Heat Transfer 1986

Proceedings of
The Eighth International
Heat Transfer Conference

Volume 6

Heat Transfer 1986

Proceedings of
The Eighth International Heat Transfer Conference
San Francisco, California USA

Volume
6
General Papers

Edited by
C. L. Tien, V. P. Carey, and J. K. Ferrell

in cooperation with the members of the International Scientific Committee

M. Combarnous, M. Cumo, J. K. Ferrell, E. Hahne, G. Hetsroni, G. F. Hewitt, C. J Hoogendoorn, M. V. Krishnamurthy, M. Majcen, J. H. Masliyah, T. Mizushina, H. C. Simpson, M. A. Styrikovich, C. L. Tien

and members of the U.S. Scientific Committee

V. P. Carey, J. C. Chen, J. K. Ferrell, L. S. Fletcher, J. R. Howell, L. A. Kennedy, D. E. Metzger, R. K. Shah, K. H. Sun, C. L. Tien

The logo of these Proceedings is an interferogram of natural convection flow around two horizontal cylinders held one above the other. It was taken by R. B. Goldstein in the Heat Transfer Laboratory of the University of Minnesota.

The Eighth International Heat Transfer Conference was held in San Francisco, California USA, August 17–22, 1986. The conference was organized under the authority of the Assembly for International Heat Transfer Conferences, in cooperation with the International Scientific Committee, the U.S. Scientific Committee, The American Society of Mechanical Engineers, and The American Institute of Chemical Engineering.

In order to make these volumes available as economically and as rapidly as possible, the authors' typescripts have been reproduced in their original form.

HEAT TRANSFER 1986

1 2 3 4 5 6 7 8 9 0 BRBR 8 9 8 7 6

Library of Congress Cataloging in Publication Data

International Heat Transfer Conference (8th : 1986 : San Francisco, Calif.)
Heat transfer, 1986.

Bibliography: p.
Includes index.
Contents: v. 1. Plenary and keynote papers—v. 2–6. General papers.
1. Heat—Transmission—Congresses. I. Tien, Chang L. II. Carey, V. P. (Van P.) III. Ferrell, J. K. (James K.) IV. Title.
QC319.8.I57 1986 621.402'2 86-12043
ISBN 0-89116-559-2 (set) Hemisphere Publishing Corp.
ISBN 0-89116-594-0 (vol. 6) Hemisphere Publishing Corp.

DISTRIBUTION OUTSIDE NORTH AMERICA:
ISBN 3-540-16896-6 Springer-Verlag Berlin

Preface

These six volumes contain the invited and general papers presented at the Eighth International Heat Transfer Conference. The papers consist of 2 plenary lectures, 28 keynote lectures and 450 general presentations.

As indicated in the first plenary lecture by Dr. E. R. G. Eckert, the series of International Heat Transfer Conferences started in London (1951) as an International Discussion on Heat Transfer. The general conference format was established in the Second Conference in Boulder, Colorado (1961). The regular four-year cycle of the Conferences began at the Third Conference in Chicago (1966). The Conference immediately became the major event of the international heat transfer community, with ever increasing participation of heat transfer engineers and scholars from all over the world as manifested in the subsequent Conferences in Versailles (1970), Tokyo (1974), Toronto (1978), and Munich (1982).

The Eighth International Heat Transfer Conference has again received most enthusiastic responses from the international community, reflecting a continuing state of growth and vitality. In many countries, the number of good-quality papers offered for presentation far exceeded the allocation, thus making the selection a most difficult task. For this, we owe special thanks to the members of the International Scientific Committee and their national editors and reviewers. We are also grateful to the other members of the U.S. Scientific Committee who have labored long and hard on the Conference Scientific Program. The strong support of the Conference Executive Committee under Chairman R. J. Goldstein for the Scientific Program and its publication is essential and very much appreciated.

Chang-Lin Tien
Van P. Carey
James K. Ferrell

Nomenclature

Symbol	Quantity	SI Unit
A (or S)	area, cross section	m^2
a	thermal diffusivity	m^2/S
a_t	turbulent (eddy) thermal diffusivity	m^2/s
C	heat capacity	J/K
C_B	molecular concentration of component B	mol/m^3
C_D (or ζ)	drag coefficient	—
c	specific heat capacity	J/(K kg)
c_p	specific heat capacity at constant pressure	J/(K kg)
c_v	specific	
D	diffusion coefficient	m^2/s
d (or D)	diameter	m
d_e	equivalent (hydraulic) diameter	m
E	energy	J
E_e	irradiance	W/m^2
F	force	N
f	friction factor	—
G	weight	N
g	local gravitational acceleration, (standard acceleration, $g_n = 9.80665\ m/s^2$)	m/s^2
H (or I)	enthalpy	J
h (or i)	specific enthalpy	J/kg
h	height	m
h (or α)	heat transfer coefficient	$W/(m^2K)$
Δh_v	specific latent heat of vaporization	J/kg
Δh_s	specific latent heat of solidification	J/kg
K	equilibrium constant	—
k (or U)	overall heat transfer coefficient	$W/(K\ m^2)$

Symbol	Quantity	SI Unit
k (or λ)	thermal conductivity	W/(m K)
L	length	m
m	mass	kg
m	mass flow rate	kg/s
M	molar mass	kg/mol
n	amount of substance	mol
P	power	W
P	pressure	N/m^2
Q	quantity of heat	J
Q (or ϕ)	heat flow rate	W
q (or ϕ_h)	heat flux density	W/m^2
R	universal gas constant, R = 8.3144 J/(mol K)	J/(mol K)
R_i	individual (specific) gas constant	J/(kg K)
r	radius	m
S	entropy	J/K
S (or A)	cross section	m^2
s	specific entropy	J/(kg K)
T	thermodynamic temperature	K
t	time	s
U (or k)	overall heat transfer coefficient	W/m^2K
V	volume	m^3
V_m	molar volume	m^3/mol
v	specific volume	m^3/kg
W	work	J
x	quality	—
Greek Letters		
α (or h)	heat transfer coefficient	W/m^2K
α_r	absorptance for radiation	—
α,β,γ	plane angles	rad
β	mass transfer coefficient	m/s
γ (or β_T)	cubic (volumetric) expansion coefficient	K^{-1}
δ (or d)	thickness	m
ϵ	emissivity	—
ϵ (or ψ)	void fraction	—

Symbol	Quantity	SI Unit
Greek Letters (Continued)		
ζ (or C_D)	drag coefficient	—
η (or μ)	dynamic viscosity	kg/(sm)
v	Celsius temperature	°C
λ (or k)	thermal conductivity	W/(m K)
λ_t	turbulent thermal conductivity	W/(m K)
μ (or η)	dynamic viscosity	kg/(s m)
μ	chemical potential	J/kg
ν	kinematic viscosity	m^2/s
ν_t	turbulent kinetic viscosity (eddy diffusivity for momentum)	m^2/s
ρ	mass density	kg/m^3
ρ_r	reflectance	—
ρ_B	mass concentration of substance B	kg/m^3
ρ_l	density of liquid	kg/m^3
ρ_v	density of vapor	kg/m^3
σ	Stefan-Boltzmann constant	$W/(k^4\ m^2)$
σ	surface tension	W/m
τ_r	transmittance	—
τ_s	shear stress	N/m^2
ϕ (or $\dot{Q}$)	heat flow rate	W
ϕ_n (or q)	heat flux density	W/m^2
ϕ_m	mass flux density	$kg/(s\ m^2)$
ψ	relative humidity	—
ψ (or ϵ)	void fraction	—
Ω	solid angle	sr
Coordinates		
x,y,z	cartesian coordinates	
r,ϕ,z	cylindrical coordinates	
r,ϕ,ψ	spherical coordinates	

Symbol and Definition	Name
Dimensionless parameters	
$Ar = \frac{g_n L^3 \Delta\rho}{\nu^2 \rho}$	Archimedes number

Symbol and Definition	Name
Dimensionless parameters (Continued)	
$Bi = \frac{\alpha \cdot L}{\lambda\ solid}$	Biot number
$Fo = \frac{a \cdot L}{L^2}$	Fourier number
$Fr = \frac{u}{\sqrt{gl}}$	Froude number
$Gr = \frac{gL^3\gamma\ \Delta T}{\nu^2}$	Grashof number
$Ja = \frac{c_p\rho_l\ \Delta T}{\rho_l\ \Delta h_v}$	Jakob number
$Le = \frac{a}{D}$	Lewis number
$Nu = \frac{\alpha L}{\lambda}$	Nusselt number
$Pe = \frac{uL}{a} = Re \cdot Pr$	Peclet number
$Pe^* = \frac{uL}{D} = Re \cdot Sc$	Peclet number for mass transfer
$Pr = \frac{\nu}{a} = \frac{c_p\eta}{\lambda}$	Prandtl number
$Re = \frac{uL}{\nu}$	Reynolds number
$Sc = \frac{\nu}{D}$	Schmidt number
$Sh = \frac{\beta L}{D}$	Sherwood number
$St = \frac{\alpha}{\rho\ uc_p} = \frac{Nu}{Re\ Pr}$	Stanton number
$St^* = \frac{\beta}{u} = \frac{Sh}{Re\ Sc}$	Stanton number for mass transfer
$We = \frac{u^2\ \rho L}{\sigma_s}$	Weber number

Conference Officers

Assembly for International Heat Transfer Conferences

President—U. Grigull, F.R.G.
Vice President—R. J. Goldstein, U.S.A.
Secretary—T. W. Simon, U.S.A.

Conference General Chairman, R. J. Goldstein

Executive Committee

R. J. GOLDSTEIN, *Chairman*
T. W. SIMON, *Secretary*

Members
J. K. FERRELL
S. J. GREEN
C. L. TIEN

Organizing Committee

S. J. GREEN, *Chairman*
G. J. BENKLY
R. J. MOFFAT
D. R. MULLEN
V. E. SCHROCK
E. R. MILLER
J. R. ZIOLKO

Exhibits Subcommittee

R. K. SHAH
K. J. BELL

Short Course Subcommittee

A. D. KRAUS
A. E. BERGLES

Delegates

M. Combarnous, France
M. Cumo, Italy
J. K. Ferrell, U.S.A.
R. J. Goldstein, U.S.A.
J. Gosse, France
U. Grigull, F.R.G.
E. Hahne, F.R.G.
G. F. Hewitt, U.K.
C. J. Hoogendoorn, The Netherlands
Y. Katto, Japan
S. S. Kutateladze, U.S.S.R.
M. Majcen, Yugoslavia
J. H. Masliyah, Canada
T. Mizushina, Japan
D. Moalem-Maron, Israel
D. Poljak, Yugoslavia
A. Ramachandran, India
S. Sideman, Israel
M. Silvestri, Italy
H. C. Simpson, U.K.
S. P. Sukhatme, India
D. A. de Vries, The Netherlands
M. Yovanovich, Canada
A. Zukauskas, U.S.S.R.

International Scientific Committee

A large number of national associate editors and reviewers, whose names are not listed here, have supported the members of the International Scientific Committee in the process of reviewing the papers. Their assistance was invaluable for ensuring the quality of the proceedings, and is hereby gratefully acknowledged.

U. S. Scientific Committee

Contents of Volumes 1–6

VOLUME 2

NUMERICAL TECHNIQUES AND MODELING

MEASUREMENT TECHNIQUES

RADIATION AND COMBUSTION

VOLUME 3

INTERNAL FORCED CONVECTION