OXFORD SCIENCE PUBLICATIONS

OXFORD STUDIES IN PHYSICS

The physical principles of heat pipes

M.N. Ivanovskii, V.P. Sorokin, and I.V. Yagodkin

Translated by
R. Berman and G. Rice

THE PHYSICAL PRINCIPLES OF HEAT PIPES

BY

M. N. IVANOVSKII, V. P. SOROKIN,
and I. V. YAGODKIN

TRANSLATED BY R. BERMAN

Translation edited by G. Rice

CLARENDON PRESS · OXFORD
1982

Oxford University Press, Walton Street, Oxford OX2 6DP
London Glasgow New York Toronto
Delhi Bombay Calcutta Madras Karachi
Kuala Lumpur Singapore Hong Kong Tokyo
Nairobi Dar es Salaam Cape Town
Melbourne Auckland
and associates in
Beirut Berlin Ibadan Mexico City Nicosia

First published by Atomizdat, Moscow, 1978

Published in the United States by Oxford University Press, New York

British Library Cataloguing in Publication Data

Ivanovskii, M. N.
The physical properties of heat pipes.—
(Oxford studies in physics)
1. Heat pipes
I. Title II. Sorokin, V. P.
III. Yagodkin, I. V.
621.402′5 TJ264

ISBN 0-19-851466-2

Filmset by Eta Services (Typesetters) Ltd., Beccles, Suffolk
Printed in Great Britain
at the University Press, Oxford
by Eric Buckley,
Printer to the University

OXFORD STUDIES IN PHYSICS

GENERAL EDITORS

B. BLEANEY, D. W. SCIAMA, D. H. WILKINSON

FOREWORD

Every year heat pipes attract more attention from scientists, designers, and engineers in those parts of technology where need arises for thermostatic control of certain processes and apparatus, where highly efficient heat conductors, high rates of heat transfer, or the control or conversion of heat flows are required. A wide range of specialists in atomic energy, space research, chemistry, electronics, and in other branches of technology have to become acquainted with the physical principles governing the operation and the processes occurring in heat pipes, with the basis of their construction and use, with the numerous ideas about how best to design them, with their critical characteristics and with their possible applications. Several books and collections of articles devoted to heat pipes have already appeared in the USSR.[1–5] The present book is an attempt at a systematic discussion of the physical basis of heat pipes. The engineering and technological problems will be discussed in the book *The technological basis of heat pipes*, which the authors intend to write immediately after the present book and which will be its logical sequel.

In the ten odd years since the study of heat pipes started, a large amount of information has been accumulated about various aspects of their design, testing, and applications. Some of this work is now out of date, but other aspects have been confirmed experimentally and have been developed further. Every year more original design ideas appear and they are verified experimentally and incorporated into technology. Recently, as always occurs with new ideas, excessive optimism in the outlook for application of heat pipes for some branches of technology has waned, while at the same time they have, on a firmer research basis, won the right to effective application in other branches of technology. The possibilities of developing new heat-pipe designs are certainly far from being exhausted today. At present the wide application of heat pipes in technology is essentially only just starting.

The authors were faced with a dilemma when writing this book: it is necessary to discuss general problems and to describe the processes occurring in heat pipes in a sufficiently popular way for the non-specialist; on the other hand, readers who are specializing in designing devices incorporating heat pipes require a deeper and more detailed presentation and analysis of the results of work already carried out. The essence of the problem is to adopt a systematic form of presentation from simple notions to a detailed description. In the final count, the centre of gravity must lie in the detailed description and analysis of the physical principles of heat pipes. The authors have aimed at a systematization of the material, to make a whole out of individual results, and to make recommendations about methods for calculations on heat pipes and their design.

The main part of the material in this book is expounded on the basis of the authors' investigations carried out in the thermal physics section of the Physicoenergetics Institute of the State Committee on the use of Atomic Energy, USSR. The authors thank N. P. Kolmogorov, L. M. Kuznetsov, L. M. Prorok, and E. N. Strozhkov for help in preparing the manuscript.

The authors will be grateful to readers who send their views and comments on the contents of the book.

PRINCIPAL SYMBOLS AND SUFFICES

A—cross-sectional area.
a—velocity of sound.
c_p—specific heat at constant pressure.
d—diameter.
f—coefficient of friction.
G—volume or mass flow rate.
g—acceleration due to gravity.
h—height.
K—permeability.
k—Boltzmann's constant.
L—latent heat of evaporation.
l—length.
M—molecular weight.
p—pressure.
Q—heat flow.
q—heat flux.
R—gas constant.
r—radius.
s—entropy.
T—Kelvin temperature.
t—Celsius temperature.
V—volume.
W—flow velocity.
α—heat-transfer coefficient.
γ—ratio of principal specific heats.
δ—film thickness, gap width.
ε—porosity.
η—kinematic viscosity.
θ—contact angle.
κ—filling coefficient.
λ—thermal conductivity.
μ—dynamic viscosity.
ν—relative superheating.
ρ—density.
σ—surface tension.
Ψ—potential.

M—Mach number.
Re—Reynolds number.
We—Weber number.

ad—adiabatic.
b—bulk.
c—condensation.
cap—capillary.
circ—circulation.
eff—effective.
evap—evaporation.
f—friction.
g—gravitational.
h—hydraulic.
in—inertia.
l—liquid.
men—meniscus.
ph—phase transition.
sat—saturated.
sh—shield.
son—sonic.
v—vapour.
w—wick.

CONTENTS

INTRODUCTION

Grover and his co-workers (Los Alamos Laboratory, USA) were the first to introduce the term *heat pipe* in 1963, and they initiated studies of these devices and discussion of their technological uses.[6,7] It would be more accurate to call heat pipes *heat transfer pipes*. However, the original name has already had wide circulation so that it is evidently advisable to preserve it.

The idea of constructing a heat conductor in which the heat transfer was achieved by means of the evaporation and condensation of the working medium, while capillary forces are used to transfer the liquid, was proposed by Gaugler in 1942 for application in refrigeration engineering.[8] However, the invention did not find an application in technology for more than 20 years. The development of high-temperature space power systems brought about a rebirth of the idea.

We should note that heat pipes had a predecessor in the so-called *Perkins pipes*. The Perkins pipes are unwicked conductors in which the heat transfer is also achieved through the latent heat of evaporation, while circulation of the heat carrier is brought about by gravitational forces. These devices were invented by Perkins in 1897 and were successfully used initially in the bread-making industry and later found numerous other fields of application. Unwicked tubes were used long before the appearance of heat pipes in, for example, the construction industry; in regions of permanent frost they made possible the preservation of frozen soil under the foundations of the buildings erected. However, the use of capillary forces in vapour–liquid heat conductors was certainly in the main a new step in their development.

The first experiments in the USA confirmed the high efficiency of conductors operating on this principle. They acted as the start of a 'chain reaction' in the study, development, and application of new conductors in different parts of the world. After the USA, such work was started in West Germany, England, France, Italy, Holland, and also in the USSR and some Eastern European countries (Czechoslovakia and Yugoslavia). Now studies and developments in heat pipes are being carried out in nearly all developed countries. The range of work in the USA is especially wide—the development and applications of heat pipes and studies of the processes in the devices are being carried out by more than a hundred firms and research organizations. There is close cooperation in the investigations carried out in the USA and in European countries.

Since 1965 the results of studies on heat pipes have been presented at various conferences and symposia. More recently, specialized international conferences have been held on heat pipes. The first of these was in Stuttgart

(West Germany) in 1973, the second in Bologna (Italy) in 1976, and the third in San Francisco (USA) in 1978.

The interest in heat pipes comes from the whole range of valuable properties which such heat conductors can show. Most important is the high degree to which they are isothermal. In fact, pipes with liquid metal heat transfer media can have an effective heat conductivity a thousand or even tens of thousands of times greater than that of the best metallic heat conductors, silver and copper. Even low-temperature pipes, with heat transfer media of relatively low heat conductivity and latent heat of evaporation, can have a thermal resistance tens of times less than the best metallic conductors.

Since they can operate through only capillary forces, heat pipes can be used in conditions of weightlessness. The combination of this property with their small mass makes possible their widespread use for transferring and getting rid of heat in various components of space structures. Heat pipes also work efficiently under terrestrial conditions. Gravitational forces can assist the transfer of the working fluid and appreciably increase the heat transfer capacity of these devices.

The ability of heat pipes to transform heat flows is an important property. One can have a high heat inlet density in one part of a tube while there is a low heat discharge density in another, and vice versa. The degree of conversion can be controlled over wide limits. Incidentally, we may remark that heat pipes with liquid metal heat transfer media allow an exceptionally intense heating. The heat flux can exceed 10^7 W m^{-2} in the heating zone. Such a record high rate of heat removal can only be achieved by evaporating the medium from the surface of a capillary porous body.

Heat pipes of special designs (for example, gas-filled) can provide automatic or forced control of thermal resistance or change the surface for effective heat transfer. It is relatively easy with the help of heat pipes to solve problems in creating thermal diodes, temperature regulators, and thermostabilizers.

The fact that heat pipes are self-contained is an undoubted convenience. Each separate pipe is an independent component of the system, requiring neither pumps nor other accessory apparatus.†

In principle these heat conductors can be used over a very wide temperature range, from low, cryogenic temperatures (starting from 1 K) to the highest (2500–3000 K). The optimal working fluid is chosen for a given working temperature level: liquefied gases, organic liquids, and low-boiling metals. In general each fluid is optimal over only a limited temperature range (100–300 K). Pipes with liquid metal heat transfer media have exceptionally good heat transfer characteristics. They can carry very large

† Electromagnetic heat pipes are an exception.

amounts of heat; up to 10^8 W and more per m^2 of pipe cross-section. As the operating temperature level decreases, the physical properties of the heat transfer media worsen and the heat transfer power of the pipes decreases. However, much depends on the design of the heat pipes and on the actual conditions of operation. In spite of the simplicity of their construction, the processes taking place in heat pipes are rather complicated and require comprehensive study. It is only with a detailed acquaintance of the processes occurring in heat pipes that it is possible to evaluate the applicability of these devices under particular conditions and to choose the optimal conditions.

I.1. The design and principle of operation of heat pipes

Heat pipe is the name given to an evaporation–condensation device for transferring heat in which the latent heat of vaporization is transferred by means of evaporating the liquid in the heat inlet region and condensing its vapour in the discharge region, while a closed circulation of the working fluid is maintained by capillary action or bulk forces.

Extremely wide variations in the design of heat pipes are possible. In the simplest type† (see Fig. I.1) there is a sealed case, the inner surface of which is covered with a layer of capillary-porous material, the wick, which is saturated with the liquid phase of the working fluid. Various porous materials can act as wick (gauzes or sintered porous structures), it can consist of grooves on the inner surface of the pipe case, shields with perforations, or of some other structure capable of bringing about a transfer of liquid from the condensation zone to the heating zone by means of capillary forces. Any chemically pure materials or compounds which have a liquid and vapour phase at the pipe's operating temperature and wet the wick material can be used as heat transfer agent. By using as transfer media, liquid helium, nitrogen, alcohol, freon, water, and alkali metals etc., heat pipes can be constructed to operate both at low, cryogenic temperatures and at high temperatures of the order of 2500 °C and even higher.

We shall consider the operation of a heat pipe of the simplest type in the absence of bulk forces. Heat is introduced into the pipe as a result of conduction through its casing and, often, through parts of the wick to the working fluid. Evaporation of the liquid wetting the wick leads to the formation or increase in curvature of the concave meniscus at the surface of the liquid in the pores of the wick in the heating zone. Under the action of surface tension forces, a capillary pressure Δp_{cap} arises in the concave menisci acting on the liquid and tending to reduce their curvature. The

† In what follows, unless it is specially mentioned, the discussion applies to just such heat pipes.

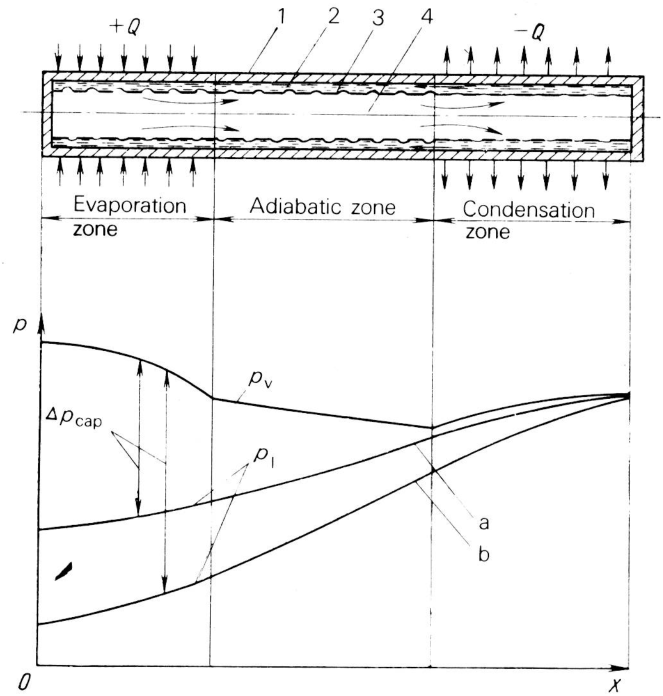

FIG. I.1. Sketch of cylindrical heat pipe with the qualitative pressure distribution in the vapour, p_v, and in the liquid, p_l, (a) in the absence of bulk forces and (b) in a gravitational field directed opposite to the flow of liquid in the wick.

1—case; *2*—wick; *3*—liquid; *4*—vapour.

capillary pressure in the meniscus is determined by Laplace's formula

$$\Delta p_{cap} = \sigma(1/r_1 + 1/r_2), \tag{I.1}$$

where Δp_{cap} is the capillary pressure and r_1, r_2 are the principal radii of curvature of the surface of the meniscus.

Condensation of the liquid in the heat-discharge zone leads to flooding of the wick. The curvature of the menisci of the liquid inside the wick in this zone is, as a rule, negligible compared with the corresponding curvature in the heating zone of the pipe. The difference in curvature of the menisci and, correspondingly, of the capillary pressures in these two zones of the pipe leads to a pressure drop which is the driving force in transferring liquid along the wick from the condensation zone to the evaporation zone. A 'capillary pump' is thus used in a heat pipe to achieve closed circulation of the working fluid. Bulk forces, gravitational, centrifugal, electromagnetic etc., can also act in the operation of heat pipes as well as capillary forces. Bulk forces can both improve the circulation of the heat transfer agent in heat pipes and hinder it.

The following processes take place in an operating pipe when the working fluid is circulating: (i) evaporation of the liquid phase of the medium in the heating zone on the introduction of heat from the source; (ii) transfer of vapour to the zone with lower pressure, the heat discharge and condensation zone; (iii) condensation of the vapour in the heat-discharge zone; (iv) transfer of liquid from the condensation zone to the evaporation zone under the action of capillary and bulk forces.

Each of these processes takes place with a change in pressure along the line of the circulating working fluid. As the vapour flows along the vapour channel, the pressure change is brought about both through hydraulic losses, produced by friction, and through inertial effects; the static pressure in the vapour changes as a mass of vapour is injected into the stream (evaporation) or removed (condensation). The pressure in the liquid moving along the wick under the action of capillary forces, changes mainly as a result of friction. In the evaporation and condensation zones there is a pressure drop at the phase transition at the interface between the liquid and gaseous phases in addition to the capillary pressure, brought about by the dynamic interaction in the evaporating or condensing medium. Over any cross-section of a pipe in the steady state, the pressure differential between the phases is balanced by the capillary pressure:

$$p_v - p_l + \Delta p_{ph} = \Delta p_{cap}, \tag{I.2}$$

where Δp_{ph} is the pressure difference between vapour and liquid as a result of the phase transition.

A typical pressure distribution in the vapour and liquid along the length of a heat pipe is shown in Fig. I.1. The curvature of the menisci and the capillary pressure both change along the length of the pipe. The maximum curvature occurs at the start of the evaporation zone of the pipe and the minimum at the end of the condensation zone. Curve (a) represents the pressure variation in the liquid in the absence of the action of bulk forces; curve (b) gives, for comparison, the pressure distribution in the liquid along the length of the pipe taking gravity into account for the case of gravity hindering the circulation of liquid. For a fixed value of the heat transferred by the pipe, the effect of gravity amounts to the fact that the capillary pump must develop a higher pressure drop than is the case for a pipe working in conditions of weightlessness.

In cases where gravitational or other forces (centrifugal or electromagnetic) are capable of producing a transfer of liquid from the condensation to the heating zone, heat pipes without a capillary structure, un-wicked heat pipes, can be used. The design of a heat pipe without a capillary structure and operating by using gravitational forces, is shown in Fig. I.2. It is usual to call such a heat pipe an evaporative thermosiphon.

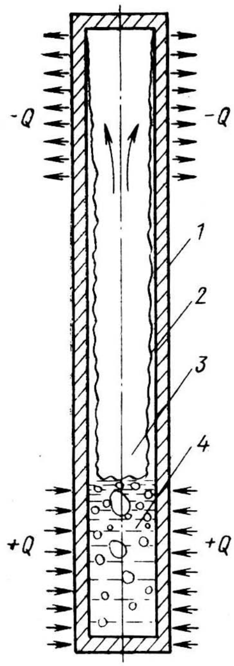

FIG. I.2. Sketch of an evaporative thermosiphon.
1—case; *2*—condensate film; *3*—vapour; *4*—volume of boiling liquid.

I.2. Constraints on the operating parameters of heat pipes

The physical processes occurring during the operation of heat pipes impose a number of constraints on their operating parameters. We will first consider those constraints which determine the maximum heat transfer rate and fix the range of parameters for achieving normal working of the pipe (see Fig. I.3). Factors which limit the heat transfer may be:

1. Attainment of the speed of sound by the vapour flow in some part of the pipe, usually at the start of the condensation zone. In this case one refers to the *sonic limit*† to the heat transfer of the tube.

2. The ability of a given capillary structure to provide circulation of the given medium only up to a certain limit. Such limitations are generally called *capillary limitations*. In the general case one should refer to *hydrodynamic limitations*.

† We shall adopt the convention in what follows to refer to a *limit* in cases where the heat pipe does not lose its ability to operate and to a *limitation* when critical phenomena occur (drainage of the wick, overheating of the pipe etc.).

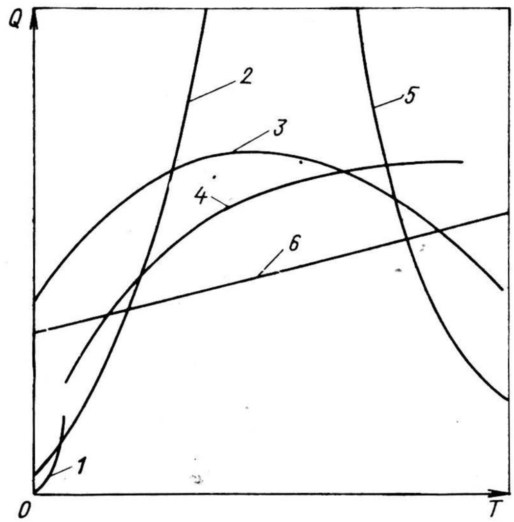

FIG. I.3. The limitations of the maximum heat transfer power of a heat pipe.

1–viscous limit; *2*—sonic limit; *3*—capillary limitation (or wicking limit); *4*—limitation brought about by the entrainment of liquid from the wick in the vapour stream; *5*—limitation due to boiling of the liquid in the wick; *6*—limit set by the possible rate of heat removal from the pipe.

3. Friction in the vapour phase at low temperatures limiting the circulation of the medium and thus leading to the occurrence of a *viscous limit* to the heat transfer.

4. *Entrainment of liquid* from the wick in the vapour stream which leads to a premature onset of capillary limitation.

5. *Boiling of the medium* and other effects lead to critical phenomena and to a limitation of the *heat flux* which can be attained in the heating zone.

6. The possibility of carrying the heat away from the heat pipe.

For high-temperature heat pipes (in particular, for pipes operating in a controlled inert medium at $T > 1000$ °C), the main difficulty is in achieving long-term stability of the constructional materials. One therefore sometimes refers to a seventh limitation imposed on the operating parameters of heat pipes, the safe working life. The safe life of a heat pipe is limited by corrosion and mechanical stability of the materials of the wall and of the capillary structure, operating in contact with the working fluid usually under stressed-state conditions, complicated by the effect of high temperature.

The limiting factor can be any one of the limitations mentioned depending on the tube design, the type of working fluid, the level of the operating temperature, and the heat transferred by the pipe.