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Solar Space Power System Optimization with Ultralight Radiator

A. F. Massardo,* L. A. Tagliafico,† M. Fossa,‡ and A. Agazzani§
Università di Genova, Genova 16145, Italy

The goal of this work is to demonstrate the performance of a solar space dynamic system coupled with a very light radiator [in particular a liquid droplet radiator (LDR)] replacing the traditional heat-pipe radiator. The results show that it is possible to obtain convincing improvements in terms of specific surface (m^2/kWe) and specific mass (kg/kWe) of the whole system. The design procedures of the conversion powerplant, of the LDR, and their system integration are described in detail and discussed in this work.

Nomenclature

β = compression ratio of the closed Brayton cycle
ε = recuperator effectiveness
η = first law thermodynamic efficiency of the CBC cycle

Introduction

TO generate several kilowatts of electric power for space applications, the so-called dynamic solutions operating by means of thermodynamic cycles are considered irreplaceable.[1–4]

In particular, with reference to the orbital NASA space station, which is one of the most significant examples, the closed Brayton cycle (CBC) system seems to be suitable for its efficiency and reliability.[2,5]

The crucial points in setting up a solar space power system is the cost and technological limits of the launching equipment, mainly because of its weight and size. The radiator, which represents by itself about 40% of the overall weight and surface of the system, is the component to which the greatest design efforts must be given to optimize performance.

The current limits for mass and surface of the traditional heat-pipe and pumped-loop radiators cannot be easily overcome because of the conductive and convective thermal resistances interposed between the cooling fluid and the surface that radiates toward the space heat sink. Starting from these considerations, new concepts of space radiator models (liquid-sheet or droplet radiators) have been proposed to allow the refrigerating medium to be directly exposed to the space radiating environment, with a large decrease in the weight and size of the radiating system. Some early studies are available[6,7]; further developments have been devoted to liquid drop radiators (LDRs)[8,9] and liquid-sheet radiators (LSRs).[10]

An integrated analysis has been carried out for both the CBC plants and LDR to evaluate the possible performance improvement of a solar dynamic powerplant when the traditional heat-pipe radiator is replaced with the LDR. Attention has been given to the decrease in the specific mass and surface of the CBC system when LDR is used, and to the influence of the optimized design criteria on the performance standards of the CBC system.

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*Associate Professor, Istituto di Macchine e Sistemi Energetici, Via Montallegro, 1.
†Associate Professor, Dipartimento di TermoEnergetica e Condizionamento Ambientale, Via all'Opera Pia 15a.
‡Full Researcher, Dipartimento di TermoEnergetica e Condizionamento Ambientale, Via all'Opera Pia 15a.
§Ph.D. Student, Istituto di Macchine e Sistemi Energetici, Via Montallegro 1.

Power Generation System

The Solar Dynamic Power Module (SDPM) of the NASA space station, based on a CBC system, is shown schematically in Fig. 1. It consists of the following basic equipment groups: the heat source, the heat engine, and the heat sink. The heat source includes the concentrator and the receiver. Sunlight is captured by the concentrator and focused into the solar receiver. The receiver performs two functions: 1) it works as a heat exchanger that transfers the incoming solar heat to the cycle gas, and 2) as a thermal energy storage (TES) device that stores solar energy during the daylight portion of the orbit for later use during the eclipse period.

The heart of the SDPM is the CBC power conversion unit (PCU). It consists of a turboalternator–compressor, a gas cooler, and a recuperator. The recuperator recovers energy from the turbine exhaust and returns it to the cycle, thus enhancing the overall efficiency of the system. A mixture of helium and xenon gases is used as the working fluid. These inert gases are not affected by the extreme temperatures encountered in space and in the cycle nor by gravity, and they do not chemically react with other components within the system.

The heat sink consists of a heat-pipe radiator coupled to the PCU by means of a liquid-to-gas heat exchanger (the gas cooler). A cooling fluid (refrigerant fluorocarbon FC75) is pumped through the cooler, receiving heat from the helium–xenon gas, which then returns to the compressor. The heated cooling fluid is then directed to the radiator, where the waste heat is radiated to space. The liquid coolant is also used to remove heat from cold-plates, the alternator, and bearings.

A fraction of the helium–xenon mass flow rate is extracted from the compressor exit, cooled inside the bleed-cooler by the cooling fluid (FC75), and utilized for the cooling of the bearings that support the system rotating unit.

The presence of the cold-plates for the cooling of the electronic equipment requires restricted thermodynamic conditions at the radiator exit (point *c*0 in Fig. 1); in particular, the liquid temperature entering the cold-plate must not exceed a limit imposed by the working requirements associated with the electronic components. Since fixed operating conditions do not exist (the insolation is strongly variable during a single orbit), the PCU system operates in transient conditions.

Studies of this solar space dynamic plant[2,5,11,12] prove that the radiating system size strongly affects the weights and surfaces of the plant, and is in turn affected by the energy conversion efficiency as well as by the space sink temperature. As an example, Fig. 2 shows the distribution of weights and surfaces if sunset maximum insolation orbital condition data are

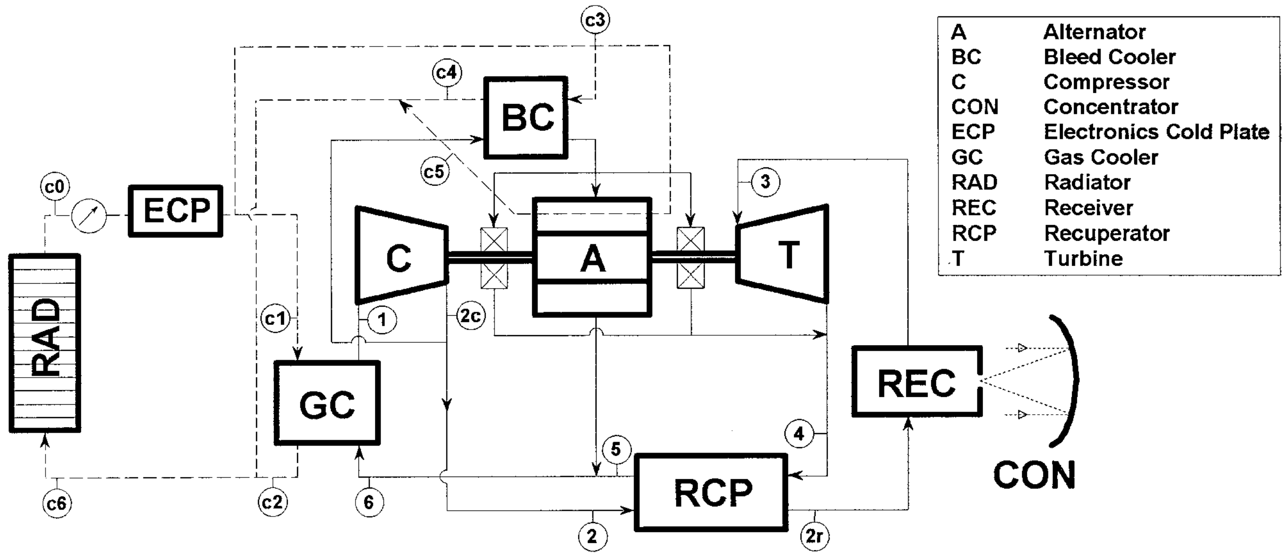

Fig. 1 Solar space CBC system layout.

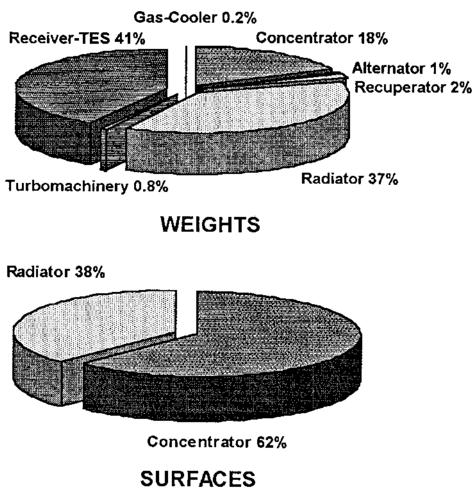

Fig. 2 Mass and surface distributions for NASA Space Station Freedom CBC system (condition 1: maximum insolation at sunset).[2]

utilized for the plant design procedure. The dominating influence of the concentrator, receiver, and radiator is quite evident.

Lightweight Radiators

LDRs and LSRs are among the most promising technologies proposed to realize lightweight heat exchangers for space applications. The basic working concept consists of avoiding any interposed thermal resistance between the working fluid and the space environment. To this aim, the fluid to be cooled is directly exposed to space. A major problem in this case is the requirement that the working fluid must have a very low vapor pressure to minimize evaporative losses. As a result, possible working fluid candidates are limited to certain silicone-based oils or to liquid metals, depending on the working temperature range.

The liquid droplet radiator is able to generate and collect a cloud of submillimetric droplets radiating directly into space (Fig. 3); whereas traditional radiators consist of an array of finned pipes or finned heat pipes heated by a diatermic fluid. Several studies have been devoted to the development of each LDR component.[6–8] Some experimental data are available from ground vacuum chambers, with particular reference to the droplet sheet stability and its thermal behavior in a rarefied

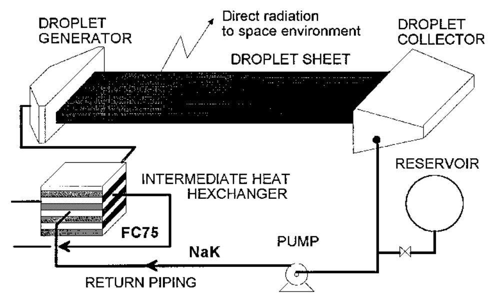

Fig. 3 Direct radiation heat exchanger (LDR).

gas.[13] Furthermore, a flight experiment was designed and discussed for a Space Shuttle-attached LDR mission.[14]

The main feature of an LDR with respect to traditional solid surface devices concerns the favorable rejected heat flux over mass ratio. This parameter, commonly used to assess space radiator performance, has typical values ranging from 0.1 to 0.2 kW/kg for finned-pipe radiators, while the LDR systems can achieve (at the same operating temperatures of around 300–400 K) values up to 1.4 kW/kg.[8] Other advantages with respect to conventional radiators concern the stowage in the launch vehicle, the deployment in space, the decreased vulnerability to micrometeoroid damage, and the reduced frontal surface. On the other hand, these favorable performances can be achieved provided that accurate optimization of the global system is performed, since several parameters must be taken into account, such as the droplet size, droplet spacing, sheet dimensions, and working temperatures. Indeed, each LDR component can be designed to work the best on the basis of its proper physical modeling; however, since the working parameters of each component strongly affect the design constraints of all the other components, a global optimization procedure is required. Furthermore, unlike traditional radiators, the fluids used are generally neither suitable to be used as working fluid in the thermal bus system nor can they be directly employed in a thermodynamic power cycle. As a consequence, an intermediate heat exchanger is needed to match the radiator to the heat disposal system of the space unit. For these reasons the LDR project requires great care and accurate tradeoff analysis. In previous works on the subject,[9] a calculation procedure to evaluate the performance of rectangular LDRs was developed, to be employed together with an optimization algorithm to get the main characteristics of the LDR components as a function of the droplet sheet parameters and the working conditions (temperatures, apparent space temperature, required heat fluxes, etc.). The influence of the intermediate heat exchanger coupling the radiator to the thermal bus system was considered to investigate the possibility of employing the LDR in a wide range of space applications by direct substitution of conventional solid surface heat exchangers with an LDR or similar direct external flow radiator.[15]

As an example, Fig. 4 shows the performance parameter (rejected heat flux/mass) as a function of the working temperature for a rectangular LDR working with a sodium–potassium (Na56%–K) mixture and with the intermediate heat exchanger working with FC75, in a configuration perfectly suited for the coupling with the CBC considered in the present work. Further information is given by the mass distribution analysis, related to a mean working temperature of 320 K, where the maximum performance is achieved (the pie chart in Fig. 4). In the graph of Fig. 4, the relative mass of the reservoir for the makeup fluid is also reported, showing that when the mean working temperature becomes high, almost 50% of the total LDR mass is devoted to the storage of the fluid needed to compensate the evaporation losses. The amount of stored fluid blows up as soon as the vapor pressure increases with temperature. Such an effect is amplified by the long lifetime period (30 years) assumed for the LDR permanence in space without maintenance (space station application).

The maximum performance for the LDR as a single component is reached around 320 K. However, the global mass reduction of the CBC as a whole should be reached for lower working temperatures, since in the range below 320 K, the LDR performance is not so heavily affected; on the contrary, interesting benefits are to be expected for the thermodynamic efficiency when the minimum working temperature is lowered. Therefore, significant mass reductions should be achieved for the same generated electrical power.

Integrated CBC–LDR Optimization Procedure

So that the plant design of the current configurations of the previously mentioned CBC for space application is not greatly affected, the proposed solution studied here simply replaces the traditional heat-pipe radiator with a rectangular LDR, introducing an appropriate intermediate compact heat exchanger (HEX) to perform the cooling of the liquid fluid (FC75) inside the cooling thermal bus system by means of a fluid (Na56%–K) suitable for the direct radiation in space.

The two design and performance analysis algorithms (the first one for the CBC, the second one for the LDR) have been integrated into a global performance and optimized design procedure. For the present first-step coupled analysis the two independent procedures have been used in cascade, according to the schematic flow chart shown in Fig. 5.

The parameter that most affects the optimum design of a solar space dynamic system is the minimum temperature of the power cycle [i.e., compressor inlet temperature (CIT)]. For the same electric power to be produced and to have the same design parameters [in particular the turbine inlet temperature (TIT)], the conversion efficiency increases by reducing the CIT, and therefore the input heat of the cycle decreases as well as the size and mass of the concentrator and receiver/TES. On the other hand, even if the heat rejected is reduced, the radiator increases its weight and size, because by decreasing its mean temperature, the radiated heat (which depends on the temperature raised to the fourth power), needs larger surfaces. Therefore, the optimum CIT is the one that represents the best compromise between these two contrasting effects.[2]

The objective function of the design procedure for assigned produced electric power is the mass and surface area, which have to be minimized.

According to previous results,[2] the main CBC working parameters affecting the conversion process efficiency are the compression ratio and the recuperator effectiveness; therefore, these were the parameters considered in the CBC optimization, assuming they had the same TIT and fixed radiator performance characteristics. The obtained results define the working conditions of the hot side of the intermediate HEX, which represent the key linking the CBC powerplant to the radiator. In particular, the waste heat flux to be radiated and the mean working temperatures are clearly defined.

The subsequent LDR optimization procedure, based on the design program described in Ref. 15, gives the best HEX and LDR working conditions for minimum radiator mass, and therefore defines new, better performance characteristics of the radiator, which can be exploited by the CBC.

Finally, the global optimization procedure integrates the two design processes to achieve the minimum mass or surface area as a function of the CIT, which is assumed as the independent design parameter.

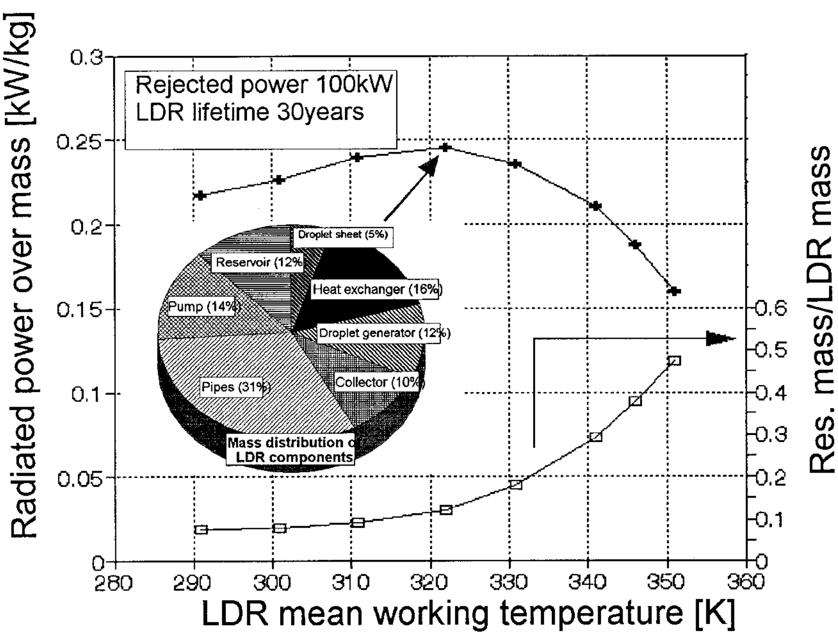

Fig. 4 Optimized performance and mass distribution of a single-sheet LDR of the type in Fig. 3.

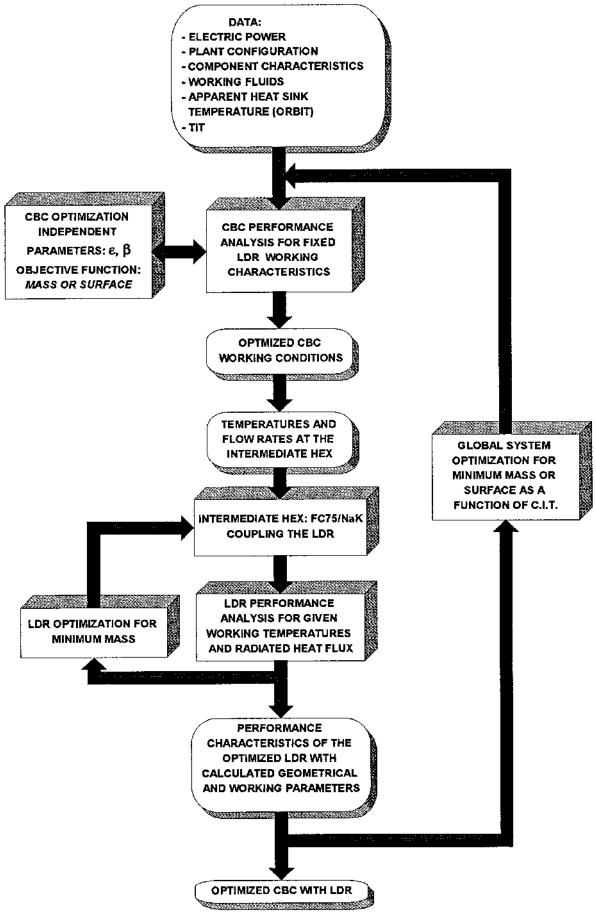

Fig. 5 Summary of the design flow chart.

Performance of the CBC System with a Rectangular LDR

Different approaches were utilized to assess the LDR influence on the design and performance of a solar space CBC power system. In the first stage of the analysis the CBC data and state points are fixed (see Table 1), and the mass and surface modifications of the whole system are directly correlated to the alternative use of different radiators (heat-pipes, radiator, or LDR).

The comparison between the specific mass (kg/kWe) of the system with the traditional heat-pipe radiator and the specific mass of the system with the innovative droplet radiator is clearly shown in Fig. 6.

The radiator mass reduction is considerable for the three analyzed conditions, it always exceeds 50% and reaches 60% for the first two configurations. This allows the following specific mass reductions of the plant to be obtained: case A, −20%; case B, −27%; and case C, −26%.

The plant surface decrease is even larger when an LDR is used. Indeed, for the same operating conditions, the input heat to the Brayton cycle as well as the concentrator surface remain unchanged, while the LDR radiator engages a surface that is almost negligible. The operating phases in which the problem of the plant surfaces arises must be considered: 1) the size problems during the launch; 2) the drag that makes a periodical correction of the orbit necessary during plant operation (in fact, in low orbit an atmosphere is still present, even if rarefied); and 3) the possible damage caused by micrometeorites. In all of these cases the LDR does not present any problem, since during the launch the droplets sheet is contained in a compact tank, and during the system operation the droplets cannot transmit any dynamic reaction to the station structure.

Table 1 CBC data utilized for LDR influence evaluation

	Case		
CBC data	A	B	C
CIT, K	287	338	294
TIT, K	1011	1034	1013
Electrical power, kW	32.15	36.42	40.9
Sink temperature, K	186	191	190
Compressor pressure ratio	1.90	1.74	1.85
Compressor efficiency	0.842	0.847	0.825
Turbine efficiency	0.896	0.901	0.891
Recuperator effectiveness	0.940	0.926	0.940

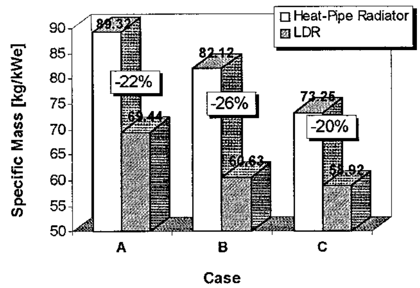

Fig. 6 Specific mass comparison.

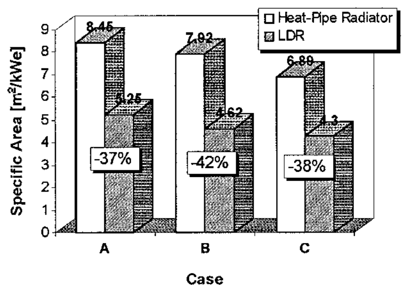

Fig. 7 Specific surface comparison.

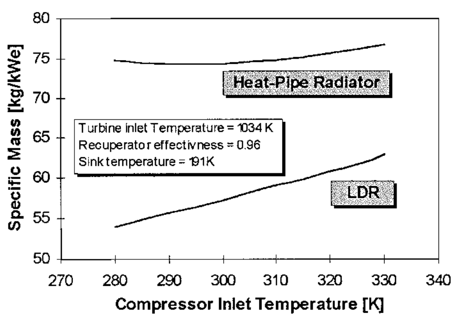

Fig. 8 CIT influence on specific mass of the global system.

Figure 7 shows the specific area (m^2/kWe) comparison between the plant with a traditional heat-pipe radiator and the plant with the innovative LDR. The percentage decrease of the specific area is large and reaches the following values for the three different analyzed configurations: case A, −37%; case B, −41%; and case C, −38%.

To evaluate the influence of one of the most important CBC design parameters[2] (the compressor inlet temperature), a sensitivity analysis was carried out varying the CIT. This second-stage approach emphasizes the performance comparison, in terms of specific mass and surface, between the plant utilizing the traditional heat-pipe radiator with the plant that employs the LDR. For each different CIT value only the CBC pressure ratio is optimized to maximize the conversion efficiency; whereas TIT, T_{sink}, and recuperator effectiveness are fixed (Figs. 8 and 9).

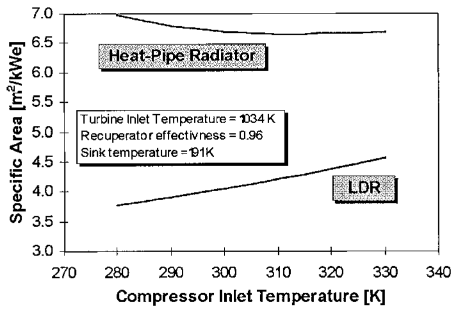

Fig. 9 CIT influence on specific surface of the global system.

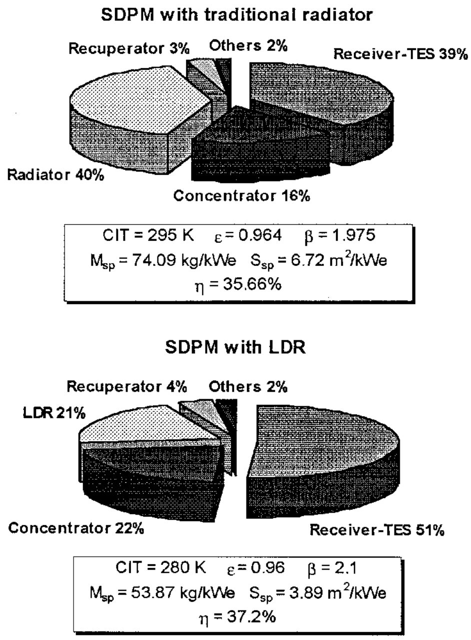

Fig. 10 Optimized specific mass distribution. CBC system with a heat-pipe radiator and LDR.

For a system with a heat-pipe radiator, the specific mass reaches a minimum value in CIT correspondence of about 290 K, with the specific surface showing a minimum for a CIT equal to about 320 K. Instead, with the LDR, the two curves are always decreasing and therefore, the minimum points could be theoretically located in a CIT correspondence of less than 280 K. However, this is not possible since, in these conditions, the sheet temperature is lower than the NaK solidification temperature (about 260 K).

Finally, the third step uses the previously mentioned design optimization procedure (Fig. 5). The design variables in this particular case are CIT, β, and ε; whereas the objective function selected is the mass of the whole system. The fixed variables are similar to those related to the case B in Table 1 (TIT = 1034 K; T_{sink} = 191 K). Figure 10 shows the values of the optimized design variables, the specific area, the specific mass, and the percentage distribution of weights for both cases (with LDR or heat-pipe radiator).

The LDR halves its influence on the total mass and allows a 27% decrease in the specific mass to be obtained, while the reduction in the specific area is about 43%.

Conclusions

The performance improvements in terms of specific surface (m^2/kWe) and specific mass (kg/kWe) in optimized solar space power systems have been proved by coupling a traditional solar CBC system with LDR. The global design and optimization procedure have been described both for CBCs and LDRs, and the main aspects of their integration have been analyzed.

The CIT has been assumed as the main variable in the global optimization procedure while other specific variables have been considered separately for CBC and LDR system optimization.

The traditional plant with a heat-pipe radiator shows the specific mass and area vs CIT to have a minimum point around 300 K; whereas the results of the LDR case present a continuously decreasing trend. In this last case a lower CIT can be selected as an optimum design point, allowing better global specific performance parameters to be derived and to have conversion efficiency improvements.

Since efficiency is maximized, the thermal power to produce a given electrical output is minimized; therefore, the size of the concentrator and the thermal energy storage will be minimized.

The estimated minimum specific mass of the system with an LDR in a typical condition assumed for reference is significantly lower than the specific mass of the system with a heat-pipe radiator. The minimum specific mass is estimated around 53.9 kg/kWe (−27% mass savings), while the minimum specific area is 3.9 m^2/kWe (−43% surface savings).

Acknowledgment

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References

[1]Massardo, A. F., "High-Efficiency Solar Dynamic Space Power Generation System," *Journal of Solar Energy Engineering*, Vol. 113, Aug. 1991, pp. 131–137.

[2]Massardo, A.F., "Design and Performance Evaluation of a CBC Solar Space Power System: The Influence of Orbital and Solar Conditions," American Society of Mechanical Engineers, Paper 93-GT-180, June 1993.

[3]Agazzani, A., and Massardo, A., "Advanced Solar Dynamic Space Power System—Part I: Efficiency and Surface Optimization," *Journal of Solar Energy Engineering*, Vol. 117, No. 4, 1995, pp. 265–273.

[4]Agazzani A., and Massardo A.,"Advanced Solar Dynamic Space Power System—Part II: Detailed Design and Specific Parameters Optimization," *Journal of Solar Energy Engineering*, Vol. 117, No. 4, 1995, pp. 274–281.

[5]Harper, W., and Kudija, C., "Solar Dynamic CBC power for space station Freedom," American Society of Mechanical Engineers, Paper 90-GT-70, June 1990.

[6]Mattick, A. T., and Hertzberg, A., "Liquid Droplet Radiators for Heat Rejection in Space," *Journal of Energy*, Vol. 5, No. 6, 1981, pp. 387–393.

[7]Brandell, B., "Analytical Approach and Computer Model Development for Performance Investigations of Liquid Droplet Radiators," Society of Automotive Engineers, Paper 840977, 1984.

[8]White, K. A., "Liquid Droplet Radiator Development Status," AIAA Paper 87-1537, July 1987.

[9]Tagliafico, L. A., and Devia, F., "Thermal Design of a Liquid Droplet Radiator," Society of Automotive Engineers, TP 921205, July 1992.

[10]Chubb, L., and Calfo, F. D., "Current Status of Liquid Sheet Radiator Research," *Aerospace Heat Exchanger Technology*, edited by R. K. Shah and A. Hashemi, Elsevier, Amsterdam, 1993.

[11]Boyle, R., Coombs, M. and Kudija, C., "Solar Dynamic Power Option for the Space Station," Inst. of Electrical and Electronics Engineers, Paper 889163, New York, Aug. 1989.

[12]Spencer, S., and Bons, R., "Off-Design Modeling and Performance of the Space Station Solar Dynamic Power System," Inst. of Electrical and Electronics Engineers, Paper 899279, New York, 1989.

[13]Dimitriev, A. S., Klimenko, A. V., Sleptson, A. M., and Chaschihin, D. B., "The Study of the Processes in the Liquid Droplet Radiators," *Aerospace Heat Exchanger Technology*, edited by R. K. Shah and A. Hashemi, Elsevier, Amsterdam, 1993.

[14]Pfeiffer, S., and White, A., "Conceptual Design of a Liquid Droplet Radiator Space Flight Experiment," Society of Automotive Engineers, TP 891565, July 1989.

[15]Tagliafico, L. A., and Fossa, M., "Light Weight Radiator Optimization for Heat Rejection in Space," *Heat and Mass Transfer* (to be published).