Knowledge-Based Engineering Approach For

Optimal Design of Pressure Vessels

By

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16984

Dissertation submitted in partial fulfillment of the requirements for the

Bachelor of Engineering (Hons) (Mechanical)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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(MECHANICAL)

Approved by,

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(Dr. Dereje Engida Woldemichael)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Arun Raj A/L Latchumanan

ABSTRACT

Optimization techniques play an important role in pressure vessels design, the very purpose of which is to find the best ways so that a designer or a decision maker can derive a maximum benefit from the available resources. The basic idea behind intuitive or indirect design in engineering is the memory of past experiences, subconscious motives, incomplete logical processes, random selections or sometimes mere superstition which can be called as knowledge-based engineering approach. This, in general, will not lead to the best design. The shortcomings of the indirect design can be overcome by merging optimal design procedure along together with adapting knowledge-based engineering approach which is the main scope of this project.

The objective function is obtained by calculating each event and multiplies it by the corresponding probability to get the optimum design. The sum of all such products will be the total objective function. The constraints and boundaries in this case are based on previous experience and reference from ASME standards. Finally a result is produced using Microsoft Excel Solver. Other than that material database also was developed to enhance liability of material selection according to applied temperature. Since Microsoft Excel Solver is limited in terms of functionality, the model was developed using MATLAB whereby previous knowledge from Solver is applied as well as enhancement of additional optimization knowledge into the model. By run the iteration with provided information from user, the model able to compute necessary data to design pressure vessels by complying to design codes. Validation test was conducted to ensure obtained results are reliable.

Graphical User Interface (GUI) was developed to integrate concept of user-friendly for developed software. Every aspect of it was given detailed consideration in making the interface easy to use without special skills. Finally the obtained results from optimization process can be used with parametric 3D Pressure Vessel design in AutoCAD to generate the pressure vessel drawing.

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Firstly, I would like to express my sincere gratitude to my supervisor Dr. Dereje Engida Woldemichael for the continuous support of my Final Year Project (FYP) and for his patience, motivation and immense knowledge. His guidance helped me in all the time of research and writing of this paper. I could not have imagined having a better supervisor for my FYP.

Besides my supervisor, I would like to thank my family: my parents and my siblings for supporting me mentally throughout completing this paper. Apart from that, I want to express my heartfelt gratitude to my friends for giving me useful inputs, which I used to develop this Optimization of Pressure Vessel Design Software.

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CHAPTER 1
INTRODUCTION

1.1 Project Background

High pressure is developed in the pressure vessel thus it has to withstand severe forces. So the selection of pressure vessel is most critical. In other word, pressure vessel is the heart for storage of high pressure fluid. Pressure vessels have been utilized in wide number of industries for long time since industrial revolution in Great Britain. Pressure vessels include but are not limited to compressed gas storage such as air, oxygen, nitrogen tank but also anhydrous ammonia tanks, hydro pneumatic tanks, autoclaves, hot water storage tanks, chemical reactors and refrigerant vessels. Pressure vessels are designed for a pressure greater than 15 psi and a volume greater than 5 cubic feet in volume or one and one-half cubic feet in volume with a pressure greater than 600 psi. Pressure vessels stands of various shapes and sizes according to application it will used to. The designation and geometry of pressure vessels vary according to standards in the industries. This project uses the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII Division 1 as the main reference whereby all the procedures and works follows the standard.

Knowledge-Based Engineering (KBE) is a research field that studies methodologies and technologies for capture and re-use of product and process engineering knowledge. Verhagen et al discussed in his paper that objective of KBE is to reduce time and cost of product development, which is primarily achieved through automation of repetitive design tasks while capturing, retaining and reusing design knowledge [1]. It is critical for the engineers and designers to have designing software or application to straightforwardness their work in outlining the pressure vessels nowadays. Hence, this project is exceptionally crucial as the task is to outline a knowledge-based engineering approach for optimal design of pressure vessel by integrate the concept into standalone software.

1.2 Problem Statement

There are available engineering software applications for modeling of pressure vessel components and features in the existing global market. Unfortunately, all of them are only based on concept of designing while there are no features of knowledge-based engineering approach in the application. A knowledge-based system (KBS) is a computer program that reasons and uses a knowledge-based engineering approach to solve complex problems and in this case it will be used for optimal design of pressure vessel. Furthermore, available engineering software are hard to find and the genuine license is expensive whereby TABLE 1 describes the prices in detail [2].

TABLE 1. The Cost of CAD Software Today

CAD Software	Price
Alibre Design Standard	$999
Autodesk	$1995
ArchiCAD	$4250
IMSI/DESIGN	$1295
DoubleCAD XT Pro	$695
PTC	$4995

However, for the beginner users, such as the university students or fresh graduated engineers, they will take time to fully understand the tools and manuals for the advanced software applications. Before they can start to design the pressure vessel models, they must first have the access for the software and a long period of time to complete their tasks. A good design of the pressure vessels could give good results for the pressure vessels to be manufactured and purchased. Therefore, a simple design tool to support the pressure vessels design would be suffice to help the beginners especially engineering student.

1.3 Objectives

The objectives of this project are:

- To adapt knowledge-based engineering approach to model and optimize pressure vessels design consisting of shell and head.

- To develop a software which introduce optimization process of pressure vessels design based on knowledge-based engineering approach by complying ASME VIII Division 1 standards and codes.
- To conduct validation test for the developed model.

1.4 Scope of Study

- Optimization process on reduction of pressure vessel dimension parameters with respect to user defined volume, manufacturing constraints and boundaries.
- Material properties developed as compliance with ASME Section IID Table 1A. Part of Table 1A is shown in Figure 1.
- Cost of material is assumed to be the same for those in same class. Cost of forming and welding for all types of pressure vessel's head assumed to be the same.

TABLE 1A
SECTION I; SECTION III, CLASSES 2 AND 3;* SECTION VIII, DIVISION 1; AND SECTION XII
MAXIMUM ALLOWABLE STRESS VALUES *S* FOR FERROUS MATERIALS
(*See Maximum Temperature Limits for Restrictions on Class)

Line No.	Nominal Composition	Product Form	Spec No.	Type/Grade	Alloy Designation/ UNS No.	Class/ Condition/ Temper	Size/Thickness, in.	P-No.	Group No.
1	Carbon steel	Sheet	SA-1008	CS-A	...	...	...	1	1
2	Carbon steel	Sheet	SA-1008	CS-B	...	...	...	1	1
3	Carbon steel	Bar	SA-675	45	...	...	...	1	1
4	Carbon steel	Wld. pipe	SA-134	A283A	...	...	...	1	1
5	Carbon steel	Plate	SA-283	A	...	...	...	1	1
6	Carbon steel	Plate	SA-285	A	K01700	...	...	1	1
7	Carbon steel	Wld. pipe	SA-672	A45	K01700	...	...	1	1
8	Carbon steel	Sheet	SA-414	A	K01501	...	...	1	1
9	Carbon steel	Wld. tube	SA-178	A	K01200	...	...	1	1
10	Carbon steel	Wld. tube	SA-178	A	K01200	...	...	1	1
11	Carbon steel	Smls. tube	SA-179	...	K01200	...	...	1	1
12	Carbon steel	Smls. tube	SA-192	...	K01201	...	...	1	1
13	Carbon steel	Wld. tube	SA-214	...	K01807	...	...	1	1
14	Carbon steel	Smls. tube	SA-556	A2	K01807	...	...	1	1
15	Carbon steel	Wld. tube	SA-557	A2	K01807	...	...	1	1
16	Carbon steel	Wld. pipe	SA-53	E/A	K02504	...	...	1	1
17	Carbon steel	Wld. pipe	SA-53	E/A	K02504	...	...	1	1
18	Carbon steel	Wld. pipe	SA-53	E/A	K02504	...	...	1	1

FIGURE 1. ASME Section IID Table 1A

CHAPTER 2
LITERATURE REVIEW

2.1 Optimized Solution of Pressure Vessel Design

High-pressure vessels, such as ammonia converters, urea reactors and supercritical fluid extractors, etc., are widely used in chemical, oil refining, energy industries, and so on. Such vessels are key equipment in various processes industries and storage as well, thus the potential hazards are very high [3]. Besides safety, much attention has been paid to use them safely and to lower their costs, with great progress being made in the last century. For example, Solving Pressure Vessel Design Problems by an Effective Global Harmony Search Algorithm (EGHS) written by Liqun Gao et al. not only tells the use of method to solve mixed-integer non-linear programming problems with several constraints but also demonstrated that the EGHS has strong convergence and capacity of space exploration on solving pressure vessel design problems [4]. Design & weight optimization of Pressure Vessel due to thickness using finite element analysis by Vishal V. Saidpatil and Arun S. Thakare also tells the use of computer programs instead of hand calculations for analyzing the high stress area’s and different end connections [5]. Design of pressure vessels using shape optimization with an integrated approach by Carbonari et al discusses shape optimization of axisymmetric pressure vessels considering an integrated approach in which the entire pressure vessel model is used in conjunction with a multi-objective function that aims to minimize the von-Mises mechanical stress from nozzle to head [6].

2.2 ASME Boiler and Pressure Vessel Code

The ASME - American Society of Mechanical Engineers - International Boiler and Pressure Vessel Code is made of 11 sections and contains over 15 divisions and subsections [7]. For this project, author only concentrate on Section VIII. Pressure Vessels, Division I which provides requirements applicable to the design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures exceeding 15 psig.

2.3 Knowledge-Based Engineering Approach

Knowledge based systems (or expert systems) are computer applications that use stored knowledge for solving problems in a specific domain [8]. Similarly to a human expert, a KBS makes use of some kind of reasoning mechanism, the so called inference mechanism, to derive an answer to the posed problem.

A concise definition of KBE is given by Kim et al. as follows: KBE has roots in computer aided design (CAD) and knowledge- based systems and from early success as a support system for a design engineer within the context of product design to the basis for generative design, it can have a wide scope that covers the full range of activities related to Product Life cycle Management (PLM) and Multi-disciplinary Design Optimization (MDO) [9].The scope of KBE includes design, analysis, manufacturing, and support.

In addition, global collaborative design approach can be implemented using Web-based approach. For example, Ming-Chyuan Lin et al. has developed an interactive interface for considering customer needs in the early phase of product development [10]. To facilitate quick development of new knowledge based systems, special software tools, called shells, are available. The initial idea behind shells was to reduce or eliminate the need of programming activities in the development of a KB system. However, it became clear that the bottleneck in KBS development was the knowledge acquisition and formalization phase, rather than the actual programming work [11]. Current developments in the research field of Knowledge-Based Engineering (KBE) are aimed at addressing these issues. KBE opens up the possibility of engineering automation while retaining the requisite knowledge [12], which may reduce design time significantly while improving quality of design decisions and output.

CHAPTER 3
METHODOLOGY

The methodology applied in this project is based on the project development phases that commonly applied for all projects which each and every step are interlinked. Research methodology will explains in detail on steps covered in conducting this project. The division of work throughout the Final Year Project 1 is depicted in the Key Milestone and the Gantt chart.

3.1 Research Methodology

This project starts with the title selection whereby author choose preferred project provided by supervisors according to field of expertise. After few meeting with respective supervisor, author gets clear picture of expectations and the return of making this project successful. Problem statement of the topic was clearly defined in preliminary report preparation which it makes sure author is going in right way towards completion of project. Articles related to the topic are being search from website such as IEEE Explore, sciencedirect.com and Google Scholars by using the correct keywords. Keywords that are being used include: design of pressure vessel, ASME standards of pressure vessel design and Net Framework manual. With all the papers and articles available, the gap in the field is being determined and stated as the scope of study. All the related materials which are being studied are cited in the references part of this report. After determining introduction for the project, detailed literature review is being carried out to further verify the problem and hence determining the objective of the project. Literature review is also being carried out so that more knowledge about the topic can be obtained. The literature review process should be carried out for a long period of time so that the updates and new technologies can be identified while the project is being carried out. Besides, design parameters of pressure vessels such as the material, pressure and temperature were determined based on priority which narrows down the scope to be applied. Mathematical derivation of equations applied for design of pressure vessels also been worked out which will be implemented into knowledge-based engineering application and act as core of the project. On the same time, research on programming tools to be used also being performed so that we are familiar with the software and functionalities. Process such as setup and configuration of the futures is being explored and set as criteria for selection. With all the necessary information and equations for optimal design of pressure vessels obtained, an algorithm will be developed to be implemented into the programming tool which will act as knowledge-based engineering system as per objective of the project. Validation test will be conducted on the developed model for verification purpose. The results of the project is then recorded and compiled into the report. Final presentation about the findings of the project will be given to the supervisor and examiner in the end of the course.

The research methodology for this project depicted as in flow chart below:

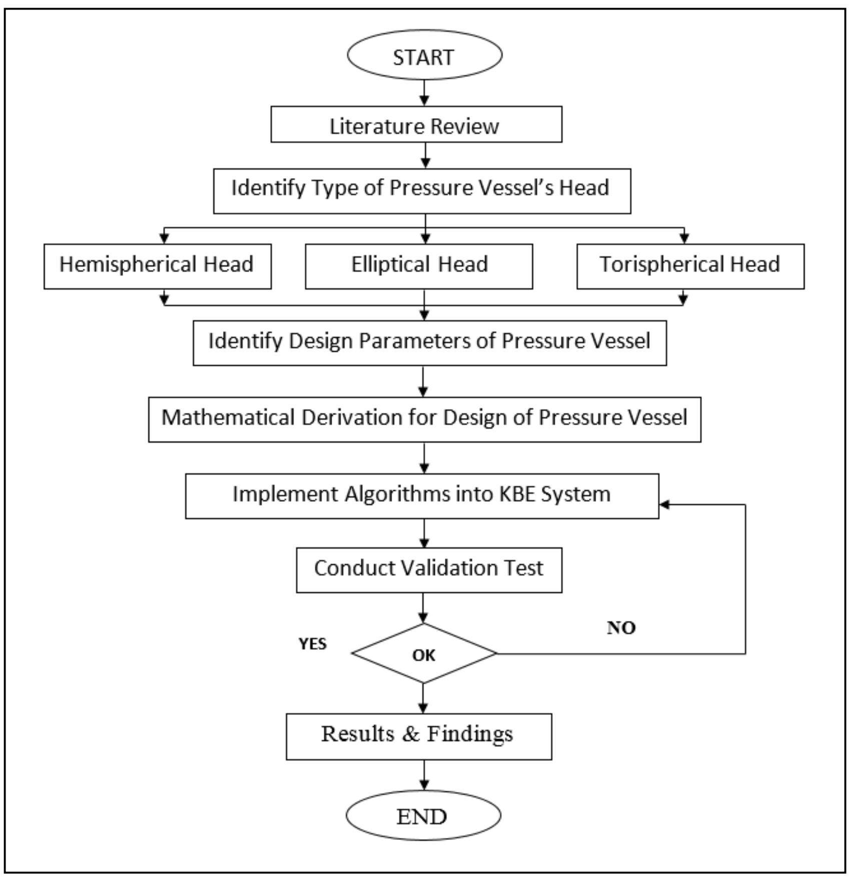


FIGURE 2. Project Flow Chart

3.2 Tools Used

- MATLAB

MATLAB software is used specifically to design the Knowledge-Based Engineering support system for optimum pressure vessel design based on the suitable algorithm and equations in second phase.

- Microsoft Excel and Word

Microsoft Excel is used to create material database as well as the Solver function to conduct optimization on first model of pressure vessel design. Microsoft Word primarily used in documentation phase.

3.3 Project Gantt Chart

A Gantt chart, commonly used in project management, is one of the most popular and useful ways of showing activities, tasks or events displayed against time. On the left of the chart is a list of the activities and along the top is a suitable time scale. Each activity is represented by a bar; the position and length of the bar reflects the starting week, duration and ending week of the activity.

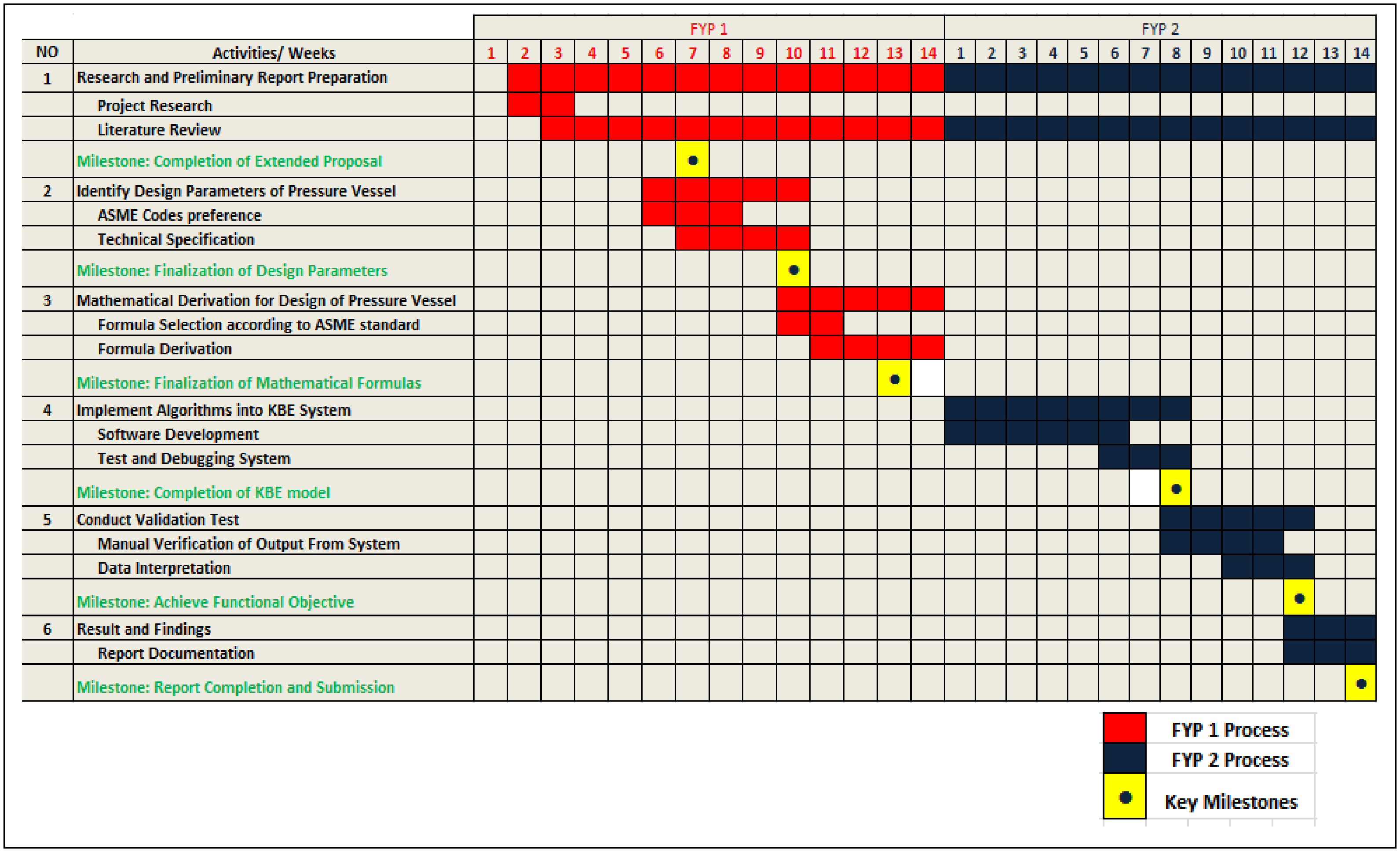


FIGURE 3. Project Gantt Chart

3.4 KEY MILESTONES

This projects have a work plan that lays out the specific steps and actions that are necessary to complete the project. Specific steps in that plan was chosen as key milestones so that author able to keep track of progress toward completion. Assigning specific completion dates for each milestone helps author to determine if everything are staying on track to meet the final deadline.

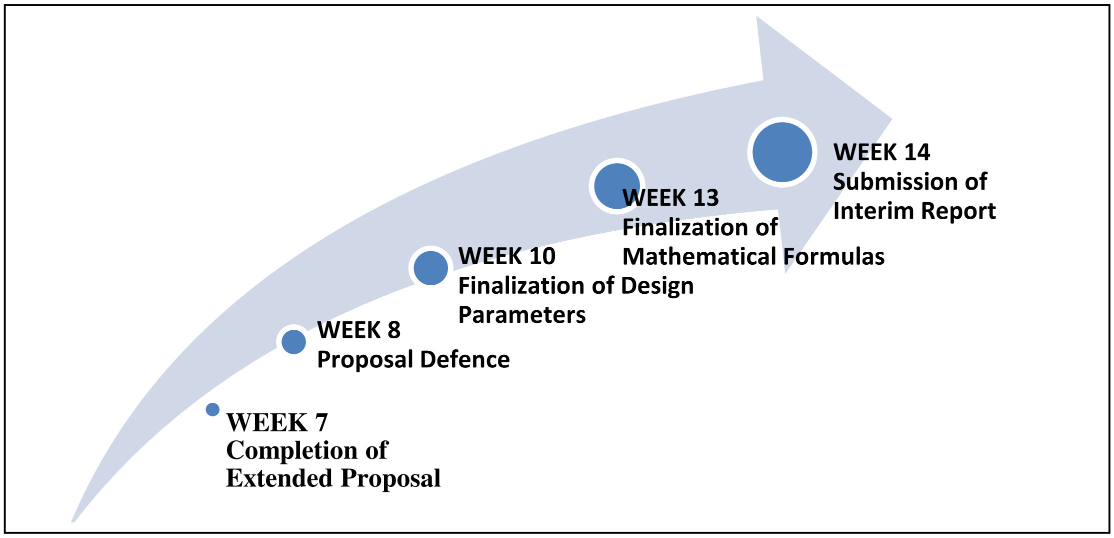


FIGURE 5. Key Milestones for FYP 1

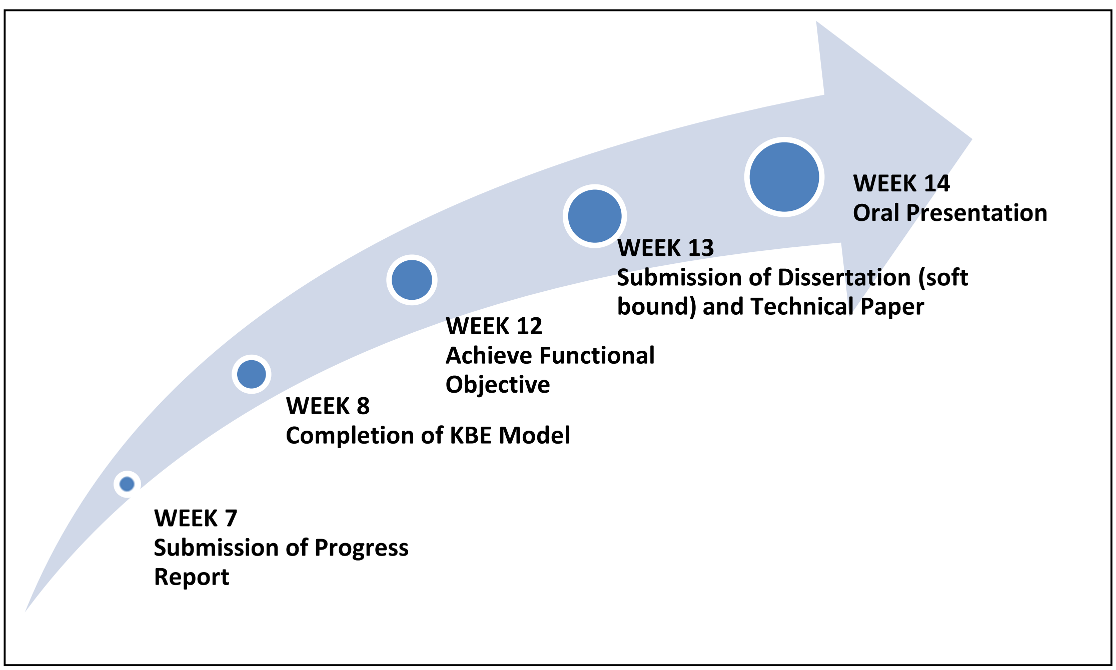


FIGURE 4. Key Milestones for FYP 2

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Optimization of Pressure Vessels Design using Microsoft Excel Solver

Based on objective of this research, author have decided to adapt knowledge-based engineering approach for modelling of support system of optimum pressure vessel design by considering only shell and head as for case study throughout the project. A program using built in app of Microsoft Excel; Solver was developed to solve problems regarding optimization of pressure vessel design by adapting knowledge-based engineering approach.

The objective of design optimization of pressure vessels is to reduce weight with adequate strength and stiffness by design pressure vessel with optimum dimension. Optimization is the act of obtaining the best result under given circumstances. Conventional design aims at finding acceptability design which merely satisfies the functional and other requirements of the problem. In general, there will be more than one acceptable designs and the purpose of design optimization is to choose the best. In the present work parameters such as thickness of the shell, and dish end, length and radius of the pressure vessel are optimized by making use of Solver to obtain optimum design of pressure vessel. Design parameters of pressure vessel whereby it is user defined need to be filled in to conduct the analysis and sample of design parameters shown in TABLE 2. There are three design constraints, four boundaries for variables as shown in TABLE 3 And TABLE 4 respectively. Using the values from Solver, minimum shell thickness, head thickness and maximum allowable pressure for pressure vessel will be determined using formulas from ASME Section VIII Division 1 as in TABLE 5, TABLE 6 and TABLE 7 respectively. Finally the overall result in form of pressure vessel design parameters will be calculated as shown in TABLE 8. Objective function used to solve the optimization problem as for this stage is as in equation 1.

$$f(x) = \pi r^2 \mathrm{h} + \frac{4}{3}\pi r^3 \qquad (1)$$

TABLE 2. Design Parameters for Pressure Vessel

r/t > 10	Thin walled PV		
r/t < 10	Thick walled PV		
r/t =	18.65588404		
Pressure, P (Psi)	1000	6.894759087	(MPa)
Volume, V (in^3)	1296000.003	21.23762981	(m^3)
Weld Efficiency, E	0.9		
Allowable Stress, S (Psi)	21400	147.5478445	(MPa)
Corrosion Allowance, C (in)	0.000787402	2E-05	(m)
Material			
Temperature, T (F)	400		

TABLE 3. Constraints Applied for Design

Constraint 1	-0.42910592	<	0
Constraint 2	-2.78	<	0
Constraint 3	0	<	7.918280789

TABLE 4. Boundary Conditions Applied for Design

boundary 1	10	<x1<	200
boundary 2	10	<x2<	200
boundary 3	0.0625	<x3<	5
boundary 4	0.0625	<x4<	5

TABLE 5. Shell thickness calculation

t1 (longitudinal)	3.37765366		
t2 (circular)	1.619399211		
t min	3.378441062	0.085812403	m

TABLE 6. Head thickness calculation (Hemispherical)

tm1	1.645542551	0.041796781	m

TABLE 7. Maximum Allowable Pressure for Pressure Vessel

P1 (longitudinal)	999.9927377		
P2 (Circular/	2109.529025		
P max	999.9927377	6.894709015	MPa

TABLE 8. Result from Optimization Process

x1 =	63.02780	radius of shell
x2 =	19.79570	length of shell
x3 =	3.37844	thickness of shell
x4 =	1.64554	thickness of dish end

The outcome of the developed model was the program able to solve pressure vessel design using input parameter as in TABLE 2. By specify a desired volume and design parameters, Solver will implement the optimization concept problem solving by gives the best solution from the aspect of optimum radius and length of pressure vessel with consideration of constraints and boundary conditions and followed by other crucial parameters by using these two variables.

Main design variables that was considered for this analysis were:

- radius of the shell
- length of the shell
- thickness of the shell
- thickness of the dish ends
-

The four important design constraints under consideration are:

- Hoop stress ≤ Allowable stress

  G1(x) = 0.0193x1 – x4 ≤ 0
- Longitudinal stress ≤ Allowable stress

  G2(x) = 0.00954x1 – x3 ≤ 0
- Volume ≤ Desired volume

  G3(x) = $\frac{4}{3}\pi r^3 - \pi x1^2\, x2$ ≤ Volume

The program also have flexibility in setting up own boundary values for variables for future case if there is any manufacturing limitations. Additional constraints can be added for better accuracy on optimum design of pressure vessels. Interface of Solver program is as in FIGURE 6.

Design Parameters

r/t > 10	Thin walled PV		
r/t < 10	Thick walled PV		
r/t =	18.65588404		
Pressure, P (Psi)	1000	6.894759087	(MPa)
Volume, V (in^3)	1296000.003	21.23762981	(m^3)
Weld Efficiency, E	0.9		
Allowable Stress, S (Psi)	21400	147.5478445	(MPa)
Corrosion Allowance, C (i	0.000787402	2E-05	(m)
Material			
Temperature, T (F)	400		

Converter

mm	inch
0.02	0.000787402
MPa	psi
30	4351.131
m^3	inch^3
30	1830712.2

$$\textbf{Objective Function,} \quad f(x) = \pi r^2 \,\mathrm{h} + \frac{4}{3}\pi r^3$$

Optimized result

x1 =	63.02780	radius of shell
x2 =	19.79570	length of shell
x3 =	3.37844	thickness of shell
x4 =	1.64554	thickness of dish end

Constraints

Constraint 1	-0.42910592	<	0
Constraint 2	-2.78	<	0
Constraint 3	0	<	7.918280789

Boundary Conditions

boundary 1	10	<x1<	300
boundary 2	10	<x2<	300
boundary 3	0.0625	<x3<	5
boundary 4	0.0625	<x4<	5

Shell thickness calculation

t1 (longitudinal)	3.37765366		
t2 (circular)	1.619399211		
t min	3.378441062	0.085812403	m

Head thickness calculation (Hemispherical)

tm1	1.645542551	0.041796781	m

Max Allowable Pressure

P1 (longitudinal)	999.9927377		
P2 (Circular/	2109.529025		
P max	999.9927377	6.894709015	Mpa

FIGURE 6. Optimization Excel Spreadsheet

4.2 Knowledge-Based Engineering Approach

To achieve the objective of this project, other than optimization of pressure vessel design, a material database was developed to implement the scope of knowledge-based engineering. The material behavior under different temperatures is an important parameter to be considered because it can, in many cases, determine the upper bound on the temperatures at which a material has suitable properties.

The effect of thermal damage on metallic materials is a degradation of static strength (yield and tensile strengths) at the exposed temperature, a degradation of static strength at room temperature after exposure to a higher temperature, the relaxation of beneficial compressive residual stresses and, potentially, some degradation of environmental cracking resistance of the affected material. The degree to which the thermal exposure will affect component material properties is dependent upon several factors including temperature and duration of exposure, thermal conductivity, alloy temper, surface treatment (e.g. peening and corrosion protection schemes used), and the thickness and configuration of the component. Generally, the higher the exposure temperature and the longer the exposure time, the greater the likelihood of degradation in the mechanical properties of the material.

Thus a database with all important materials commonly used for construction of pressure vessels followed by respective data on allowable stress according to temperature also been included. By entering the operation temperature of pressure vessel, the database will provides us options on choosing the material available to carry on the task. Other than that, design pressure also can be calculated by refer to type of fluid will be used in pressure vessel. The database was prepared based on ASME Section II D Table 1A. Besides, the constraints used for this analysis was based on ASME Rules for Construction of Pressure Vessels Section VIII Division I. Interface of Material Database is as in FIGURE 7.

Material Database

Material Properties:

400.0 Temp [F] - maximum design temperature

Material		Allowable Stress (psi)	Design Allowable Stress (psi)	Max °F	
SA-36	Plate	16,600	16,600	900	Carbon Steels
SA-106 B	Seamless Pipe	17,100	17,100	1,000	
SA-234 WPB	Fittings	17,100	17,100	1,000	
SA-105	Forging	20,000	20,000	1,000	
SA-516 70	Plate	20,000	20,000	1,000	
SA-414 G	Sheet	21,400	21,400	900	
SA-213 TP316L	Sms Tube	16,700	15,700	850	Stainless Steel 316L
SA-240 316L	Plate	16,700	15,700	850	
SA-312 TP316L	Sms. and Wld. Pipe	16,700	15,700	850	
SA-403 316L	Sms and Weld Fittings	16,700	15,700	850	
SA-479 316L	Bar	16,700	15,700	850	
SA-213 TP316	Sms Tube	20,000	19,300	1,500	Stainless Steel 316
SA-240 316	Plate	20,000	19,300	1,500	
SA-312 TP316	Sms. and Wld. Pipe	20,000	19,300	1,500	
SA-403 316	Sms and Weld Fittings	20,000	19,300	1,500	
SA-479 316	Bar	20,000	19,300	1,500	
SA-213 TP304L	Sms Tube	16,700	15,800	1,200	Stainless Steel 304L
SA-240 304L	Plate	16,700	15,800	1,200	
SA-312 TP304L	Sms. and Wld. Pipe	16,700	15,800	1,200	
SA-403 304L	Sms and Weld Fittings	16,700	15,800	1,200	
SA-479 304L	Bar	16,700	15,800	1,200	
SA-213 TP304	Sms Tube	20,000	13,800	1,500	Stainless Steel 304
SA-240 304	Plate	20,000	13,800	1,500	
SA-312 TP304	Sms. and Wld. Pipe	20,000	18,300	1,500	
SA-403 304	Sms and Weld Fittings	20,000	18,300	1,500	
SA-479 304	Bar	20,000	18,300	1,500	
SB-209 6061-T6 plate 0.051-0.249", wld		6,000	3,500	400	Aluminum
SB-209 6061-T651 plate 0.25-5", wld		6,000	3,500	400	
SB-209 6061-T6 plate 0.051-0.249"		10,900	4,000	400	
SB-209 6061-T651 plate 0.25-4.0"		10,900	4,000	400	
SB-209 6061-T651 plate 4.0-5.0"		10,300	4,000	400	
SB-211 A96061-T6 bar 0.125-0.249", wld		6,000	3,500	400	
SB-234 A96061-T6 tubes 0.025-0.200", wld		6,000	3,500	400	
SB-241 A96061-T6 sms. Pipe, wld		6,000	3,500	400	
SB-247 A96061-T6 forging, wld		6,000	3,500	400	
SB-308 A96061-T6 shapes, wld		6,000	3,200	400	

Material properties are compliant with ASME Section IID Table 1A

Fluid Specific Gravity (g/cm^3)
Water, 1.000
Ethanol, 0.789
Alcohol, 0.789-0.855
Ammonia, .662
Beer, 1.01
Bromine, 2.900
Butane, 0.594
Crude Oil, 0.790-0.843
Gasoline, 0.680-0.740
Glucose, 1.350-1.440
Kerosene, 0.780-0.820
Milk, 1.020-1.050
Sufuric Acid, 1.814

Fluid Properties:

300.0 P [psi] - pressure at top of vessel
100.00 H [ft] - fluid height
1.000 SG - specific gravity

Pdesign [psi] = P+0.433*SG*H   design pressure including static head   300+0.433*1*100 = 343.3 (psi)

Pdesign is to be used in the design of subsequent components (shell, head, nozzle, etc)

FIGURE 7. Material Database

4.3 Optimization of Pressure Vessels Design using MATLAB

As planned in Final Year Project One, the ultimate objective of the project was to come up with a platform which provides knowledge based engineering approach to support optimal design of pressure vessels. Simpler version using Excel Solver was developed in first phase while in second phase, more detailed and diversified version of model was developed using MATLAB. Same optimization concept was introduced into the new platform and all the coding were done to get desired output. More modelling concepts were introduced in the current model including types of pressure vessels and dished heads.

Detailed research was conducted to determine the formulas will be used for different cases and it was implemented into the system to enhance scope of the model. Developed model for Material Database using Microsoft Excel will be used temporarily in the original form until it is fully imported into MATLAB readable format. The design problem is to develop a spherical or cylindrical Pressure Vessel with options of hemispherical, ellipsoidal and tori-spherical dished head which is capable of containing fluid at a particular pressure. Using a rolled steel plate, the shell is to be made out of two halves that are joined by two longitudinal welds to form a cylinder. The pressure vessel is capped at both ends by dished heads and each head is forged and then welded to the shell.

The objective of design optimization of pressure vessels is to reduce weight with adequate strength and stiffness by design pressure vessel with optimum dimension. The design variables are shown in Figure…. Variables L and R and continuous while T_H and T_S are discrete. The thickness of the shell, T_S and the head, T_H are both required to be standard sizes. In current market, pressure vessel's material such as steel plates and etc. available in multiples of 0.0625 inches. The labelling of four variables that used widely in this project are labelled as in FIGURE 8.

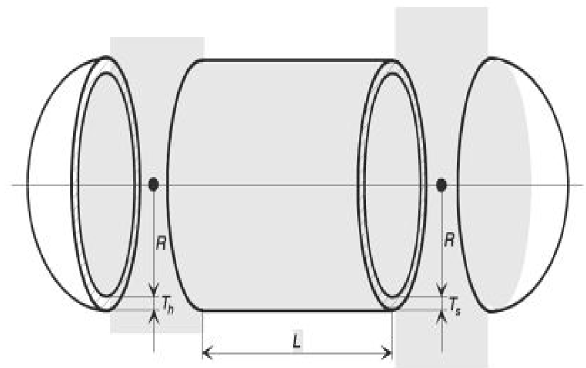


FIGURE 8. Labelling of Pressure Vessel

The problem can be formulated as follows:

Find

$X = (x_1, x_2, x_3, x_4) = (T_S, T_H, R, L)$

To minimize

$f(x) = 0.6224x(1)x(3)x(4) + 1.7781x(2)x(3)^2$

$+3.1661x(1)^2x(4) + 19.84x(1)^2x(3)$

$f(x) = \pi R^2 L + \frac{4}{3}\pi R^3$

(Hemispherical)

$f(x) = \pi R^2 L + \left[\frac{\pi}{3}R^3 + \pi R^2 S.F\right]2$

(2:1 Ellipsoidal)

$f(x) = \pi R^2 L + [\ 0.0847(8R^3) + \pi R^2 S.F\ ]2$

(Torispherical)

Subject to

Hoop stress ≤ Allowable stress

$G_1(x) = 0.0193x(1) - x(4) \leq 0$

Longitudinal stress ≤ Allowable stress

$G_2(x) = 0.00954x(1) - x(3) \leq 0$

Volume ≤ Desired volume

$G_3(x) = \frac{4}{3}\pi r R^3 - \pi x(1)^2\, x(2) \leq$ Volume

Length of Shell

$G_4(x) = x(4) \ -240 \leq 0$

Thickness of the Shell

$G_5(x) = 1.1 - \ x(1) \leq 0$

Thickness of the Head

$G_6(x) = 0.6 - \ x(2) \leq 0$

The simple boundaries

$0.0625 \ \leq \ x(1), x(2) \leq 99 \times 0.0625$

$10.0 \ \leq \ R, L \leq 240$

The objective function, $f(x)$ represents the volume of pressure vessel as a function of the design variables. The constraints, $G_1, G_2, G_3, G_4, G_5, G_6$, quantify the restrictions to which the pressure vessel design must adhere. These limits arise from a variety of sources. The minimal wall thickness of the shell and heads with respect to the shell radius are limited by the pressure vessel design code. The volume of the pressure vessel limited to user input. Available rolling equipment limits the length of the shell to no more than 20 feet. According to the pressure vessel design code, the thickness of the shell is not to be less than 1.1 inches and the thickness of the head is not to be less than 0.6 inches.

The constraints are pure boundary, so they were handled as lower boundary constraints for $x(1)$, $x(2)$ and as an upper boundary constraint for $x(4)$ respectively. The lower boundaries for $x(1)$ and $x(2)$ can be set to zero, since common sense demands that they must be non-negative values. The upper boundaries for $x(1)$, $x(2)$, and $x(3)$ however must still be specified in order to define the search space. Consequently, these bounds were set high enough to make it highly probable for global optimum to lie inside of the defined search space. The flowchart of the developed model will indicates the process flow of model whereby

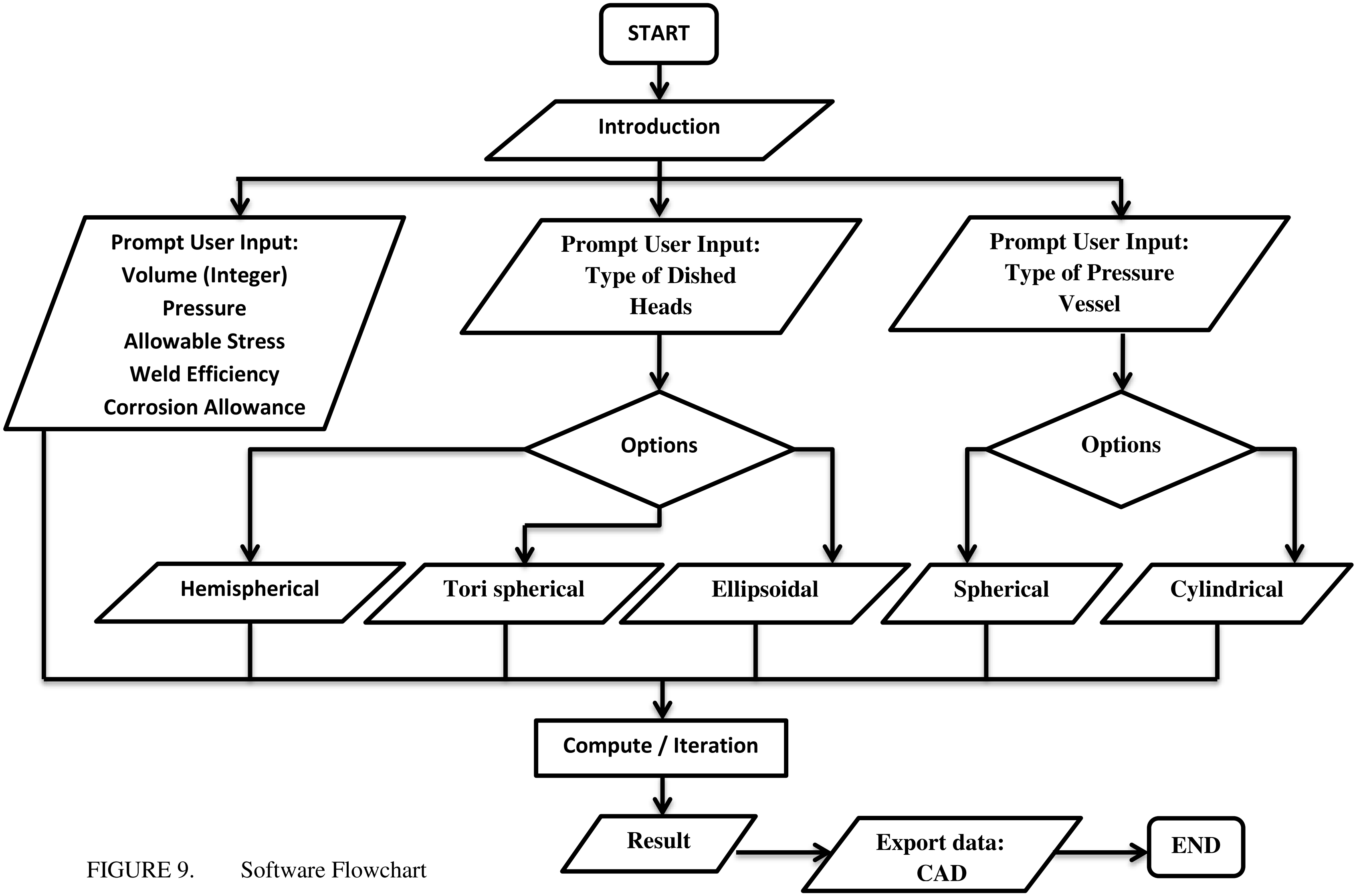


FIGURE 9. Software Flowchart

The outcome of current version of MATLAB concept optimization program as below:

```
Command Window
>> PV_OPTIMIZATION_HMS
What is the design volume[cubic inch]? 1200000
What is the constraint volume[cubic inch]? 1200000
Following results are Thickness of Shell[inch],
Thickness of Head[inch],Radius of Shell[inch] and
Length of Shell[inch]
    3.9357
    0.6599
   62.9147
  113.9075

fx What is the design volume[cubic inch]?
```

FIGURE 10. Outcome of Iteration

The MATLAB program was prepared as when its run, a prompt will ask user to give input on design volume as in FIGURE 10. Then it's followed by the constraint parameters for material. The output from the optimization process will be the thickness of shell, thickness of head, radius of shell and finally the length of shell. The unit used for this stage of research is only limited to imperial unit.

4.4 Graphical User Interface of Developed Software

GUIs (also known as graphical user interfaces or UIs) provide point-and-click control of software applications, eliminating the need to learn a language or type commands in order to run the application. MATLAB apps are self-contained MATLAB programs with GUI front ends that automate a task or calculation. The GUI typically contains controls such as menus, toolbars, buttons, and sliders. This part of report discuss about development of user-friendly graphical user interface, which facilitates the use of Knowledge-Based Engineering Approach for Optimal Design of Pressure Vessel in the MATLAB environment. The use of the interface is illustrated through the design of horizontal pressure vessel with hemispherical head. This example comprises a step-by-step description of how to use the software, including the startup of software, pressure vessel head selection, data entry procedure, outcome of optimization process and finally model-building process in AutoCAD using an externally available plug-in.

There are total of five interfaces overall and everything is interlinked to form the whole software. Other than that, Material Database created in Microsoft Excel and generation of pressure vessel drawing in AutoCAD using external plug-in will be linked directly to the interface using MATLAB functions. GUIDE (graphical user interface design environment) was used to design these five interfaces as it provides all the required tools for designing of GUI. Using the GUIDE Layout Editor, UI can be graphically designed. GUIDE then automatically generates the MATLAB code for constructing the UI, which later on will be modified to program the behavior of developed software.

As shown in FIGURE 11, the interface comprises of main title which is Knowledge-Based Engineering Approach for Optimal Design of Pressure Vessel, Universiti Teknologi PETRONAS's logo as an indication that the project was carried of UTP student and the window is titled "Introductory Page". By using the "Start" button, second interface which is "Head Selection Panel" can be opened. The software can be closed using "Close" button with "x" logo on top right corner.

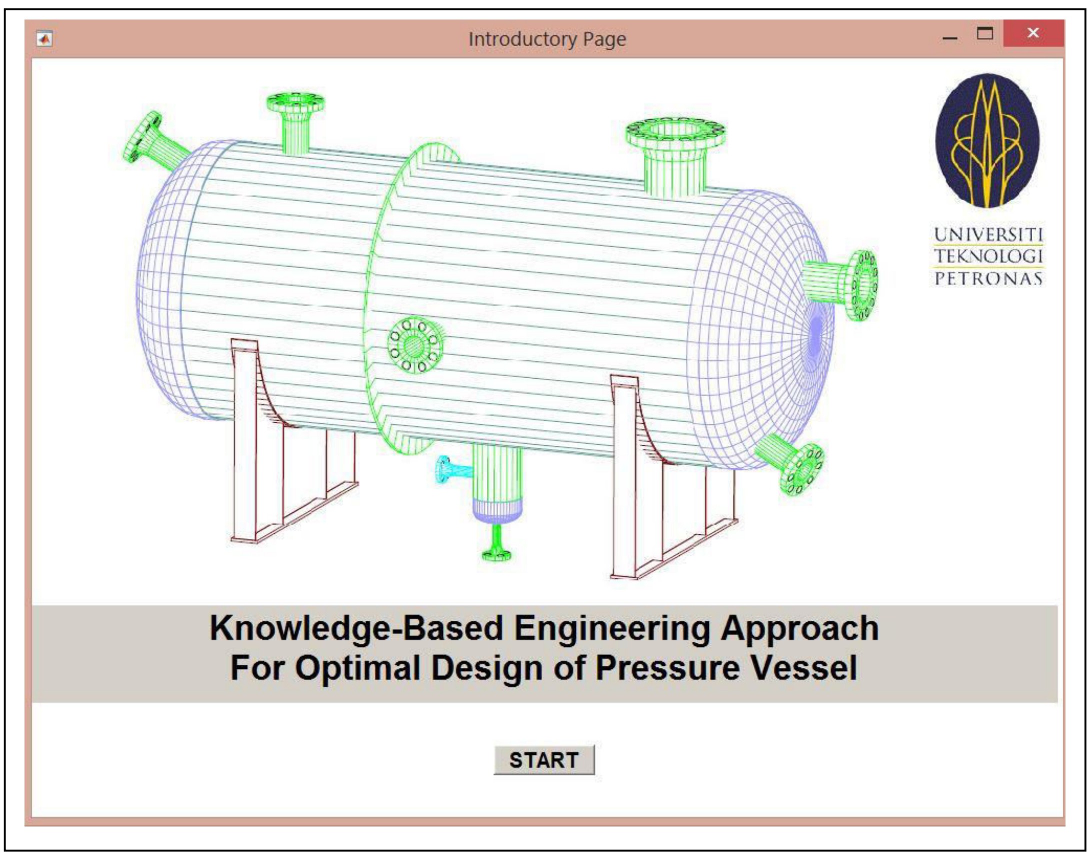


FIGURE 11. Introductory Page of Software GUI

As shown in FIGURE 12, the interface window titled “Head Selection Panel” whereby user need to select either “Hemispherical”, “Elliptical” or “Tori spherical” button to indicate type of head will be used along together with shell for analysis of optimization. The software can be closed using “Close” button with “x” logo on top right corner. Other than that, to emphasize on user-friendly approach, detailed description of every head consist of dimension parameters was shown to give clearer idea on which head to be chose according to application.

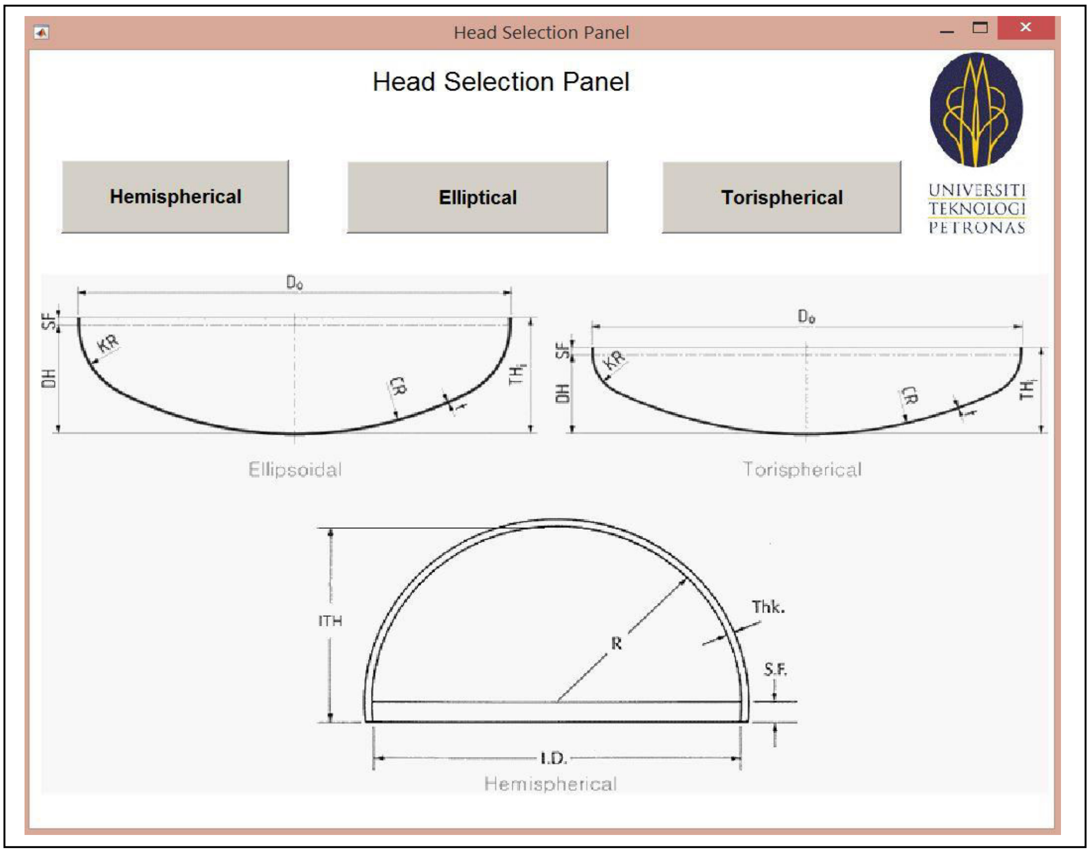


FIGURE 12. Head Selection Panel

Followed by Head Selection, “Hemispherical Head Pressure Vessel” titled window will expand and let user to provide necessary data to proceed with analysis as in FIGURE 13. At top left corner, panel of “Unit Selection” was placed whereby it allows user to select desired unit for all the process. An option of “Imperial Unit System” and “S.I. Unit System” given to user to select. For “Imperial Unit System”, units like inch, cubic inch, psi whereby for “S.I. Unit System”, units like meter, cubic meter and Pascal will be used.

This is another way of emphasizing user-friendly approach for developed software. User need to provide the data on design parameters of pressure vessel such as design volume, internal pressure, allowable stress of material to be used according to operating temperature of medium whereby it is interlinked with excel as shown in FIGURE 14, weld efficiency which considered the same for circular and longitudinal weld, and finally the corrosion allowance of material. The intermediate process will be carried out using “fmincon” function whereby all the necessary inputs, boundaries, linear and nonlinear constraints will solved using MATLAB solver. The outcome of the process will be shown in “Results” panel which are “Shell Radius”, “Shell Length”, “Shell Thickness”, “Shell Pressure” and “Head Thickness”. Furthermore, user can generate drawing by put in the result into plug-in for AutoCAD which will produce drawing with provided parameters as in FIGURE 17. Interface will vary for elliptical head pressure vessel and tori spherical head pressure vessel whereby additional of data which is “Straight Face” need to be provided by user to carry out the analysis. “Elliptical Head Pressure Vessel” and “Tori spherical Head Pressure Vessel” interface is shown as in FIGURE 15 and FIGURE 16.

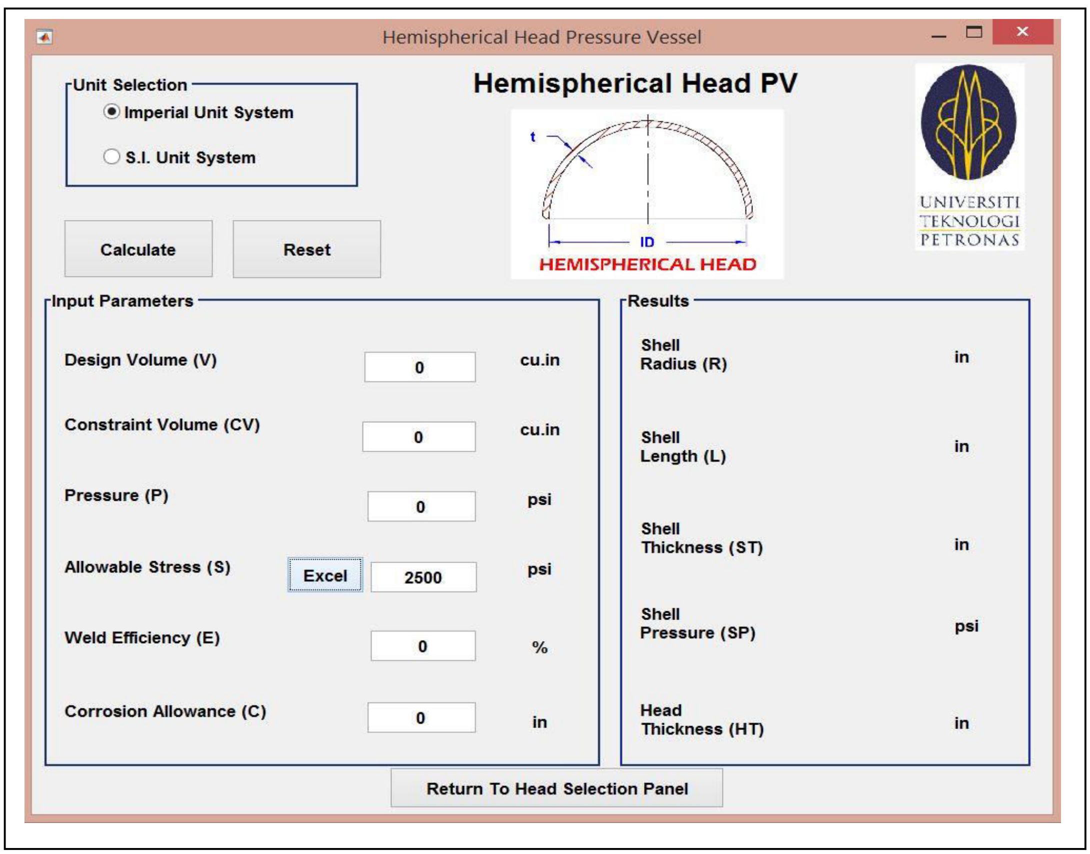
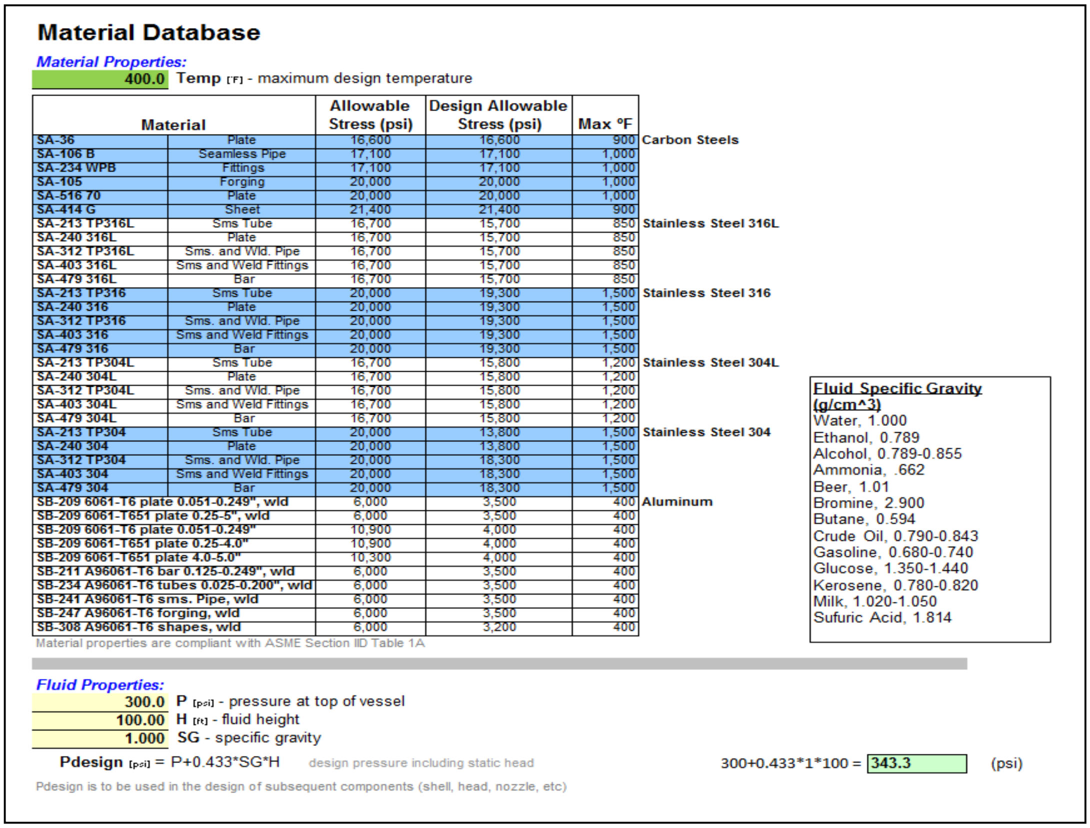


FIGURE 13. Hemispherical Head Pressure Vessel Design Page



Material Database

Material Properties:

400.0 Temp [F] - maximum design temperature

Material		Allowable Stress (psi)	Design Allowable Stress (psi)	Max ºF	
SA-36	Plate	16,600	16,600	900	Carbon Steels
SA-106 B	Seamless Pipe	17,100	17,100	1,000	
SA-234 WPB	Fittings	17,100	17,100	1,000	
SA-105	Forging	20,000	20,000	1,000	
SA-516 70	Plate	20,000	20,000	1,000	
SA-414 G	Sheet	21,400	21,400	900	
SA-213 TP316L	Sms Tube	16,700	15,700	850	Stainless Steel 316L
SA-240 316L	Plate	16,700	15,700	850	
SA-312 TP316L	Sms. and Wld. Pipe	16,700	15,700	850	
SA-403 316L	Sms and Weld Fittings	16,700	15,700	850	
SA-479 316L	Bar	16,700	15,700	850	
SA-213 TP316	Sms Tube	20,000	19,300	1,500	Stainless Steel 316
SA-240 316	Plate	20,000	19,300	1,500	
SA-312 TP316	Sms. and Wld. Pipe	20,000	19,300	1,500	
SA-403 316	Sms and Weld Fittings	20,000	19,300	1,500	
SA-479 316	Bar	20,000	19,300	1,500	
SA-213 TP304L	Sms Tube	16,700	15,800	1,200	Stainless Steel 304L
SA-240 304L	Plate	16,700	15,800	1,200	
SA-312 TP304L	Sms. and Wld. Pipe	16,700	15,800	1,200	
SA-403 304L	Sms and Weld Fittings	16,700	15,800	1,200	
SA-479 304L	Bar	16,700	15,800	1,200	
SA-213 TP304	Sms Tube	20,000	13,800	1,500	Stainless Steel 304
SA-240 304	Plate	20,000	13,800	1,500	
SA-312 TP304	Sms. and Wld. Pipe	20,000	18,300	1,500	
SA-403 304	Sms and Weld Fittings	20,000	18,300	1,500	
SA-479 304	Bar	20,000	18,300	1,500	
SB-209 6061-T6 plate 0.051-0.249", wld		6,000	3,500	400	Aluminum
SB-209 6061-T651 plate 0.25-5", wld		6,000	3,500	400	
SB-209 6061-T6 plate 0.051-0.249"		10,900	4,000	400	
SB-209 6061-T651 plate 0.25-4.0"		10,900	4,000	400	
SB-209 6061-T651 plate 4.0-5.0"		10,300	4,000	400	
SB-211 A96061-T6 bar 0.125-0.249", wld		6,000	3,500	400	
SB-234 A96061-T6 tubes 0.025-0.200", wld		6,000	3,500	400	
SB-241 A96061-T6 sms. Pipe, wld		6,000	3,500	400	
SB-247 A96061-T6 forging, wld		6,000	3,500	400	
SB-308 A96061-T6 shapes, wld		6,000	3,200	400	

Material properties are compliant with ASME Section IID Table 1A

Fluid Specific Gravity (g/cm^3)
Water, 1.000
Ethanol, 0.789
Alcohol, 0.789-0.855
Ammonia, .662
Beer, 1.01
Bromine, 2.900
Butane, 0.594
Crude Oil, 0.790-0.843
Gasoline, 0.680-0.740
Glucose, 1.350-1.440
Kerosene, 0.780-0.820
Milk, 1.020-1.050
Sufuric Acid, 1.814

Fluid Properties:

300.0 P [psi] - pressure at top of vessel
100.00 H [ft] - fluid height
1.000 SG - specific gravity

Pdesign [psi] = P+0.433*SG*H design pressure including static head 300+0.433*1*100 = 343.3 (psi)

Pdesign is to be used in the design of subsequent components (shell, head, nozzle, etc)

FIGURE 14. MATLAB linked Material Database

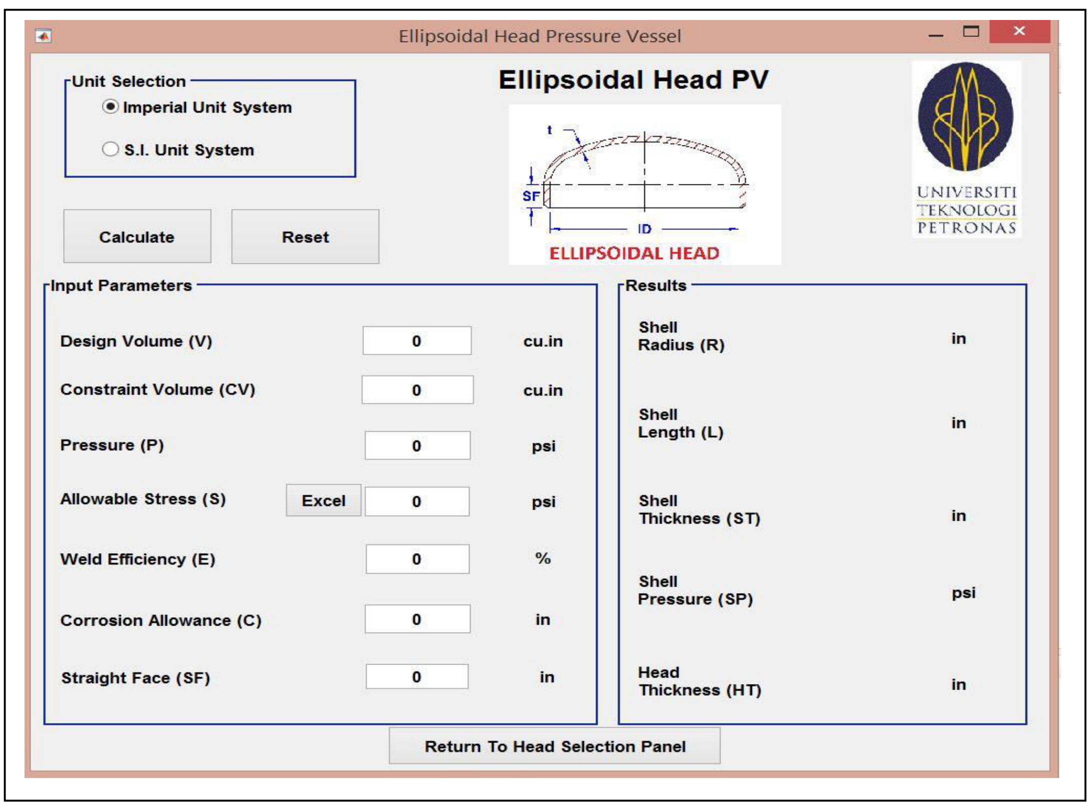


FIGURE 15. Ellipsoidal Head Pressure Vessel Design Page

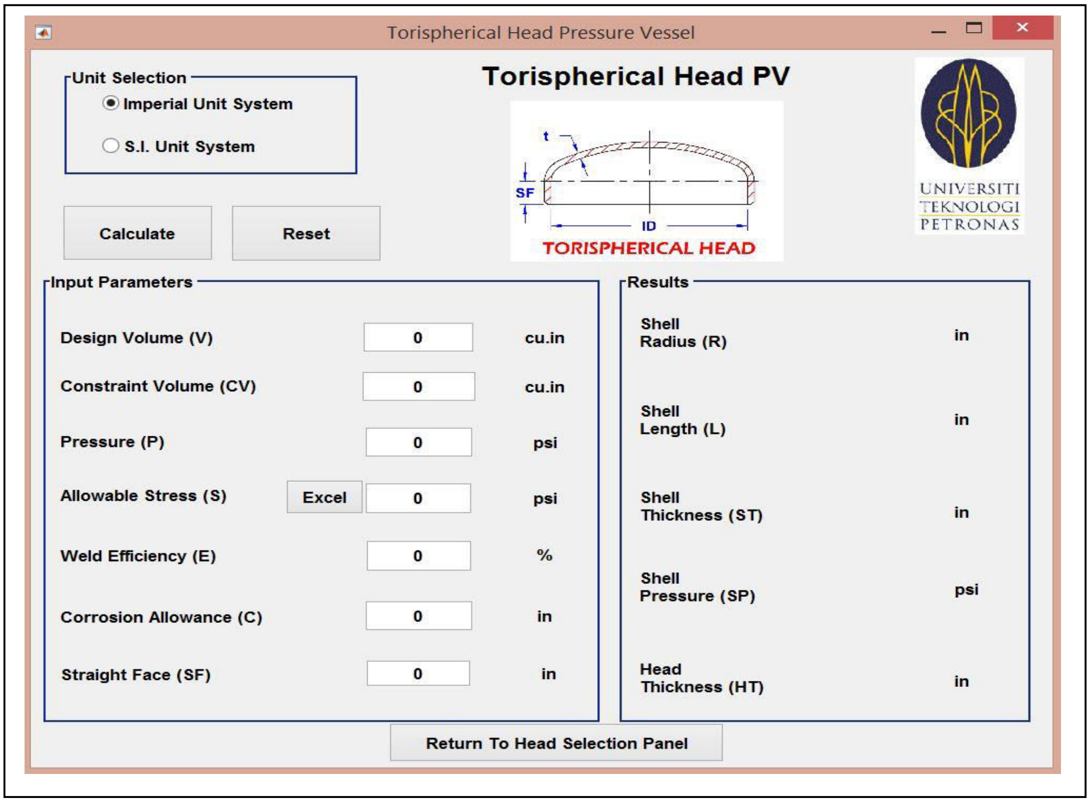


FIGURE 16. Tori Spherical Head Pressure Vessel Design Page

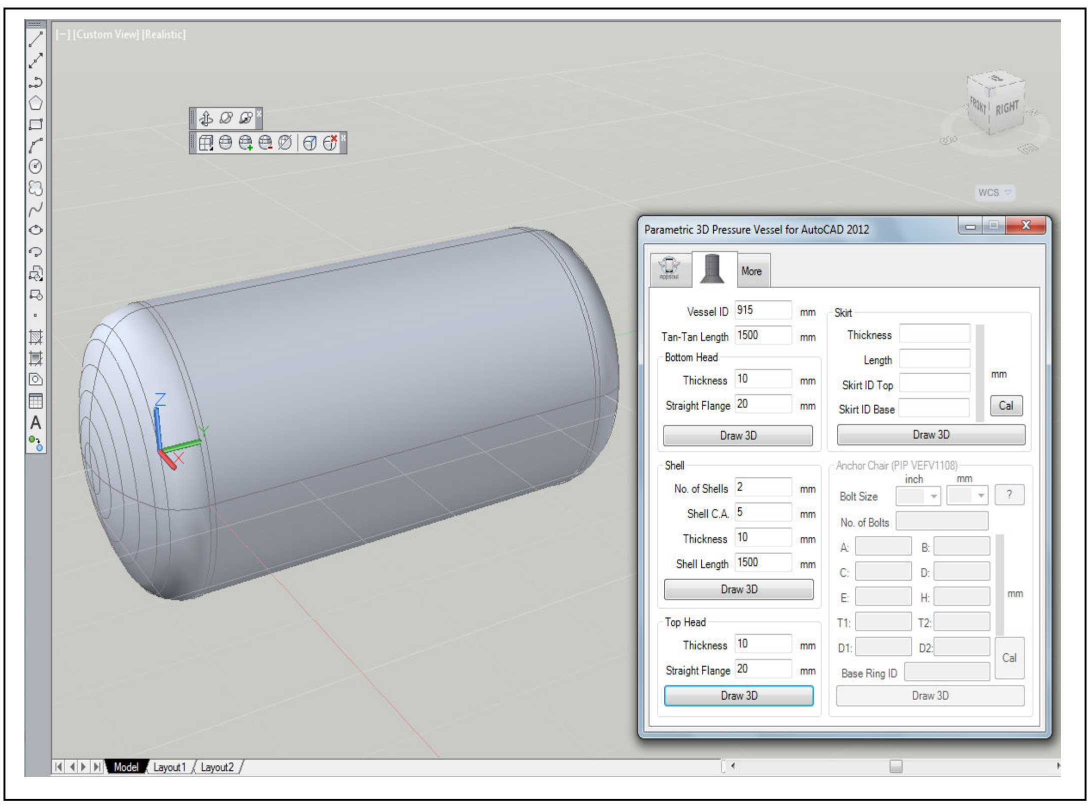


FIGURE 17. Generated Pressure Vessel Drawing Using AutoCAD Plug-In

4.5 Validation Test for Results from Developed Software

As for case study 1, a hemispherical head pressure vessel was used as benchmark to verify the outcome from this software after optimization process. Design specification of the pressure vessel are as below:

- Design Volume = 1296000 cubic inch
- Design Pressure = 1000 psi
- Material Allowable Stress = 78321 psi
- Weld Efficiency = 0.9 = 90%
- Corrosion Allowance = 0.08 inch

The optimum values are obtained at 6th iteration and 35th Function-Count. Optimization completed because the objective function is non-decreasing in feasible directions, to within the selected value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

The result are as below:

- Thickness of the Shell (x1) = 0.7276 inch
- Thickness of the Head (x2) = 0.3596 inch
- Radius of the Shell (x3) = 37.6990 inch
- Length of the Shell (x4) = 240.00 inch

According to American Society of Mechanical Engineers Rules for Construction of Pressure Vessels Section VIII Division I, minimum requirement of pressure vessel corresponding to design specification mentioned above are:

- Minimum thickness of the Shell = 0.6183 inch
- Minimum thickness of the Head = 0.3472 inch
- Maximum operating pressure of Pressure Vessel = 1201 psi

As for case study 2, the optimum values obtained are compared with previous works using various other optimization methods and it is shown as in Table 2.

TABLE 9. Result Comparison with Other Methods Used Previously

Method	ARGA [5]	GP [6]	Present Work (fmincon)	Error (%) ARGA vs fmincon	Error (%) GP vs fmincon
x1 (inch)	0.75	0.7277	0.7276	2.99	0.014
x2 (inch)	0.375	0.3597	0.3596	4.11	0.028
x3 (inch)	38.858	37.70	37.6990	2.98	0.003
x4 (inch)	221.402	240.00	240.00	7.75	0

ARGA – Adaptive Range Genetic Algorithm

GP – Geometric Programming

Fmincon – MATLAB built-in Optimization Solver

From the table, it can be clearly seen that present work's result margin error with previously done research are very small. Thus it can be concluded that optimization program using fmincon function with integrated Microsoft Excel based material databases is feasible to use.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In the present work parameters such as thickness of the shell, and dish end, length and radius of the pressure vessel are optimized by making use of optimization tool which is Solver whereby as for first phase it is to ensure correct implementation of optimization concept to reduce weight of designed pressure vessel. The result fully complied with standard code and had been employed on practical design of pressure vessel. Selection material referring to ASME standard also been developed which enhanced selection basis of material for design of pressure vessels.

In second phase, the objective is achieved by creating real reliable model using MATLAB to conduct optimization process for optimal design of pressure vessel. GUI with main concept of user-friendly and functionality was developed for developed model to change the whole project into standalone software. Material selection program was reused and linked to MATLAB. Other type pressure vessel models was added into program to diversify the usage of software. Unit selection flexibility in the developed model also implemented to widen up concept of user-friendly. Other than that, author used external plug-in to retrieve the output parameters from the analysis into AutoCAD to generate computer aided drawing which will be useful for engineering analysis. A detailed validation test for the results obtained from the developed software was conducted to ensure the software is reliable to use.

5.2 Recommendations

As for recommendation, further research can be done on spherical pressure vessel by find out respective objective functions with related boundary conditions, linear and nonlinear inequalities for the analysis. Besides, direct link up from MATLAB to AutoCAD also can be developed by using respective programming language to avoid dependence on external plug-ins.

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APPENDICES

Minimum Thickness (Longitudinal), $T_1 = \frac{P \cdot Ri1}{S \cdot E\text{-}0.6P}$

Minimum Thickness (Circular), $T_2 = \frac{P \cdot Ri1}{2S \cdot E + 0.4P}$

Minimum required design thickness, $Tmin = \text{Max}\ (T_1\ , T_2) + C$

Longitudinal Pressure, $P_1 = \frac{SE \cdot T}{Ri1 + 0.6nt}$

Longitudinal Pressure, $P_2 = \frac{2SE \cdot T}{Ri1\text{-}0.4nt}$

Maximum Allowable Pressure, $Pmax = \text{Min}\ (P_1\ , P_2)$

Minimum Thickness (Head), $T_1 = \frac{P \cdot Ri1}{2S \cdot E\text{-}0.2P} + C$

R = radius of shell

t = thickness of shell

P = applied pressure (inside)

Ri1 = Pressure Vessel inside radius (after adjust corrosion allowance)

S = Maximum allowable stress

E = Efficiency of weld

C = Corrosion allowance

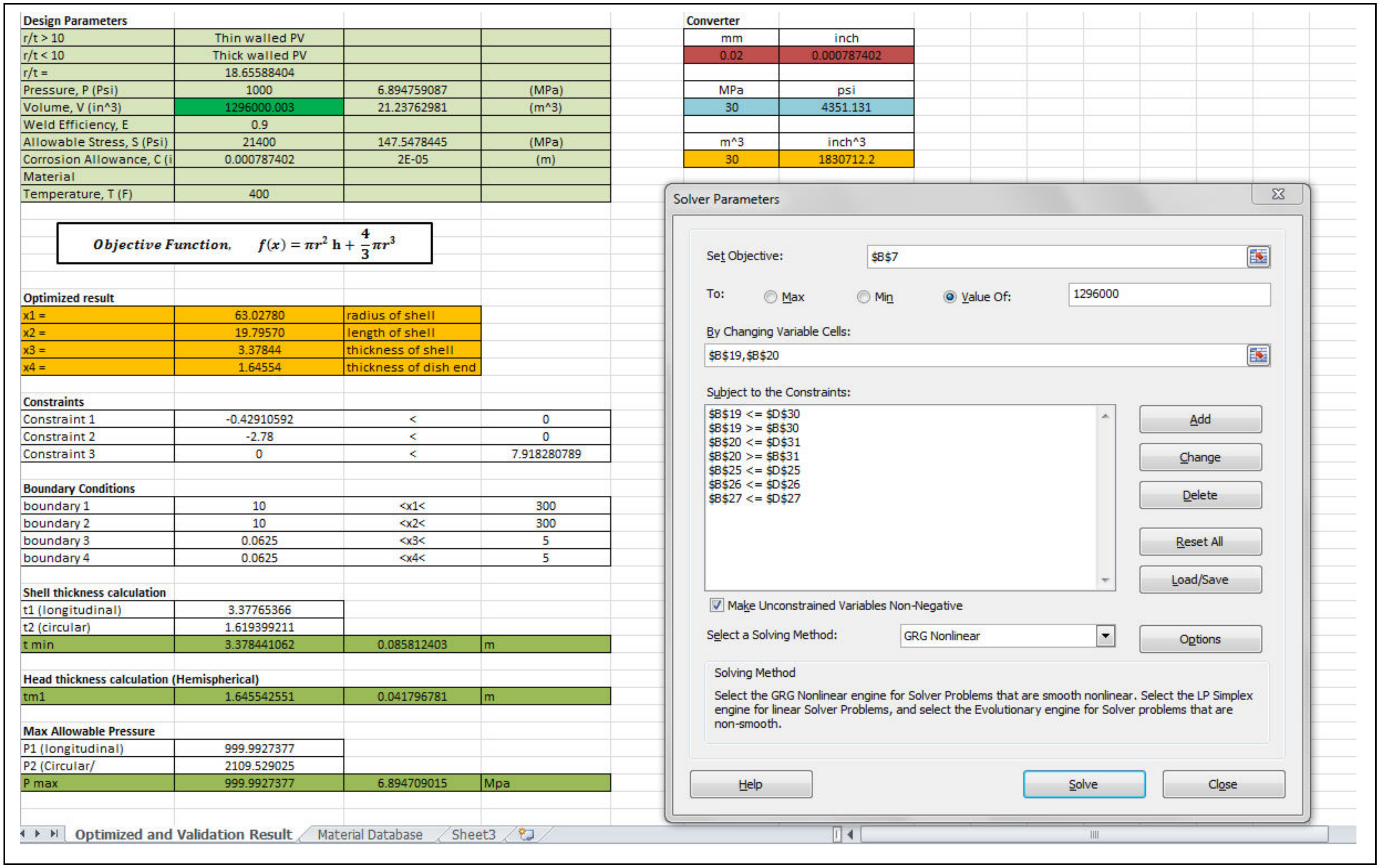

FIGURE 1. Solver Optimization Approach

```
% ----------------------------------------------------------------   %
% Matlab Programs included the Appendix in the research paper:       %
%  Arun Raj Latchumanan, Knowledge-Based Engineering Approach        %
%  to Support Optimal Design of Pressure Vessels V2.0                %
%  Mechanical Engineering Department                                 %
%  Universiti Teknologi PETRONAS                                     %
%  Last Updated: August 2015                                         %
% ----------------------------------------------------------------   %


% ---------------------------------------------------------------    %
% Design Optimization of a Pressure Vessel using Knowledge Based     %
% Engineering Approach and fmincon function to evaluate the          %
% objective function                                                 %
% -----------------------------------------------------------------  %

function PV_OPTIMIZATION_HMS
  % Smallest thickness of material available
  d=0.0625;

  % Linear inequality constraints
  A=[-1 0 0.0193 0;0 -1 0.00954 0;0 0 0 1];
  b=[0; 0; 240];

  % Variable boundaries
  Lb=[d; d; 10; 10];
  Ub=[99*d; 99*d; 240; 240];

  % Initial value
  x0=Lb+(Ub-Lb).*rand(size(Lb));

  % Creates an optimization options structure where the specified options
  % (parameters) have specified values and unspecified options are set to
  % []
  options=optimset('Algorithm','active-set','Display','iter','TolFun'...
   ,1e-08);
  % Returns the value of the objective function at the value x
  [x,fval]=fmincon(@objfun,x0,A,b,[],[],Lb,Ub,@nonfun,options);


function f=objfun(x)
  % Objective function
  f = 0.6224*x(1)*x(3)*x(4)+1.7781*x(2)*x(3)^2+3.1661*x(1)^2*x(4)+...
       19.84*x(1)^2*x(3);
  % Prompt that asking for input
  %prompt = 'What is the design volume[cubic inch]? ';
  % User input
  %f = input(prompt);
```

FIGURE 2. MATLAB Coding (1)

```
  % Nonlinear constraints
function [g,geq]=nonfun(x)
  % Nonlinear inequality
  g=[];
  % Prompt that asking for input
  %prompt = 'What is the constraint volume[cubic inch]? ';
  % User input
  y = input(prompt);
  % Equality constraint
  geq = (pi*x(3)^2*x(4)+(4/3)*pi*x(3)^3)-y;

  prompt = 'What is the Pressure [psi]? ';
  p = input(prompt);
  prompt = 'What is the Allowable Stress[psi]? ';
  s  = input(prompt);
  prompt = 'What is the Weld Efficiency ? ';
  e = input(prompt);
  prompt = 'What is the Corrosion Allowance[inch]? ';
  c = input(prompt);

  % t1 = minimum required thickness at longitudinal seam welds
  t1=(p*(x(3)-c))/(s*e-0.6*p);
  % t2 = minimum required thickness at circular seam welds
  t2=(p*(x(3)-c))/(2*s*e+0.4*p);
  % tr = minimum required design thickness
  tr=max(t1,t2)+c;
  % p1 = longitudinal pressure applied to PV (shell)
  p1=(s*e*(x(1)-c))/((x(3)-c)+0.6*(x(1)-c));
  % p2 = circular pressure applied to PV (shell)
  p2=(2*s*e*(x(1)-c))/((x(3)-c)-0.4*(x(1)-c));
  % pr = maximum allowable pressure inside PV
  pr=min(p1,p2);
  % trh = minimum required thickness for hemispherical head
  trh=(p*(x(3)-c))/(2*s*e-0.2*p)+c;

%Display the results (Variables)
  disp('Following results are Thickness of Shell[inch],')
  disp('Thickness of Head[inch],Radius of Shell[inch] and')
  disp('Length of Shell[inch]')
  disp (x)
  disp('Minimum required Thickness for Shell[inch],')
  disp (tr)
  disp('Minimum required Thickness for Hemispherical Head[inch],')
  disp (trh)
  disp('Maximum allowable Pressure for Shell and Hemispherical Head[psi],')
  disp (pr)
```

FIGURE 3. MATLAB Coding (2)

```
%Display the results (Variables)
  disp('Following results are Thickness of Shell[inch],')
  disp('Thickness of Head[inch],Radius of Shell[inch] and')
  disp('Length of Shell[inch]')
  disp (x)
  disp('Minimum required Thickness for Shell[inch],')
  disp (tr)
  disp('Minimum required Thickness for Hemispherical Head[inch],')
  disp (trh)
  disp('Maximum allowable Pressure for Shell and Hemispherical Head[psi],')
  disp (pr)


% -----------------------------------------------------------------  %
% Sample Software provided by Embedded Author is for research        %
% purposes only which provides the users with optimization           %
% information on design of Pressure Vessels                          %
% This software is provided without any warranties and support       %
% Embedded Author assumes no responsibility or liability for the use %
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FIGURE 4. MATLAB Coding (3)

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