

# Heat Transfer 1986

Proceedings of  
The Eighth International  
Heat Transfer Conference

Volume 6



# Heat Transfer 1986

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The Eighth International  
Heat Transfer Conference  
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Volume

6

General  
Papers

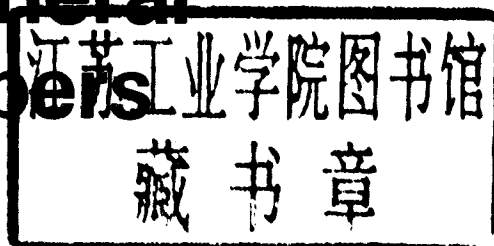
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C. L. Tien, V. P. Carey,  
and J. K. Ferrell

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V. P. Carey, J. C. Chen, J. K. Ferrell, L. S.  
Fletcher, J. R. Howell, L. A. Kennedy, D. E.  
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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.

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# 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 Con-

ference 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 <sup>2</sup>        |
| a                            | thermal diffusivity   | m <sup>2</sup> /s     |
| a <sub>t</sub>               | turbulent (eddy) thermal diffusivity  | m <sup>2</sup> /s     |
| C                            | heat capacity   | J/K                   |
| C <sub>B</sub>               | molecular concentration of component B  | mol/m <sup>3</sup>    |
| C <sub>D</sub> (or $\zeta$ ) | drag coefficient  | —                     |
| c                            | specific heat capacity  | J/(K kg)              |
| c <sub>p</sub>               | specific heat capacity at constant pressure   | J/(K kg)              |
| c <sub>v</sub>               | specific  |                       |
| D                            | diffusion coefficient   | m <sup>2</sup> /s     |
| d (or D)                     | diameter  | m                     |
| d <sub>e</sub>               | equivalent (hydraulic) diameter   | m                     |
| E                            | energy  | J                     |
| E <sub>e</sub>               | irradiance  | W/m <sup>2</sup>      |
| F                            | force   | N                     |
| f                            | friction factor   | —                     |
| G                            | weight  | N                     |
| g                            | local gravitational acceleration, (standard acceleration, g <sub>n</sub> = 9.80665 m/s <sup>2</sup> ) | m/s <sup>2</sup>      |
| H (or I)                     | enthalpy  | J                     |
| h (or i)                     | specific enthalpy   | J/kg                  |
| h                            | height  | m                     |
| h (or $\alpha$ )             | heat transfer coefficient   | W/(m <sup>2</sup> K)  |
| $\Delta h_v$                 | specific latent heat of vaporization  | J/kg                  |
| $\Delta h_s$                 | specific latent heat of solidification  | J/kg                  |
| K                            | equilibrium constant  | —                     |
| k (or U)                     | overall heat transfer coefficient   | W/(K m <sup>2</sup> ) |

| Symbol                   | Quantity   | SI Unit             |
|--------------------------|--|---------------------|
| $k$ (or $\lambda$ )      | thermal conductivity                                   | W/(m K)             |
| $L$                      | length   | m                   |
| $m$                      | mass   | kg                  |
| $\dot{m}$                | mass flow rate   | kg/s                |
| $M$                      | molar mass   | kg/mol              |
| $n$                      | amount of substance                                    | mol                 |
| $P$                      | power  | W                   |
| $P$                      | pressure   | N/m <sup>2</sup>    |
| $Q$                      | quantity of heat                                       | J                   |
| $\dot{Q}$ (or $\phi$ )   | heat flow rate   | W                   |
| $q$ (or $\phi_h$ )       | heat flux density                                      | W/m <sup>2</sup>    |
| $R$                      | universal gas constant, $R = 8.3144 \text{ J/(mol K)}$ | 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 <sup>2</sup>      |
| $s$                      | specific entropy                                       | J/(kg K)            |
| $T$                      | thermodynamic temperature                              | K                   |
| $t$                      | time   | s                   |
| $U$ (or $k$ )            | overall heat transfer coefficient                      | W/m <sup>2</sup> K  |
| $V$                      | volume   | m <sup>3</sup>      |
| $V_m$                    | molar volume   | m <sup>3</sup> /mol |
| $v$                      | specific volume  | m <sup>3</sup> /kg  |
| $W$                      | work   | J                   |
| $x$                      | quality  | —                   |
| <i>Greek Letters</i>     |  |                     |
| $\alpha$ (or $h$ )       | heat transfer coefficient                              | W/m <sup>2</sup> K  |
| $\alpha_r$               | absorptance for radiation                              | —                   |
| $\alpha, \beta, \gamma$  | plane angles   | rad                 |
| $\beta$                  | mass transfer coefficient                              | m/s                 |
| $\gamma$ (or $\beta_T$ ) | cubic (volumetric) expansion coefficient               | K <sup>-1</sup>     |
| $\delta$ (or $d$ )       | thickness  | m                   |
| $\epsilon$               | emissivity   | —                   |
| $\epsilon$ (or $\psi$ )  | void fraction  | —                   |

| Symbol                           | Quantity  | SI Unit                            |
|----------------------------------|---|------------------------------------|
| <i>Greek Letters (Continued)</i> |   |                                    |
| $\zeta$ (or $C_D$ )              | drag coefficient  | —                                  |
| $\eta$ (or $\mu$ )               | dynamic viscosity   | kg/(sm)                            |
| $v$                              | Celsius temperature   | °C                                 |
| $\lambda$ (or $k$ )              | thermal conductivity  | W/(m K)                            |
| $\lambda_t$                      | turbulent thermal conductivity                              | W/(m K)                            |
| $\mu$ (or $\eta$ )               | dynamic viscosity   | kg/(s m)                           |
| $\mu$                            | chemical potential  | J/kg                               |
| $\nu$                            | kinematic viscosity   | m <sup>2</sup> /s                  |
| $\nu_t$                          | turbulent kinetic viscosity (eddy diffusivity for momentum) | m <sup>2</sup> /s                  |
| $\rho$                           | mass density  | kg/m <sup>3</sup>                  |
| $\rho_r$                         | reflectance   | —                                  |
| $\rho_B$                         | mass concentration of substance B                           | kg/m <sup>3</sup>                  |
| $\rho_l$                         | density of liquid   | kg/m <sup>3</sup>                  |
| $\rho_v$                         | density of vapor  | kg/m <sup>3</sup>                  |
| $\sigma$                         | Stefan-Boltzmann constant                                   | W/(K <sup>4</sup> m <sup>2</sup> ) |
| $\sigma$                         | surface tension   | W/m                                |
| $\tau_t$                         | transmittance   | —                                  |
| $\tau_s$                         | shear stress  | N/m <sup>2</sup>                   |
| $\phi$ (or $Q$ )                 | heat flow rate  | W                                  |
| $\phi_n$ (or $q$ )               | heat flux density   | W/m <sup>2</sup>                   |
| $\phi_m$                         | mass flux density   | kg/(s m <sup>2</sup> )             |
| $\psi$                           | relative humidity   | —                                  |
| $\psi$ (or $\epsilon$ )          | void fraction   | —                                  |
| $\Omega$                         | solid angle   | sr                                 |
| <i>Coordinates</i>               |   |                                    |
| $x, y, z$                        | cartesian coordinates                                       |                                    |
| $r, \phi, z$                     | cylindrical coordinates                                     |                                    |
| $r, \phi, \psi$                  | spherical coordinates                                       |                                    |

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### Symbol and Definition

### Name

#### *Dimensionless parameters*

$$Ar = \frac{g_n L^3 \Delta \rho}{\nu^2 \rho}$$

Archimedes number

| Symbol and Definition                                | Name                             |
|--|----------------------------------|
| <i>Dimensionless parameters (Continued)</i>          |                                  |
| $Bi = \frac{\alpha \cdot L}{\lambda_{\text{solid}}}$ | 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                   |
| $Re'_\zeta = \frac{uL}{\nu}$                         | Reynolds number                  |
| $Sc = \frac{\nu}{D}$                                 | Schmidt number                   |
| $Sh = \frac{\beta L}{D}$                             | Sherwood number                  |
| $St = \frac{\alpha}{\rho u c_p} = \frac{Nu}{Re Pr}$  | 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                     |



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