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Design and Development of a Symmetrical Wobble-Plate Compressor for Natural Gas Vehicle Refueling

Ardiyansyah, Md Nor Musa, Ainullotfi Abdul-Latif, & Muhamad Adlan Abdullah

Keywords: Wobble plate, compressor, natural gas, and vehicle refueling

Abstract

This paper discusses the design and development of a compressed natural gas (CNG) vehicle refueling compressor. It describes the concept and design features of a new concept of symmetrical wobble plate compressor. Unlike most existing wobble plate compressors used in the automotive air-conditioning systems which are single-staged, the proposed compressor is multi-staged due to the very high pressures of compression required. Employing a symmetrical configuration using two sets of identical wobble plates and pistons, this new design is expected to give a better performance in terms of noise, vibration, capacity and mechanical efficiency.

The development of the compressor started with a study on the requirements and technical specifications. Product architecture was then established according to the functional components of the compressor, with a schematic breakdown that represents the operation of the compressor. Concept development was performed to optimally select the number of stages of compression for the proposed configuration and specifications, and other concepts of systems, e.g. cooling system, anti-rotating mechanism, lubrication system, driver system and piping work. The detail design with analyses of thermodynamics, kinematics and dynamics, stressing, lubrication, etc, was then carried out using both theoretical and computational approaches in order to refine and optimise the geometries and dimensions of components before the fabrication of the prototype. The major outcome of this compressor development exercise is the delivery of a production-ready compressor design with a prototype that has successfully passed all the performance tests.

1. Introduction

With the Kyoto Protocol coming into force early this year reflecting the environmental concerns of the world community on air pollution, the use of CNG as an alternative, “cleaner” fuel for vehicles is increasingly promoted in Malaysia, especially as the country is also blessed with a huge reserve of natural gas.[5] Natural gas can be combusted more completely than gasoline or petroleum with little pollutant while its price is relatively cheap. More public vehicles are encouraged to convert fully to CNG or to dual fuel (petrol/CNG) usage. In line with this, more natural gas vehicle (NGV) refueling facilities are being built by Petronas (Malaysia national petroleum company) to serve this increasing demand. However, using natural gas as vehicle fuel requires different refueling and storage technology as it involves compressing the gas to a very high working pressure (up to 250 bars) to ensure compact storage.

While most conventional compressors for natural gas refueling utilize the crankcase design, wobble-plate type compressors are more popular in automotive air-conditioning systems which involve low compression pressures. Currently these wobble-plate compressors available are single-sided. In this work a symmetrical concept is proposed instead using the wobble-plate design; furthermore the challenge is to develop a multi-staged design for high pressures in CNG refueling. The significant differences between them are that the current wobble plate design has one side to compress and it is single-staged; while the new design have two identical sides to compress and it is multi-staged [1]. However, in general, wobble plate compressors have several advantages such as compact design, smooth operation with low torque variation as was attained with this 5-cylinder construction, universal mounting method, and the durability [4]. For this reason the wobble plate design is used in this system.

The NGV refueling compressor designed is for the medium capacity of 10 Nm^3/hr, and could be used in mini stations for housing blocks, office clusters, vehicle fleet or shopping malls. It is not intended for fast refueling such as in full-fledged commercial stations with high throughput, but it would provide a faster refueling than over-night home refueling appliances. This would be suitable for busy people on the move who could leave their vehicles on automatic refueling for half an hour to one hour while doing other work then.

The main components for such a mini station would cover the compression system, the driver system, and dispenser and controls [6], [3]. This paper discusses only the compression part. Such a refueling unit is generally a self-contained, oil-free outdoor appliance that will fill the vehicle gas storage cylinder at a rate of 10 Nm^3/hr to a pressure of 210 bars (3600 psig) @ 27^0C within 0.5-1 hours, giving an average mass flow rate of 0.67 kg/min.

2. Preliminary design

2.1. Concept development

The concept development phase of the development process demands perhaps more coordination between functions than any other. In this case we expand the concept development phase into what we call the front-end process. This repetition of normally complete activities is known as development *iteration* [2]. The concept development process includes the following activities as illustrate in Figure 1 below:

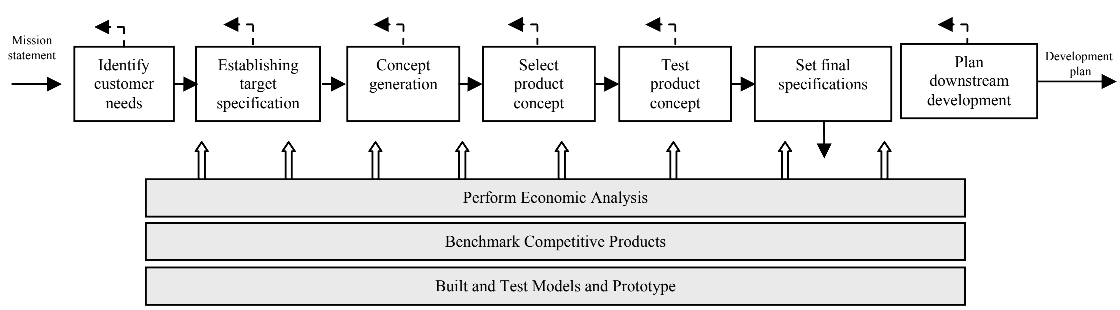


Figure 1. The many front-end activities comprising the concept development phase [2]

Identify customer needs: based on Petronas requirements the following considerations must be taken in the new NGV compressor design:

Table 1. Customer needs for the vehicle refueling appliance compressor and their relative importance

No	Need	Importance
1	Manufacturing costs	4
2	Maintenance-free lubrication	4
3	Safety	4
4	Light weight	3
5	Small space	3
6	Low vibration & noise	2
7	Ease of use	2
8	Power requirements	2
9	Filling time	1

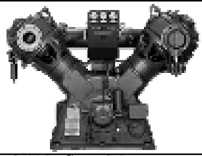
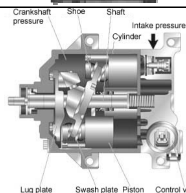
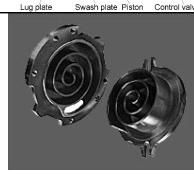
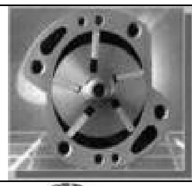
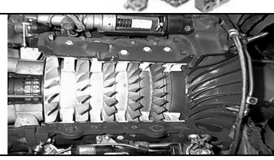
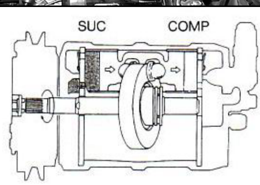
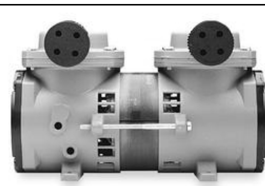
Establishing target specification: the designer determines the specification target based on customer needs (request) by translating them into the technical terms. The target specifications are:

Table 2. The target specification

No	Metric	Importance	Unit	Value
1	Discharge pressure	10	psi	3000
2	Inlet pressure	10	psi	50
3	Power (motor phase)	10	-	Single
4	Light weight	8	Kg	100-150
5	Optional storage tank	7	Liter	55-280
6	Easy to remove compressor	7	-	modular
7	Moderate power consumption	6	kW	15-25
8	Low vibration & noise	6	dB	60
9	Filling time	6	Minute	30
10	Maintenance-free lubrication	5	-	-
11	Small space	3	Ft	1ft x 1ft x 3ft
12	Wall-mounted	1	-	-

Concept generation: the goal of the concept generation phase is to thoroughly explore the range of product concepts that may address the customer needs. Concept generation includes a mix of external search, creative problem solving within the team, and systematic exploration of the solution fragments the team generates [2]. Several design concepts for compressors were identified as follows:

Table 3. Several compressor concepts

Type of Compressor	**Feature**
	Crank case compressor: - Low Capacity - High pressure - Geometry (big)
	Wobble Plate compressor: - Low Capacity - Low pressure - Compact design - Smooth & low vibration
	Scroll compressor: - Medium Capacity - Low pressure - Compact design - Smooth & low vibration
	Multi vane compressor: - High Capacity - Low pressure - Compact design - Ware of vane
	Multi vane compressor: - High Capacity - Low pressure - Smooth & low vibration
	Centrifugal compressor : - High Capacity - Low pressure
	Swash-plate compressor - Low Capacity - Low pressure - Compact design - Not balance
	Diaphragm compressor: - Low Capacity - Low pressure
	Scotch-yoke compressor: - Low Capacity - High pressure - Compact design - Not balance

Of all the above concepts – bearing in mind the respective advantages and disadvantages – only the reciprocating types (i.e. crankcase, scotch-yoke, swash-plate and wobble-plate concepts) are short listed as they are more suitable for use at high pressures.

Concept selection: Given the advantages of the wobble plate concept over the others compressor such as the compactness in design, the low vibration and smooth [4], the concept was chosen to be further developed. A symmetrical design, with two sets of wobble plates and pistons, was conceived to increase throughput rate as well as make the loads more balanced, thus reducing vibrations. In order to compress to the high specification pressure, a multistage design was incorporated. Comparison for concept selection was done as in Tables 4 and 5.

Table 4. The concept screening matrix. For the compressor concept

	Concept				
Selection Criteria	**A Crank Case**	**B Scotch Yoke Drive**	**C Wobble Plate**	**D Swash Plate**	**E Symm. Wobble Plate**
Maintenance-free lubrication	-	+	-	-	+
Light weight	-	+	+	+	+
Small space	-	+	+	+	+
Low vibration & noise	-	0	+	+	+
Power	0	0	+	+	0
Balancing	-	-	+	-	+
High pressure	+	+	-	-	+
Capacity	0	0	0	0	+
Sum +'s	1	4	5	4	7
Sum 0's	1	3	1	1	1
Sum -'s	6	1	2	3	0
Net score	-5	3	3	1	7
Rank	5	2	3	4	1
Continue?	No	Yes	Yes	No	Yes

Table 5. The concept scoring matrix

		Concept					
		B Scotch Yoke Drive (Reference)		**C Wobble Plate**		**E Symmetrical Wobble Plate**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Maintenance-free lubrication	10%	3	0.3	1	0.1	3	0.3
Light weight	10%	3	0.3	3	0.3	3	0.3
Small space	10%	3	0.3	3	0.3	3	0.3
Low vibration & noise	15%	2	0.3	5	0.75	5	0.75
Power	5%	2	0.1	3	0.2	3	0.2
Balancing	15%	2	0.3	4	0.6	5	0.75
High pressure	20%	3	0.6	1	0.2	3	0.6
Capacity	15%	2	0.3	3	0.45	5	0.75
	Total Score	2.5		2.9		3.95	
	Rank	3		2		1	
	Continue?	No		No		Develop	

Concept testing: Once the concept has been chosen, Petronas, as the end-user of the product, was consulted and the go-ahead was obtained for further development.

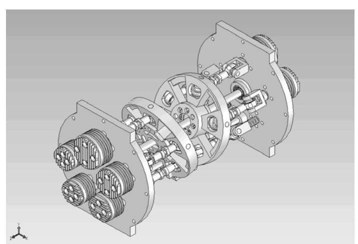


Figure 2. Proposed symmetrical wobble plate compressor concept

2.2. System-level design

A product can be thought of in both functional and physical terms. The *functional elements* of a product are the individual operations and transformation that contribute to the overall performance of the product [2]. For a symmetrical wobble plate compressor, some of the functional elements are “rotate shaft” and “compress gas”. Functional elements are usually described in schematic form before they are reduced to specific technologies, component, or physical working principles [2].

The *physical elements* of a product are the parts, components, and subassemblies that ultimately implement the product’s functions. The physical elements become more defined as the development progresses. Some physical elements are dictated by the product concept, and others become defined during the detail design phase. For example, the compression mechanism is a product concept involving a gas delivery device, implemented by a cylinder, a piston and valves.

Based on the concept development and the system level design (Product Architecture), the specifications and configurations of a symmetrical wobble plate compressor are produced, which would be used in the design work. The schematic diagram of vehicle refueling appliance system and the product architecture of the system are illustrated as in Figures 3 and 4 below.

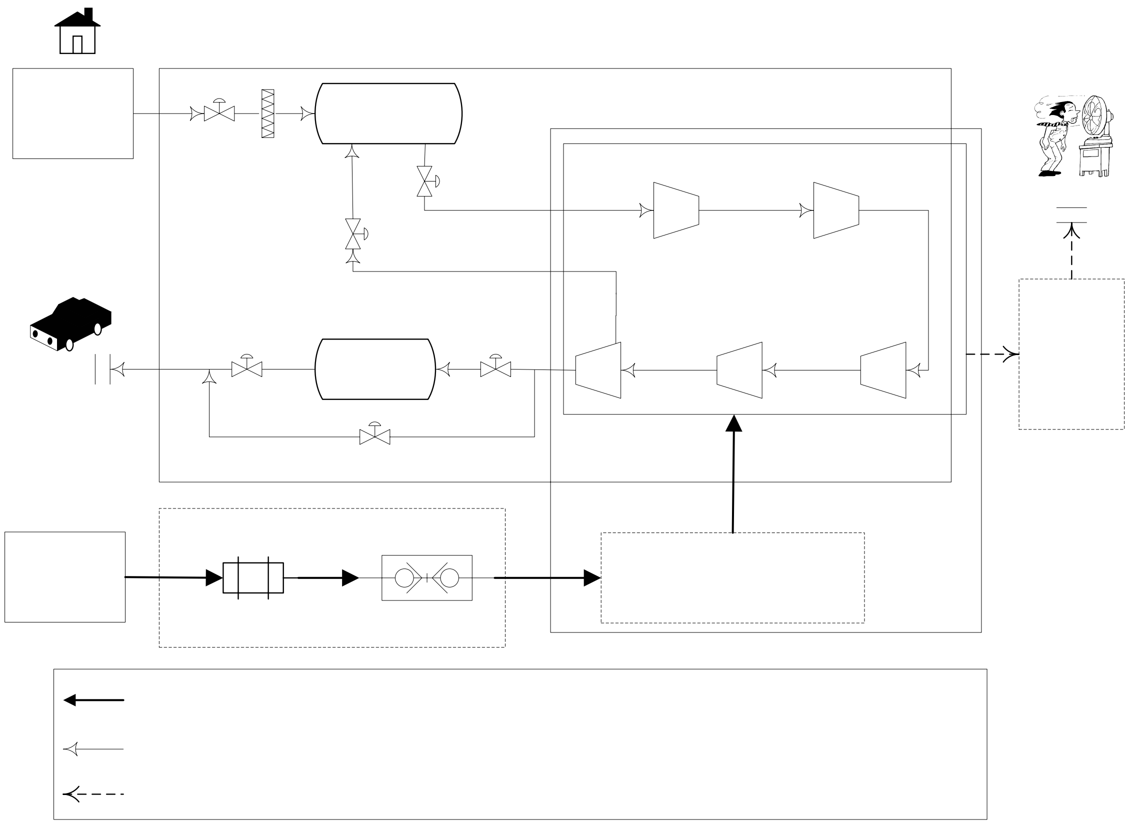


Figure 3. Schematic diagram of the vehicle refueling appliance system

Home NG
Supply

P_1

Dryer/
Filter

V_1

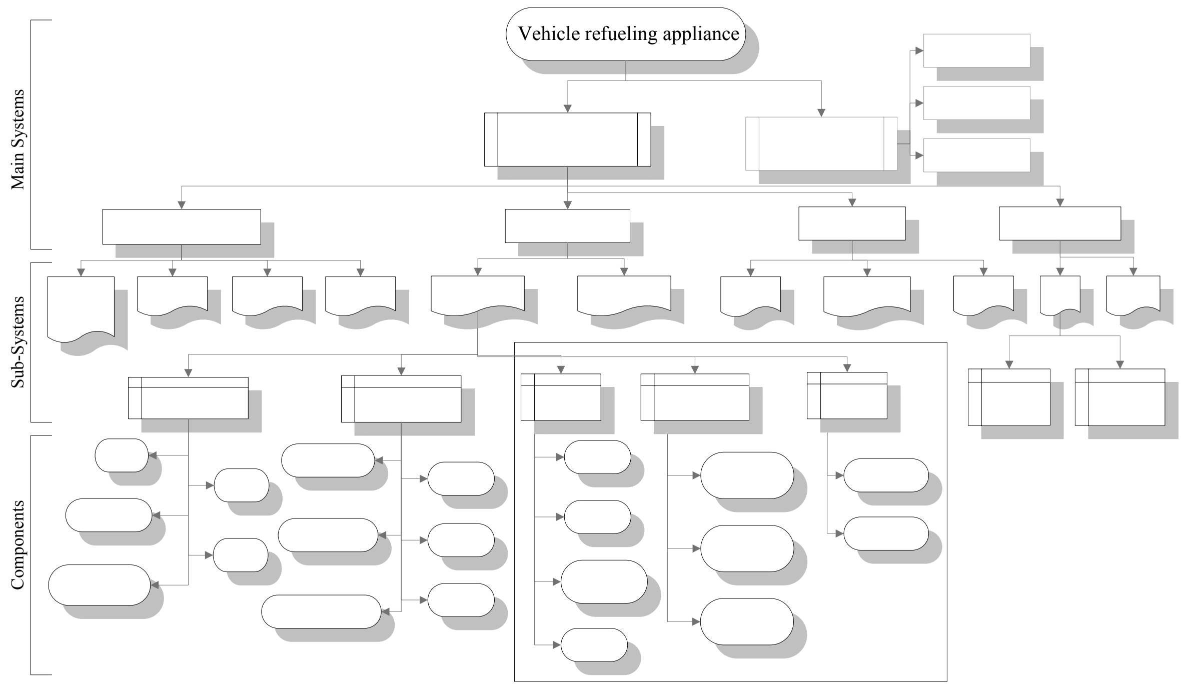


Figure 4. Vehicle Refueling Appliance Product Architecture

3. Detail design

The detail design phase consists of two stages: first, identification of all standard parts that could be purchased from suppliers, and second, complete specification of the geometry, materials, and tolerances of all of the other unique parts in the product. A function may be implemented by either a readily available standard part in the market, or a part to be designed fully by the team and then custom manufactured. In making a decision of which to be chosen, factors like cost and full-compatibility with the intended function are to be considered. A standard part is normally cheaper, but may not fully execute the role intended satisfactorily compared to the custom-designed equivalent.

3.1. Identification of all of the standard parts that be could be purchased from suppliers

Whenever possible the use of readily available standard parts is preferred. This would facilitate design, improve inter-changeability of parts and avoid difficult and specialised manufacturing processes. As an illustration of this, for the link to transmit force from the wobble plate to the piston, a standard end-joint was preferred over a custom-designed ball and socket joint, due to worries about caulking processes and precision machining available to the team, even though the latter would have provided a more compact design.

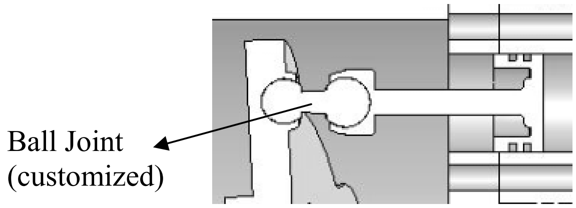


Figure 5. Ball Joint Concept

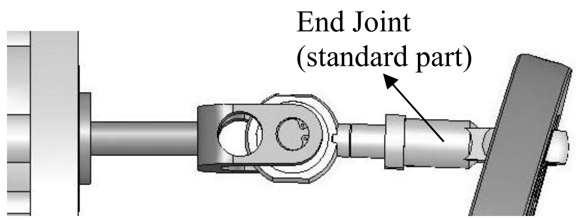


Figure 6. End Joint Concept

3.2. Complete specification of the geometry, materials, and tolerances of all of the unique parts in the product

Given the specialised nature of the product, several parts need to be designed completely to select the geometry, the material, the tolerance, etc. The customised parts could be seen clearly in the product architecture stages.

The first group of components that must be designed is the compression system. This system includes the cylinder block, pistons, piston rings, seals, and compressor valves. In designing the compression system the optimum dimensions need to be specified because these govern the performance of the product. The compressor pressure very high and it is come into high-pressure compressor classification. As mentioned earlier a multistage design was required to ensure the high pressure compression could be achieved. The actual number of stages is chosen considering the several factors such as the optimum work to be done as well as capacity, shaft speed (rpm), wobble plate tilting angle, and limitations of cylinder block diameter. Graphs 7 and 8 illustrate the optimizations done for pressure ratio and number of stages.

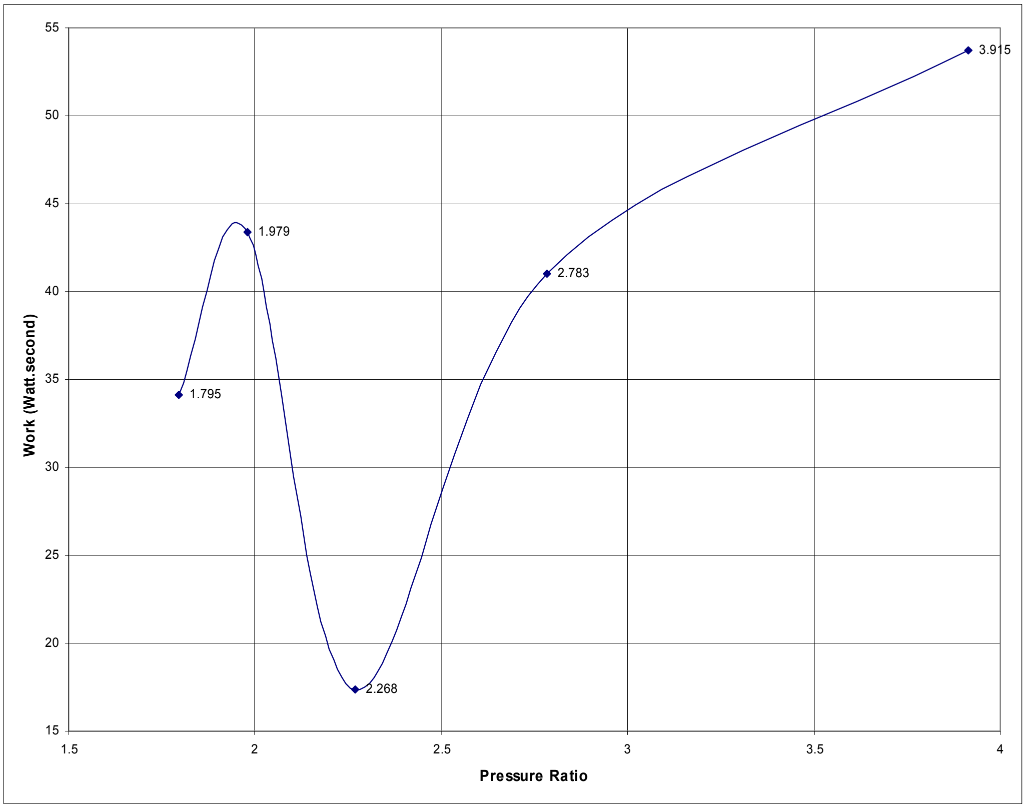


Figure 7. Optimization of pressure ratio

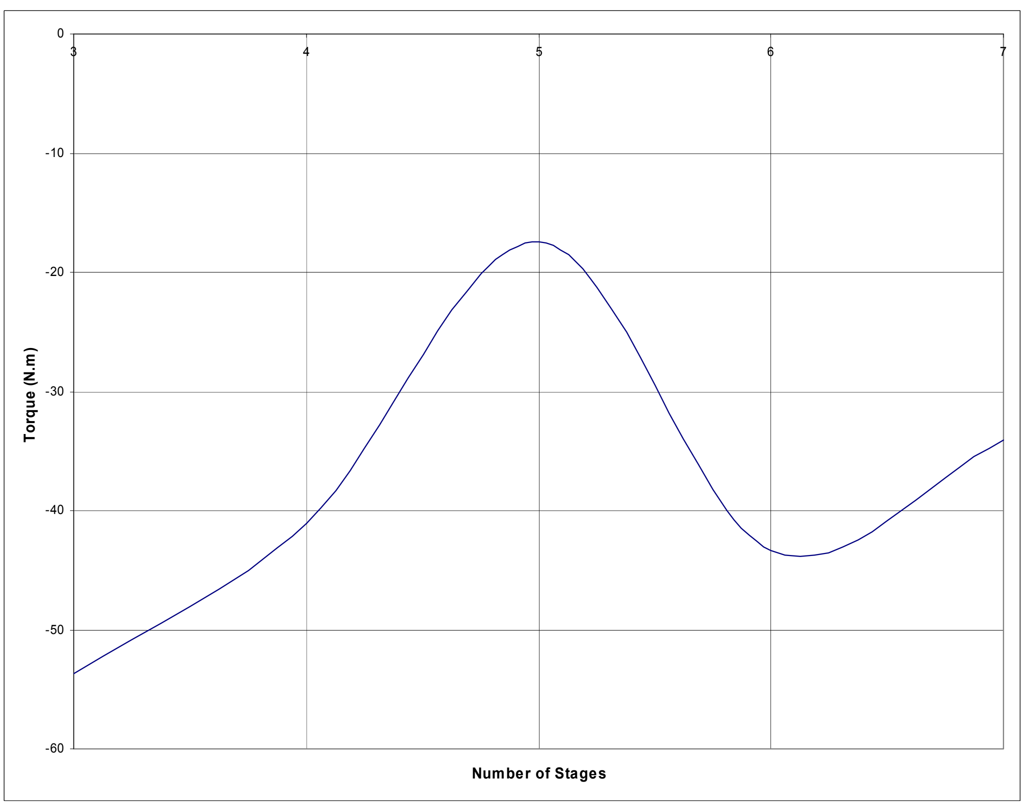


Figure 8. Optimization of number of stages

Parameters which influence the cylinder block design include wobble-plate tilting angle, limitations on the space to be occupied by cylinder and the speed of the shaft. The tilting angle influences the compressor capacity directly; if the tilting angle is bigger, stroke would increase and hence the compression capacity increases too, if the cylinder diameters are kept constant. On the other hand tilting angle also influences the torque required; a larger tilting angle requires a larger torque to turn, and hence a greater workload for the motor. However varying the cylinder diameters would also vary the force on each piston. Figure 9 provides some indication of the force variations as the shaft is rotated one full cycle. From all these considerations the sizing of the cylinder blocks are proposed.

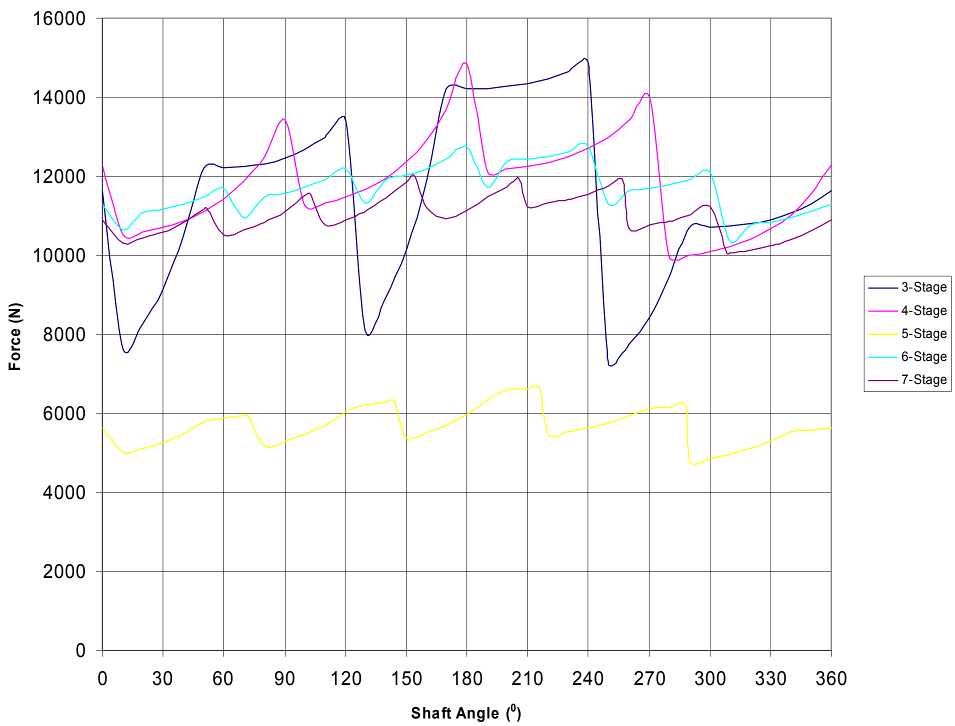


Figure 9. Wobble plate radius and piston diameter for different stages of compression

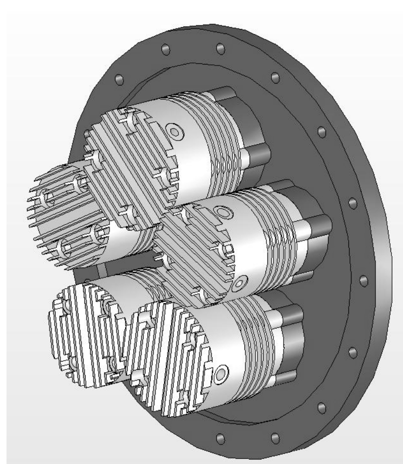


Figure 10. assembly cylinder block with end plate

The next set of components to be designed is the motion-mechanism system. This includes the connecting rod, the anti-rotating mechanism, the wobble plate, the bearings, the rotor and the shaft. The design of these was based on the dimensions and the loads from the compression system. In order to avoid contamination of the gas with oils an oil-free lubrication system was incorporated.

The third sub-system includes the casing, the lubrication system and sealing. Again available space governs the sizing of these.

The complete design is illustrated below. The final specifications of the symmetrical wobble plate compressor are given in Table 6.

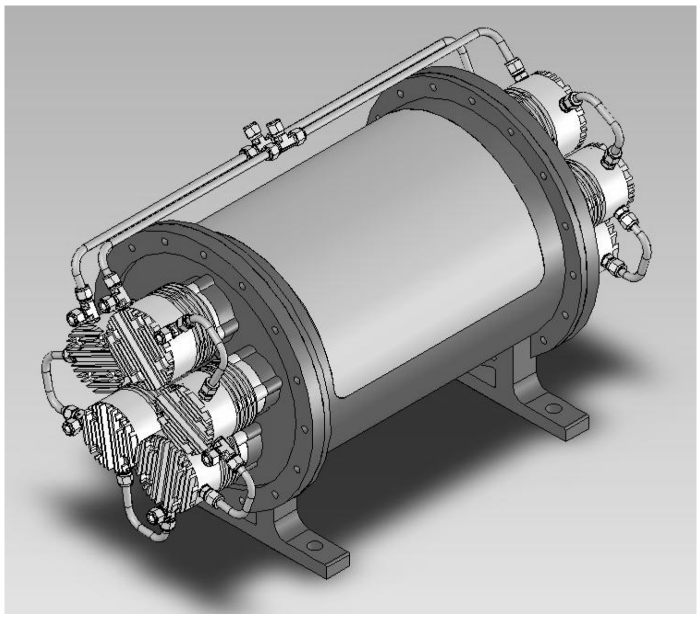


Figure 11. Complete drawing symmetrical wobble plate compressor

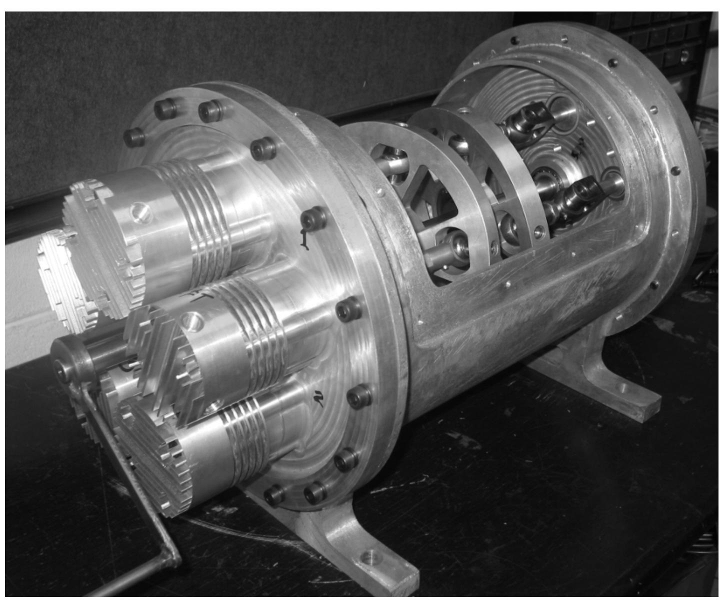


Figure 12. Ssymmetrical wobble plate compressor prototype

Table 6. Specification of symmetrical wobble plate compressor

Input Data	Reference Value				
	First Stage	Second Stage	Third Stage	Fourth Stage	Fifth Stage
Cylinder diameter	39 mm	28.25 mm	20.47 mm	14.83 mm	10.74 mm
Suction Pressure	50 psi	113.4 psi	257.176 psi	583.26 psi	1322.79 psi
Discharge Pressure	113.4 psi	257.176 psi	583.26 psi	1322.79 psi	3000 psi
Stroke	47.96 mm				
Fluid	Natural gas				
Rotating Speed	1500 rpm				
Power	19 kW				
Tilting Angle	16^o				
Pressure ratio	2.698				
Capacity	10 Nm^3/hr				

4. Conclusion

A new concept of symmetrical wobble-plate multistage compressor for use in natural gas vehicle refueling appliance has been developed and designed based on the specifications and limitations provided. The actual performance of the compressor under the specified high pressure conditions would be observed during actual testing on the prototype built from this design.

5. Acknowledgement

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Ardiyansyah
ardiyansyah@utm.my
Ardiyansyah_utm@yahoo.com
Dept. of Thermofluids
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Skudai
Johor – Malaysia
Tel : +6075534878
Fax : +6075566159

Prof. Dr. Md. Nor Musa
mdnor@fkm.utm.my
Dept. of Thermofluids
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Skudai
Johor - Malaysia
Tel : +6075534567
Fax : +6075566159

Ainullotfi Abdul-Latif
lotfi@fkm.utm.my
Dept. of Aeronautics and Automotive
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Skudai
Johor – Malaysia
Tel : +6075534754
Fax : +6075566159

Muhamad Adlan Abdullah,
madlan_abdullah@petronas.com.my
Research Executive
Petroleum Products Group
Petronas Research & Scentific Services Sdn. Bhd.
Lot 3288 & 3289, off Jln Ayer Itam
Kawasan Institusi Bangi
43000 Kajang
Selangor DE