System integration of high intensity energy subsystems – a thermal management challenge

D. M. Pratt and D. Moorhouse
Air Force Research Laboratory
Wright-Patterson AFB
OH, USA

ABSTRACT

Current and future Air Force weapons systems lack the necessary power and cooling capacity to provide full systems level capability as a result of energy and thermal management limitations. Cooling capacity of fuel is already fully utilised leaving little room for additional cooling needs. Additionally, increasing speed, power, and miniaturisation of future systems continue to stress any thermal management capability that we can now deliver. Thus, the focus of this paper is a conceptual assessment of the key energy and thermal management technologies to meet the future energy challenges. It presents an overview of the current state of the art and also possible future research.

NOMENCLATURE

A	area (m^2)
c_p	constant pressure specific heat (J/kg-K)
g	acceleration due to gravity (m/s^2)
h_{lv}	latent heat of vaporisation (J/kg)
Q,q	heat transfer (W)
T	temperature (oC)

Subscripts

c	cold
h	hot
s	saturation
sp	single phase
tp	two phase
w	wall

Superscripts

·	rate (flow)

1.0 INTRODUCTION

Aerospace vehicle design has progressed in an evolutionary manner, with certain discrete changes such as turbine engines replacing propellers for higher speeds. The evolution has worked very well for commercial aircraft because the major components can be optimised independently. This is not true for many military configurations which require a more integrated approach. In addition, the introduction of aspects for which there is no pre-existing database requires special attention. This paper addresses the challenges of integrating a high-energy subsystem which are very different from conventional power-related equipment.

The use of directed energy weapons (DEW) such as high power microwaves (HPM) and high energy lasers (HEL) present unique energy challenges. These devices are inefficient, therefore a large portion of the energy required to operate the device is converted to waste heat and must be transferred to a suitable heat sink. For HPM, the average heat load during one 'shot' is on the same order as traditional

Paper No. 3149. Manuscript received 3 November 2006, accepted as review paper 22 April 2008.

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press

subsystems and thus designing a thermal management system is possible. The challenge is transferring the heat from the HPM device to a heat sink. The power density of each shot could be hundreds of megawatts. This heat must be transferred from the HPM beam dump to a sink. The heat transfer must occur at a rate that will support shots in the 10-100Hz range. For HEL systems, in addition to the high intensity, there are substantial system level thermal loads required to provide an 'infinite magazine.' Present models are inadequate to analyse these problems, current systems are unable to sustain the energy dissipation required and the high intensity heat fluxes applied over a very short duration phenomenon is not well understood. Focused research efforts are thus crucial to enable the utilisation of DEW.

Research needs to be performed that addresses multidisciplinary areas of assessment capabilities, two-phase flow, thermal capacitors, advanced fluids and materials and energy conversion technologies to enable the integration of high power weapons systems onto vehicle platforms. The paper is organised to present an overview of each of these broad subject areas.

2.0 BACKGROUND

Quantitative technology assessment can be divided into two broad sub-areas, that of traditional physics based modeling and that of advanced concepts to enable energy optimised systems. Both of these sub-areas require information technologies to enable interchange of information across remote networks, insurance of shared proprietary rights, non-unique data fusion and output and a common basis for interfacing eclectic disciplines. In the traditional physics based modeling sub-area, advances must be made in the description of the fundamental physics associated with the energy and mass transport within DEW as well as their integration and the quantification of uncertainties.

Heat transport systems capable of dissipating high intensity heat energy and transporting large amounts of thermal energy over distances are required to cool the DEW devices and to integrate these devices at the system and platform level. Of the heat transport concepts under consideration in this regime, the most attractive utilise the latent heat of vaporisation through liquid-vapor phase change or two phase flow. However, the risk associated with two phase systems is beyond that which is currently acceptable to air platform system integrators. To fully reap the potential benefits of these concepts, they must be matured. Additionally, working fluids that change phase in the 200-400ºC range require development.

DE weapons are envisioned to require large spikes in energy during 'shots.' If these high intensity spikes can be absorbed during the sort duration that they occur and then dissipated over relatively longer time scales, the system impact of the spikes could be minimised. Thermal capacitors are devices that may enable the absorption of these spikes followed by dissipation of the energy over more reasonable time constants. Thermal capacitor concepts that require pursuit include phase-change materials with high conductivity embedded components, chemical reaction chambers and adsorption beds.

DEW systems are extremely inefficient and thus have large quantities of high quality energy that must be dissipated, or harvested for other use if practical. If devices that could convert this energy into useful work were available, the overall efficiency of the weapons system would be drastically increased. Energy harvesting or the recovery, conversion and re-use of the energy requires substantial development. New ideas need to be created and new concepts must be developed and matured.

Exergy, entropy generation minimisation, and energy optimisation are examples of technologies that can enable the creation of energy optimised systems. These approaches allow the manipulation of fundamental equations governing thermodynamics, heat transfer, and fluid mechanics to produce minimised irreversibilities at the vehicle, subsystem and device levels. Applying these techniques to the aircraft systems would identify not only which subsystems are inefficient but also those that are close to their maximum theoretical efficiency. Such analyses would obviously guide researchers and designers to the areas having the highest payoff.

There has been considerable interest in the use of entropy generation or exergy metrics to evaluate aircraft subsystems and systems. An example is the papers published in a special section of the AIAA *J Aircr*, January-February 2003. As a lead into these papers Moorhouse[1] proposed a system-level approach of defining the vehicle as a device to do work. A certain amount of exergy is required to do this mission work, and the 'overhead' (exergy destruction, waste irreversibilities) should be minimised. For example Bejan and Siems[2] showed a linkage between aircraft size reduction and minimum exergy destroyed and Figliola *et al*[4] showed a connection between system weight minimisation and minimal exergy destruction. Roth and Mavris[4] demonstrated the potential for using thermodynamic work potential in aerospace vehicle design. They suggest that "at the most fundamental level, it is the usage and loss of thermodynamic work potential that drives virtually every aspect of a vehicle's design and performance." They point out that the work potential (availability or exergy) makes it possible to estimate the absolute loss associated with each loss mechanism in terms of a single figure of merit applicable to all vehicle components, processes and systems – offering potentially significant benefits to aircraft design. In a related but different context, Constructal theory is another possible avenue of obtaining an energy optimised system. It is a means 'to construct complex structures by connecting simple elements and to optimise each connection'[5]. This theory may lead through an independent path to a means of optimising vehicles.

3.0 TECHNOLOGY ASSESSMENT

To operate high-energy lasers on tactical air vehicle platforms requires first the ability to assess and assimilate thermal management architectures that incorporate everything from device level heat transport concepts to platform level energy sink constraints. To do this involves overcoming "show-stopping" issues. The issues that must be resolved are managing the excess heat produced by the devices, reducing the impact of this thermal management on the desired operational capabilities of the aircraft and power technologies that are required to deploy. So we must be able to resolve these issues by:

- developing thermal loads simulation models of tactical airborne lasers. PreFlight• source magnet –> UPS 20 kW
- cathode heater - 1kW
- modelling thermal management system architectures to manage those thermal loads
- conducting military utility studies to identify the trades between thermal management and operational capabilities
- developing key power technologies required to deploy including light weight, compact, high efficiency generators; reliable
- developing light weight advanced power conditioners to transform generator output into usable weapon power
- additionally, integrating effective thermal management strategies and concepts into DEW power system design from the inception is required–heat dissipation is the limiting factor in every revolutionary DEW power system.

Very preliminary assessments have shown that the system shown in Figure 1 has great potential for use in DEW air vehicle integration. This figure shows a three loop system. The first loop transports energy from the cyclic source to a thermal capacitor which permits a

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press

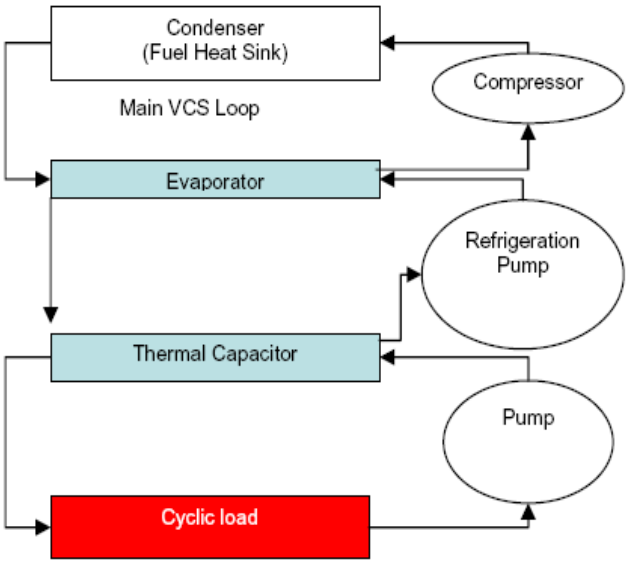


Figure 1. DEW thermal management systems.

time averaging of the source load. The second loop transports that time averaged load from the capacitor to the vehicles primary cooling loop. Finally, the main loop transports the energy to the vehicle fuel heat sink. Thus for the remainder of paper Fig. 1 will be used as the basis.

Some physics-based models have been developed and can be utilised for most of the concept under consideration with the exception of the very high intensity heat transport technologies at the device level. Understanding and describing the physics of extremely high heat flux energy transport on the order of kilowatts per centimeter squared must be pursued. Models must be developed that can be incorporated into any technology assessment frameworks.

Preliminary assessment have shown that high powered microwave systems will require

- 5-10 MW electrical
  - 4kW input power for cryogenic cooler (30K) for super conducting magnet
  - ~1kW input power for cathode heater

while being less than 50% efficient. Added complication occurs when you included the user's desire for near continuous duty cycle. These preliminary assessments also gave insight into HPL requirements that include

- 1-2kHp input power
- ~10% device efficiency
- 1,000W/cm^2 heat fluxes

While the user desires only seconds between shots and an infinite magazine, this leads to demands on the thermal management systems of

- high heat flux of 100-1,200W/cm^2
- high thermal power of 10-100'skW – 10'sMW
- duty cycle of seconds to minutes to near continuous
- isothermality for solid state lasers of less than 2°C and device defined performance generally <50°C
- operational temperatures consistent with device performance
  - electronics 100-4000°C
  - laser devices 0-200°C
  - high power microwave devices 300-4,000°C
- operation in high-g environments

These parameters define the system constraints. The preliminary assessments also determine that the integration of DEW system allows or requires the examination of the thermal management concepts into discrete classifications, those of local or device cooling, intermediate or capacitor/damping concepts and finally subsystem or platform energy dissipation. An overview of each of these areas is presented in the following sections.

3.1 Device cooling and two-phase flow

Table 1 details high heat flux device level technologies that may be feasible to meet the parameters mandated for the detailed device level components.

Now to differentiate and do the trades between the two most feasible solutions shown in Table 1, i.e. single phase liquid flow cooling and two phase flow cooling, Fig. 2 is presented. This figure is a comparison of these two cooling phenomena for a given working

Table 1
High heat flux cooling technologies

	Heat flux W/cm^2	Temp, 0C/heat flux, W/cm^2	Transport capacity, W-m
Heat pipes	<10-20	—	100s
Loop heat pipes, capillary pumped loops	10-20	—	1000s
Single phase liquid low cooling	1,000s (high flow rate/pumping penalty)	—	1000s
Two phase flow cooling		50-70/100	1000s
-	100-1000	20/200	—
-	100-1000	20/500	—
-	100-1000	100/1000	—
***Thermal energy storage**	<1kW/s	—	—

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press

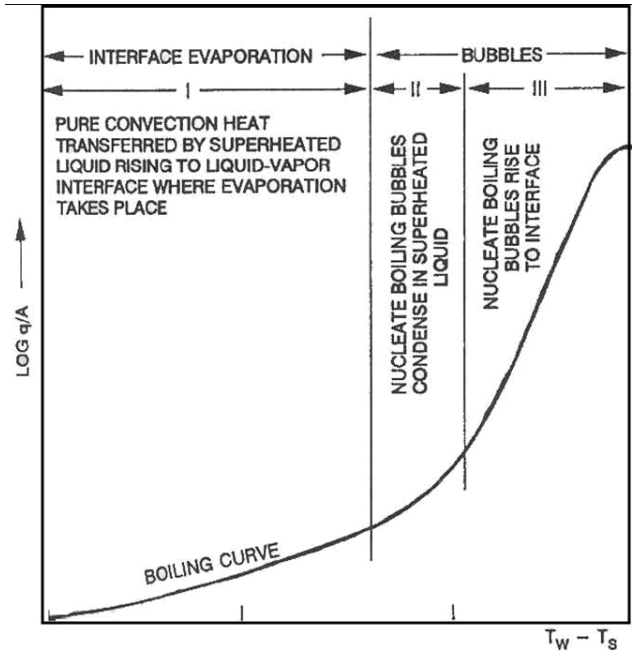


Figure 2 Fluid thermophysics (ASHRAE[6]).

fluid. It yields insight into the advantages of using two phase flow systems which is an order of magnitude increase in the local heat flux. Another advantageous aspect of two phase systems as shown in the figure is that they acquire these large heat fluxes isothermally. Both of these parameters are desired by DEW systems.

Concepts for single phase liquid cooling heat fluxes, such as single phase jet impingement cooling and sub-cooled nucleate boiling, have demonstrated the ability to meet the local flux requirement but the single phase problem is what do you do with all that liquid. It takes a huge flow rate to remove the requisite heat using single phase schemes. This problem is highlighted in Equation 1 which is a comparison of the required mass flow rate for single and two phase flow systems. Two phase systems are not problem free. The two phase problem is what do you do with all that vapor and how do you separate it from the liquid during high-g maneuvers? As opposed to the single phase problem which is inherent to thermophysics, the later is a design consideration which can be overcome by maturation of the technology.

$$\dot{m}_{SP} = \frac{\dot{Q}}{Cp\Delta T} \quad \dot{m}_{TP} = \frac{\dot{Q}}{h_{LV}} \Rightarrow \left(\frac{\dot{m}_{SP}}{\dot{m}_{TP}}\right)_{lim} = \frac{Cp\Delta T}{h_{LV}} = \frac{2454\ kJ/kg}{(4.8\ kJ/kgK)(1K)} \approx 500 \text{ for } H_2O \quad \ldots (1)$$

So now we have a concept to locally remove the energy but there still exist considerations for the required duty cycles. Figure 3 shows an approximate duty cycle for a HPM system integrated into a vehicle. Figure 4 shows the thermal management considerations for an HEL. For HEL the minimum useful duty cycle is ten seconds between shots or a 40% duty cycle with 100kW output, 10% efficient continuously pulsed laser of 4sec on, 10 sec off. An infinite magazine is desirable, so we must evaluate impacts as the numbers are reduced. Duty cycles of these types lead to the incorporation of a thermal capacitor between the local energy removal system and the platform thermal management system as shown in Fig. 1.

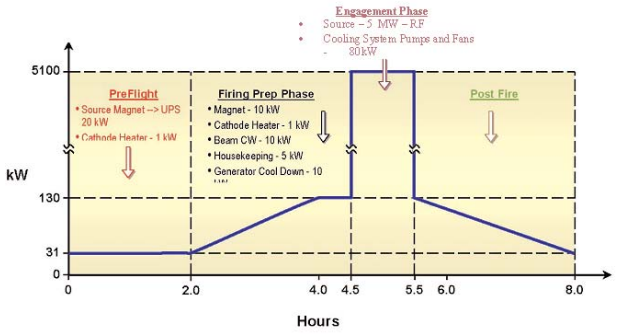


Figure 3. Notional high power microwave mission profile.

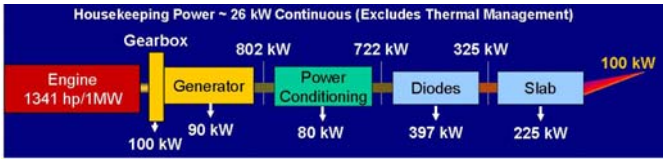


Figure 4. High energy laser thermal requirements.

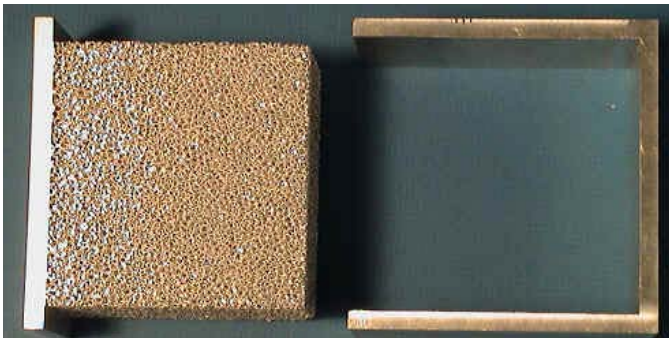


Figure 5. High conductivity foams (http://widget.ecn.purdue.edu[13]).

3.2 Thermal capacitors

Traditional thermal capacitors include phase change materials (PCMs) (Hale[7]) such as waxes, chemical adsorption beds, chemical reaction system, among others. Of these the one most common considered is a PCM bed. These beds have drawbacks in that they have relatively huge capacities however they have very low thermal conductivity[8]. This leads to unacceptable time constants associated with the energy transport into the bed. Thus research must be pursued in optimally embedding high conductivity material in the PCM to decrease the time constant associated with the energy storage systems. Means of doing this include infiltrating PCM into high conductivity foams, an example of which is shown in Figure 5 (Klett[9], Hagar[10], and Wierschke[11], into fin or honeycomb structures like in Fig. 6, or into graphite heat exchanges as in Fig. 7 or encapsulating them in a micro encapsulation process as shown in Fig. 8 (Fossett[12]).

3.3 Energy conversion

DEW systems are extremely inefficient and thus have large quantities of high quality energy that must be removed from the weapon. In general, this energy must then be dissipated. However, if devices that could convert this energy into useful work were available, the overall efficiency of the weapons system would be

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press



Figure 6. Finned heat sink (www.trade-taiwan.org[14]).

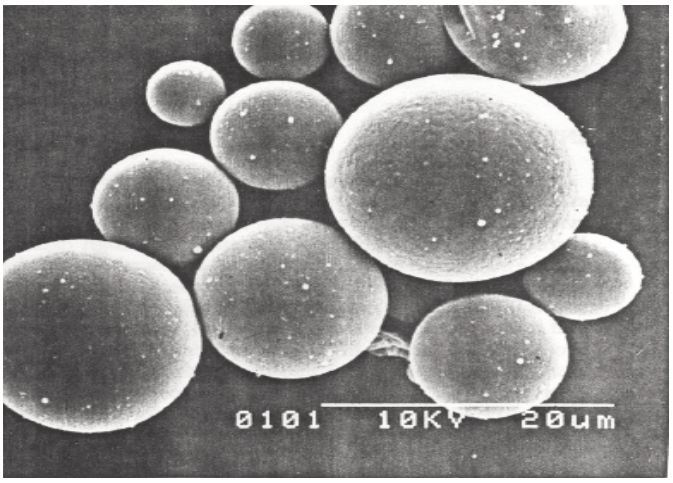


Figure 8. Microencapsulated phase change materials (Colvin[16]).

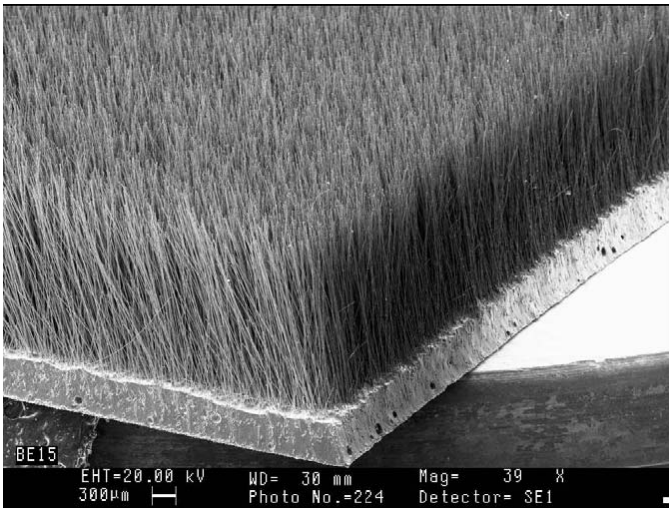


Figure 7. Carbon heat exchanger (http://www.esli.com[15]).

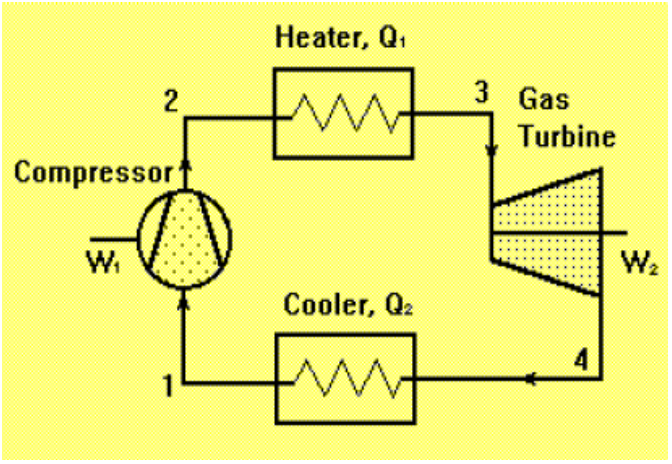


Figure 9. Typical heat engine (Brayton Cycle) (http://www.taftan.com/thermodynamics[18]).

increased. This requires the development of energy harvesting or recovery, conversion and re-use concepts. Sodano[17] reviewed and detailed some of the topics in power harvesting that have been undergoing recent research. These included energy harvesting from mechanical vibration, biological systems, and the effects of power harvesting on the vibration of a structure but like most other recent researches Sodano emphasised the conversion of vibrational energy into electrical power. DEW systems are concerned more with thermal energy conversion into useful work. Systems of this nature include heat engines and heat pump. A heat engines is defined as a device that converts heat energy into mechanical energy or more exactly a system which operates continuously and only heat and work may pass across its boundaries (Fig. 9).

While these systems have been under development for decades, consideration for the isothermal constraints, heat flux levels, and total energy dissipation requirements associated with DEW integration must be explored.

A heat pump is a device that transfers heat energy from a low temperature reservoir to a high temperature reservoir requiring the input of energy such as refrigeration cycles. If however you 'drive' these devices in reverse, that is if a temperature gradient exists, you can produce useable output energy. An example of such as system is a thermoelectric device shown in Fig. 10. Thermoelectric devices are solid-state devices that convert thermal energy from a temperature gradient into electrical energy by the Seebeck effect or convert electrical energy into a temperature gradient by the Peltier effect. Heat pumps like heat engines have been under development for decades however they still require substantial work to overcome the constraints associated with DEW integration.

4.0 SUMMARY

Constraints, concerns, system impacts and device level considerations associated with the integration of DEW systems such as high power microwaves and high energy lasers into air vehicles have been explored. The inefficiencies of these devices lead to the requirement for research being performed in multidisciplinary areas of assessment capabilities, two-phase flow, thermal capacitors, advanced fluids and materials and energy conversion technologies. Short overviews of each of these broad areas were presented with inclusion of required paths forward.

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press

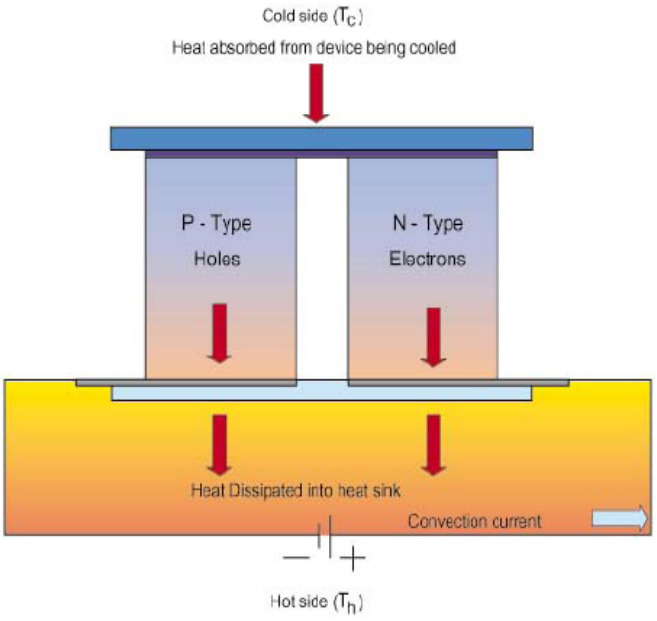


Figure 10. Thermoelectric device (http://www.electronics-cooling.com/Resources/EC_Articles/MAY96/images/tb1.jpg[19]).

REFERENCES

1. MOORHOUSE, D.J. A proposed system-level multidisciplinary analysis technique based on exergy methods, *AIAA J Aircr*, **40**, (1), pp 11-15.
2. BEJAN, A. and SIEMS, D.L. The need for exergy analysis and thermodynamic optimization in aircraft development, *Exergy Int J*, 2001, **1**, (1), pp 14-24.
3. FIGLIOLA, R.S., TIPTON, R. and LIE, H. Exergy approach to decision based design of integrated aircraft thermal systems, *AIAA J Aircr*, 2003, **40**, (1), pp 49-55.
4. ROTH, B. and MAVRIS, D. Generalized model for vehicle thermodynamic loss management, *AIAA J Aircr*, 2003, **40**, (1), pp 56-61.
5. BEJAN, A. Constructal theory: tree-shaped flows and energy systems for aircraft, *AIAA J Aircr*, **40**, (1), pp 43-48
6. ASHRAE, 1997 *ASHRAE Handbook, Fundamentals*, SI Edition, Ch 4, Two Phase Flow, p 41.
7. HALE, D.V., HOOVER, M.J. and O'NEIL, M.J. *Phase Change Materials Handbook*, September 1971, NASA CR-61363.
8. ZALBA, B., MARIN, J.M., CABEZA L.F. and MEHLING, H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Eng*, 2002, **23**, pp 251-283.
9. KLETT, J. Pitch-based carbon foam heat sink with phase change material, 2004, United States Patent # 6,780,505.
10. HAGAR, J.W. and LAKE, M.L. Novel hybrid composites based on carbon foams, 1992, Materials Research Society Symposium Proceedings, **270**.
11. WIERSCHKE, K.W., FRANKE, M.E., WATTS, R. and PONNAPPAN, R. Heat dissipation with pitch based carbon foams and phase changer materials, 2005, 38th AIAA Thermophysics Conference proceedings.
12. FOSSETT, A.J., MAGUIRE, M.T., KUDIRKA, A.A., MILLS, F.E. and BROWN, D.A. Avionics passive cooling with microencapsulated phase change material, *J Electronic Packaging*, 1998, **120**, pp 238-242.
13. http://widget.ecn.purdue,edu/~CTRC/research/projects/Phase%20change/phase_3.jpg
14. http://www.trade-taiwan.org/vender/12995636/image/TPCU10. jpg
15. http://www.esli.com
16. COLVIN, D.P., MULLIGAN J.C. and BRYANT Y.G. Enhanced heat transport in environmental systems using microencapsulated phase change materials, 1992, SAE Technical Paper Series, **921224**, p 2.
17. SODANO H.A., PARK G. and INMAN D.J. 2004, Estimation of electric charge output for piezoelectric energy harvesting, *Strain*, May 2004, **40**, (2), pp 49-58(10).
18. http://www.taftan.com/thermodynamics/BRAYTON.HTM
19. http://www.electronics-cooling.com/Resources/EC_Articles/MAY96/images/tb1

https://doi.org/10.1017/S000192400000244X Published online by Cambridge University Press