

Contents

| | |
|--|----|
| 1. Introduction | 1 |
| 1.1. The Basic Task of Energy Storage | 1 |
| 1.2. The Economic Parameters of Energy Storage Plants | 2 |
| 1.3. Optimization | 5 |
| 1.3.1. Energy Supply Systems with One Energy Converter | 5 |
| 1.3.2. Multi-source Energy Supply Systems | 6 |
| 1.3.3. Optimum Portion of Base Load Plants | 13 |
| 1.4. The History of Thermal Energy Storage (TES) | 17 |
| | |
| 2. Basics | 23 |
| 2.1. Classifications | 23 |
| 2.2. Storage of Sensible Heat in Saturated Fluids | 26 |
| 2.2.1. Sliding-pressure Storage | 27 |
| 2.2.2. Steam Cushion Storage | 33 |
| 2.2.3. Expansion-type Storage | 33 |
| 2.2.4. Indirect Sliding-pressure Storage | 35 |
| 2.3. Storage of Sensible Heat in Pressurized (Subcooled) Liquids | 36 |
| 2.3.1. Storage Capacity | 37 |
| 2.3.2. Types | 38 |
| 2.3.3. Storage Media | 40 |
| 2.4. Sensible Heat Storage in Solids | 40 |
| 2.4.1. Types | 42 |
| 2.4.2. Solid Storage Media | 43 |
| 2.5. Latent Heat Storage | 44 |
| 2.5.1. Storage Capacity | 44 |
| 2.5.2. Storage Media | 45 |
| 2.5.3. Charge and Discharge Equipment | 48 |
| 2.6. Pressurized Gas Storage | 51 |
| 2.7. Other Thermal Storage Systems | 54 |
| 2.7.1. Sorption Heat Storage | 55 |
| 2.7.2. Thermochemical Storage | 58 |
| 2.8. Comparison of Storage Capacity | 59 |
| 2.8.1. Energy Density | 59 |
| 2.8.2. Exergy Density | 60 |

| | |
|---|-----|
| 2.9. Efficiency Factors of Heat Storage | 61 |
| 2.9.1. Stagnation Losses | 61 |
| 2.9.2. Charge and Discharge Losses | 63 |
| 2.9.3. Overall Storage Losses | 66 |
| | |
| 3. Storage Systems | 67 |
| 3.1. Power Plant Storage Systems | 67 |
| 3.1.1. Basic Principles | 67 |
| 3.1.2. Flow Storage Systems in Steam Power Plants | 69 |
| 3.1.3. Flow Storage Systems in Gas Turbine Power Plants | 70 |
| 3.1.4. Gas Turbine Pumped Storage Plants (Compressed Air Energy Storage, CAES) | 71 |
| 3.1.5. Pneumatic Pumped Storage | 72 |
| 3.1.6. Heat Pump Storage Systems | 73 |
| 3.1.7. Integrated Pumped Storage Systems | 74 |
| 3.2. Storage Efficiency | 74 |
| 3.2.1. Definition | 75 |
| 3.2.2. Pumped Storage Systems | 76 |
| 3.2.3. Flow Storage Systems | 77 |
| 3.2.4. Feed Water Storage | 79 |
| 3.2.5. Losses in Storage Power Plants | 81 |
| 3.3. Limitations of Charge and Discharge Power | 84 |
| 3.3.1. Limitations by Plant Layout | 84 |
| 3.3.2. Limits of Components | 84 |
| 3.3.3. Thermodynamic Limitations | 84 |
| 3.4. Control and Load Distribution in Storage Power Plants | 87 |
| 3.4.1. Non-integrated Storage Plants | 87 |
| 3.4.2. Integrated Storage Plants | 88 |
| 3.4.3. Steam Power Plant with Buffer Storage | 91 |
| | |
| 4. Storage Vessels | 93 |
| 4.1. Vessel Shape | 94 |
| 4.1.1. Optimum Material Utilization | 94 |
| 4.1.2. Optimum Surface Area | 96 |
| 4.1.3. Limitations | 97 |
| 4.1.4. General Optimization | 97 |
| 4.2. Internals | 99 |
| 4.2.1. Internals for Sliding-pressure Storage Vessels | 99 |
| 4.2.2. Internals for Displacement Storage Vessels | 101 |
| 4.3. Welded Pressure Vessels | 104 |
| 4.4. Underground Pressure Vessels | 105 |
| 4.4.1. Pressurized Air Storage in Salt Domes | 106 |
| 4.4.2. Hot Water Displacement Storage in Rock Caverns | 107 |
| 4.4.3. Hot Water Sliding-pressure Storage in Rock Caverns | 109 |
| 4.4.4. Flexible Containers | 112 |

| | |
|--|------------|
| 4.5. Prestressed Pressure Vessels | 112 |
| 4.5.1. General | 112 |
| 4.5.2. Prestressed Concrete Pressure Vessel (PCPV) | 113 |
| 4.5.3. Prestressed Cast Iron Vessel (PCIV) | 116 |
| 4.6. Unpressurized Vessels | 120 |
| 4.6.1. Unpressurized High-temperature Vessels | 120 |
| 4.6.2. Unpressurized Low-temperature Vessels | 121 |
| 5. Thermal Energy Storage in Industry | 125 |
| 5.1. General | 125 |
| 5.2. Solid Storage | 127 |
| 5.2.1. Regenerators | 127 |
| 5.2.2. Heat Recovery from Hot Waste Gas | 129 |
| 5.2.3. Heat Recovery from Hot Solid Products | 132 |
| 5.3. Hot Water Storage | 135 |
| 5.3.1. Jet Pumps | 135 |
| 5.3.2. Storage Integrated with a Waste Heat Boiler | 136 |
| 5.3.3. Storage in Industrial Steam and Hot Water Grids | 138 |
| 5.4. Conclusions | 141 |
| 6. Thermal Energy Storage for Space Heating and Cooling | 142 |
| 6.1. General | 142 |
| 6.2. Heating Boilers | 143 |
| 6.3. Electric Heating | 145 |
| 6.4. Solar Heat | 146 |
| 6.4.1. General | 146 |
| 6.4.2. Sensible Heat Storage | 146 |
| 6.4.3. The Solar Pond | 147 |
| 6.4.4. Latent Heat Storage | 148 |
| 6.4.5. Passive Systems | 150 |
| 6.5. Heat Pumps | 150 |
| 6.5.1. General | 150 |
| 6.5.2. Buffer Storage | 151 |
| 6.5.3. Low-temperature Heat Storage | 152 |
| 6.5.4. Low-temperature Subsoil Storage | 153 |
| 6.5.5. Concentration Difference Energy Storage | 153 |
| 6.6. District Heating | 155 |
| 6.6.1. General | 155 |
| 6.6.2. Types and Operation of Heating Plant and Heat Store | 157 |
| 6.6.3. Hot Water Storage in a Waste Heat Incineration Plant | 160 |
| 6.6.4. Hot Water Storage in Gas Turbine CHP Plants | 160 |
| 6.6.5. Hot Water Storage in Steam CHP Topping Plants | 162 |
| 6.6.6. Hot Water Storage in Bleeding Steam CHP Plants | 163 |
| 6.6.7. Hot Water Storage in Combined Gas Turbine and Steam CHP Plants | 164 |
| 6.6.8. Combined District Heating and Feed Water Storage | 164 |

| | |
|---|------------|
| 6.7. Large-scale Seasonal Thermal Storage | 165 |
| 6.8. Conclusions | 167 |
| | |
| 7. Power Plants with Thermal Energy Storage | 168 |
| 7.1. General | 168 |
| 7.2. Steam Pumped Storage | 168 |
| 7.3. Storage in Gas Turbine Power Plants | 170 |
| 7.3.1. Pneumatic Pumped Storage | 170 |
| 7.3.2. Compressed Air Energy Storage (CAES) | 171 |
| 7.3.3. Air Storage for Open-cycle Gas Turbine Quick Start-up ... | 176 |
| 7.4. Thermal Storage in Coal-fired Power Plants | 178 |
| 7.4.1. Built Peak and Instantaneous Reserve Plants | 179 |
| 7.4.2. New Proposals for TES in Coal-fired Power Plants | 184 |
| 7.5. Thermal Storage in Nuclear Power Plants | 188 |
| 7.5.1. Feed Water Storage | 190 |
| 7.5.2. Indirect Feed Water Storage | 190 |
| 7.5.3. Steam Storage Systems | 190 |
| 7.5.4. Overloadable Turbine versus Separate Peaking Turbine ... | 190 |
| 7.5.5. Combined Feed Water and Steam Storage (Cascading) ... | 191 |
| 7.5.6. Integrated Steam Pumped Storage | 193 |
| 7.6. Thermal Energy Storage in Solar Power Plants | 193 |
| 7.6.1. General | 193 |
| 7.6.2. Single-cycle Solar Steam Plants with Direct Thermal Storage | 195 |
| 7.6.3. Single-cycle Solar Steam Plants with Indirect Thermal Storage | 200 |
| 7.6.4. Double-cycle Solar Steam Plants | 200 |
| 7.6.5. Solar Open-cycle Gas Turbine | 202 |
| 7.6.6. Solar Closed-cycle Gas Turbine | 203 |
| 7.7. Conclusions | 204 |
| | |
| 8. Thermal Energy Storage in Vehicles | 205 |
| 8.1. General | 205 |
| 8.2. Air and Sea Vehicles | 206 |
| 8.2.1. Hot Water Rockets | 206 |
| 8.2.2. Steam Catapults | 207 |
| 8.2.3. Torpedoes | 207 |
| 8.3. Rail Vehicles | 207 |
| 8.3.1. Pressurized Air Locomotive | 208 |
| 8.3.2. Thermochemical Storage Locomotive | 209 |
| 8.3.3. Steam Storage Locomotive | 210 |
| 8.4. Road Vehicles | 213 |
| 8.4.1. Road Vehicles with Pressurized Air Storage | 213 |

| | |
|---|------------|
| 8.4.2. Road Vehicles with Thermochemical Storage | 214 |
| 8.4.3. Road Vehicles with Storage of Latent and Sensible Heat . . | 214 |
| 8.5. Conclusions | 216 |
| References | 217 |
| Subject Index | 226 |