

Contents

1	Introduction	1
1.1	Thermal energy storage systems	2
1.1.1	Current trends in CSP plants	4
1.1.2	New generation challenges	5
1.2	Scope of the thesis	6
1.2.1	General objective	6
1.2.2	Specific objectives	6
1.3	Outline of the thesis	7
2	Review on modeling approaches for packed-bed thermal storage systems	8
2.1	Introduction	8
2.2	Operation and key variables	11
2.2.1	Charging and discharging processes	12
2.2.2	Storage structure	13
2.2.3	Materials and thermophysical properties	13
2.3	Empirical heat transfer coefficients	17
2.3.1	Conduction	17
2.3.2	Convection: Volumetric heat transfer coefficient	18
2.3.3	Fluid/wall heat transfer coefficient	22
2.3.4	Pressure drop	24

2.4	Numerical modeling	25
2.4.1	Single-phase models	25
2.4.2	Two-phase models	27
2.4.3	Three phases models	28
2.5	Experimental studies	33
2.6	Radiation exchange	37
2.6.1	View factors	38
2.6.2	Relevance of radiation heat transfer on packed-bed modeling	39
2.7	Conclusions	46
3	Assessing the use of copper slags as thermal energy storage material for packed-bed systems	48
3.1	Introduction	48
3.1.1	Packed-bed thermal storage	49
3.1.2	Packed-bed systems using waste materials	52
3.2	Thermal characterization of copper slags	53
3.2.1	Thermophysical properties	54
3.2.2	Thermogravimetric Analysis (TGA)	54
3.2.3	Differential Scanning Calorimetry (DSC)	55
3.2.4	Thermal conductivity and density	56
3.3	1-D Modeling of a copper slag packed-bed storage	58
3.3.1	Heat transfer model	58
3.3.2	Model validation	61
3.4	Parametric analysis	63
3.4.1	System description	63
3.4.2	Performance indicators	64
3.5	Results and Analysis	67

3.5.1	Temperature profiles	68
3.5.2	Round-trip efficiency	69
3.5.3	Exergy efficiency and energy density	71
3.6	Conclusions	73
4	Comparative and parametric study on packed-bed flow topologies for high-temperature thermal energy storage	75
4.1	Introduction	75
4.1.1	Packed-bed TES systems	76
4.1.2	Analysis of packed-bed storage topologies	77
4.2	Mathematical model	79
4.2.1	Heat transfer modeling	81
4.2.2	First-law analysis	85
4.2.3	Second-law analysis	86
4.2.4	Pressure drop	86
4.3	Results and Discussion	87
4.3.1	Cyclic operation of packed-bed TES	87
4.3.2	Parametric analysis	92
4.4	Conclusions	97
5	General conclusions and future work	99
Bibliography		100
Appendices		121
A Experimental facilities		121
A.1	Description of storage tanks and test facilities	121
A.1.1	Medium-temperature storage	122

A.1.2	High-temperature storage	124
A.2	Equipment available	126
A.2.1	Heat sources	126
A.2.2	Measuring instruments	128
A.3	Experimental methods	130
A.3.1	Rocks selection for tests	130
A.3.2	Tests proposals	131
A.3.3	Safety considerations	134