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Eric A. Silk
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1 Introduction

1.1 Background

Over the course of the past several years, I have had the opportunity to teach spacecraft thermal design to both undergraduate and graduate students. In researching texts for my first year of teaching the subject, I quickly found that there was no textbook available that methodically walked the student through the process of thermal design and analysis of space-based systems. Standard heat transfer texts simply did not provide detailed content addressing thermal design considerations and constructs for analysis of space-based systems: contemporary engineering texts only provided a cursory overview of space-based conduction and radiation phenomena. Texts that explicitly addressed the topic of spacecraft thermal design did so in the context of an overall systems perspective, with thermal as one of several chapters dedicated to different subsystems. Other chapters covered topics such as mechanical, guidance navigation and control, electrical, etc. Last but not least there was a lack of detailed treatment of techniques and methodologies developed from fundamental heat transfer, thermodynamics and fluid dynamics principles. In creating the lecture content for my course, I found this limited the conveyance of important subject matter to students. Ultimately, the solution for providing course participants with a coherent stream of lecture content was to combine information in previously published texts on the subject with information I deemed important. Information was collected in written form as class notes and provided to students as the primary text for the course. Ironically, while it is some years since I became a lecturer in aerospace, the absence of a single introductory text for students on spacecraft thermal design persists. Arguably, this is a key void in the literature associated with space systems. This volume aims to fill that void with teaching materials covering the topic of spacecraft thermal design. I hope that the concepts and principles conveyed in this book will inspire early-career practitioners and students enrolled in space-based courses, and enable them to gain a fundamental understanding of the thermal environment in space, as well as the basic skills required to perform spacecraft thermal design and analysis.

1.2 Why Is Space Important?

While this text focuses on the thermal aspects of the space environment and the design of systems that mitigate potentially negative effects associated with the extreme temperatures experienced in space, a greater realization often sparks our interest in this topic: that space is important and highly relevant to our lives as citizens of planet Earth. However, in the face of contemporary societal challenges (e.g., the race towards a cure for cancer, solving world hunger and preserving the environment) one might ask: “Why is space important?” In discussions of the need for increased national and/or international investment to accelerate the goals of the space program, this question is often posed with cynical overtones, implying that other vital and immediate concerns are more worthy of investment than space-based pursuits. However, with a little contemplation, the relevance of space in all our lives is painstakingly apparent. To begin with, we reside on planet Earth, which resides in space as a living planet and does not display the attributes of what many would classify a “dead” planet, such as Mars. Many space researchers believe that Mars was once hospitable to carbon-based life forms similar to those found on Earth today. Much of the contemporary exploration of the Martian environment has therefore been dedicated to validating the presence of remnant forms of life on the surface and in the soil. Whichever side of the debate regarding life on Mars individuals may find themselves on, it is abundantly clear that the present environmental conditions on the Martian landscape are not conducive to human life (nor carbon-based life forms in general). Another way to interpret this is to state that Mars has poor planetary health. How is this relevant to Earth and its inhabitants? While our planet is today a living planet, “today” is an operative term. If Mars once contained life and somehow lost it, identifying the events that led to Mars’ present state may help educate the human family about what we need to do on Earth today to avoid similar pitfalls, and the near-term and long-term challenges of maintaining our planet in a living state.

The human family faces many important challenges. Three that have plagued societies since the foundation of civilization (although the list is not exhaustive) are war, disease and pestilence and famine. Although famine is not usually acknowledged as a threat to contemporary first-world countries, the reduction in their quantity of farmland, combined with increasing global demands for food production, could easily tax the existing food supply chain in years to come. A fourth challenge that has arisen in recent years is that of changing weather patterns and natural disasters, confirmed via phenomena such as extreme drought in the western United States, the melting of polar ice shelves, increased frequency of flooding events along America’s east coast (resulting from the La Nina/El Nino weather cycle off the west coast of Africa) and continual record-setting summer-time temperatures worldwide. While these changing weather patterns have been closely coupled to the concept of global warming, scientists have yet to unanimously agree upon the causes. The debate regarding whether or not global warming is manmade continues to rage, although the evidence that it is occurring is irrefutable.

Human beings living in environments that have been subject to chemical pollutants have been shown to routinely develop adverse health conditions. Environmental pollutants have shown similar effects in animal, insect and plant life. By the early 2000s there was a noticeable reduction in bee populations throughout the United States. Less bees means less pollination capability for crops and ultimately lower food yields. Left unaddressed, a chain of events like this could lead to destabilization of the food table, which could reduce the ability to sustain society. (For a detailed assessment of the bee

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crisis, see the documentary *More than Honey*.) While it is undoubtedly true that the planet will remain regardless of the outcome of these challenges, the key question is whether or not human life can be sustained after these events.

What about our neighborhood in space?

If we examine our planet in the context of the larger universe, it can easily be seen that we live in a dangerous neighborhood. By January 2020, NASA's Center for Near Earth Object Studies had identified 21,699 NEAs (near-earth asteroids). When an object like the Chelyabinsk meteor of 2013 (approximate size 20 m) enters the Earth's atmosphere, the resultant land strike can devastate human populations in the area surrounding the impact zone. In addition, the Sun, which sustains life on our planet, is a decaying star; approximately 1.5 billion years remain before it burns out. While we do have the option of improving local conditions in order to sustain ourselves in the Earth's environment, even in the best-case scenario of not being adversely affected by challenges internal to the planet, human existence on Earth is term limited. One day we will be forced to leave. If we don't invest the time and effort into developing enabling technologies and a higher understanding of the universe that will allow us to efficiently transition the human race from our planet to another when the time comes for departure, we may not be ready. Extinction would be a sad conclusion to the human family. Thus, space is highly relevant and vital to our future as a species. If we succeed in identifying a new home conducive to human life, technical challenges that will need to be addressed in preparation for our transport to "new Earth" include:

- ➢ Heavy lift capability/reusable space vehicles
- ➢ Survivability in space (must be addressed in order to get to our intended celestial destination)
  - μ-g effects (long term)
  - Radiation dosage outside the Earth's magnetic field
- ➢ Logistics of transport to "new Earth"
  - Earth's present population is approximately 7.5 billion
- ➢ Reduction in launch costs
  - Average cost is US$10,000/lb. of launch mass [1]
  - One trip to the International Space Station costs approximately US$58 million.

Members of the space community are charged with working towards answers for today's challenging spacecraft thermal problems that will benefit society in the future. This text is designed to help refine the reader's craft in the technical area of spacecraft thermal design. Welcome aboard and enjoy the reading.

1.3 Space-Based Thermal Energy Analysis Constructs

Spacecraft thermal design presents many problems associated with thermal and/or temperature control of space platform components. Most problems will require temperature control of an embedded component dissipating thermal energy remote from the platform's thermal interface with the space environment. The overall challenge then becomes maintaining temperature and getting the heat out. In Figure 1.1, which illustrates this problem, the source term for the energy to be dissipated by the remote component is $\dot{g}$. Using this construct, there is a thermal conductance coupling (C_{tot}) between the temperature-controlled item at temperature T_i and the radiator surface (where heat rejection from the space platform takes place), as well as a radiative coupling between the temperature-controlled item and the interior surfaces of the structure within its field of view (FOV). The heat-flow path between the temperature-controlled item and the heat rejection location can consist of multiple components, assembly of which will have an effective total thermal conductance. The total thermal conductance term in Figure 1.1 has units of [W/K]. The variable A is the area. Successful operation of the temperature-controlled item will typically require it to be maintained within high and low temperature values. Thermal analysis and design of the whole system, in other words, heat transfer analysis, ensures that the temperature requirements are satisfied while operational in the space environment.

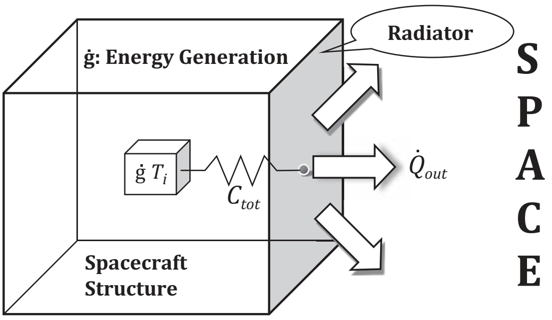

Figure 1.1 Heat flows onboard a simplified space structure

1.4 Units

Heat transfer is defined as the transfer of thermal energy that takes place as a result of temperature differences. In our study of heat transfer and related basic thermodynamics topics, it is important to establish conventions for common variables that allow us to seamlessly interleave the heat transfer concepts and constructs with those commonly used in thermodynamics. In general, thermodynamics deals with energy transfer. Examples of ways that energy is transferred include work, heat and kinetic energy. Regardless of the method of energy transfer, the base unit for energy often used in thermodynamics is the joule [J]. Both work and heat use joules. Heat transfer deals with the rate of thermal energy transfer (i.e., dQ/dt or $\dot{Q}$), which has units of [J/s] or Watts [W]. For equations defining heat transfer mechanisms, heat transfer texts typically use the variable Q and attribute units of [W] to it, as opposed to $\dot{Q}$. For consistency, $\dot{Q}$ (which has units of [W]) will be used throughout this text to define the heat transfer rate. Table 1.1 provides a summary of the base SI units used in the text. Kelvin will be used as the primary unit for temperature. However, Celsius will be used interchangeably for some calculations.

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Table 1.1 Base units of measure

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Temperature	Kelvin	K
	Celsius	°C
Heat	Joules	J
Heat transfer rate	Joules per second	W

1.5 Fundamental Heat Transfer Mechanisms

The majority of this text will focus on conduction and radiation, both of which are highly applicable to the space environment. Note, however, that radiative heat transfer has also been known to dominate convection for surfaces in thermal communication with ambient at suborbital altitudes. While convective heat transfer outside a platform in space is non-existent, boiling and condensation processes, which have been widely investigated, are the basis for heat transfer in several technologies frequently used in thermal control system architectures on space-based platforms. Since boiling and condensation are typically treated as convection based, the constructs used in this text will rely on all three basic mechanisms in heat transfer theory: conduction, convection and radiation.

1.5.1 Conduction

Fourier's Law for conduction (equation 1.1) is the relationship used to model thermal energy exchange between two locations in solid media.

$$\dot{Q} = \frac{kA(T_1 - T_2)}{\Delta x} \tag{1.1}$$

where

k: Thermal conductivity [W/m · K]
A: Heat exchange surface area [m^2]
Δx: Length of conducting path [m]
T_1, T_2: Temperature at each location [K]

The rate of thermal energy transfer $\left(\dot{Q}\right)$ is equal to the product of the thermal conductivity (k), the cross-sectional area for heat flow ($A = \Delta y \cdot \Delta z$) and the temperature difference at the two discrete measurement locations ($T_1 - T_2$), all of which is divided by the length (Δx) over which heat flow occurs. Based on the direction of the heat flow, in the example of the solid experiencing heat transfer shown in Figure 1.2, $T_1 > T_2$. It is important to note that while the value for the thermal conductivity has temperature

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dependence (as is the case for all thermophysical properties) it is shown in equation 1.1 as a constant. The acceptance of the thermal conductivity as a constant is generally applicable for steady-state room temperature scenarios (i.e., 270K ↔ 370K). In cryogenic applications, the temperature dependence of this property is important for determining accurate predictions of heat flows at temperature. This will be revisited and expanded upon in Chapter 7.

In the Fourier's Law conduction equation, the thermal conductivity is the constant of proportionality for the product of the A/L ratio and the temperature gradient. From a physical perspective at standard-size scale, it is the rate at which energy is transferred via diffusion through the media per unit length, per unit temperature. From a solid-state physics perspective, materials are atoms configured into a lattice structure (example in Figure 1.3). The lattice structure contains both immobile electrons (bound at the atoms) and mobile electrons (also known as conduction electrons) that have transport capability through the structure [2]. Conduction-based thermal energy transfer through a material is a function of conduction electron mobility (through the material), as well as vibrations of the material's lattice itself (otherwise known as phonons) [2–4]. The total thermal conductivity is the sum of these two individual contributions (as shown in equation 1.2).

$$k_{tot} = k_e + k_{lat} \tag{1.2}$$

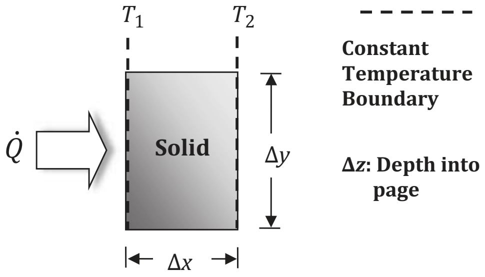

Figure 1.2 1-D heat flow through a solid

For pure metals, the contribution to k_{tot} from the conduction electrons has a much greater magnitude than that from phonons. However, as the amount of impurities in a metal increases, the phonon contribution will also increase. For non-metals, k_{tot} is primarily determined by the phonon level of the lattice structure. Both k_e and k_{lat} can be modeled using kinetic gas theory [2–6]. For pure metals, the electron component of the thermal conductivity (k_e) is inversely proportional to the electrical resistivity (ρ_e) of the material. The equation which captures the relationship between these two properties is the Wiedemann–Franz Law [7], shown in equation 1.3.

$$\rho_e = \frac{L_o}{k} T \tag{1.3}$$

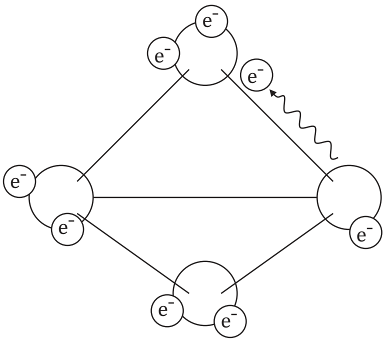

Figure 1.3 Molecular lattice

where

ρ_e: Electrical resistivity [Ohms · m]
L_o: Constant of 2.45×10^{-8} [W · Ohms/K^2]
k: Thermal conductivity [W/m · K]
T: Temperature [K]

In the Wiedemann–Franz relationship, the electrical resistivity is equal to the temperature divided by the thermal conductivity times a constant of proportionality (L_o). The Wiedemann–Franz Law is typically applicable to pure metals at temperatures from 4 K to 300 K and is used in cryogenics to determine thermal conductivity at low temperatures when the electrical resistivity is known and the thermal conductivity is not [7]. However, experimental studies have shown that the Wiedemann–Franz Law can have reduced accuracy in predicting the thermal conductivity of particular metals (e.g., phosphor bronze) in the cryogenic temperature regime [8]. When applying this law attention should be paid to the material in question and the segment of the temperature regime being designed for.

1.5.2 Convection

The fundamental relationship used to model thermal energy exchange between a fluid (either liquid or vapor phase) and a surface is Newton's law of cooling. This relationship is shown in equation 1.4 and illustrated in Figure 1.4.

$$\dot{Q} = h_{conv}A\cdot\left(T_{surf} - T_l\right) \tag{1.4}$$

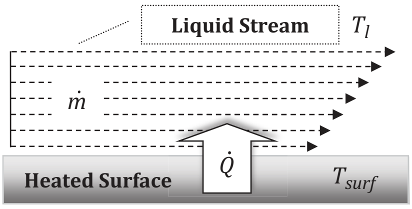

Figure 1.4 Heat transfer resultant from fluid flow over a heated surface

where

h_{conv}: Convection coefficient [W/m^2 · K]
A: Heat exchange surface area [m^2]
T_{surf}: Temperature of heat exchange surface [K]
T_l: Temperature of bulk fluid stream [K]

Depending on the direction of the temperature gradient between the fluid and the surface, the fluid is either heating or cooling the surface. In the example in Figure 1.4, $T_{surf} > T_l$. Thus, the fluid is providing cooling to the surface. In equation 1.4, the rate of heat transfer $(\dot{Q})$ is equal to the product of the heat transfer coefficient (h_{conv}), the temperature difference $T_{surf} - T_l$ and the surface area of the fluid contact (A). The heat transfer coefficient is the constant of proportionality for the process. Furthermore, h_{conv} is a function of the thermophysical properties of the fluid and the flow. In order for Newton's law of cooling to be applicable, the fluid present must satisfy the continuum hypothesis. The continuum hypothesis is valid if the mean free path (i.e., the average distance for molecule-to-molecule collisions) is significantly less than the characteristic length of travel to the bounding surface [9]. The equation used to determine the mean free path is

$$\lambda_{MFP} = \frac{k_B T}{2^{\frac{5}{2}} \pi R_m^2 P} \tag{1.5}$$

where

k_B: Boltzmann's Constant, 1.3805×10^{-23} [J/K]
T: Temperature of bounding surface [K]
R_m: Radius of molecule [m]
P: Pressure [N/m^2]

Otherwise, a molecular dynamics-based approach must be used to determine the rate of heating and/or cooling on the surface.

1.5.3 Radiation

The Stefan–Boltzmann Law (equation 1.6) is the fundamental relationship used to model radiative thermal energy rejection from any surface that is at a temperature above the zero point (i.e., 0 K).

$$\dot{Q} = \varepsilon \sigma A T_{surf}^4 \tag{1.6}$$

where

ε: Emissivity $0 < \varepsilon < 1.0$
σ: Stefan–Boltzmann constant, 5.67×10^{-8} [W/m^2 · K^4]
A: Heat exchange surface area [m^2]
T_{surf}: Temperature of heat exchange surface [K]

Figure 1.5 shows a surface radiating thermal energy away from it. In the Stefan–Boltzmann Law the heat transfer rate is the product of the emissivity (ε), the Stefan–Boltzmann constant (σ), the surface area emitting energy away (A) and the fourth power of the temperature (T_{surf}). The emissivity is an indicator of how efficiently the surface in question emits thermal energy relative to an ideal surface (i.e., $\varepsilon = 1.0$).

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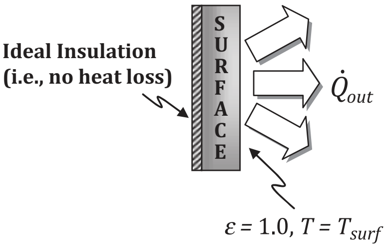

Figure 1.5 A surface radiating thermal energy away

The heat transfer rate's dependence upon the fourth-order temperature suggests that the phenomenon inherent to the process is fundamentally different than those observed in the other two mechanisms (i.e., conduction and convection). The Stefan–Boltzmann Law establishes the analytical relations for radiative thermal energy exchange between multiple surfaces, and will be examined in detail in Chapter 3.

1.6 The Energy Balance

One of the key concepts in mechanical engineering is the law of conservation, which can be applied to mass, momentum and energy. In the heat transfer context, it is also called the energy balance. The principle of conservation of energy is often used to bookkeep heat flows, and the transfer or storage of thermal energy. Throughout the text we will be performing steady-state and transient analysis of thermal circuits containing multiple individual components, using CV (control volume) theory. Figure 1.6 illustrates the energy balance where thermal energy exchange is occurring across non-adiabatic surfaces.

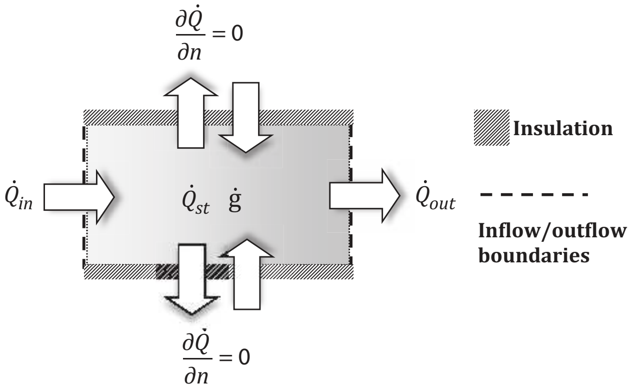

Figure 1.6 Control volume undergoing thermal energy exchange, storage and generation

The corresponding energy balance relationship is shown in equation 1.7.

$$\dot{Q}_{in} + \dot{g} - \dot{Q}_{out} = \dot{Q}_{st} \tag{1.7}$$

This equation states that the rate of thermal energy transfer into the CV plus the rate at which energy is generated ($\dot{g}$) internal to the CV minus that which is exiting the CV is

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equal to the rate at which thermal energy is stored internally. When no energy is generated, this equation simply reduces to

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{st} \tag{1.8}$$

Once a system has reached equilibrium the energy storage term goes to zero, leaving

$$\dot{Q}_{in} = \dot{Q}_{out} \tag{1.9}$$

The energy balance can be relied upon as a sanity check to confirm that all energy in a system is accounted for in the temperature solution determined.

1.7 Supplemental Resources

A seasoned spacecraft thermal engineer may often perform thermal analysis of an instrument or system with a high node count (30,000–50,000). Thermal models with such a high node count are referred to as a DTM (detailed thermal model). DTM models require computationally intensive software tailored to the space community, preferably with preprocessor and post-processor capability built in. Thermal Desktop® is an example of such a software package. However, the examples and problems in this text are designed for either calculation by hand or solution of an RTM (reduced thermal model) using a standard equation solver. The combined mode heat transfer problems found in the latter part of the text, for example, require limited nodalization schemes (15 nodes or less). Both Matlab and EES (Engineering Equation Solver) are viable solvers for these problems. Internet resources such as the Thermophysical Properties for Fluid Systems section of NIST’s Webbook, as well as their online Cryogenic Materials Property Database, are reliable reference sources for thermophysical properties data. Finally, online video content displaying boiling phenomena and the behavior of fluids in the microgravity environment will be referenced in the Chapter 5 discussion on multiphase heat transfer conductance technologies.

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