## HEAT TRANSFER

The single objective of this book is to provide engineers with the capability, tools, and confidence to solve real-world heat transfer problems. The textbook includes many advanced topics, such as Bessel functions, Laplace transforms, separation of variables, Duhamel's theorem, and complex combination, as well as high-order explicit and implicit numerical integration algorithms. These analytical and numerical solution methods are applied to topics not considered in most textbooks. Examples are heat exchangers involving fluids with varying specific heats or phase changes, regenerators, semi-gray surface radiation exchange, and numerical solutions to internal flow problems. To improve readability, derivations of important results are presented completely, without skipping steps, which reduces student frustration and improves retention. The examples in the book are ubiquitous, not trivial "textbook" exercises. They are rather complex and timely real-world problems that are inherently interesting. This textbook integrates the computational software packages Maple, MATLAB, FEHT, and Engineering Equation Solver (EES) directly with the heat transfer material.

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# Heat Transfer

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*This book is dedicated to Stephen H. Nellis . . . thanks Dad.*

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# PREFACE

The single objective of this book is to provide engineers with the capability, tools, and confidence to solve real-world heat transfer problems. This objective has resulted in a textbook that differs from existing heat transfer textbooks in several ways. First, this textbook includes many topics that are typically not covered in undergraduate heat transfer textbooks. Examples are the detailed presentations of mathematical solution methods such as Bessel functions, Laplace transforms, separation of variables, Duhamel's theorem, and Monte Carlo methods as well as high order explicit and implicit numerical integration algorithms. These analytical and numerical solution methods are applied to advanced topics that are ordinarily not considered in a heat transfer textbook.

Judged by its content, this textbook should be considered as a graduate text. There is sufficient material for two-semester courses in heat transfer. However, the presentation does not presume previous knowledge or expertise. This book can be (and has been) successfully used in a single-semester undergraduate heat transfer course by appropriately selecting from the available topics. Our recommendations on what topics can be included in a first heat transfer course are provided in the suggested syllabus. The reason that this book can be used for a first course (despite its expanded content) and the reason it is also an effective graduate-level textbook is that all concepts and methods are presented in detail, starting at the beginning. The derivation of important results is presented completely, without skipping steps, in order to improve readability, reduce student frustration, and improve retention. You will not find many places in this textbook where it states that "it can be shown that . . . " The use of examples, solved and explained in detail, is ubiquitous in this textbook. The examples are not trivial, "textbook" exercises, but rather complex and timely real-world problems that are of interest by themselves. As with the presentation, the solutions to these examples are complete and do not skip steps.

Another significant difference between this textbook and most existing heat transfer textbooks is its integration of modern computational tools. The engineering student and practicing engineer of today is expected to be proficient with engineering computer tools. Engineering education must evolve accordingly. Most real engineering problems cannot be solved using a sequential set of calculations that can be accomplished with a pencil or hand calculator. Engineers must have the ability to quickly solve problems using the powerful computational tools that are available and essential for design, parametric study, and optimization of real-world systems. This book integrates the computational software packages Maple, MATLAB, FEHT, and Engineering Equation Solver (EES) directly with the heat transfer material. The specific commands and output associated with these software packages are presented as the theory is developed so that the integration is seamless rather than separated.

The computational software tools used in this book share some important characteristics. They are used in industry and have existed for more than a decade; therefore, while this software will certainly continue to evolve, it is not likely to disappear. Educational versions of these software packages are available, and therefore the use of these tools should not represent an economic hardship to any academic institution or student. Useful versions of EES and FEHT are provided on the website that accompanies this textbook (www.cambridge.org/nellisandklein). With the help provided in the book, these tools are easy to learn and use. Students can become proficient with all of them in a reasonable amount of time. Learning the computer tools will not detract significantly from material coverage. To facilitate this learning process, tutorials for each of the software packages are provided on the companion website. The book itself is structured so that more advanced features of the software are introduced progressively, allowing students to become increasingly proficient using these tools as they progress through the text.

Most (if not all) of the tables and charts that have traditionally been required to solve heat transfer problems (for example, to determine properties, view factors, shape factors, convection relations, etc.) have been made available as functions and procedures in the EES software so that they can be easily accessed and used to solve problems. Indeed, the library of heat transfer functions that has been developed and integrated with EES as part of the preparation of this textbook enables a profound shift in the focus of the educational process. It is trivial to obtain, for example, a shape factor, a view factor, or a convection heat transfer coefficient using the heat transfer library. Therefore, it is possible to assign problems involving design and optimization studies that would be computationally impossible without the computer tools.

Integrating the study of heat transfer with computer tools does not diminish the depth of understanding of the underlying physics. Conversely, our experience indicates that the innate understanding of the subject matter is enhanced by appropriate use of these tools for several reasons. First, the software allows the student to tackle practical and relevant problems as opposed to the comparatively simple problems that must otherwise be assigned. Real-world engineering problems are more satisfying to the student. Therefore, the marriage of computer tools with theory motivates students to understand the governing physics as well as learn how to apply the computer tools. The use of these tools allows for coverage of more advanced material and more interesting and relevant problems. When a solution is obtained, students can carry out a more extensive investigation of its behavior and therefore obtain a more intuitive and complete understanding of the subject of heat transfer.

This book is unusual in its linking of classical theory and modern computing tools. It fills an obvious void that we have encountered in teaching both undergraduate and graduate heat transfer courses. The text was developed over many years from our experiences teaching Introduction to Heat Transfer (an undergraduate course) and Heat Transfer (a first-year graduate course) at the University of Wisconsin. It is our hope that this text will not only be useful during the heat transfer course, but also provide a life-long resource for practicing engineers.

G. F. Nellis
S. A. Klein
May, 2008

## Acknowledgments

The development of this book has taken several years and a substantial effort. This has only been possible due to the collegial and supportive atmosphere that makes the Mechanical Engineering Department at the University of Wisconsin such a unique and impressive place. In particular, we would like to acknowledge Tim Shedd, Bill Beckman, Doug Reindl, John Pfotenhauer, Roxann Engelstad, and Glen Myers for their encouragement throughout the process.

Several years of undergraduate and graduate students have used our initial drafts of this manuscript. They have had to endure carrying two heavy volumes of poorly bound paper with no index and many typographical errors. Their feedback has been invaluable to the development of this book.

We have had the extreme good fortune to have had dedicated and insightful teachers. These include Glen Myers, John Mitchell, Bill Beckman, Joseph Smith Jr., John Brisson, Borivoje Mikic, and John Lienhard V. These individuals, among others, have provided us with an indication of the importance of teaching and provided an inspiration to us for writing this book.

Preparing this book has necessarily reduced the "quality time" available to spend with our families. We are most grateful to them for this indulgence. In particular, we wish to thank Jill, Jacob, and Spencer and Sharon Nellis and Jan Klein. We could have not completed this book without their continuous support.

Finally, we are indebted to Cambridge University Press and in particular Peter Gordon for giving us this opportunity and for helping us with the endless details needed to bring our original idea to this final state.

# STUDY GUIDE

This book has been developed for use in either a graduate or undergraduate level course in heat transfer. A sample program of study is laid out below for a one-semester graduate course (consisting of 45 class sessions).

**Graduate heat transfer class**

| *Day* | *Sections in Book* | *Topic* |
|---|---|---|
| 1 | 1.1 | Conduction heat transfer |
| 2 | 1.2 | 1-D steady conduction and resistance concepts |
| 3 | 2.8 | Resistance approximations |
| 4 | 1.3 | 1-D steady conduction with generation |
| 5 | 1.4, 1.5 | Numerical solutions with EES and MATLAB |
| 6 | 1.6 | Fin solution, fin efficiency, and finned surfaces |
| 7 | 1.7 | Other constant cross-section extended surface problems |
| 8 | 1.8 | Bessel function solutions |
| 9 | 2.2 | 2-D conduction, separation of variables |
| 10 | 2.2 | 2-D conduction, separation of variables |
| 11 | 2.4 | Superposition |
| 12 | 3.1 | Transient, lumped capacitance problems – analytical solutions |
| 13 | 3.2 | Transient, lumped capacitance problems – numerical solutions |
| 14 | 3.3 | Semi-infinite bodies, diffusive time constant |
| 15 | 3.3 | Semi-infinite bodies, self-similar solution |
| 16 | 3.4 | Laplace transform solutions to lumped capacitance problems |
| 17 | 3.4 | Laplace transform solutions to 1-D transient problems |
| 18 | 3.5 | Separation of variables for 1-D transient problems |
| 19 | 3.8 | Numerical solutions to 1-D transient problems |
| 20 | 4.1 | Laminar boundary layer concepts |
| 21 | 4.2, 4.3 | The boundary layer equations & dimensionless parameters |
| 22 | 4.4 | Blasius solution for flow over a flat plate |
| 23 | 4.5, 4.6 | Turbulent boundary layer concepts, Reynolds averaged equations |
| 24 | 4.7 | Mixing length models and the laws of the wall |
| 25 | 4.8 | Integral solutions |
| 26 | 4.8, 4.9 | Integral solutions, external flow correlations |
| 27 | 5.1, 5.2 | Internal flow concepts and correlations |
| 28 | 5.3 | The energy balance |
| 29 | 5.4 | Analytical solutions to internal flow problems |
| 30 | 5.5 | Numerical solutions to internal flow problems |
| 31 | 6.1, 6.2 | Natural convection concepts and correlations |

| | | |
|---|---|---|
| 32 | 8.1 | Introduction to heat exchangers |
| 33 | 8.2, 8.3 | The LMTD and $\varepsilon$-NTU forms of the solutions |
| 34 | 8.5 | Heat exchangers with phase change |
| 35 | 8.7 | Axial conduction in heat exchangers |
| 36 | 8.8, 8.10 | Perforated plate heat exchangers and regenerators |
| 37 | 10.1, 10.2 | Introduction to radiation, Blackbody emissive power |
| 38 | 10.3 | View factors and the space resistance |
| 39 | 10.3 | Blackbody radiation exchange |
| 40 | 10.4 | Real surfaces, Kirchoff's law |
| 41 | 10.5 | Gray surface radiation exchange |
| 42 | 10.5 | Gray surface radiation exchange |
| 43 | 10.5 | Semi-gray surface radiation exchange |
| 44 | 10.7 | Introduction to Monte Carlo techniques |
| 45 | 10.7 | Introduction to Monte Carlo techniques |

A sample program of study is laid out below for a one-semester undergraduate course (consisting of 45 class sessions).

**Undergraduate heat transfer class**

| *Day* | *Sections in Book* | *Topic* |
|---|---|---|
| 1 | A.1 | Review of thermodynamics, Using EES |
| 2 | 1.2.2-1.2.3 | 1-D steady conduction, resistance concepts and circuits |
| 3 | 1.2.4-1.2.6 | 1-D steady conduction in radial systems, other thermal resistance |
| 4 | | More thermal resistance problems |
| 5 | 1.3.1-1.3.3 | 1-D steady conduction with generation |
| 6 | 1.4 | Numerical solutions with EES |
| 7 | 1.6.1-1.6.3 | The extended surface approximation and the fin solution |
| 8 | 1.6.4-1.6.6 | Fin behavior, fin efficiency, and finned surfaces |
| 9 | 1.9.1 | Numerical solutions to extended surface problems |
| 10 | 2.1 | 2-D steady-state conduction, shape factors |
| 11 | 2.8.1-2.8.2 | Resistance approximations |
| 12 | 2.9 | Conduction through composite materials |
| 13 | 2.5 | Numerical solution to 2-D steady-state problems with EES |
| 14 | 3.1 | Lumped capacitance assumption, the lumped time constant |
| 15 | 3.2.1, 3.2.2 | Numerical solution to lumped problems (Euler's, Heun's, Crank-Nicolson) |
| 16 | 3.3.1-3.3.2 | Semi-infinite body, the diffusive time constant |
| 17 | 3.3.2, 3.3.4 | Approximate models of diffusion, other semi-infinite solutions |
| 18 | 3.5.1-3.5.2 | Solutions to 1-D transient conduction in a bounded geometry |
| 19 | 3.8.1-3.8.2 | Numerical solution to 1-D transient conduction using EES |
| 20 | 4.1 | Introduction to laminar boundary layer concepts |
| 21 | 4.2, 4.3 | Dimensionless numbers |
| 22 | 4.5 | Introduction to turbulent boundary layer concepts |
| 23 | 4.9.1-4.9.2 | Correlations for external flow over a plate |
| 24 | 4.9.3-4.9.4 | Correlations for external flow over spheres and cylinders |
| 25 | 5.1 | Internal flow concepts |

| | | |
|---|---|---|
| 26 | 5.2 | Internal flow correlations |
| 27 | 5.3 | Energy balance for internal flows |
| 28 | | Internal flow problems |
| 29 | 6.1 | Introduction to natural convection |
| 30 | 6.2.1-6.2.3 | Natural convection correlations |
| 31 | 6.2.4-6.2.7 | Natural convection correlations and combined forced/free convection |
| 32 | 7.1, 7.2 | Pool boiling |
| 33 | 7.3, 7.4.3, 7.5 | Correlations for flow boiling, flow condensation, and film condensation |
| 34 | 8.1 | Introduction to heat exchangers, compact heat exchanger correlations |
| 35 | 8.2 | The LMTD Method |
| 36 | 8.3.1-8.3.3 | The $\varepsilon$-$NTU$ Method |
| 37 | 8.3.4 | Limiting behaviors of the $\varepsilon$-$NTU$ Method |
| 38 | 8.10.1, 8.10.3-4 | Regenerators, solution for balanced & symmetric regenerator, packings |
| 39 | 10.1, 10.2 | Introduction to radiation, blackbody emission |
| 40 | 10.3.1-10.3.2 | View factors |
| 41 | 10.3.3 | Blackbody radiation exchange |
| 42 | 10.4 | Real surfaces and Kirchoff's law |
| 43 | 10.5.1-10.5.3 | Gray surface radiation exchange |
| 44 | | Gray surface radiation exchange |
| 45 | 10.6 | Radiation with other heat transfer mechanisms |

# NOMENCLATURE

| | |
|---|---|
| $a_i$ | $i^{th}$ coefficient of a series solution |
| $A_c$ | cross-sectional area ($m^2$) |
| $A_{min}$ | minimum flow area ($m^2$) |
| $A_p$ | projected area ($m^2$) |
| $A_s$ | surface area ($m^2$) |
| $A_{s,fin}$ | surface area of a fin ($m^2$) |
| $A_{tot}$ | prime (total) surface area of a finned surface ($m^2$) |
| $AR$ | aspect ratio of a rectangular duct |
| $AR_{tip}$ | area ratio of fin tip to fin surface area |
| $Att$ | attenuation (-) |
| $B$ | parameter in the blowing factor (-) |
| $BF$ | blowing factor (-) |
| $Bi$ | Biot number (-) |
| $Bo$ | boiling number (-) |
| $Br$ | Brinkman number |
| $c$ | specific heat capacity (J/kg-K) |
| | concentration (-) |
| | speed of light (m/s) |
| $c''_a$ | specific heat capacity of an air-water mixture on a unit mass of air basis (J/$kg_a$-K) |
| $c''_{a,sat}$ | specific heat capacity of an air-water mixture along the saturation line on a unit mass of air basis (J/$kg_a$-K) |
| $c_{eff}$ | effective specific heat capacity of a composite (J/kg-K) |
| $c_{ms}$ | ratio of the energy carried by a micro-scale energy carrier to its temperature (J/K) |
| $c_v$ | specific heat capacity at constant volume (J/kg-K) |
| $C$ | total heat capacity (J/K) |
| $\dot{C}$ | capacitance rate of a flow (W/K) |
| $C_1, C_2, \ldots$ | undetermined constants |
| $C_{crit}$ | dimensionless coefficient for critical heat flux correlation (-) |
| $C_D$ | drag coefficient (-) |
| $C_f$ | friction coefficient (-) |
| $\overline{C_f}$ | average friction coefficient (-) |
| $C_{lam}$ | coefficient for laminar plate natural convection correlation (-) |
| $C_{nb}$ | dimensionless coefficient for nucleate boiling correlation (-) |
| $C_R$ | capacity ratio (-) |
| $C_{turb,U}$ | coefficient for turbulent, horizontal upward plate natural conv. correlation (-) |
| $C_{turb,V}$ | coefficient for turbulent, vertical plate natural convection correlation (-) |

| | |
|---|---|
| $Co$ | convection number (-) |
| $CTE$ | coefficient of thermal expansion (1/K) |
| $D$ | diameter (m) |
| | diffusion coefficient ($m^2$/s) |
| $D_h$ | hydraulic diameter (m) |
| $dx$ | differential in the $x$-direction (m) |
| $dy$ | differential in the $y$-direction (m) |
| $e$ | size of surface roughness (m) |
| $err$ | convergence or numerical error |
| $\dot{E}$ | rate of thermal energy carried by a mass flow (W) |
| $E$ | total emissive power (W/$m^2$) |
| $E_b$ | total blackbody emissive power (W/$m^2$) |
| $E_\lambda$ | spectral emissive power (W/$m^2$-μm) |
| $E_{b,\lambda}$ | blackbody spectral emissive power (W/$m^2$-μm) |
| $Ec$ | Eckert number (-) |
| $f$ | frequency (Hz) |
| | dimensionless stream function, for Blasius solution (-) |
| | friction factor (-) |
| $\overline{f}$ | average friction factor (-) |
| $f_l$ | friction factor for liquid-only flow in flow boiling (-) |
| $F$ | force (N) |
| | correction-factor for log-mean temperature difference (-) |
| $F_{0-\lambda_1}$ | external fractional function (-) |
| $F_{i,j}$ | view factor from surface $i$ to surface $j$ (-) |
| $\hat{F}_{i,j}$ | the “F-hat” parameter characterizing radiation from surface $i$ to surface $j$ (-) |
| $fd$ | fractional duty for a pinch-point analysis (-) |
| $Fo$ | Fourier number (-) |
| $Fr$ | Froude number (-) |
| $Fr_{mod}$ | modified Froude number (-) |
| $g$ | acceleration of gravity (m/$s^2$) |
| $\dot{g}$ | rate of thermal energy generation (W) |
| $\dot{g}'''$ | rate of thermal energy generation per unit volume (W/$m^3$) |
| $\dot{g}'''_{eff}$ | effective rate of generation per unit volume of a composite (W/$m^3$) |
| $\dot{g}'''_v$ | rate of thermal energy generation per unit volume due to viscous dissipation (W/$m^3$) |
| $G$ | mass flux or mass velocity (kg/$m^2$-s) |
| | total irradiation (W/$m^2$) |
| $G_\lambda$ | spectral irradiation (W/$m^2$-μm) |
| $Ga$ | Galileo number (-) |
| $Gr$ | Grashof number (-) |
| $Gz$ | Graetz number (-) |
| $h$ | local heat transfer coefficient (W/$m^2$-K) |
| $\overline{h}$ | average heat transfer coefficient (W/$m^2$-K) |
| $\tilde{h}$ | dimensionless heat transfer coefficient for flow boiling correlation (-) |
| $h_D$ | mass transfer coefficient (m/s) |
| $\overline{h}_D$ | average mass transfer coefficient (m/s) |
| $h_l$ | superficial heat transfer coefficient for the liquid phase (W/$m^2$-K) |

| | |
|---|---|
| $\bar{h}_{rad}$ | the equivalent heat transfer coefficient associated with radiation (W/m$^2$-K) |
| $i$ | index of node (-) |
| | index of eigenvalue (-) |
| | index of term in a series solution (-) |
| | specific enthalpy (J/kg-K) |
| | square root of negative one, $\sqrt{-1}$ |
| $i''_a$ | specific enthalpy of an air-water mixture on a per unit mass of air basis (J/kg$_a$) |
| $I$ | current (ampere) |
| $Ie$ | intensity of emitted radiation (W/m$^2$-μm-steradian) |
| $Ii$ | intensity of incident radiation (W/m$^2$-μm-steradian) |
| $j$ | index of node (-) |
| | index of eigenvalue (-) |
| $J$ | radiosity (W/m$^2$) |
| $j_H$ | Colburn $j_H$ factor (-) |
| $k$ | thermal conductivity (W/m-K) |
| $k_B$ | Bolzmann's constant (J/K) |
| $k_c$ | contraction loss coefficient (-) |
| $k_e$ | expansion loss coefficient (-) |
| $k_{eff}$ | effective thermal conductivity of a composite (W/m-K) |
| $Kn$ | Knudsen number (-) |
| $l_1$ | Lennard-Jones 12-6 potential characteristic length for species 1 (m) |
| $l_{1,2}$ | characteristic length of a mixture of species 1 and species 2 (m) |
| $L$ | length (m) |
| $L^+$ | dimensionless length for a hydrodynamically developing internal flow (-) |
| $L^*$ | dimensionless length for a thermally developing internal flow (-) |
| $L_{char}$ | characteristic length of the problem (m) |
| $L_{char,vs}$ | the characteristic size of the viscous sublayer (m) |
| $L_{cond}$ | length for conduction (m) |
| $L_{flow}$ | length in the flow direction (m) |
| $L_{ml}$ | mixing length (m) |
| $L_{ms}$ | distance between interactions of micro-scale energy or momentum carriers (m) |
| $Le$ | Lewis number (-) |
| $M$ | number of nodes (-) |
| | mass (kg) |
| $m$ | fin parameter (1/m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $\dot{m}''$ | mass flow rate per unit area (kg/m$^2$-s) |
| $m_{ms}$ | mass of microscale momentum carrier (kg/carrier) |
| $mf$ | mass fraction (-) |
| $MW$ | molar mass (kg/kgmol) |
| $n$ | number density (#/m$^3$) |
| $n_{ms}$ | number density of the micro-scale energy carriers (#/m$^3$) |
| $\dot{n}''$ | molar transfer rate per unit area (kgmol/m$^2$-s) |
| $N$ | number of nodes (-) |
| | number of moles (kgmol) |
| $N_s$ | number of species in a mixture (-) |
| $Nu$ | Nusselt number (-) |

 

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| | |
|---|---|
| $\overline{Nu}$ | average Nusselt number (-) |
| $NTU$ | number of transfer units (-) |
| $p$ | pressure (Pa) |
| | pitch (m) |
| $P$ | *LMTD* effectiveness (-) |
| | probability distribution (-) |
| $p_\infty$ | free-stream pressure (Pa) |
| $\tilde{p}$ | dimensionless pressure (-) |
| $Pe$ | Peclet number (-) |
| $per$ | perimeter (m) |
| $Pr$ | Prandtl number (-) |
| $Pr_{turb}$ | turbulent Prandtl number (-) |
| $\dot{q}$ | rate of heat transfer (W) |
| $\dot{q}_{i\text{ to }j}$ | rate of radiation heat transfer from surface *i* to surface *j* (W) |
| $\dot{q}_{max}$ | maximum possible rate of heat transfer, for an effectiveness solution (W) |
| $\dot{q}''$ | heat flux, rate of heat transfer per unit area (W/m$^2$) |
| $\dot{q}''_s$ | surface heat flux (W/m$^2$) |
| $\dot{q}''_{s,crit}$ | critical heat flux for boiling (W/m$^2$) |
| $Q$ | total energy transfer by heat (J) |
| $\tilde{Q}$ | dimensionless total energy transfer by heat (-) |
| $r$ | radial coordinate (m) |
| | radius (m) |
| $\tilde{r}$ | dimensionless radial coordinate (-) |
| $R$ | thermal resistance (K/W) |
| | ideal gas constant (J/kg-K) |
| | *LMTD* capacitance ratio (-) |
| $R_{\overline{A}}$ | thermal resistance approximation based on average area limit (K/W) |
| $R_{ac}$ | thermal resistance to axial conduction in a heat exchanger (K/W) |
| $R_{ad}$ | thermal resistance approximation based on adiabatic limit (K/W) |
| $R_{bl}$ | thermal resistance of the boundary layer (K/W) |
| $R_c$ | thermal resistance due to solid-to-solid contact (K/W) |
| $R_{conv}$ | thermal resistance to convection from a surface (K/W) |
| $R_{cyl}$ | thermal resistance to radial conduction through a cylindrical shell (K/W) |
| $R_e$ | electrical resistance (ohm) |
| $R_f$ | thermal resistance due to fouling (K/W) |
| $R_{fin}$ | thermal resistance of a fin (K/W) |
| $R_{i,j}$ | the radiation space resistance between surfaces *i* and *j* (1/m$^2$) |
| $R_{iso}$ | thermal resistance approximation based on isothermal limit (K/W) |
| $R_{\overline{L}}$ | thermal resistance approximation based on average length limit (K/W) |
| $R_{pw}$ | thermal resistance to radial conduction through a plane wall (K/W) |
| $R_{rad}$ | thermal resistance to radiation (K/W) |
| $R_{s,i}$ | the radiation surface resistance for surface *i* (1/m$^2$) |
| $R_{semi\text{-}\infty}$ | thermal resistance approximation for a semi-infinite body (K/W) |
| $R_{sph}$ | thermal resistance to radial conduction through a spherical shell (K/W) |
| $R_{tot}$ | thermal resistance of a finned surface (K/W) |
| $R_{univ}$ | universal gas constant (8314 J/kgmol-K) |
| $R''_c$ | area-specific contact resistance (K-m$^2$/W) |
| $R''_f$ | area-specific fouling resistance (K-m$^2$/W) |
| $Ra$ | Rayleigh number (-) |

 

| | |
|---|---|
| $Re$ | Reynolds number (-) |
| $Re_{crit}$ | critical Reynold number for transition to turbulence (-) |
| $RH$ | relative humidity (-) |
| $RR$ | radius ratio of an annular duct (-) |
| $s$ | Laplace transformation variable (1/s) |
| | generic coordinate (m) |
| $S$ | shape factor (m) |
| | channel spacing (m) |
| $Sc$ | Schmidt number (-) |
| $Sh$ | Sherwood number (-) |
| $\overline{Sh}$ | average Sherwood number (-) |
| $St$ | Stanton number (-) |
| $t$ | time (s) |
| $t_{sim}$ | simulated time (s) |
| $th$ | thickness (m) |
| $tol$ | convergence tolerance |
| $T$ | temperature (K) |
| $T_b$ | base temperature of fin (K) |
| $T_{film}$ | film temperature (K) |
| $T_m$ | mean or bulk temperature (K) |
| $T_s$ | surface temperature (K) |
| $T_{sat}$ | saturation temperature (K) |
| $T_\infty$ | free-stream or fluid temperature (K) |
| $T^*$ | eddy temperature fluctuation (K) |
| $T'$ | fluctuating component of temperature (K) |
| $\overline{T}$ | average temperature (K) |
| $TR$ | temperature solution that is a function of $r$, for separation of variables |
| $Tt$ | temperature solution that is a function of $t$, for separation of variables |
| $TX$ | temperature solution that is a function of $x$, for separation of variables |
| $TY$ | temperature solution that is a function of $y$, for separation of variables |
| $th$ | thickness (m) |
| $U$ | internal energy (J) |
| | utilization (-) |
| $u$ | specific internal energy (J/kg) |
| | velocity in the $x$-direction (m/s) |
| $u_{char}$ | characteristic velocity (m/s) |
| $u_f$ | frontal or upstream velocity (m/s) |
| $u_m$ | mean or bulk velocity (m/s) |
| $u_\infty$ | free-stream velocity (m/s) |
| $u^*$ | eddy velocity (m/s) |
| $u^+$ | inner velocity (-) |
| $\tilde{u}$ | dimensionless $x$-velocity (-) |
| $u'$ | fluctuating component of $x$-velocity (m/s) |
| $\overline{u}$ | average $x$-velocity (m/s) |
| $UA$ | conductance (W/K) |
| $v$ | velocity in the $y$- or $r$-directions (m/s) |
| $v_\delta$ | $y$-velocity at the outer edge of the boundary layer, approximate scale of $y$-velocity in a boundary layer (m/s) |
| $v_{ms}$ | mean velocity of micro-scale energy or momentum carriers (m/s) |

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| | |
|---|---|
| $\tilde{v}$ | dimensionless $y$-velocity (-) |
| $v'$ | fluctuating component of $y$-velocity (m/s) |
| $\overline{v}$ | average $y$-velocity (m/s) |
| $V$ | volume ($m^3$) |
| | voltage (V) |
| $\dot{V}$ | volume flow rate ($m^3/s$) |
| $vf$ | void fraction (-) |
| $w$ | velocity in the $z$-direction (m/s) |
| $\dot{w}$ | rate of work transfer (W) |
| $W$ | width (m) |
| | total amount of work transferred (J) |
| $x$ | $x$-coordinate (m) |
| | quality (-) |
| $\tilde{x}$ | dimensionless $x$-coordinate (-) |
| $X$ | particular solution that is only a function of $x$ |
| $x_{fd,h}$ | hydrodynamic entry length (m) |
| $x_{fd,t}$ | thermal entry length (m) |
| $X_{tt}$ | Lockhart Martinelli parameter (-) |
| $y$ | $y$-coordinate (m) |
| | mole fraction (-) |
| $y^+$ | inner position (-) |
| $\tilde{y}$ | dimensionless $y$-coordinate (-) |
| $Y$ | particular solution that is only a function of $y$ |
| $z$ | $z$-coordinate (m) |

## Greek Symbols

| | |
|---|---|
| $\alpha$ | thermal diffusivity ($m^2/s$) |
| | absorption coefficient (1/m) |
| | absorptivity or absorptance (-), total hemispherical absorptivity (-) |
| | surface area per unit volume (1/m) |
| $\alpha_{eff}$ | effective thermal diffusivity of a composite ($m^2/s$) |
| $\alpha_\lambda$ | hemispherical absorptivity (-) |
| $\alpha_{\lambda,\theta,\phi}$ | spectral directional absorptivity (-) |
| $\beta$ | volumetric thermal expansion coefficient (1/K) |
| $\delta$ | film thickness for condensation (m) |
| | boundary layer thickness (m) |
| $\delta_d$ | mass transfer diffusion penetration depth (m) |
| | concentration boundary layer thickness (m) |
| $\delta_m$ | momentum diffusion penetration depth (m) |
| | momentum boundary layer thickness (m) |
| $\delta_{vs}$ | viscous sublayer thickness (m) |
| $\delta_t$ | energy diffusion penetration depth (m) |
| | thermal boundary layer thickness (m) |
| $\Delta i_{fus}$ | latent heat of fusion (J/kg) |
| $\Delta i_{vap}$ | latent heat of vaporization (J/kg) |
| $\Delta p$ | pressure drop ($N/m^2$) |
| $\Delta r$ | distance in $r$-direction between adjacent nodes (m) |

| | |
|---|---|
| $\Delta T$ | temperature difference (K) |
| $\Delta T_e$ | excess temperature (K) |
| $\Delta T_{lm}$ | log-mean temperature difference (K) |
| $\Delta t$ | time step (s) |
| | time period (s) |
| $\Delta t_{crit}$ | critical time step (s) |
| $\Delta x$ | distance in $x$-direction between adjacent nodes (m) |
| $\Delta y$ | distance in $y$-direction between adjacent nodes (m) |
| $\varepsilon$ | heat exchanger effectiveness (-) |
| | emissivity or emittance (-), total hemispherical emissivity (-) |
| $\varepsilon_{fin}$ | fin effectiveness (-) |
| $\varepsilon_H$ | eddy diffusivity for heat transfer ($m^2$/s) |
| $\varepsilon_\lambda$ | hemispherical emissivity (-) |
| $\varepsilon_{\lambda,\theta,\phi}$ | spectral, directional emissivity (-) |
| $\varepsilon_M$ | eddy diffusivity of momentum ($m^2$/s) |
| $\varepsilon_1$ | Lennard-Jones 12-6 potential characteristic energy for species 1 (J) |
| $\varepsilon_{1,2}$ | characteristic energy parameter for a mixture of species 1 and species 2 (J) |
| $\phi$ | porosity (-) |
| | phase angle (rad) |
| | spherical coordinate (rad) |
| $\eta$ | similarity parameter (-) |
| | efficiency (-) |
| $\eta_{fin}$ | fin efficiency (-) |
| $\eta_o$ | overall efficiency of a finned surface (-) |
| $\kappa$ | von Kármán constant |
| $\lambda$ | dimensionless axial conduction parameter (-) |
| | wavelength of radiation (μm) |
| $\lambda_i$ | $i^{th}$ eigenvalue of a solution (1/m) |
| $\mu$ | viscosity (N-s/$m^2$) |
| $v$ | frequency of radiation (1/s) |
| $\theta$ | temperature difference (K) |
| | angle (rad) |
| | spherical coordinate (rad) |
| $\tilde{\theta}$ | dimensionless temperature difference (-) |
| $\theta^+$ | inner temperature difference (-) |
| $\theta R$ | temperature difference solution that is only a function of $r$, for separation of variables |
| $\theta t$ | temperature difference solution that is only a function of $t$, for separation of variables |
| $\theta X$ | temperature difference solution that is only a function of $x$, for separation of variables |
| $\theta Xt$ | temperature difference solution that is only a function of $x$ and $t$, for reduction of multi-dimensional transient problems |
| $\theta Y$ | temperature difference solution that is only a function of $y$, for separation of variables |
| $\theta Yt$ | temperature difference solution that is only a function of $y$ and $t$, for reduction of multi-dimensional transient problems |
| $\theta Zt$ | temperature difference solution that is only a function of $z$ and $t$, for reduction of multi-dimensional transient problems |

| | |
|---|---|
| $\rho$ | density (kg/m$^3$) |
| | reflectivity or reflectance (-), total hemispherical reflectivity (-) |
| $\rho_e$ | electrical resistivity (ohm-m) |
| $\rho_{eff}$ | effective density of a composite (kg/m$^3$) |
| $\rho_\lambda$ | hemispherical reflectivity (-) |
| $\rho_{\lambda,\theta,\varphi}$ | spectral, directional reflectivity (-) |
| $\sigma$ | surface tension (N/m), |
| | molecular radius (m) |
| | ratio of free-flow to frontal area (-) |
| | Stefan-Boltzmann constant (5.67 $\times$ 10$^{-8}$ W/m$^2$-K$^4$) |
| $\tau$ | time constant (s) |
| | shear stress (Pa) |
| | transmittivity or transmittance (-), total hemispherical transmittivity (-) |
| $\tau_{diff}$ | diffusive time constant (s) |
| $\tau_{lumped}$ | lumped capacitance time constant (s) |
| $\tau_\lambda$ | hemispherical transmittivity (-) |
| $\tau_{\lambda,\theta,\varphi}$ | spectral, directional transmittivity (-) |
| $\tau_s$ | shear stress at surface (N/m$^2$) |
| $\upsilon$ | kinematic viscosity (m$^2$/s) |
| $\omega$ | angular velocity (rad/s) |
| | humidity ratio (kg$_v$/kg$_a$) |
| | solid angle (steradian) |
| $\Omega_D$ | dimensionless collision integral for diffusion (-) |
| $\Psi$ | stream function (m$^2$/s) |
| $\zeta$ | tilt angle (rad) |
| | curvature parameter for vertical cylinder, natural convection correlation (-) |
| $\zeta_i$ | the $i^{th}$ dimensionless eigenvalue (-) |

## Superscripts

| | |
|---|---|
| $o$ | at infinite dilution |

## Subscripts

| | |
|---|---|
| $a$ | air |
| $abs$ | absorbed |
| $ac$ | axial conduction (in heat exchangers) |
| $an$ | analytical |
| $app$ | apparent |
| | approximate |
| $b$ | blackbody |
| $bl$ | boundary layer |
| $bottom$ | bottom |
| $c$ | condensate film |
| | corrected |
| $C$ | cold |
| | cold-side of a heat exchanger |
| $cc$ | complex conjugate, for complex combination problems |
| $char$ | characteristic |
| $cf$ | counter-flow heat exchanger |

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| | |
|---|---|
| *cond* | conduction, conductive |
| *conv* | convection, convective |
| *crit* | critical |
| *CTHB* | cold-to-hot blow process |
| *dc* | dry coil |
| *df* | downward facing |
| *diff* | diffusive transfer |
| *eff* | effective |
| *emit* | emitted |
| *evap* | evaporative |
| *ext* | external |
| *f* | fluid |
| *fc* | forced convection |
| *fd,h* | hydrodynamically fully developed |
| *fd,t* | thermally fully developed |
| *fin* | fin, finned |
| *h* | homogeneous solution |
| *H* | hot |
| | hot-side of a heat exchanger |
| | constant heat flux boundary condition |
| *hs* | on a hemisphere |
| *HTCB* | hot-to-cold blow process |
| *i* | node *i* |
| | surface *i* |
| | species *i* |
| *in* | inner |
| | inlet |
| *ini* | initial |
| *int* | internal |
| | interface |
| | integration period |
| *j* | node *j* |
| | surface *j* |
| *l* | liquid |
| *lam* | laminar |
| *LHS* | left-hand side |
| *lumped* | lumped-capacitance |
| *m* | mean or bulk |
| | melting |
| *max* | maximum or maximum possible |
| *min* | minimum or minimum possible |
| *mod* | modified |
| *ms* | micro-scale carrier |
| *n* | normal |
| *nac* | without axial conduction (in heat exchangers) |
| *nb* | nucleate boiling |
| *nc* | natural convection |
| *no-fin* | without a fin |
| *out* | outer |
| | outlet |
| *p* | particular (or non-homogeneous) solution |

| | |
|---|---|
| *pf* | parallel-flow heat exchanger |
| *pp* | pinch-point |
| *r* | regenerator matrix |
| | at position $r$ |
| *rad* | radiation, radiative |
| *ref* | reference |
| *RHS* | right-hand side |
| *s* | at the surface |
| *sat* | saturated |
| | saturated section of a heat exchanger |
| *sat,l* | saturated liquid |
| *sat,v* | saturated vapor |
| *sc* | sub-cooled section of a heat exchanger |
| *semi-*$\infty$ | semi-infinite |
| *sh* | super-heated section of a heat exchanger |
| *sph* | sphere |
| *sur* | surroundings |
| *sus* | sustained solution |
| *T* | constant temperature boundary condition |
| | at temperature $T$ |
| *top* | top |
| *tot* | total |
| *turb* | turbulent |
| *uf* | upward-facing |
| *unfin* | not finned |
| *v* | vapor |
| | vertical |
| | viscous dissipation |
| *w* | water |
| *wb* | wet-bulb |
| *wc* | wet coil |
| *x* | at position $x$ |
| | in the $x$-direction |
| $x^-$ | in the negative $x$-direction |
| $x^+$ | in the positive $x$-direction |
| *y* | at position $y$ |
| | in the $y$-direction |
| $\infty$ | free-stream, fluid |
| 90° | solution that is 90° out of phase, for complex combination problems |

## Other notes

| | |
|---|---|
| $A$ | arbitrary variable |
| $A'$ | fluctuating component of variable $A$ |
| | value of variable $A$ on a unit length basis |
| $A''$ | value of variable $A$ on a unit area basis |
| $A'''$ | value of variable $A$ on a unit volume basis |
| $\tilde{A}$ | dimensionless form of variable $A$ |
| $\hat{A}$ | a guess value or approximate value for variable $A$ |
| $\frown{A}$ | Laplace transform of the function $A$ |

| | |
|---|---|
| $\overline{A}$ | average of variable A |
| $\underline{A}$ | denotes that variable A is a vector |
| $\underline{\underline{A}}$ | denotes that variable A is a matrix |
| $\bar{d}A$ | differential change in the variable $A$ |
| $\delta A$ | uncertainty in the variable $A$ |
| $\Delta A$ | finite change in the variable $A$ |
| $O(A)$ | order of magnitude of the variable $A$ |