivity of variable emittance coating is not a matter anymore: the external surface of the upper stage is a conventional solar reflector.

In order to verify the efficiency of the new radiator concept proposed here, it was considered an application where the radiator lies on the outter surface of a satellite panel, which has coupled to its inner surface on the same position an equipment, as shown in Figure 2. All surfaces but the radiator is covered with multilayer insulation blankets (MLI), and a heater is attached to the equipment. Such configuration is typical for 3-axis stabilized micro satellites, like the Brazilian Equars (httm://www.laser.inpe.br/equars/) or SSR1 (Kono et al., 2003), and also similar to the one adopted for the thermal control of the battery compartment of the China-Brazil Earth Resources Satellite 1&2 (CBERS 1 and 2). For the purpouses of the present conceptual analysis, heat conduction in the panel's XY plane is neglected. Hence, all heat dissipated by the equipment is transfered to the botton plate of the radiator.

3. Thermal mathematical model

The main equations for the heat transfer through the path equipment/radiator/external environmental in steady state, under hot and cold conditions, are presented below.

For hot conditions:

Heat transfer from equipment to radiator internal stage:

$$Q_{eq,\max} = G_{eq}(T_{eq,\max} - T_{r1,\max}) \tag{1}$$

Heat transfer from internal radiator stage to radiator external stage :

$$Q_{eq,\max} = \varepsilon_{12}(T_{r1,}T_{r2,})A_{12}\sigma(T^4_{r1,\max} - T^4_{r2,\max}) \tag{2}$$

We assume for this feasibility study, that the radiator base plate has a square shape, i.e. $L_r=B_r$. The heat exchange between the external radiator surface and the outer environment is given by equation 3.

$$Q_{eq,\max} = (L^2 + 2\eta_{f2}LH_f)\left(\varepsilon\sigma T^4_{r2,\max} - \alpha q_{s\max} - \varepsilon q_{IR\max}\right) \tag{3}$$

Where η_f accounts for the fin efficiency, whose expression will be introduced later in the text.

For hot conditions, the equilibrium temperatures of the radiator and equipment $\{T_{eq,\max}, T^4_{r1,\max}, T^4_{r2,\max}\}$ can be calculated solving sequencially equations (3), (2) and (1). Because of the dependency of ε_{12} with temperature, T_{r1max} was obtained from Equation (2) via an iterative procedure using the secant method.

For cold conditions, the heater dissipation is added to the equilibrium equations and the temperatures of the radiator and equipment calculated following the same procedure used for the hot case. The equilibrium equations for the cold case take the form:

$$Q_{eq,\min} + Q_h = G_{eq}(T_{eq,\min} - T_{r1,\min}) \tag{4}$$

$$Q_{eq,\min} + Q_h = \varepsilon_{12}(T_{r1,}T_{r2,})A_{12}\sigma(T^4_{r1,\min} - T^4_{r2,\min}) \tag{5}$$

$$Q_{eq,\min} + Q_h = (L^2 + 2\eta_{f2}LH_f)\left(\varepsilon\sigma T^4_{r2,\min} - \alpha q_{s\min} - \varepsilon q_{IR\min}\right) \tag{6}$$

Inside the radiator, the fins form $2N_f$ almost-closed enclosures; one of them is depicte in Figure 3.

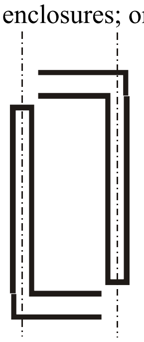

Figure 3. Closed envelope for consideration of radiative heat transfer between the radiator stages.

The total average effective area of radiative heat transfer between the upper an botton parts of the radiator is given by :

$$A_{12} = (L-(2N_f+1)\delta_f)L + N_f\eta_{f1}H_fL + N_f\eta_{f2}H_fL \tag{7}$$

For this preliminary study, it is assumed a simplified mode of radiative heat transfer between the parts of the radiator by using the concept of effective area with fin efficiency coefficient. Hence, the fin efficiency can be calculated from the analitical solutions of heat conduction problem for a fin with side radiative heat transfer (Isachenko, Sukomel, 2000).

$$\eta_{f1} = \frac{\tanh(r_1H_f)}{r_1H_f}; \qquad r_1 = \sqrt{\frac{8\varepsilon_v(T_{r1})\sigma T_{r1}^3}{k\delta_f}} \tag{8}$$

$$\eta_{f2} = \frac{\tanh(r_2H_f)}{r_2H_f}; \qquad r_2 = \sqrt{\frac{8\varepsilon_v(T_{r2})\sigma T_{r2}^3}{k\delta_f}} \tag{9}$$

The effective mutual emissivity inside each individual enclosure can be approximately evaluated by the relationship for radiative heat transfer between two gray plates of homogeneous temperature each (Isachenko, et al., 2000):

$$\varepsilon_{12}(T_{r1},T_{r2}) = \frac{1}{\dfrac{1}{\varepsilon_v(T_{r1})} + \dfrac{1}{\varepsilon_v(T_{r2})} - 1} \tag{10}$$

The mass of the radiator is obtained by:

$$M_t = \rho\left(L^2\delta_r + N_fLH_f\delta_f\right) + \rho\left(L^2\delta_r + 2LH_f\delta_f + (N_f-1)\chi(N_f-1)LH_f\delta_f\right) + \rho_A A_{12f} \tag{11}$$

Here N_f is the number of fins on the internal stage (bottom plate in Fig. 1). Note that on the upper plate two lateral fins are always presented. So, on the upper plate there are $2+N_f-1=N_f+1$ fins. If $N_f=0$ (no fins in internal stage), there are only two lateral fins on the upper plate. Analytically we can express the number of fins for the upper plate through the Heaviside step function: $2+(N_f-1)\chi(N_f-1)$.

The last term in Equation (11) is the total mass of the variable emittance coating, which depends on the total surface area involved in internal radiative heat transfer, which is given by:.

$$A_{12f} \cong 2*(L-(2N_f+1)\delta_f) + 2*N_fH_fL + 2*N_fH_fL \tag{12}$$

For comparison purposes, a conventional radiator is dimensioned for the same operation conditions imposed to the two-stage new radiator concept proposed here. The conventional radiator is a flat plate with the same thickness δ_r of the main base plate as for the new one. Its coating is the same as the outter surface of the two-stage radiator. The conventional radiator is sized to keep the equipment temperature within the same operational range of the equipment temperature. Hence, a heater is also turned on if the equipment temperature falls below the lower limit (T_{min}) dissipating Q_{h0}.

The radiator length L_0 is defined by hot conditions:

$$Q_{eq,\max} = G_{eq}(T_{\max} - T_{r0,\max}) \tag{13}$$

$$Q_{eq,\max} = L_0^2\left(\varepsilon\sigma T_{r0,\max}^4 - \alpha q_{s\max} - \varepsilon q_{IR\max}\right) \tag{14}$$

After obtaining L_0, the minimal equipment temperature ($T_{eq0,min}$) can be obtained:

$$Q_{eq,\min} = G_{eq}(T_{eq0,\min} - T_{r0,\min}) \tag{15}$$

$$Q_{eq,\min} = L_0^2\left(\varepsilon\sigma T_{r0,\min}^4 - \alpha q_{s\min} - \varepsilon q_{IR\min}\right) \quad (16)$$

If $T_{eq0,\min} < T_{\min}$, heater power must be applied to warm up the equipment. The minimum heater power necessary to drive the equipment temperature to a level above the minimum required can be obtained by solving the following equations:

$$Q_{eq,\min} + Q_{h0} = G_{eq}(T_{\min} - T_{r0,\min}) \quad (17)$$

$$Q_{eq,\min} + Q_{h0} = L_0^2\left(\varepsilon\sigma T_{r0,\min}^4 - \alpha q_{s\min} - \varepsilon q_{IR\min}\right) \quad (18)$$

The above system of equations can be easily solved with respect to $\{Q_{h0,}T_{r0,\min}\}$ -

The total mass of the convetional radiator is given by:

$$M_{t0} = \rho\left(L_0^2\delta_r\right) \quad (19)$$

The values Q_{h0} and M_{to} are used in the definition of criteria of optimization.

4. Criteria of optimization, design variables and fixed parameters

The design of the radiator is formulated as an optimization problem as:

Minimize: $f\{M_t, Q_h\}$ (20)

Subject to:

$x_{\min} \le x \le x_{\max}$, and

$$T_{\min} \le T_{eq} \le T_{\max} \quad (21)$$

Where **x** is the vector of design variables and T_{eq} is the equipment temperature. The design variables, with the respective feasible ranges are presented in Table 1. The temperature of the equipment must lie in the range [-10, +45] ^{o}C, which is the temperature range usually used as requirement for operation of general electronic equipment in satellites.

For the present analysis the multi-objective problem (minimizing of heater power and radiator mass) was transformed in a mono-objective one by the weight penalty method (Vanderplaats, 1998), and the objective function defined as:

$$f_o = \lambda_m \frac{M_t}{M_{t0}} + \lambda_h \frac{Q_h}{Q_{h0}}$$
$$\lambda_m + \lambda_h = 1 \quad (22)$$

The objective function was normalized by the mass and power of the conventional radiator. Ideally, the mass of the proposed radiator would match the mass of the conventional one, whereas its heater dissipation would come to zero, that is:

$$\frac{M_t}{M_{t0}} \to 1; \quad \frac{Q_h}{Q_{h0}} \to 0$$

The optimization variables are the dimensions of the base plate and the dimensions and number of fins.

The optimized variables are summarized in the following table.

Table 1. Design variables.

Name	feasible range	type	Description
L	[0.3, 0.5] m	Continuous	Length of radiator
H_f	[0.02, 0. 16]m	Continuous	Height of fins
δ_f	[0.0001, 0.0015] m	Continuous	Thickness of fin
N_f	[1, 32]	Integer	Number of fins
Q_h	[0, 15] W	Continuous	Heater Power

The fixed parameters used in the design optimization is given in Tab. (2).

Table 2. Fixed parameters.

Name	Value	Description
α	0.2	Absortivity of optical coating of external surface
ε	0.85	Emissivity of optical coating of external surface
T_{min}	-10C	Minimum allowable temperature of equipment
T_{max}	+40C	Maximum allowable temperature of equipment
$Q_{eq,min}$	5W	Minimal dissipation of equipment
$Q_{eq,max}$	25W	Maximal dissipation of equipment
$q_{s,max}$	750 W/m^2	Solar maximal incidence heat flux (hot case)
$q_{IR,max}$	60 W/m^2	Earth infrared maximal heat flux (hot case)
$q_{s,min}$	40 W/m^2	Solar minimal incidence heat flux (cold case)
$q_{IR,min}$	30 W/m^2	Earth infrared minimal heat flux (cold case)
δr	2.0 mm	Thickness of base plate
w_{min}	1 mm	Limit on minimal space between fins
δ_ε	0.1mm	Thickness of variable emissivity coating
ρ_A	0.85 kg/m2	Specific weight of the variable emissivity coating
G_{eq}	10 W/K	Thermal conductance of the equipment interface
k	120 W/K/m	Thermal conductivity of radiator material (Al)
ρ	2768 kg/m3	Density of radiator material

We assume that the internal surfaces of radiator are covered with the coating of variable emissivity, having the temperature-dependent performance curve, as presented by Tachikawa et al (2000).

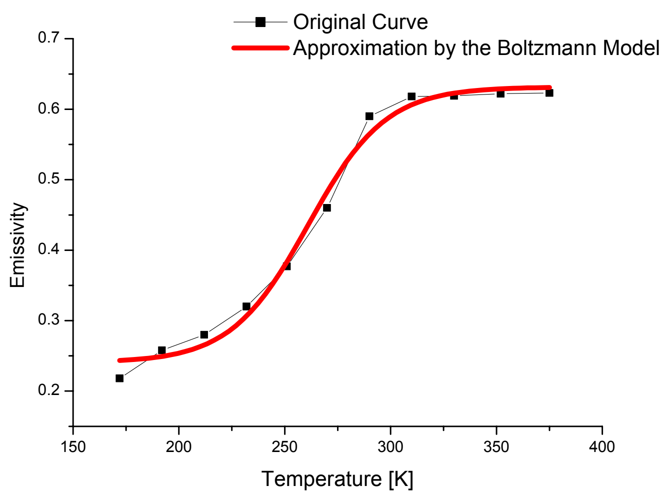

Figure 4. Approximation of experimental data for variable conductance coating.

The emissivity as a function of temperature has been approximated by the Boltzmann model in the temperature range 150-350 K:

$$\varepsilon_v(T) = \varepsilon_2 - \frac{\varepsilon_2 - \varepsilon_1}{1 - e^{\frac{T - T_0}{\Delta T}}} \tag{23}$$

The fitted parameters are ε_2=0.62165, ε_1=0.24052, T_0=261.10302, ΔT=18.29369

5. The Generalized Extremal Optimization algorithm

The Generalized Extremal Optimization (GEO) is a brand new evolutionary algorithm, devised to be applied in complex optimization problems. Based on the Bak-Sneppen simplified model of evolution (Bak and Sneppen, 1993), it has been applied sussccesfully to design optimization problems (Souza et al., 2003 and Vlassov et al, 2006). GEO makes no use of derivatives and can be applied to multimodal or disjoint design spaces, that may have any combination of different types of design variables (continuos, integer and/or, discrete). This makes it very suitable to be used in the problem being tackle here, which has an objective function with implicity design variables of different types. The main steps of GEO are depicted in Figure 5.

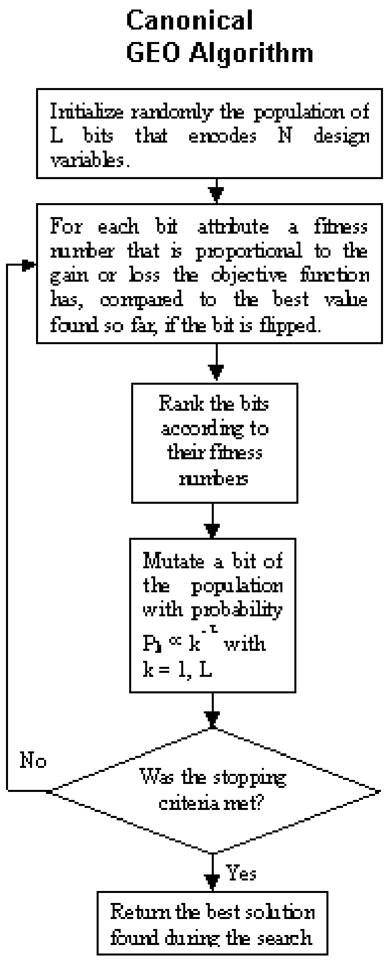

Figure 5. The canonical GEO algorithm.

In the canonical GEO equally and inequality constraints are take into account by assigning to the bits that when flipped lead the search to an infeasible region a high fitness value. Bound constraints are take into account directly by the binary encoding. A very attractive feature of GEO is that it has only one free parameter to adjust, τ. This makes it easier to be set to give its best performance in a given application than other popular metaheuristics, such as Simulated Annealing or Genetic Algorithms, that have each of them at least three free parameters to be set. In GEO a string of L bits is considered a population of species. That is, each bit is a species. The string encodes the N design variables. For each of them is associated a fitness number that is proportional to the gain (or loss) the objective function value has in mutating (flipping) the bit. All bits are then ranked from k = 1, for the least adapted bit, to k = L for the best adapted. A bit is then mutated according to the probability distribution $P \propto k^{-\tau}$, where k is the rank of a selected bit candidate to mutate. Making $\tau \to 0$, all bits have the same probability to mutate, whereas for $\tau \to \infty$, only the least adapted bit will be mutated. In practice, it has been observed that the best value of τ, i.e., the one that yields the best performance of the algorithm for a given application generally lies within the range [0.75, 3.0]. Detailed descriptions of GEO, including another implementation where one bit per variable is flipped at each iteration, can be found in Sousa et al. (2003).

6 Results

In GEO the design variables are coded in a binary string. The number of bits used to encode each design variable was defined in function of its required precision. In Tab. (3) the number of bits and the associated resolution of each design variable are presented.

Table 3. Resolution and number of bits of the design variables.

Design Variable	Resolution	Number of bits
L	5 mm	6
H_f	0.5 mm	9
δ_f	0.025 mm	6
N_f	1	5
Q_h	0.1 W	8

Figures (6) through (9) show the sets of near-optimal solutions, plotted as a function of the best values found for all geometrical design variables.

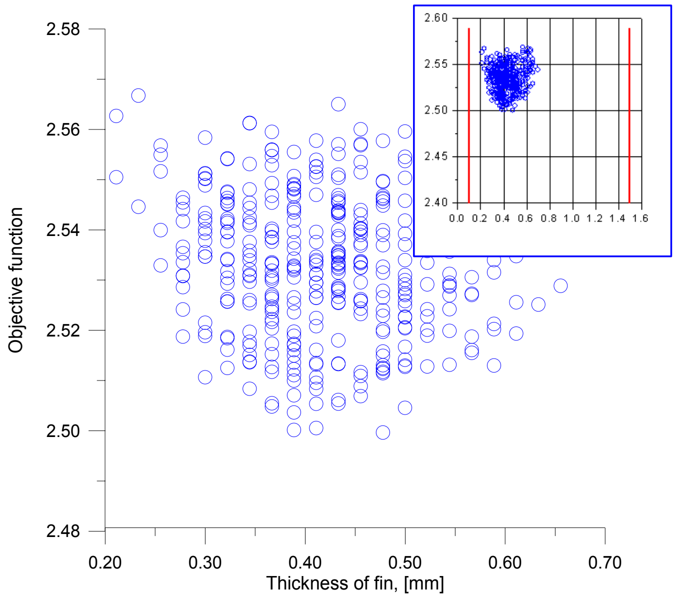

Figure 6. Mapping of near-optimal solutions, plotted as a function of fin thickness.

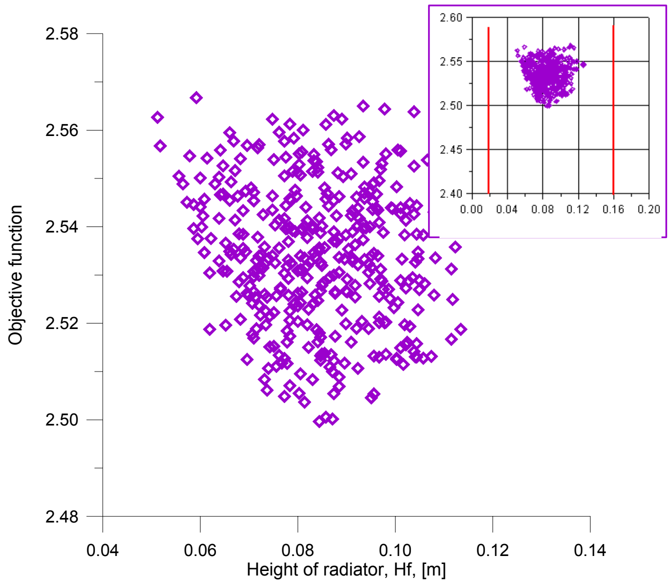

Figure 7. Mapping of near-optimal solutions, plotted as a function of the radiator fin height.

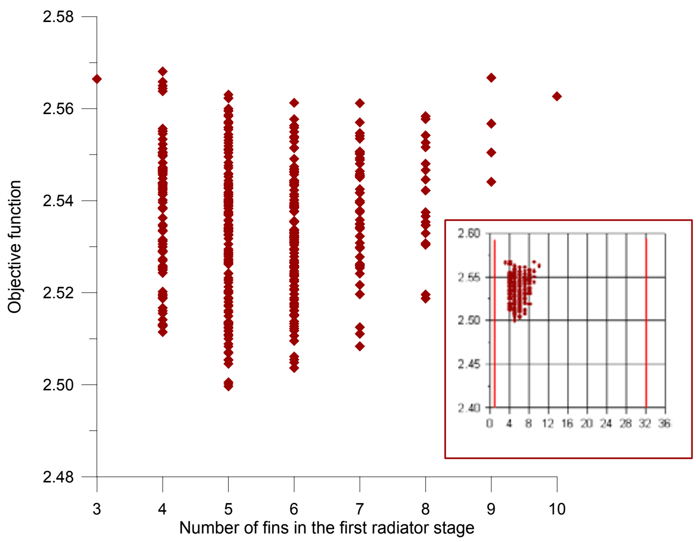

Figure 8. Mapping of near-optimal solutions, plotted as a function of fin number

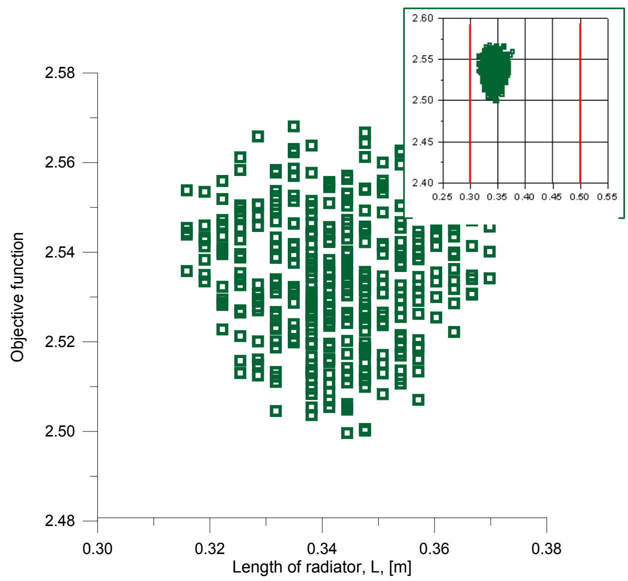

Figure 9. Mapping of near-optimal solutions, plotted as a function of the radiator length.

For the setting of the parameter τ, some preliminary numerical experiments were done running GEO for the radiator problem with different values of τ. They ranged from τ = 0.25 to τ = 5.00, in steps of 0.25. Fifty executions were done for each τ, and for each execution the algorithm stopped after 10000 function evaluations. In average, GEO performed better with τ = 2.0. This value was then used in the searchs performed to find the optimal parameters of VESPAR.

Each graph shows the best objective function values found in 400 independent runs of GEO. Each run was stopped after 10^6 function evaluations. In the small box inside each Figure, these sets are plotted in a scale that shows the bound constraints for the geometric design variables.

In Tab. (4) the four best solutions obtained from the set of results for VESPAR are presented, together with the design parameters calculated for the conventional radiator.

Table 4. Best Design parameters for VESPAR (4 best results) and the conventional radiator.

Type of Radiator	fo	Q_h [W]	M_t [kg]	L [m]	H_f [cm]	δ_f [mm]	N_f
VESPAR	2.499	7	2.551	0.344	8.438	0.478	5
	2.500	7.29	2.541	0.347	8.712	0.389	5
	2.500	7.17	2.546	0.347	8.575	0.411	5
	2.503	7.52	2.536	0.338	8.137	0.389	6
Conventional	-	15.00	0.560	0.320	-	-	-

From Tab. (4) it can be seen that a around half the heater power used in the conventional assembly is necessary for a design using VESPAR, operating in the same boundary conditions. The penalty in mass was around 2 kg. It can also be seen that the radiator area of VESPAR is almost the same as the area of the conventional one, so there will be no impact on the area of the satellite covered by the radiator, by using VESPAR. These results indicate that the VESPAR concept can be a very attractive option for satellites with limited availability of electrical power to be used by the thermal control subsystem, such as micro-satellites.

All results shown above were obtained using equal weighting factors (λ_m=λ_h=0.5) in the definition of the objective function. That is, was given the same importance for each optimization criterium. However, there is a trade-off between radiator mass and heater power. So it is important to have the complete set of possible trade-off solutions so that the chief design engineer can choose one that better fits the requirements at system level. This set is known as the Pareto frontier of non-dominated solutions (Messac, et al., 2000). A good approximation of the Pareto-optimal frontier can be obtaining by performing the optimization for different values of weighting factors. Figure 10 shows such an approximation (also including some dominated solutions), obtained from 3 sets of near-optimal solutions: i) the basic case (λ_m=λ_h=0.5), ii) one with greater importance to minimize heater power (λ_m=0.1, λ_h=0.9) and iii) other with greater importance to minimize the radiator mass (λ_m=0.9, λ_h=0.1).

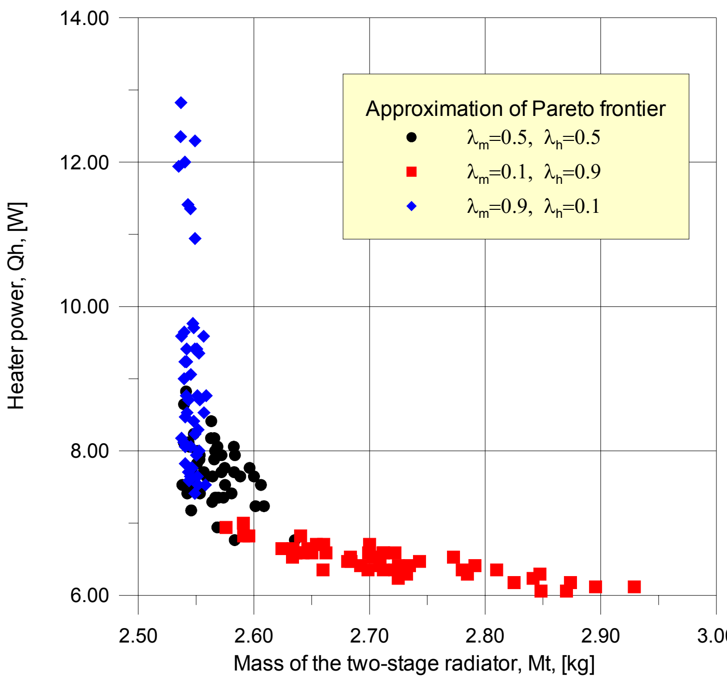

Figure 10. Plot of approximation of Pareto optimal solutions domain.

From Figure 10, it can be seen that minimizing both criterias simultaneously leads to optimal values at $Q_h \cong 7$W and $M_t \cong 2.5$ kg:. The power consumption in principle can be reduced down to about 6 W, however an extra mass penalty of about 0.5 kg is needed to achieve it.

Conclusions

A new concept of a space radiator with variable emittance was presented. Using a recently developed temperature dependent variable emissivity coating and an innovative geometry, it has no moving parts being in principle more reliable than the conventional thermal louvers. Named VESPAR, it had its concept feasibility verified numerically through a design optimization approach, and the results show that it has a great potential to be used in applications where the electrical power available to be used by the satellite thermal control subsystem is very limited.

It is envisioned that the utilization of such kind of radiator in micro-satellites would lead to considerable electric power savings and contribute to a longer satellite life.

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