MODELLING AND APPLICATION OF ADVANCED THERMAL STORAGE MATERIALS

A Thesis Presented

by

Anthony Joseph Rawson

BEng (Mechanical) (Honours 1) BSci (Physics) (Distinction) (*Newcastle)*

to

The Graduate Office of the University of Newcastle

In Partial Fulfilment of the Requirements

for the Degree of Doctor of Philosophy

Specialising in Mechanical Engineering

Submitted January, 2016

Supervisors – Prof. Erich Kisi and Dr Heber Sugo

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ABSTRACT

Instantaneous availability of power is taken for granted in much of the developed world. Provided a fuel source is unlimited and readily available, the expectation of instant power is readily fulfilled with available technology. However, it is now accepted that human kind's most utilised fuels (coal, oil and natural gas) are in fact diminishing and their availability cannot be guaranteed as demand outstrips supply. Not only supply limitations exist, the burning of these fuels contributes heavily to dangerous climate change. Thus technology needs to be developed to efficiently utilise fuels intermittently or take advantage of other energy sources which may also be intermittent.

Thermal energy storage devices store heat energy through sensible heating, a phase change or a combination of the two. A device can be coupled to a power cycle to provide thermal inertia to the system. Power cycles that generate electricity from an intermittent heat source are an obvious application. Applications also exist in industrial processes requiring continuous heat for drying or a chemical reaction and control of air temperature in sensitive environments.

Many thermal energy storage devices exist, tailored to particular temperature ranges and storage capacities. This thesis introduces the Miscibility Gap Alloy as a potential thermal storage technology. Miscibility Gap Alloys overcome a number of the shortcomings of molten salt, paraffin and sensible storage media but their properties are not yet well communicated.

Material properties, lifetime estimates, economic characteristics and implementations of Miscibility Gap Alloys are discussed in this dissertation. Through

analysis of these aspects a number of novel methodologies, theories and devices were developed.

The Lattice Monte Carlo method was successfully employed to model effective conductivity of binary composites. The results of these analyses and existing homogenisation models were generalised for volume fraction and constituent conductivity ratio through a novel concept titled ‘microstructural efficiency’. This work enabled the effective thermal conductivity (and indeed any 2^{nd} rank tensor property obeying Fick’s Law) to be estimated with great accuracy for a number of idealised and common morphologies with generality in volume fraction and conductivity ratio of constituents.

Best practice manufacturing methods for different Miscibility Gap Alloys were identified through experiment and presented. This led to knowledge of the morphology of the materials (including potential porosity). From this, good estimates were made of all material properties relevant to the alloys use as thermal storage. The hypothesised material property advantages of Miscibility Gap Alloys are thus confirmed and compared with the existing state of the art.

A discussion of the long term behaviour of Miscibility Gap Alloys follows. Consideration is given to diffusion as well as mechanical and chemical dominated aging mechanisms. It was found that diffusion dominated aging is most likely for systems with non-negligible solubility of the components and where discrete large powders undergo large temperature changes through cycling. Mechanical effects should not contribute beyond the first few cycles as the matrix deforms to accommodate any mismatch in thermal expansion. Chemical aging is likely for systems exposed to air or water but may be mitigated through isolation of the material.

Establishment of material and long term properties of the alloys enables a discussion of the comparative economics of using Miscibility Gap Alloys as thermal storage. The alloys are shown to be extremely competitive compared to existing thermal energy storage solutions. They have a higher capital cost generally, due to the high cost of metals. However, the infrastructure and maintenance costs required are a fraction of that for most other thermal storage media.

Finally a number of potential implementations are introduced ranging from thermal inertia for power production to heating for the drying of foods. Detailed calculations and engineering drawings are provided for an air heater device intended for room heating. Specific methods of storage for concentrated solar thermal plants are described before more exotic implementations are presented.

The thesis concludes with a summary of work and a critical evaluation of the potential of Miscibility Gap Alloys as thermal storage media. Potential work for future research is provided with guidance as to how it might be initiated.

CITATIONS

Material from this thesis has been published in the following form:

A.J. Rawson, H. Sugo, E. Kisi, T. Fiedler, Effective Conductivity of Cu-Fe and Sn-Al Miscibility Gap Alloys, International Journal of Heat and Mass Transfer, 77 (2014) 395-405.

A.J. Rawson, H. Sugo, E. Kisi, Characterising Thermal Properties of Miscibility Gap Alloys for Thermal Storage Applications, in: Solar2014: The 52nd Annual Conference of the Australian Solar Council, Melbourne, Australia, 2014.

A.J. Rawson, E. Kisi, C. Wensrich, Microstructural Efficiency: Structured Morphologies, International Journal of Heat and Mass Transfer, 81 (2014) 820-828.

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ACKNOWLEDGEMENTS

The author of this dissertation would like to acknowledge the following professional organisations:

The University of Newcastle, for supervision use of facilities and general support through the duration of the candidates PhD.

The Australian Renewable Energy Agency (ARENA), formerly the Australian Solar Institute (ASI), for a motivating scholarship.

The author would like to specially acknowledge the hard work and direction provided from his supervisors:

Professor Erich Kisi

Dr. Heber Sugo

The author of this dissertation would like to acknowledge the following friends, colleagues and family:

Dr. Thomas Feidler

Dr. Chris Wensrich

Professor Graeme Murch

Professor Irina Belova

Professor Chris Howard

Professor Michael Carpenter

Jemima Emily Jackson

Lynette and Alan Rawson

Shaun Joseph Carter

The Condors:

~~David~~ Bradney

Mohammed ‘Moei’ Hasan

Samuel ‘Swann’ Evans

Syed Imran ‘Dhost’ Shafiq

Dylan ‘Dyran’ Cuskelly

Joss ‘Special K’ Kesby

Alex ‘Postie’ Post

Hoda

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NOMENCLATURE

Latin alphabet

Symbol		As a super/subscript
A	Area	
C	Heat Capacity, Stiffness	
D	Diffusivity	
E	Young's Modulus	
F	Helmholtz Free Energy	
G	Gibb's Free Energy	
H	Enthalpy	
L	Length	Liquid
N	Number, Number of atoms	
Q	Heat Transfer	
R	Universal Gas Constant	
S	Entropy, Compliance	
T	Temperature	
U	Internal Energy	
V	Volume	
c	Mass Specific Heat Capacity, Cost, Concentration	
d	Dimensionality	
e	Thermal Effusivity	Per Unit Energy
h	Mass Specific Enthalpy	
i		Index

Symbol		As a super/subscript
k	Thermal Conductivity	
m	Mass	
n	Number of moles	Index
p	Pressure	Constant Pressure (Isobaric)
q	Heat Flux	
r	Radius, Rate	
t	Time	Total
u	Mass Specific Internal Energy, Load factor	
v	Mass Specific Volume, Velocity	
Constant Volume (Isochoric)		
x	Cartesian coordinate, Molar Composition	

Greek Alphabet

Symbol		As a super/subscript
Δ	Increment of …	
∇	Grad of …	
α	Thermal Diffusivity	A-rich alpha phase (matrix)
β		B-rich beta phase (distributed)
γ	Surface Energy	
ε	Strain, Linear Thermal Expansion Coefficient	
η	Efficiency, Equilibrium Approach	
κ	Phase Gradient Energy	
λ	Latent Heat of Transition	
μ	Chemical Potential, Dynamic Viscosity	Microstructural
ν	Poisson's Ratio	
ρ	Density	
φ	Volume Fraction	
ϕ		Phase
ψ	Mass Fraction	

Abbreviations

Symbol		As a super/subscript
Nu	Nusselt Number	
Pr	Prandtl Number	
Re	Reynolds Number	
atm		Atmospheric
bcc	Body Centred Cubic Crystal Structure	
bct	Body Centred Tetragonal Crystal Structure	
fcc	Face Centred Cubic Crystal Structure	

Other Notations Let a be arbitrary

$\vec{a}$	Vector
$\underline{a}$	Tensor
$\dot{a}$	Temporal Rate of Change