Contents

Preface V

List of Symbols VII

1 Numerical Design of Thermal Systems 1
- 1.1 Introduction 1
- 1.2 General Description of the System 2
- 1.3 District Heating Network 5
- 1.4 Thermal Load 8
- 1.5 Heat Storage 11
- 1.6 Thermal Plant 13
- 1.7 References 15

2 Continuum Mechanics 17
- 2.1 Introduction 17
- 2.2 Continuum Hypothesis 18
- 2.3 Vectors and Tensors 19
- 2.4 Differential Operators 23
- 2.5 The Divergence Theorem 25
- 2.6 Conservation Laws 26
- 2.7 Conservation of Mass: the Continuity Equation 26
- 2.8 The Momentum Equation 29

2.8.1 The substantial derivative 35
2.8.2 Newtonian fluids....37
2.9 The Energy Equation 39
2.9.1 Mechanical energy equation 42
2.9.2 Internal energy and enthalpy equations....44
2.10 Boundary Conditions and Initial Conditions 47
2.11 Application of Continuum Mechanics to a Medium-Scale Energy Storage System 52
2.11.1 Mathematical Model....54
2.11.2 Boundary and initial conditions 57
2.11.3 Results 59
2.12 References....67

3 One-Dimensional Modeling of Fluid Networks 69
3.1 Introduction 69
3.2 One Dimensional Models....72
3.2.1 The fluid dynamic model 72
3.2.2 The thermal model 78
3.3 Topological Description of a Network 81
3.4 Steady-State Modeling of a Fluid Network 82
3.4.1 The fluid dynamic problem....82
3.4.2 The thermal problem....87
3.5 The SIMPLE Algorithm 89
3.5.1 Boundary conditions and under-relaxation 92
3.5.2 Numerical solution of the momentum equation 95
3.6 The Upwind Scheme....97
3.6.1 Assembling the stiffness matrix 98
3.6.2 Boundary conditions 100
3.7 Unsteady State Modeling of a Fluid Network 103
3.7.1 The fluid dynamic problem....104
3.7.2 The thermal problem....107

3.8 Design of a District Heating Network 108
3.8.1 Calculation of pipe diameters 111
3.8.2 Calculation of the mass flow rates and pressures 113
3.8.3 Calculation of the temperature at the nodes 116
3.9 References 118

4 Radiative Heat Transfer 121
4.1 Introduction 121
4.2 Thermal Radiation and Basic Definitions 123
4.2.1 Solid angles 125
4.2.2 Radiation intensity and emissive power 126
4.3 Blackbody Radiation 128
4.4 Introduction on Opaque Surfaces 130
4.4.1 Kirchhoff's law 133
4.5 Radiative Heat Transfer Between Black Surfaces 134
4.6 Radiative Heat Transfer Between Gray Diffuse Surfaces 138
4.6.1 Two-surface enclosure 140
4.7 The Zonal Method 142
4.7.1 Radiative exchange between two infinitely long cylinders 147
4.8 Energy Balance Equations for Surface Zones 149
4.9 Radiation Exchange with Participating Media 151
4.10 Radiative Heat Transfer Between Black Surfaces with Participating Media 153
4.10.1 Surface-to-surface exchange 154
4.10.2 Volume-to-surface exchange 155
4.10.3 Volume-to-volume exchange 157
4.11 The Zonal Method with Participating Media 158
4.12 Energy Balance Equations for Surface Zones and Gas Zones 166
4.13 Radiative Heat Transfer in the Furnace of a Waste-to-Energy Plant 169
4.14 Application of the Zonal Method to the Furnace 171
4.14.1 Characterization of the air and combustion gas 174

4.14.2 Numerical calculation of the direct interchange areas.....178
4.14.3 Numerical calculation of the total interchange areas.....185
4.14.4 Energy balance equations and temperature field.....187
4.15 Design of the Heat Recovery Steam Generator.....190
4.15.1 Evaporator design.....192
4.15.2 Superheater design.....198
4.16 References.....203
Annex A – Alternative methods for the analysis of networks.....205