EFFECT OF COMPOSITION AND SINTERING TEMPERATURE ON SILICA-NICKEL OXIDE FOAMS BY SLURRY METHOD

SYAZWANI BINTI BAHAROM

A thesis submitted in partial fulfilment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

JULY 2017

"Special dedicated with much love and affection to my beloved father Baharom bin Mohammed, my beloved mother Rokiah binti Baharom, all my brothers, my supervisor Prof Madya Dr Sufizar binti Ahmad, my co-supervisor Prof Madya Dr Hariati binti Taib and also to all my fellow friends who always helped me and gave me an encouragement to complete my study in Degree Master of Mechanical Engineering."

ACKNOWLEDGEMENT

In the name of Allah, Most Gracious, Most Merciful

Alhamdulillah, all the praise for Allah S.W.T. the most graceful and merciful; who give me the courage and faith for me along the period to complete this project. Praise be to Allah for, without His will, I would have not able to complete this project. Firstly, I would like to express my deepest gratitude to both my supervisor and co-supervisor; Prof Madya Dr Sufizar binti Ahmad and Prof Madya Dr. Hariati binti Taib for their endless support, guidance, supervision, advices, patience, ideas and unlimited encouragement through my research.

Besides that, millions of thank to my beloved parents for keep supporting me physically and mentally. I am also want to praise all my friends for their kind support, encouragement and understanding during completion this research. I would like to extend my appreciation to those who indirectly helped me; lecturers, laboratory technical assistants; Encik Abu Bakar, En Fazlannudin, En Tarmizi and En Anuar and all the staff in Faculty of Mechanical and Manufacturing Engineering (FKMP), Universiti Tun Hussein Onn Malaysia. This accomplishment would not have been possible without them. With that, thank you very much. May Allah S.W.T. bless all of you. Ameen.

ABSTRACT

It has been a long-standing effort to create materials with low density but high strength. Foam materials are very light, but compared with bulk materials, their strength is quite low because of their random structures. Natural lightweight materials such as bone, is a cellular solid with optimized structure. The aim of this study is to fabricate silica-nickel oxide (SiO_2-NiO) foams with 20 µm to 800 µm open pore size, 50% to 80% of porosity, good physical and mechanical properties. In this research, silica (SiO_2) powder and nickel oxide (NiO) powder with different compositions of 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.% and 10 wt.% were mixed together with binders which were polyethylene glycol (PEG) and carboxymethyl cellulose (CMC) to prepare slurry solution for impregnation of polyurethane (PU) sponge as the template. Silica-Nickel Oxide foams were fabricated by slurry method and sintered at 1000ºC, 1100ºC, 1200ºC and 1300ºC. Characterisation of SiO_2-NiO foams included morphological analysis, porosity and density test, and compression test were done to determine the foam microstructure, apparent porosity, bulk density and compressive strength. The morphology of SiO_2-NiO foam showed open pore with size ranging from 20 µm to 739 µm, interconnected cells by strut and close pore. The result of apparent porosity and bulk density of SiO_2-NiO foams calculated according to Archimedes' principle. The lowest result for apparent porosity obtained was 53.03% and the highest was 66.21%, while the lowest and highest value for bulk density were 0.89 g/cm^3 and 1.22 g/cm^3, respectively. The result for compressive strength of SiO_2-NiO foam was within the range of 0.21 MPa to 1.86 MPa. The foam with good physical and mechanical properties obtained by 6 wt.% of SiO_2-NiO foams sintered at 1300°C and will be used for further research in steam methane reforming application.

ABSTRAK

Pelbagai usaha telah dilakukan untuk menghasilkan bahan yang mempunyai ketumpatan yang rendah dengan kekuatan yang tinggi. Bahan berbusa merupakan bahan yang sangat ringan, tetapi jika dibandingkan dengan bahan pukal, kekuatan bahan berbusa agak rendah kerana struktur rawaknya. Bahan semulajadi seperti tulang merupakan pepejal selular dengan struktur yang dioptimumkan. Tujuan penyelidikan ini adalah untuk menghasilkan silika-nikel oksida (SiO_2-NiO) berbusa dengan liang bersaiz 20 µm hingga 800 µm, 50% hingga 80% jumlah keliangan, dengan sifat-sifat fizikal dan mekanikal yang baik. Dalam penyelidikan ini, silika (SiO_2) dan nikel oksida (NiO) dengan komposisi berbeza yang terdiri daripada 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.% dan 10 wt.% dicampurkan dengan pengikat iaitu politena glikol (PEG) dan karbosimetil selulosa (CMC) untuk menyediakan buburan bagi proses perendaman span poliuretena (PU) yang bertindak sebagai pemegang aram. Silika-Nikel Oksida berbusa dihasilkan melalui kaedah buburan dan disinter pada suhu 1000ºC, 1100ºC dan 1300ºC 1200ºC. Pencirian SiO_2-NiO berbusa termasuk analisis morfologi, ujian keliangan dan ketumpatan, dan ujian mampatan telah dilakukan untuk mengetahui mikrostruktur, keliangan terbuka, ketumpatan pukal dan kekuatan mampatan. Morfologi SiO_2-NiO berbusa menunjukkan liang terbuka dengan saiz dalam lingkungan 20 µm hingga 739 µm, saling dihubung oleh sangga dan liang tertutup. Hasil keliangan terbuka dan ketumpatan menyeluruh untuk SiO_2-NiO berbusa telah dikira berdasarkan prinsip Archimedes'. Jumlah keliangan terbuka paling rendah ialah 53.03% dan paling tinggi ialah 66.21%, manakala nilai paling rendah bagi ketumpatan pukal ialah 0.89 g/cm^3 dan paling tinggi ialah 1.22 g/cm^3. Hasil kekuatan mampatan untuk SiO_2-NiO berbusa ialah dalam lingkungan 0.21 MPa hingga 1.86 MPa. Ciri-ciri fizikal dan mekanikal berbusa yang paling baik diperolehi oleh 6 wt.% SiO_2-NiO berbusa yang telah dibakar pada suhu 1300°C dan akan digunakan dalam kajian perubahan gas metana menggunakan wap.

TABLE OF CONTENTS

TITLE **i**
DECLARATION **ii**
DEDICATION **iii**
ACKNOWLEDGEMENT **iv**
ABSTRACT **v**
ABSTRAK **vi**
TABLE OF CONTENT **vii**
LIST OF TABLES **xi**
LIST OF FIGURES **xiii**
LIST OF ABBREVIATIONS **xviii**
LIST OF APPENDICES **xx**

CHAPTER 1 INTRODUCTION

1.1 Background of Study 1
1.2 Problem Statements 3
1.3 Research Objectives 5
1.4 Scopes of Study 5

CHAPTER 2 LITERATURE REVIEW

2.1 Cellular Structure 7
2.2 Type of Cellular Ceramic 8
  2.2.1 Open Cell Structure 9
  2.2.2 Closed Cell Structure 11
  2.2.3 Honeycomb 12
2.3 Various Method in Foam Fabrication 13
  2.3.1 Replication Method 14
  2.3.2 Compaction Method 17

2.3.3 Direct Foaming 18
2.4 Types of Foam and Applications 19
2.4.1 Silica Foam 20
2.4.2 Alumina Foam 21
2.5 Nickel Oxide Supported on Silica Foam 22
2.5.1 Properties of Nickel Oxide Supported on Silica Foam 23
2.5.2 Application of Nickel Oxide Supported on Silica Foam 24
2.6 Raw Materials Selection and Properties 26
2.6.1 Properties of Silica 27
2.6.2 Properties of Nickel Oxide Powder 32
2.6.3 Polymeric Foam as Template 35
2.6.4 Types of Binder used in Foam Fabrication 36
2.6.4.1 Carboxymethyl Cellulose 36
2.6.4.2 Polyethylene Glycol 37
2.7 Factors Influencing in Foam Fabrication 38
2.7.1 Material Composition 39
2.7.2 Temperature of Processing 41
2.7.2.1 Sintering Process 42
2.8 Chapter Summary 46

CHAPTER 3 METHODOLOGY

3.1 Introduction 47
3.2 Specification of Raw Material for Silica and Silica-Nickel Oxide Foam Fabrication 50
3.2.1 Silica Powder 50
3.2.2 Nickel Oxide Powder 51
3.2.3 Polyurethane Sponge as Template 51
3.2.4 Binder used in Slurry Preparation 52
3.3 Foam Fabrication Method 53
3.3.1 Sample Preparation 53
3.3.2 Powder Mixing Process 57

3.3.3 Impregnation of Polyurethane Sponge 58
3.3.4 Foam Drying Process 60
3.3.5 Sintering Process 61
3.4 Techniques for Sample Characterisation 62
3.4.1 Surface Morphology Studies 63
3.4.2 Material Phase Identification 64
3.4.3 Thermal Degradation Behaviour 65
3.4.4 Porosity and Density Test 66
3.4.5 Mechanical Test 67
3.5 Chapter Summary 69

CHAPTER 4 RESULT AND DISCUSSION

4.1 Introduction 70
4.2 Analysis of Silica Powder 71
4.2.1 Morphology of Silica Powder 71
4.2.2 Chemical Composition of Silica Powder 72
4.2.3 Phase Identification of Silica Powder 72
4.2.4 Mass Degradation of Silica Powder 73
4.3 Fabricated Silica Foams and Its Properties 74
4.3.1 Structure of Different Composition of Silica Foams after Sintering 75
4.3.2 Morphological Studies of Silica Foams 77
4.3.3 Apparent Porosity Analysis of Silica Foams 82
4.3.4 Bulk Density Analysis of Silica Foams 83
4.3.5 Summary for Silica Foams Fabrication 85
4.4 Silica-Nickel Oxide Foam Analysis 86
4.4.1 Brittle Structure of Silica-Nickel Oxide Foams after Sintering 88
4.4.2 Morphological Studies of Silica-Nickel Oxide Foams 91
4.4.3 Particle Distribution Studies on Foam Microstructure 96

4.4.4 Phase Identification of Silica-Nickel Oxide Foams at Various Sintering Temperature 100
4.4.5 Apparent Porosity Analysis of Silica-Nickel Oxide Foams 102
4.4.6 Bulk Density Analysis of Silica-Nickel Oxide Foams 104
4.4.7 Compressive Strength Analysis of Silica-Nickel Oxide Foams 105
4.4 Chapter Summary 110

CHAPTER 5 CONLUSIONS

5.1 Conclusions 111
5.2 Recommendations 113
REFERENCES **114**

LIST OF TABLES

2.1 Features of different porous materials (Ishizaki *et al.*, 2013) 8

2.2 Classification of pore size for ceramic foam microstructure (Cai *et al.*, 2013) 10

2.3 Compressive strength of porous foam obtained by previous researchers 17

2.4 Advantages of using ceramic foam compare to conventional pellet (Twigg and Richardson, 2002) 22

2.5 Comparison of parameter for steam methane reforming by previous researchers 24

2.6 Effect of powder properties on porous materials (Ishizaki *et al.*, 2013) 26

2.7 Comparison of different chemical compound obtained from different types of silica 28

2.8 Composition of rice husk ash (An *et al.*, 2011) 30

2.9 Properties of silica (Venezia, 2001) 31

2.10 The difference of solid loading used by several researchers 39

2.11 Comparison of temperature range studied by previous researchers 42

2.12 Schematic illustration of densification stages by sintering process (Ishizaki *et al.*, 2013) 45

3.1 Properties of silica powder 50

3.2 Properties of nickel oxide powder 51

3.3 Specification of polyurethane sponge grade D25 52

3.4 Polyethylene glycol flakes properties 52

3.5 Carboxymethyl cellulose powder specification 52

3.6	Raw materials composition compositions to prepare the slurry for silica foams	54
3.7	Raw material compositions to prepare the slurry for silica-nickel oxide foams	54
3.8	Samples naming to fabricate silica foams	55
3.9	Samples naming to fabricate silica-nickel oxide foams	56
3.10	Equipment for powder characterisation	62
4.1	Compounds existed in silica powder	72
4.2	Silica foams with different compositions before sintering and after sintering	75
4.3	Colour changes of silica-nickel oxide foams observed before and after sintering	87
4.4	Colour changes of silica-nickel oxide foams at different sintering temperatures	87
4.5	Elements and compounds of nickel oxide powder	88
4.6	Image of sintered of silica-nickel oxide foams with 10 wt.% of nickel oxide composition at different sintering temperatures	89
4.7	Elements obtained for 10 wt.% of nickel oxide composition sintered at 1300°C	96
4.8	Summarised peaks obtained for silica-nickel oxide foams	101

LIST OF FIGURES

2.1 The different types of cellular structure (Salvo *et al.*, 2014) 7

2.2 Structure of reticulated foam (Matos *et al.*, 2007) 10

2.3 Level of porous ceramic foam, (1) Macro pores, (2) Micro pores, (3) Submicron pores (Cesarano *et al.*, 2005) 11

2.4 Foam microstructure with closed cell structure (Matos *et al.*, 2007) 11

2.5 Morphology of ceramic foam at different slurries density (Nor *et al.*, 2008) 12

2.6 Cross-section of honeycombs structure under optical microscope (Colombo, 2006) 13

2.7 Simplified schematic of the formation of porous ceramic in slurry method (Mendez *et al.*, 2007) 14

2.8 Morphology of the prepared porous SiO_2 ceramics with with controlled pore size which A, B, C, D, E and F Ranging from 2.2 mm to 5.7 mm (Wen *et al.*, 2007) 16

2.9 Schematic drawing of direct foaming process for macro porous ceramic production (Mishra *et al.*, 2009) 19

2.10 Classification of applications depending on the type of porosity (Banhart, 2001) 20

2.11 The uses of silica in various applications (Shen *et al.*, 2014) 21

2.12 The relationship between density, porosity and microsphere content (Kim *et al.*, 2005) 24

2.13 Steam reforming process flow (Amin *et al.*, 2010) 25

2.14 Silica polymorph graph (Ford *et al.*, 2004) 27
2.15 Tetrahedral structure of silica (Lechtenstein *et al.*, 2012) 28
2.16 The extraction steps of SiO_2 from natural sources (Vaibav *et al.*, 2015) 29
2.17 FESEM micrographs for (a) Synthetic SiO_2, (b) Crystalline -RHSiO_2 and (c) Amorphous-RHSiO_2 (Azmi *et al.*, 2016) 31
2.18 X-ray diffractograms (a) Crystalline silica rice husk and (b) Amorphous silica rice husk (Azmi *et al.*, 2016) 32
2.19 Polycrystalline structure of nickel oxide nanoparticles (Rifaya *et al.*, 2012) 33
2.20 Neck growth of nickel sphere (German, 2010) 34
2.21 Morphology of nano Ni particles synthesized at (a) 60°C, (b) 80°C and (c) 100°C (Haque *et al.*, 2012) 34
2.22 Structure of sintered ceramic foam using different pore density of PU template (a) 10, (b) 17 and (c) 27 ppi (Hadi *et al*., 2015) 35
2.23 Comparison of Si_3N_4 foam obtained by using different Binder; (a) and (b) using polyvinyl alcohol while (c) and (d) using carboxymethyl cellulose (Juanli *et al.*, 2013) 37
2.24 The different void at the strut produced (a) without carbon coating, (b) with carbon coating (Jun *et al.*, 2006) 41
2.25 Sintering profile for binder removal and firing (Ahmad *et al.*, 2010) 43
2.26 Changes of microstructure during sintering process which led to the foam strengthening (German, 2010) 44
2.27 (a) Densification of high density body and (b) coarsening mechanism of continuous network of solid material (white) and porosity (black) (Rahaman, 2007) 46
3.1 Workflow for silica foams fabrication 48
3.2 Workflow for silica-nickel oxide foams fabrication 49
3.3 Polyurethane sponge used as the template 51
3.4 Polyurethane sponge cut into cylindrical dimension 53

3.5 Example of samples naming for silica foams 55
3.6 Example of samples naming for silica-nickel oxide foams 57
3.7 Mixing process using mechanical stirrer; (a) Silica slurry and (b) Silica-nickel oxide slurry 57
3.8 Impregnation of polyurethane sponge into prepared slurry for (a) Silica foams and (b) Silica-nickel oxide foams 59
3.9 Squeezing the impregnated polyurethane sponge to remove excess slurry 59
3.10 Polyurethane sponge after squeezing 60
3.11 Samples after drying process 60
3.12 Sintering profile for sintering process 61
3.13 Sample preparation for X-ray diffraction test 64
3.14 Fracture occurred after applying load on silica-nickel oxide foams 67
3.15 Typical load-time curve for ceramic materials under compression test 68
4.1 Image of silica powder at magnification (a) X500 and (b) X1000 71
4.2 X-ray diffractograms for unsintered pure silica 73
4.3 Thermogravimetric analysis curve for silica powder 74
4.4 Slurry contained 65 wt.% of silica composition 76
4.5 Morphology of different composition of silica foams sintered at 1000°C; (a) 45 wt.%, (b) 50 wt.%, (c) 55 wt.% and 60 wt.% (OP=open pore, CP=closed pore, S=strut) 77
4.6 55 wt.% of silica composition at different temperature, (a) 1000°C, (b) 1100°C, (c) 1200°C and (d) 1300°C (OP=open pore, CP=closed pore, S=strut) 79
4.7 The microporous structure of sintered silica observed at magnification (a) X500 and (b) X2000 80
4.8 Morphology of silica foams after sintered at (a) 1000°C, (b) 1100°C, (c) 1200°C and (d) 1300°C 81

4.9 Apparent porosity result with different of silica composition 82
4.10 Bulk density result with variation of silica composition silica composition 84
4.11 Image of broken strut observed for 45 wt.% of silica composition 85
4.12 Energy dispersive spectra for nickel oxide powder 88
4.13 10 wt.% of nickel oxide composition foam after sintered at all sintering temperatures 90
4.14 Morphology of different composition of silica-nickel oxide foams sintered at 1000°C, (a) 2 wt.%, (b) 4 wt.%, (c) 6 wt.%, (d) 8 wt.% and (e) 10 wt.% (OP=open pore, CP=closed pore, S=strut) 91
4.15 Morphology of the 10 wt.% of silica-nickel oxide foams sintered at (a)1000 ºC, (b)1100 ºC, (c)1200ºC and (d)1300ºC (OP=open pore, CP=closed pore, S=strut) 93
4.16 Morphology of silica-nickel oxide foams at different sintering temperature (a) 1000°C, (b) 1100°C, (c) 1200°C, and (d) 1300°C 95
4.17 Element distribution by elemental mapping for 10 wt.% of nickel oxide composition sintered at 1300°C 97
4.18 The distribution of nickel particles with different nickel oxide composition samples (a) 2 wt.%, (b) 4 wt.%, (c) 6 wt.%, (d) 8 wt.%, and (e) 10 wt.% 98
4.19 The distribution of nickel particles after sintered at (a) 1000°C, (b) 1100°C, (c) 1200°C and (d) 1300°C 99
4.20 XRD analysis for 6 wt.% of nickel oxide at different sintering temperature 101
4.21 Apparent porosity result for silica-nickel oxide foams at different sintering temperature 103
4.22 Bulk density result for silica-nickel oxide foams at different sintering temperature 104
4.23 Compressive strength of silica-nickel oxide foams 105

4.24 8 wt.% of silica-nickel oxide foams sintered at 1200°C 107

4.25 The presence of cracks observed at strut of silica-nickel oxide foams 107

4.26 The struts of silica-nickel oxide foams observed under microscope 108

LIST OF ABBREVIATIONS

SiO_2 - Silica
NiO - Nickel oxide
SiO_2-NiO - Silica-Nickel oxide
CMC - Carboxymethyl cellulose
PEG - Polyethylene glycol
PU - Polyurethane
Al_2O_3 - Aluminium oxide
Fe_2O_3 - Iron oxide
Na_2O - Sodium oxide
K_2O - Potassium oxide
CaO - Calcium oxide
MgO - Magnesium oxide
P_2O_5 - Phosphorus oxide
SO_3 - Sulphur oxide
H - Hydrogen
H_2 - Hydrogen gas
CH_4 - Methane
TGA - Thermal Gravimetric Analysis
XRD - X-Ray Diffraction
SEM - Scanning Electron Microscopy
EDS - Electron Dispersive X-ray Spectroscopy
XRF - X-Ray Fluorescence
XRD - Energy Dispersive Spectroscopy
UTM - Universal Testing Machine
MPa - Mega pascal
µm - Micrometer

nm	-	Nanometer
mm	-	Milimeter
wt.%	-	Weight percentage
σ	-	Compressive strength
°C	-	Degree Celsius
g/cm^3	-	Gram/centimetre cubic (Density)
W_d	-	Weight of dry sample
W_s	-	Weight of the sample in water
W_w	-	Weight of the sample in the air after water fill up the pores

LIST OF APPENDICES

APPENDIX	TITLE
A1	Morphology of polyurethane template
B1	Morphology of silica foam
C1	Element composition for silica powder
D1	Thermogravimetric analysis
E1	Proceeding and Journal Paper

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Porous materials show a dramatic development nowadays instead of solid materials which have been used for the fabrication of variety applications. The applications include catalysis, filtration, thermal insulation, impact-absorbing structures, high specific strength materials, performs for metal-ceramic composites, biomedical implants and high-efficiency combustion burners (Dhara and Bhargava, 2003). For ceramic material, it offers higher temperature and environmental stability in comparison to conventional polymers or metals, and typical materials used for manufacturing cellular ceramics including crystalline inorganic materials such as silicon carbide, alumina, zirconia, cordierite, mullite, and also silicate glass and carbon as well as concrete (Colombo, 2006).

Cellular ceramics constitute a specific class of materials containing a high level of porosity (greater than 60 vol%) which are characterized by the presence of a recognizable ‘cell’, that is an enclosed empty space possessing faces and solid edges. The faces can either be fully solid or void, giving a closed cell or an open cell material, respectively (Colombo, 2006). Silica foam comes with close, fully open or partial interconnected porosity that can be produced from a broad range of ceramic materials in both oxide and non-oxide. Besides, it consists of open and closed cell that is commonly used for thermal insulation, fire protection, molten metal filtration, diesel engine and hot gas filtration. Most applications of porous microspheres are based on the porous structure such as porosities, pore sizes, and surface areas.

Silica foams are typically porous materials with the volume fraction of porosity ranging from 70% to 90%, and density varying from 0.3 to 0.6 g/cm^3. Porosity plays an important role in determining the capacity of efficiency and release kinetics (Cai *et al.*, 2013). Porous ceramics offer interesting properties in comparison with dense ceramics such as permeability to fluids, high specific surface area, low density, low thermal conductivity, thermal stability, high corrosion and wear resistance (Sciamanna *et al.*, 2015). These properties depend on the composition and the microstructure of the porous ceramic. The microstructure features are highly influenced by the processing route used such as slurry method, compaction method, gel-casting and a few more that has been widely used in order to produce the porous material.

There are several methods used for the preparation of cellular ceramics such as foams, honeycomb structures and interconnected rods, fibres and hollow spheres as reviewed by Colombo (2006). The examples of fabrication method are replication of a sacrificial foam template or also known as slurry method, direct foaming and burn-out of fugitive pore formers. There are also other fabrication methods in order to produce porous silica foam such as gel-casting, powder metallurgy, freeze casting, gas entrapment and few more. Among those various type of fabrication methods, slurry method has been chosen to fabricate porous silica foam product. Slurry method has been founded and patented by Schwartzwalder and Somer (1963) state that cellular ceramic articles are produced in accordance with the present invention by immersing an open-celled porous element of synthetic polymer or natural organic material in a slurry of finely-divided ceramic powder plus ceramic binder so as to uniformly coat the inner cell defining walls of the element with a thin layer of the slurry. About 1 to 5 wt.% of binder composition is adding to the ceramic slurry to enhance the compressive strength of ceramic foam up to 1 to 2 MPa (Han *et al.*, 2002).

Ceramics with engineered porosity are promising materials for a number of functional and structural applications such as thermal insulation, filters, catalyst support, bio-scaffolds for tissue engineering, and performs for composite fabrication that has been enlightened by Hammel *et al.* (2014). In this research study, porous structure of SiO_2-NiO foam will be used as a catalyst support in steam methane reforming technology.

Steam methane reforming technology is important to produce hydrogen gas (H_2) which is the simplest and the most plentiful gas in the universe (Amin *et al.*, 2010). Reforming reactions of methane, which is the main component of natural gas, plays an important role in the production of synthesis gas and hydrogen from natural gas (Li *et al.*, 2011). The demand for hydrogen gas (H_2) grows as it is widely used as raw material in chemical industry, food processing, hydrogenation process, production of ammonia and methanol, in the Fischer-Tropsch synthesis and in the pharmaceutical industry (Alves *et al.*, 2013). It has been investigated in biomass pyrolysis that nickel (Ni) is one of the best metal catalysts for tar elimination because it catalyses the cleavage of C-C, O-H, and C-H bonds, as well as the water-gas reaction (Widyaningrum *et al.*, 2012).

It is necessary to identify this slurry method which promises a foam with the morphology consists of 50% to 80% of porosity, open pore size within 20 µm to 800 µm and interconnected microstructure. The structure of foam which consists of large number of open pores and sinter at high temperature increase the reforming reaction compare to the material with dense structure. Materials containing high porosity exhibit special properties such as permeability to fluid, high specific surface area and low density that usually cannot be achieved by the conventional dense counterparts (Sciamanna *et al.*, 2015). It is also compulsory to fabricate SiO_2-NiO foams with good morphology, physical and mechanical properties to withstand stress during assembling and long-term operation, as they have to guarantee an adequate operation lifetime instead of reducing the production cost.

1.2 Problem Statement

Morphology of ceramic foam is a study to observe the microstructure which consists of open pore, closed pore and interconnected cells by strut. The size of open pore obtains from replication method within the range of 1 µm up to 2 mm which cannot be obtained by other method. The variation of strut sizes which connect the pores increase the strength of the foam. Ceramic foam with high porosity approximately 90%, low bulk density under 1.0 g/cm^3 and good compressive strength is fabricated by selecting the proper composition of raw materials to prepare the slurry solution for replication process. This is because the quality of ceramic coating on the polymeric sponge is highly dependent on the viscosity of the slurry instead of density of polymeric sponge (Nor *et al.*, 2009). Proper selection of SiO_2 powder, NiO powder and binders will determine the slurry concentration and affect final properties of sintered foam which includes the morphology of the foam.

Apart of selecting the composition of raw material, processing temperature is also one of the challenges for material’s scientists to select the suitable temperature for foam fabrication. A research on several sintering temperatures are compulsory to obtain a porous SiO_2-NiO foams with morphology which consisted of 50% to 80% of porosity, and also has good mechanical and physical properties. In firing stage, the green body undergoes numerous endothermic and exothermic processes, including organic removal like binder or space holder, dehydration, decomposition and phase formation (Gupta *et al.*, 2010). The common problem occurs in the production of porous ceramic product is associate with low strength. Defects can be minimized and the sintered body would not crack with proper heating and atmosphere control such as low heating and cooling rate which is 2°C/min for SiO_2-NiO foams fabrication.

There are several factors such as material composition, size of raw material, fabrication method, type of binder and its distribution that affect the morphology, physical and mechanical properties of porous ceramic foam. Porosity is one of the crucial factors that controlling the performance, properties, strength, and density of the ceramic foam. Materials containing 50% up to 80% of porosity is preferable compared to dense ceramics because it offers interesting properties such as permeability to fluids, low density, high corrosion and wear resistance. It is suitable for steam methane reforming application because the foam with open pore structure let the methane gasses pass through the foam easily for gas conversion process. The conversion of gas from methane (CH_4) to hydrogen gas (H_2) occurs at temperature of 400°C to 900°C (Amin *et al.*, 2011).

1.3 Research Objectives

The objectives below are the solution to the problem statements in the fabrication of porous materials. The objectives of this research are:

1) To investigate the composition of SiO_2 powder based on the SiO_2 foams morphology to fabricate SiO_2-NiO foams.
2) To identify the suitable composition and sintering temperature for SiO_2-NiO foams fabrication process.
3) To characterise physical properties and mechanical properties of SiO_2-NiO foams after sintering process.

1.4 Scope of Study

Several scopes and criteria have been studied and determined to carry out laboratory works for foam fabrication. The scope in this research study can be divided into several points which are material usage, fabrication and finally the characterisation of SiO_2 foams and SiO_2-NiO foams. The scopes of this research study are summarized as below:

i. Raw materials used in this study are SiO_2 powder, NiO powder, polyurethane (PU) sponge as the template, polyethylene glycol (PEG) and carboxymethyl cellulose (CMC) as binder and distilled water.
ii. Various compositions of SiO_2 foams from 45 wt.%, 50 wt.%, 55 wt.%, 60 wt.% and 65 wt.% are studied with 2.5 wt.% of CMC and 2.5 wt.% PEG fabricated by slurry method.
iii. Method to fabricate SiO_2-NiO foams is slurry method with 55 wt.% of SiO_2 and variation of NiO compositions consisting of 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.% and 10 wt.%. The composition for binders which are PEG and CMC is 2.5 wt.%, respectively.
iv. Two stages of sintering profile are set up with sintering temperatures of 1000°C, 1100°C, 1200°C, and 1300°C.

REFERENCES

Abbad, S.Z., Dupont, V. & Mahmud, T. (2016). Kinetics study and modelling of steam methane reforming process over a NiO/Al_2O_3 catalyst in an adiabatic packed bed reactor. *International Journal of Hydrogen Energy,* 42(5), 1-5.

Abou Rida, M. & Harb, F. (2014). Synthesis and characterization of amorphous silica nanoparticles from aqueous silicates using cationic surfactants. *Journal of Metals, Materials and Minerals,* 24(1), 37-42.

Ahmad, S., Halim, N.H., Taib, H. & Harun, Z. (2014). Effect of sintering temperature on the physical properties of titania-alumina-silver nitrate foam. *Applied Mechanics and Materials*, 465-466, 877-880.

Ahmad, S. (2010). *Kesan parameter pensinteran terhadap sifat mekanik dan fizikal titanium tulen dan aloi titanium berbusa.* Universiti Kebangsaan Malaysia; Ph.D. Thesis.

Al-Qureshi, H., Galiotto, A. & Klein, A. (2005). On the mechanics of cold die compaction for powder metallurgy. *Journal of Materials Processing Technology*, 166(1), 135-143.

Alves, H., Bley Junior, C., Niklevicz, R., Frigo, E., Frigo, M. & Coimbra-Araújo, C. (2013). Overview of hydrogen production technologies from biogas and the applications in fuel cells. *International Journal of Hydrogen Energy*, 38(13), 5215-5225.

Amin, A., Croiset, E. & Epling, W. (2011). Review of methane catalytic cracking for hydrogen production. *International Journal of Hydrogen Energy*, 36(4), 2904-2935.

An, D., Guo, Y., Zou, B., Zhu, Y. & Wang, Z. (2011). A study on the consecutive preparation of silica powders and active carbon from rice husk ash. *Biomass and Bioenergy*, 35(3), 1227-1234.

Azmi, M.A., Ismail, N.A.A., Muda, R., Hasif, W.M. & Taib, H. (2016). Characterisation of silica derived from rice husk (Muar, Johor, Malaysia) decomposition at different temperature. *AIP Conference Proceeding, 1756,* 020005-1-020005-7.

Baker, M., Walsh, S., Schwartz, Z. & Boyan, B. (2012). A review of polyvinyl alcohol and its uses in cartilage and orthopedic applications. *Journal of Biomedical Materials Research*, 100B(5), 1451-1457.

Banhart, J. (2001). Manufacture, characterisation and application of cellular metals and metal foams. *Progress in Materials Science*, 46(6), 559-632.

Bansiddhi, A. & Dunand, D. (2008). Shape-memory NiTi foams produced by replication of NaCl space-holders. *Acta Biomaterialia*, 4(6), 1996-2007.

Bauer, J., Hengsbach, S., Tesari, I., Schwaiger, R. & Krafta, O. (2014). High-strength cellular ceramic composites with 3D microarchitecture. *Proceedings of the National Academy of Sciences*, 111(7), 2453–2458.

Batista, R.M. & Muccillo, E.N.S. (2011). Influence of small amount of NiO on the electrical conductivity of 8YSZ. *ECS Transactions*, 35 (1), 1161-1169.

Bhattacharjee, P.P., Sinha, S.K. & Upadhyaya, A. (2007). Effect of sintering temperature on grain boundary character distribution in pure nickel. *Scripta Materialia*, 56, 13–16.

Bekoz, N. & Oktay, E. (2014). The role of pore wall microstructure and micropores on the mechanical properties of Cu–Ni–Mo based steel foams. *Materials Science and Engineering: A*, 612, 387-397.

Berger, M.B. (2010). The importance and testing of density/porosity/permeability/pore size for refractories in *Refractories 2010 Conference*, The Southern African Institute of Mining and Metallurgy, 101-115.

Biasetto, L., Colombo, P., Innocentini, M. & Mullens, S. (2007). Gas permeability of microcellular ceramic foams. *Industrial and Engineering Chemistry Research*, 46(10), 3366-3372.

Bienvenu, Y. (2014). Application and future of solid foams. *Comptes Rendus Physique*, 15, 719-730.

Cai, W., Ye, L., Zhang, L., Ren, Y., Yue, B., Chen, X. & He, H. (2014). Highly dispersed nickel-containing mesoporous silica with superior stability in carbon dioxide reforming of methane: the effect of anchoring. *Materials,*7, 2340-2355.

Cai, Y., Chen, Y., Hong, X., Liu, Z. & Yuan, W. (2013). Porous microsphere and its applications. *International Journal of Nanomedicine*, 8, 1111–1120.

Cesarano, J, Dellinger, J.G., Saavedra, M.P., Gill, D.D., Jamison R.D., Grosser, B. A., Sinn-Hanlon, J.M. & Goldwasser, M.S. (2005). Customization of load-bearing hydroxyapatite lattice scaffolds. *International Journal of Applied Ceramic Technology*, 2(3), 212-220.

Chaim, R., Levin, M., Shlayer, A. & Estournès, C. (2008) Sintering and densification of nanocrystalline ceramic oxide powders: A review. *Advances in Applied Ceramics: Structural, Functional and Bioceramics Journal - Advances in Psychiatric Treatment*, 107(3), 159-169.

Chandrasekhar, S., Satyanarayana, K.G., Pramada, P.N. & Raghavan, P. (2003). Review processing, properties and applications of reactive silica from rice husk- an overview. *Journal of Materials Science,* 38, 3159-3168.

Chen, P., Kim, G. & Ni, J. (2007). Investigations in the compaction and sintering of large ceramic parts. *Journal of Materials Processing Technology*, 190(1-3), 243-250.

Chindaprasirt, P., Jaturapitakkul, C. & Rattanasak, U. (2009). Influence of fineness of rice husk ash and additives on the properties of lightweight aggregate. *Fuel*, 88(1), 158-162.

Colombo, P. (2006). Conventional and novel processing methods for cellular ceramics. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 364(1838), 109-124.

Conde, Y., Despois, J., Goodall, R., Marmottant, A., Salvo, L., San Marchi, C. & Mortensen, A. (2006). Replication processing of highly porous materials. *Advanced Engineering Materials*, 8(9), 795-803.

Davila, L.P., Risbud, S.H. & Shackelford, J.F. (2008). Quartz and silicas. Ceramic and Glass Materials: Structure, Properties and Processing, pp. 71-86.

Dhara, S. & Bhargava, P. (2003). A simple direct casting route to ceramic foams. *Journal of the American Ceramic Society*, 86(10), 1645-1650.

Eom, J. & Kim, Y. (2013). Processing and properties of macroporous silicon carbide ceramics: A review. *Journal of Asian Ceramic Societies,* 3(1), 220-242.

Erjavec, M. (2011). *Mechanical properties of cellular materials*. University of Ljubljana: Seminar.

Fain, J.S., Mares, J.W. & Weiss, S.M. (2015). Size-controlled nickel oxide nanoparticle synthesis using mesoporous silicon thin films. *Journal of Nanoparticle Research,* 17, 331.

Falamaki C., Afarani M.S. & Aghare A. (2004). Initial sintering stage pore growth mechanism applied to the manufacturing of ceramic membrane support. *Journal of European Ceramic Society,* 24, 2285-2292.

Faure, R., Rossignol, F., Chartier, T., Bonhomme, C., Maître, A., Etchegoyen, G., Del Gallo, P. & Gary, D. (2010). Alumina foam catalyst supports for industrial steam reforming processes. *Journal of European Ceramic Society,* 31(3), 303-312.

Ford, M.H., Auerbach, S.M. & Monson, P.A. (2004). On the mechanical properties and phase behavior of silica: A simple model based on low coordination and strong association. *Journal of Chemical Physics*, 121(17), 8415-8422.

Franczyk, E., Gołębiowski, A., Borowiecki, T., Kowalik, P. & Wróbel, W. (2015). Influence of steam reforming catalyst geometry on the performance of tubular reformer-simulation calculations. *Chemical and Process Engineering,* 36 (2), 239-250.

Gadkaree, K. & Jaroniec, M. (2000). Pore structure development in activated carbon honeycombs. *Carbon*, 38(7), 983-993.

Garrido, G.I., Patcas, F.C., Lang, S. & Kraushaar-Czarnetzki, B. (2008). Mass transfer and pressure drop in ceramic foams: A description for different pore sizes and porosities. *Chemical Engineering Science,* 63, 5202-5217.

German, R.M. (2010). Coarsening in sintering: grain shape distribution, grain size distribution, and grain growth kinetics in solid-pore systems. *Critical Reviews in Solid State and Materials Sciences,* 35(4), 263-305.

Gómez, S., Alvarez, O., Escobar, J., Rodrigues Neto, J., Rambo, C. & Hotza, D. (2012). Relationship between rheological behaviour and final structure of Al_2O_3 and YSZ foams produced by replica. *Advances in Materials Science and Engineering,* 1-9.

Grano, A., Sayler, F., Smått, J. & Bakker, M. (2013). In situ observation of sintering of nickel nanoparticles during nanocasting into mesoporous silica. *Materials Letters,* 111, 154-157.

Guarino, V. & Ambrosio, L. (2014). Properties of biomedical foams for tissue engineering applications. *Biomedical Foams for Tissue Engineering Applications*, 40-70.

Gupta, S., Green, D., Messing, G. & Peterson, I. (2010). Thermomechanical behavior of ceramic green bodies during presintering. *Journal of the American Ceramic Society,* 93(9), 2611-2616.

Grano, A.J., Sayler, F.M., Smatt, J.H. & Bakker, M.G. (2013). In situ observation of sintering of nickel nanoparticles during nanocasting into mesoporous silica. *Materials Letters*, 111, 154–157.

Hadi, A., Baghshahi, S., Emadi, R. & Naghavi, S. (2015). Different pore size alumina foams and study of their mechanical properties. *Ceramics – Silikáty,* 59(1), 6-9.

Hamimah, A.R., & Guan, Y.P. Preparation of ceramic foam by simple casting process. Universiti Tun Hussein Onn Malaysia; 2007.

Hammel, E., Ighodaro, O. & Okoli, O. (2014). Processing and properties of advanced porous ceramics: An application based review. *Ceramics International*, 40(10), 15351-15370.

Han, Y.S., Li, J.B. & Chen, Y.J. (2003). Fabrication of bimodal porous alumina ceramics. *Materials Research Bulletin*, 38, 373-379.

Han, Y.S., Li, J.B., Chi, B. & Wen, Z.H. (2002). The effect of sintering temperature on porous silica composite strength. *Journal of Porous Materials*, 10, 41–45.

Haque, K.M.A., Hussain, M., Alam, S.S. & Islam S.M.S. (2012). Effect of temperature on the synthesis of nano-nickel particles. *Nanoscience and Nanotechnology,* 2(4), 104-108.

Haslinawati, M.M., Katori, K.A., Wahab, Z.A., Sidek, H.A.A. & Zainal, T. (2009). Effect of temperature on ceramic from rice husk ash. *International Journal of Basic & Applied Sciences,* 9(9), 1985–1988.

Hermida, L., Abdullah, A.Z. & Mohamed, A.R. (2013). Synthesis and characterization of mesostructured cellular foam (MCF) silica loaded with nickel nanoparticles as a novel catalyst. *Materials Sciences and Applications,* 4, 52-62.

Higginson, R.L., Jackson, C. P., Murrell, E. L., Exworthy, P. A. Z., Mortimer, R. J., Worrall, D. R. & Wilcox G. D. (2015). Effect of thermally grown oxides on colour development of stainless steel. *Materials at High Temperatures*, 32 (1-2), 113-117.

Iatsenko, A., Sych, O. & Tomila, T. (2015). Effect of Sintering Temperature on Structure and Properties of Highly Porous Glass-Ceramics. *Processing and Application of Ceramics*, 9(2), 99–105.

Ibrahim, E., Razooqi, A.M. & Mahdi, S.A. (2013). The effect of sintering time on the properties of ceramic composites reinforced by aluminium. *Australian Journal of Basic and Applied Sciences,* 7(7), 176-184.

Ishizaki, K., Komarneni, S. & Nanko, M. (2013). *Porous Materials: Process Technology and Applications:* Springer US.

Ispas, C., Sokolov, I. & Andreescu, S. (2008). Enzyme-functionalized mesoporous silica for bioanalytical applications. *Analytical and Bioanalytical Chemistry*, 393(2), 543-554.

Jana, P. & Ganesan, V. (2010). Processing of low-density alumina foam. *Journal of the European Ceramic Society*, 31(1-2), 75-78.

Jeangros, Q., Hansen, W.T., Wagner, J.B., Damsgaard, C.D., Dunin-Berkowski, R.E., He´bert, C., Van herle, J. & Hessler-Wyser, A. (2013). Reduction of nickel oxide particles by hydrogen studied in an environmental TEM. *Journal of Materials Science*, 48, 2893–2907.

Jha, N., Mondal, D., Dutta Majumdar, J., Badkul, A., Jha, A. & Khare, A. (2013). Highly porous open cell Ti-foam using NaCl as temporary space holder through powder metallurgy route. *Materials & Design*, 47, 810-819.

Juanli, Y., Jinlong, Y., Qingchuan, Z. & Yong, H. (2013). Effect of carboxymethyl cellulose addition on the properties of Si_3N_4 ceramic foams. *Ceramics International*, 39, 2775-2779.

Jun, I., Koh, Y, Song, J., Lee, S. & Kim, H. (2006). Improved compressive strength of reticulated porous zirconia using carbon coated polymeric sponge as novel template. *Materials Letters,* 60, 2507-2510.

Kamardan, M.G., Zaidi, N.H.A., Dalimin, M.N., Zaidi, A.M.A., Jamaludin, S.B. & Jamil, M.M.A. (2010). The sintering temperature effect on the shrinkage behavior of cobalt chromium alloy. *American Journal of Applied Sciences*, 7(11), 1443-1448.

Kar, G., Hrdina, K.E., Wight J.F. & Yu, C. (2003). Silica glass honeycomb structure from silica soot extrusion. U.S. Patent 6,548,142 B1.

Kennedy, A. (2012) “Porous Metals and Metal Foams Made from Powders,” in *Powder Metallurgy*, edited by K. Kondoh (Ed.), pp. 31-46.

Kim, Y., Jin, Y., Chun, Y., Song, I. & Kim, H. (2005). A simple pressing route to closed-cell microcellular ceramics. *Scripta Materialia*, 53(8), 921-925.

Kitouni, S. & Harabi, A. (2011). Sintering and mechanical properties of porcelains prepared from algerian raw materials. *Ceramica,* 57, 453-460.

Klein, C. & Hurlbut Jr, C.S. *Manual of Mineralogy*, 21st ed., John Wiley, NY, 1993, 527.

Kordatos, K., Gavela, S., Ntziouni, A., Pistiolas, K.N., Kyritsi, A & Rigopulou, V.K. (2008). Synthesis of highly siliceous ZSM-5 zeolite using silica from rice husk ash. *Microporous and Mesoporous Materials,* 115, 189–196.

Krebs, R.E. (2006). *The History and Use of Our Earth’s Chemical Elements: A Reference Guide:* Greenwood Press.

Kumar, M. & Nagabhatla, V. (2008). Role of pore size analysis in development of zeolite reforming catalyst. *Catalysis Today*, 130, 501-508.

Larbi, K.K. *Synthesis of high purity silicon from rice husks.* Ph.D. Thesis. University of Toronto; 2010.

LeBeau, J.M. & Boonyongmaneerat, Y. (2007). Comparison study of aqueous binder systems for slurry-based processing. *Materials Science and Engineering A*, 458, 17–24.

Lechtenstein, L., Heyde, M. & Freund, H. (2012). Atomic Arrangement in Two-Dimensional Silica: From Crystalline to Vitreous Structures. *Journal of Physical Chemistry C,* 116, 20426-20432.

Lefebvre *et al.*, (2006). Method of making open cell materials. U.S. Patent 7,108,828 B2.

Likibi, F., Assad, M, Coillard, C., Chabot, G. & Rivard C.H. (2005). Bone integration and apposition of porous and nonporous metallic orthopaedic biomaterials. *Annales de Chirurgie*, 130(4), 235–241.

Li, D., Nakagawa, Y. & Tomishige, K. (2011). Methane reforming to synthesis gas over Ni catalysts modified with noble metals. *Applied Catalysis A: General,* 408(1-2), 1-24.

Li, X., Wu, P. & Zhu, D. (2013). Properties of porous alumina ceramics prepared by technique combining cold-drying and sintering. *International Journal of Refractory Metals and Hard Materials,* 41, 437-441.

Li, Y., Cao, W., Gong, L., Zhang, R. & Cheng, X. (2016). Properties of highly porous cordierite ceramic obtained by direct foaming and gelcasting method. *Ceramic-Silikáty*, 60 (2), 91-98.

Li, Y., Cheng, X., Gong, L., Feng, J., Cao, W., Zhang, R. & Zhang, H. (2015). Fabrication and characterization of anorthite foam ceramics having low thermal conductivity. *Journal of the European Ceramic Society*, 35(1), 267-275.

Liu, D., Lau, R., Borgna, A. & Yang, Y. (2009). Carbon dioxide reforming of methane to synthesis gas over Ni-MCM-41 catalysts. *Applied Catalysis A: General*, 358(2), 110-118.

Liu, D., Quek, X.Y., Waha, H.H.A., Zeng, G., Li, Y. & Yang, Y. (2009). Carbon dioxide reforming of methane over nickel-grafted SBA-15 and MCM-41 Catalysts. *Catalysis Today*, 148(3-4), 243-250.

Liu, J. & Miao, X. (2005). Porous alumina ceramics prepared by slurry infiltration of expanded polystyrene beads. *Journal of Materials Science*, 40(23), 6145-6150.

Liu, J.A. (2006). *Kinetics, Catalysis and Mechanism of Methane Steam Reforming*. Worcester Polytechnic Institute: Master. Thesis.

Luyten, J., Mullens, S., Cooymans, J., De Wilde, A., Thijs, I. & Kemps, R. (2009). Different methods to synthesize ceramic foams. *Journal of the European Ceramic Society*, 29(5), 829-832.

Majewski, A.J., Wood, J. & Bujalski, W. (2013). Nickel-silica core@shell catalyst for methane reforming. *International Journal of Hydrogen Energy*, 38, 14531-14541.

Mansourighasri, A., Muhamad, N. & Sulong, A. (2011). Processing titanium foams using tapioca starch as a space holder. *Journal of Materials Processing Technology*, 212(1), 83-89.

Mao, X., Wang, S. & Shimai, S. (2008). Porous ceramics with tri-modal pores prepared by foaming and starch consolidation. *Ceramics International*, 34(1), 107-112.

Marba´n, G. & Valde´s-Solı´s, T. (2007). Towards the hydrogen economy. *International Journal of Hydrogen Energy*, 32(12), 1625-1637.

Matos, M.J., Dias, S. & Oliveira, F.A. (2007). Macrostructural changes of polymer replicated open cell cordierite based foams upon sintering. *Advances in Applied Ceramics*, 106(5), 209-215.

Mbakaan, C., Onojah, A.D. & Gbaakpen, M. (2013). Sintering temperature dependent variation of compressive strength with porosity of rice husk ash ceramics. *International Journal of Engineering Research & Technology,* 2(9), 2950-2953.

Méndez, E., Vlasova, M., Leon, I., Kakazey, M., Dominguez-Patiño, M., Isaeva, L. & Tomila, T. (2007). Low temperature synthesis of porous silicate ceramics. *Science of Sintering*, 39(1), 39-49.

Mishra, S., Mitra, R. & Vijayakumar, M. (2009). Processing and microstructure of particle stabilized silica foams. *Materials Letters*, 63(30), 2649-2651 (a).

Mishra, S., Mitra, R. & Vijayakumar, M. (2009). Structure and properties of short fibre reinforced silica matrix composite foams. *Ceramics International*, 35(8), 3111-3116 (b).

Mohan, R.B., O'Toole, B.J., Malpica, J., Hatchett, D.W., Kodippili, G. & Kinyanjui, J.M. (2008). Effects of processing temperature on recrete polyurethane foam. *Journal of Cellular Plastics*, 44, 327-345.

Mohanta, K., Kumar, A., Parkash, O. & Kumar, D. (2014). Processing and properties of low cost macroporous alumina ceramics with tailored porosity and pore size fabricated using rice husk and sucrose. *Journal of the European Ceramic Society*, 34(10), 2401-2412.

Mondal, D., Patel, M., Das, S., Jha, A., Jain, H., Gupta, G. & Arya, S. (2014). Titanium foam with coarser cell size and wide range of porosity using different types of evaporative space holders through powder metallurgy route. *Materials & Design*, 63, 89-99.

Mondal, D., Patel, M., Jain, H., Jha, A., Das, S. & Dasgupta, R. (2014). The effect of the particle shape and strain rate on microstructure and compressive deformation response of pure Ti-foam made using acrowax as space holder. *Materials Science and Engineering: A*, 625, 331-342.

Moulijn, J.A., Diepen, A.E. & Kapteijn, F. (2001). Catalyst Deactivation: Is it Predictable? What to do? *Applied Catalysis A: General*, 212, 3-16.

Mourhly, A., Khachani, M., Elhamidi, A., Kacimi, M., Halim, M. & Arsalane, S. (2015). The synthesis and characterization of low-cost mesoporous silica from local pumice rock. *Nanomaterials and Nanotechnology,* 5, 35.

Mulsow, L. & Tangboriboon, N. (2013). Preparation of calcium aluminosilicate catalyst foams from eggshells and polyurethane template. *Journal of Materials Science and Engineering B,* 3(2), 84-89.

Nieva, M.A., Villaverde, M.M., Monzon, A., Garetto, T.F. & Marchi, A.J. (2014). Steam-methane reforming at low temperature on nickel-based catalysts. *Chemical Engineering Journal,* 235, 158–166.

Niu, W., Bai, C., Qiu, G. & Wang, Q. (2009). Processing and properties of porous titanium using space holder technique. *Materials Science and Engineering: A,* 506 (1-2), 148-151.

Nor, M.A.A.M., Hong, L.C., Ahmad, Z.A. & Akil, H.M. (2008). Preparation and characterization of ceramic foam produced via polymeric foam replication method. *Journal of Materials Processing Technology*, 207, 235-239.

Nor, M.A.A.M., Akil, H.M. & Ahmad, Z.A. (2009). The effect of polymeric template density and solid loading on the properties of ceramic foam. *Science of Sintering*, 41(3), 319-327.

Ohji, T. & Fukushima, M. (2012). Macro-porous ceramics: processing and properties. *International Materials Reviews,* 57 (2), 115-131.

Oliveira, F., Dias, S., Vaz, M. & Fernandes, J. (2006). Behaviour of open-cell cordierite foams under compression. *Journal of the European Ceramic Society*, 26 (1-2), 179-186.

Oliveira, F.A.C., Dias, J., Mascarenhas, J., Ferreira, J.M.F., Olhero, D. & Dias, D. (2004). Fabrication of cellular cordierite foams. *Materials Science Forum.* 455-456, 177-181.

Parvanian, A., Saadatfar, M., Panjepour, M., Kingston, A. & Sheppard, A. (2014). The effects of manufacturing parameters on geometrical and mechanical properties of copper foams produced by space holder technique. *Materials & Design,* 53, 681-690.

Peng, H. X., Fan, Z. & Evans, J.R.G. (2000). Factors affecting the microstructure of a fine ceramic foam. *Journal of Ceramics International*, 26(8), 887-895.

Priyanka, A.J. & Jha, A.K. (2012). Effect of sintering temperature on the grain growth and electrical properties of barium zirconate titanate ferroelectric ceramics. *Journal of Materials Science: Material Electron,* 24, 1511–1518.

Pu, X., Liu, X., Qiu, F. & Huang, L. (2004). Novel method to optimize the structure of reticulated porous ceramics. *Journal of American Ceramic Society*, 87(7), 1392-1394.

Rahaman, M.N. Ceramic Processing and Sintering. 2nd ED: united State of America: Marcel Dekker, Inc. 2007.

Richerson, D. Richerson, D.W. & Lee, W.E. (2005). *Modern Ceramic Engineering: Properties, Processing, and Use in Design, Third Edition.* CRC Press.

Riedel, R., Ionescu, E., and Wei, C. (2008). Modern Trends in Advanced Ceramics. *Ceramic sciences and Technology*, VCH, Weinheim, Germany, 1, pp. 1-38.

Rifaya, M.N., Theivasanthi, T. & Alagar, M. (2012). Chemical capping synthesis of nickel oxide nanoparticles and their characterizations studies. *Nanoscience and Nanotechnology*, 2(5), 134-138.

Saha, B., Kumar, V., Joshi, S., Balakrishnan, A. & Martin, C. (2012). Investigation of compaction behavior of alumina nano powder. *Powder Technology*, 224, 90-95.

Salvo, L., Martin, G., Suard, M., Marmottant, A., Dendievel, R., & Blandin, J.J. (2014). Processing and structure of solid foams. *Comptes Rendus Physique*, 15, 662–673.

Sankaranarayanan, S. & Srinivasan, K. (2012). Carbon dioxide – A potential raw material for the production of fuel, fuel additives and bio-derived chemicals. *Indian Journal of Chemistry*, 51, 1252-1262.

Sarkar, R., Ghosal, P., Premkumar, M., Singh, A.K., Muraleedharan, K., Chakraborti, A., Bagchi, T.P. & Sharma, B. (2008). Characterisation and sintering studies of mechanically milled nano tungsten powder. *Powder Metallurgy,* 51(2), 166-170.

Sathiyanarayanan, P., Karunakaran, R.J., Gomathi, T. & Sudha, P.N. (2015). Synthesis and characterization of carboxymethyl cellulose/polyethylene glycol/montmorillonite clay blends. *International Journal of Novel Trends in Pharmaceutical Sciences,* 5(2), 36-41.

Sato, N., Ohsaki, K., Kikuchi, K., Hirota, Y., Numaguchi, T. & Mochiduki, N. (1991). *Catalyst for Steam Reforming*. U.S. Patent 4, 990,481.

Scheffler, M., and Colombo, P. (2005). Cellular Ceramics: Structure, Manufacturing, Properties and Applications. Weinheim: Wiley-VCH.

Schwartzwalder, K. & Somers, A.V. (1963). Method of making porous ceramic articles. U.S. Patent No. 3090094.

Sciamanna, V., Nait-Ali, B. & Gonon, M. (2015). Mechanical properties and thermal conductivity of porous alumina ceramics obtained from particle stabilized foams. *Ceramics International*, 41 (2), 2599-2606.

Sharmiwati, M.S., Mizan, R.M. & Noorhelinahani, A.B. (2014). Preparation and characterization of ceramic sponge for water filter. *International Journal of Scientific & Technology Research*, 3(6), 103-106.

Shen, Y., Zhao, P. & Shao, Q. (2014). Porous silica and carbon derived materials from rice husk pyrolysis char. *Microporous and Mesoporous Materials*, 188, 46-76.

Singh, R.C., Sing, M.P., Sing, O. & Chandi, P.S. (2009). Influence of synthesis and calcination temperatures on particle size and ethanol sensing behaviour of chemically synthesized SnO_2 nanostructures. *Sensors and Actuators B*, 143 (1), 226-232.

Soltani, N., Bahrami, A., Pech-Canul, M. & González, L. (2015). Review on the physicochemical treatments of rice husk for production of advanced materials. *Chemical Engineering Journal*, 264, 899-935.

Staciu, L.A., Kodash, V.Y. & Groza, J.R. (2001). Effects of heating rate on densification and grain growth during field-assisted sintering of α-Al_2O_3 and $MoSi_2$ powders. *Metallurgical and Materials Transactions*, 32, 2633-2638.

Strachota, A., Černý, M., Chlup, Z., Rodzeń, K., Depa, K., Halasová, M., Šlouf, M. & Schweigstillová, J. (2015). Preparation of finely macroporous SiOC foams with high mechanical properties and with hierarchical porosity via pyrolysis of a siloxane/epoxide composite. *Ceramics International*, 41(7), 8402-8410.

Studart, A., Gonzenbach, U., Tervoort, E. & Gauckler, L. (2006). Processing routes to macroporous ceramics: A review. *Journal of the American Ceramic Society*, 89(6), 1771-1789.

Surace, R., De Filippis, L., Ludovico, A. & Boghetich, G. (2009). Influence of processing parameters on aluminium foam produced by space holder technique. *Materials & Design,* 30(6), 1878-1885.

Tang, F., Fudouzi, H., Uchikoshi, T. & Sakka, Y. (2004). Preparation of porous materials with controlled pore size and porosity. *Journal of the European Ceramic Society,* 24, 341-344.

Thema, F.T., Manikandan, E., Gurib-Fakim, A. & Maaza, M. (2016). Single phase bunsenite NiO nanoparticles green synthesis by *Agathosma Betulina* natural extract. *Journal of Alloys and Compounds,* 657, 655-661.

Tietz, F. Francisco, J.D., Simwonis, D, & Stover, D. (2000). Evaluation of commercial nickel oxide powders for components in solid oxide fuel cells. *Journal of the European Ceramic Society,* 20(8), 1023-1034.

Todorova, E., Chernev, G. & Djambazov, S. (2014). Structure and properties of functionalized porous silica hybrid materials. *Open Journal of Inorganic Non-metallic Materials,* 4, 35-43.

Tripkovic, D., Radojevic, V. & Aleksic, R. (2006). Factors affecting the microstructure of porous ceramics. *Journal of the Serbian Chemical Society,* 71(3), 277-284.

Tsetsekou, A., Agrafiotis, C., Leon, L. & Milias, A. (2001). Optimization of the rheological properties of alumina slurries for ceramic processing applications. *Journal of the European Ceramic Society,* 21, 493-506.

Twigg, M.V. & Richardson, J.T. (2002). Theory and application of ceramic foam catalysts. *Trans IChemE,* 80, 183-189.

Vaibhav, V., Vijayalakhsmi, U. & Roopan, S.M. (2015). Agricultural waste as a source for the production of silica nanoparticles. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy,* 139, 515–520.

Vasanth, D., Uppaluri, R. & Pugazhenthi, G. (2011). Influence of sintering temperature on the properties of porous ceramic support prepared by uniaxial dry compaction method using low-cost raw materials for membrane applications. *Separation Science and Technology,* 46, 1241–1249.

Venezia, A.M., Parola, V.L., Longo, A. & Martorana, A. (2001). Effect of alkali ions on the amorphous to crystalline phase transition of silica. *Journal of State Chemistry,* 161, 373-378.

Vilčeková, Z., Kašiarová, M., Domanická, M., Hnatko, M. & Šajgalík, P. (2013). Influence of the preparation of Si_3N_4 based foams on the compressive strength and processing flaws. *Powder Metallurgy Progress,* 13, 139-146.

Vogt, U.F., Gorbar, M., Dimopoulos-Eggenschwiler, P., Broenstrup, A., Wagner, G. & Colombo, P. (2010). Improving the properties of ceramic foams by a vacuum infiltration process. *Journal of the European Ceramic Society,* 30(15), 3005-3011.

Voigt, C., Aneziris, C.G. & Hubálková, J. (2015). Rheological Characterization of Slurries for the Preparation of Alumina Foams via Replica Technique. *Journal of the American Ceramic Society,* 1-4.

Wan, W., Feng, Y., Yang, J., Xu, S. & Qiu, T. (2015). Preparation of mesoporous silica ceramics with relatively high strength from industrial wastes by low-toxic aqueous gel-casting. *Journal of the European Ceramic Society*, 34(7), 2163-2170.

Wen, Z., Han, Y., Liang, L. & Li, J. (2007). Preparation of porous ceramics with controllable pore sizes in an easy and low-cost way. *Materials Characterization*, 59(9), 1335-1338.

Widyaningrum, R., Church, T., Zhao, M. & Harris, A. (2012). Mesocellular-foam-silica-supported Ni catalyst: Effect of pore size on H_2 production from cellulose pyrolysis. *International Journal of Hydrogen Energy*, 37(12), 9590-9601.

William, A.D. & Robert, A.H. (2004). *Rock-forming Minerals: Silica Minerals, Volume 4B*. 2nd Ed. London: Geological Society.

Wu, H., Parola, V.L., Pantaleo, G., Puleo, F., Venezia, A.M. & Liotta, F. (2013). Ni-Based Catalysts for Low Temperature Methane Steam Reforming: Recent Results on Ni-Au and Comparison with Other Bi-Metallic Systems. *Catalysts*, 3, 563-583.

Xiang, C., Zhang, Y., Li, Z., Zhang, H., Huang, Y. & Tang, H. (2011). Preparation and compressive behaviour of porous titanium prepared by space holder sintering process. *Procedia Engineering*, 27, 768-774.

Xie, F., He, X., Cao, S., & Qu, X. (2013). Structural and mechanical characteristics of porous 316l stainless steel fabricated by indirect selective laser sintering. *Journal of Material Processing Technology,* 213(16), 838-843.

Xin, C., Jiahao, L., Zhicheng, F. & Zhengzhong, S. (2004). Macroporous chitosan/carboxymethylcellulose blend membranes and their application for lysozyme adsorption. *Journal of Applied Polymer Science,* 96, 1267–1274.

Yahya, N., Masoud, R.A.H., Daud, H., Aziz, A. & Zaid, H.M. (2009). Synthesis of $Al_3Fe_5O_{12}$ cubic structure by extremely low sintering temperature of sol-gel technique. *American Journal of Engineering Applied Sciences*, 2, 76-79.

Yakubu, A., Abbas, Z., Hashim, M. & Fahad, A. (2015). Effect of Sintering Temperature on $Co_{0.5}Zn_{0.5}Fe_2O_4$ Nano-Particles Evolution and Particle Size Distribution. *Advances in Nanoparticles*, 4, 37-44.

Yen, S., Hsieh, C., Chang, H., Yen, C. & Chang, Y. (2015). Synergistic effect of coupling agents and fibre treatments on mechanical properties and moisture absorption of polypropylene–rice husk composites and their foam. *Composites Part A: Applied Science and Manufacturing*, 68, 313-322.

Yuan, W., Cai, Y., Chen, Y., Hong, X. & Liu, Z. (2013). Porous microsphere and its applications. *International Journal of Nanomedicine*, 8, 1111–1120.

Yu-Ming, T., Peng-fei, Z., Xiang-chen, K., Ai-ping, L., Kai-yue, W., Yue-sheng, C., Zhan-gang, L. & De-fu, L.V. (2015). The effect of sintering temperature on the structure and properties of corundum/mullite ceramics. *Science of Sintering*, 47, 273-278.

Zhang, J., Fu, Y. & Zeng, X. (2006). Compressive properties of open-cell ceramic foams. *Transactions of Nonferrous Metals Society of China*, 16, 453-456.

Zhang, L., Ferreira, J, Olhero, S., Courtois, L., Zhang, T., Maire, E. & Rayhe, C. (2012). Modeling the mechanical properties of optimally processed cordierite–mullite–alumina ceramic foams by X-ray computed tomography and finite element. *Acta Materialia*, 60, 4235 – 4246.

Zhang, L., Zhou, D., Chen, Y., Liang, B. & Zhou, J. (2014). Preparation of high open porosity ceramic foams via direct foaming molded and dried at room temperature. *Journal of the European Ceramic Society,* 34(10), 2443-2452.

Zhao, C. (2012). Review on thermal transport in high porosity cellular metal foams with open cells. *International Journal of Heat and Mass Transfer*, 55(13-14), 3618-3632.

Zhao, Y., Han, F. & Fung, T. (2004). Optimisation of compaction and liquid-state sintering in sintering and dissolution process for manufacturing Al foams. *Materials Science and Engineering: A*, 364(1-2), 117-125.

Zhao, Y.H., Wee, K.H. & Bai, R.B. (2010). Highly hydrophilic and low-protein-fouling polypropylene membrane prepared by surface modification with sulfobetaine-based zwitterionic polymer through a combined surface polymerization method. *Journal of Membrane Science*, 362, 326-333.

Zhao, Y.Y. & Sun, D.X (2001). A novel sintering-dissolution process for manufacturing Al foams. *Scripta Materialia*, 44(1), 105-110.

Zhu, X., Jiang, D., Tan, S., & Zhang, Z. (2001). Improvement in the strut thickness of reticulated porous ceramics. *Journal of the European Ceramics Society*, 84(7), 1654-1656.