Bahman Zohuri

Heat Pipe Design and Technology

Modern Applications for Practical Thermal Management

Second Edition

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This book is dedicated to my wife Firouzeh, my daughters Natasha and Natalie, and son Sasha
I am also dedicating this book to my mother Marzieh and father Akbar
without their individual encouragement, this book would not have been written.

Preface for the Second Edition

Now that the second edition of this book is out, the reader will need to know additional information and improvements that are in this edition. First of all, the errors found in the first edition were corrected and certain sections were eliminated when there was no need for them based on the input from kind readers such as Mahboobe Mahdavi and Saeed Tiari.

A complete section was added to Chap. 4 entitled "Heat Pipe Applications in Thermal Energy Storage Systems" including all the subsections, which were graciously provided by Mahboobe Mahdavi and Saeed Tiari of the Mechanical Engineering Department of Temple University at Philadelphia, Pennsylvania, where further applications of heat pipes are identified along with Concentrated Solar Power (CSP) system. CSP recently has shown a great potential as part of renewable energy infrastructure.

The heat pipe is one of the remarkable achievements of thermal physics and heat-transfer engineering in this century because of its unique ability to transfer heat over large distances without considerable losses. The main applications of heat pipes deal with the problems of environmental protection and energy and fuel savings.

Heat pipes have emerged as an effective and established thermal solution, particularly in high heat flux applications and in situations where there is any combination of non-uniform heat loading, limited airflow over the heat-generating components, and space or weight constraints. This book will briefly introduce heat pipe technology and then highlight its basic applications for passive thermal control.

After a review of heat and mass transfer theory relevant to heat pipe performance, mathematical models are developed for calculating heat-transfer limitations of high-temperature heat pipes and heat-transfer limitations and temperature gradient of low-temperature heat pipes. Calculated results are compared with the available experimental data from various sources to increase confidence in the present mathematics models.

For the convenience of the users of the present theory, a few computer codes and their application are mentioned and they are available from Galaxy Advanced Engineering, Inc. These codes are designed to handle interactive input from users of the codes, and two computer programs for high- and low temperature heat pipes respectively are reported. These programs enables the performance of wrapped-screen heat pipes, rectangular-groove heat pipes, or screen-covered rectangular-groove wick to be predicted. These codes are especially helpful in design of steady-state heat pipe and are executable on Window/PC computing platforms.

Additionally, whenever the author finds the need to understand the basic physics and mathematics and for those readers to refresh their knowledge, sections of Wikipedia are presented in this book to further clarify certain complexities and advanced approaches for different equations and description of various topics on physics of fluid mechanics, heat transfer, and gas dynamics.

Heat pipe technology is pertinent to the design and application of self-controlled, variable conductance heat pipes for spacecraft thermal control is discussed. Investigations were conducted to (1) provide additional confidence in existing design tools, (2) to generate new design tools, and (3) to develop superior variable conductance heat pipe designs. A computer program for designing and predicting the performance of the heat pipe systems was developed.

Within this book a comprehensive review and analysis of all aspects of heat pipe technology pertinent to the design of self-controlled, variable conductance devices for spacecraft thermal control is also presented. Subjects considered include hydrostatics, hydrodynamics, heat transfer into and out of the pipe, fluid selection, materials compatibility, and variable conductance control techniques. Also included is a discussion of VCHP design techniques.

A variable-conductance heat pipe system (VCHPS) and its design have been discussed, and various references have been identified for further information to provide a thermal control for a transmitter experiment package (TEP) to be flown on the Communications Technology Satellite. The VCHPS provides heat rejection during TEP operation and minimizes the heat leak during power down operations. The VCHPS described features a unique method of aiding priming of arterial heat pipes and a novel approach to balancing heat pipe loads by staggering their control ranges.

This book introduces operational and design principles for heat pipes. A heat pipe is essentially a passive device that can quickly transfer heat from one point to another. They are often referred to as the “superconductors” of heat as they possess an extraordinary heat-transfer capacity and rate with almost no heat loss. The heat transferred from the hot source evaporates the fluid in the wick, causing the vapor to expand into the center core of the heat pipe. The latent heat of vaporization is carried with the vapor to the cold end of the tube, where it is removed by transference to the heat sink as the vapor condenses. The condensate is then carried back in the wick to the hot end of the tube by capillary action and by gravity (if the tube is tilted from the horizontal), where it is recycled. This two-phase heat-transfer mechanism results in heat-transfer capabilities from 100 to several thousand times that of an equivalent piece of copper.

The heat pipe is compact and efficient because (1) the finned-tube bundle is inherently a good configuration for convective heat transfer in both ducts and (2) the evaporative-condensing cycle within the heat pipes is a highly efficient method of transferring heat internally.

The effects of different factors on the performance of the heat pipe—compatibility of materials, operating temperature range, diameter, power limitations, thermal resistances, and operating orientation— will be considered in the book.

Heat pipes can be designed to operate over a very broad range of temperatures from cryogenic (less than 30 K) applications to high temperature systems (more than 2000 K). Until recently, the use of heat pipes has been mainly limited to space technology due to its cost-effectiveness and complex wick construction. There are several applications of heat pipes in this field, such as spacecraft temperature equalization component cooling, temperature control, and radiator design in satellites. Currently heat pipe technology has been integrated into modern thermal engineering designs, such as terrestrial thermal control systems, solar energetic, etc.

The increasing power and shrinking size of electronic components presents growing thermal management challenges. While solid metal conductors such as aluminum extrusions may provide acceptable cooling for individual components in certain situations, broad-level solutions with more advanced cooling technologies are needed in a growing number of applications.

After a review of heat and mass transfer theory, relevant to heat pipe performance, math models are developed for calculating heat-transfer limitations of high-temperature heat pipes and heat-transfer limitations and temperature gradient of low-temperature heat pipes. Calculated results are compared with the available experimental data from various sources to increase confidence in the present math models.

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These programs enables the performance of wrapped-screen heat pipes, rectangular-groove heat pipes, or screen-covered rectangular-groove wick to be predicted.

Few more computer programs are also mentioned, and some are obtainable either from US government organization or from Galaxy Advanced Engineering, Inc. or from other commercial companies that help in the design of steady-state heat pipe and, most of them, are executable on Window/PC computing platform. These codes are additional help for readers to calculate working fluid properties. They also assist heat-transfer analysis for design of fins for both constant and variable heat pipes. In addition, Excel spreadsheets that evaluate analytical solutions of four view factor geometries (perpendicular and rectangular shape with a common edge, coaxial parallel disks, coaxial cylinders, and aligned parallel rectangles) may be downloaded from Galaxy Advanced Engineering website at www.gaeinc.com, please contact this company.

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