Handbook of Heat Transfer Applications

Second Edition

Editors

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Preface

Introduction

Heat transfer plays an important role in practically every industrial and environmental process as well as in the vital areas of energy production and conversion. In the generation of electrical power, whether by nuclear fission, the combustion of fossil fuels, magnetohydrodynamic processes, or the use of geothermal energy sources, numerous heat transfer problems must be solved. These problems involve conduction, convection, and radiation processes and relate to the design of components such as boilers, condensers, and turbines. Engineers are constantly confronted with the need to maximize or minimize heat transfer rates and to maintain the integrity of materials under conditions of extreme temperature.

In the preparation of the second edition of the *Handbook of Heat Transfer* it was the editors' goal to provide the information needed by engineers to deal with the heat transfer problems encountered in their daily work. The major objective of the editors was to prepare a handbook which contains information essential for practicing engineers, consultants, research engineers, university professors, students, and technicians involved with heat transfer technology. Since the publication of the first edition of the *Handbook of Heat Transfer* there have been many developments in the field, both in fundamentals and in applications. Consequently, to achieve our goal it was necessary to expand the first edition of the *Handbook of Heat Transfer* into two separate handbooks: *Handbook of Heat Transfer Fundamentals* and *Handbook of Heat Transfer Applications*.

Coverage

The *Handbook of Heat Transfer Applications* provides broad coverage of the practical aspects of the field, building on several chapters in the first edition and adding nine completely new chapters. In particular, the chapter Mass Transfer Cooling offers more detailed information on film cooling, while the chapter Techniques to Augment Heat Transfer has been completely updated to reflect new developments. The section Heat Exchangers has been greatly expanded to cover basic design methods with special attention given to both compact and process heat exchangers.

Seven of the new chapters cover recent developments in the critical field of energy. These include Heat Transfer in Fluidized and Packed Beds; Solar Energy; Geothermal

Heat Transfer; Cooling Ponds and Cooling Towers, Thermal Energy Storage; Heat Pipes; and Heat Transfer in Buildings.

An important chapter on Measurement of Temperature and Heat Transfer has been added to the second edition. Rounding out the coverage is a chapter dealing with Non-newtonian Fluids, a topic of increasing interest in the chemical, pharmaceutical, and food industries.

It is assumed that the user of the *Handbook of Heat Transfer Applications* has a knowledge of the basic information appearing in the companion text, the *Handbook of Heat Transfer Fundamentals*. Taken together, these two handbooks provide the most comprehensive coverage available of the science and art of heat transfer.

Units

It is recognized at this time that the English Engineering System of units cannot be completely replaced by the International System (SI). Transition from the English System of units to SI will proceed at a rational pace to accommodate the needs of the profession, industry, and the public. The transition period will be long and complex, and duality of units probably will be demanded for at least one or two decades. Both SI and English units have been incorporated in this edition to the maximum extent possible, with the goal of making the Handbook useful throughout the world. Each numerical result, table, figure, and equation in the handbook is given in both systems of units, wherever presentation in dimensionless form is not given. In a few cases some tables are presented in one system of units, mostly to save space, and conversion factors are printed at the end of such tables for the reader's convenience.

Nomenclature

An attempt has been made by the editors to use a unified nomenclature throughout the Handbook. Given the breadth of the technical coverage, some exceptions will be found. However one symbol has only one meaning within any given section. Each symbol is defined at the end of each section of the Handbook. Both SI and English units are given for each symbol in the nomenclature list.

Index

An added feature in this edition is a comprehensive alphabetical index designed to provide quick reference to information. Taken together with the Table of Contents, this edition now provides quick and easy access to any topic in the book.

Acknowledgments

The editors owe a great deal to the dedication with which the authors of the second edition made their expertise available. Their cooperation on the content and length of their manuscripts and in incorporating all of the above-mentioned specifications coupled with the high quality of their work has resulted in a Handbook which we believe will fulfill the needs of the engineering community for many years to come. We also wish to thank the professional staff at McGraw-Hill Book Company who were involved with the production of the Handbook at various stages of the project for their outstanding cooperation and continued support. The outstanding editorial work of Richard K. Mickey and Peggy Lamb is gratefully acknowledged. Finally, thanks are also due to the staff of the Energy Resources Center at the University of Illinois at Chicago, especially Dr. E. Y. Kwack and J. Wiet who provided proofreading assistance and organizational help throughout the editorial process.

Closing Remarks

The Handbook is ultimately the responsibility of the editors. Meticulous care has been exercised to minimize errors, but it is impossible in a work of this magnitude to achieve an error-free publication. Accordingly the editors would appreciate being informed of any errors so that they may be eliminated from subsequent printings. The editors would also appreciate suggestions from readers on possible improvements in the usefulness of the Handbook so that they may be included in future editions.

W. M. ROHSENOW
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Contents

Detailed contents of each chapter appear on the opening page of the chapter. A detailed alphabetical index follows Chapter 12.

CHAPTER 1

Mass Transfer Cooling

By J. P. Hartnett

University of Illinois, Chicago

A. INTRODUCTION

The term *mass transfer cooling* includes transpiration cooling, film cooling with a liquid, and film cooling with a gas as well as various ablation schemes. A pictorial representation of various forms of mass transfer cooling is given in Fig. 1. With the exception of film cooling with a gas all of the systems are physically similar. The major difference in the methods shown in Fig. 1*b* through *d* is that the mass transfer distribution may be independently controlled for the systems in Fig. 1*b* and *c* while for the other systems the mass transfer rate is set by the thermodynamics of the system.

In light of these considerations, Sec. B of this chapter will deal with transpiration cooling and then follow with a brief note on the applicability of these results to liquid film cooling and ablation. Throughout Sec. B the effects of suction will also be discussed. The chapter will conclude with Sec. C dealing with gaseous film cooling.

B. TRANSPIRATION COOLING

1. Forced-Convection Laminar Flow

a. The Flat Plate with Constant Properties

The system of differential equations describing the physical situation where a constant-property gas flows in laminar motion over a porous flat plate with mass addition into the boundary layer (Fig. 1*b*) is

$$\text{Continuity} \qquad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\text{Momentum} \qquad \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \mu \frac{\partial^2 u}{\partial y^2} \tag{2}$$

$$\text{Energy} \qquad \rho c_p u \frac{\partial T}{\partial x} + \rho c_p v \frac{\partial T}{\partial y} = k \frac{\partial^2 T}{\partial y^2} + \mu \left(\frac{\partial u}{\partial y}\right)^2 \tag{3}$$

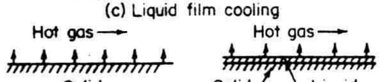
$$\text{Species} \qquad \rho u \frac{\partial Y}{\partial x} + \rho v \frac{\partial Y}{\partial y} = \rho D_{12} \frac{\partial^2 Y}{\partial y^2} \tag{4}$$

Strictly speaking, in a constant-property flow there is no need for the species equation. However, it can be assumed that the injected gas, although having the same transport and thermodynamic properties as the free-stream gas, is given special identification (e.g., it may be an isotope of the free-stream gas or it may be "tagged" with a radioactive tracer). The resulting mass fraction profile and the value of the mass fraction at the wall may be of value in actual binary flows when the free-stream and the secondary gas are not markedly different in physical properties (e.g., nitrogen injected into air).

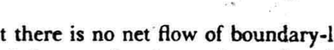
This system of equations requires seven boundary conditions. The following boundary conditions lead to a set of ordinary differential equations:

$$\left.\begin{aligned} u &= 0 \\ T &= T_w \\ v &\sim u_\infty/\sqrt{\mathrm{Re}_x} \end{aligned}\right\} \text{ at } y = 0 \tag{5}$$

$$\left.\begin{aligned} u &= u_\infty \\ T &= T_\infty \\ Y &= 0 \end{aligned}\right\} \text{ at } y \to \infty \tag{6}$$



(a) Film cooling (b) Transpiration cooling



(c) Liquid film cooling

(d) Ablation cooling

FIG. 1 Various mass transfer cooling schemes.

The next and last boundary condition states that there is no net flow of boundary-layer fluid into the plate surface. This fixes the value of the mass fraction at the surface $Y_{y=0}$

$$v = -\frac{D_{12}}{1 - Y}\frac{\partial Y}{\partial y} \qquad \text{at } y = 0 \tag{7}$$

Note that the resulting solution is restricted to the case where the distribution of the injected mass varies as $x^{-1/2}$. This blowing distribution is selected since it gives rise to a system of ordinary differential equations. For this physical system the resulting velocity distribution, local skin friction coefficient, and local dimensionless heat transfer coefficients are shown in Figs. 2 to 4 [1].

For mass transfer to a laminar boundary on a flat plate the following conclusions may be drawn from Fig. 2:

1. Mass addition to a zero–pressure gradient boundary layer results in an S-shaped velocity profile. Since this is known to be an unstable profile, mass transfer is destabilizing (i.e., mass addition to a laminar boundary-layer flow on a flat plate may cause the boundary layer to become turbulent). This conclusion does not apply to flows with favorable pressure gradient.

   Conversely, removal of mass from a zero–pressure gradient boundary layer (i.e., suction) is stabilizing.

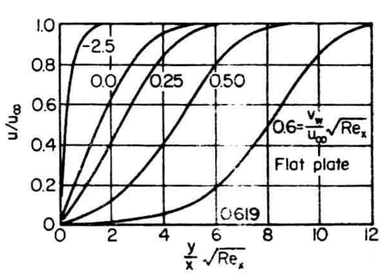


FIG. 2 Dimensionless velocity distribution u/u_∞ for constant-property laminar flow over a flat plate for various values of the blowing parameter $(v_w/u_\infty)\sqrt{Re_x}$ [1].

2. The maximum value of the dimensionless blowing parameter $(\rho_w v_w/\rho_\infty u_\infty)\sqrt{Re_x}$ is 0.619. Beyond this value the boundary-layer equations do not describe the flow.

The local shearing stress may be determined from Fig. 3 and the equation

$$\tau_w = \frac{c_f}{2}\rho u_\infty^2 \tag{8}$$

The local heat transfer rate is calculated as

$$q_w'' = h(T_w - T_{aw}) \tag{9}$$

The local heat transfer coefficient is given on Fig. 4 as a function of the blowing or suction rate. The adiabatic wall temperature T_{aw} is determined from the relation

$$T_{aw} = T_\infty + r\frac{u_\infty^2}{2c_p} = T_\infty\left(1 + r\frac{\gamma - 1}{2}Ma_\infty^2\right) \tag{10}^*$$

In Eq. (10) the temperatures are absolute values in °R or K. The recovery factor r is given in Fig. 5. Note that the recovery temperature approaches the free-stream temperature for low-velocity flow and is equal to it in the limiting case of zero Mach number.

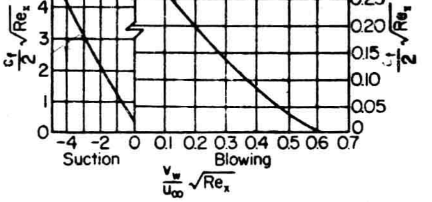


FIG. 3 Local skin friction coefficient for constant-property laminar flow over a flat plate for various values of the blowing parameter $(v_w/u_\infty)\sqrt{Re_x}$ [1].

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*The adiabatic wall temperature is also called the recovery temperature. These two terms are used interchangeably throughout the chapter.

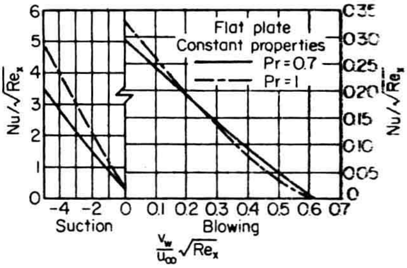

FIG. 4 Local dimensionless heat transfer coefficient $Nu/\sqrt{Re_x}$ for constant-property laminar flow over a flat plate for various values of the blowing parameter $(v_w/u_\infty)\sqrt{Re_x}$ [1].

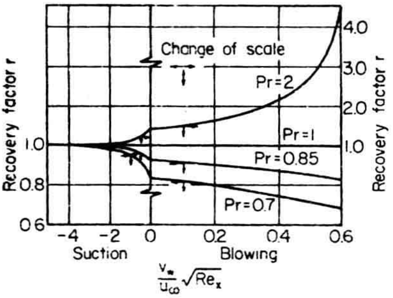

FIG. 5 Recovery factor for constant-property laminar flow over a flat plate for various values of the blowing parameter $(v_w/u_\infty)\sqrt{Re_x}$ [1].

b. The Flat Plate with Variable Properties Including Foreign Gas Injection into an Air Boundary Layer

The effect of variable physical properties is taken into account by the use of the Eckert reference method [2]. First the heat transfer coefficient, the skin friction coefficient, and the recovery factor are determined for a solid surface exposed to the same free-stream conditions and held at the same surface temperature as the mass transfer–cooled plate. The reference temperature T^* is first calculated from

$$T^* = T_\infty + 0.5(T_w - T_\infty) + 0.22(T_{aw} - T_\infty) \tag{11}$$

where

$$T_{aw} = T_\infty + r_0^* \frac{u_\infty^2}{2c_p^*} \tag{12}$$

and

$$r_0^* = \sqrt{\text{Pr}^*} \tag{13}$$

The physical properties of the free-stream gas are known as functions of temperature and pressure and it is assumed that the wall temperature and the free-stream velocity and temperature are prescribed. The Prandtl number Pr* and the specific heat c_p^* are to be evaluated at the reference temperature T^*. An initial estimate of these two properties is made, leading to a value for T_{avg} and for T^*. New values of c_p^* and Pr* and T^* may now be determined since T^* is known. The calculation is repeated until a consistent set of values of c_p^*, Pr*, and T^* is achieved. The local skin friction coefficient c_{f0} and local Stanton number St_0 are then calculated from

$$\frac{c_{f0}}{2} = \frac{0.332}{\sqrt{u_\infty x/\nu^*}} \tag{14}$$

and

$$St_0 = \frac{c_{f0}}{2}(\text{Pr}^*)^{-2/3} \tag{15}$$

The reference temperature method has been shown to be valid for air, nitrogen, carbon dioxide, and hydrogen [3, 4].

The local skin friction coefficient c_f and the local Stanton number St in the presence of mass transfer with air as the free-stream gas for various injectant gases are shown in

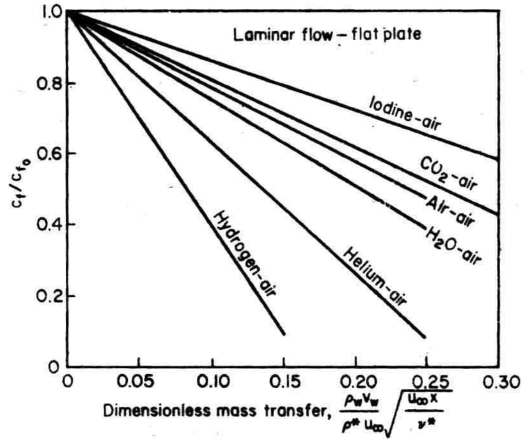

FIG. 6 Normalized skin friction coefficient c_f/c_{f0} for transpiration cooling in a laminar boundary layer on a flat plate as a function of the dimensionless mass transfer for foreign gas injection into an air boundary layer [5].

Figs. 6 and 7 in a normalized form c_f/c_{f0} and $\mathrm{St}/\mathrm{St}_0$ as a function of the dimensionless mass transfer rate

$$\frac{\rho_w v_w}{\rho^* u_\infty} \sqrt{\frac{u_\infty x}{\nu^*}}$$

where ρ^* and ν^* are density and kinematic viscosity of the free-stream gas evaluated at

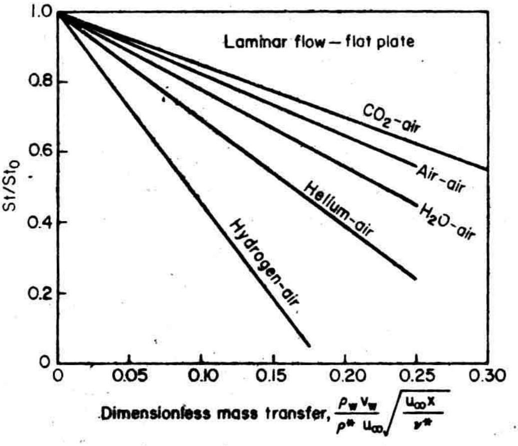

FIG. 7 Normalized Stanton number $\mathrm{St}/\mathrm{St}_0$ for transpiration cooling in a laminar boundary layer on a flat plate as a function of the dimensionless mass transfer for foreign gas injection into an air boundary layer [5].