DESIGN AND DEVELOPMENT OF A MULTISTAGE SYMMETRICAL WOBBLE COMPRESSOR

ARDIYANSYAH BIN SYAHROM

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

PSZ 19:16 (Pind. 1/97)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN STATUS TESIS ♦

JUDUL: DESIGN AND DEVELOPMENT OF MULTISTAGE SYMMETRICAL WOBBLE PLATE COMPRESSOR

SESI PENGAJIAN : 2006 / 2007

Saya **ARDIYANSYAH BIN SYAHROM**

mengaku membenarkan tesis (~~PSM~~/Sarjana/~~Doktor Falsafah~~)* ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut :

1. Tesis adalah hakmilik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (√)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh Organisasi/badan di mana penyelidikan dijalankan)

[√] TIDAK TERHAD

Disahkan oleh

(TANDATANGAN PENULIS)

(TANDATANGAN PENYELIA)

Alamat Tetap: **Jl. Rd. Saleh gg. Cimpago No. 12**
Padang – Sumatera Barat
Indonesia 25115

Tarikh : 27 Desember 2006

PROF. DR MD. NOR MUSA
Nama Penyelia

Tarikh : 27 Desember 2006

CATATAN :
* Potong yang tidak berkenaan.
** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.
♦ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

"We hereby declare that we have read this thesis and in our opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Master of engineering (thermo-fluid)"

Signature :

Name of supervisor I : **Prof. DR. Md Nor Musa**

Date : 27 December 2006

Signature :

Name of supervisor II : **Prof. Ir. DR. Wan Ali Bin Wan Mat**

Date : 27 December 2006

BAHAGIAN A – Pengesahan Kerjasama*

Adalah disahkan bahawa projek penyelidikan tesis ini telah dilaksanakan melalui kerjasama antara ________________________ dengan ________________________

Disahkan oleh:

Tandatangan : .... Tarikh : ....

Nama : ....

Jawatan : ....
(Cop rasmi)

* *Jika penyediaan tesis/projek melibatkan kerjasama.*

BAHAGIAN B – Untuk Kegunaan Pejabat Fakulti Kejuruteraan Mekanikal

Tesis ini telah diperiksa dan diakui oleh:

Nama dan Alamat Pemeriksa Luar : **Prof. Dr.Masjuki bin Hassan**
Jabatan Kejuruteraan Mekanikal
Fakulti Kejuruteraan
Universiti Malaya
50603 Kuala Lumpur

Nama dan Alamat Pemeriksa Dalam I : **Prof. Dr. Farid Nasir bin Hj. Ani**
Jabatan Termo-Bendalir
Fakulti Kejuruteraan Mekanikal
UTM, Skudai.

Pemeriksa Dalam II :
(Tiada)

Nama Penyelia Lain :
(jika ada)

Disahkan oleh Timbalan Pendaftar di Fakulti Kejuruteraan Mekanikal:

Tandatangan : .... Tarikh : ....

Nama : **MOHAMED TAJUDDIN BIN OSMAN**

DESIGN AND DEVELOPMENT OF MULTISTAGE SYMMETRICAL WOBBLE COMPRESSOR

ARDIYANSYAH BIN SYAHROM

A thesis submitted in fulfilment of the

requirements for the award of the degree of

Master of Engineering

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

DECEMBER 2006

I declare that this thesis entitled, "***The Design and Development of Multistage Symmetrical Wobble Plate Compressor***" is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : **Ardiyansyah Bin Syahrom**

Date : **27 December 2006**

Specially Dedicated to My Beloved :

Wife (Harisaweni. ST),
Daughter (Nanila Salwa Ardiyansyah),
Parent (Syahrom) and (Rosni),
Parent-in-law (M. Nasir) and (Dra. Hernita Rais),
and also My Sweet and Brother Sister
(Chrisnawati) and (Heri Yanto)
(Hersi Oliva, S.Si), and (M. Fadli Arif)
Nephew (Deca Rizky Fahlefi) and (Gita Suci Aulia)

ACKNOWLEDGEMENT

Vision, values and courage are the main gift of this thesis. I am grateful for the inspiration and wisdom of many thoughts that have been instrumental in its formulation.

First of all, I have readily acknowledged and thank to Allah SWT, the Omnipotent and Omniscient who created everything and in giving me the ability to begin and complete this project. I also wish to express my sincere appreciation to my supervisor, Prof. Dr. Md. Nor Musa and Prof. Ir. DR. Wan Ali bin Wan mat, for his guidance, advice, motivation, critics and friendship. Without his help, this thesis would not have been the same as presented here.

I would like to thank En. Ainullotfi Abd Latif, Assoc. Prof. DR. Amran Ayob. P.Eng, Prof. DR. Mohd Nasir Tamin, Prof. DR. Mat Nawi Wan Hassan group NGV team (M. Zair Asrar, Mohd. Nor Ilham, Hamdi, DR. Ong Kian Liong, and Andril Arafat), Mohd Sofian, Rahim and Imran for the many useful discussions and help in NGV Project. I am also indebted to Universiti Teknologi Malaysia (UTM) for support in providing the research grant for this project entitled “NGV Refueling Facilities and Equipment” (IRPA Vot 74536).

My sincere appreciation is also extended to Pak DR. Ir. Henry Nasution, MT, Pak Ir. M.Okta Viandri, MT, and Pak Ir. Saiful Jamaan. M.Eng for help and kindness, so that I can pursue my study here.

Last but certainly not least, I want to thank my wife, my daughter, mama, papa, my sister, my brother and all of my big family, for their affection, prayer and support throughout my study. I love you all.

ABSTRACT

There are many types of compressor design based on variation applications from the low pressure to the high pressure compression. For the high pressure application, the horizontal opposed reciprocating compressor is the most popular. However, for the smaller flow-rate natural gas refueling appliance compressors, scotch-yoke type has just been introduced into the market. Judging from the advantages and disadvantages from these compressor types, the wobble-plate and swash-plate compressor were chosen to be the combined concept for development of the new compressor. Both compressor concepts are currently used only for low pressure application with single stage compression. For this new compressor design development, both compressor types were combined to develop into a new symmetrical multi-stage wobble-plate compressor. The new compressor design operates with the suction pressure of 3 bar and discharge pressure of 206 bar. This new compressor design inherits the advantages of the wobble-plate and the swash-plate compressor which are compact and able to operate at high operating speed. Main improvement in this new compressor design is the introduction of the symmetrical wobble-plate configuration which allows for higher compressor capacity and balanced horizontal forces. The rotor concept from the swash-plate compressor has also been adopted in this new design. The normal connecting rod with the two ended ball joints has been replaced by the connecting rod with standard end-joints at both ends. This has eased the manufacturing process as the end-joints are available on the shelves. However, this standard universal end joint has limit the tilting angle of the wobble plate to a maximum of 16º.

Against this limitation and for the compressor to operate with minimum possible operating torque and optimum pressure ratio, analysis conducted concludes that the optimum number of stages is five. Flow analysis was conducted to simulate pressure and gas velocity distributions. This has helped in the conceptual development and this design of the suction and discharge port, the value and the cylinder of each stage. Heat transfer analysis was also conducted to simulate the temperature distribution on the cylinder block. The predicted temperature is about 302ºC at the first stage. Temperature rise due to compression of the air for both prototypes was found to be insignificant. As such the inter-cooler and after-cooler provided were found unnecessary and were not used. Both prototypes operated with good stability at all speeds and noise generated was acceptably low. The 1.00 m^3/hr prototype compressor was run at 1100 rpm producing a discharge pressure of 260 bar and for flow rates of 10 m^3/hr was run at 400 rpm producing a discharge pressure of 180 bar.

ABSTRAK

Kebanyakan pemampat direkabentuk berdasarkan aplikasi bermula dari pemampat bertekanan rendah hinggalah ke pemampat bertekanan tinggi. Bagi aplikasi bertekanan tinggi, pemampat salingan berkedudukan mendatar adalah yang paling popular. Walaubagaimanapun, untuk kadaralir yang kecil pemampat jenis *scotch-yoke* lebih sesuai dan telah berada di pasaran. Setelah semua kebaikan dan keburukan bagi semua pemampat diambil kira, konsep pemampat jenis plat wobal dan plat *swash* telah digabungkan dan dipilih sebagai pemampat baru yang akan dibangunkan. Pada masa kini, kedua-dua konsep pemampat digunakan untuk aplikasi satu peringkat dan bertekanan rendah. Kedua-dua konsep pemampat ini digabungkan untuk membentuk satu konsep pemampat baru iaitu pemampat salingan plat wobal simetri berbilang peringkat. Pemampat baru ini direkabentuk untuk beroperasi dalam keadaan tekanan masukan 3 bar dan tekanan keluaran 206 bar. Pemampat baru ini lebih kecil dan boleh beroperasi dalam kelajuan tinggi. Penambahbaikan utama pemampat baru ini ialah dengan pengenalan ciri plat wobal simetri yang mana akan dapat menambahkan kapasiti pemampat dan mengimbangkan daya mendatar yang terhasil. Konsep rotor bagi pemampat jenis plat *swash* juga telah diadaptasi di dalam rekabentuk baru ini. Rod penyambung asal yang berbentuk bebola di kedua-dua hujung telah ditukar dengan dua *end-joint* piawai di kedua-dua hujung. Penggunaan komponen piawai ini akan memudahkan lagi proses pembuatan. Namun demikian komponen piawai ini mempunyai had sudut kemiringan maksimum tersendiri iaitu 16 darjah.

Bagi membolehkan pemampat beroperasi dengan daya kilas yang minimum dan nisbah tekanan yang optimum, analisis telah dijalankan dan didapati bilangan peringkat yang sesuai ialah pada 5 peringkat. Selain itu, analisa aliran juga dibuat untuk mensimulasikan tekanan dan pengagihan halaju gas. Ini telah membantu dalam membangunkan konsep yang baik terutamanya dalam merekabentuk bahagian masukan dan keluaran pada setiap blok silinder. Analisis pemindahan haba juga dijalankan untuk mensimulasi taburan suhu pada blok silinder. Suhu anggaran pada blok silinder pertama adalah setinggi 302 darjah Celsius. Bagi kedua-dua prototaip, didapati peningkatan suhu tidak disebabkan oleh tekanan. Oleh itu penggunaan penyejuk (*inter-cooler/after-cooler)*tidak diperlukan. Kedua-dua prototaip beroperasi dengan stabil dan pada kebisingan yang rendah. Prototaip pemampat bagi 1.00 m^3/jam beroperasi pada kelajuan 1100 ppm dan menghasilkan tekanan keluaran 260 bar dan bagi prototaip pemampat 10m^3/jam pula yang beroperasi pada 400 ppm telah menghasilkan tekanan keluaran setinggi 180 bar.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia has a huge reserve of natural gas as compared to that of oil. Most of the natural gas is exported to Japan and Korea, while the remaining substantial amount is consumed by local industries. A pipeline network has been installed by Gas Malaysia a subsidiary of national petroleum agency, PETRONAS, throughout the peninsular running through major industrial areas. This infrastructure is put in place to encourage industries to use natural gas as an alternative fuel.

To encourage automotive vehicles to use natural gas, PETRONAS has been instructed to build NGV refueling stations throughout the country. So far, 24 stations have been built in Klang Valley, 1 station in Negeri Sembilan and 4 stations in Johor.

Petronas is also embarking into developing domestic natural gas refueling facilities. The concept is that of slow refueling over a fairly long period of time. Petronas has drawn up a set of specifications where by the design is relatively small, light and produces low levels of noise and vibration. This challenge is now partly translated into a scope of the present work. A symmetrical swash wobble plate multistage reciprocating compressor is found to fulfil the specification and will be the subject of the research.

1.2 Research Scopes

The scope of this research which can be summarized as follows:

i. Review on literature, patents and existing models of wobble plate reciprocating gas compressor.
ii. Develop the new concept of a wobble plate compressor.
iii. Set the operating specification and conduct thermodynamic, heat transfer and flow analyses on wobble plate compressor.
iv. Design compressor and conduct design analysis
v. Analytical Simulation.
vi. Fabrication and testing
vii. Write report (thesis).

1.3 Objectives

The objectives of this study are as follows:

i. To develop a new concept of "Symmetrical Wobble Plate Multistage Reciprocating Compressor".
ii. To design a Symmetrical wobble plate multistage reciprocating compressor for compression natural gas from pressure 3 bar to 206 bar.
iii. To design a reciprocating compressor that is effective and efficient to the application of home Refueling.

1.4 Importance of Research

i. Malaysia has to fully utilize compressed natural gas.
ii. Universiti Teknologi Malaysia (UTM) together with Petronas Research & Scientific Services (PRSS) and Universiti Teknologi Petronas (UTP) are to

develop domestic natural gas refueling facilities. UTM is to develop the compression system.

iii. The compression system has to be small, compact, light and of low noise and vibration levels.

1.5 Research Problem

The problems of energy supply shortage, polluted and poor air quality and high energy costs have contributed to the importance of natural gas as an alternative to fossil oil based fuels. As a transportation fuel, the gas must be compressed to increase its storage capacity in order for the vehicle to travel a much longer distance but still using the standard size tank. The compressor therefore becomes important primary equipment to the natural gas (CNG) refueling station.

The present design of reciprocating compressor that is used in the NGV refueling station is relatively huge, heavy, and occupies a lot of space [22]. Alternative to this is a smaller, compact and low noise vibration levels compressors when installed in a modular arrangement which can also meet the specification of the present model large compressor. If a concept of home refueling is to be implemented a single module of this small compressor may be sufficient to meet the requirement of a slow refueling rate.

After exhaustive review of the open literature which includes journal, conference proceedings and patent it is concluded that more research should be carried out to develop a compressor which is small in size, compact in the assembly and stable in the operation. A scotch-yoke concept has already been developed but the compressors are still not available in the market probably because of the problem of stability.

Many wobble or swash plate compressors are used in the automotive sector especially for air conditioners, where the maximum operating pressure is relatively low at about 14 bar. The normal wobble plate or swash plate compressor models are designed with only one side compression mechanism which creates instability especially running at high speed. The design of the compressor is to achieve smaller size, compact and stable. Instability problem at the existing compressor can be solved by developing the same system on the opposite side. The symmetrical wobble plate piston-cylinder assembly is thought to produce a dynamically balance compression machine and further development work on the piston, piston rings and cylinder liner should be able to produce a system that can compress and discharge a natural gas up to a very high pressure of 206 bar.

However, it was expected that there would be a number of parameters needed to be investigated during the development of this new concept. These parameters are interdependent on each other that finding an optimum design will be a problematical but challenging task.

1.6 Research Design and Methodology

The work involved design and development new concept high pressure compressor, analysis and simulation, and experimental. The methodology of research showed Figure 1.1.

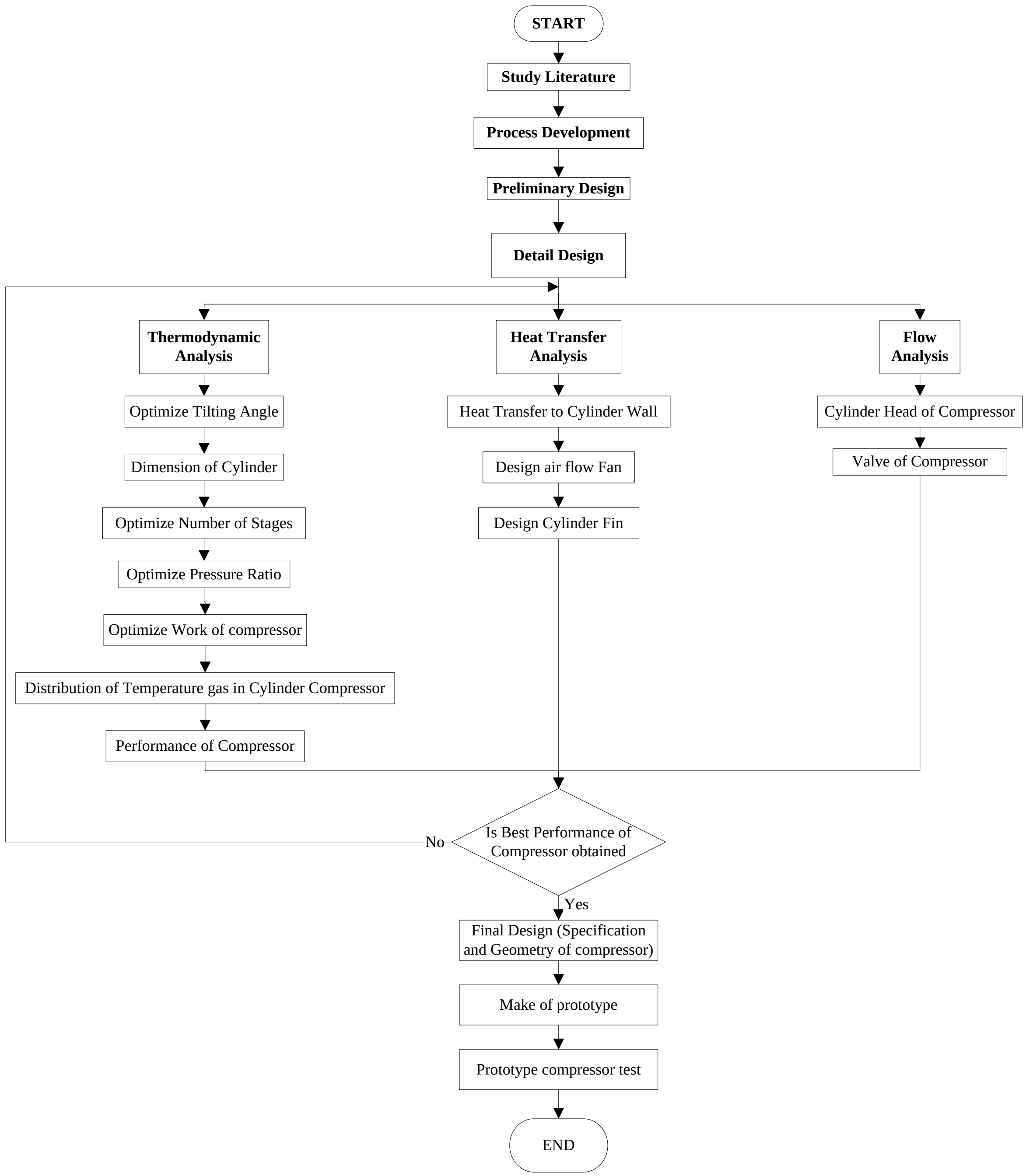

Figure 1.1 Methodology of research

REFERENCES

Adam Weisz-Margulescu (2001). Compressed Natural Gas For Vehicle Fueling. In: Paul C. Hanlon. *Compressor Handbook*. New York: McGraw-Hill. 10.1-10.15.

Ahn Hew Nam (2003). *Piston-Rotation Preventing Structure for Variable Displacement Swash Plate Type Compressor*. (EP1167758).

A. longo Giovanni., and Gasparella Andrea (2003). Unsteady state analysis of the compression cycle of a hermetic reciprocating compressor. *International journal of refrigeration 26*.

American Petroleum Institute Standard (1995). *Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Service*. 4th ed. Washington, D.C, API Standard 618.

ASME (1995). *Safety Standard for Air Compressor System*. New York: The American Society of Mechanical Engineerings, ASME B19.1-1995.

Azlir Darisun (1992). *Pemampat Salingan*. Kuala Lumpur: Dewan Bahasa dan Pustaka Kementrian Pendidikan Malaysia.

Boyd Gary Lewis (2001). *Non-lubricated rolling element ball bearing*. (US6318899).

British Standards Institution (1987). *Testing of Positive Displacement Compressos & Exhausters*. Milton Keynes, BS 1571 : Part 1.

Cliffort Matheus (2002). *Engineers' to Rotating Equipment*. London: Professional Engineering Publishing Limited.

Damson, Daniel, and Schwarzkopf Otfried (2003). *Swash or Wobble Plate Compressors*. (EP1333176).

Eastop. T.D., and McConkey. (1995). *Applied Thermodynamics For Engineering Technologists*. 5th ed. New York: John Wiley & sons, INC.

Edwin M. Tal Bott (1993). *Compressed Air System A GuideBook on Energy and Cost Savings*. 2th ed. Atlanta: Published by The Fairmont Press, Inc.

Eric Winandy., Claudio SaavedraO., and Jean Lebrun (2002). Simplified modeling of an open-type reciprocating compressor. *International journal thermal sciences.* 41: 183-192.

Frank P. Inclopera and David P. Dewitt (1990). *Introduction to Heat Transfer*. 2th ed. New York: John Wiley & Sons.

Hans-Georg G. Pressel (2003). Shuttle Piston Assembly With Dynamic Valve. (US2003072654).

Harvey Nix. (2001). Compressor Analysis. In: Paul C. Hanlon. *Compressor Handbook*. New York: McGraw-Hill. 5.1-5.34.

Heidorn John H (1962). *Refrigerating apparatus with compressor output modulating means*. (US3062020).

Heinz Baumann. (1998). Design and Development of an Oilfree, Hermatic High Pressure Compressor. *International Compressor Engineering Conference at Purdue University*. July 14-17, 1998. West Lafayette: Purdue University. 171-176.

Higuchi Teruo., Kikuchi Sei., Takai Kazuhiko., Kobayashi Hideto., and Terauchi Kiyoshi. (1998). *Wobble plate compressor*. (EP0280479).

Hiraga Masaharu and Shimizu Shigemi (1977). *Lubrication system for compressor unit.* (US4005948).

Hiroshi Ishii., Yoshikazu Abe., Tatsuhisa Taguchi., Teruo Maruyana., and Takeo Kitamura (1990). Dynamic Behavior of variable Displacement wobble plate compressor Automotive Air Conditioners. *International Compressor Engineering Conference at Purdue.* July 17-20 1990. West Lafayette: Purdue University. 345-353.

Hiroshi Toyada., and Masaharu Hiraga. (1990). Historical Review of The Wobble Plate and Scroll Type Compressors. *SAE Congress Paper.*

Hoerbiger Corporation Of America, Inc. *Valve Theory and Design*. America: Compressor Technology Valve. 1989.

Ikeda Hayato., Onomura Hiroshi., and Kitahama Satoshi (1988). *Shoe-and-Socket Joint In A Swash Plate Type Compressor*. (US4762468).

Jean Donea and Antonio Huerta (2003). *Finite Element Methods for Flow Problem*. New York: John Wiley & Sons.

John F. Below., and David A. Miloslavich (1984). Dynamics of The Swash Plate Mechanism. *1984 International Compressor Engineering Conference at Purdue.* July 11-13-1984. West Lafayette: Purdue University. 76-81.

Kato Takayuki., Katayama Seiji., Enokijima Fuminobu., and Hoshida Takahiro (2001). *Swash Plate Compressor Piston*. (EP 1134411).

Kayukawa Hiroaki., Takenaka Kenji., Okamoto Takashi., and Hyodo Akihiko (1991). *Wobble Plate Type Refrigerant Compressor Having A Thrust Bearing Assembly for A Wobble Plate Support*. (US4981419).

Kenji Tojo., Kunihiko Takao., Masaru Ito and Isao Hayase., and Yukito Takahashi. (1990). Dynamic Behavior of variable Displacement Compressor for Automotive Air Conditioners. *SAE Congress Paper.*

Kenji Tojo, Kunihiko Takao, Youzou Nakamura, kenichi Kawasima and Yukio Takahashi. (1988). A Study on The Kinematics of A Variable Displacement Compressor For Automotive Air Conditioning. *1988 International Compressor Engineering Conference at Purdue.* July 18-21-1988. West Lafayette: Purdue University. 496-504.

Kimura Kazuya., Takenaka Kenji., Fujisawa Yoshihiro., and Kayukawa Hiroaki (1996) *Compressor with rotation detecting mechanism*. (US5540560).

Kimura Kazuya., Kayukawa Hiroaki (1994). *Variable Capacity Swash Plate Type Refrigerant Compressor Having A Double Fulcrum Hinge Mechanism*. (US5336056).

KiyoshiTerauchi (1990). *Wobble Plate Type Compressor With Variable Displacement*. (US4913626).

KiyoshiTerauchi (1990). *Wobble Plate Compressor with Suction-Discharge Differential Pressure Control of Displacement*. (US4850811).

Kurakake Hirotaka., Inaji Satoshi., Adaniya Taku., and Ota Masaki (2000). Bearing for Swash Plate Compressor (EP1052403).

Loy Christoph., Droese Heiko., Gebauer Klaus., Reske Thomas., and Nissen Harry (2003). *Plunger Used In A Wobble Plate Compressor In An Air Conditioner Comprises Jaws for Receiving A Sliding Block*. (DE10231212).

Manring Noah D (2000). *Designing the Shaft Diameterfor Acceptable Levels of Stress Within an Axial-Piston Swash-Plate Type Hydrostatic Pump.* Journal of mechanical design (ASME) Vol 122 / 553

Masaharu Hiraga (1981). *Fluid suction and discharge apparatus*. (US4283166).

Todescat, M. L., Fagotti. F., Prata. A.T., and Ferreira, R.T.S.., (1992). Thermal Energy An Analysis in Reciprocating Hermetic Compressor. *1992 International Compressor Engineering Conference at Purdue.* July 14-17 1992. West Lafayette: Purdue University. 1419-1428.

Mohd Shafawi Mohd Tahir, Mohd Yunus Abdullah and Md Nor Musa, "Kajian Dinamik bagi Pemampat Plat Swash-Wobble", Kongres dan Seminar S & T, Kuala Lumpur 2003

Musa M.N (2005). *Wobble plate compressor*. (PI 2005 5456).

Suryanarayana, N.V., and ŏner Arici (2003). *Design & Simulation of Thermal Systems*. New York: Mc Graw Hill.

New Zealand Standard (1994). *Code of Practice for CNG Compressor and Refueling Stations Part 1 – On Site Storage and Location of Equipment.*. New Zealand, NZS 5425.

Olson John W JR (1971). *Compressor Unit With Self-Contained Drive Means*. (US3552886).

Ong, K. L., Musa, M. N., and Abdul-Latif, A. "A State Space Approach to the Management of Concurrent Design Tasks in the Design of a Symmetrical Wobble Plate Compressor" EdiProD International Conference Rydzyna, Poland, 7-9 Oct 2004

Ong, K. L., Musa, M. N., and Abdul-Latif, A. "Improving the Performance of a Natural Gas Compressor Design Process", Int'l Conf on Engg Design (ICED 2005), 15-18 Aug 2005, Melbourne, Australia

Parsch Willi. (2004). *Wobble Plate Piston Mechanism*. (US2004007126).

P.C. Bevis (1950). *Air Compressors Control and Installation*. London: SIR ISAAC PITMAN & SONS, LTD.

Pokorny F. (1974) *Refrigeration Compressor*. (US3838942).

Richard E. Sonntag and Gardon J. Van Wylen (1991). *Introduction to Thermodynamics Classical and Statistical*. 3th ed. New York: John Wiley & Sons.

Ren Shen. On The Design, Construction, and Testing of A Two Stage, Reciprocating Air Compressor Test Stand. Master. Thesis. Albert Nerken School Of Engineering; 1997.

Robert L. Norton. *Design of Machinery An Introduction to The Synthesis and Analysis of Mechanisms and Machines.* 3th ed. Boston: Mc Graw Hill. 2004.

Robert W. Fox and Alan T. McDonald (1994). *Introduction to Fluid Mechanic*. 4th ed. New York: John Wiley & Sons.

Roycas N. Brown (1986). *Compressor Selection and Sizing*. Houston: Gulf Publishing Company.

Schwarzkopf Otfried (2004). *Cylinder Block of An Axial Piston Compressor With Elongated Cylinder Face*. (US6672199).

Schwarzkopf Otfried. (2003). *A wobble plate arrangement for a compressor.* (EP1363022).

Schwarzkopf Otfried. (2003). *Swash or Wobble Plate Compressors.* (US2003140779).

Shane Harte., Lavlesh Sud., David Herder., and Yong (2001). *Piston Having Anti-Rotation for Swash Plate Compressor*. (US 6325599).

Shimizu Shigemi., Shimizu Hidehiko., and Terauchi Kiyoshi (1989). *Wobble plate type compressor*. (US4869651).

Slack Don S (1979). *Swash plate compressor.* (US4138203).

Simon. Touber. A Contribution to The Improvement of Compressor Valve Design. PhD. Thesis. Technische Hogeschool Delft; 1976.

Takahiro Nishikawa., hirosi Nishikawa., Tomio Obokata., and Tsuneaki Ishima. (2000). A Study for Improvement on High Pressure Multistage Reciprocating Compressor. I*nternational Compressor Engineering Conference at Purdue University*. July 25-28, 2000. West Lafayette: Purdue University. 105-112.

Takai Kazuhiko (1989). *Compressor With Variable Displacement Mechanism*. (US4850811).

Takenaka Kenji., Kimura Kazuya., and Kayukawa Hiroaki (1993). *Piston Coupling Mechanism For A Swash Plate Compressor*. (US5201261).

Thomas T. Gill (1941). *Air and Gas Compression.* New York: John Wiley & Sons, Inc.

Toyoda Hiroshi., Shimizu Shigemi., Hatakeyama Hideharu., Kumagai Shuzo., and Takahashi Hareo (1989). *Wobble plate type compressor with a drive shaft attached to a cam rotor at an inclination angle.* (US4870894).

Turner, K. K (1936). *Improvements Relating to Reciprocating Engines, Pumps or Compressors of The Swash- or Wobble-Plate Type*. (GB458360).

Umemura Yukio (1996). *Variable Displacement Swash Plate Type Compressor*. (EP0748936).

Vedat S. Arpaci., Shu-Hsin Kao., and Ahmet Selamet (1999). *Introduction to Heat Transfer*. New Jersey: Preatice Hall.

Vladimir Chlumsky (1966). *Reciprocating and Rotary Compressors*. Czechoslovakia: Publishers of Technical Literature.

Werner Soedel (1984). *Design and Mechanics of Compressor Valve.* Indiana: Office of Publication Purdue University.

W. H. Hsieh., and T.T. Wu. (1997). Experimental Investigation of Heat Transfer in a High-Pressure Reciprocating Gas Compressor. *Applied Energy*, Vol. 56, Nos ¾, pp. 395-405.

Woolatt Derek. (2001). Compressor Theory. In: Paul C. Hanlon. *Compressor Handbook*. New York: McGraw-Hill. 1.1-1.15.

Woolatt Derek., and Heidrich Fred (2001). Compressor Performance Positive Displacement. In: Paul C. Hanlon. *Compressor Handbook.* New York: McGraw-Hill. 2.1-2.25.

Yang Ming., Kraft-Oliver Terry., Xiao Yan Guo., and Tian Min Wang (1997) Compressed Natural Gas Vehicles : Motoring Towards a Cleaner Beijing. *Applied Energy*, Vol. 56, Nos ¾, pp. 395-405.

Ma, Y.-C., and Min, O.-K., (2001). Pressure Calculation in Compressor Cylinder by A Modified New Helmholtz Modeling. *Journal of sound and vibration*. 243(5): 775-776.