



**DESIGN OF A GAS ATOMISING SYSTEM CAPABLE OF PRODUCING SUITABLE
ALUMINIUM POWDER FOR SELECTIVE LASER MELTING (SLM) PROCESS**

By

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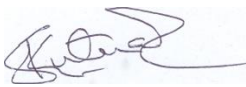
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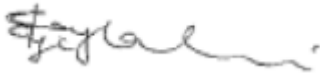
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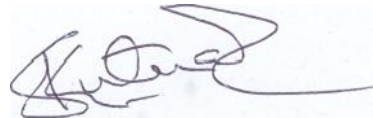
Certification

The undersigned certifies that he has read and hereby recommends for acceptance by the Faculty of Engineering and Technology a dissertation titled: “*Design of a gas atomising system capable of producing suitable aluminium powder for selective laser melting (SLM) process.*” in fulfilment of the requirements for the degree of Master of Engineering in Manufacturing Engineering of the BIUST.



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"He asked me, "Son of man, can these bones live?" I said, "Sovereign LORD, you alone know." Ezekiel 37: 3.

Dedication

This dissertation is dedicated to my dearest kids; Lilly and Fena, their mother; Neo, my family (mother and siblings), my supervisors and everyone who supported me in any way at any given point during the course of this study. Let me take this moment to recognise and appreciate all the love and support you gave me throughout the project. I get emotional when I recall how good you have been to me. God bless all of you.

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Table of Contents

	Page
Declaration and copyright -----	i
Certification -----	ii
Acknowledgments -----	iii
Dedication -----	v
Table of Contents -----	vi
List of Figures -----	xi
List of Tables -----	xiii
List of Appendices -----	xv
List of Abbreviations -----	xvi
Abstract -----	xvii
Chapter One: Introduction -----	1
1.1 Introduction -----	1
1.2 Background of the research -----	1
1.3 Problem statement -----	4
1.4 General and specific objectives -----	5
1.4.1 General objectives -----	5
1.4.2 Specific objectives -----	5
1.5 Delimitation of scope -----	6
1.6 Specific themes investigated -----	6
1.7 Sources of data and methodologies -----	7

1.8 Expected outcomes -----	9
1.9 Outline of the dissertation -----	9
1.10 Summary -----	10
Chapter Two: Literature review-----	11
2.1 Introduction -----	11
2.2 Background information on aluminium alloys, -----	11
2.3 Additive manufacturing processing of metal powders -----	16
2.3.1 The nature of additive manufacturing and its variants -----	16
2.3.1.1 Selective laser sintering/ melting (SLS/SLM) ----	18
2.4 Selective laser melting process and the nature of powder-laser material interactions -----	19
2.5 Atomisation of melts -----	22
2.5.1 Water atomisation of aluminium -----	23
2.5.2 Gas atomisation of aluminium -----	24
2.5.3 Centrifugal Atomisation -----	27
2.6 Critical components in atomisation and their design considerations --	29
2.6.1 Operations and design considerations of a furnace -----	29
2.6.1.1 Induction furnace (IF) -----	30
2.6.1.2 Electrical crucible furnace (ECF) -----	31
2.6.1.3 Electric arc furnace (EAF) -----	31
2.6.2 Operation and design considerations of atomizing nozzle -----	32
2.6.2.1 Water and gas atomizing device -----	33
2.6.2.2 Centrifugal atomizing device -----	35

2.6.3 Atomising chamber	37
2.7 The role of computational fluid dynamics simulation in designing atomizing nozzle	38
2.7.1 CFD codes and their applications	39
Chapter 3: Methodologies	41
3.1 Introduction	41
3.2 Methodologies	41
3.2.1 Methodology for conceptual design framework	41
3.2.2 Evaluation of sub-system variants	45
3.2.3 Methodology for mechanical design of components	48
3.2.4 Methodology for CFD investigation of the nozzle	50
3.3 Final design solution	51
3.4 Summary	52
Chapter 4: Design of an aluminium powder atomizing system	53
4.1 Introduction	53
4.2 Selection of appropriate atomizing system	53
4.2.1 Specific powder requirements for SLM	55
4.2.2 Developing conceptual design framework for setting up a gas atomising system	55
4.2.2.1 Selection of appropriate furnace	56
4.2.2.2 Selection of appropriate nozzle	61
4.2.2.3 Selection of appropriate atomising gas	62
4.2.2.4 Selection of appropriate atomising chamber	66

4.3 Framework for designing a gas atomising system -----	66
4.4 Mechanical design of components -----	73
4.4.1 Mechanical design of the induction furnace -----	74
4.4.1.1 Geometrical design of the furnace -----	74
4.4.1.2 Electrical and thermal design of the furnace -----	78
4.4.2 Mechanical design of the atomising nozzle -----	84
4.4.2.1 Geometrical design of the nozzle -----	85
4.4.3 Mechanical design of the atomising chamber -----	89
4.4.4 Auxiliary components/sub-systems -----	89
4.4.4.1 Gas delivery system -----	89
4.4.4.1.1 Gas supply requirements -----	90
4.4.4.2 Gas and powder particle recovery system -----	90
4.4.4.3 Data acquisition and control system -----	90
4.4.4.4 Safety features of the system -----	91
4.5 Design optimisation of the gas atomising nozzle via computational fluid dynamics (CFD) simulation -----	91
4.5.1 Computational fluid dynamics code validation -----	92
4.5.2 Experimental setup -----	93
4.5.3 Boundary conditions -----	95
4.5.4 Model assumptions -----	96
4.5.6 Grid independence -----	98
4.5.7 Findings from the CFD experiment -----	97
4.6 Bill of Quantities -----	103

Chapter 5: Conclusions and future work -----	105
5.1 Introduction -----	105
5.2 A brief overview of this research -----	105
5.3 Achievements of this research -----	108
5.4 Limitations of this research -----	109
5.5 Future Work -----	110
5.6 Conclusion -----	111
List of references -----	112
Appendices -----	128

List of Figures

	Page
Figure 1.1 Water atomisation process (Asgarian, 2019) -----	2
Figure 1.2 Engine bracket (China manufacturer, 2020) -----	3
Figure 1.3 Research methodology formulated -----	8
Figure 2.1 Selective laser melting process (AMRG, 2018) -----	18
Figure 2.2: Scanning electron microscopy image of blended powder -----	20
Figure 2.3 Gas atomising system set up (Zheng, <i>et al.</i> 2009) -----	24
Figure 2.4 Gas atomisation melt droplet break-up (Mi <i>et al.</i> 2008) -----	27
Figure 2.5a Spinning disc (Graco Inc., 1995) -----	28
Figure 2.5b Plasma rotating electrode (Palmer, 2019) -----	28
Figure 2.6a Induction furnace (Physicsmax.com, 2019) -----	30
Figure 2.6b Electric crucible furnace (El-Akruiti <i>et al.</i> 2016) -----	30
Figure 2.6c Electric arc furnace (Zimmermann, <i>et al.</i> 2018) -----	30
Figure 2.7a Freefall atomiser (Fritsching and Uhlenwinkel, 2012) -----	34
Figure 2.7b Close-coupled atomiser (Fritsching and Uhlenwinkel, 2012) -----	34
Figure 2.8 Nozzle design consideration (Xin-Ming <i>et al.</i> 2009) -----	35
Figure 2.9a Horizontal chamber (Rejeesh, 2014) -----	38
Figure 2.9b Vertical chamber (German and Vassileva, 2007) -----	38
Figure 3.1 Conceptual design methodology (Matsagopane <i>et al.</i> 2019) -----	43
Figure 3.2. Flow chart showing sequence of activities (Matsagopane <i>et al.</i> 2019) -	44
Figure 3.3 System structure diagram (Maier, <i>et al.</i> 2009) -----	45
Figure 3.4 Mechanical design methodology formulated -----	49

Figure 3.5 Computational fluid dynamics methodology formulated-----	51
Figure 4.1a Conceptual design framework hierarchy -----	70
Figure 4.1b A section of the framework highlighting on the tasks -----	71
Figure 4.2 Experimental domain used as baseline data -----	94
Figure 4.4 Inflation layers at the walls -----	97
Figure 4.5 Grid generated -----	97
Figure 4.6 (a) Gas velocity through the fluid body -----	100
Figure 4.6 (b) Gas velocity at exit -----	100
Figure 4.7 High gas velocity beyond nozzle tip -----	101
Figure 4.8 (a) Gas velocity at throat diameter 0.3mm, length 3mm -----	101
Figure 4.8 (b) Gas velocity at throat diameter 0.4 mm, length 4 mm -----	102
Figure 4.9 Gas velocity through various distances away from the throat -----	103

List of Tables

	Page
Table 2.1 Physical properties of aluminium (Royal Society of Chemistry, 2017) --	12
Table 2.2 Mechanical properties of aluminium -----	13
Table 2.3 Properties of aluminium at its melting point (Cao, <i>et al.</i> 2003) -----	13
Table 2.4 Effects of alloying elements on aluminium (Kopeliovich, 2012) -----	14
Table 2.5 General powder requirements for SLM application-----	20
Table 2.6. Common atomising gases and their properties -----	25
Table 2.7 Summary of atomising techniques -----	29
Table 2.8 Types of electric furnaces and their properties -----	32
Table 3.1: Layout of the product design specifications -----	46
Table 3.2 Screening of possible solutions -----	47
Table 3.3 Evaluation Matrix -----	48
Table 4.1: Atomisation variants' selection and evaluation -----	54
Table 4.2: Ranked SLM powder requirements -----	55
Table 4.3: Ranked melting/holding furnace requirements -----	57
Table 4.4: Specifications for the gas atomising system and its key components -	58
Table 4.5: Evaluation and selection of melting/holding furnace -----	60
Table 4.6: Ranked atomising nozzle requirements -----	61
Table 4.7: Variant evaluation and selection of the nozzle -----	62
Table 4.8 Ranked key requirements for atomizing gas -----	63
Table 4.9: Atomising gas variants' screening -----	63
Table 4.10 Evaluation of atomising gases -----	64

Table 4.11	Definition of activities for conceptual design framework -----	68
Table 4.12	Values for mechanical design of the furnace -----	78
Table 4.13	Values for thermal and electrical design of the furnace -----	84
Table 4.14	Values for geometrical design of the nozzle -----	88
Table 4.15	Comparison of validation results -----	92
Table 4.16	Sets of varying throat diameters and expansion lengths -----	95
Table 4.17	Velocity magnitude of various configurations -----	99
Table 4.18a	Bill of quantities for the nozzle -----	103
Table 4.18b	Bill of quantities for the chamber -----	104
Table 4.18c	Bill of quantities for the furnace -----	104

List of Appendices

	Page
Appendix A1: Induction furnace design -----	145
Appendix A2: Induction furnace casing -----	146
Appendix A3: Refractory wall -----	147
Appendix A4: Crucible design and winding -----	148
Appendix B: Nozzle design -----	149
Appendix C: Atomising chamber design -----	150
Appendix D1: Presentation/Assembly drawing -----	151
Appendix D2: Front elevation of the assembled drawing -----	152

List of Abbreviations

AM – Additive manufacturing

AMRG – Additive Manufacturing Research Group

CCGAS – Close-Coupled Gas Atomising System

C-D – Converging-Diverging

CFD – Computational Fluid Dynamics

BIUST – Botswana International University of Science and Technology

CAD – Computer-Aided design

CBA – Cost-Benefit Analysis

CSIR – Council for Scientific and Industrial Research

EBM – Electron Beam Melting

EDD – Economic Diversification Drive

IT – Information Technology

LC – Laser Cladding

LD – Laser Deposition

LENS – Laser-Engineered Net Shaping

PDS – Product Design Specifications

PhD – Doctor of Philosophy

PM – Powder Metallurgy

SADC – Southern African Development Community

SLM – Selective Laser Melting

UVA – Use – Value Analysis

ABSTRACT

Documentation on the correct process parameters and component requirements for setting up efficient aluminum powder production systems capable of manufacturing powder that meets the requirements for the selective laser melting (SLM) process is not available due to its proprietary nature. This hinders powder metallurgy (PM) trainees in acquiring knowledge and skills needed in setting up such metal powder production systems. To address this challenge, powder requirements for the SLM process and powder production techniques for manufacturing metal powder that meets SLM requirements were identified and defined via literature review. User-value analysis (UVA) and cost–benefit analysis (CBA) techniques were applied as evaluation tools to identify the best components and process parameters for aluminum powder production via gas atomisation. A conceptual design framework for setting up an aluminum powder gas atomizing system which meets SLM requirements is developed with a view to improving the delivery of PM education in developing countries as trainees gain knowledge and skills for setting up powder production systems. The outcome of the conceptual design framework suggests that powdered particles obtained from gas atomisation technique meets the SLM requirements. Therefore, the mechanical design of the components of the metal powder gas atomiser was carried out via empirical relations. Components of the metal powder gas atomiser designed include a 5kg/hr melting and holding induction furnace, close-coupled nozzle and the atomising chamber. A parametric design of the nozzle was carried out via computational fluid dynamics (CFD) by exploring how aspect ratio (throat area and expansion area) influence gas velocity required during high pressure gas atomization (HPGA). Outcomes of CFD analysis indicate that maximum velocity (2880 m/s) was attained at expansion length of 2.0 mm and throat diameter of 0.35 mm, hence the configurations were adopted for this research.

Keywords: *additive manufacturing (AM), gas atomising system, aluminium powder, selective laser melting (SLM), CFD simulation, mechanical design*

CHAPTER 1: INTRODUCTION

1.1 Introduction

In this Chapter, the background to this research is presented. The research motivation, objectives and the delimitation of scope are also highlighted. General and specific objectives are explicitly stated to guide the research. The chapter also describes specific themes to be investigated, source of data and methodologies, and expected outcomes. Finally, the outline of the dissertation as well as the conclusion of this chapter is presented.

1.2 Background of the research

Powder metallurgy (PM) entails the manufacturing and characterisation of metallic particles in micron sizes, as well as its processing and consolidation into usable engineering components for automotive, biomedical, jewellery making, nuclear and wear applications (Danninger and Gierl-Mayer 2013; Yenwiset and Yenwiset 2011). According to Yenwiset and Yenwiset (2011) PM is gaining wider interest in the academic and industrial research sectors because of its capability to (i) produce high yield at low cost per operation and (ii) allow alloying of different metal powders to produce high quality metal alloys. Such high-quality metal alloys include Al₁₀SiMg which consists of aluminium (Al), silicon (Si) and magnesium (Mg). In Al₁₀SiMg, magnesium is added to improve weldability and corrosion resistance (Mohammed and Alias 2017; Polmear *et al.* 2017) while silicon is added for improved wear resistance (Subramanian 2010) and lowering of the melting point (Mathers 2002). Metal powder production techniques include solid-state reduction (Li, *et al.* 2019), atomisation (Neikov 2019; Dunkley 2013) and electrolysis (Chen 2013) among others.

Tian *et al.* (2017) indicated that atomisation has the capability to control powder characteristics much easily and produce fine, clean and spherical powder particles. According to Dunkley (2012) and Antipas (2012), atomisation is the disintegration of molten metal by strong jets of fluids (either liquid or gas) that impinge the melt to form droplets (*primary atomisation*) that further disintegrate into finer droplets (*secondary*

atomisation). These finer droplets cool and solidify *on flight* along the height of the atomising chamber to form powdered particles that collect at the bottom of the atomising chamber. The range of metals that can be atomised extends only to those that can be melted and poured into a continuous stream (e.g. aluminium, copper, stainless steel, brass and iron). However, it is difficult to atomise refractory metals such as tungsten (W) and molybdenum (Mb) because there is no crucible that can hold them at their melting temperatures of 3422 and 2623°C respectively. Common atomisation techniques include gas (Alvarez *et al.* 2018), water (Dunkley 2013) and centrifugal atomisation (Zhang and Zhao 2017). Figure 1.1 shows an atomisation technique in which pressurised jet of atomising medium impinges on the melt as it falls from the crucible. Inside the structure, critical process parameters such as superheat temperature of the melt (Luo *et al.* 2017), nozzle geometric design (Leng *et al.*, 2018), velocity and pressure of the atomising medium (Yang, *et al.*, 2019) are observed in order to produce metal powders that meet the required specifications (Clark *et al.*, 2018).

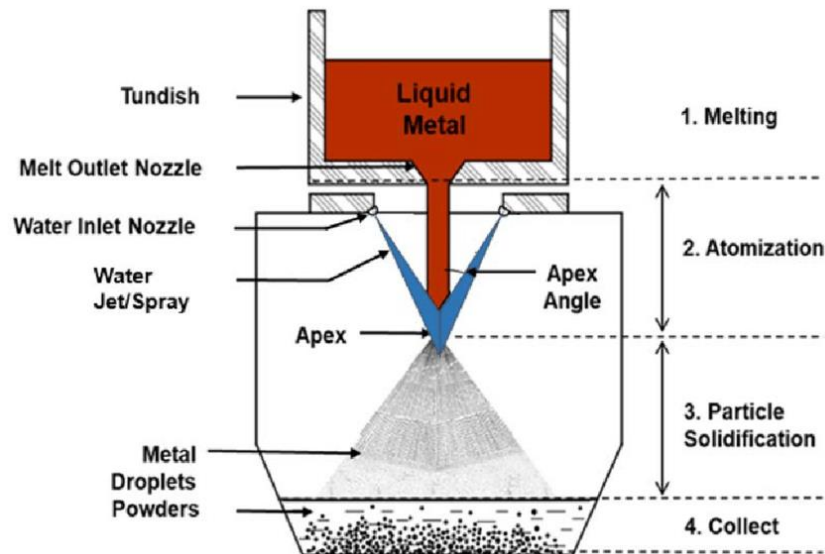


Figure 1.1 Water atomisation process (Source: Asgarian, 2019)

Different atomisation techniques produce different powder characteristics. Therefore, the nature of manufacturing process influences powder characteristics that subsequently determines the product's quality.

Additive manufacturing (AM) builds engineering components in layer-wise fashion by transforming digital designs into three-dimensional (3-D) objects using metal powder (Ligon *et al.* 2017) produced via metal production techniques such as atomisation. Some of the variants of AM include: electron beam melting (EBM) (Klassen *et al.* 2017), selective laser melting (SLM) (Kempen *et al.* 2011, Popovich *et al.* 2016), laser cladding (LC) (Bhavar 2014) and laser-engineered net shaping (LENS) (Cong and Ning 2017). Advantages of AM over traditional processes of producing components (such as casting and extrusion moulding) is that AM is quick and produces components with near-net shape that eliminates post processing (Olakanmi *et al.* 2015). Also, AM allows for alloying of metallic powders to produce new powders with improved qualities that meet the current needs of the manufacturing industry. This research aims at designing a school laboratory-scale atomising system capable of producing aluminium powder required for selective laser melting (SLM) process. The said powder could be used to fabricate various engineering components such as engine brackets (Figure 1.2), gears, cylinder heads and many other automobile components. Aluminium powder is selected for this research because it is corrosion resistant and has excellent strength-to-weight ratio (Olakanmi *et al.* 2015).



Figure 1.2 Engine bracket (Source: China manufacturer, 2020)

1.3 Problem Statement

There is shortage of training facilities and skilled manpower in the specialty of PM in Botswana and Africa as a whole. This shortage hinders development of (i) PM industry that supplies raw powdered metals for various AM processes (Rannar *et al.* 2017) as well as (ii) educational curriculum aimed at developing a critical mass of PM engineers for the industry. A critical evaluation of studies dwelling on atomisation of metal powders reveals that attention had been paid primarily to powder processing and component design only. These include effects of nozzle geometry (Singh *et al.* 2019; Chen *et al.* 2018), optimisation of the process parameters on the quality of powder (Thompson *et al.* 2016) and particle size distribution (Zhang and Zhao 2017). Furthermore, a critical review of literature dwelling on the mechanical design of metal powder atomising systems indicates that most studies had focused on nozzle design or considered various components of the atomising system separately, hence ignoring the design considerations of the *complete system*. For instance, Motaman *et al.* (2013) investigated back stream flow during close coupled gas atomization while Si *et al.* (2014) designed and evaluated a laval-type supersonic low-pressure gas atomiser. This illustrates how previous studies addressed various issues surrounding atomisation and never addressed holistic design of the system. However, there is no study that addressed the design of a complete atomising system, and this is a challenge to novices in the PM industry who are interested in setting up atomising systems for their work. The studies mentioned here are lacking in holistic information necessary in imparting PM trainees with knowledge regarding how key components of the metal powder atomising systems are designed, and how they relate to one another in a complete system. Consequently, there is a significant knowledge gap between what has been achieved (mainly customised component designs) and the aim of this research.

To provide a holistic understanding of the mechanical design considerations for a metal powder production system, this research identifies critical issues connected to the design of all key components of the system. It also provides guidance in determining geometrical and performance parameters of the key components of the

system via the employment of empirical relationships, data and computational fluid dynamics (CFD) investigation of the atomising nozzle. The novelty of this research lies in generating conceptual design framework for setting up metal atomising systems and, using relevant equations, showing explicitly how configurations for key components are attained to produce a holistic metal powder production system ready for fabrication.

1.4 General and specific objectives

1.4.1 General objectives

The primary goal of this study was to design a school laboratory-scale atomising system capable of producing aluminium powder required for selective laser melting (SLM) processing of engineering components such as an engine bracket.

1.4.2 Specific objectives

- a) To identify an appropriate atomisation technique capable of producing aluminium powder that meet specifications for SLM processing.
- b) To generate and define product design specifications (PDS) for the overall design of the identified atomising system.
- c) To formulate a conceptual design framework for setting up an atomising system to produce suitable aluminium powder.
- d) To identify, analyse and evaluate suitable system components variants capable of producing desirable aluminium powder characteristics for SLM with economic, environmental and technical benefits.
- e) To optimise the efficiency of the system via computational fluid dynamics (CFD) simulation.

1.5 Delimitation of scope

Considering the aims and objectives of this research, as well as time and financial constraints, it is important to indicate that this research has its own limitations. Consequently, it will not focus on:

- Fabrication and testing of all the system's components.
- Cyclone design and its associated theories
- Combustion furnaces and their tendency to cause air pollution.
- Detailed analysis of droplet break-up mechanism during aluminium atomisation.
- Resultant powder characterisation because no powder will be produced at this stage.

1.6 Specific themes investigated

The themes were derived from the objectives stated in Section 1.4 and they are identified as follow:

a) Determining appropriate metal atomisation technique

Variants of metal atomisation were explored and evaluated with a view to identify the best technique for producing suitable aluminium powder for SLM processing.

(b) Generation and analysis of the Product Design Specifications (PDS)

Technical requirements of the atomising system were generated to set out expectations of the complete system. These were then used to guide the conceptual design of the selected atomising system. Attributes such as costs (both manufacturing and operating), materials, gas velocity, process parameters (e.g. pressure and temperature), and design configurations were considered.

(c) Identification, analysis and selection of system components

Various system components were identified and analysed in order to identify the ones that performed better than the rest and were selected for incorporation into the final product. Using similar to approaches as adopted by Song *et al.* (2019) and Vianello *et al.* (2019), relevant evaluation techniques such as use-value analysis (UVA) and cost-

benefit analysis (CBA) were employed to justify selection, based on the requirements of the PDS. Furthermore, selection was mainly influenced by powder characteristics.

(d) Mechanical design of key components

Mechanical design solutions of the key components of the atomising system were generated in accordance with the powder and system requirements using available empirical data. Equations and scientific laws were applied in the design of components in order to obtain accurate results. During the design phase, emphasis was placed on functionality and harmonisation of related components. Each design was then evaluated via UVA and CBA with reference to the overall PDS and specific requirements for that particular component. Due to the iterative nature of the methodology followed, whenever conflict arose between components, an attempt was made to harmonise the components by modifying either the geometric design or PDS. Finally, selected components were then adopted and incorporated into the system with a view to optimising the atomisation process of aluminium powder.

(e) Computational fluid Dynamics (CFD) investigation of a critical component

A chosen critical component of the atomising system was investigated via CFD in an attempt to enhance its efficiency and ultimately that of the system to ensure efficient atomisation of the molten metal. CFD was chosen because of its ability to analyse fluid flow (either melt or atomising medium), hence its relevance to this research. ANSYS R1 2019 Fluent academic version was used and the results were incorporated into the final design.

1.7 Source of data and methodologies

The research methodology developed and adopted is presented in Figure 1.3. Existing problems in PM industry and PM education in Botswana were identified and the motivation for carrying out the study was established. The problems were analysed in order to have clear understanding of what was to be done. This was carried out by breaking down the problem into sub-components and understanding how they relate

to one another (*problem decomposition*). Post-conceptualisation aims and objectives of the study were formulated to address the problems identified.

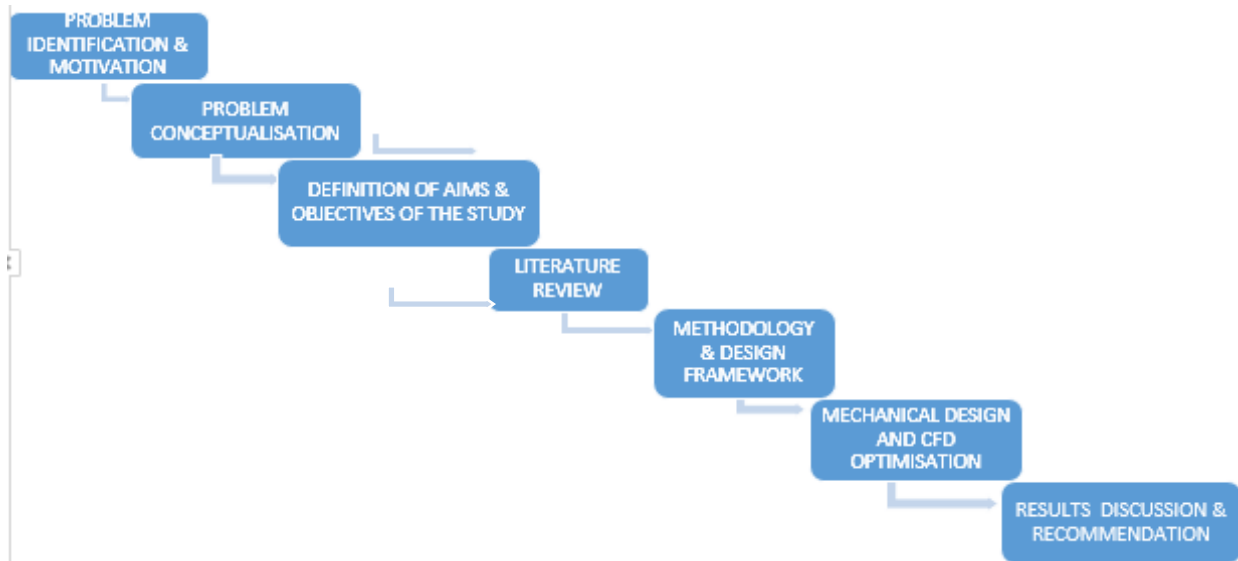


Figure 1.3 Research methodology formulated.

These were measurable, realistic and achievable within the time frame and budget set for this research. Thereafter, literature was reviewed via online and print sources that discuss various techniques of metal atomisation and SLM fabrication of components. Furthermore, the suitability of aluminium properties for SLM process was investigated. A suitable conceptual design framework for setting up the identified atomising system, mechanical design and CFD investigation methodologies were then formulated and adopted. These were guided by the objectives of this research. Subsequent to that, mechanical design of key components of the identified system was carried out. Solidworks and ANSYS (Fluent) were the design/engineering software that assisted with visual conceptualisation and process optimisation. Finally, the results were analysed and recommendations were made. The following research materials were critical to the fulfilment of the whole process:

- Internet, textbooks, journals, conference papers, online group discussions, industrial attachment, site visits and seminars.
- Software applications such as SolidWorks and ANSYS (Fluent) are important in modelling the ideas during mechanical design and optimisation of the performance of some components.
- Consultations with research supervisors.

1.8 Expected outcomes

The novelty of this research lies in: (i) formulating a conceptual design framework for setting up a metal powder atomising system and (ii) the development of mechanical design considerations for all the *key components* of the atomising system. Therefore, it is hoped that the design of a laboratory-scale atomising system that produces suitable aluminium powder required for SLM process will facilitate the training of personnel for the PM industry in Botswana. Furthermore, the conceptual design framework will assist PM trainees to fully understand how the identified atomising system works and the underlying factors influencing geometrical configurations of the key components of the system. Trainees should be able to use the outcomes of this research when selecting or fabricating components for setting up metal atomising systems to produce any other metal powder required for other AM processes of their choice. Additionally, it is hoped that this research will enable PM educators to easily explain design concepts of key components of the identified atomising system.

1.9 Outline of the dissertation

Chapter one introduces the research work carried out in this dissertation. It explains the direction that this research took to solve the problems identified. It also identifies the problems to be solved, aims and objectives of the study as well as the methodology to be adopted towards achieving the objectives of the study. Delimitation of the scope and specific themes investigated are also stated and discussed in detail. Chapter two presents a review of literature concerning the research topic and its associated themes. Journals, conference papers, lecture notes, books and other online resources

were used to obtain detailed information regarding this study. Chapter three describes the research methodologies adopted for developing the conceptual design framework for setting up an identified metal powder atomising system which produces aluminium powders that meet the specifications for selective laser melting (SLM). The methodology for mechanical design of key components of the metal powder atomising systems and the computational fluid dynamics (CFD) optimisation of the atomising nozzle are also presented. Chapter four presents and discusses findings from (i) the conceptual design framework for an atomising system capable of producing aluminium powder required for SLM process; (ii) mechanical design of the key components of the atomising system and (iii) CFD optimisation of the performance of the atomising nozzle. The results of the experiment were compiled, and a complete atomising system was assembled. Chapter five summarises findings from this study and makes recommendations for future work to be undertaken to improve the work already covered in this research.

1.10 Summary

This chapter presented the background to this research, the problem statement, study objectives and delimitation. It also highlighted how the research was carried out as well as its expected outcomes. Lastly, the layout of this dissertation is outlined.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, background information on the properties and technological application of aluminium and its alloys is presented. The implementation, merits and demerits of selective laser melting (SLM) process is described as well as its powder requirements for fabricating defect-free parts. Mechanisms of atomisation and peculiar powder properties associated with various metal powder atomising systems are also elucidated. Key components of various atomising techniques are identified, and their basic operations and design considerations are highlighted. The role of computational fluid dynamics (CFD) simulation in the design of metal powder atomising systems is emphasised. Summary of findings from this chapter is presented.

2.2 Background information on aluminium alloys

Aluminium is extracted from a mineral called bauxite, which is converted via the Bayern process to aluminium oxide and further processed to become aluminium metal (Tabereaux and Peterson 2014). Aluminium is a chemical element denoted Al on the periodic table, with atomic number 13. Its abundance makes it the third most common element in the earth's crust after oxygen and silicon. It accounts for 8% of the earth's crust by weight and has a density and melting point of 2700 kg/m^3 and 660°C respectively (Davis 2001). Al is lustrous and ductile. It is also characterised with good corrosion resistance, high electrical and thermal conductivity (Rana *et al.* 2012). Tables 2.1, 2.2 and 2.3 show the physical, mechanical and molten state properties of pure aluminium respectively. Pure Al is very soft, hence, it cannot be used in manufacturing engineering components that are capable of withstanding wear and high temperature working conditions. Therefore, this necessitates the addition of alloying elements to aluminium to improve its working properties such as ductility and toughness. For instance, Al at its melting point has a high surface tension of 0.84 N/m (Table 2. 3) which may be attributed to the availability of the oxide layer that forms naturally on its surface. High surface tension means it is not easy to break Al droplet due to greater attraction of molecules to one another (cohesion). In order to lower the surface tension

of Al, magnesium (Mg) is usually added. When alloyed with other elements, Al exhibits good properties such as improved strength, wear resistance and ductility. Table 2.4 shows effects of different alloying elements on Al.

Table 2.1 Physical properties of aluminium (Source: Royal Society of Chemistry, 2017)

Physical property	Description
Density	Light, with a specific weight of 2700 kg/m ³ .
Strength	Strength increases with addition of alloying elements such as silicon and copper.
Corrosion resistance	Naturally generating a protective oxide coating
Thermal conductivity	A very good conductor of heat.
Electrical conductivity	A good conductor of electricity
Reflectivity	Excellent reflector of radiant energy.
Odour	No taste and odour
Toxicity	Non-toxic
Magnetism	Non-magnetic
Ductility	Can be drawn into thin wires without braking.
Recyclability	100% recyclable with no deterioration in quality.
Machinability	Easily worked with low energy input using most machining methods

Major addition of alloying elements to aluminium include copper, zinc, magnesium, silicon, manganese, and lithium (Rannar *et al.* 2012). Minor additions of chromium, titanium, zirconium, lead, bismuth and iron are also added to aluminium (Davis 2001). The effects of these alloying elements are summarised in Table 2.4. Aluminium alloys are categorised into heat treatable, non-heat treatable and casting alloys. Heat treatable aluminium alloys have their strength and other properties enhanced by various heat treatment processes such as annealing, homogenising, natural aging, and artificial aging (also known as precipitation hardening).

Table 2.2 Mechanical properties of aluminium

Property	Description
Tensile strength	Between 40 and 700 MPa, depending on the property of alloying element.
Microhardness	Varies with thickness and depends on holding temperature and application
Fracture toughness	Varies with thickness and alloy properties
Wear resistance	Generally poor, but varies depending on alloying element

Table 2.3 Properties of aluminium at its melting point (Source: Cao *et al.* 2003)

<i>Properties (unit)</i>	<i>Pure Al</i>
Ionisation energy (Ev)	6
Specific heat (J/kgK)	1080
Specific heat of fusion (J/kg)	4×10^5
Melting point (K)	933
Boiling point (K)	2603
Viscosity (kg/ms)	0.0013
Surface tension (N/m)	0.84
Thermal conductivity (W/mK)	94.03
Thermal diffusivity (m ² /s)	3.65×10^{-5}
Expansion co-efficient (1/K)	24×10^{-6}
Density (kg/m ³)	2385
Elastic modulus (N/m ³)	7.1×10^{10}

Table 2.4 Effects of alloying elements on aluminium (Source: Kopeliovich 2012)

Alloying element	Effects on aluminium
Silicon, Si (up to 17%)	• Enhances castability of Al because of improved fluidity and lower shrinkage of the alloy. • Improves the strength and wear resistance of the aluminium-silicon (Al-Si) alloy produced.
Copper, Cu (up to 6.5%)	• Improves tensile strength, fatigue strength and hardness of the alloys due to the effect of solid solution hardening. • Strengthens some Al alloys (e.g. cast Al alloy 201.0) after undergoing heat treatment.
Magnesium, Mg (up to 10%)	• Strengthens and hardens the alloys by solid solution hardening mechanism without considerable decrease of ductility (e.g. Cast aluminium alloy 518.0). • Addition of silicon or zinc allows to strengthen the alloys by heat treatment, e.g. wrought aluminium-magnesium-silicon alloys (6xxx),
Manganese, Mn (up to 1.5%)	• Strengthens and hardens the alloy by solid solution hardening and dispersion hardening mechanisms (e.g. 3-series wrought aluminium-manganese alloys). • Enhances the ductility of aluminium alloys containing iron and silicon
Zinc, Zn (up to 8%)	• Addition of zinc strengthens the alloys by heat treatment (e.g. 7-series wrought aluminium-zinc-magnesium alloys) • Minimises chances of cracking.
Chromium, Cr (up to 0.3%)	• Suppresses the grain growth at elevated temperatures (e.g. during heat treatment).

	• Like manganese, Cr improves ductility and toughness of aluminium alloys containing iron and silicon • Minimises chances of stress corrosion cracking.
Nickel, Ni (up to 2%)	• Enhances hardness and strength of aluminium-copper at elevated temperatures (e.g. 2-series wrought aluminium-copper alloys and wrought aluminium-silicon alloy 4032). • Reduces the coefficient of thermal expansion.
Titanium, Ti (up to 0.35%)	• Refines primary aluminium grains (grains formed during the Solidification) due to formation of fine nuclei. When Ti and Boron are added to aluminium alloys they have a synergistic grain size refining effect.
Lithium, Li (up to 2.6%)	• Enhances strength after heat treatment. • improves modulus of elasticity and reduced density
Zirconium, Zr (up to 0.3%); Vanadium, V (up to 0.2%)	• Increase the recrystallization temperature.

Examples of commercially-available heat treatable Al alloys include 2000 (Al–Cu or Al–Cu–Mg), 6000 (Al–Mg–Si), and 7000 (Al–Zn–Mg) series alloys (Zhang *et al.* 2019). On the other hand, non-heat-treatable Al alloys are strengthened by additions of other alloying elements such as manganese, silicon and magnesium (Nellippallil *et al.* 2016). Casting aluminium alloys are commonly used for casting applications because of their relatively high fluidity and good surface finish. An example of casting aluminium alloy would be Al-Si in which silicon lowers the melting point of the alloy. Due to its lightweight, Al is commonly used for manufacturing large vessels such as aeroplanes and ships. It is also used to make household items such as cupboards, cutlery and utensils because of its non-toxicity. Because of its versatility, Al has become the most widely used metal after steel.

Current market trends indicate that there is a growing need for aluminium powders as it is utilised in fabricating engineering components via additive manufacturing (AM) process (Abdulhameed *et al.* 2019; Chua 2014; Manfredi *et al.* 2014). This may be attributed to the fact that aluminium alloy components fabricated via AM have a net or near-net shape and respond well to a variety of finishing processes (Abdulkhair *et al.* 2019). Other benefits of using aluminium powder to manufacture engineering components via AM include ability to increase strength through alloying and precipitation hardening. Consequent to this, production of sophisticated, customised engineering components from aluminium alloy powder via AM has proved to be more economical as compared to other methods of producing similar artefact. Furthermore, in aluminium powder metallurgy, the microstructure can be more improved and homogenous than in an ingot or a cast (Meluch 2009). Examples of Al components that can be produced via AM include engine pipes, cylinder heads, pistons, bearing caps, mirror brackets, mag wheels and pumps.

2.3 Additive manufacturing processing of metal powders

This section defines additive manufacturing (AM) and discusses selective laser melting (SLM) technique as one of the various AM techniques. Because of its ability to produce high quality products of intricate shapes at low costs (Olakanmi *et al.* 2015), SLM is chosen as a suitable AM technique for this research. SLM procedure, technological applications, equipment used as well as merits and demerits are also discussed.

2.3.1 The nature of additive manufacturing technology and its variants

Additive manufacturing (AM) is a process of turning digital designs into three-dimensional (3-D) objects. The process manufactures parts by using specialised computers to send signals in the form of digital data to the machine (3D printer) where powdered metal, polymers, ceramics and composites are deposited layer upon layer and selectively fused using thermal energy (Duda and Raghavan 2016). According to Olakanmi *et al.* (2015), traditional part making techniques such as casting, forging and extrusion moulding have been found to impart components with coarse grain structure and poor mechanical properties resulting from low cooling rate. In that case, such

components exhibit low strength, characterised with cracks and porosity and consequently prone to structural failure. Furthermore, these traditional manufacturing methods increase production costs and lead time as they necessitate the use of moulds, thereby, affecting the profitability and productivity of the operation. Unlike traditional part-making methods, AM provides tremendous advantages such as shorter lead times, less waste, the ability to make more complex, flexible and customised designs of light weight components as well as thin walls and shapes impossible to be produced by casting (Attaran 2017). Furthermore, no mechanical tooling, jigs or fixtures are needed during AM processing. Therefore, AM is a quick, convenient and affordable way to make prototypes as well as finished products. It is also suitable for mass production set up. All these account for increased preference for AM technologies over traditional manufacturing processes. Process and materials parameters for AM include thermal energy density, scan speed, powder characteristics and the stand-off distance (Li and Gu 2014; Zielinski *et al.* 2017; Baitimerov, *et al.* 2018). These parameters play critical role in the determination of mechanical characteristics of parts made by AM. For example, if the dissipated thermal energy density for consolidation is too low, it will not adequately melt the powdered particles, therefore, a porous product will be produced (Li and Gu 2014). Such a product will have detrimental effects on the user as it may break in use and cause adverse effects to users.

Examples of AM techniques include laser-engineered net shaping (LENS) (Cong and Ning 2017) selective laser melting (SLM) (Li *et al.* 2019), electron beam melting (EBM) (Klassen *et al.* 2017) and direct laser deposition (DLD) or laser cladding (LC) (Bhavar 2014). SLM and EBM are categorised as powder-bed fusion (PBF) methods (Mukherjee and DebRoy, 2018) in which thermal energy is used to selectively fuse layers of powder laid upon each other in order to produce a 3-D component. On the other hand, LENS and DLD are powder-deposition techniques in which the powder is deposited onto the surface of a substrate from a nozzle. Powder-deposition techniques are mainly used for both refurbishment of worn-out equipment and manufacturing of parts while PBF is applied in manufacturing of components. It is worth noting that each

AM application mentioned requires unique metal powder characteristics. In the next section, SLM technique as AM technique of choice in this research is discussed and reasons for its selection are advanced.

2.3.1.1 Selective laser sintering/ melting (SLS/SLM)

SLS/SLM is an additive, freeform manufacturing process in which laser energy is applied to powder beds to create 3-D components using the 3-D computer-aided design (CAD) description of the part geometry derived from a 2-D stack of layers representing the part (Li *et al.* 2014 Olakanmi *et al.* 2015). The layers are created by scanning a laser beam over the required cross-sectional area, thereby melting, sintering and bonding particles together in a thin lamina as illustrated in Figure. 2.1. The formed layers are then bonded using laser energy. The process is repeated until the entire stack has been bonded to create a complete 3-D model as described by the 3-D CAD input.

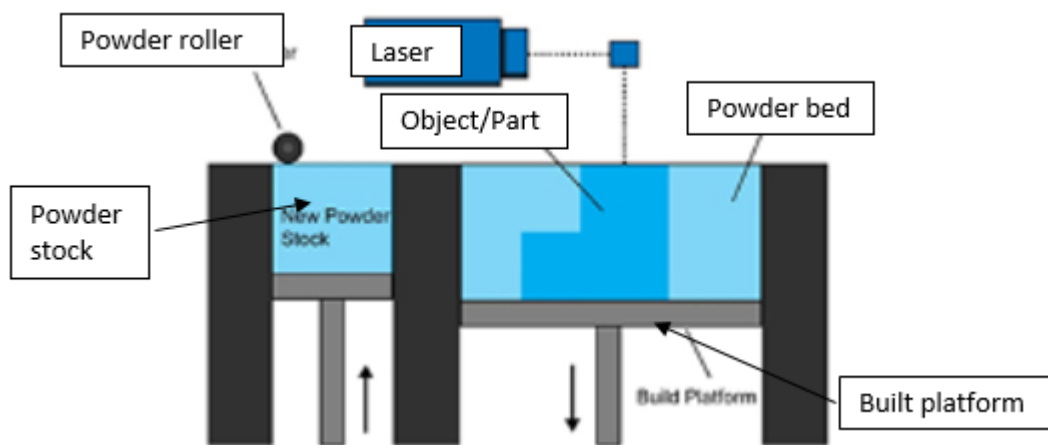


Figure 2.1 SLM process (Source: Additive manufacturing research group (AMRG) 2019)

There is a slight difference between selective laser melting (SLM) and selective laser sintering (SLS). In SLS, the laser beam is not fully melting the powder, but rather heating it to the point that the powder can fuse together at a molecular level as seen in polymers (Santos *et al.* 2018). SLM, on the other hand, is metal-based and is

implemented in the same way as sintering but uses the laser to achieve a full melting at an atomic level. This means that the powder is not merely fused together but is consolidated into a homogenous melt. SLS/SLM efficiently delivers new personalised commodities within a shorter time, hence gaining more consumer markets and increasing profit margins. Du *et al.* (2018) also pointed out that SLM has received increasing attention due to its ability to fabricate metal and composites components with complex geometry and superior mechanical properties. The process is repeatable and reliable. It can also be employed to fabricate various engineering components for automobile, aerospace, and aircraft applications. The summary of the procedure for implementing SLM process as outlined by Brandt (2017) is presented as follows:

- A layer of metal powder, typically 50 μm thick with spherical particles ranging between 30–100 μm in diameter is spread uniformly across a metal platform.
- High-speed XY galvanometers based on the computer-generated tool path are utilised to manipulate a laser beam to scan across the powder bed or newly spread layers.
- The high-powered, focused laser beam completely melts the metal powder around the selected area and fuses it to the previous layer below.
- The platform descends one-layer thickness so that the next layer can be deposited, and the whole process is repeated until the complete component is produced.

2.4 Selective laser melting (SLM) process and metal powder requirements

During SLM process, high powder packing density ensures effective particle contact which enhances thermal conductivity across the powder bed. This avoids formation of defects such as porosity, cracks, distortion and poor surface finish in the final product (Duda and Raghavan 2016). Based on materials selection, the quality of aluminium parts fabricated via SLM is affected by powder properties such as porosity of the particles, high oxide content on powder particles, powder morphology and particle size and distribution (PSD). All these powder properties are functions of the atomisation and cooling history of the powder during powder manufacturing process. They also determine the nature of laser-material interaction during SLM process (Antipas 2012).

General powder requirements for SLM processes are presented in Table 2.5, hence aluminium powder, the focus of this research is no exception.

Table 2.5. General powder requirements for SLM application

Powder requirements	Explanation
Particle size and geometry	Particle shape must be fine and spherical with particle size and distribution ranging between 30 and 100 μm
Flow-ability	A nice, even flowing powder is required. This is achievable via spherical powder particles.
Packing density	The powder must have a high packing density of at least 0.95 to eliminate porosity and promote strength and densification of the product.
Material	Must have desirable qualities as dictated by the specifications of the component to be manufactured.
Safety	Powder particles must not explode during SLM processing.
Purity	Particles must be oxygen-free and clear of any impurities to facilitate bonding.

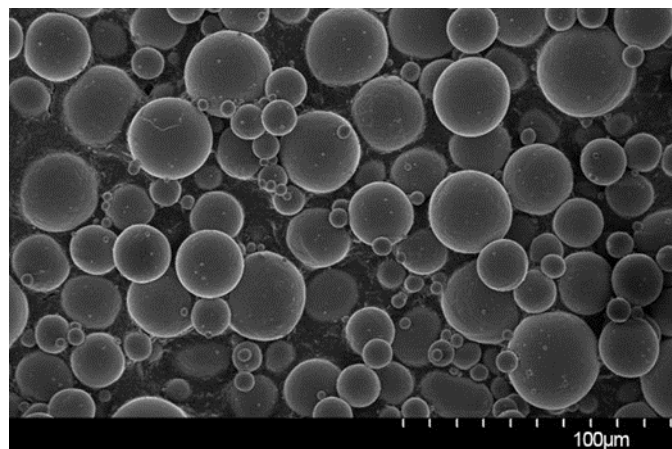


Figure 2.2 Scanning Electron Microscope (SEM) image of blended powder observed at Centre for Scientific and Industrial Research (CSIR), Pretoria, South Africa.

One of the basic principles of SLM is that a homogenous powder with a broad spectrum of particle size distribution (PSD) is recommended, so that smaller particles fit in spaces created between larger particles and improve the packing density (Abu-Lebdeh *et al.* 2019). Figure 2.2 illustrates the ideal powder (ranging from 30 to 100 microns (μm) of spherical titanium powder suitable for SLM processing. One advantage of using blended powder such as the one shown in Figure 2.2 is that it leads to formation of a fully dense component during SLM processing (Vora *et al.* 2015). Spherical powder particles are specifically recommended for SLM because of their good flowability property that provides good packing density (Prescott and Barnum 2000) that promotes formation of an extensive, well distributed melt pool. Therefore, SLM processability of aluminium powder requires that appropriate particle size distribution (PSD) ranging between 10 and 60 μm be adopted so that correct layer thickness (70 μm) which promotes complete melting of powder particles across the layers is achieved. Inappropriate particle size distribution result in having inappropriate layer thicknesses that lead to dissipation of insufficient laser energy to the powder bed. This eventually leads to formation of large and interconnected pores in the SLM fabricated structure that degrades the quality of the component produced.

The use of larger particle sizes (over 100 μm) results in increased balling phenomenon which is an undesirable processing condition. This occurs when the surface tension gradient and the thermo-capillary convection are changed due to oxide contamination around the edge of the melt pool. (Dai and Gu 2016). Fine metal powder with particle size less than 0.1 μm is classified as nano-powder (Dunkley 2013). However, very small particles sizes are difficult to deposit because they have a tendency to stick to one another or to the equipment (Lu 2015), hence difficult to process. Additionally, fine particles are subjected to higher hardening velocities during powder production and may as a result not effectively bond together, therefore compromising the quality of the component or surface finish produced. This can occur as a result of varying cooling rates that makes it difficult for adjacent layers to effectively bond. For that reason, nano-powders are not recommended for SLM applications.

Furthermore, high oxygen content in aluminium powder particles can make bonding difficult due to high melting temperatures of the oxides that make it impossible to completely melt the powder (Flumerfelt 1998). This situation will result in residual porosity that will weaken the mechanical strength of the component. This is because oxidation of aluminum is an exothermic reaction, thus delaying solidification in the region of the oxide and consequently leading to porosity. Also, very small particle size ($38\text{ }\mu\text{m}$ or less) are highly susceptible to oxidation during heating, therefore, optimum particle size must be ensured at all times (Niu and Chang 1999). Various strategies have been suggested to overcome oxidation during powder production and SLM processing. One such strategy involves the utilisation of an inert gas (such as argon, helium or nitrogen) during powder production and SLM processing to provide an inert environment.

In summary, a good aluminium powder for SLM processing is expected to have a spherical morphology, particle size distribution within the range of $+45\text{-}70\text{ }\mu\text{m}$ (Brandt 2017) and oxide content below 0.1wt% (Upadhyaya 2007; Olakanmi *et al.* 2015), with a view to promoting appropriate laser-powder interactions. Such powder characteristics are suitable for SLM as the powder flow and particles bond easily during processing.

2.5 Atomisation of melts

Metal powder production techniques include mechanical comminution (Yang 2015), carbothermal reduction (Orlandi *et al.* 2017; Shen 2015) atomisation (Dunkley 2013) and electrolysis (Zhang *et al.* 2017). However, atomisation is considered in this research as the best technique to produce the required aluminium powder because of its ease of control of particle shape and size with low energy consumption and high production yield (Dunkley 2013; Palmer 2018). Also, freedom of alloying makes it easy for new composite materials to be formed, hence excellent mechanical properties can be imparted. Atomisation is the breaking of molten metal into tiny droplets that form powder particles on solidification (Dunkley 2013). Process parameters such as component design, pressure of the atomising medium, superheat temperature and

melt velocity play a critical role in the development of powder characteristics (Zhao 2006; Dunkley 2013; Thompson *et al.* 2016). According to Thompson *et al.* (2016), metal powder atomisation techniques have become dominant methods of powder production for various metals and their alloys required for SLM process. Therefore, three atomisation techniques are discussed in this section to provide necessary information for making informed decision regarding the selection of appropriate atomising technique that produce aluminium powders which meet SLM requirements. Variants of atomisation are discussed as follow:

2.5.1 Water atomisation

According to Dunkley (2013), water atomisation (WA) involves the use of high-pressure water jets to break the molten metal stream into tiny particles that solidify to form powder on cooling (Figure. 1.1). During WA, the molten stream is broken by the impact of high velocity water jets that strike the molten stream, thereby creating some molten fragments that subsequently cool and solidify into metal powder. Water is used because of its high viscosity and quenching ability. This technique is widely used for the production of both ferrous and non-ferrous metal powders. When used for atomisation, water produces highly oxidised metal powder particles (Persson *et al.* 2012) that are difficult to melt and bond due to the persistent oxide layer. Powder particles produced through WA are more irregular than gas atomised powders, and also have satellites (Dunkley 2013). This is due to the solidification rate which is more rapid in WA than in gas atomisation. Process parameters such as pressure and velocity of the water, melt superheat, water and melt flowrate, water and melt velocity, influence the quality of the powder produced. Similar Raleigh-Plateau mechanism as will be explained in Section 2.5.2 governs the break-up of molten metal ligaments formed as the molten droplet falls through the height of the atomising chamber. Because of their irregular shapes, water-atomised powder particles are difficult to lay and they produce porous and low density products as a result of poor packing density. Furthermore, powder particles produced via WA have the potential to explode during laying because of rapid hydrogen emission (Joy 2015).

2.5.2 Gas atomisation

The working principle of gas atomisation is the same as in water atomisation, the only difference being that instead of water, high velocity gas is used as the atomising medium. Oxidation-free, fine and spherical metal powder particles can be produced when inert gases such as argon (Ar) or helium (He) are used as the atomising medium (Alvarez *et al.* 2018). However, when natural air is used as the atomising medium, the resultant powdered particles become oxidised (Antipas 2012). Nitrogen (N) has also been used as atomising gas in some instances and has been found to pose a health hazard due to its asphyxiation effects and its ability to react with some metals to form nitrides. Table 2.6 summarises the properties of various gaseous media used in atomising metal powders as well as their effects on the quality of the powder. During the process, high pressure gas impinges the molten metal droplet and breaks it into tiny particles that cool and solidify to become metal powder (Thompson *et al.* 2016). This eventually gives rise to a process termed *primary atomisation*. The high kinetic energy in the impinging gas jet exerts enormous force on the surface of the aluminium melt droplet, thereby overcoming the surface tension of the droplet that ultimately breaks into tiny droplets. Due to drag and other aerodynamic forces, the droplets further disintegrate into finer particles that cool and solidify to become fine powder, and the process is called *secondary atomisation*. Figure 2.3 illustrates the gas atomising system.

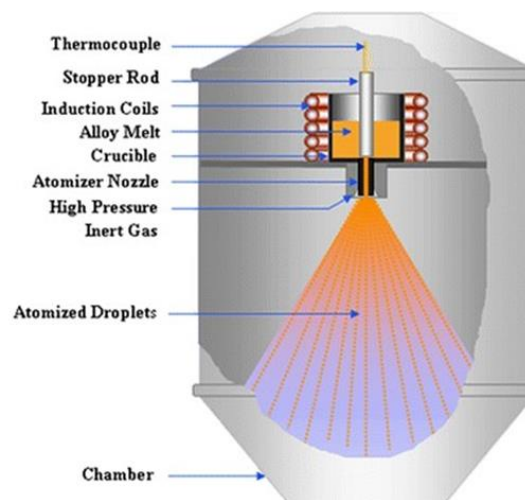


Figure 2.3 Gas atomising system (Source: Zheng *et al.* 2009)

Table 2.6: Common atomising gases and their properties

Properties	Atomising gases			Comment
	Argon (Ar)	Helium (He)	Nitrogen (N)	
Molecular weight (kg/mol)	0.04	0.004	0.028	Low molecular weight means it is cheaper to use the gas for purging since it will not require immense pressure to propel it. Heavy gases are difficult to propel. According to the values here, He has the lowest molecular weight.
Density (kg/m ³) at STP	1.449	0.164	1.165	Similar to molecular weight, a dense gas will be expensive to propel because of the high pressure required to propel it. In this case N is heavier than all the gases discussed here.
Thermal conductivity (W/m.K)	0.018	0.15	0.26	During gas atomisation, good thermal conductivity means the gas can allow heat energy to pass through it, thereby minimising chances of melt freeze at the melt tip.
Specific heat (kJ/kg.K) at constant pressure	0.5203	5.19	1.039	A high specific heat means lower temperature rise hence lower expansion. High gas expansion is beneficial to gas atomisation because gas molecules will gain kinetic energy required to manifest into high velocity necessary for efficient atomisation.

Garcia-Escorial and Lieblich (2014) elucidated that with suitable process parameters, gas atomisation is capable of producing clean, fine and spherical metal powders with particles less or equal to $20\text{ }\mu\text{m}$ in diameter. Spherical powder particles are achievable because droplets have more time to spheroidise before solidification as a result of adequate falling distance, unlike in water atomisation where cooling is rapid. Dombrowski and Johns (1963) carried out an investigation to model the liquid jet disintegration in an attempt to elucidate the phenomenon of gas atomisation. The outcome of their investigations indicated that the bulk molten metal droplet is disrupted as the droplet undergoes a dispersed phase due to the action of external forces exerted by the atomising atmosphere.

Although, the droplet is deformed, the surface tension manage to keep the droplet in shape, while on the other hand, viscosity acts against shape modification. During this phase, the disturbances caused by the aerodynamic and jet forces overcome the resisting components and the droplet becomes unstable and break into even tinier particles that cool and solidify to collectively become metal powder. The falling distance which is determined by the height of the atomising chamber (Yule and Dunkley 1994) has an effect on the cooling and solidification rate of the atomised droplets. This break-up mechanism is illustrated in Figure 2.4 where t_{def} is the time it takes for the initial spherical droplet to deform into an elongated cylinder, due to the drag on the droplet as it falls. The $t_{\text{break-up}}$ is the time it takes for this unstable, elongated cylinder to break-up into smaller spherical droplets. This obeys the Plateau-Rayleigh instability principle which is the physics that governs the breakup of the stream of molten metal during water or gas atomisation. According to the Plateau-Rayleigh instability principle, a vertically falling stream of water will break up into drops if its wavelength is greater than about 3.13 to 3.18 times its diameter (Breslouer 2010).

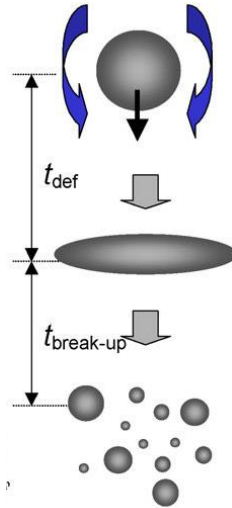


Figure 2.4 Gas atomisation melt droplet break-up model (Source: Mi, *et al.*, 2007)

Note the deformation of the droplet due to external forces acting on its surface before it breaks into smaller droplets of various sizes.

2.5.3 Centrifugal Atomisation

Centrifugal atomisation is a technique in which molten metal is thrown outwards by rotational (centrifugal) forces and broken into tiny droplets that cool and solidify to become powder (Tian *et al.* 2017). There are many approaches of implementing centrifugal atomisation. In this section, only two approaches namely *spinning disk* and *plasma-rotating electrode process* (PREP) are discussed. In the spinning disk method, the molten metal is deposited into a high-speed rotating disk. The melt is then thrown outwards by centrifugal forces that causes it to break into tiny particles (Figure 2.5a). As for PREP, a consumable cylindrical electrode is rotated at high speed while at the same time it is melted by an arc at the other end (Figure 2.5b). The molten metal in the periphery of the bar is then thrown outwards and broken into tiny droplets that form powder on cooling and solidification (Palmer 2018; Yefimov 2009). Helium gas is used as shielding gas to avoid contamination by tungsten that may compromise the purity of the powder produced. It also enhances arc stability and aids in convective cooling of the droplets. Powders atomised by this technique are of high purity since there is no contamination of the molten metal. The interplay between the centrifugal forces and the drag facilitates the formation of spherical and satellite free powder particles.

Particle size usually ranges between 1 to 600 μm with a median particle size of about 200 μm (Palmer, 2018). This atomisation technique is capable of producing highly spherical powder particles.

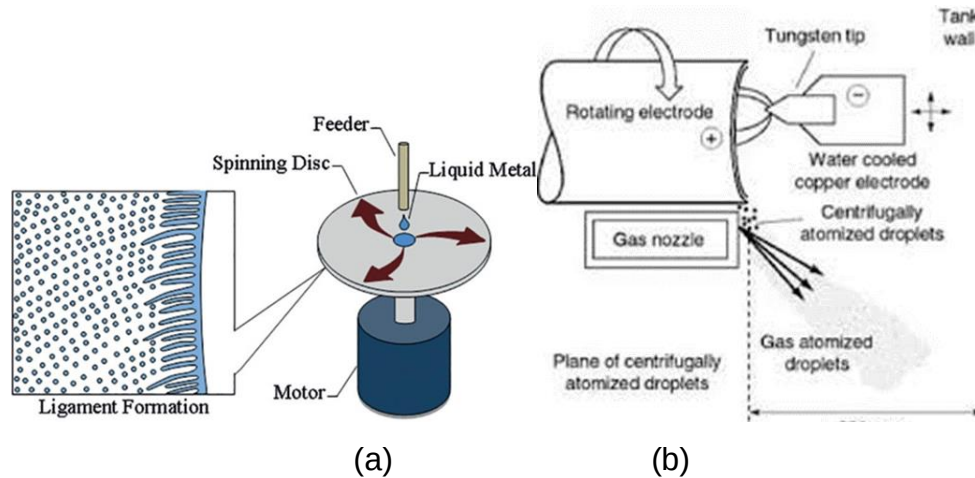


Figure 2.5 Centrifugal atomisation **(a)** spinning disk (Source: Graco Inc. 1995), **(b)** plasma-rotating electrode (Palmer, 2018)

Tian and co-investigators (2017) pointed out that the technique has been applied in the production of tin, lead, aluminium, magnesium, zinc, titanium, nickel and cobalt and their alloys. It has been established that when spinning disk method is applied, angular speed influences the morphology and yield of the resultant powder. This is because the droplet is “thrown out” at high velocity and the impact of the droplet as it hits the air at high velocity crashes into tiny droplets (Sungkhaphaitoon *et al.* 2012). This shows that both primary and secondary atomisation occur during spinning disk centrifugal atomisation. Primary atomisation occurs first when the melt is thrown out of the spinning disk, while secondary atomisation occurs as the droplets further disintegrate as a result of the collision with aerodynamic forces. A summary of the properties of powders obtained from different atomisation techniques is presented in Table 2.7.

Table 2.7 Summary of atomisation techniques

Atomisation technique	Particle size distribution (PSD)	Particle shape	Powder purity	Cost
Water	Broad spectrum (60-500 μm)	Irregular with satellites	Highly oxidised	Cheap
Gas (inert)	Narrow spectrum (1-150 μm)	Spherical	High purity	Expensive
Centrifugal	Broad spectrum (1-600 μm)	Highly spherical	High purity	Expensive

2.6 Critical components in atomisation system and their design considerations

Each of the different atomising techniques discussed in Section 2.5 has critical components that make it possible to produce metal powders with specific characteristics. Critical components in metal powder atomisation systems include (i) the melting or holding furnace, (ii) the atomising device (the nozzle or the spinning disk) and (iii) the atomising chamber. This section aims at describing the operations of the critical components of the metal powder atomising systems as well as special design features that allow each of them to produce its particular powder characteristics.

2.6.1 Operations and design considerations of a furnace

Pfeifer (2017) described a furnace as a device used in heat treatment of materials so that the materials attain the requisite properties (mechanical, physical, or chemical properties) for the intended application. Furnaces can be classified in various ways depending on several factors such as source of energy, size and shape, charge material, operating parameters and many others (Mullinger and Jenkins 2014). However, this analysis considered the heating/holding furnace only because of its relevance to this particular study. A heating/holding furnace is a furnace that heats and holds the melt for further processing, without necessarily having to transfer the melt. An ideal heating/holding furnace for aluminium melt ensures effective heating of the aluminium charge material, minimize energy consumption and maintain the melt's superheat temperature (Strauss and Miller 1996). An appropriate heating/holding

furnace is also expected to ensure minimal or no melt contamination as well as high yield. Bureau of Energy Efficiencies (2017) in India categorised furnaces into two types, based on heat source. These are the *combustion type* that uses fuels such as coal, oil and gas, and the *electric type* such as electric arc and induction furnace that uses electrical energy. Taking environmental factors and legislation into considerations, this research focused on electric type of furnaces (induction furnace, electrical crucible furnace and electric arc furnaces) as shown in Figure 2.6 in order to minimise air pollution.

2.6.1.1 Induction furnace (IF)

An induction furnace (Figure 2.6a) is an electrical furnace comprising of a non-conductive crucible that holds the charge material, with a copper tube wound around the crucible in which runs the electric current (Campbell 2013) that heats and melts the charge material. During the melting process, electromagnetic induction heats the electrically conducting charge material through heat generated in the crucible by eddy currents. Induction furnaces have different capacities depending on the scope of use (industrial or laboratory), and they range from less than one kilogram to hundreds of tonnes capacity.



Figure 2.6 Different electric furnace designs **(a)** Induction furnace (Physicsmax.com 2019), **(b)** Electric crucible furnace, (El-Akruti *et al.* 2016) **(c)** Electric arc furnace (Zimmermann *et al.* 2018)

They are used to melt iron, steel, copper, aluminium and other precious metals. Besides their cleanliness (no combustion), induction furnace heating has low energy consumption and allows controllable melting process in comparison with many other methods of melting metal (Anaidhuno and Mgbemena 2015). Controllability of the heating process prevents loss of valuable alloying elements. In response to issues of environmental sustainability and green technology as advocated by governments around the world, the furnace is now gaining popularity amongst modern foundries. It is slowly replacing the conventional use of cupolas that emit dust and other pollutants (Biswas *et al.* 2001). Induction furnace usage in foundries is known to have a serious challenge of lack of refining capacity. Therefore, charge materials should be free of impurities to prevent oxidation (Bala 2005) that may contaminate the powder particles and result in losing some alloying elements (Hocine *et al.* 2009). In that case, there would be a need for re-addition of the alloying elements to the melt, thereby increasing production costs.

2.6.1.2 Electrical Crucible Furnaces (ECF)

This is one of the oldest and simplest types of furnaces used in foundry work. The metal charge is placed in the conductive crucible in which the charge is heated via conduction through the walls of the crucible (Webster 1980). It uses electricity as a source of energy for heating. These furnaces are available in different sizes, hence suitable for even small batches of low melting point alloys of non-ferrous metals (Shyamal and Swartz 2016). Figure 2.6b shows a small version of an electrical crucible furnace used to melt aluminium for casting projects in a school foundry workshop. However, they are rarely available as heating/holding furnaces.

2.6.1.3 Electric Arc Furnaces (EAF)

Electric arc furnaces (EAFs) are widely used for production of molten metal by melting scrap metals and adjusting their chemistry (Madias 2013; Shyamal and Swartz 2018). Melting metal using EAF is a high- energy intensive, complex batch process (Khodabandeh *et al.* 2017). It operates via an electric arc (an electrical disintegration of gas) in order to produce a continuous electrical discharge. Electrodes are used to

transfer electrical energy to the charge material. In an arc furnace, the feedstock is directly exposed to an electric arc as shown in Figure 2.6c, and the current in the furnace terminals passes through the charged material thereby melting it.

Table 2.8 Types of electric furnaces and their properties

Design considerations	IF	ECF	EAF
Melt contamination	No chances of melt contamination	High chances of melt contamination	High chances of melt contamination
Heat loss	Minimum heat loss	High heat loss	High heat loss
Power consumption	Low power consumption	High power consumption	High power consumption
Yield	Low yield	High yield	High yield

Table 2.8 summarises the operation as well as the quality characteristics of melt obtained from different furnaces on the basis of design considerations which include degree of melt contamination, heat loss during heating/holding, power consumption and melt yield. These four are the key design considerations when selecting a furnace for melting metal for atomisation.

2.6.2 Operations and design considerations of an atomising device

Depending on the atomisation technique selected, the atomising device may either be the atomising nozzle (for water or gas atomisation) or the rotating disk (for centrifugal atomisation). Therefore, design configuration of the atomising device is a very critical issue in setting up an appropriate atomisation system required in this research. Because of that, operation and design considerations for atomising devices of water, gas and centrifugal atomisation are discussed with in order to understand how the devices operate and their design considerations.

2.6.2.1 Water and gas atomising device

Both water and gas atomisation techniques are combined in this section because of similarities in their operations, the only difference being the atomising medium. As

already stated in Section 2.5.1 and 2.5.2 respectively, water atomisation uses water as atomising medium while gas atomisation uses gases. The critical atomising device in these techniques is the atomising nozzle (Thompson *et al.* 2016; Si *et al.* 2014). A nozzle is a device designed to control the direction of flow, flow rate, shape and size of a melt droplet on entering the atomising chamber (Duangkhamchan *et al.* 2012). The type and configuration of atomising nozzles play a pivotal role in particle characterization (Unal 1987; Mullis *et al.* 2011). In aluminium atomisation, atomising nozzles work by regulating and exerting certain amount of disturbances caused by the atomising medium (water or gas) on the surface of aluminium melt droplets. Consequently, it disintegrates the droplets into tiny particles before they rapidly cool and solidify to become aluminium powder (Dunkley 2013).

Atomising nozzles can be of different design configurations namely: free fall (Figure 2.7a) and close-coupled or confined (Figure 2.7b) (Neikov 2009). In free fall atomisation, the melt is atomised upon travelling a certain distance after leaving the nozzle tip. In a close-coupled atomising nozzle, the melt is impinged immediately as it leaves the nozzle tip. One obvious advantage of the free fall nozzle design is that, it is easier to control the gas-melt interaction as compared to a close-coupled design due to time allowance given before the gas-melt interaction. It is important that functional requirements of atomising nozzles are clearly stated. This is because it has a significant effect on the overall performance of the system, as well as metal powder characterisation (Dunkley 1989). Small sized nozzles produce finer powders, while large sized ones produce coarser particles (Anderson and Terpstra 2000). Neikov (2009) discovered that the use of free-fall nozzle is not economical due to high loss of thermal energy as a result of time taken before the gas jet hits the melt, hence high chances of cooling before the gas can break the melt. This nozzle also produces low quality metal powders as a result of a broader powder particle distribution. This is because the particle size distribution is difficult to control and the process efficiency is lower. On the other hand, close-coupled atomization has the advantage of allowing the melt ligament to be more effectively disrupted than in the free-fall atomization due to the proximity of both the gas jets and the melt delivery nozzle (Antipas, 2012). The

confined nozzle configuration yield higher atomisation efficiencies with regard to smaller and narrow particle size and distribution (Antipas 2012). Mullis and co-investigators (2011) corroborated that the rapidly solidified metal powder formed as a result of high cooling rate associated with this particular technique, exhibits fine powder particles with excellent chemical homogeneity and extended solid solution.

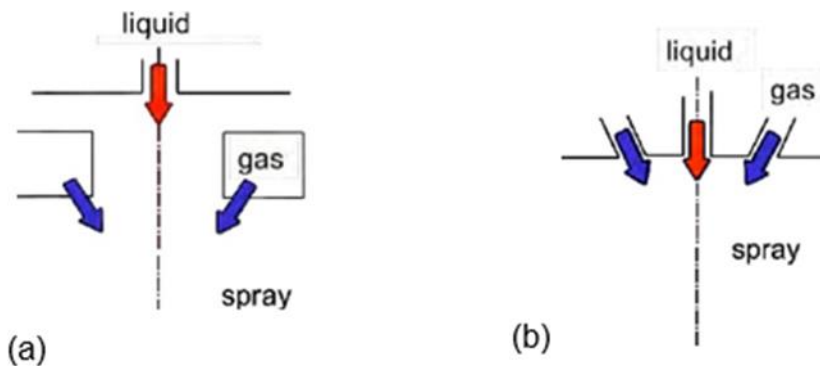


Figure 2.7 Schematic diagram of **(a)** Freefall nozzle and **(b)** Close-coupled nozzle (Source: Fritsching and Uhlenwinkel 2012).

With regard to flow dynamics of the atomising medium, atomising nozzles are categorised into diverging-converging (DC) and converging-diverging (CD) nozzles, with the latter being referred to as *de-Laval* nozzle (Allimant *et al.* 2008). A CD nozzle is tapered (converge) towards the throat and diverge after the throat, while DC nozzle converge at the nozzle exit. DC nozzles decelerate the atomising gas, while CD nozzles accelerate it (Rao *et al.* 2016). In simpler terms, a CD nozzle will increase the velocity of the atomising medium and reduce its pressure while DC will do the opposite. In a CD nozzle, this promotes the breakdown of melt droplet due to aspiration pressure at the nozzle tip that allows the melt to flow down easily and thereby preventing freezing of the melt in the melt path. Figure 2.8 shows various design considerations for a gas or water atomising nozzle. It shows the apex angle (α) which is the angle from which the atomising medium hits the melt, the protruding height (h) and the melt path that directs the melt to the impinging atomising medium (β). Other design considerations for an atomising nozzle are throat diameter, number of holes and expansion area.

The apex angle (α) also plays a significant role on the determination of particle size and distribution. Smaller (α) produces coarse particles while larger (α) produces fine particles (Jiao *et al.* 2017).

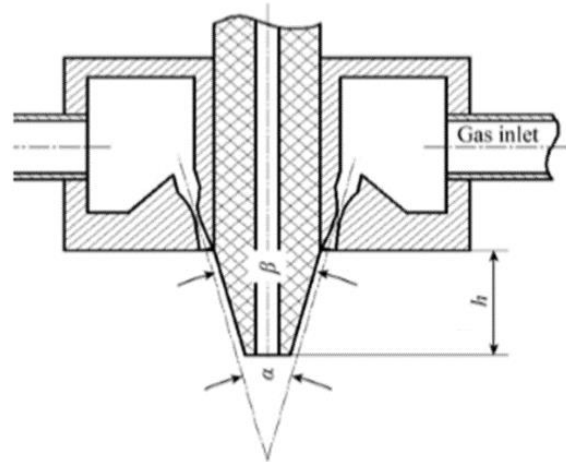


Figure 2.8 Nozzle design considerations for water and gas atomisation processes showing the gas inlet, apex angle (α), melt path (β) and protruding height (h) (Source: Xin-Ming *et al.* 2009)

Various investigators including Sofuoglu *et al.* (2013) and Thompson *et al.* (2016) have studied effects of apex angle on particle size distribution, while Mir *et al.* (2017) studied the relationship between the throat diameter and the expansion area. On the other hand, Unal (1987) investigated the influence of nozzle geometry in gas atomisation of rapidly solidified aluminium alloys. These studies and many others were carried out to establishing how nozzle configurations affect powder characteristics, hence their relevance in this particular research.

2.6.2.2 Centrifugal atomising device

Unlike gas and water atomising techniques, centrifugal atomisation uses the spinning disk and motor as the critical components of the system. Additionally, process parameters such as slope angle of atomiser wall and flow rate of cooling water play an important role in particle size (Zhao 2006). In spinning disk centrifugal atomisation, it

is very important to consider the configurations of the spinning disk and motor because smaller droplet sizes are produced when the disk rotation speed and disk radius are increased (Zhao 2006) and for larger droplets the opposite is true. Since the motor provides the rotation speed, attention must be paid when making specifications for the motor. In order to achieve smaller particle sizes (less than $100\mu\text{m}$), a very powerful motor that can attain speed around 18 000 revolutions per minute (rpm) is recommended (Zhao 2006). Experience has shown that motors with very high rpm rating such as 60 000 rpm produce very fine powder particles but pose a challenge of stability (Zhang and Zhao 2017). Because of the enormous power, the motor “shakes” the whole system and end up disturbing the process, thereby compromising the quality of the metal powder produced.

It is desirable to have a larger radius of the spinning disk that will accelerate the metal droplet towards the edge of the disk before it is finally flung out. The maximum diameter of the disk is determined after considering the power of the motor because it is the motor that provides the rotational speed needed to throw out the droplets. The slope angle on the spinning disc ensures that the droplet is not released prematurely as that may lead to production of large, irregular powder particles (Zhao 2004). This implies that the slope angle has to be large enough to ensure sufficient spread of the melt on the disk. Xie *et al.* (2004) suggested that a slope angle ranging between 60 to 70° produces very fine particles of less than $20\mu\text{m}$. Therefore, the smaller the slope angle, the larger the droplet size.

Because of the high temperatures experienced during centrifugal atomisation, the system is normally water-cooled because this atomising technique is usually used for high melting temperature metals such as titanium. Water cooling creates a solid layer (0.1 to 2mm) of the metal being atomised on the surface of the disk so that the disk is not eroded as that may contaminate the melt. Therefore it is important to ensure that correct and consistent flow rate of the water is attained throughout the process. It is difficult to set a standard flow rate because flow rate of the cooling water is influenced by many factors such as the pouring temperature of the molten metal, density of the

water, specific heat of water, volume of the water, temperature of the disk at interaction with the cooling water and temperature of the disk at interaction with the melt. These are not constant and varies with different set-ups; hence the flow rate is usually estimated after considering the above-mentioned factors. In view of the above, it is clear that the following considerations have to be made when setting up a centrifugal atomiser:

- Selection of the right motor with the correct power,
- The right diameter of the disk that will match the power of the selected motor,
- The right slope angle that will produce the desired droplet size and
- The right flow rate of the water coolant.

2.6.3 The atomising chamber

The atomisation process occurs inside the atomising chamber under controlled process parameters (Thompson *et al.* 2016). All the sub-systems involved in aluminium atomisation are assembled into the atomising chamber. An average atomising chamber (atomising tower) usually ranges between 1 to 9 meters in height and approximately 1 meter in diameter depending on the metal powder particles requirements. It is crucial that the chamber be of a correct height because the height assists during secondary atomisation by allowing the molten droplet to fall through some distance and solidify before collecting at the bottom of the chamber. There are two types of atomising chambers, namely horizontal (Figure 2.9a) and vertical (Figure 2.9b). The difference between the two is that the vertical atomising chamber minimises the formation of satellites because it ensures that particles solidifies before collecting at the bottom of the chamber while a horizontal one does not offer that. Therefore, the horizontal atomising chamber (Figure 2.9a) is *rarely* used in atomisation of molten metals. The atomising tower is usually made from stainless steel sheets due to its high thermal and corrosion resistance (Krauss 2015). Austenitic type of steel, stainless steel 304 (Singh *et al.* 2018) is mainly used because of its characteristic combination of weldability and formability. This type of steel contains chromium and nickel that enhance corrosion resistance and prevents oxidation of aluminium.

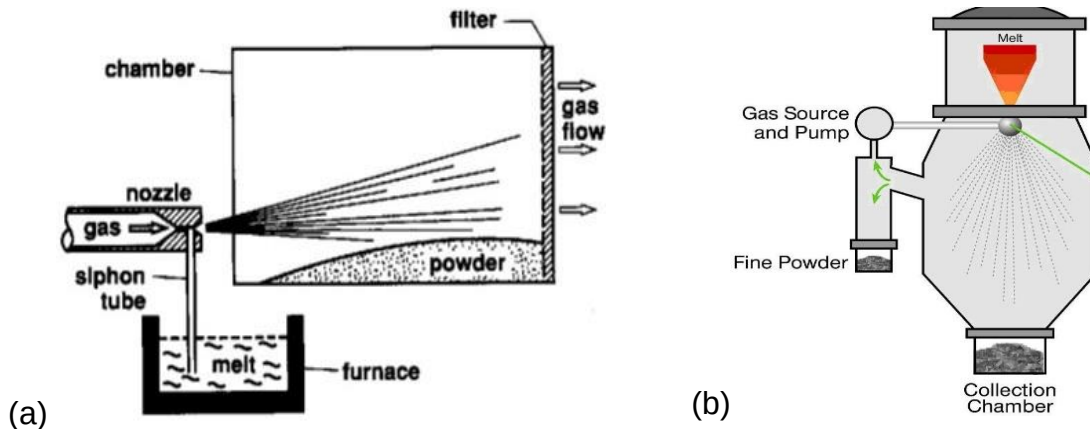


Figure 2.9 Types of atomising chambers, **(a)** Horizontal atomising chamber (Rejeesh 2014) **(b)** vertical atomising chamber (German and Vassileva 2007).

2.7 The role of computational fluid dynamics (CFD) in designing atomisers

During the design of metal powder atomising devices, accuracy is of great importance since design errors may give rise to production of powder with undesirable characteristics. This may consequently lead to loss of profit and production time. The application of computational fluid dynamics (CFD) simulation to the design of metal powder atomising systems is aimed at ensuring design accuracy of components during their operations. Optimising the performance of a metal powder atomising system prior to manufacture ensures that it is manufactured to the best possible configurations. Consequently, this saves time, energy and materials that would have been wasted through production of dysfunctional components (Slagter 2011).

There are various simulation software and they include Ansys, SimScale, Autodesk and SimFlow. Different software applications are used for different investigations. Therefore, it is important to validate and establish the relevance of a simulation software to a study before it is used. Computational fluid dynamics (CFD) simulation is one of the many simulation techniques that engineers use to determine fluid flow performance of their designs prior to realisation (Zhai 2006; Cheshmehzangi 2017). Numerical modelling of various studies on flow of atomising medium in metal powder atomising systems is based on analytically solving a discretized set of Navier-Stokes

equations of momentum, conservation and continuity. For instance, Xin-Ming *et al.* (2009) investigated the effect of varying atomization gas pressure on the gas flow field in supersonic gas atomisation using close-coupled nozzle, while Motaman *et al.* (2013) reported “the numerical and experimental investigation into the effects of different gas jet mismatch angles (for an external melt nozzle wall) on the back-stream flow in close coupled gas atomisation.” Furthermore, Thompson *et al.* (2016) employed CFD to predict the effect of process parameters on the particle size distribution (PSD) of metal powder. Aydin and Unal (2011) and Zeoli and Gu (2008) optimised C-D nozzle design via numerical modelling using CFD. Therefore, CFD is appropriate in this study because the research intends to investigate and optimise fluid flow in an atomisation technique that produces powders which meet SLM requirements.

2.7.1 Computational fluid dynamics (CFD) codes and their applications

Different CFD codes are available for use depending on the stage of simulation. These include solvers, grid generation, visualisation and solver coupling. Solvers are the solution algorithm used to solve the energy and continuity equations governing the design and the process being simulated (Acharya 2016). Examples of solvers include: Fluent which is a 3D-solver for incompressible Navier-Stokes in fluids, CFD2D which is a 2D-solver for incompressible Navier-Stokes, CFD2k which is a 2D-solver for compressible ideal gases, and CFDPack which is a collection of academic codes. Grid generation codes are codes that are applied when generating grid or mesh for the model. These include: Engrid, NETGEN and GMSH. Selecting a grid generation code depends on what the investigator wants to achieve. However, fine grid is desirable in most simulations in order to improve accuracy of the results (Baker *et al.* 2019). On the other hand, visualisation codes are CFD codes that are used as postprocessor for the analysis and visualisation of what is being investigated and they include COVISE and DISLIN. The visualisation codes follow the grid texture, as such the user is limited in making any choices regarding the visualisation code to use. So, these are the basic CFD codes that help in optimising a design prior to its manufacture. It is worth-mentioning that with the recent CFD software packages, governing equations are

solved simultaneously as the data input is done, hence the investigator is relieved of the burden of discretising governing equations.

In summary, CFD is concerned with predicting fluid flow, heat transfer, mass transfer, and related phenomena by solving the mathematical equations which govern these processes using a numerical process (Bakker and Marshall 2006). At the end of the experimentation, CFD results are used for:

- Conceptual studies of new ideas to solve design problems.
- Detailed product development.
- Troubleshooting in an endeavour to overcome some shortcomings.
- Rectification of mistakes and redesigning components before actual manufacture
- Complementing testing and experimentation.
- Reducing manufacturing costs, time and labour required in the laboratory.

CHAPTER 3: METHODOLOGIES

3.1 Introduction

This chapter discusses different methodologies for different phases of this research. Such methodologies are to be followed in order to ultimately develop an appropriate atomising system capable of producing aluminium powder that meets the stated requirements. Initially, the methodology for conceptual design framework for setting up an atomising system is generated so that it will guide mechanical design of system components. Then follows the methodology for mechanical design of components to guide the procedure for developing various system components. Next, methodology for computational fluid dynamics (CFD) investigation of the critical component of the identified atomising technique is generated to direct procedure for investigating how certain design configurations of such component affect its efficiency. Lastly, a summary of the methodologies is given. It is worth noting that at this stage, an appropriate metal powder production technique has not been identified.

3.2 Methodologies

3.2.1 Methodology for conceptual design framework

The performance objective of the atomising system developed in this research was to produce aluminium powder that meets selective laser melting (SLM) requirements for fabricating various engineering components such as an engine bracket. Literature sources that discuss production of aluminium powder and SLM processes were studied and SLM requirements were identified. Following that, a suitable aluminium powder production technique was identified and specifications for the system and its sub-systems were developed. Subsequently, product design specifications (PDS) for guiding generation of sub-system variants that meet the overall system requirements were drawn up and elaborated. Sub-system variants were developed via brainstorming and similar designs and peer-reviewed journals. Thereafter, selection of the sub-system variants was implemented via the use of cost-benefit analysis (CBA) and use-value analysis (UVA) techniques (Pahl *et al.* 2007; Fernandes 2015). Evaluation matrices employing both UVA and CBA principles were used to identify and select

variants that conform to most or all of the PDS attributes. During selection, attention was paid to economic viability and process efficiency. If the variant fell short of the PDS and it was evident that it could add value to the system, it was refined until there was harmony between the PDS and the solution. This made the methodology iterative in nature since in some instances it was either the requirement was relaxed to accommodate the variant or the variant was modified to fit the requirement.

In order to validate the relevance of the conceptual design framework developed in this research, opinion was sought from a team of five (5) expert powder metallurgists from Council of Scientific and Industrial Research (CSIR) in Pretoria, South Africa with extensive experience in metal powder atomising systems. They were requested to critique the framework and make suggestions. The developed framework was presented to the experts via email to seek their comments regarding its validity. Out of the five (5) experts consulted, only three (3) gave feedback. The following suggestions were made: (i) the need to clarify the weighting and ranking parameters; (ii) consulting literature that supports the engagement of gas atomised powders for SLM process; (iii) paying attention to issues of risk and safety in equipment handling and (iv) justification for setting up a system rather than buying. This approach of validation was adopted as it was not reasonable at this stage to bring on board commercial metal powder producers to ratify the use of an untested framework. Furthermore, it is also impracticable to introduce the preliminary framework to engineers working on a live project and expect them to apply it with enthusiasm. In addition, there is uncertainty in expecting that anything useful could be gained from testing the preliminary framework without first developing and refining it with contribution from the experts. Therefore, the validation of the framework by the experts confers some level of acceptance such that it could be applied in setting up a metal powder production system for immediate use by PM practitioners. Figure 3.1 illustrates the methodology for developing the conceptual design framework while Figure 3.2 outlines the sequence of activities followed in order to realise the conceptual design framework adopted in this study.

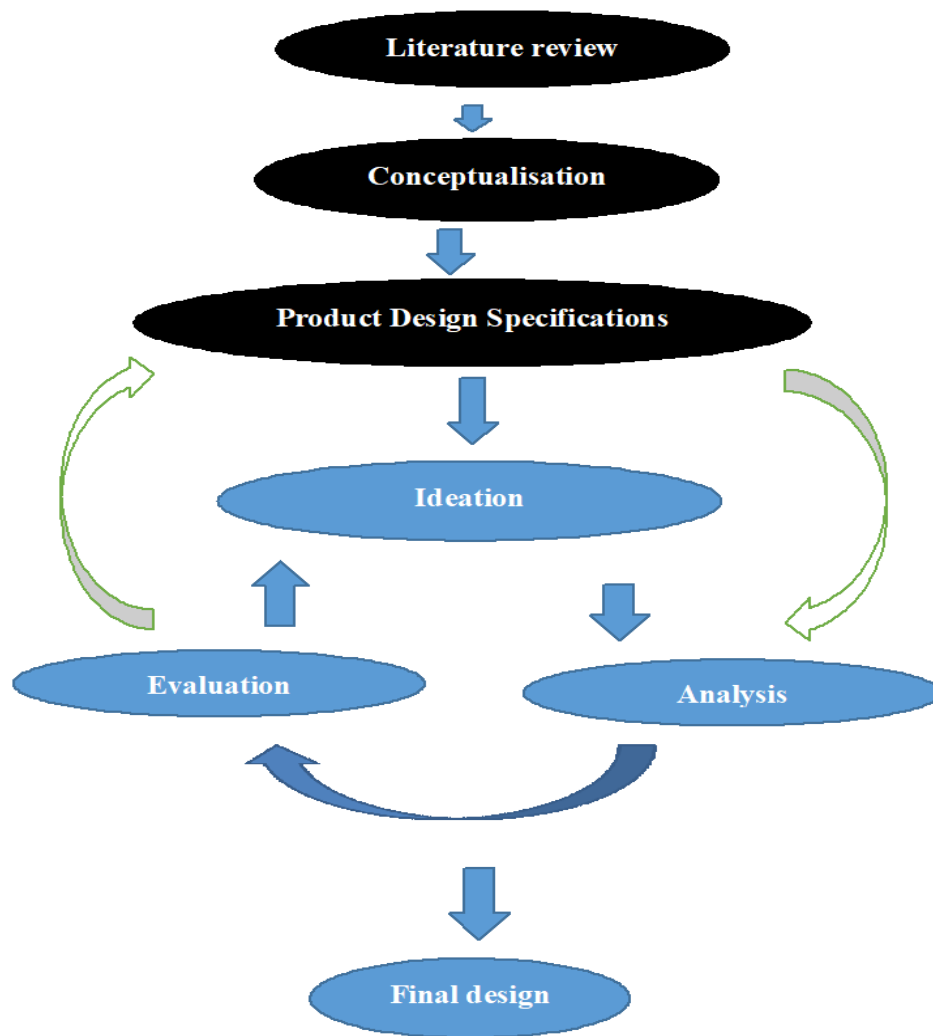


Figure 3.1 Conceptual design methodology (Matsagopane *et al.* 2019)

According to Figure 3.1, conceptualisation of the design framework of an atomising system began with literature review in which sources of data such as online publications and books were investigated to find out finer details underlying the process of metal atomisation, its critical components and process parameters. Next, the problem was identified and the atomising system was broken down into schematic areas. This was done so that the research problem was authenticated and fully understood. The product design specification (PDS) was then formulated to outline the system's overall requirements. The mechanical designs were then subjected to a cyclic

process of analysis and evaluation against the PDS, occasionally modifying some until a better solution was achieved. A sequential explanation of this methodology is provided in Figure 3.2.

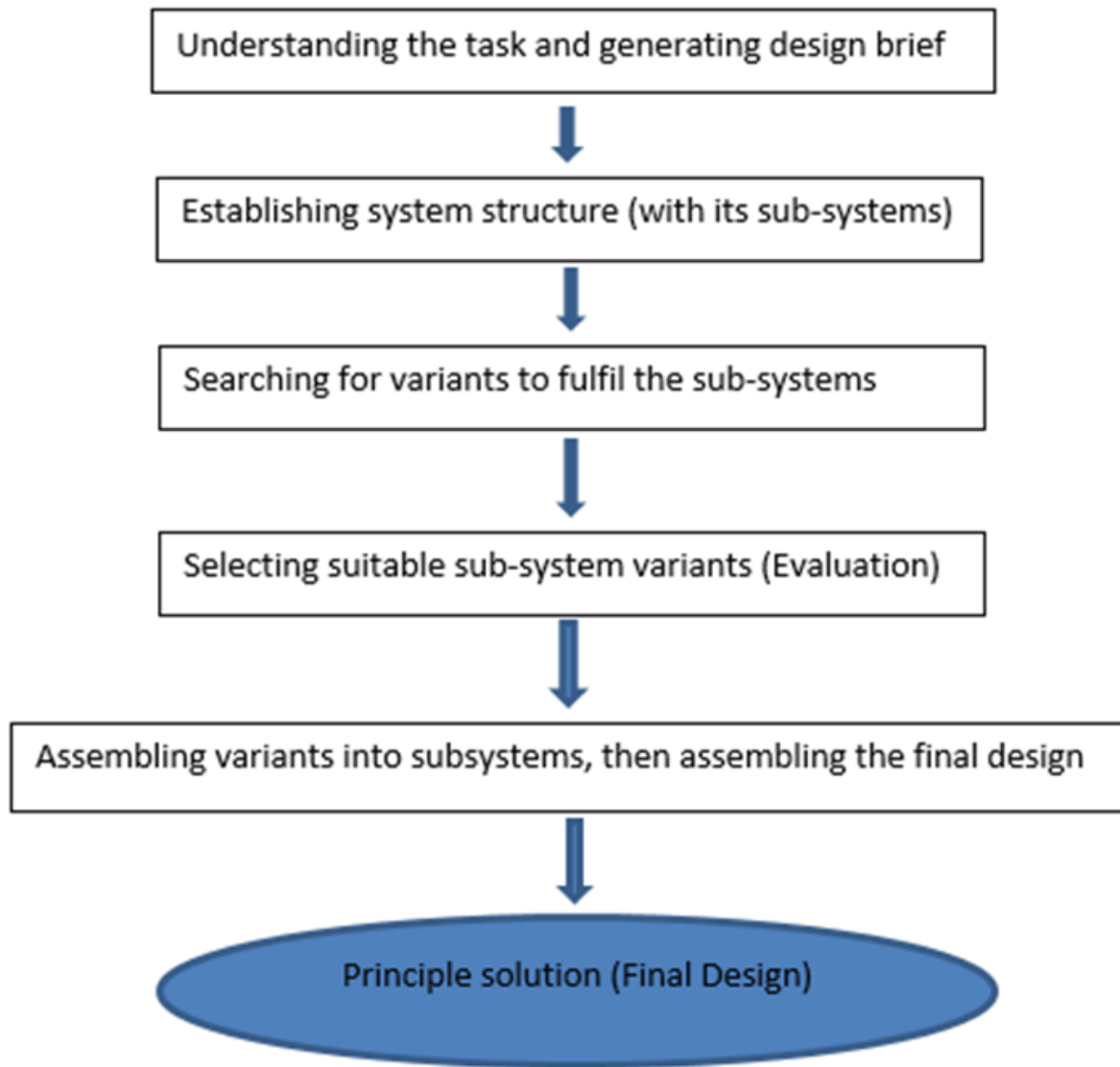


Figure 3.2. Flow chart showing sequence of activities (Matsagopane *et al.* 2019)

Figure 3.2 summarises the activities as follows: firstly, the need to design a metal powder production system for use in Botswana was analysed to establish its relevancy. Literature review qualified the shortage of metal powder production systems in Botswana, and the problem associated with the shortage was established before

breaking the system down into sub-systems that formed the schematic areas mentioned earlier. A system structure with all the sub-systems (SS) and their variants (SV) was then adopted as illustrated in Figure 3.3. The schematic diagram shows how the sub-systems (SS1, SS2,...) that make up the overall atomising system relate or link to one another during atomisation. After establishing how different sub-systems link to one another, their variants (SV1, SV2,...) were developed. The said variants were generated according to the PDS and were critically analysed and evaluated. During analysis, some modifications were made in some of the sub-system variants (where necessary) in order to harmonise the component(s) with the PDS. The variants were then assembled into a final solution.

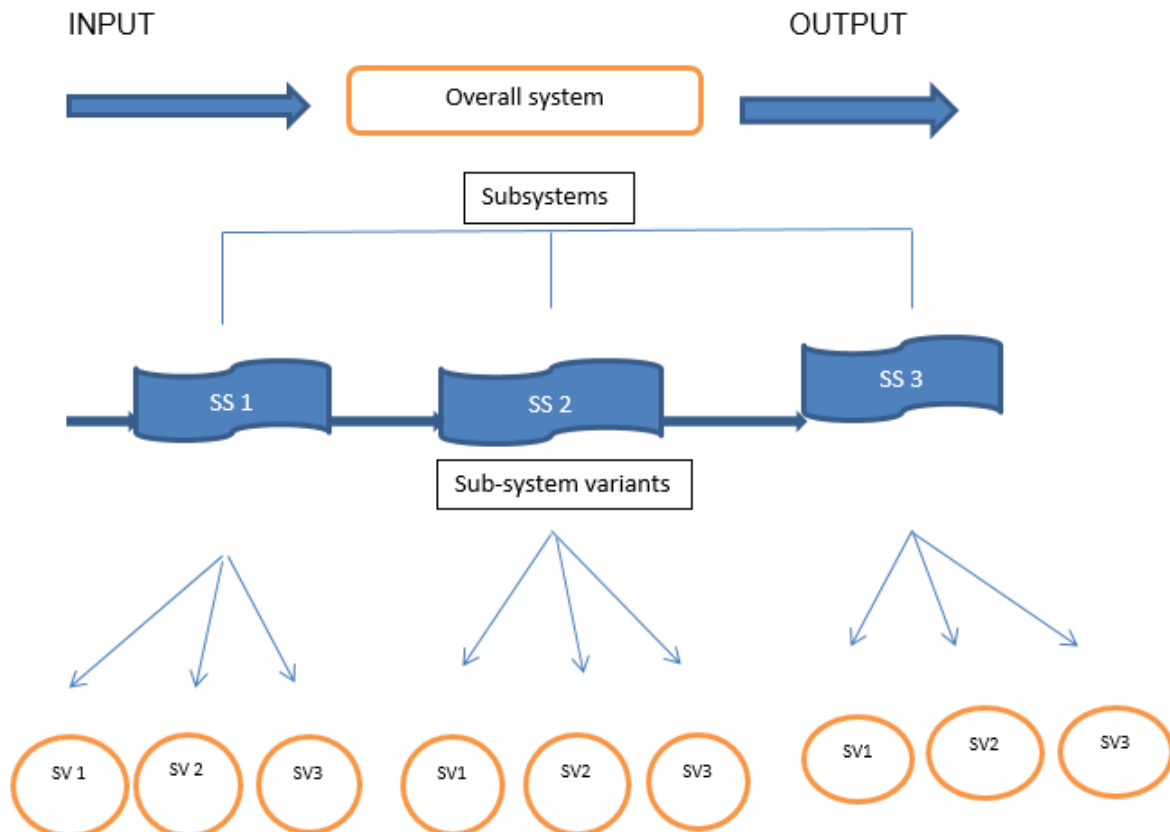


Figure 3.3 System structure

3.2.2 Evaluation of sub-system variants

The evaluation criteria applied in this research is explained as follows:

Firstly, the requirements of the system were categorised as either a “*demand*” (D) or a “*wish*” (W). A PDS item awarded “D” status denoted that the requirement was critical

such that if not adequately addressed, it could compromise the quality of the powder. On the other hand, a PDS item deemed of a relatively lesser importance was assigned “W”. That was done to identify critical requirements and accord them the attention they deserved. However, an item denoted “W” did not imply that the PDS item was useless. Rather, the statement was just used for classification purposes and to indicate PDS items that needed to be fulfilled at all costs. Table 3.1 shows the layout of the PDS.

Table 3.1: Layout of the Product Design Specifications (PDS)

D W	Requirements
Is item D/W?	Requirement with quantitative and/or qualitative data

D – Demand

W – Wish

Following the identification of the PDS items as either “D” or “W,” design solutions that conformed to their requirements were subjected to a screening process to select the best amongst them, which would then be carried forward for incorporation into the final design. The process was carried out following a quick, systematic and approximate screening procedure as illustrated in Table 3.2. The procedure was such that PDS items of a given component were placed in the first column while possible solutions (PS1, PS2, PS3....) were placed in the subsequent columns. The possible solutions were then evaluated against the requirements and for every requirement fulfilled, a plus (+) was awarded while for every requirement not met a minus (-) was given. At the end, all the (+)’s and (-)’s were added for a given component and the totals were used for ranking the solutions with the highest scoring solution ranking number 1 and ultimately adopted.

Table 3.2 Screening of possible solutions

	Possible solutions			
SELECTION CRITERIA	PS1	PS2	PS3	PS..
Complexity of design	+	+	-	
Material	+	-	+	
Durability	+	+	-	
Pluses	3	2	1	
Minuses	0	1	2	
Net score	3	1	-1	
Rank	1	2	3	

Finally, evaluation matrices (Table 3.3) were used to select best components. PDS items were assigned weights according to their relative importance and were expressed as percentages (Khandani 2005). Also the attributes were rated on a scale of 1 to 5 with 5 being the highest rating a requirement could be given, while 1 was the lowest. To rate a PDS item, critical requirements that if not fulfilled would otherwise affect the efficiency of the system were identified and competed against one another for awarding of the points. For example: in Table 3.3, powder morphology was found to be very critical as compared to other PDS items listed and was thus awarded 5 and weighed 30%, which is higher than any other rating and weighting respectively. Still in Table 3.3, ease of operation was awarded 1 and percentage weight of 10 because as compared to other requirements, the ease of operation was considered to be of lesser importance to the system. Subsequently, the ratings were achieved as follow: taking variant 1 (V1) under “*powder morphology*” as an example, a rating of 5 was awarded and multiplied by the criterion weighting factor of 30% to get a weight rating of 1.50. The same was done for other requirements (purity, costs, safety...) and all the weight ratings were later summed up to get a total score of 3.70 for V1. The highest ranked solution was adopted for assimilation into the final product. According to Table 3.3, V2 scored 4.00 and in that case would be adopted.

Table 3.3 Evaluation Matrix

	Sub-system variants						
		SV1		SV2		SV3	
Criteria	Weight%	Ranking	Weight rating	Ranking	Weight rating	Ranking	Weight rating
Powder morphology	30	5	1.50	4	1.30	3	1.00
Purity of powder	25	4	1.00	5	1.25	4	1.00
Safety	20	3	0.60	4	0.80	4	0.80
Manufacturing cost	15	2	0.30	3	0.45	3	0.45
Ease of operation	10	1	0.10	2	0.20	3	0.30
Total score	100		3.50		4.00		3.55

Ratings: 1= not matter, 2 = matters a bit, 3 = really matters, 4 = very important, 5 = crucial.

3.2.3 Methodology for mechanical design of components

Relevant engineering and scientific equations were used to configure key components of the identified atomising system. Such equations were applied after the selection of appropriate atomising technique in Section 4.2. At this stage, it was difficult to identify relevant equations since the atomising technique had not been selected. It was only after selecting the appropriate atomising technique that it was possible to identify equations to design the features of key components of the atomising system and determine appropriate process parameters. The calculations were crucial because it was only through them that efficient variants could be achieved. Ideas generated were then subjected to evaluation criteria outlined in Section 3.2.1. Finally, a methodology relevant to mechanical design of various components of the atomising system was formulated as shown in Figure 3.4.

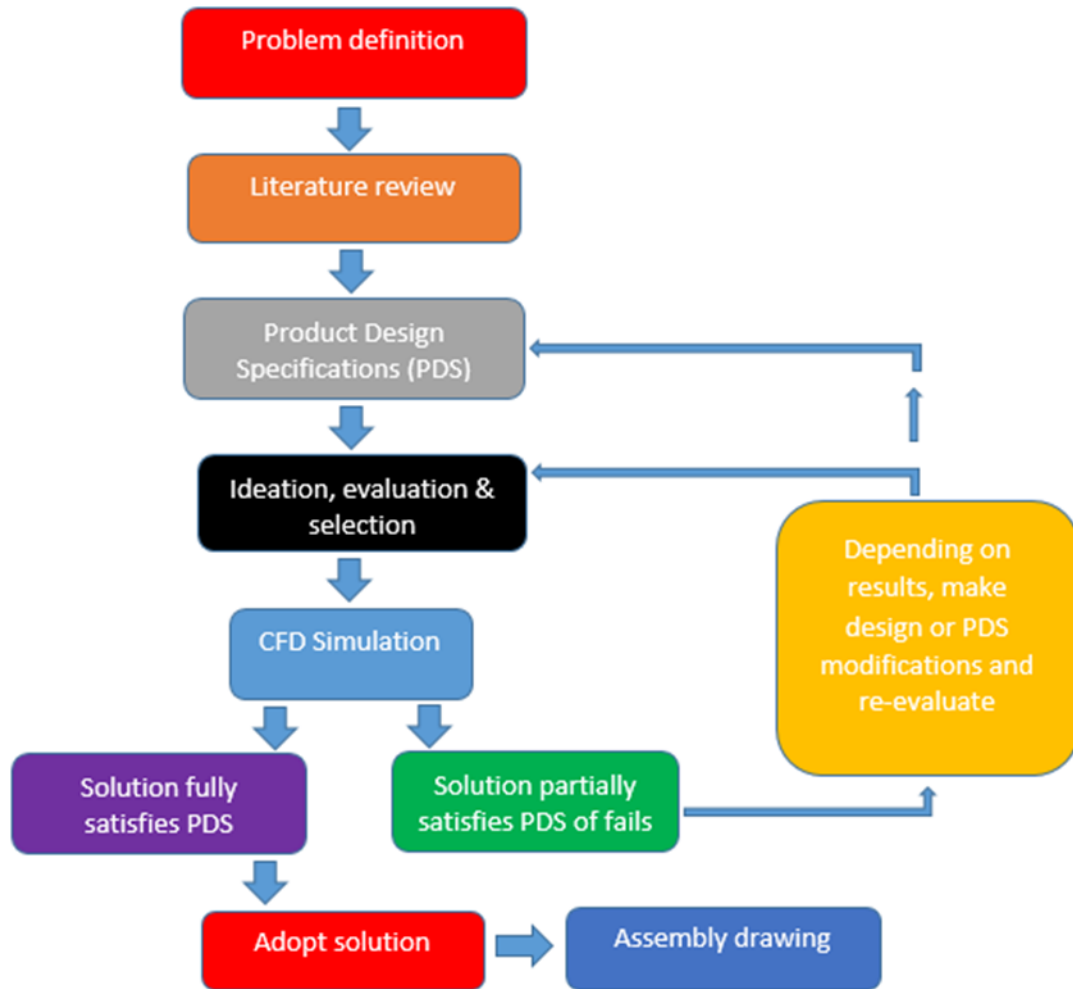


Figure 3.4 Mechanical design methodology formulated

Taking design of a furnace as an example, the methodology was applied such that firstly a problem that necessitated the design of a new furnace was formulated. The problem was critically analysed to establish its authenticity. When satisfied that indeed the problem was genuine, then available literature regarding design and operation of existing furnaces was reviewed. That is when classification of furnaces and their challenges was identified. Based on the findings of literature review, PDS was formulated, after which the development of ideas (ideation) began. All the ideas were subjected to evaluation and modifications to suit the PDS and finally the best idea of a selected critical component was taken forward for CFD simulation to optimise its

efficiency. This means from the many key components of an identified atomising technique, *one critical component that matters the most was simulated*.

3.2.4 Methodology for CFD investigation of the nozzle

A critical component that the whole atomising system depends mostly on was identified and certain geometrical configurations of it were simulated to investigate how the configurations affect powder quality. A CFD methodology was devised as illustrated in Figure 3.5. It began with validation of the experiment using similar experiment performed by Sofuoglu *et al.* (2013). That particular experiment was selected because it investigated similar problems that this research investigated. The problems will be clear in Chapter 4 after the selection of the appropriate atomising technique. Pre-experimental validation of the software used was important in determining the appropriateness of the ANSYS version for the investigation to be carried out. Amongst the many issues that Sofuoglu *et al.* (2013) investigated, of relevance to this research was the influence of varying the expansion area and throat diameter in a close-coupled nozzle; hence the use of their experiment in this research justified.

After validation, a baseline model was developed using data from mechanical design of the nozzle. Configurations of the identified *critical* component were varied until the best optimisation results were attained. The combination of the optimum configurations resulted in the design of an effective critical component capable of producing the desired aluminium powder. Figure 3.5 illustrates the model followed as discussed above.

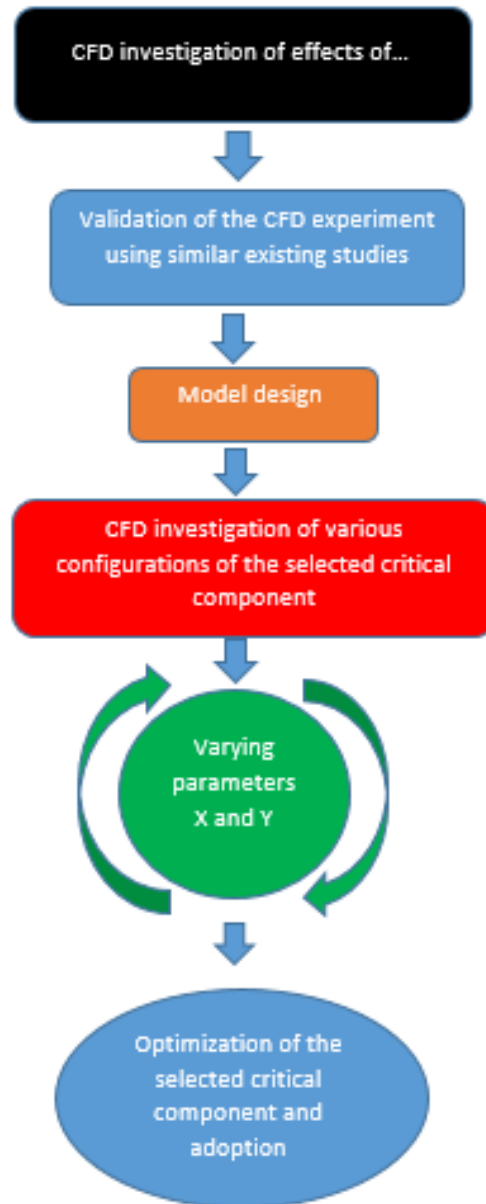


Figure 3.5: The CFD methodology generated

3.3 Final design solution

An assembly drawing of the selected atomising system was presented from the selected components, including the CFD optimised critical component. Compatibility of the variants to the overall principal solution, both functional and geometrical, was ensured so that a smooth flow of energy and material would be achieved. Furthermore, the final design solution was expected to meet the functional requirements of the system, be it hard engineering requirements such as geometric design or power

consumption, or softer areas of concern such as economic and legal requirements (Ruder *et al.* 2007). Material selection for the components was carried out based on both mechanical and physical properties relevant to the type of atomisation selected. Properties such as high melting point and corrosion resistance were considered in order to select a material that has a higher melting point than aluminium that will not contaminate both the molten metal and atomising medium.

3.4 Summary

The methodologies formulated were geared towards the realisation of the aims and objectives of this research and were followed in Chapter 4 during the actual design of identified key components. The conceptual design framework gave an insight into what is expected when designing a metal powder atomising system while the iterative mechanical design methodology gave the step-by-step guidance for the actual designing of various components of the system. On the other hand, the CFD investigation methodology provided guidance during the simulation of a critical atomising component.

CHAPTER 4: DESIGN OF AN ALUMINIUM POWDER ATOMISING SYSTEM

4.1 Introduction

This chapter intends to identify the appropriate atomising technique capable of producing aluminium powder required for selective laser melting (SLM). A conceptual design framework for setting up the selected atomising system was formulated to provide guidance in establishing the system. Mechanical design of key components of the selected atomising system was carried out using relevant equations. Performance of the critical component of the selected atomising system was investigated via CFD with a view to optimise its efficiency. Finally, all the mechanical designs of the key components, including CFD results are then incorporated into the final design of the complete system and an assembly drawing is presented.

4.2 Selection of appropriate atomising system

To identify an appropriate metal powder atomising technique which produces aluminium powder that meets SLM requirements, water, gas and centrifugal atomisation techniques were evaluated by employing both user-value analysis (UVA) and cost-benefit analysis (CBA) techniques (Tiwari *et al.* 2016). The evaluation criteria considered important requirements of the product (a metal powder atomising system) to the user (SLM manufacturer) while paying attention to economic implications of each criteria. The atomising techniques were evaluated against five key requirements (Table 4.1) namely: (i) powder characterisation, (ii) powder purity, (iii) energy consumption, (iv) yield and (v) financial requirements. These requirements were considered critical because of their immense contribution towards achieving the desired metal powder characteristics. For this research to achieve its aim and objectives, it was imperative that the selected atomising technique achieve the said critical requirements. Failure to achieve the key requirements would lead to production of wrong powder characteristics that subsequently lead to loss of time, business and waste of material. The approach of selecting the best metal powder atomising system which meets SLM process requirements follows the same evaluation technique elucidated in Section 3.2.2 and

presented in Tables 3.2 and 3.3. Also the findings from Table 2.7 were considered when making the selection.

Table 4.1 Atomisation variants' selection and evaluation

	Variant selection of atomisation techniques			Evaluation of atomisation techniques						
Selection criteria	Water	Gas	Centrifugal	Weight (%)	Water		Gas		Centrifugal	
					Ranking	Weight rating	Ranking	Weight rating	Ranking	Weight rating
Powder characterization (particle size and distribution, spherical morphology and powder flowability)	-	+	+	30	3	0.75	5	1.25	4	1.00
Powder purity (99.9%)	-	+	+	30	2	0.50	5	1.25	3	0.75
Energy consumption	-	+	-	20	3	0.60	4	0.80	3	0.60
Yield	+	-	-	20	4	0.80	3	0.60	3	0.60
Pluses	2	3	2							
Minuses	3	2	3							
Net score	-1	1	-1							
Rank	2	1	2							
Total weighting					3.15		4.20		3.15	

During variant selection, gas atomisation performed better than the other two atomisation techniques. However, centrifugal and water atomisation techniques performed at par and scored 3.15 each. Regarding this “tie”, this research ranked centrifugal atomisation as a better option after gas atomisation because centrifugal atomisation produces spherical particles in comparison to water. Therefore, going forward, gas atomisation was adopted as an appropriate atomisation technique for producing suitable aluminium powder for SLM manufacturing.

4.2.1 Specific powder requirements for selective laser melting

Now that gas atomisation was selected as the best atomising technique for producing the right aluminium powder requirements for this research, it was important that key gas-atomised powder requirements for SLM application were identified. Using information gathered from literature review in Section 2.4 and particularly Table 2.5, the identified gas-atomised powder requirements were ranked in order of importance to the quality of the desired aluminium powder as shown in Table 4.2 below. From the rankings, particle size and morphology, powder purity and safety were considered *crucial* in determining the quality of the powder, hence they were ranked 5. Flowability was considered *very important* in determining quality of metal powder for SLM application and was ranked 4. The ranking made use of information explained in Section 3.2.2 and is very important when evaluating variants as shown in Table 4.1.

Table 4.2 Ranked SLM powder requirements

Ranking	Key powder particle requirements
5	Particle size and morphology: Particle morphology should be spherical and of fine texture, ranging between +45-100 μm (Brandt 2017).
5	Purity: Particle purity should be high, approximately 99.9%. Clean, oxidation-free particles are highly recommended to facilitate both inter-bonding and intra-bonding during SLM process.
4	Flowability: A nice, even flowing powder is required for good and uniform packing density. It should fuse easily onto the powder bed.
5	Safety: Particles should be non-corrosive to the SLM equipment and for operator's personal safety

4.2.2 Developing conceptual design framework for setting up a gas atomising system

Generating a conceptual design framework is one of the key objectives of this research and forms part of the factors contributing to the novelty of this research because such information is currently not available. To achieve this, it is crucial that all the requirements of an effective gas atomising system are identified. According to German

and Vassileva (2007), a suitable gas atomiser for producing the required aluminium powder must be characterised by the following functions:

- An atomising nozzle to deliver gas at a velocity over 550 m/s (Zhao *et al.* 2009) thereby impinging on the melt droplet to break it into desired powder particle size.
- Impinging inert gas temperature at room temperature (25 °C) and gas pressure ranging between 0.6 to 1 MPa. This pressure range is common in most laboratories.
- Optimum cooling rate to allow formation of fully dense particles and avoid satellite formation.
- Optimum gas-melt interaction to ensure complete atomisation.

These functions assisted in establishing the specifications for an aluminium powder gas atomising system as outlined in the first column of Table 4.4. Having established the requirements list for a complete system, specifications for various components of the atomiser were developed. Previous studies have already indicated that furnace (Mullinger and Jenkins 2014) and nozzle (Thompson *et al.* 2016) design have effects on the quality of powder particles, hence that is taken into considerations during the formulation of the conceptual design framework. Conceptual design of key components is discussed in Sections 4.3.1, 4.3.2 and 4.3.3 respectively. It must be noted that although most of the atomising system requirements were discussed in Chapter 2, their relevance to SLM requirements were never considered. Therefore, in this section, the relevance of gas atomisation to SLM requirements is investigated to identify the best choice of components or gas for the atomising system.

4.2.2.1 Selection of appropriate furnace

Requirements for an appropriate melting/holding furnace were listed in the third column of Table 4.4 and were used to evaluate the three types of electric melting/holding furnaces for selecting the most suitable furnace for this research. From literature review in Section 2.6.1 *induction furnace*, *electric crucible furnace* and *electric arc furnace* were identified as common furnaces used in atomisation of melts. Key factors to

consider for a melting/holding furnace were identified as melt contamination, heat loss, energy consumption and yield. These requirements were then ranked in order of importance with regard to their use in producing good aluminium powder for SLM application. According to Table 4.3, melt contamination, heat loss and energy consumption were considered *crucial* in determining the quality of the powder, hence they were ranked 5. However, ease of operation and yield were also considered *very important* and were subsequently ranked 4. These rankings made use of information explained in Section 3.2.2 and are very important when evaluating variants as shown in Table 4.5.

Table 4.3 Ranked melting/holding furnace requirements

Ranking	Key furnace requirements
5	Melt contamination: For gas atomisation of aluminium melt, purity is of paramount importance. For this reason a non-corrosive crucible with high heat resistance is required to avoid melting the crucible together with charge material as that may contaminate the Al melt.
5	Heat loss: Minimum (or if possible) no heat loss must be ensured so that melt superheat temperature is maintained throughout the atomisation process (from melting to atomising).
5	Energy consumption: The furnace must consume minimum energy possible (1kWh per cycle at most) in order to minimise operational costs.
4	Ease of operation: Must require just basic operation skills only. No complicated controls.
4	Yield: Must be able to produce at least 5kg of aluminium powder per cycle

Table 4.4: Specifications for the gas atomising system and its key components, (Source: Matsagopane, *et al.*, 2019)

Complete gas atomiser	Nozzle	Melting/holding furnace
1. Geometry All components must have minimum possible dimensions to be able to achieve desired yield and powder particles' specifications. 2. Kinematics Must be able to melt aluminum at 660 °C in 15 minutes. Must be able to maintain the aluminium melt at 760 °C throughout the atomisation process. Must utilise low gas pressure (between 5 to 10 bars) available in most laboratories. This will also minimise operation costs. 3. Energy It must use clean energy for melting, with minimum air pollution. Must operate at constant manageable pressure (≥ 10 bars) using inert gas. It must be able to operate in a 1kHz power supply. 4. Safety The system must have safety measures (pressure sensors, fume extractors, personal protective equipment (PPE)) in place to prevent accidents. It must also have emergency controls for use in emergency situations. Release valves must be available to monitor pressure build-up inside the atomising chamber. 5. Quality The artifact must be of good quality and at least conform to minimum market standards. 6. Operation It must be able to be operated by non-specialists. No complicated controls to be included in the system. 7. Manufacturability	1. Energy Must ensure a good heat transfer and fair distribution of thermal energy between the nozzle exit and the melt. Pressure must be efficiently used and not lost to the environment. 2. Complexity of the design The nozzle must not demand complicated skills to manufacture and complex operations to function. Operation manual must be able to guide use. 3. Durability The nozzle must last longer than the existing nozzles, with a lifespan between three and five years. Wear should be slow in order to reduce replacement frequency, thereby reducing maintenance costs. (Expectation is that the atomiser will be used at least twice a week for experiments, with production of 5kg Al per cycle) 4. Kinematics Gas flow rate must be controllable in order to regulate gas-melt interaction with a view to optimising production. 5. Forces Must be able to withstand pressure up to 10 bars for optimum atomization. 6. Operation Must be able to provide a uniform controlled supply of pressurised gas at velocity range of 600-650 m/s and still be able to achieve constant velocity.	1. Function The device must be able to melt aluminium at 660 °C and maintain the molten metal at superheat of fluidity of around 770 °C. Thus, it must fulfil the duties of both a melting and a holding furnace. 2. Efficiency The furnace must have a high efficiency value for effective melting of the charge material. Heat loss due to conduction and radiation must be greatly minimised. 3. Material Non-corrosive material must be used to guard against oxidation. The material used must have high thermal resistance to avoid contaminating the melt, as well as to minimise heat loss through conduction mode. 4. Yield The device must be able to produce at least five (5) kilograms of pure molten aluminium in fifteen minutes per batch. This translates into around 5.6kg charge material per cycle (taking into considerations issues of slag at 8% of total green mass). 5. Energy The device must be able to utilise/operate on a 3-phase power supply available in the workshop, at most. It must consume

It must be possible to fabricate and assemble components in a simple laboratory/workshop with minimum skilled manpower needs.

8. Diagnosis/Accessibility

Parts must be easily accessed for ease of diagnosis and subsequent repair/replacement.

9. Maintenance

It must be easy to fix/repair/replace broken components. No specialised skills/tools should be required during maintenance of the equipment (tolerances & interchangeability emphasised)

10. Size

It must be of minimum possible dimensions so that it does not occupy a lot of space in the workshop.

7. Material

It must be made from material with high thermal and corrosion resistance to avoid contaminating the melt during gas-melt interaction.

8. Maintenance

Must be easily repaired/replaced without the need to dismantle the whole system. No skilled labour should be needed to replace/rehabilitate/clean the nozzle

minimum possible energy required to melt the charge material.

6. Size

The device must be of a minimum possible size and dimensions to minimise costs emanating from demand for more materials, as well as to save accommodation space in the workshop during storage.

7. Safety

High level of safety standards must be incorporated into the device in order to minimise chances of injury. Adequate insulations and casings must be ensured.

The rankings from Table 4.3 were then used to evaluate the three furnaces as shown in Table 4.5. It must be noted that for a furnace to be selected, it had to outperform other furnaces relative to the achievement of the key requirements as mentioned in Table 4.3. Similar to the approach carried out in Section 4.2, the furnaces were evaluated via both user-value analysis (UVA) and cost-benefit analysis (CBA) techniques and the induction furnace emerged the best (at 4.75) for producing clean aluminium powder at low energy consumption and with minimum heat loss. It was followed by the electric crucible and electric arc, respectively. During evaluation, information about their operation (gathered via literature review in Section 2.6.1) was used to make an informed decision regarding their relevance to this research. According to the evaluation results, both electric crucible and electric arc furnaces scored minuses (-) for critical requirements of contamination of the melt and power consumption while the induction furnace scored pluses (+) for both requirements. That meant they were capable of contaminating the melt and consuming high power during the melting process, hence they were disqualified.

Table 4.5 Evaluation and selection of furnace

	Variant selection of melting/holding furnaces			Evaluation of melting/holding furnaces						
Selection criteria	Induction	Electric crucible	Electric arc	Weight	Induction		Electric crucible		Electric arc	
					Weight rating	Rating	Weight rating	Rating	Weight rating	Rating
Melt contamination	+	-	-	30	5	1.50	3	0.90	2	0.60
Heat loss	+	+	-	25	5	1.25	4	1.00	1	0.25
Power consumption	+	-	-	20	5	1.00	3	0.60	1	0.20
Ease of operation	+	+	+	15	4	0.60	3	0.45	2	0.30
Yield	+	+	+	10	4	0.40	4	0.40	5	0.50
Pluses	5	3	2							
Minuses	0	2	3							
Net score	5	1	-1							
Rank	1	2	3							
Total weight						4.75		3.35		1.85

4.2.2.2 Selection of appropriate nozzle

Factors to consider when designing a gas atomising nozzle were discussed in Section 2.6.2 and the specifications for the nozzle were listed in Table 4.4. Four key nozzle requirements were identified as *design*, *material*, *energy* and *forces*. These were selected after considering their importance in the operation of the nozzle and were ranked according to their importance, employing the procedure as explained in Section 3.2.2. Design configuration, material and energy were ranked 5 because of the critical roles they play to ensure the nozzle is effective. Forces were ranked 4 because although it is important that the nozzle withstand a certain amount of pressure, however, it is not as important as the other three key requirements. Table 4.6 shows ranked nozzle requirements while Table 4.7 shows the evaluation of the two types of nozzles (free fall and close-coupled).

Table 4.6 Ranked atomising nozzle requirements

Ranking	Key nozzle requirements
5	Design: Must enable the nozzle to attain optimum gas velocity (above 650 m/s) at exit to ensure effective atomization of the melt.
5	Material: Must be non-corrosive and have high thermal resistance (higher than 760°C) so that it does not corrode or melt and contaminate the melt.
5	Energy: Must ensure a good heat transfer and fair distribution of thermal energy between the nozzle exit and the melt.
4	Forces: Must withstand gas pressure up to 1MPa

According to Table 4.7, close-coupled nozzle is better than free fall atomiser (at 4.50) because it recorded pluses (+) for all the critical requirements rated 5 (design, material and energy). On the other hand, because of the way they operate, the free-fall nozzle scored minuses (-) for design and energy, hence it was discarded and the close-coupled nozzle was adopted in this research.

Table 4.7 Variant selection and evaluation of atomising nozzles

Variant selection of atomising nozzles			Evaluation of atomising nozzles				
Selection criteria	Free fall	Close-coupled	Weight	Free fall		Close-coupled	
				Rating	Weight rating	Rating	Weight rating
Design	-	+	30	2	0.60	5	1.50
Kinematics	-	+	25	2	0.50	5	1.25
Energy	-	+	20	5	1.00	3	0.60
Complexity of design	+	+	15	3	0.45	5	0.75
Financial implication	+	-	10	5	0.50	4	0.40
Material	+	+					
Durability	+	+					
Pluses	4	6					
Minuses	3	1					
Net score	1	5					
Rank	2	1					
Total weighting					3.05		4.50

4.2.2.3 Selection of appropriate atomising gas

Information gathered from literature review in Section 2.5.2 and Table 2.6 in particular is used to select appropriate atomising gas. Argon (Ar), helium (He) and nitrogen (N) are evaluated to establish their suitability for producing Al powder suitable for SLM process as discussed in Section 2.4. Three key requirements for a good atomising gas required in this research were identified as *reactivity*, *kinematics* and *safety*. Similarly, the key requirements acquired from the specifications in Table 4.3 were rated to gauge their importance to the performance of the atomising system (Table 4.8) and the gases were later screened in Table 4.9 and evaluated in Table 4.10. Reactivity and kinematics were ranked 5 because of the need for the gas to be unreactive to aluminium and be easily propelled. Safety was ranked 4 because it is important that the gas be safe to use so that it does not cause harm to the operator and the environment. Furthermore, the selection of the atomising gas considered literature findings in Section 2.5.2 and Table 2.6.

Table 4.8 Ranked key requirements for atomising gas

Ranking	Requirements
5	<u>Reactivity</u> The gas must not react with the melt to avoid contamination.
5	<u>Kinematics</u> Must have low density so that it can be easily propelled and have good aerodynamic properties to achieve high velocity for efficient atomisation. Should be easily compressed to attain high pressure required for effective atomisation.
4	<u>Safety</u> The gas must be non-toxic and non-asphyxia to ensure safety of the operator. It must also be non-flammable to avoid causing fires.

Table 4.9 Atomising gas variants' screening

Criteria	Helium	Argon	Nitrogen
Reactivity	Does not react with Al	Does not react with Al	May react with Al to form aluminium nitrate
Kinematics	Have the lowest molecular weight of 0.004 kg/m and density of 0.164kg/m ³ , hence the easiest to propel	Have molecular weight (0.04kg/m) and density (1.449kg/m ³) higher than He hence may be too heavy to propel	Have the highest density (1.165kg/m ³) of all the gases considered.
Safety	Non-toxic and safe to use	Non-toxic, but may asphyxiates	Have asphyxiation effects (choking)

Table 4.10 Evaluation of atomising gases

SELECTION CRITERIA	Helium	Argon	Nitrogen
Reactivity	+	+	-
Kinematics	+	-	-
Safety	+	+	-
Pluses	3	2	0
Minuses	0	1	3
Net score	3	1	-3
Rank	1	2	3

According to Table 4.10, He outclassed the other two gases as it scored points in all key requirements. On the other hand, N failed to meet any of the gas requirements. Therefore, He is adopted as the appropriate atomising gas for the production of clean, oxidation-free aluminium powder for use in SLM manufacturing of engineering components. Although more expensive than N, when used in gas atomisation, He produces clean powders and has no asphyxiation effects that pose danger to the operator. In agreement with Legoux *et al.* (2010), this research also recommends recycling of He gas in order to significantly reduce the operating costs. The He recycling issue will be address during component design. Despite its abundance, N was found not suitable for atomising aluminium due to its high density and molecular weight that make it very difficult to propel to attain the high velocity required. Though Ar has properties similar to those of He, it is 10 times denser hence difficult to propel, resulting in low velocity. Propulsion make use of the density and molecular weight of the gas. With its larger specific heat ratio and a lower molecular weight, He is an appropriate gas to atomise aluminium used in this research.

4.2.2.4 Selection of the appropriate atomising chamber

Because of the need to use a high falling distance of the melt droplet to achieve effective secondary atomisation as pointed out in Section 2.6.3, a vertical atomising chamber is very appropriate for the production of fine Al powder required in this research. Furthermore, a longer falling distance helps in spheroidisation of the melt

droplet, a factor that assists in giving the powder particle the final spherical shape recommended in SLM processing. Following the approach of previous researchers such as Ozbilen (2013) and Francis (2016), this research adopted a vertical atomising system. An average atomising chamber usually ranges between 1 to 9 meters in height and approximately 1 meter in diameter, depending on the metal powder particles requirements (Dunkley, 1994). However, considering Yule and Dunkley's (1994) suggestion regarding height of the chamber, and the observation made in this research, it is evident that a chamber of not more than 2 meters high is appropriate in this research. This is because the required powder morphology is of fine particles, hence they would not need a greater falling distance (more than 2 meters) to cool and solidify (Yule and Dunkley 1994), unlike if they were larger than the 45-70 μm recommended in this research. This is further supported by the findings by Bauckahage, *et al.* (1988) in which they discovered that larger particles have lower velocities than smaller ones, therefore require more time to solidify, hence they require a larger falling distance as compared to finer particles. That means for fine particles (45-70 μm) that this research intends to produce, a relatively smaller falling distance is acceptable. Furthermore, the fact that a smaller droplet from the melt path (3mm diameter) is expected, coupled with the use of high velocity atomising gas makes it reasonable to have a 2 meters atomising chamber. In this regard, one may only be innovative and enhance the safety aspect of the chamber, and this research intends to do exactly that. In summary, Yule and co-investigator (1994) suggested that:

“In the case of fairly sharp melting alloys with high melting points ($900 + ^\circ\text{C}$) and atomising coarse powders, with more than 10 percent over 250 μm , a vessel 3-4 m tall is needed to restrict platting to 1-2 percent. If much finer material is being produced, for example 10 percent over 100 μm , then a vessel 1-2 m tall is sufficient for a similar level of splatting. The reduction in vessel height is partly due to the smaller particles and partly due to the more forceful cooling by the higher gas/metal ratio used to make such fine particles.” - Atomisation of melts for powder production and spray deposition, p. 334

To further substantiate the idea of adopting predecessors' work, this study reviewed the work of Morakotjinda *et al.* (2010) where they carried out a similar study investigating gas atomisation of low melting-point metal powders. Because of the targeted larger particle sizes (90-150µm) than the ones expected in this research, Morakotjinda *et al.* (2010) used a chamber of 3 meters height. On the other hand, Fritsching and Uhlenwinkel (2012) recommended a 2 meters high chamber to produce fine metal powder particles. Consequently, this research adopted the 2 meters high chamber for incorporation into the final design of the gas atomising system.

4.3 Framework for designing the gas atomising system

The conceptual design framework for setting up an aluminium powder gas atomising system which produces powder that meet SLM requirements is presented in Figure 4.1 (a and b) and supplementary Table 4.11. The framework was developed by categorising design tasks from similar case study projects through literature search (Macmillan *et al.* 2001). Figure 4.1 (a) and Table 4.11 employ framework hierarchy with identified task providing a basis for development of the conceptual design framework. The framework (Figure 4.1 (a)) consists of 5 levels of which the second contains two stages, the third contains five phases and the fourth contains thirteen generic activities. The fifth level (Figure 4.1.(b)) consists of tasks which define each of the activities specified in level 4 which allows for implementation of this conceptual design framework for aluminium powder gas atomisers. The grouping of tasks is based on shared objective which indicates the generic group characteristics (level 5 in Figure 4.1 (b)). The clustering of tasks is designated as activities (see level 4 in Figure 4.1 (a) and fourth column in Table 4.11) while the nature of each activity is defined (fifth column of Table 4.11). The clustering of the tasks and activities enables the definition of the bottom level design activity for an aluminium powder gas atomising system. The third level of the conceptual design framework development clusters the activities based on the overall phase objective (third column of Table 4.11 and see level 3 in Figure 4.1 (a)) towards establishing the next level of generality. This was reiterated until the only possible manner of clustering the components was under the objective "Implement conceptual design of Al alloy powder gas atomising system" (see Figure

4.1 (a)). This conceptual design framework hierarchy is generic such that it can accommodate metal powder production methods for other AM techniques as well as process descriptions.

Table 4.11 Definition of activities for conceptual design framework

Level 1	Level 2 (Stages)	Level 3 (Phases)	Level 4 (Activities)	Definition
1. Implement conceptual design framework of Al alloy powder gas atomising system.	1.1 Develop technology need into design for materials and manufacturing strategy.	1.1.1 Interpretation of need	1.1.1.1 Specify technology need (the goal)	The performance specification objective of a powder manufacturing system is to produce aluminium powder which meets SLM requirements for fabricating components of sound structural integrity for technological applications. Information is gathered to develop the project goal in line with the specification.
			1.1.1.2 Assess AM technique via part's specification	Establish if a customised full-dense and light-weight Al alloy part characterized with complex geometries and exceptional precision is required. If an Al alloy part meets this specification, then choose SLM.
			1.1.1.3 Identify SLM process requirements for Al alloy powder	SLM requirements for Al alloy powder include (i) very low oxide content (<0.10%) to prevent balling (ii) spherical particle morphology for good flowability (iii) particle size/distribution of +45 to -100 μm which ensures layer deposition at thickness less than 100 μm , good powder bed packing density for good thermal conductivity between the particles.
			1.1.1.4 Evaluate Al alloy powder production methods	Consider various powder production methods which meet both SLM and economic requirements in regard to (i) particle size/distribution (+45 to -100 μm); (ii) spherical morphology; (iii) powder purity (99.9%); (iv) non-porous particle; (v) ease of control of particle morphology and size; (vi) complexity of the process; (vii) financial requirements; (viii) yield; (ix) energy consumption. Gas atomization meets all these requirements, then it is selected.
	1.2 Develop gas atomiser design parameters	1.1.2 Develop gas atomiser design parameters	1.1.2.1 Develop overall functional requirement of gas atomising system	State the overall functional requirements of the aluminium powder gas atomising systems in term of (i) geometry; (ii) kinematics; (iii) energy consumption; (iv) safety of the equipment; (v) quality; (vi) operation; (vii) manufacturability (viii) diagnosis/accessibility, (ix) maintenance and (x) size.
			1.1.2.2 Identify individual sub-systems of atomising system and develop their functional requirement.	Individual sub-systems of aluminium powder gas atomising system include (i) atomising nozzle; (ii) melting/holding furnace; (iii) atomising chamber. State the functional requirements of atomising nozzle in term of (i) energy consumption; (ii) complexity of the design; (iii) materials; (iv) durability; (v) kinematics; (vi) forces; (vii) operation (viii) materials and (ix) maintenance. State the overall functional requirements of the melting/holding furnace in term of (i) function; (ii) efficiency; (iii) material; (iv) yield; (v) energy consumption (vi) size and (vii) safety. State the overall functional requirements of the atomising chamber in term of (i) chamber height; (ii) materials; (iii) manufacturability; (iv) safety; (v) maintenance and (vi) size.

			1.1.2.3 Determine appropriate sub-systems for Al alloy powder atomiser	The sub-system variants of a gas atomiser are determined with a view to providing an objective basis for decisions. Procedures are developed to enable selection of appropriate sub-system variants and necessary solution principles so that they are compared against each other, and pre-set value hierarchy of design characteristics and requirements.
			1.1.2.4 Characterise sub-system components of Al powder gas atomiser	Each requirement is ranked in order of their importance in contributing to the performance of each sub-system or the whole gas atomiser. This forms a value tree or hierarchy which defines the characteristics of the gas atomiser. It also sets the value datum against which the conceptual design framework is evaluated.
			1.1.2.5 Determine appropriate atomisation parameters	Use gas atomising literature to identify gas atomization parameters which produce Al alloy which meet SLM requirements in regard to (i) type of atomising gas; (ii) type of nozzle; (iii) superheat temperature and (iv) gas pressure
	1.2 Develop design for materials and manufacturing strategy into conceptual design framework for Al alloy powder gas atomising system.	1.2.1 Divergent search	1.2.1.1 Create initial conceptual design framework	Solutions are developed based on requirements via literature review, creative thinking, experience and prior knowledge as at when occasion demands. Developed concepts are then recorded in structured manner.
		1.2.2 Transformation of conceptual design framework	1.2.2.1 Transform and combine conceptual design framework	All conceptual design framework generated are transformed and combined to further develop them into more usable framework at both overall atomising system level and sub-system level. This enables, functional requirements to be addressed more realistically.
			1.2.2.2 Select suitable combination of conceptual design framework	Unsuitable proposals are eliminated while consideration is given to most functionally and economically feasible conceptual design framework
		1.2.3 Convergence to conceptual design framework	1.2.3.1 Improve conceptual design framework via validation using experts' opinion	The conceptual design framework is continually improved via validation by experts' opinion. This enables important unknown variables to be further developed to a level where they constitute little or no risk to successful development of gas atomiser.

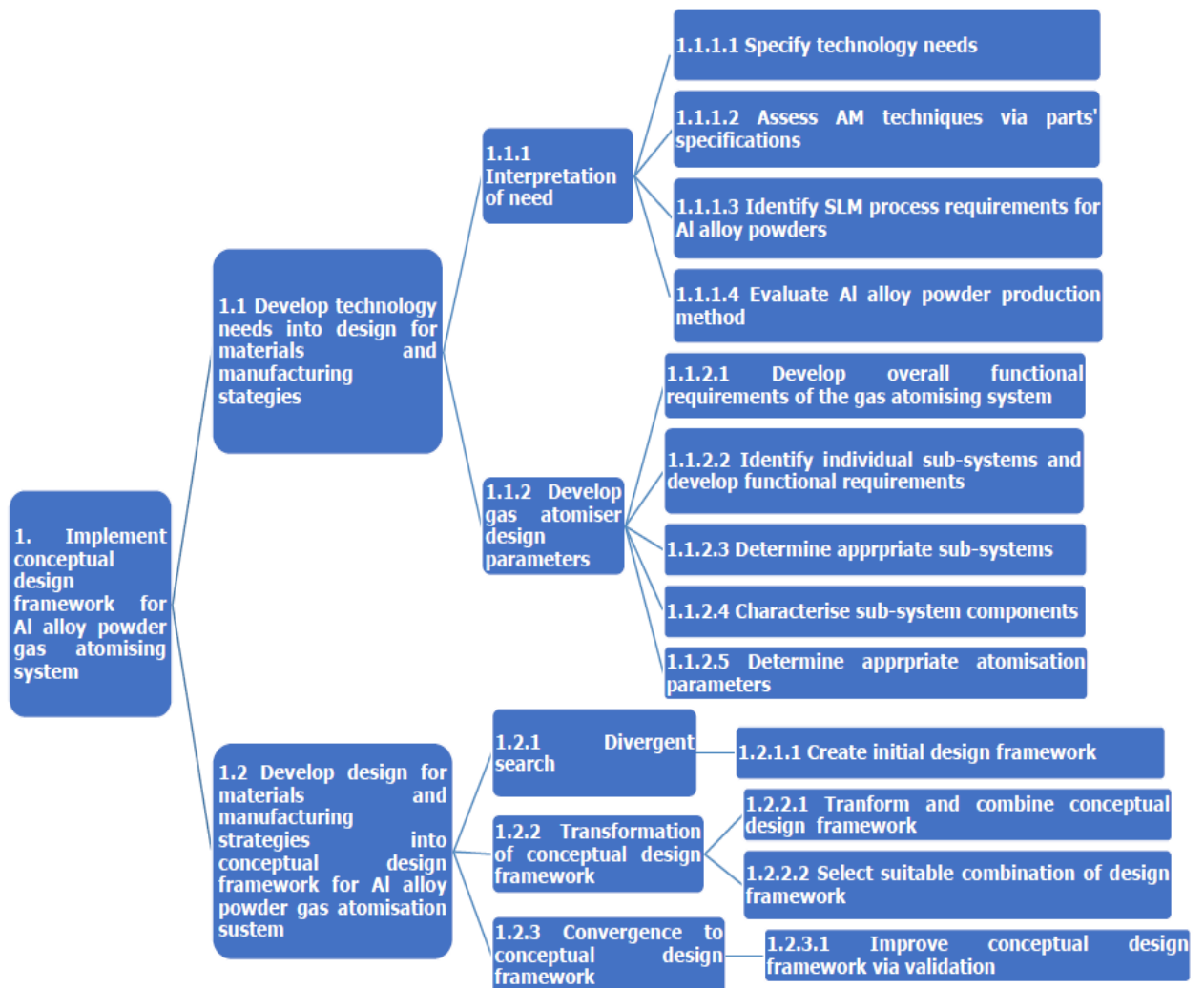


Figure 4.1 (a): Conceptual design framework hierarchy

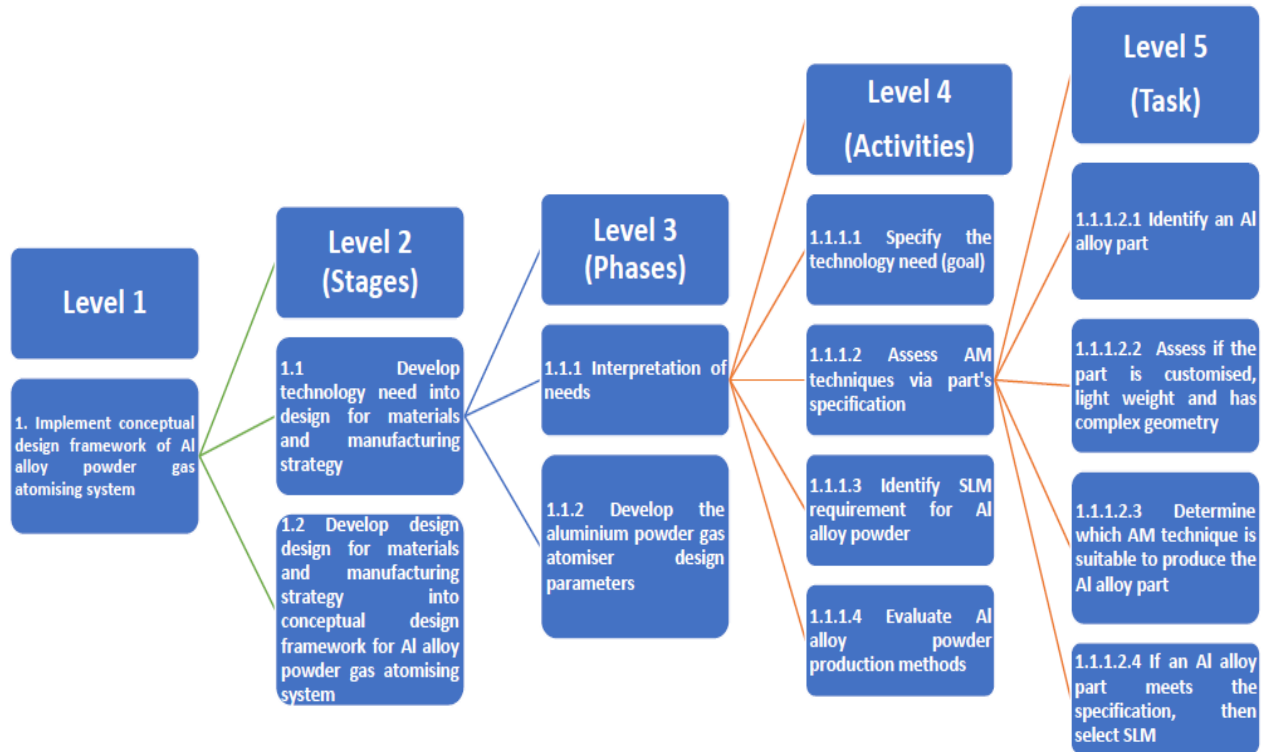


Figure 4.1 (b): A section of the framework highlighting on the tasks

4.4 Mechanical design of components

Mechanical design of the key components (melting/holding furnace and the close-coupled atomising nozzle) of an aluminium powder gas atomising system is carried out in this section. Relevant mathematical relationships and empirical data are employed in mechanical design of the key system components following the methodologies described in Chapter 3.

4.4.1 Mechanical design of the induction furnace

The furnace is required to melt aluminium at 660°C and further maintain it at superheat of 760°C. Heat loss due to conduction and radiation was minimised by making the crucible from Makoro clay (a locally available refractory material). Makoro clay was selected as material for crucible because it has high heat resistance and does not contaminate or react with aluminium melt. Thin crucible wall was employed to ensure that more heat energy from the heating coils is directed to the charge material. Identified, relevant governing equations were applied for geometrical and electrical

design of the furnace in order to generate optimum designs that meet the furnace requirements in Table 4.3.

4.4.1.1 Geometrical design of the furnace

This analysis is based on the expected output of 5.5 kg aluminium powder produced from 6 kg charge aluminium in approximately 15 minutes cycle (from melting to atomisation). Slag is assumed to range between 5 and 8 wt% of charge material (Antipas 2012). This research assumes aluminium slag to be 8 wt%. Hence, total output is expected to be around 5.5 kg considering spillage and other incidental issues. A cylindrical crucible is selected because it ensures uniform distribution of heat and non-turbulent melting. The crucible inner base is tapered towards exit to aid melt flow and ensures that no melt is left in the crucible at the end of atomisation. The internal diameter of the crucible (D_c) and height of the melt (H_m) are related according to equation 4.1 wherein the ratio of H_m to D_c range between 1.6 to 2.0 (Bala 2005). This research adopted 1.6 as the ratio of H_m to D_c . Also, since the furnace is cylindrical, the diameter of the crucible D_c is equal to the diameter of the melt D_m . Therefore, the dimensions are calculated as follows:

Height of melt

$$H_m = 1.6D_c \quad (4.1)$$

Volume of charge aluminium

$$V = \frac{\pi D_c^2}{4} \times 1.6D_c \quad (4.2)$$

Hence diameter of crucible

$$D_c = \sqrt[3]{\frac{4V}{1.6\pi}} \quad (4.3)$$

Considering the 6 kg charge aluminium, this internal diameter of the crucible (D_c) and the height of melt (H_m) are suitable. However, in order to enhance the safety of the crucible and avoid over-spilling of melt, the dimensions are slightly increased to give allowance for convectional stirring of the melt due to eddy currents. To achieve that, during calculations, the mass of charge is assumed to be 15 kg so that a larger crucible

is designed. An enlarged crucible is adopted so as to enhance safety during melt pouring. During the real operation, the mass of charge aluminium shall remain 6kg.

This size of crucible will be safe for melting 6kg charge aluminium because there will be enough space for handling the device as well as holding the material during melting and at superheat. Additional height prevent over spilling of the melt.

To determine the external/outer diameter (D_2) of the crucible, the thickness of the refractory material is taken into account. This will later assist in calculating the thickness of the crucible wall because both internal and external diameters of the crucible will be known. According to Bala (2005), the thickness of the refractory material R_t is determined using the following relationship:

$$R_t = 0.0084\sqrt{T} \quad (4.4)$$

where T = crucible capacity in tonnes

External diameter of crucible

$$D_2 = D_c + 2R_t \quad (4.5)$$

In order to determine the internal diameter of the wound inductor (D_{in}), equation 4.6 is applied as follows:

$$D_{in} = D_c + 2(R_t + B_{ins}) \quad (4.6)$$

where B_{ins} = thickness of insulation layer which under normal circumstances is such that it should be between 5 & 6 mm thick (Bala 2005). In this work, it is taken as 5 mm (0.005 m) because it is expected that the thinner the insulation layer, the lower the heat loss.

Bala (2005) indicated that the ratio of the height of inductor (H_{in}) to the height of melt (H_m) ranges between 1.1 and 1.2. Therefore, in this study the lower range of 1.1 is adopted to utilise minimum possible configurations in order to reduce the overall size of the system, hence;

$$H_{in} = 1.1 H_m \quad (4.7)$$

Considering the height of the crucible, the height of the inductor and the safety aspect, the number of turns for the induction coil is suggested as 6, hence the length of the coil can be calculated as:

$$L = N\pi D_{in} \quad (4.8)$$

The external diameter (d_{t2}) of the inductor coil used was 8 mm and internal diameter (d_{t1}) was 6 mm, hence the thickness of the inductor coil (t_c) is found by

$$t_c = \frac{d_{t2} - d_{t1}}{2} \quad (4.9)$$

Melting charge metal in a furnace produces slag. it is therefore important to consider the volume of slag because its removal will affect the final volume of useful melt produced. Similar to Beheshti (2017) and Antipas (2012), this research assume slag to be 8% of the total volume of melt. Therefore, 0.48 kg is going to be slag. Assuming the density of the slag to be the same as that of the aluminium, the volume of the slag formed will be

$$V_s = \frac{m}{\rho} \quad (4.10)$$

and the height of slag

$$H_s = \frac{4V_s}{\pi d^2} \quad (4.11)$$

The height of the furnace from the bottom of the bath to the pouring spout is found from the relationship

$$H_f = H_m + H_s + b_t \quad (4.12)$$

where H_s and b_t are height of the slag formed and thickness of refractory lining, respectively.

This is the internal height of the furnace from the base to the spout. It is important that it is lower than the height of the inductor coil which means all the melt will be sufficiently covered during melting and superheat. After finding the height of slag, the height of the

required melt (H_{fm}) after removing slag is determined. This is found by subtracting the height of slag (H_s) from the height of melt (H_m).

$$H_{fm} = H_m - h_s \quad (4.13)$$

The final volume of melt (V_{fm}) to be atomised is therefore

$$V_{fm} = V - V_s \quad (4.14)$$

All these design parameters of the induction furnace are summarised in Table 4.12.

4.4.1.2 Electrical and thermal design of the furnace

Thermal equations governing the design of an induction furnace are applied to come up with an efficient design. Important issues affecting operation of the furnace such as heat loss, superheat temperature, heat energy requirements and material resistivity are critically analysed in order to determine the design that would give optimum results.

Firstly, total heat energy required to melt the charge is calculated using equation 4.15 (Ilori,1991). It is used to determine the required heat energy consumed to melt the charge material as it is (including impurities in it; slag).

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} - Q_{ex} \quad (4.15)$$

where Q_{th} = total heat energy required

Q_m = amount of heat energy to melt 6kg of charge aluminium, J;

Q_{sh} = amount of heat energy to superheat, J;

Q_s = heat required to melt slag forming materials, J;

Q_{en} = energy required for endothermic process, J;

Q_{ex} = amount of heat energy lost to the surroundings as a result of exothermic reactions, J.

Table 4.12 Values for the mechanical design of the furnace.

No.	Parameters	Value	Unit
1	Volume of melt (V_m)	0.0022	m ³
2	Height : Diameter (of melt) ($H_m : D_m$) ratio	1:1.6	
3	Height of melt (H_m)	0.262	m
4	Refractory thickness of wall	0.00103	m
5	Crucible shape	Cylindrical	
6	Crucible capacity	15	kg
7	Mass of charge	6	kg
8	Required amount of Al powder	5.5	kg
9	Internal diameter of coil (D_{in})=Ext. dia. cruc	0.176	m
11	Height of inductor coil (H_{in})	0.288	m
12	Length of inductor coil	3.32	m
13	Enhanced height of furnace (H_f)	0.300	m
14	Thickness of insulation layer (fibre glass)	5	mm
15	Number of turns	6	
16	Protrusion height of melt delivery tube	7	mm

It should be noted that theoretically, energy required for endothermic reaction is equivalent to energy lost due to exothermic reaction, hence $Q_{en} = Q_{ex}$ resulting in the two energies cancelling one another.

Equation 4.15 therefore reduces to:

$$Q_{th} = Q_m + Q_{sh} + Q_s$$

Where,

$$Q_m = mc_p(t_2 - t_1) + mh_l \quad (4.16)$$

Where; m = mass of charge, kg;

c_p = specific heat capacity of charge aluminium, being 1100 J/kgK;

t_2 = melting temperature of aluminium charge, which is 660 °C

t_1 = ambient/room temperature, taken as 25 °C in Botswana

h_l = enthalpy of fusion of aluminium, being 8660 J/kgK

$$Q_{sh} = m \theta_{sh} \quad (4.17)$$

where C_m = average heat capacity of molten aluminium, which is 992 J/kgK

θ_{sh} = amount of superheat temperature, taken as 100 °C

Amount of heat required to melt slag is

$$Q_s = K_s G_s \quad (4.18)$$

where K_s = quantity of slag formed, kg, taken as 8 % of total charge material,

G_s = heat energy for aluminium slag = 18 kJ/kg (Bala, 2005; Mansoor & Shahid, 2014)

Taking the time taken to melt the charge as 15 minutes, then the power needed is

$$P = \frac{Q_{th}}{t} \quad (4.19)$$

Total energy induced in charge due to eddy currents is found by applying equation 4.9 (Alshaikhli, et al. (2014)),

$$Q_{ec} = \frac{\pi^3 f^2 H_m B_{max}^2 d_m^2}{8\rho} \quad (4.20)$$

where f = frequency of power supply, 1kHz;

B_{max} = maximum flux density, H;

ρ = resistivity of charge material, for aluminium = $2.83 \times 10^{-8} \Omega m$

$$\text{Maximum } B_{max} = \sqrt{\frac{8\rho Q_{th}}{\pi^3 f^2 d_m^4 H_m}} \quad (4.21)$$

The allowable current density in the inductor is given by equation 4.22 which states thus;

$$J = \frac{I}{A_t} \quad (4.22)$$

where I = current in inductor in amperes, A;

A_t = cross sectional thickness area of conducting tube (mm^2), taking external diameter of inductor coil (d_{t2}) to be 5 mm and internal diameter (d_{t1}) to be 4mm.

N.B. Current density J , ranges from 20 to 40 A/ mm^2 , and in this case it is taken as 20A/ mm^2 .

The cross-sectional thickness area of the tube is calculated as

$$A_t = \frac{\pi}{4} (D_o^2 - D_i^2) \quad (4.23)$$

Current in inductor coil is therefore: $I = JA_t$

The resistance of a material is influenced by its length (L) and resistivity, ρ , and various literature including Aspecore (2019) has documented resistivity of copper to be $\rho=1.7 \times 10^{-8} \Omega/m$ at 25 °C.

Resistance of the copper tubing is therefore found to be

$$R_{t0} = \rho \frac{L}{A} \quad (4.24)$$

Resistance also depends on temperature, usually increasing as the temperature increases. For reasonably small changes in temperature, the change in resistivity, and therefore the change in resistance, is proportional to the temperature change.

Resistance at any given temperature θ is given by the equation

$$R_t = R_{t_0}[1 + \alpha_o(t - t_o)] \quad (4.25)$$

Where temperature coefficient of copper at ambient temperature $\alpha_o = 3.9 \times 10^{-3} \text{ K}^{-1}$.

As the coil is heated, its resistance changes. The coil heat loss due to resistance is given by the equation

$$P_c = I^2 R_\theta \quad (4.26)$$

During melting of the charge material, heat is going to be lost through conduction (Shrets *et al.* 1987). Equation 4.27 assists in determining the amount of heat lost so that it can be reduced;

$$Q_l = \frac{\pi H_m(t_2 - t)}{\frac{1}{2} \left[\frac{1}{\lambda_{mc}} \ln \frac{d_2}{D_c} + \frac{1}{\lambda_{mt}} \ln \frac{D_{in}}{d_2} + \frac{1}{\lambda_{cu}} \ln \frac{d_3}{D_{in}} \right]} \quad (4.27)$$

Where λ = thermal conductivity, with subscripts for makoro clay (mc), mica tape (mt) and copper (cu) respectively.

$$\lambda_{mc} = 2.093 \text{ W/mK}; \lambda_{mt} = 0.71 \text{ W/mK}; \lambda_{cu} = 380 \text{ W/mK}$$

d_3 = inductor diameter surrounding crucible + 2 x thickness of coil, where thickness of coil is 0.5 mm

And t = outlet temperature of fluid; $^{\circ}\text{C}$;

Outlet temperature of hot water (θ) with similar specific heat as cold water in a heat exchanger has been taken as 358K (85 $^{\circ}\text{C}$) (Chegg study 2018).

This is a minimum heat loss looking at the fact that for other materials that may be used to make the crucible such as alumina and magnesia have higher heat losses at

similar temperature. In their study, Mohite *et al.* (2017) found heat losses of alumina and magnesia for the same wall thickness as used in this study to be 0.0626 and 0.0587 kWh, respectively. So, 0.293 kWh is acceptable. The thermal and electrical designs of the induction furnace are summarised in Table 4.13 and the geometric design is presented in Appendix A1 to A4.

4.4.2 Mechanical design of the atomising nozzle

In this study, a close-coupled gas atomising nozzle was developed for gas atomisation of aluminium melts. In order to design a good gas nozzle, several factors such as mass flow rate of both gas and melt, velocities of both gas and melt, pressure of atomising gas, aspect ratio (ratio of throat diameter to expansion length) and the gas jet apex angle were determined with the aim to obtain a gas nozzle capable of producing high velocity needed for effective atomisation. Empirical data in the form of engineering equations and laws relevant to close-coupled gas atomising nozzles were identified and applied to create some important design features of the nozzle. Throat diameter and expansion area are some of the influential features of the nozzle. Upon the determination of the basic geometric designs of the nozzle, CFD was used to optimise the gas nozzle such that maximum velocity at exit is maintained in order to effectively break the melt droplet. The findings were then incorporated into the final design and a pictorial representation was presented in Appendix B.

Table 4.13 Values for thermal and electrical design of the furnace

No.	Parameter	Value	Units
1	Operating frequency (f)	1	kHz
2	Total heat energy required (Q_{th})	4786.2	kJ
3	Power required	5.38	kW
4	Superheat temperature (Q_{sh})	100	°C
5	Time required to melt a batch	15	mins
6	Internal diameter of inductor coil	6	mm
7	External diameter of inductor coil	8	mm
8	Length of coil	3.15	m
9	No. of turns	6	
10	Coil resistance	3.6×10^{-8}	Ω m
11	Coil current	141.4	A
12	Resistance of charge (Al)	2.56×10^{-8}	Ω m

4.4.2.1 Geometrical design of the nozzle

The rate at which the melt is fed into the atomiser is important to know when designing a close-coupled nozzle. Therefore, equation 4.28 (Si *et al.*, 2014) is applied to establish the melt velocity such that:

$$v = \sqrt{2gH - \frac{2\Delta P}{\rho}} \quad (4.28)$$

Where H is the height of the melt plus nozzle protrusion height ($H = 0.332$, Table 4.11) and ΔP is the aspiration pressure, namely the gas pressure at the tip of metal delivery tube less pressure in the atomizer.

Pressure inside the chamber is taken as 100 000 Pa (1 bar).

Aspiration pressure (ΔP) at tip of delivery tube (pressure of melt – ambient pressure).

Since the density of the melt is 2375 kg/m³, then,

It is important to determine the melt flow rate because if the flow rate is too high for the gas velocity, atomisation may not be effectively executed on all the droplets, resulting in poor powder morphology. With the above velocity and a melt outlet diameter of 0.003 m, the melt flow rate is determined such that:

$$M_f = VA \quad (4.29)$$

Whereby V = melt velocity and A = cross-sectional area of the melt outlet

Gas flow rate is determined from the following equation:

$$G = A_t \left[\gamma \rho_o P_o \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{1/2} \quad (4.30)$$

Where;

A_t = area of gas exit with dia. 2 mm

γ = adiabatic value (C_p/C_v) = 1.67 (Kyle, 2000)

P_o = atomizing pressure (0.6 MPa)

ρ_o = density of helium at 300 K

Gas velocity is found by engaging equation 4.16, which states;

$$V_g = \frac{G}{\rho A_t} \quad (4.31)$$

For the gas atomiser to be able to effectively break the melt, droplet size also plays a significant role in determining the critical features of the nozzle. The droplet size is determined using the following equation (Lubanska 1970):

$$d_m = KD \left[\frac{V_L}{v_g We} \left(1 + \frac{M_f}{G} \right) \right]^{\frac{1}{2}} \quad (4.32)$$

where K = a constant that ranges between 4×10^{-6} and 5×10^{-6} (Si *et al.*, 2014) and 4×10^{-6} is adopted with the aim to adopt the minimum possible values to reduce droplet size.

D = the diameter of melt delivery tube where 3 mm imposed in this study.

V_l = viscosity of molten aluminium ranging between 1.0 and 1.4 mPa (Dinsdale and Quested, 2004), with 1.4 mPa selected in this study because of the natural oxide that covered aluminium droplet and make it difficult to break the droplet.

v_g = viscosity of helium gas taken as 1.96×10^{-5}

M_f = melt flow rate

G = gas flow rate

W_e = Weber number

The Weber number is found using the following equation;

$$W_e = U^2 \rho_g d_o / \gamma_m \quad (4.33)$$

Where, U = approximately V_g

ρ_g = density of gas, taken as 0.16147 kg/m^3

d_o = throat diameter taken as 1.0 mm (0.001 m)

γ_m = surface tension of aluminium melt, taken as 0.868 N/m (Brainbridge and Taylor, 2013).

This Weber number is important because of the high velocity gas that violently breaks the surface tension of the molten droplet. This means that the kinetic energy of the atomising gas is more dominant than the surface tension of the molten droplet. This is a desirable situation during gas atomisation of melts because violent breaking of the melt means the droplet bursts into very tiny droplets that cool and solidify to become tiny metal powder particles.

The design configurations of the nozzle is presented in Table 4.14 and the presentation drawing is illustrated in Appendix B1 and B2. This study adopted the expansion angle

of 28° as used in Sofuoglu and co-investigators (2013) work and that was imposed in the final solution. That was done considering the fact that the said expansion angle worked well for Sofuoglu and co-investigators (2013) who were doing a similar work.

Table 4.14 Values for geometrical design configurations of the nozzle

No.	Parameter	Value	Units
1	Delivery tube diameter	3	mm
2	Apex angle	37.5	°
3	Expansion angle	28	°
	Expansion length	2.5	mm
3	Atomising gas pressure	0.6	MPa
4	Atomising gas temperature	25	°C
5	Atomising gas velocity	572.5	m/s
6	Atomising gas flow rate	0.000290132	m ³ /s
7	Diameter of gas exit		mm
8	Throat diameter	0.30	mm
9	Expansion length	2	mm
10	Melt velocity	2.63	m/s
11	Melt flow rate	1.86 x 10 ⁻⁵	m ³ /s

4.4.3 Mechanical design of the atomising chamber

The design of the atomising chamber was largely based on the findings from literature in Sections 2.6.3 and 4.2.3.4 in which a vertical atomising chamber was recommended for this research. An atomising chamber with a diameter of 1 meter and height of 2 meters was selected as appropriate. The overall dimensions are shown in appendix C. Furthermore, there are some auxiliary components or sub-systems that assist during

atomisation to achieve the intended results. These are discussed in Section 4.4.4 and are intended to enhance the safety and efficiency of the atomising system.

4.4.4 Auxiliary components/sub-systems

Auxiliary components were identified as an area that could be explored to enhance the safety and efficiency of the powder production system. These were some of the developments introduced into the system that make the current design different from the already existing designs. This research introduced gas and powder particle recovery system (GPPRS), the data acquisition and control system (DACS) and safety features to enhance the overall performance of the system and prevent hazards to the operators and the environment.

4.4.4.1 Gas delivery system

A good gas delivery system must provide accurate gas flow rate enough to atomise the melt. Safety measures were ensured to guard possible explosion as a result of excessive pressure in the chamber. Pressure relief valves were introduced to assist in this regard. Non-toxic and debris-free gas must be used during the process to avoid asphyxiation and contamination of the melt. Ideally, a relatively cheap gas must be used to ensure that the system remains economically viable. However, since more emphasis is on the powder quality, it is not always that production of suitable metal powder for AM processing always use cheaper atomising gases. This is because inert gases by their nature are expensive. The gas used must be warmed to suitable temperature to excite its kinetic energy and also ensure that it does not have rapid cooling effects on the melt, a situation that may lead to the melt droplet not being effectively atomised. Preheating the atomising gas also increases gas velocity that is very much needed in disintegrating the melt droplet (Li, *et al.*, 2006). Increasing temperature for a given gas pressure result in an increase in gas velocity.

4.4.4.1.1 Gas supply requirements

Both naturally occurring and commercially produced atomising gases exist. As already mention in Chapter 2, atomising gas type influences powder purity and consequently influence the properties of the component manufactured via SLM process. Table 4.6 illustrates the requirements for the atomising gas.

4.4.4.2 Gas and powder particle recovery system

During powder production, it is important to recover the un-atomised particles for re-melting and re-atomisation. It is also important to recover the gas to minimise production costs. For powder recovery, powder separators will be installed at the bottom of the atomising chamber where the powder collects, in order to segregate larger particles falling out of the desired particle size distribution (+45 – 70 μm) and take them for re-melting and subsequent re-atomisation. As a gas recovery strategy, instead of releasing the atomising gas that would have built unnecessary pressure inside the chamber into the atmosphere, the gas is collected into a reservoir. The gas is then allowed to cool to desired atomising temperature before being re-introduced into the process again, thereby creating a recycling process. However, during the recycling of the gas, it is crucial that due diligence is exercised to guard against introduction of oxygen into the system. Seals must be used for proper control of the atomising environment.

4.4.4.3 Data acquisition and control system (DACS)

Once in full operation, the system is semi-automated for efficiency and accuracy through a simple electronic circuit code-named DACS (data acquisition and control system). The monitoring system consists of a processor, monitor, control and communication hardware, software and a programmable logic controller (PLC). The gas nozzle and melt path are all interfaced to the PLC to ensure process optimisation through monitoring of gas pressure and melt flow rate to ensure optimum gas-melt interaction. A window on the atomising chamber allows the operator to observe the process and communicates to the PLC through the user interface that allows the operator to change the system's settings in response to any given situation. The PLC is also linked to the particle recovery system through the operation of the segregator.

4.4.4.4 Safety features of the system

Basic general safety measures had to be ensured to make the operation less likely to have adverse effects on the operator(s) and the environment. Electrical hazards were eliminated by insulating all electrical wires and “*earthing*” all the equipment. Furthermore, emergency switches were introduced to allow quick electricity cut in dire situations where life would be under threat. The use of pressure sensors was employed to alert the operators whenever pressure surpasses expected limits. The system is expected to be used in a fully aerated environment with air extractors to suck out fumes that may be generated during melting. One of the reasons why nitrogen was not selected was due to its tendency to have asphyxiation effects that may affect the respiratory health of the operator. Before collecting powder from the bottom of the chamber, firstly it must be ensured that the system has come to a complete stop and be allowed to cool. Also, proper personal protective equipment (PPE) such as mask, leather gloves, safety boots and overalls should be worn to enhance safety. A heating/holding furnace eliminates chances of burning the operator during the transfer of melt. Lastly, proper monitoring of the process must be ensured.

4.5 Design optimisation of the gas atomising nozzle via computational fluid dynamics (CFD) simulation

In order to optimise the design of the atomising nozzle, computational fluid dynamics (CFD) simulation of gas nozzle was carried out to investigate the effects of aspect ratio (relationship between throat diameter and expansion length) on the velocity of the atomising gas. In this case, aspect ratio refers to the ratio of the throat diameter to expansion length in the converging-diverging (CD) nozzle (T_d/E_l). This was aimed at identifying the correct position of the throat and expansion area so that maximum gas velocity at nozzle exit is generated. In order to ensure its relevance to this research, the CFD version used was validated using previous study. A model was generated and the solution was used as baseline data for CFD investigation. Other process parameters obtained via the application of the said empirical data such as flow rate

(melt and gas) and pressure were also used as constant values during the experiment. Throughout the experiment, only throat diameter and expansion length were varied while other process parameters were kept constant. The methodology for carrying out this experiment was outlined in Chapter 3, Figure 3.5. ANSYS R1 2019 academic version was used to simulate the process.

4.5.1 Computational fluid dynamics (CFD) code validation

For technical validation of the ANSYS R1 2019 Fluent academic version, a previous study by Sofuoglu *et al.* (2013) was carried out and the results were then compared to find if they match what Sofuoglu *et al.* (2013) obtained. In their experiment, Sofuoglu and co-authors, (2013) investigated atomisation of molten metal stream as well gas velocity in a close-coupled nozzle as part of their study. This is relevant to this research because it is also investigating gas velocity through a nozzle. Sofuoglu *et al.* (2013) used four different geometry designs with varying nozzle exit angles, protrusion lengths and throat diameters as shown in Table 4.15 to investigate gas pressure at melt tip during gas-melt interaction. Pressure and velocity are inversely proportional to each other, hence where there is low pressure, velocity is high and vice-versa. Sofuoglu *et al.*, (2013) established that the lowest pressure of -3288.86 Pa was recorded when the throat diameter was 0.30 mm (Table 4.15), and they adopted that configuration because lowest pressure meant highest velocity.

Table 4.15 Comparison of results for validation

Geometry	Nozzle exit angle (°)	Throat diameter (mm)	Tip pressure (Pa) (Sofuoglu et al, 2013)	Validated Tip pressure (Pa)
1	28	0.25	-2164.7	-2162.39
2	26	0.2	-1492.83	-1494.79
3	28	0.25	-2732.96	-2731.83
4	28	0.3	-3288.86	-3287.98

During the validation process, pressure at melt tip in Sofuoglu's work was taken to be the same as pressure at nozzle exit because of the small distance between the melt path tip and the atomising gas nozzle exit tip. The pressure at nozzle exit for the aspiration pressure recorded in geometry case 4 was calculated so that comparison can be made. Table 4.15 shows the comparison of the results from Sofuoglu *et al.*,

(2013) and the same experiment as carried out during validation. The results can be interpreted as comparable, hence the validity of the CFD code for this work is assured. Similar approach was adopted by Poorasadion *et al.* (2013), Ting and Anderson, (2004), Guducu (2015) and Zhao *et al.* (2012) when they validated the relevance of CFD codes to their investigations. However, it must be noted that in CFD simulation, it is close to impossible to attain exactly the same results repeatedly because of the high accuracy of the software and the existence of the inevitable human error.

There are some similarities between validation results and original results by Sofuoglu *et al.* (2013). Minor differences in values may be a results of human errors and some tolerances in boundary conditions that this research may have failed to capture. Nevertheless, both results are in harmony regarding the highest aspiration pressure recorded at nozzle 4 and they are within the acceptable 5% discrepancy (Paz *et al.* 2019). Consequently, the results validate ANSYS R1 2019 academic version as a suitable CFD software for use in this research and it is adopted.

4.5.2 Experimental setup

A gas nozzle of known dimensions was modelled via ANSYS 2019 R1 academic version as shown in Figure 4.2 and was later revolved to become a 3-D geometry representing the fluid body (gas). Various throat diameters (0.25, 0.3, 0.35 and 0.4 mm), and expansion lengths (2, 3, 3.5 and 4 mm) were used to investigate their effects on gas velocity at nozzle exit during close coupled gas atomisation (CCGA) of aluminium melt. The experimental procedure was such that an expansion angle of 28° was adopted from literature and kept constant (Sofuoglu *et al.* 2013) as an ideal angle. Only the throat diameter and the expansion length were varied as shown in Table 4.16. According to the table, a total of four (4) sets of experiments were carried out to identify the best throat diameter and expansion length configuration that produces high gas velocity required to effectively break the melt. This was achieved in a space of eight weeks and boundary conditions were kept constant for all the experiments. Only model configurations were altered to include dimensions under investigations.

Discrete phase model (DPM) was selected because this research was interested in simulating gas velocity profile through the nozzle only, which is a single-phase flow. For this reason, Volume of fluid (VoF) model could not be used because it is mostly suitable for multi-phase fluid flow simulation. Furthermore, stream-wise flow (either specified mass flow rate or specified pressure drop) cannot be modeled via VoF model. Therefore, this research focused on analysing the effect of changing the converging and diverging nozzle geometric parameters and position of the nozzle's throat on the magnitude of exit velocity by using one phase fluid flow (gas), hence, the relevance of DPM. However, VoF and DPM methods can be coupled for instance, in situations where gas-melt interaction is analysed based on selected nozzle geometrical parameters in order to track the particle distribution.

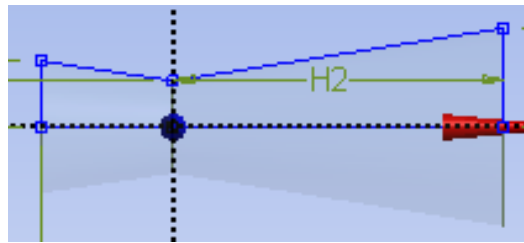


Figure 4.2 Experimental model used as baseline data

The dimensions in mm were as follow:

Nozzle end diameter = 0.75

Throat diameter = 0.30

Expansion length (H2) = 2.5

A close-coupled nozzle with similar designs to the one shown in Figure 2.9 was investigated. During initial design, the model was configured to sustain maximum pressure of 0.6 MPa at inlet with inlet velocity provided as 572.5 m/s. The velocity at exit was expected to increase exponentially as a result of the design and size of the throat and the expansion area. Material selected to fabricate the nozzle was stainless steel 316l because of its high melting point and non-reactivity with He and Al. The values used for the expansion angle of 28° were obtained from Sofuoglu *et al.* 2013)

and utilized in this research because that particular angle was ideal for producing finer particles. During experimentation, in one set the throat diameter was kept constant for four different expansion lengths. Finally, all the results were evaluated and the best combination of features was selected.

4.5.3 Boundary conditions

The experimental domain had an inlet (where the pressurized atomising gas entered the nozzle) and an outlet (where a high velocity gas leaves the nozzle). Between the entrance and the exit, there was gas flow only from the inlet to the outlet, via the throat. Expansion length started from the throat to the tip of the nozzle at the outlet and it was kept constant at an angle of 28° throughout the experiment. Walls were only made along the length of the nozzle. Helium (He) was used as atomising gas and was fed to the inlet at 0.6 MPa. The temperature of the walls and the gas inlet were assumed to be at ambient temperature (300 K).

Table 4.16 Sets of varying throat diameters and expansion lengths.

Experiment No.:	Throat diameter (mm)	Expansion lengths (mm)
1	0.25	a) 2.0
		b) 3.0
		c) 3.5
		d) 4.0
2	0.3	a) 2.0
		b) 3.0
		c) 3.5
		d) 4.0
3	0.35	a) 2.0
		b) 3.0
		c) 3.5
		d) 4.0
4	0.4	a) 2.0
		b) 3.0
		c) 3.5
		d) 4.0

4.5.4 Model assumptions

The expansion angle of the gas nozzle was a constant parameter taken as 28° throughout the experiment while the throat diameter and expansion length were varied to investigate the effects of these geometrical parameters on the gas velocity at nozzle

exit. Four different values of the throat diameter and four sets (each with four values) of expansion length were studied. Values for the throat diameter were 0.25, 0.3, 0.35 and 0.4 mm and expansion lengths investigated were 2.0, 3.0, 3.5 and 4 mm. CFD simulations were executed via pressure-based solver algorithm and flow turbulence was simulated to give a general description of turbulent flow of the atomising gas. Reynolds number (turbulence intensity) was computed at 7254. Ten inflation layers at the walls were applied to improve fluid flow as illustrated in Figure 4.4. To investigate grid independence, three different mesh qualities were used with an increase of one mm interval to test the influence of the mesh refinement. The problem was attempted using the three different mesh numbers (163 281, 178 896 and 187 344) and it emerged that beyond 187 344 elements, the baseline solution was not affected by any change in the refinement of the mesh, hence grid independence was reached (Figure 4.5). Convergence was achieved when scaled residuals were kept at 10^{-4} for energy and 10^{-3} for momentum and turbulence parameters. Helium gas was used as atomising gas and the pressure was assumed to be high at inlet and very low at outlet. On the other hand, velocity was assumed to increase exponentially as the gas passed through the throat and expanded on leaving the throat along the expansion length until it reached the nozzle tip where it got into the non-confined zone and the boundary conditions changed. In such a case, it is assumed that the proximity of the nozzle to the melt path will preserve the kinetic energy required to break the melt.

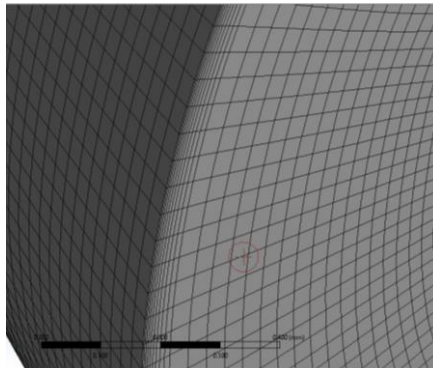


Figure 4.4 Inflation layers at the walls

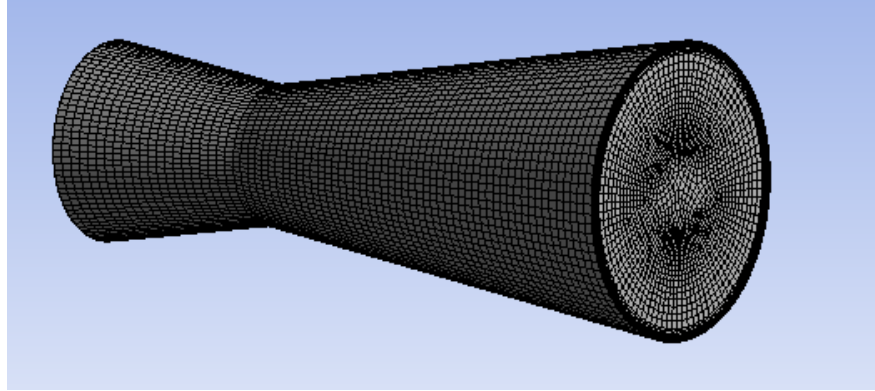


Figure 4.5 Grid generated

4.5.5 Findings from the experiment

Velocity magnitudes at nozzle exit are shown in Table 4.17 for different geometrical designs. The solution in experiment 3(a) was selected because of the highest velocity magnitude at nozzle exit and beyond. Velocity at nozzle exit reached a maximum of 2850 m/s (Figure 4.6a and b). Furthermore, it was noticed that even beyond the nozzle exit, velocity was still very high (2700 m/s) as illustrated in Figure 4.7. That gave assurance that the melt droplet would be effectively broken by the strong jet that would have not lost effective velocity at nozzle exit. Furthermore, the high impact arising from such high velocity atomising gas was likely to produce very fine particles. From the experimental results, a gas nozzle with throat diameter of 0.35 mm and an expansion length of 2.0 mm is the optimum design configuration for this research. Therefore the aspect ratio is 1:5.7.

The initial velocity computed at the throat was 572.5 m/s and the terminal velocity at exit was 2850 m/s. This translated into Mach number of 8.6. This indicates shock waves would be generated mainly at the nozzle exit. The condition is expected because of the effects of the small throat diameter (0.35 mm) and the high pressure utilised (0.6 MPa). Other investigators such as Leon *et al.* (2016) and Firmansyah *et al.* (2014) had reported the transition from supersonic to hypersonic Mach numbers as a result of higher exit gas velocity. However, overcoming the separation of boundary layers that results in creation of shock during gas atomisation is an area that Zeoli and Gu (2008), Motaman *et al.* (2012), Motaman *et al.* (2013), Motaman *et al.* (2015) have

explored so as to develop approaches of minimising the shock wave effects. Analysis of literature indicates there has been no agreement among researchers on the solution to be adopted. Several studies have proffered different solutions, hence, it is difficult to pinpoint a specific strategy for minimising shock waves. Nevertheless, it must be noted that minimum shock waves are important during gas atomisation as they ensure the vigorous gas-melt interaction, thus producing finer droplets (Kaiser *et al.* 2015). Furthermore, it is not possible to completely eliminate the trailing shock, which is due to the truncated nozzle body design (Dumnov, 1996; Zeoli and Gu, 2008). In order to address the problem of shock wave formation in this study, the boundary condition at the exit of the nozzle was presumed same as atmospheric pressure by defining gauge pressure as zero. This approach was adopted to minimise shock wave formations inside the nozzle at the specified total pressure, hence it is possible to simulate.

From the results it is clear that the closer the throat is to the nozzle tip, the higher the velocity at nozzle exit. However, if the throat diameter is too small (e.g. experiment 1), the gas gets choked at the throat and flow rate is affected, hence the resultant powder may be of a poor quality. Similarly, if the throat diameter is too big, velocity reduces and the kinetic energy required to effectively break the melt is low. This may ultimately lead to increased atomising gas consumption that increases production cost significantly.

The results indicate that at throat diameter 0.25 mm, low velocity was recorded despite the small throat size. That could be attributed to the reversed flow experienced as a result of the small throat diameter and high pressure of the atomising gas. The unacceptable situation resulted in creation of shock at the throat, hence reduced velocity. One way of overcoming the challenge was to reduce the inlet pressure, a condition that this study was not prepared to undertake because of the imposed initial pressure of 6 bars which is the lowest pressure magnitude available in the school laboratory where the atomising system was to be erected. Anything less than 0.6 MPa would not connect to the compressor that is used in the school laboratory, hence it was impossible to work with pressure below 0.6 MPa. Apart from the challenge in throat diameter 0.25 mm, all other throat diameters were able to give positive results. As for

throat diameter 0.3 mm and expansion length 2.0, the reason why it could not produce higher velocity (than that of 0.35 mm throat diameter) despite its proximity to the nozzle tip may be attributed to the fact that at some point during simulation, minimum reversed flow towards the throat was observed. That meant that the pressure was too much for the size of the throat, hence choking was experienced. On the contrary, during the simulation of throat diameter 0.35 mm, no reverse flow was recorded.

Table 4.17 Velocity magnitude of varying throat and expansion length

Experiment No.:	Throat diameter (mm)	Expansion lengths (mm)	Velocity (m/s)
1	0.25	a) 2.0	1130
		b) 3.0	990
		c) 3.5	805
		d) 4.0	685
2	0.3	a) 2.0	2790
		b) 3.0	2575
		c) 3.5	2510
		d) 4.0	2305
3	0.35	a) 2.0	2880
		b) 3.0	2805
		c) 3.5	2730
		d) 4.0	2550
4	0.4	a) 2.0	2685
		b) 3.0	2555
		c) 3.5	2510

		d) 4.0	2330
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In conclusion, this investigation observed that the *larger* the distance between the throat and the nozzle exit, the *lower* the velocity at exit, and vice-versa. From that observation, it can be argued that as the high velocity gas exits the throat, it gradually loses kinetic energy required to propel it further and maintain the velocity. That was because immediately the gas exited the throat, it tried to fill up the larger space in the expansion area of the nozzle, hence the rapid expansion of the gas molecules that culminated in the loss of critical velocity required to effectively break the melt. Additionally, the experiment showed that larger throat diameters and longer expansion lengths produced lower velocities as compared to smaller throat diameters (above 0.25 mm) and shorter expansion lengths.

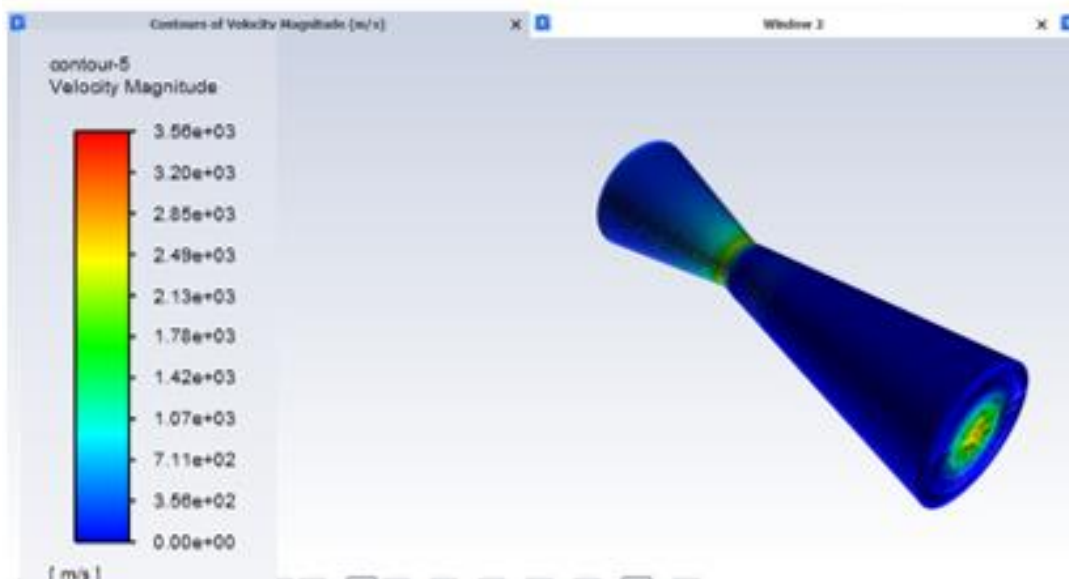


Figure 4.6 (a) Gas velocity magnitude through the fluid body.

N.B. Notice the effects of boundary layers where velocity is almost zero at the walls.

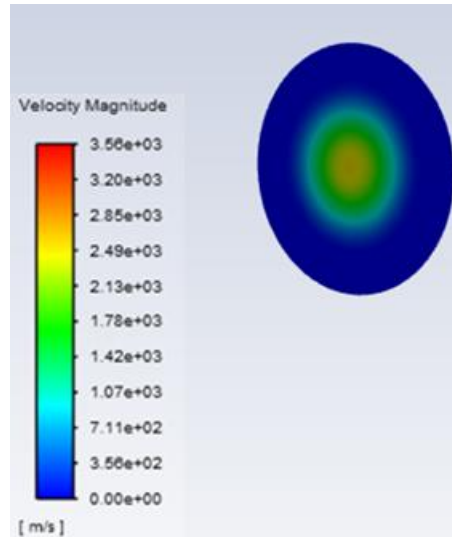


Figure 4.6 (b) Gas velocity at exit

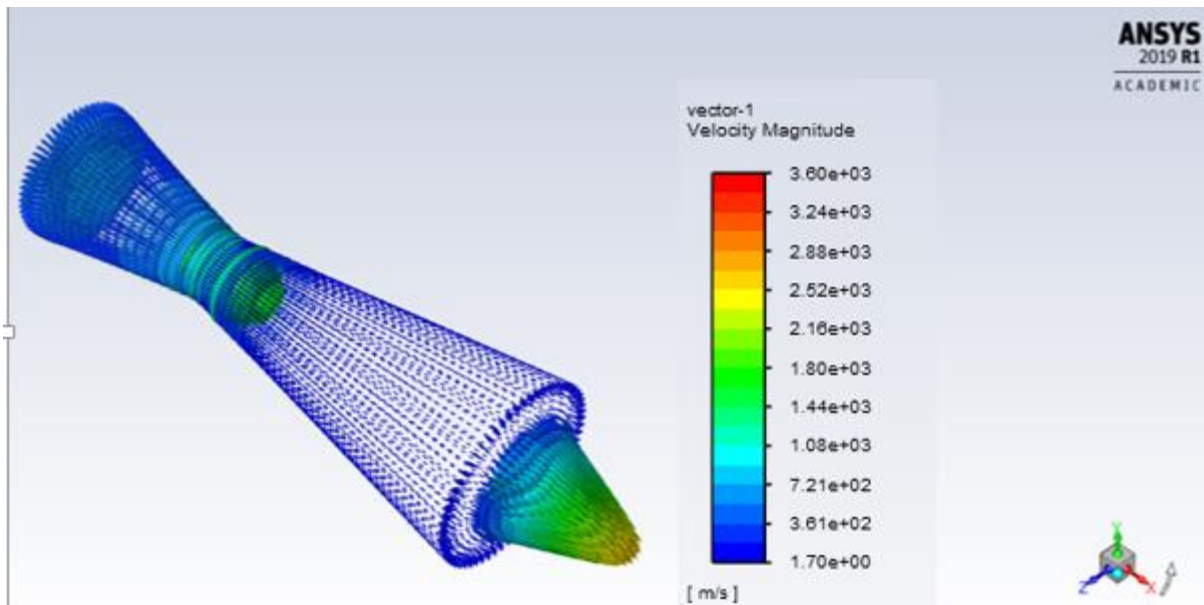


Figure 4.7 High gas velocity beyond nozzle tip.

Figures 4.8 (a) and (b) show different velocities at nozzle exit as a result of different geometric configurations with regard to size and proximity of the throat and expansion length, respectively. For figure 4.8 (a), the throat diameter was 0.3 mm while the expansion length was 3.0 mm (2575 m/s). As for Figure 4.8 (b), throat diameter was 0.4 mm while expansion length was 4.0 mm (2330 m/s).

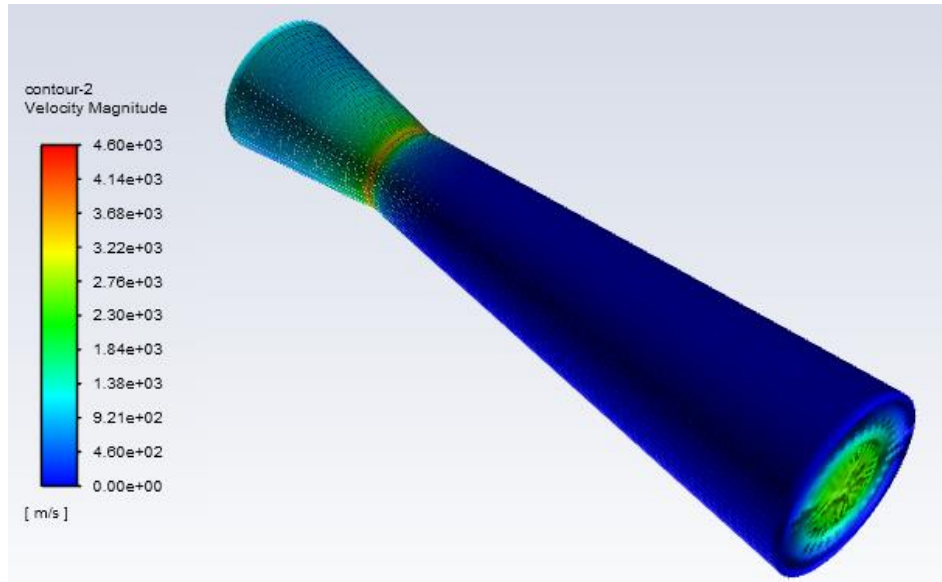


Figure 4.8 (a) Gas velocity at throat diameter 0.3mm, expansion length 3mm

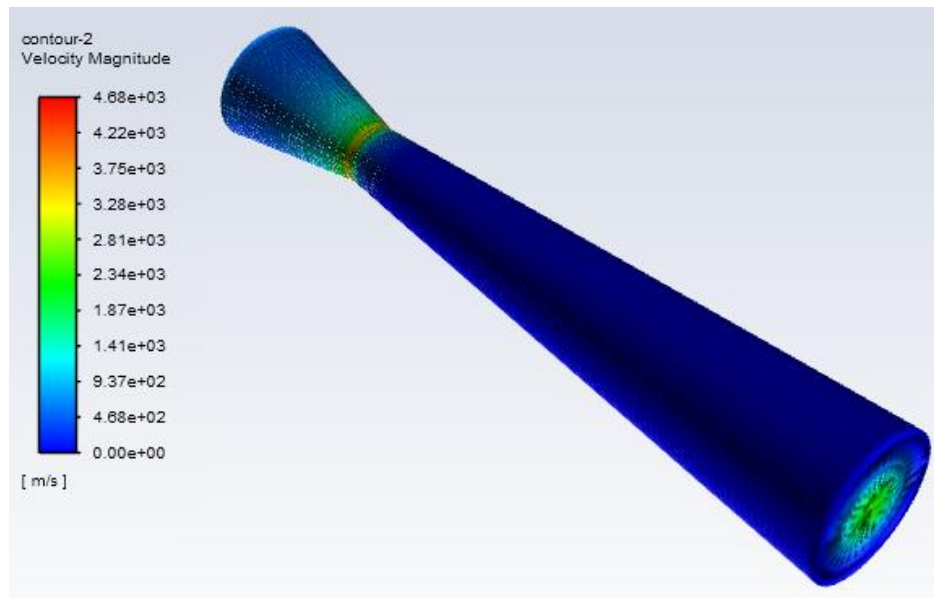


Figure 4.8 (b) Gas velocity at throat diameter 0.4 mm, expansion length 4 mm

When using throat diameter 0.35 and expansion length 2 mm, the highest velocity magnitude was attained at the throat as illustrated in Figure 4.9. From the diagram, it is clear that velocity starts increasing gradually towards the throat (at -0.0010 m away from the throat), attains maximum velocity at the throat (0.000 m) and reduces gradually until it leaves the nozzle tip at 2800 m/s. The gradual increase of velocity

towards the throat could be attributed to the confined space of the throat that forces the gas molecules to be densely populated and fight for the tight exit via the throat. This phenomenon means pressure was getting lower while velocity was increasing.

It can be concluded that constant velocity is attained at 0.0010 m after the throat. However, investigations have shown that if the expansion length is too short, the kinetic energy from the expanding gas scatters randomly and violently, therefore the velocity is rapidly reduced due to the fact that the gas will be in a non-confined space hence expands rapidly. Such velocity may not be used efficiently as it will be lost due to the immediate exposure to non-confined space. It is against this background that a 2 mm expansion length is adopted so that it can guide and maintain the direction towards the melt droplet, as well as maximise the efficiency of the velocity attained.

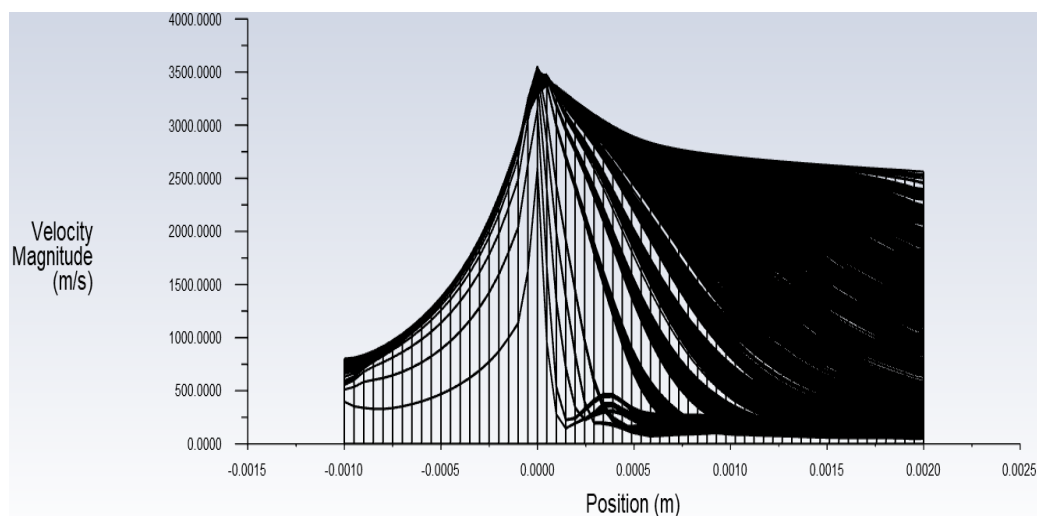


Figure 4.9 Gas velocity through various distances away from the throat.

4.6 Bill of quantities

Bill of quantities for the procurement of materials for manufacturing the gas atomising system designed in this research was prepared after considering current market prices. To cushion possible inflation, a 10% contingency was calculated and added to the cost to make up the final cost of production of the gas atomising system.

Table 4.18a Bill of quantities for manufacturing the nozzle

NO.	Material	Dimensions	QNTY	Unit price	COST (BWP)
1	Stainless steel sheets 316L	2450x1250x0.5mm	20	1200	24,000
2	Copper tubing	Dia. 10x1m	6	150/m	900
3	Mild steel tubes (round)	Dia. 25mmx6m	5	95	475
4	Mild steel tubes (square)	38x38mmx6m	10	95	950
5	Pressure relief valve		1	500	500
6	Pressure gauge		1	450	450
7	Air supply hose	Dia.15mmx10m	1	50/m	500
8	Electric cable (3-phase)	2m	5	450/m	2, 250
9	Compressor 100L Fini Pro BK119 Higher Pressure Air Compressor - 20 CFM, 5.5 HP, 3-Phase Brand: Fini	100L	1	25, 000	25,000
TOTAL					55, 025
S/No.	Material	Dimension	Quantity	Unit price	Cost
1	Stainless steel 316L rod	Dia. 100mmx1m	1	750	750
2	Specialized drill bit set	set	2	2,500.00	5, 000
3	Gasket	set	1	500	500
4	Sealant	500 ml	2	100	200
TOTAL					6, 450

Table 4.18b Bill of quantities for manufacturing the chamber**Table 4.18c:** Bill of quantities for manufacturing the furnace

S/N	Material	Dimension/size	Qty	Unit cost (BWP)	Total (BWP)
1	Mild steel sheet	2450x1250x1.5	4	550	2, 200
2	Refractory bricks	standard	40	3.00	120
3	Makoro clay	50 kg	2 bags	500	1,000
4	Mica tape		10 rolls	30	300

5	Copper tube	4mmx5mmx1.5m	4	595/m	2, 380
6	Mild steel rod	6mmx7m	1	25/m	175
7	Stainless steel rod	100mmx2m	2	150/m	600
8	Ppc cement	50 kg	2 bag	75	150
9	Electric cable – 3 phase	20m	1	450/m	9, 000
10	Electrodes	5kg	4box	75	300
TOTAL					16, 225

Sub-total: P 77, 700

12% VAT: P 9, 324

Total: P 87, 024

10% Contingency: P 8, 702. 40

Grand Total: P 95, 726. 40

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Introduction

This chapter presents the outcomes of this research regarding aims and objectives as well as the limitations of this research and suggestions for future work.

5.2 A brief overview of this research

In Chapter One, the study was introduced; its motivation, aims and objectives, specific themes to be investigated and delimitation of scope. These were presented in order to provide an insight into the focus of the study and also to assist in planning the execution of the study. Furthermore, the expected outcomes of this study were discussed.

Literature relevant to this study was reviewed in Chapter Two. Background information on aluminium alloys, their properties and technological applications was investigated in Section 2.2. Additive manufacturing (AM) processing of metal powders was discussed in Section 2.3 with emphasis on selective laser melting (SLM) as the chosen AM process for this research. Selective laser melting (SLM) process and the nature of

aluminium powder-laser materials interactions was discussed in detail in Section 2.4 and general powder requirements for SLM application were listed in Table 2.5. It was discovered that SLM process requires a homogenous powder with particle size distribution (PSD) ranging between 45 and 70 μm , with good flowability and spherical particles to ensure good packing density. Furthermore, the particles must be oxidation-free to ensure sufficient melting of the powder because oxides consume the laser energy that could be used to ensure complete melting. For that reason, the need to use inert gases for atomisation was established. In Section 2.5, three atomisation variants namely water, gas and centrifugal atomisation were discussed with the aim to get an insight of their operations and the quality of the powder they produce. Critical components of the three atomisation variants discussed in Section 2.5 were discussed in Section 2.6 with a view to establish their working principles and their distinctive geometry that enable them to perform their roles. Common components in all the three variants were identified as the furnace, the atomising device (either a nozzle or the spinning disk) and the atomising chamber. All the three variants make use of these components, albeit differently. However, the nozzle and the spinning disk were found to be critical components for water or gas atomisation and centrifugal atomisation, respectively. The design of these components play key role in ensuring that correct powder characteristics are achieved. Lastly, the role of computational fluid dynamics (CFD) simulation in design of metal powder atomising system components was investigated. It was found that CFD has been used by many authors such as Thompson *et al.* (2016), Xin-Ming *et al.* (2009) and Motaman *et al.* (2013) to investigate various issues involved in atomisation of melts. Such issues included, but not limited to: effects of varying process parameters on powder particle size distribution, atomising gas velocity dynamics and gas-melt interactions.

The methodologies formulated for conceptual design framework of the gas atomising system, mechanical design of components and CFD simulation of the nozzle were discussed in Chapter Three and illustrated in Figures 3.1, 3.4 and 3.5. In contrast to the conceptual design framework methodology, the mechanical design methodology emphasises the application of engineering equations and scientific laws to generate variants in response to the PDS requirements. It also allows design optimisation via

CFD simulation of components. CFD methodology for optimising the gas nozzle was discussed in Section 3.2.4. The idea behind generating the CFD methodology was to prepare guidelines to follow during the CFD simulation exercise. The steps were clearly discussed in the same section. During evaluation of variants, screening tables similar to Table 3.2 and evaluation matrices (Table 3.3) were used to select best variants. The procedure for carrying out the exercise was explained explicitly in Section 3.2.2.

Chapter Four presented the actual execution of the research in which the atomising techniques discussed in Chapter Two were screened and evaluated to identify the most appropriate technique for producing the required powder characteristics outlined in Table 2.5. Gas atomisation was selected as the most appropriate atomisation process for producing fine (45 to 70 μm), spherical and oxidation free aluminium powder required in this research. Furthermore, conceptual design framework (Figure 4.1a and b), mechanical design of key components (Section 4.5) and CFD optimisation of the gas atomising nozzle (Section 4.6) were discussed. Definitions of framework activities were outline in Table 4.11. Appropriate empirical data and scientific equations were used to determine the configurations of the key components. A melting/holding furnace capable of holding aluminium melt of volume 0.0022 m^3 , with seven turns of copper tube of internal diameter 0.006 m, wound around a crucible of diameter 0.121 m was designed as shown in Appendices A1 to A4. Because of their high thermal and corrosion resistance, Makoro bricks and clay were used for building the walls of the furnace and making the crucible, respectively. Additionally, this material (Makoro clay) is readily available and have been used over years to produce Makoro bricks locally. Finding dimensions for various features of the induction furnace was achieved via using equations such as equation 4.4 which was used to find the diameter of the crucible. Thickness of the refractory material was determined using equation 4.7 while thickness of the crucible wall was calculated applying equation 4.8. Ideal number of turns in the inductor coil was found using equation 4.13. Finally a summary of mechanical designs of the induction furnace was compiled in Table 4.12.

Subsequent to that, an eighteen holes close-coupled gas atomising nozzle (Appendix B) was designed applying relevant equations shown in Section 4.5.2. Equations 4.40,

4.41 and 4.42 were applied to determine the melt velocity, melt flow rate and gas flow rate respectively. In order to ensure effective atomisation of the molten aluminium, melt velocity of 9.18 m/s, melt flow rate of 1.86×10^{-5} m/s and gas flow rate of 0.000290132 kg/s were recommended for this research. Due to its unreactive tendencies and high melting point, stainless steel 317l was recommended for making the gas nozzle with the assurance that it will not contaminate the aluminium melt. Design optimisation of the nozzle was executed via CFD and it was discovered that a nozzle throat of 0.3 mm and expansion length of 3 mm were the most suitable configurations that produce the highest atomising gas velocity at 2575 m/s. As for the atomising chamber, a vertical atomising chamber of height 2 m and diameter 1 m was selected after investigating available literature on the selection of atomising chambers. The design of the chamber is shown in Appendix C.

Helium (He), Argon (Ar) and Nitrogen (N₂), were screened and evaluated as possible variants for atomising gas in Tables 4.9 and 4.10. Applying the principle of evaluation as discussed in Section 2.5.2, He emerged as the most appropriate gas that is capable of producing clean, oxygen-free aluminium powder particles. Though expensive when compared to N₂, He was selected because of its low molecular weight that makes it easier to propel the gas and achieve high gas velocity required to effectively break the molten aluminium droplet. A higher molecular weight meant that the gas would be too heavy to push through the nozzle, and that situation would require high pressure, consequently increasing the costs and the chances of pipe burst. At the end, it was observed that an effective gas atomising system for this research will consist of: i) helium gas maintained at a temperature of 25°C, ii) atomising gas pressure of 0.6 MPa, iii) atomising gas velocity of 2575 m/s, iv) melt superheat temperature kept at 760°C, v) a vertical atomising chamber of 2m height and 1m diameter, and vi) using an eighteen holes close-coupled gas nozzle with apex angle of 28°.

5.3 Achievements of this research

Overall PDS for the entire gas atomising system and requirements lists for both the furnace and the gas nozzle were developed successfully in Table 4.3. These outlined the specifications for both the entire gas atomising system and the components.

Amongst the requirements was the need to utilise gas pressure of 0.6 MPa and achieve supersonic gas velocities at nozzle exit; and that has been realised by achieving a velocity of 2575 m/s at nozzle exit. One more requirement was to have a melting/holding induction furnace that is capable of melting 6 kg aluminium charge material in 15 minutes, and according to the calculations, that have been achieved. Conceptual design framework for setting up a gas atomising system capable of producing aluminium powder required for SLM processing of engineering components was formulated to guide PM trainees during setting up of their atomising systems. A journal paper on the design framework for setting up a gas atomising system has been published. It is expected that the framework will become resourceful to PM trainees when they select components for their metal atomising systems. Simulation of atomising gas flow through the atomising nozzle added value to the study since no fabrication of the components was done. The simulation exercise helped to validate the nozzle design and optimise its efficiency. Finally, presentation/assembly drawing of a gas atomising system was prepared from the selected variants and presented in Appendix D1 and D2. The design has a close-coupled gas nozzle that have an appropriate profile that enables it to achieve high gas velocity at exit. It is expected that due to a high impact at the gas-melt interaction, very fine aluminium powder particles (even less than the required $45\text{ }\mu\text{m}$) can be produced. The gas recovery system ensures that the operational costs are minimised as the atomising gas is recycled. This is an additional feature by this research to the existing atomising systems. Finally, a bill of quantities (BoQ) of the complete gas atomising system was compiled projecting the total cost of components to be approximately BWP 95, 726. 40.

5.4 Limitations of the study

Gas atomising system components' variants were explored, generated, evaluated and the best were selected with the view to obtain best combinations that will produce a system that is economical and environmentally-friendly. However, only the theoretical evaluation of the selected solutions' technical, safety, environmental and economic values against the specifications of the overall PDS and the respective component requirements lists was executed. Practical evaluation of the components' performance

in operation was not carried out because from the onset, it was never the intention of this research to manufacture the system and run some tests. That may be done in subsequent research. As a result of this situation, the assumed theoretical performances of the designs may not be the factual ones in real operation, consequently, the selected variants might not be the optimum designs for their functions. In view of that, there is critical need to do the actual evaluation of the physical components during design phase and in operation, using measurable and quantifiable data. Prototypes have to be manufactured and tested. Characterisation of the resultant powder will also be done after the prototype has been produced. As for now, this research was mainly concerned with the design of the system and its key components.

Considering the fact that gas atomisation technology is relatively new and spread across a very wide research area, not all aspects of the process were covered extensively. That means that there is a possibility that some critical information may have been overlooked, and that may be very detrimental to the final product during operation. The following are areas that the study did not consider:

- The gas-melt interaction inside the chamber.
- Apex angle in the gas nozzle
- Cooling and solidification rate of the atomised melt droplets
- Collection, grading and packaging of the powder
- Characterisation of the resultant aluminium powder.
- Manufacturing of the components and assembling a complete system

5.5 Future Work

Future research on gas atomisation of melts will address the above-mentioned areas that were not addressed in the current research. Because of that, it is essential that a more detailed and practical research encompassing the limitations outlined in Section 5.4 is carried out in the following areas;

- Optimal design of the atomising chamber using data acquired from calculating cooling and solidification rates of molten droplets

- CFD modelling of the complete gas atomisation process to study how varying parameters affect powder morphology.
- Effect of gas-melt interaction on particle size and shape.
- Manufacturing of system components and assembling of the complete atomising system
- Characterisation of metal powder produced using techniques such as; microstructural analysis, hardness tests, tensile tests, fatigue and bend tests.
- Influence of the apex angle on powder characterisation

In order to achieve optimal gas nozzle efficiency, the following process parameters must also be studied via CFD: effects of boundary layers on the gas flow, effects of protruding length of the melt path on particle size, turbulence of the supersonic jet impinging the melt, and heat transfer between the gas jet and the molten metal. These play a significant role in achieving the required aluminium powder.

5.6 Conclusion

User-value analysis (UVA) and cost-benefit analysis (CBA) methods of evaluation were used to select gas atomisation as the best atomisation technique for the production of fine, spherical powder particles required for selective laser melting (SLM) process. The same evaluation techniques were used to select best components (furnace and nozzle) for the system. Empirical and scientific data have been used to design components of a gas atomising system that is capable of producing aluminium powder required for SLM processing of engineering components such as engine bracket. The data was used to configure the melting/holding furnace and the close-coupled gas atomising nozzle. Computational fluid dynamics (CFD) simulation was used to numerically optimise the efficiency of the nozzle. It is hoped that the simulation results would help in guiding the manufacture of the actual gas nozzle. The optimisation results gave baseline data for the fabrication of the actual nozzle. However, it is understood that experimental results do not always translate into best designs and it is expected that the results will be used in preliminary investigations for optimising the gas nozzle.

Lastly, it is expected that with support of the PM specialists, the developed gas atomising system will not only benefit PM trainees, but will also provide the platform for other manufacturing engineers in the PM field to investigate the system and improve its efficiency. In that way it would provide a research platform from which other researchers may add to the body of knowledge. Scientists and pharmacists may use the system in various applications such as pharmacology, fertilizers production, food and fabrics using standard testing methods peculiar to their field.

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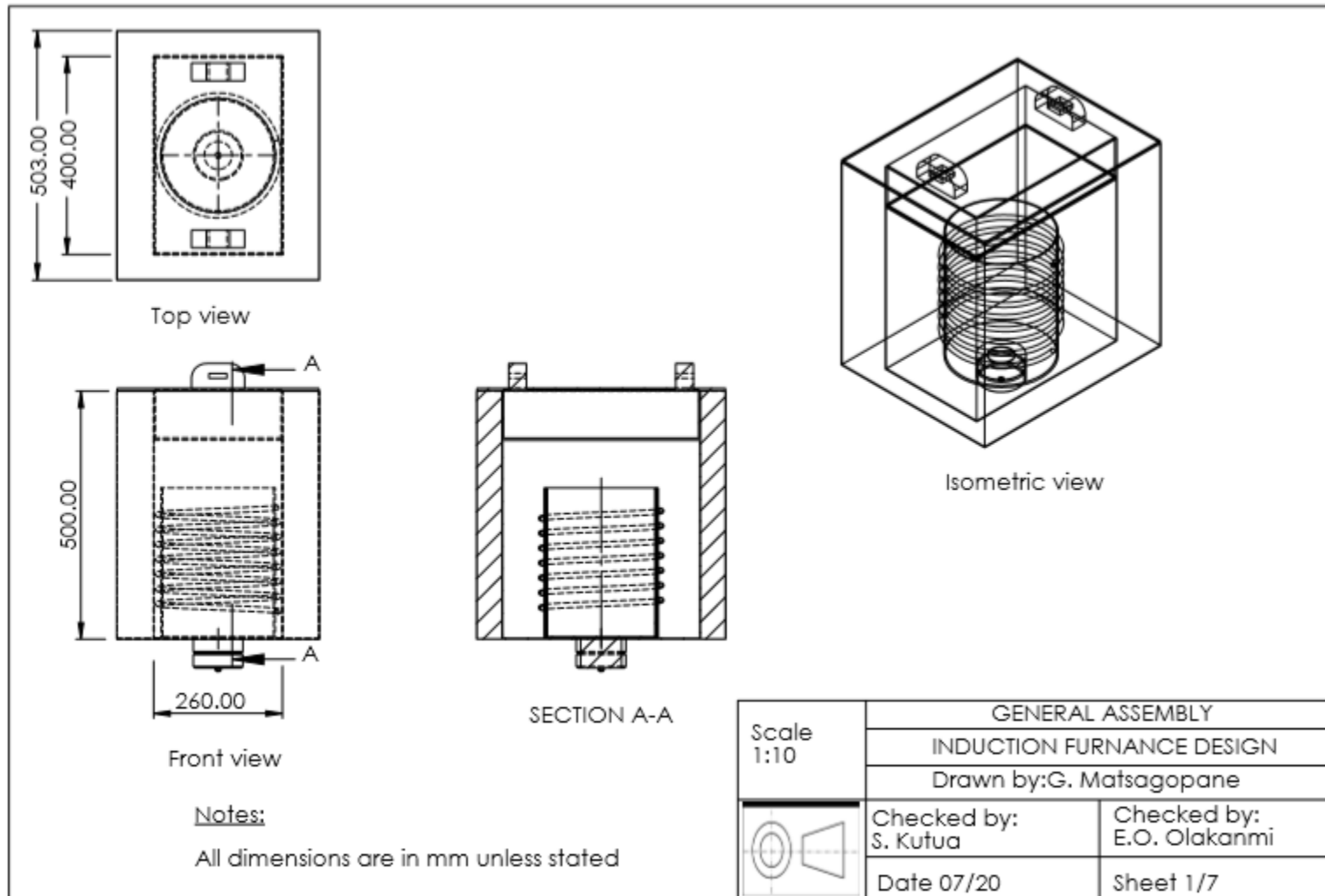
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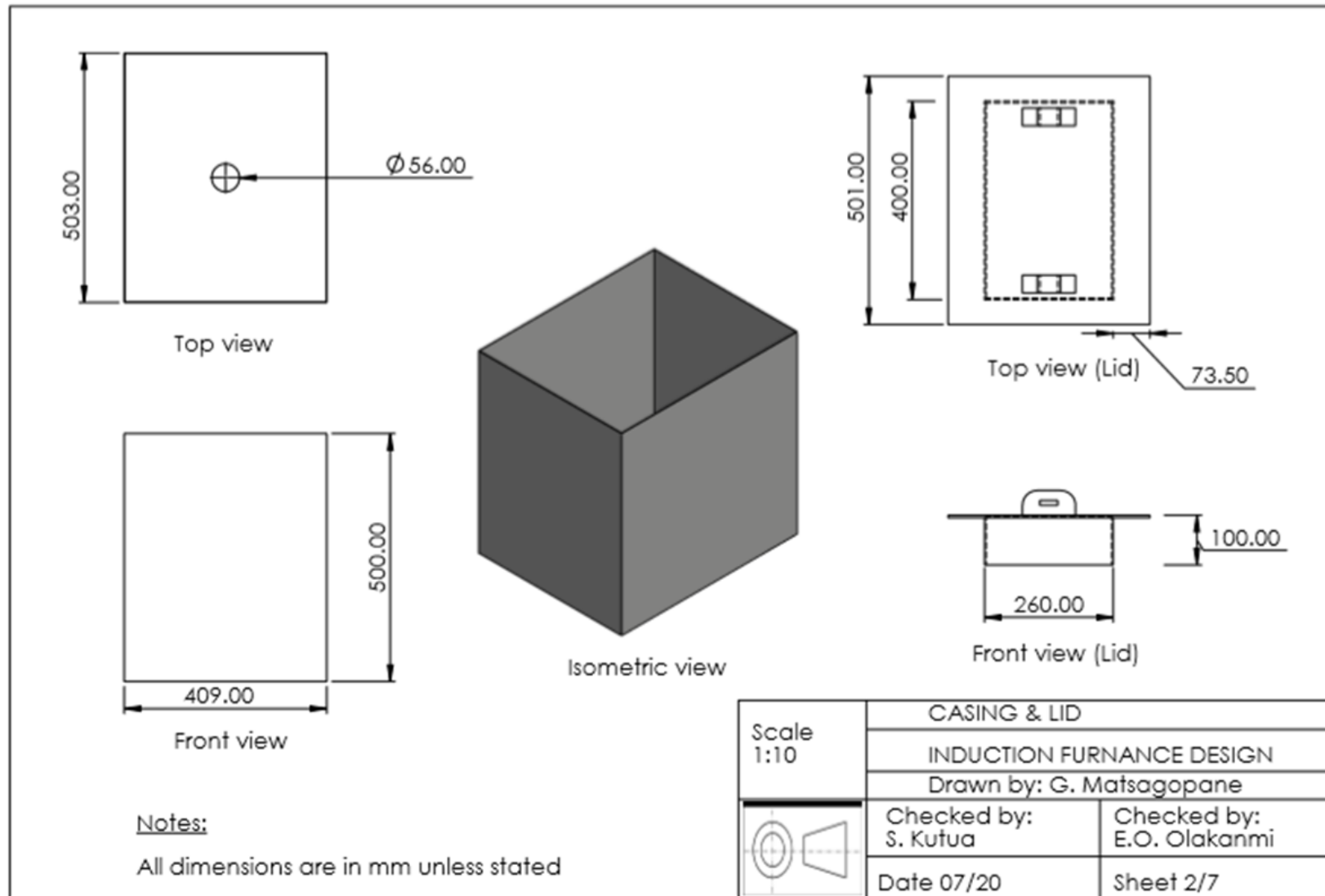
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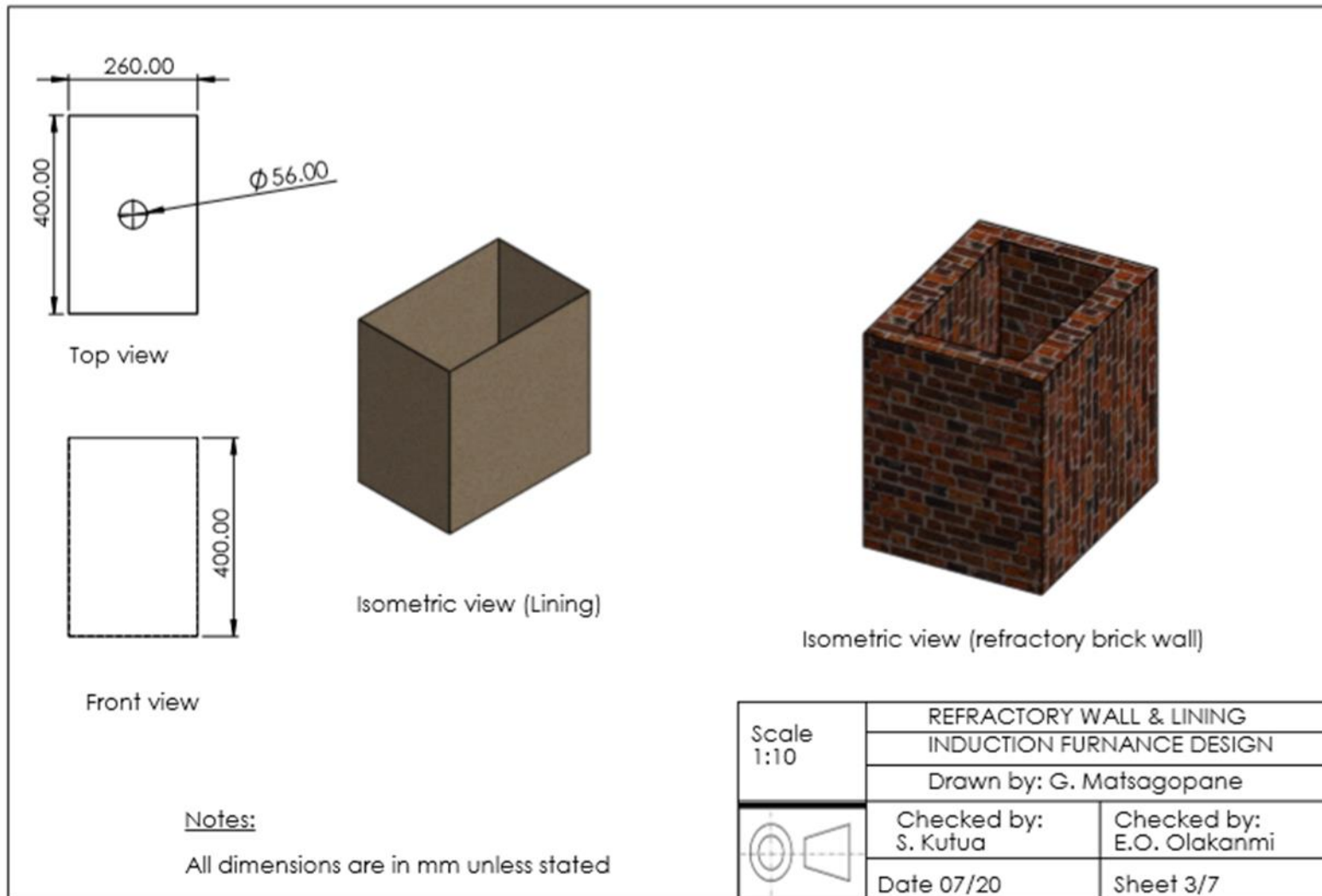
Appendix A1 – Induction furnace assembly



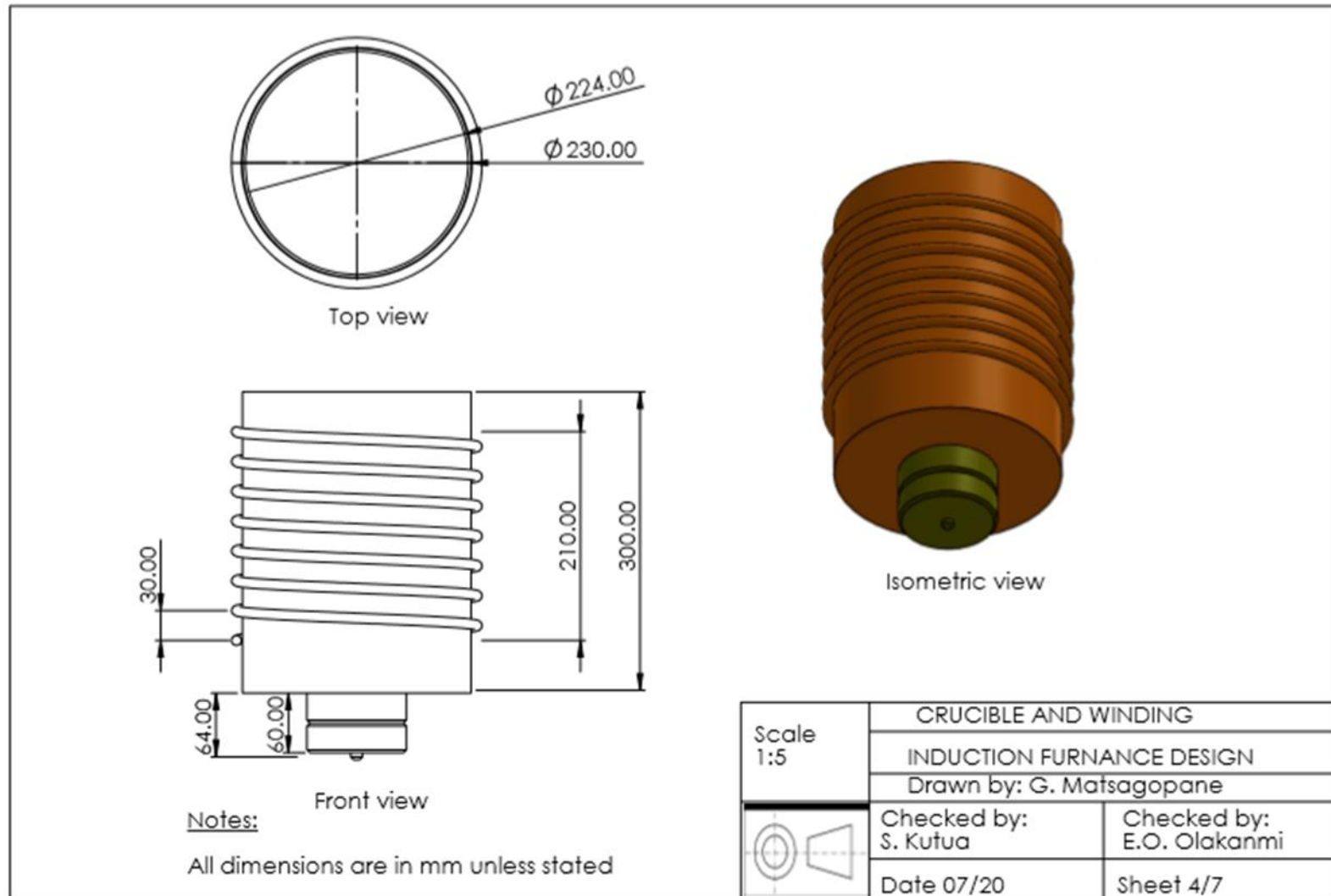
Appendix A2 – Induction furnace casing and lid



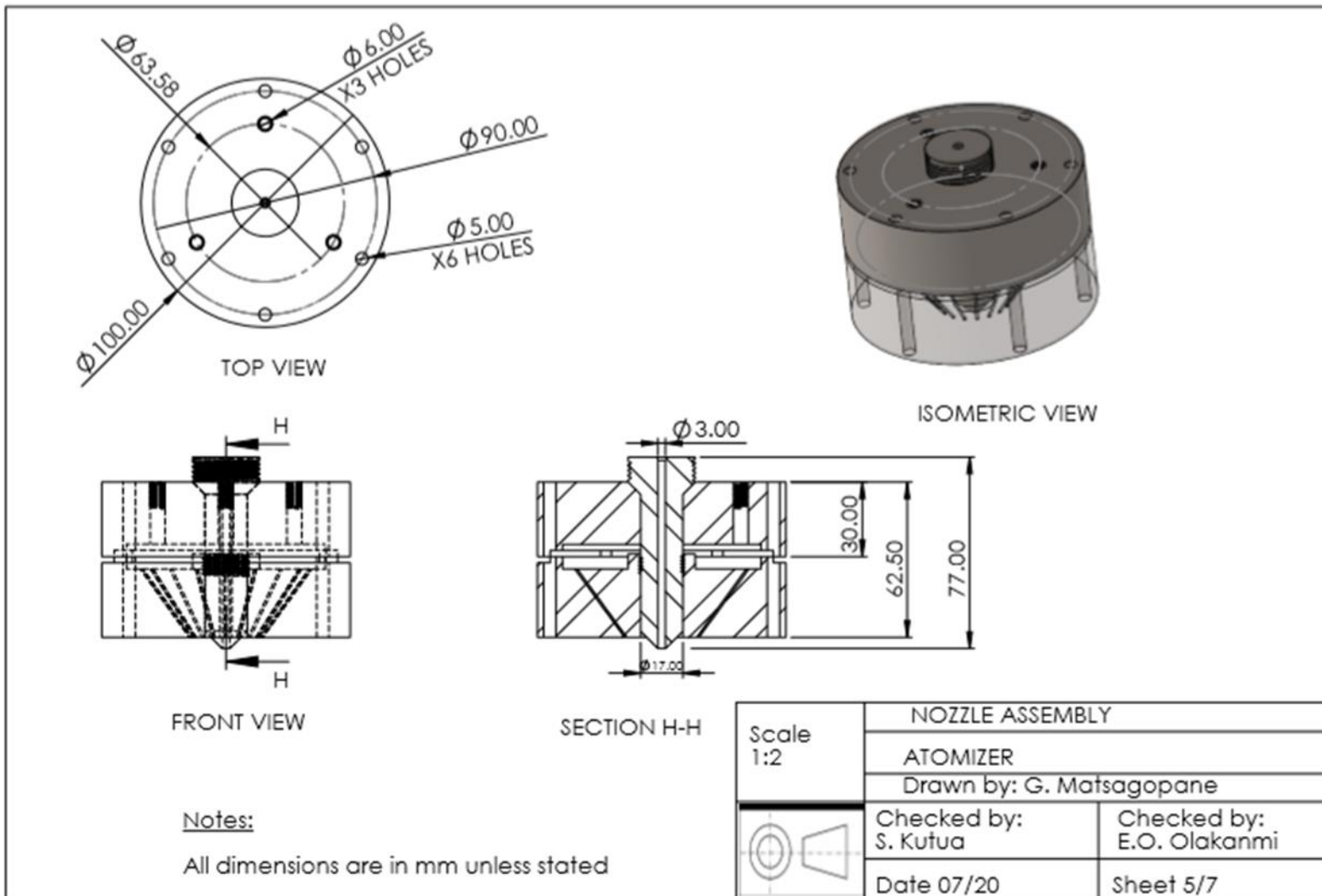
A3 – Refractory wall and lining



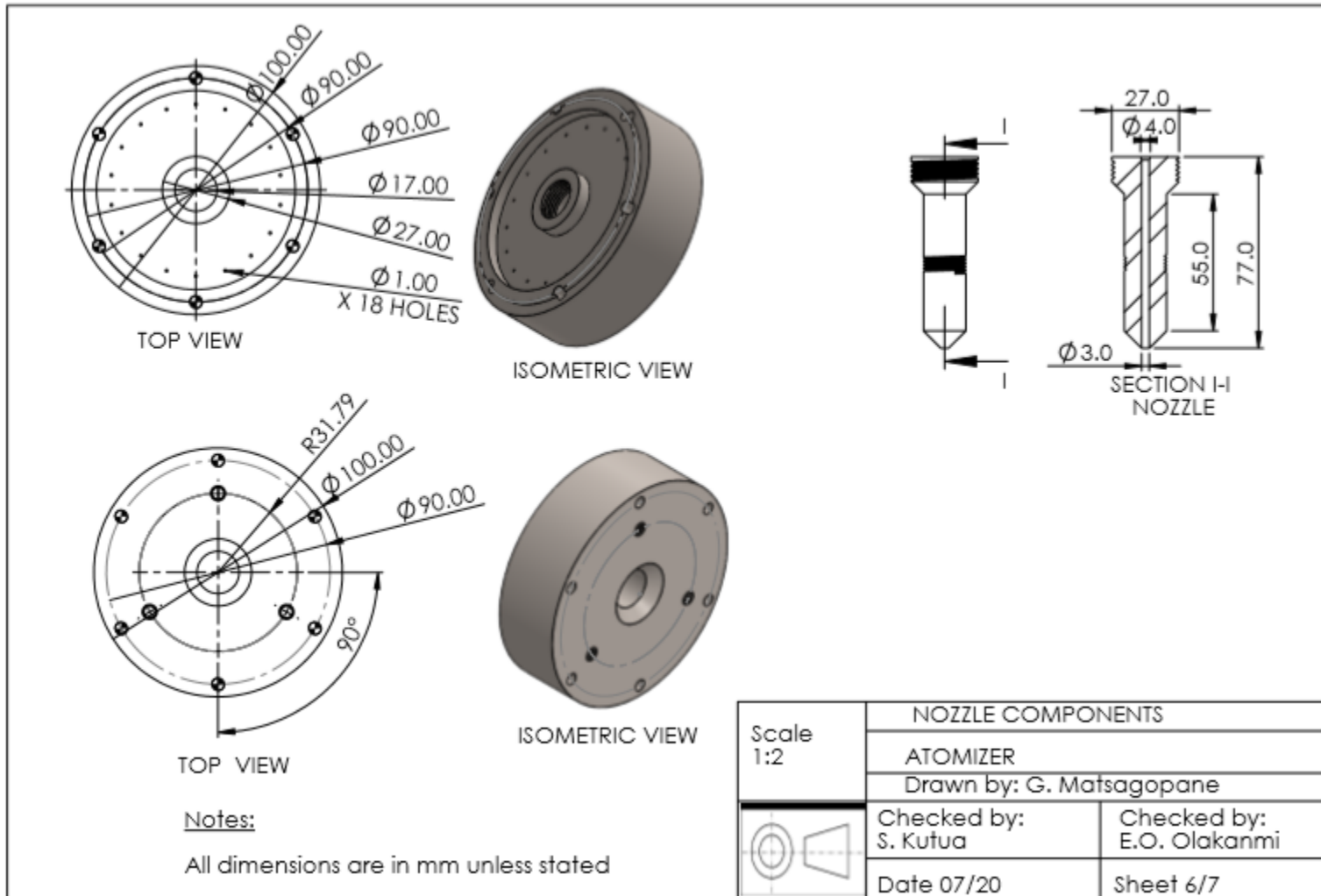
Appendix A4 – Crucible design and winding



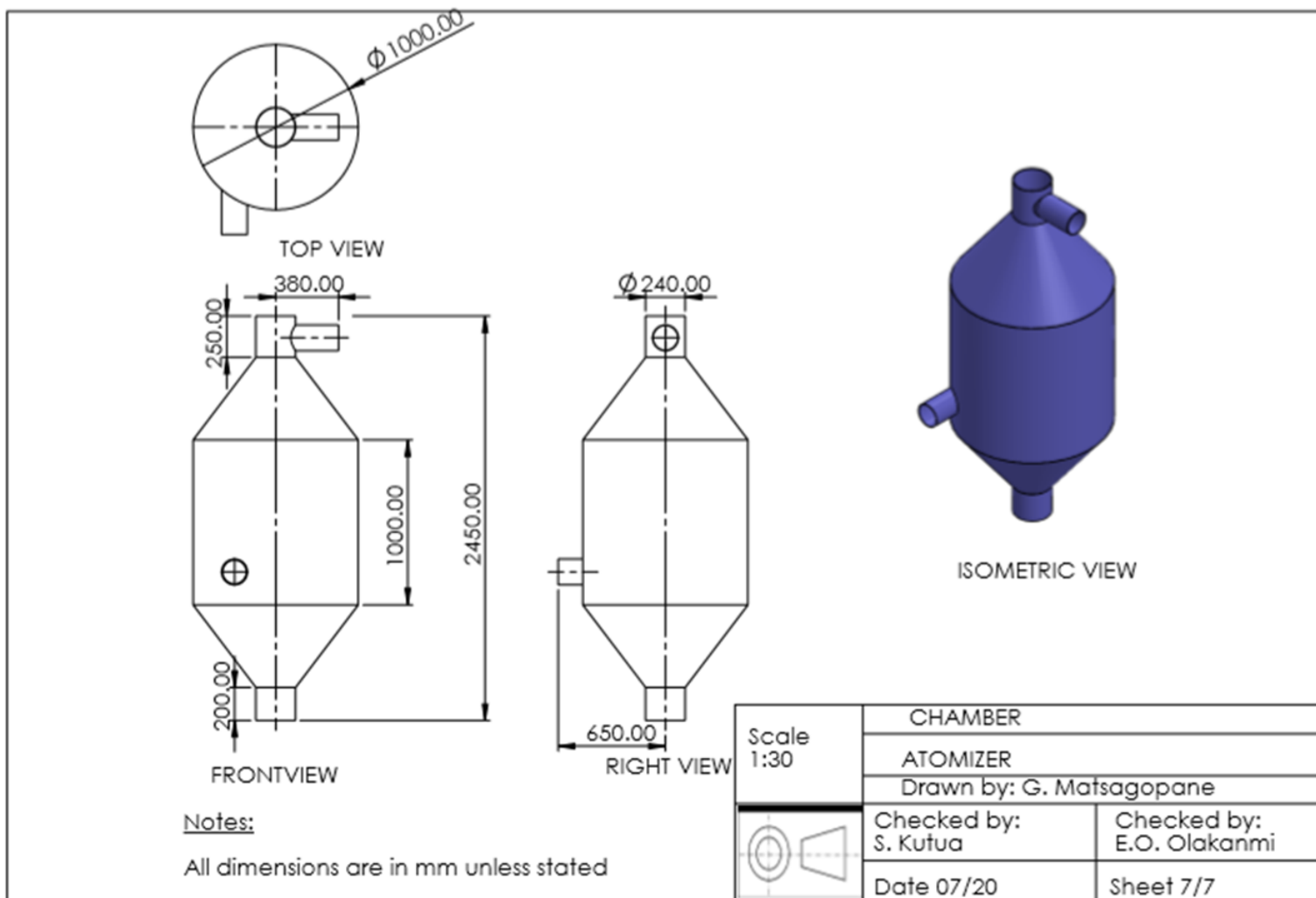
Appendix B1 – Nozzle assembly



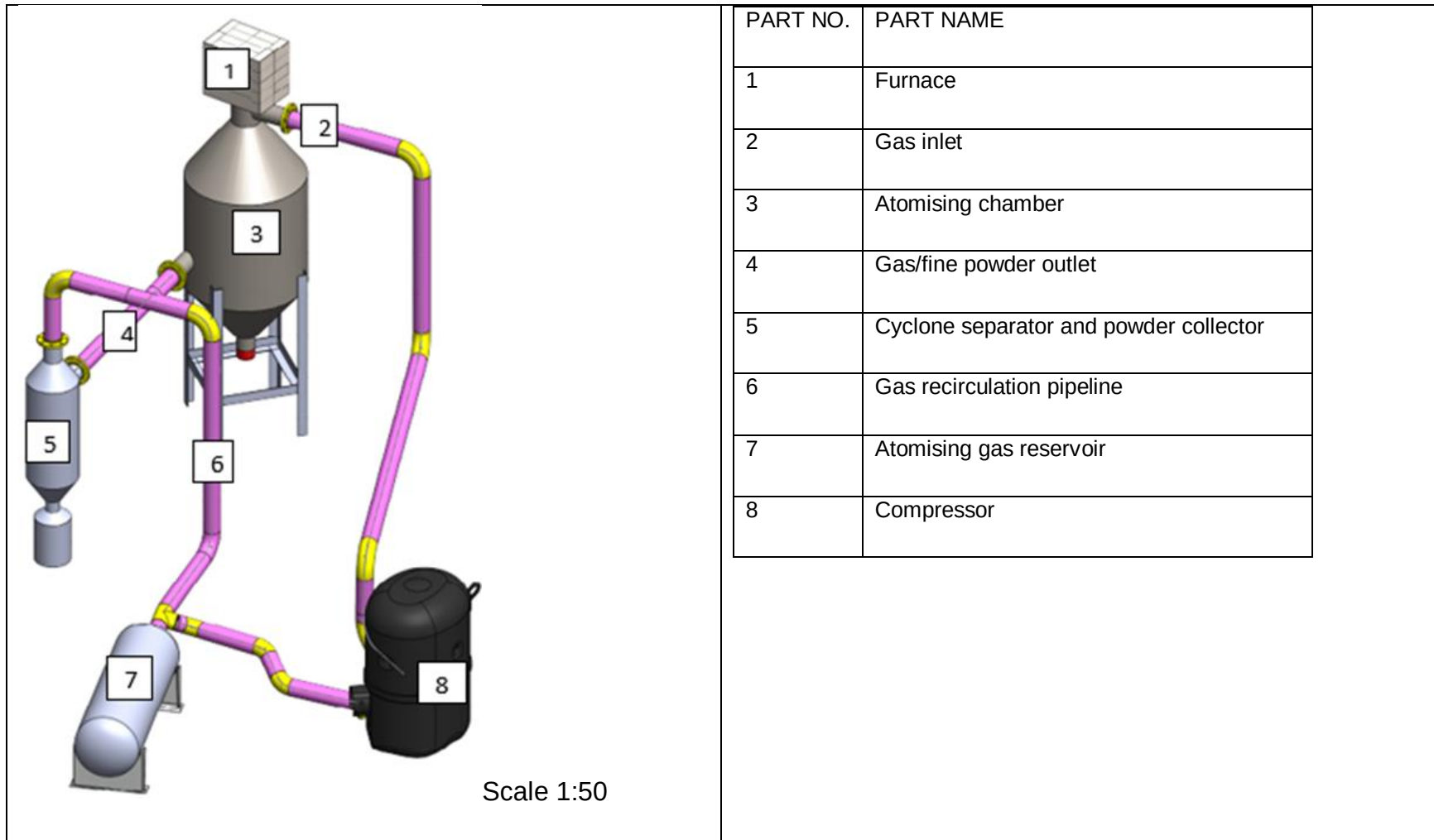
Appendix B2 – Nozzle components



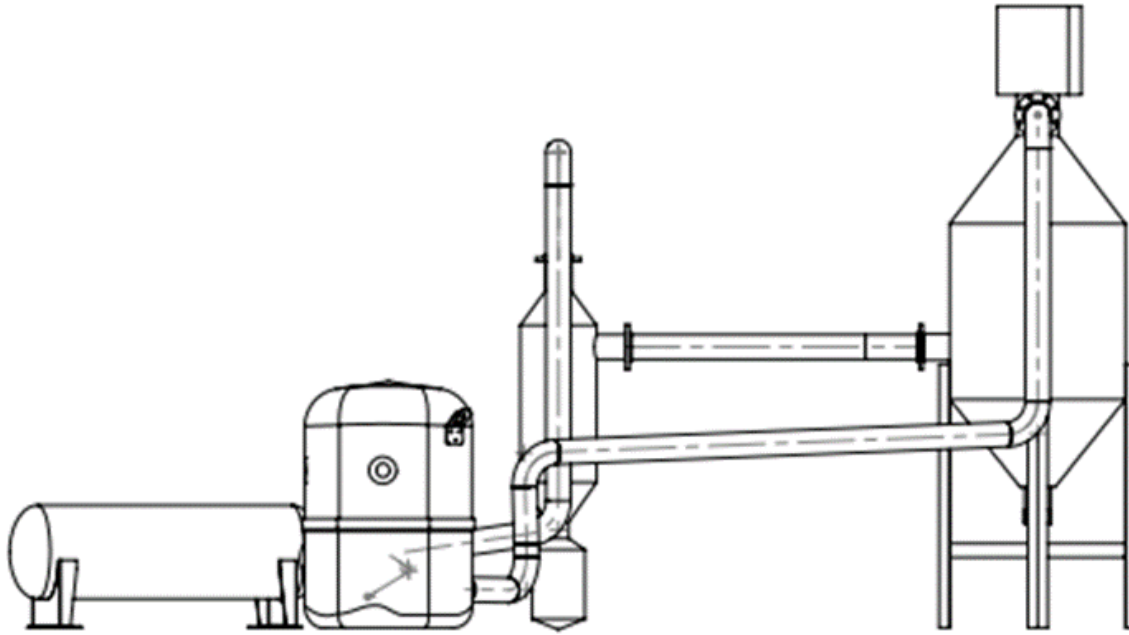
Appendix C – Atomising chamber



Appendix D1 – Presentation/Assembly drawing



Appendix D2: Front elevation of the assembled drawing



Scale: 1:50

