# CONTENTS

Preface ........................................... xiii

Chapter I. Introduction ......................... 1

Chapter II. Differential Equations and Boundary Conditions .......... 5
   A. Velocity Problem .......................... 7
      1. Hydrodynamically Developed Flow .... 7
      2. Hydrodynamically Developing Flow .... 8
   B. Temperature Problem ...................... 10
      1. Conjugated Problem .................... 11
      2. Conventional Convection Problem .... 13
   C. Thermal Boundary Conditions .............. 16
      1. Thermal Boundary Conditions for Singly
         Connected Ducts ....................... 17
      2. Thermal Boundary Conditions for Doubly
         Connected Ducts ....................... 31
      3. Thermal Boundary Conditions for Multiply
         Connected Ducts ....................... 36

Chapter III. Dimensionless Groups and Generalized Solutions .......... 37
   A. Fluid Flow .................................. 37
      1. Physical Quantities .................... 38
      2. Dimensionless Groups .................. 39
      3. Solutions in Terms of General Functional
         Relationships ......................... 44
   B. Heat Transfer ............................. 44
      1. Physical Quantities .................... 45
      2. Dimensionless Groups .................. 46
      3. Solutions in Terms of General Functional
         Relationships ......................... 57

Chapter IV. General Methods for Solutions .......................... 61
   A. Fully Developed Flow ..................... 61
   B. Hydrodynamically Developing Flow ....... 68
CONTENTS

1. Methods Incorporating Boundary Layer Type Idealizations .......................... 68
C. Thermally Developing Flow .......................... 74
   1. Hydrodynamically Developed Flow .......................... 74
   2. Simultaneously Developing Flow .......................... 77

Chapter V. Circular Duct ........................................ 78
A. Fully Developed Flow ........................................ 78
B. Hydrodynamically Developing Flow ........................................ 85
C. Thermally Developing and Hydrodynamically Developed Flow .......................... 99
D. Simultaneously Developing Flow ........................................ 138

Chapter VI. Parallel Plates ........................................ 153
A. Fully Developed Flow ........................................ 153
B. Hydrodynamically Developing Flow ........................................ 160
C. Thermally Developing and Hydrodynamically Developed Flow .......................... 169
D. Simultaneously Developing Flow ........................................ 189

Chapter VII. Rectangular Ducts ........................................ 196
A. Fully Developed Flow ........................................ 196
B. Hydrodynamically Developing Flow ........................................ 209
C. Thermally Developing and Hydrodynamically Developed Flow .......................... 213
D. Simultaneously Developing Flow ........................................ 219

Chapter VIII. Triangular Ducts ........................................ 223
A. Fully Developed Flow ........................................ 223
   1. Equilateral Triangular Duct ........................................ 223
   2. Equilateral Triangular Ducts with Rounded Corners ........................................ 225
   3. Isosceles Triangular Ducts ........................................ 227
   4. Right Triangular Ducts ........................................ 233
   5. Arbitrary Triangular Ducts ........................................ 237
B. Hydrodynamically Developing Flow ........................................ 240
C. Thermally Developing Flow ........................................ 242
   1. Equilateral Triangular Duct ........................................ 242
   2. Right-Angled Isosceles Triangular Duct ........................................ 244
   3. Isosceles Triangular Ducts ........................................ 244
CONTENTS

Chapter IX. Elliptical Ducts ........................................ 247
  A. Fully Developed Flow ...................................... 247
  B. Thermally Developing Flow ............................... 251

Chapter X. Other Singly Connected Ducts .............................. 253
  A. Sine Ducts ................................................ 253
  B. Trapezoidal Ducts ........................................ 256
  C. Rhombic Ducts ........................................... 259
  D. Quadrilateral Ducts ...................................... 260
  E. Regular Polygonal Ducts .................................. 262
  F. Circular Sector Ducts ..................................... 264
  G. Circular Segment Ducts ................................... 267
  H. Annular Sector Ducts ..................................... 269
  I. Moon-Shaped Ducts ....................................... 272
  J. Circular Ducts with Diametrically Opposite Flat Sides ........................................... 273
  K. Rectangular Ducts with Semicircular Short Sides .... 273
  L. Corrugated Ducts ......................................... 275
  M. Cusped Ducts ............................................ 276
  N. Cardiod Ducts ............................................ 277
  O. Miscellaneous Singly Connected Ducts ................... 278

Chapter XI. Small Aspect Ratio Ducts ................................ 280

Chapter XII. Concentric Annular Ducts ................................. 284
  A. Fully Developed Flow ...................................... 284
  B. Hydrodynamically Developing Flow ...................... 297
  C. Thermally Developing and Hydrodynamically Developed Flow ........................................... 301
  D. Simultaneously Developing Flow ......................... 319

Chapter XIII. Eccentric Annular Ducts .................................. 322
  A. Fully Developed Flow ...................................... 322
  B. Hydrodynamically Developing Flow ...................... 333
  C. Thermally Developing and Hydrodynamically Developed Flow ........................................... 336
  D. Simultaneously Developing Flow ......................... 337

Chapter XIV. Other Doubly Connected Ducts .............................. 341
  A. Confocal Elliptical Ducts ................................ 341
  B. Regular Polygonal Ducts with Central Circular Cores ........................................... 346
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.</td>
<td>Isosceles Triangular Ducts with Inscribed Circular Cores</td>
<td>349</td>
</tr>
<tr>
<td>D.</td>
<td>Elliptical Ducts with Central Circular Cores</td>
<td>349</td>
</tr>
<tr>
<td>E.</td>
<td>Circular Ducts with Central Regular Polygonal Cores</td>
<td>350</td>
</tr>
<tr>
<td>F.</td>
<td>Miscellaneous Doubly Connected Ducts</td>
<td>352</td>
</tr>
</tbody>
</table>

### Chapter XV. Longitudinal Flow over Circular Cylinders
- A. Fully Developed Flow                                            | 355  |
- B. Thermally Developing and Hydrodynamically Developed Flow       | 365  |

### Chapter XVI. Longitudinal Fins and Twisted Tapes within Ducts
- A. Longitudinal Thin Fins within a Circular Duct                  | 367  |
- B. Longitudinal Thin Fins within Square and Hexagonal Ducts       | 370  |
- C. Longitudinal Thin Fins from Opposite Walls within Rectangular Ducts | 372  |
- D. Longitudinal Thin V-Shaped Fins within a Circular Duct         | 374  |
- E. Longitudinal Triangular Fins within a Circular Duct            | 375  |
- F. Circular Duct with a Twisted Tape                              | 379  |

### Chapter XVII. Discussion—An Overview for the Designer and the Applied Mathematician
- A. Comparisons of Solutions                                         | 385  |
- B. Heat Exchangers with Multi-Geometry Passages in Parallel        | 389  |
- C. Influence of Superimposed Free Convection                        | 405  |
- D. Influence of Temperature-Dependent Fluid Properties             | 410  |
- E. Comments on the Format of Published Papers                      | 414  |
- F. The Complete Solution                                            | 416  |
- G. Areas of Future Research                                         | 419  |

Nomenclature                                                          | 421  |

Appendix                                                              | 428  |
CONTENTS

References .............................................. 431
Author Index .......................................... 457
Subject Index .......................................... 468