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ABSTRACT

Scroll technology for refrigerant compressors is reviewed from the initial invention to today's position as a dominant compression technology in the air conditioning industry, including a projection of the future potential of the technology. Design concepts from the past 30 years are reviewed, including scroll component vane design, compliance mechanisms, bearing and assembly architecture, and low and high side pressure vessels. Manufacturing challenges related to scroll compressor machining and assembly are also discussed. Scroll compressors are now used outside the initial residential air conditioning application to include heat pump and refrigeration systems that require scroll designs suitable for use with both higher pressure ratios and extended operating envelopes. Increased efficiency standards for air conditioning and refrigeration systems continue to drive the development of efficient capacity control methods utilizing various technologies such as discrete capacity steps, vapor injection/economizer cycle and inverter driven variable speed operation. These concepts are reviewed and their individual benefits are discussed.

1. INTRODUCTION

Scroll technology for air conditioning and refrigeration compressors has seen numerous successful advances during the past forty years of active product development, with initial production starting more than twenty five years ago. A significant part of this technology has been focused on air conditioning designs that have moved from an initial product concept to becoming the compressor of choice for today's air conditioning systems. Scroll product offerings now serve a broad range of both residential and commercial markets and are available for a broad range of applications from 1 – 60 horsepower. In addition, new emerging markets requiring the compression of carbon dioxide, helium and natural gas have evolved in recent years. Both the size and application range of scroll products demonstrate the exceptional versatility of this product, and its future potential for new applications.

The authors recognize the difficult task of including all significant developments for this technology but wish to provide herein an overview for those individuals less familiar with the background or history of scroll technology developments. This overview is also somewhat influenced by the authors experience and personal perspectives of various aspects of the technology.

2. SCROLL COMPRESSOR HISTORY

One method to assess the progress with time of any new or evolving technology is to review the history of the technology through both patent and technical paper activity. Based on a review of scroll patents, a patent by Creux (1905) is generally recognized as the first scroll patent claiming the general benefits of using two spiral members (scrolls) to pump and/or compress a fluid. At the time, manufacturing technology and practical design concepts prevented scroll type products from being seriously considered for production versus readily available and low cost piston type compression mechanisms. Also, efficiency, noise and refrigeration applications in general were not requiring the potential but unknown benefits of scroll technology.

In the 1970's, rising energy costs and energy conservation began to emerge as an important driver for air conditioning compressor designers to consider along with continuing improvements in product reliability, noise and cost. Also during this decade, Arthur D. Little, Inc. (ADL), a Cambridge, MA, USA consulting firm began to seriously develop concepts they believed would make scroll a viable option for positive displacement gas compression. In fact, one of these patents by Young and McCullough (1975) , defined the object of their invention(s) to include the following benefits still representative of today's modern scroll development objectives: 1.) to provide an improved practical and useful fluid displacement apparatus, 2.) to achieve efficient axial and radial sealing over extended operating periods, 3.) to provide a fluid displacement device which is simple and relatively inexpensive to construct, and 4.) to provide an apparatus wherein wear is essentially self compensating. The first scroll technical paper presented at the Purdue International Compressor Conference was given by Moore *et al.* (1976) from ADL in 1976. This paper discussed a scroll type compressor used for shipboard helium liquefier systems. The basics of scroll compressor operation were defined in this presentation but little information was provided concerning the practical design features presented in the ADL patents. For those present at the 1976 compressor conference, the potential value and future of scroll technology was far from apparent at that time. However, this paper and the corresponding ADL scroll patents were the first technical evidence of a potentially revolutionary compression technology.

During the second half of the 1970's, several compressor manufacturers purchased the right to utilize the ADL patents while others chose to develop their own unique scroll technology. Based on both the quantity of patents obtained and the large number of manufacturers involved, early curiosity and feasibility studies were followed by many significant new scroll compressor products starting in the 1980's. To visualize the historical progress of scroll production, Fig.1 illustrates how scroll patents and technical papers led the way to significant scroll new product introductions. Specifically, this chart demonstrates how patents and technical papers can correlate and predict the potential for future production success of a new technology. Also shown is the apparent impact of agency or government energy regulations as demonstrated by the 10.0 SEER system efficiency regulation enacted in 1992 in the US. From these early efforts in scroll technology, scroll knowledge and production volumes have continued to grow to an estimated yearly worldwide production volume of 10 million compressors.

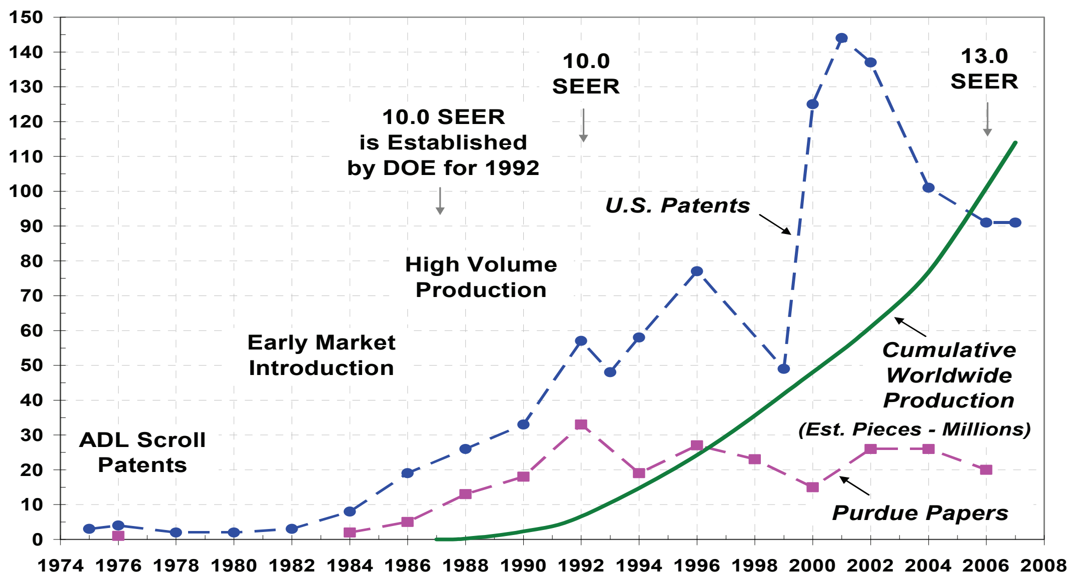

Figure 1: Scroll Technology History

3. EARLY SCROLL CHALLENGES

Scroll product development efforts today far exceed those employed in the early product development timeframe of the 1980's. Today's challenges with many models, broad horsepower range, capacity modulation, new refrigerants and new applications help drive continual innovation and improvements for scroll products. However, during the earlier 1980's development period, fundamental design decisions were required to identify how best to construct a practical scroll compressor that could be superior to existing reciprocating and rotary type compressors available at the time. This required answering basic questions related to product architecture and assembly, axial and radial compliance and scroll vane design for performance, low noise and strength. An example of the fundamental nature of this task was the decision to use either a low pressure shell or a high pressure shell and to locate the scrolls at either the top or bottom of a vertical housing. Both high and low pressure shells or housings have been used with production scroll designs but most production designs today follow the low pressure shell used with reciprocating compressors. In contrast, scroll components are generally located at the top of the compressor similar to rotary compressor practice to physically separate gas flow from the lubricant and improve thermal efficiency.

3.1 Bearing Architecture and Assembly

A major known advantage for scroll compression technology was the inherent capability for low vibration, low torque pulse and low discharge and suction gas pulsations. Low noise was also considered an inherent strength but development was required to better understand noise sources associated with the use of scroll compliance concepts to be discussed later. These inherent advantages allowed early scroll design engineers the opportunity to eliminate internal suspension components and rigidly attach the compressor and hermetic motor to the compressor shell as was common practice for rotary compressor designs. Bearing location for scroll was also unique in that the typical scroll design did not allow the compression load to be straddled as in the reciprocating and rotary case. Rather, the orbiting scroll drive required a cantilevered section of crankshaft that in turn required two additional outboard bearings for support. These bearings were generally designed to straddle the hermetic motor to minimize bearing load and stabilize the motor rotor. An alternate approach used with some open drive scroll compressors (automotive) is to minimize the distance between the orbiting scroll and main bearings such that both bearing loads are nearly in the same plane and an additional third bearing is required mostly for shaft stability. A scroll compressor design showing the straddle concept was presented by Bush and Elson (1988). With straddle bearing designs, a unique challenge was to identify a means to achieve good bearing alignment through the use of a thin wall circular shell construction versus a more traditional and costly piloted (machined) assembly that required much thicker shells and additional machining complexity. Both assembly fixtures and a weld in place concept were utilized and proven successful with these early straddle bearing designs.

3.2 Axial and Radial Compliance

The importance of axial and radial compliance to overall scroll product success may be second only to the importance of scroll component design and manufacturing. From the earliest scroll development until today, axial and radial compliance have been the subject of many technical investigations and have been essential for achieving high scroll performance through the control of gas leakage (Hayano *et al.,* 1988), (Tojo *et al.,* 1988). Both forms of compliance (or lack of) are critical to the successful operation of scroll compressors, and are the basis for such observations as "scrolls wear in, not wear out". Virtually all modern scroll compressor designs utilize radial compliance although some may have a fixed orbit radius in the outward direction with inward radial compliance. These designs try to avoid potential noise from mating flank contact but trade this benefit for additional gas leakage through the flank leakage path (Inaba *et al.,* 1986). The benefit of radial (flank) compliance is two-fold: first to insure minimal flank leakage and second to allow the passage of debris particles. On the negative side, flank contact force will typically vary with speed and compressor operating pressure difference. Thus for a broad range of operating speeds and test conditions, the design challenge is to balance flank loading to provide sufficient sealing at low speed and high differential pressure while avoiding excessive flank loading that can cause both higher noise and reduced efficiency from friction. One approach to control flank loading involves an additional component that provides a direct dynamic balance for the orbiting scroll mass. This approach (McCullough, 1975), referred to as a "swing link", has been used (Hirano *et al.,* 1988) mostly in automotive type scroll compressors where a broad speed range is required and lightweight aluminum scroll components are employed. However, many scroll designs without this special design feature have shown good performance and reliability for speed ratios up to 5:1. Axial compliance is accomplished in most current designs with three distinct design approaches: 1.) the non-orbiting scroll

member is compliant in an axial direction with gas pressure loading tied to the gas compression process, 2.) the orbiting scroll is compliant with gas pressure loading tied to the gas compression process, and 3.) both scrolls have a fixed axial location with a clearance gap filled by a pressure loaded seal installed at the tip of each scroll vane.
All of these approaches serve the same purpose of minimizing gas leakage across the tips or end of the scroll vanes and address the most significant source of scroll inefficiency.

3.3 Scroll Component / Vane Design

Although basic scroll product architecture and innovative design concepts for axial and radial compliance were major design challenges for early scroll design engineers, design technology identified for the scroll components was essential for scroll products to meet an overall new product objective of superior performance, high durability and low manufacturing cost including minimal manufacturing variability. Both compliance and scroll component design were essential for scroll to become an important and viable new product relative to existing positive displacement compressor technologies.

Scroll vane geometry and its importance for compressor performance has been the subject of numerous technical papers and patents. In general, concepts and investigations in this area have addressed various means to achieve high compression efficiency by controlling both the internal volume ratio and the rate of compression along with the affect of these parameters on gas leakage. An early study by Bush and Beagle (1992) presented a general relationship governing the conjugacy of scroll surfaces for use in the generation of conjugate scroll profiles of almost any form. Some advantages highlighted with this study were manufacturing simplifications such as circular arcs and a tailoring of the scroll compression process to fit specific applications. Li *et al.* (1996) examined the use of various involute profiles (circle, square, line) in an analytical study of gas leakage and scroll force differences with profile selection. Several gas compression studies (Yanagisawa *et al.,* 1990), (Morimoto *et al.,* 1996), showed compression efficiency of scroll designs can be maximized when the internal pressure ratio from the scroll vane design is equal to the operating pressure ratio of the air conditioning or refrigeration system. However, with scroll being a fixed volume ratio type of positive displacement compressor, a compromise is required in setting the design pressure ratio of the scrolls to provide overall performance for a broad range of operating pressure ratios. It is a generally accepted practice that the scroll design pressure ratio should be below most system operating pressure ratios (under-compression) versus operating above the system operating pressure (over-compression). To achieve good performance over a broad pressure ratio, or for high pressure ratio applications such as low temperature refrigeration, the center vane geometry of the scroll element may be modified to increase the scroll internal pressure ratio and also accommodate an optimum size discharge port backed by a dynamic discharge valve (Hundy and Kulkarni, 1996). This concept controls refrigerant backflow from a higher pressure discharge plenum to the innermost scroll compression pocket and increases the efficiency of the compression process. Other approaches for improving high pressure ratio performance effectively increase the internal scroll pressure ratio by designing scroll vanes that vary in thickness (Hagiwara *et al.,*1998), or change the vane profile (Sekita *et al.,* 2000) at the scroll center such that the rate of volume change increases as the compressed gas moves from intake to discharge. In addition, a stepped scroll has been demonstrated (Jie *et al.,* 1994), (Kimata *et al.,* 2004) to change the rate of internal volume reduction at a discrete location or wrap angle of the scroll. All of these design approaches allow rapid compression in a small space but each approach can to a varying extent increase machining complexity and leakage potential as well as increasing the risk of over compression at lower operating pressure ratios.

Scroll vane length and thickness relative to height for a given displacement volume have been modeled (Caillat *et al.,* 1986) as important parameters for reducing scroll vane leakage and improving compression efficiency. These models typically estimate the importance of vane tip and flank leakage based on assumptions for such parameters as clearance and lubricant viscosity. Some models (Etemad and Nieter, 1988), (Ishii *et al.,* 1992) also include equally important design considerations for vane height relative to thickness and the pitch or spacing between scroll vanes. As a practical matter, good scroll vane designs must have high strength for operation at high pressure ratios (high pressure difference across the inner vane) and with the high pressures associated with liquid refrigerant slugging.

4. CURRENT SCROLL DEVELOPMENT STATUS

4.1 Air Conditioning and Refrigeration

With over twenty years of production scroll compressor experience, the total number of residential / commercial scroll compressors manufactured now exceeds 100 million. These compressors cover a broad range of applications for both air conditioning and refrigeration including newer production designs demonstrating the capability to perform efficiently with higher pressure HFC refrigerants such as R410A. Early scroll designs have been replaced by continuously improved designs offering higher efficiency, better reliability, smaller size, and lower cost with high volume manufacturing. With worldwide emphasis on energy conservation and increasing energy efficiency standards for air conditioning units, scroll compressors have become the technology of choice over competing technologies such as reciprocating and rotary. For those who participated in the early stages of this technology, the extent and growth of this technology has been truly extraordinary to observe.

Scroll product development activities today can be categorized in five groups: 1.) 2-3 Hp models that deliver high efficiency and low cost competitive with rotary products, 2.) 3-6 Hp for residential air conditioning/heat pump and commercial refrigeration products competing with reciprocating products, 3.) 7 – 60 Hp commercial scrolls competing with semi-hermetic reciprocating and screw compressors, 4.) capacity modulation and performance enhancement technologies, and 5.) new refrigerant applications such as R410A and CO_2. Fig. 2 is an example of a basic but versatile scroll design used for air conditioning, heat pump and refrigeration applications (Elson *et al.,* 1990). This design represents a typical upper /lower bearing assembly with full axial and radial compliance with axial compliance being achieved through pneumatic loading of the upper scroll member. Depending on the application and refrigerant choice, the design pressure ratio of the scroll elements is generally selected to achieve optimal performance at system rating conditions. This basic design approach can also be optimized for higher pressure ratio refrigeration applications by increasing the scroll design pressure ratio and adding a dynamic discharge valve as noted earlier. The discharge valve is particularly important for pressure ratios of 6-8 or higher when the scroll design pressure ratio is significantly below the compressor operating pressure ratio and gas back flow and recompression results in excessive compression work and inefficiency. This design offers a good compromise for systems operating at both high and low pressure ratios by providing good high pressure ratio efficiency while avoiding more severe over compression losses associated with low operating pressure ratios.

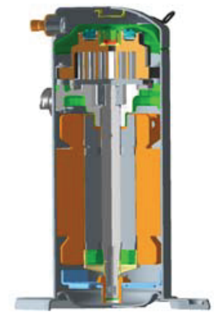
Figure 2: Residential Scroll Compressor

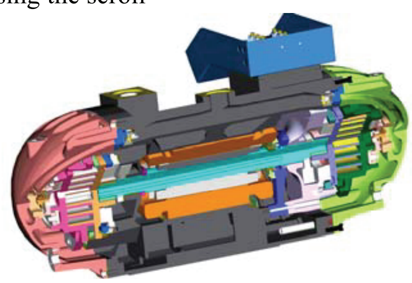
Figure 3: Twin Scroll Compressor

With ongoing development of scroll compressors, the size for a single scroll product has now reached 30 Hp for commercial application. To extend this range further, a recent twin scroll design has been introduced with two scroll elements in one enclosure as shown in Fig.3. This design features a semi-hermetic cast iron housing to address the constraints in investment as well as in shell diameter and today constitutes the largest scroll compressor available in production with a size of 60 HP as a single and 120 Hp as a tandem.

4.2 Modulation / Economizer Cycle

Modulation or capacity control for scroll compressors has evolved from earlier tandem designs using multiple compressors connected in parallel, to a variety of approaches using stepped capacity or variable speed motors within a single compressor product. One such design shown in Fig. 4 uses a solenoid actuated circular ring to open and close large ports in the upper scroll member and effectively make the scroll displacement volume change from the maximum to about 60%. Coupled with a two-staged thermostat in a residential air conditioning application, system cooling capacity can be adjusted to better meet the required cooling load to gain system efficiency with minimal system complexity and cost.


Figure 4: Two Step Modulation

For system applications requiring a higher percentage of capacity reduction, scroll compressors have been developed with multi-step capacity using an opening and closing of the scroll elements in the axial direction. With this later approach shown in Fig.5, the upper scroll element is mechanically separated from the lower element through a lifting piston assembly and a logic controlled solenoid valve that vents the top side of the piston to the low- pressure side of the compressor. With axial scroll separation, the mass flow from the compressor can be controlled from 10% - 100% with typical time cycles for this flow variation being 10 – 20 seconds. Due to the thermal inertia of the condenser coil volume and the restriction given by the system expansion valve, the effect of this pulsed mass flow is smoothed such that the system evaporator sees an integrated net mass flow with minimal flow variation. Exceptional system cooling capacity control has been demonstrated with this approach in several challenging applications that include multiple evaporator air conditioning and marine container refrigeration where a single refrigeration system must maintain cargo temperature for both fresh and frozen goods at all ambient temperatures. For further detail on this subject, see Wu and Wu (2004) for a math modeling of the flow and Ilic *et al.* (2002) for system operation performance.

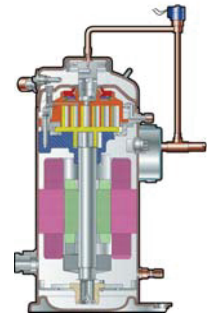

Figure 5: Multi-Step Modulation

Variable speed scroll compressors also control compressor capacity accurately to meet load requirements but generally are limited to turndown ratios of 5:1 versus the 10:1 illustrated above. The low speed limitation is due to design limitations primarily associated with speed dependant oil film bearings and the oil pumping capability of centrifugal oil pumps. For most air conditioning application this is not a significant limitation; however, for multiple evaporator air conditioning and transport refrigeration systems requiring extensive modulation, a 10:1 turndown allows the efficient capacity and temperature control required without cycling losses or inefficient suction side throttling. For transport applications where the power supplied may be a DC bus voltage, an inverter control is necessary to power the AC compressor, and variable speed compressor operation is a logical choice.

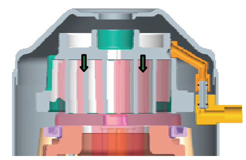

Figure 6: Scroll Vapor Injection

Another form of capacity modulation possible with scroll compressors is to use vapor injection (economizer cycle) to benefit scroll performance through the injection of high pressure vapor into the scroll compression process after outer vane closure as shown in Fig. 6. Through this cycle that can be compared to a two stage compression process, additional liquid refrigerant sub-cooling (and evaporator capacity) is achieved by flashing a portion of high pressure liquid refrigerant through a heat exchanger through which also flows the remaining liquid refrigerant. The net benefit is an evaporator capacity increase as much as 60% at high pressure ratio operating conditions such as low temperature refrigeration. An equally important benefit is a net efficiency gain up to 20%-30% due to a smaller percentage increase in compression work relative to the capacity increase. Scroll compressors with vapor injection capability have also improved heating performance for low ambient residential heating where supplemental heating (electric resistance) has been necessary to meet the heat load. In northern China, a heat pump scroll compressor with vapor injection has been developed to meet the total heating need of the residence (He *et al.,* 2006).

4.3 Transport Application

The development of scroll technology for air conditioning applications led the way to special refrigeration duty scroll products that in turn demonstrated superior value in transportation refrigeration systems where high reliability, high performance and resistance to shock and vibration are all essential. Due to the inherent high efficiency of scroll technology, and performance enhancement technologies largely unique to scroll such as multi-step modulation and vapor injection, scroll hermetic compressors have demonstrated fuel savings advantages up to 30% relative to earlier reciprocating semi-hermetic products in marine container applications. For large refrigerated trucks, an open drive scroll compressor (DeVore, 1998) has been in production for nearly ten years demonstrating both high reliability and improved performance. An evolving application for scroll transport refrigeration is refrigerated trailers where both high capacity and performance enhancement features are important to reduce fuel consumption while meeting a highly variable refrigeration load due to summer/winter ambient temperatures, and with cargo ranging from deep frozen to fresh produce. High efficiency scroll compressor of both open drive and hermetic design are being considered for this challenging application.

Transport scroll compressors for automotive air conditioning was one of the earliest production applications (Hiraga, 1983) using a compact open drive scroll design with the wide speed range capability necessary for automotive engine attachment. In recent years, hermetic scroll compressors have also been introduced to various transport applications such as auto, bus, rail and trolley. In some initial applications on large vehicles, the scroll compressors used were conventional vertical hermetic designs using standard induction motor technology. However, due to a need for light weight, compact size and high efficiency in many transport applications, sensor-less brushless permanent magnet (BPM) motors have been utilized in recent years, particularly in evolving hybrid auto applications. Typically, both these motor options require the use of an inverter to convert available power from either a DC bus or an alternator into the desired operating frequency needed to match air conditioning load. A vertical BPM motor scroll compressor was presented by Perevozchikov and Pham (2004) and a horizontal design was shown by Elson and Vehr (2006), to provide high efficiency over a broad operating speed range. This later design utilized a high side oil sump with a low side motor cavity.

4.4 Specialty Applications

A final example of the tremendous application range for scroll compressor technology is highlighted in designs made available for the compression of helium and natural gas. Both of these applications utilize a high side oil sump concept with oil flooding to cool the high heat-of-compression present with helium and natural gas (Elson and Butler, 2003). These are low volume applications but provide useful gas compression as the helium compressor is used with Magnetic Resonance Imaging machines, and the natural gas compressors are environmentally friendly due to their use to reclaim waste gas from both oil well production and non-productive (low pressure) natural gas wells.

5. FUTURE SCROLL OPPORTUNITIES

As in the past, many future compressor technology opportunities will evolve from the need to compress new refrigerants that are environmentally friendly. To date, scroll has demonstrated excellent flexibility over a broad range of applications and should be expected to be a key technology for future needs associated with both high efficiency and refrigerant choice for low environmental impact. Scroll compressors are currently in production for sub-critical CO_2 and are being developed by several manufacturers for trans-critical applications. Existing HFC refrigerants have been successfully applied to scroll compressors and future low global warming refrigerants are not expected to present an unusual technical challenge for scroll products.

6. SUMMARY

Scroll compressors have found a unique but broad fit within current positive displacement technologies. Innovations in compliance, scroll vane design and manufacturing have been particularly important to bringing scroll products to the forefront for use with many new air conditioning and refrigeration systems. With evolving trends toward high efficiency and capacity control, scroll products are uniquely positioned with various production methods for modulating refrigerant flow including stepped capacity, variable frequency and vapor injection. In addition, scroll compressors have been developed to provide superior performance and reliability with new HFC refrigerants and high heat-of-compression gases such as helium and natural gas. Applications for transportation are now in place for truck and trailer systems and are the compressor of choice for marine container refrigeration systems. Finally, future applications for scroll already include some CO_2 application with more in development.

REFERENCES

Bush, J.W., Elson, J.P, 1988, Scroll Compressor Design Criteria for Residential Air Conditioning and Heat Pump Applications. Part I: Mechanics, *Proc. 1988 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 18-21: p. 83-92.

Bush, J.W., Beagle, W.P, 1992, Derivation of a General Relation Governing the Conjugacy of Scroll Profiles, *Proc. 1992 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 14-17: p. 1079-1087.

Caillat, J.L., Bush, J.W., Seibel, S.M., 1986, Dimensional Optimization of Scroll Compressor, *Proc. 1986 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, August 4-7: p. 840-855.

Creux, L., 1905, Rotary Engine, *U.S. Patent 801,182.*

DeVore, T.A., 1998, Development of an Open Drive Scroll Compressor for Transportation Refrigeration, *Proc. 1998 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 14-17: p. 231-236.

Elson, J.P., Hundy, G.F., Monnier, K.,J., 1990, Scroll Compressor Design and Application Characteristics for Air Conditioning, Heat Pump, and Refrigeration Applications, *Proc. of the Institute of Refrigeration*, 1990-91.2-1.

Elson,J.P., Butler, B., 2003, A Hermetic Scroll Compressor for Application to High Heat-of-Compression Gases, *Proc. 2003 Int. Conf. on Compressors and their Systems*, London: p. 55-64.

Elson, J.P., Vehr, S.W., 2006, Horizontal Scroll Compressor for Transport Application, *Proc. 2006 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 17-20: C156.

Etemad, S., Nieter, J., 1988, Computational Parametric Study of Scroll Compressor Efficiency, Design, and Manufacturing Issues, *Proc.1988 Int. Compressor Eng.Conf. at Purdue,* West Lafayette, IN, July 18-21:p.56-64

Hagiwara, S., Ueda, S., Shibamoto, Y., Yoshii, T., Toyama, T., Omadaka, M., Jomura, S., Hori, K., 1998, Development of Scroll Compressor of Improved High-Pressure-Housing, *Proc. 1998 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 14-17: p. 495-500.

Hayano, M., Nagatomo, S., Sakata, H., Hatory, M., 1986, Performance Analysis of Scroll Compressor for Air Conditioners, *Proc. 1986 Int. Compressor Eng Conf. at Purdue*, West Lafayette, IN, August 4-7: p. 856-871.

He, H., Gou, W., Man-Wai, W.E., 2006, Northern China Heat Pump Application with the Digital Heating Scroll Compressor, *Proc.2006 Int. Refrigeration and A/C Conf. at Purdue*, West Lafayette, IN, July 17-20: R116.

Hiraga, M., 1983, The Spiral Compressor. An Innovative Air Conditioning Compressor for the New Generation Automobiles, *SAE Paper* No. 830540.

Hirano, T., Matsumura N., Takeda, K., 1988, Development of High Efficiency Scroll Compressors for Air Conditioners, *Proc. 1988 Int. Compressor Eng .Conf. at Purdue*, West Lafayette, IN, July 18-21: p. 65-74.

Hundy, G.F., Kulkarni, S., 1996, The Refrigeration Scroll Compressor and its Application, *Proc. of the Institute of Refrigeration*, 1996-97.6-1.

Ilic, S.M., Hrnjak, R.S., Bullard, C.W., 2002, Experimental Comparison of Continuous vs. Pulsed Flow Modulation on Vapor Compression Systems, *Proc. 2002 Int. Refrigeration and A/C Conf. at Purdue*, West Lafayette, IN, July 14-19: R4-1.

Inaba, T., Sugihara, M., Nakamura, T., Kimura, T., Morishita, E., 1986, A Scroll Compressor with Sealing Means and Low Pressure Side Shell, *Proc.1986 Int. Compressor Eng. Conf.at Purdue*, West Lafayette, IN, August 4-7: p. 887-900.

Ishii, N., Yamamoto, S., Maramatsu, S., Yamamura, M., Takahashi, M., 1992, Optimum Combination of Parameters for High Mechanical Efficiency of a Scroll Compressor, *Proc. 1992 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 14-17: p. 118a1-118a8.

Jie, Z., Disheng, W., Yunbing, L., 1994, Geometrical Analysis of Scroll Compressor for High Pressure Ratio, *Proc. 1994 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 19-22: p. 473-478.

Kimata, Y., Fujitani, M., Kobayashi, H., Miyamoto, Y., Matsuda, S., Yamazaki, H., 2004, Development of High Performance R410A Scroll Compressor For Gas Engine Heat Pump, *Proc. 2004 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 12-15: C028.

Li, L.-S., Shu, P.-C., Yu, Y.-Z., 1996, Effect of Scroll Wraps on Performances of Scroll Compressor, *Proc. 1996 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 23-26: p. 579-585.

McCullough, J.E., 1975, Positive Fluid Displacement Apparatus, *U.S. Patent 3,817,664.*

Moore, R.W., Jr., Shaffer, R.W., McCullough, J.E., 1976, A Scroll Compressor for Shipboard Helium Liquefier Systems, *Proc. 1976 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 6-9: p. 417-422.

Morimoto, T., Yamamoto, S., Hase, S., Yamada, A., Ishii, N., 1996, Development of a High SEER Scroll Compressor, *Proc. 1996 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 23-26: p. 317-322.

Perevozchikov, M.M., Pham, H.M., 2004, Scroll Compressor For Mobile HVAC/R Application, *Proc. 2004 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 12-15: C095.

Sekita, M., Itahana, T., Takeuchi, M., Miura, S., 2000, Power Saving Technology of Scroll Compressor for Car Air Conditioner, *Proc. 2000 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, July 25-28: p. 415-422.

Tojo, K., Ikegawa, M., Maeda, N., Machida, S., Shiibayashi, M., 1986, A Scroll Compressor for Air Conditioners, *Proc. 1986 Int. Compressor Eng. Conf. at Purdue*, West Lafayette, IN, August 4-7: p. 872-886.

Wu, G.H., Wu, K.Q., 2004, Design and Application Research on Digital Scroll Compressor in Air Conditioning System, *Proc. 2004 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 12-15: C120.

Yanagisawa, T., Cheng, M.C., Fukuta, M., Shimizu, T., 1990, Optimum Operating Pressure Ratio for Scroll Compressor, *Proc. 1990 Int. Compressor Eng. Conf. at Purdue,* West Lafayette, IN, July 17-20: p. 425-433.

Young, N.O., McCullough, J.E., 1975, Scroll-Type Positive Fluid Displacement Apparatus, *U.S. Patent 3,884,599*.

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