THE INSTITUTE OF REFRIGERATION

A brief overview of the Turbocor compressor - the Road to Discovery

by

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Introduction

First off, I do not claim to be an engineer, but am a simple refrigeration mechanic, who happens to be an innovator, inventor and an entrepreneur. I don't kid myself that I know it all, but rather I do employ people who do, or have the ability to learn to do.

Many times I have been asked, how I came up with the idea of the compressor, well that's not a bad place to start.

History

Back in the early 80's, I ran a compressor rebuilding business 'Compressor Parts' in Melbourne, Australia. I specialized mainly in rebuilding centrifugal chillers. Because of the captive market the manufacturers had in the industry, I found it was very easy to compete head to head. Fortunately with the help of my father-in-law, Wilf Straub, we were able to manufacture a wide range of components, and to compete very easily, when it came to replacement parts. Having no blue prints and very few manuals, we had to learned how to manufacture the bearings, shafts, gears, impellors, guide vanes and oil pumps. Usually this was out of necessity, as the alternatives made no commercial sense. A set of gears would cost us $30,000 to purchase, we could manufacture them for $3,000, so we would build our own and sell them for$20,000 and everyone was happy, except the

OEM's. We used best engineering practices and learned a lot on the way, this was a good business.

In around 1983, I received a call from one of the major car companies. They asked me how much it would cost to replace the bearings on one of their chillers. I had never seen inside one of these machines before, so I gave them a price range, knowing that if there was anything wrong with the machine, I could adjust the price. Well they gave me the go ahead, and when I pulled the machine apart, I discovered that it was totally scrambled. The impellor was smashed up, the gears were chewed up, and the bearings were totally gone. Taking a deep breath, I decided that I could fix it, however at this stage, I had never built an impellor, and knew nothing about manufacturing them, I decided that I would have to buy one. The manufacturer was still ticked off at me for stealing their job, so they refused to sell me one. The customer called and asked me what was going on. I told them the story, and they asked me if I could find another way. I told them not to worry about it - I would find an alternative. The customer did not want to deal with the chiller manufacturer again, so they said to keep them informed.

I took what was left of the impeller to a friend of mine who was a pattern maker, and asked him if he could make a pattern from it - there was only about ¼ of the original impellor left. He said that he could, so while he was making the pattern, I set about finding someone who could make the casting for me. The only person I could find who had this type of equipment was an older gentleman who had a investment casting foundry, but he didn't want to do it as he was trying to retire. I asked him if he would do it if I brought his business from him, and he finally agreed. I insisted that he train someone else to cast the impellors before he left. Ultimately that was an expensive way of getting a casting, but at that stage it was no longer about money. It had become a matter of principal.

Once I had the casting, I took it to Garrett Aero Research to ask them to machine and balance it for me. While I was there I stumbled across a small turbocharger impellor and volute. Turbochargers were just being introduced into the automotive industry and I asked them how much it cost. I could not believe it when he told me that it cost just $90. I was used to prices of $20,000 to $30,000, and I immediately thought there must be an opportunity here.

I managed to get the machine repaired. Along with another happy customer I now had the experience and tools to compete more confidently for more of the same manufacturers' machines. This was when the idea of a small centrifugal was first formed, and although I liked the idea, I had no need for such a machine.

The specification the perfect compressor

In the mid 80's I invented a modular chiller. Over the next ten years I built that business into a successful international business and established 14 factories on five continents. The operation grew rapidly and by the early 90's we were buying around 10,000 compressor per year. I was starting to be concerned by the impact of the Montreal protocol. None of the suppliers we were using seemed too interested and did not seem to have a plan for what was to come. I decided that rather than put our business at risk, I would return to the old idea and build our own compressor. Not knowing the first thing about compressor manufacturing or design, I decided to start with a fresh sheet of paper and list all of the things that, from my perspective, would make the perfect compressor. From this I wrote my specification. There was one slight problem however - there were no technologies available that could do the sorts of things I needed if it was going to work.

During the early 90's I was travelling extensively around the world establishing new factories and during these travels, had my eye open for ideas, opportunities, contacts and technologies. Once I knew a technology was possible, no matter what it cost or how far away it was from a commercial product, I ticked it off my "is it possible?" list. Once I was comfortable enough that what I was after was not on my "impossible" list, I started to chase funding to turn it into a reality.

One example of "the almost impossible, but I think I can do it" category, was the magnetic bearing. The first magnetic bearing I saw was being built for a pump for the Alaskan gas pipeline. It was an analogue magnetic bearing for a 200mm shaft. The control panel was about 9 meters long and it cost $16,000,000. I asked if it was possible to turn the bearing into digitally controlled devices. They advised that there were several universities that were experimenting with it, but that the processors were not fast enough to do the job. Knowing that computers were getting faster and faster and cheaper and cheaper, and knowing that the bearings themselves were only made from steel, copper and magnets, I figured that it might be possible to get that cost down from $16,000,000 to less than $1,000. So it went onto my 'it is possible' list.

In 1993, I started to assemble a team of experts from around the world, and to raise the necessary funding to prove out the concept. In January 1994, I held the first week long kick off conference in Melbourne. There were 34 attendees, and 30 of them were PhD's. I started off the conference by writing my specification down on a white board. I knew what I was after, but did not want to spell it out right away, I wanted the team to think about it without me interfering. Three of the PhD attendees left before the end of the first day, telling me that I was off with the fairies. The rest of the team stuck with it, and by the end of the week, they had the vision and were all fired up.

I started off by drawing a matchbox on a white board and writing down what I wanted it to do, the list was like this:

To develop a small centrifugal compressor that:

- had a capacity in the 200 – 300 kWR range,
- was environmentally friendly,
- did not to use oil as a lubricant,
- was direct drive,
- was as small as a matchbox,
- was 100% efficient,
- was silent,
- had all its features fully integrated,
- weighed less than ½ kG..
- and cost $1.00

By the end of the conference, the team finally came around to my way of thinking, and although some were still a bit skeptical, figured out that as long as I was paying the bills, then there was not a lot to lose!

Well we failed, we did not reach our objectives, but we came pretty close:

- It is rated at 200 to 300kWR, in fact it now goes to 600kWR **(tick)**
- It is designed to operate on R134a **(tick)**
- It eliminated lubricants by using Magnetic bearings **(tick)**
- It uses a high speed synchronous permanent magnet direct drive motor **(tick)**
- It is very small compared to its competition (25-30% of the size), but is not as small as a matchbox **(cross)**

- It is the most efficient compressor in the world, (IPLV –COP9.38) however we have not hit 100% efficiency yet **(cross)**
- It is very quiet (70 dBa at 1.5 meters) however it is not silent **(cross)**
- It has a fully integrated control system including bearing and inverter control **(tick)**
- It is light weight, weighing 120kG, which is about 25% the weight of its competition, however it does weigh more than ½ kG **(cross)**
- As for the $1:00 **(cross)**

The development stage

When we started the development, many of today's current technologies did not exist. PC's were at the 186 level, and CAD software was in its infancy and was very expensive. In order to get the engineers up to speed in CAD design, they all had to learn it - programs like FEA did not exist. I am inspired by the early engineers who pioneered space travel, and who got the first man to the moon and back, primarily on a slide rule. If engineers can achieve such a feat as that, with the tools they had available to them at the time, then, what should we be able to do today?

In order to make this dream become a reality, I decided that we would have to invent the core technologies. This was done for two reasons, the first is that it was the best way of controlling the outcome, and the second is that if we were ever going to meet the cost targets, then we would have to own our own technology.

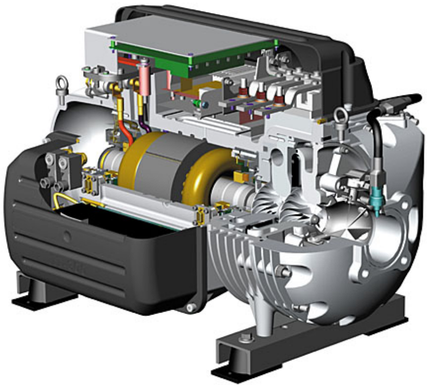
Below is the status of the technologies when we started and where we had to get to:

Available Technologies in 1993	**Required Technologies**
Motor – 75 watts @ 13,000 RPM	Motor – 75,000 watts @ 48,000 RPM
Analog Bearings @ $16,000,000	Digital Bearings – Target less than $1,000
Dc/Dc Converter – 24V to 5-10-15VDC	Dc/Dc Converter 600VDC to380/24/5/10/15VDc
PC's – Pentium 186	PC Required - Pentium 486 (minimum)
Processor – 4megDSP	Processor – 40 megDSP (Minimum)
Position Sensors -0.0001" Sensitivity	Position Sensors - 0.000002" Required Sensitivity
Soft Start – Not Available	Soft Start - Inrush current less than 2 amps
IGBT – 100 Amp air cooled	IGBT – 300 & 500 Amp refrigerant cooled

The first Prototype was commissioned in June 1995, and although it had a long way to go, I decided that the concept had potential. At that stage I decided to sell my interest in the chiller business and concentrate on making this dream a reality. The risks were high but I thought that the potential outcome was worth the effort. Looking back, I think if I had taken my money and retired, I would have ended up inventing something else and starting a new business anyway, so I might as well do something that I loved to do.

The major challenges

The development team spent the next five years knocking down the barriers of impossibility, and although some were harder to conquer than others, each hurdle was overcome and victory prevailed. We experienced absolutely no problems during the entire development processes; we had many challenges and many opportunities, but no problems. The reason being that I banned the use of the word problem, for the entire length of the project, and the team learned to look at every hurdle or barrier as a challenge and an opportunity.



What we ended up with is a small, highly efficient, oil-free centrifugal compressor that is very quiet, very smooth running and light weight. The areas of challenge were daunting:

- As there were no real ways of soft starting high powered motors, we invented one.
- As there were no compact high powered IGBT packages available, we invented one.
- As there were no high voltage Dc/Dc Converters around, we invented one.
- As there were no high powered high speed motors available, we invented one.
- As there were no low cost, accurate position sensors available, we invented one.
- As there were no digitally controlled magnetic bearings, we invented one.

We had tried very hard all the way through this process to remain an Australian company, but raising the kinds of funds that we required was all but impossible. So in 2000 we decided to move the business from Melbourne to Montreal, Quebec. This was done for several reasons. The first is that the Quebec Government invested over $20million of much needed capital into the project. The second is that the Canadian dollar had a very favorable exchange rate to the USA. And the third was that it was a cheaper place to live than Melbourne. If we were going to entice the workforce to move half way around the world, go from warm weather to close to the arctic circle (or it felt like it) and go from an English speaking environment to a French speaking environment, then it was going to be much easier to get the wives to accept moving from a three bedroom house to a four bedroom one, rather than from a three bedroom house to a tent.

When we moved 20 out of a team of 24 moved half way around the world with the project and a product that did not work. The commitment and dedication that the team had to the project goes beyond description, and without this commitment, the project would have failed.

This commitment went even further when the team packed up their belongings one more time to move the business from Montreal to Tallahassee, Florida.

The production stage

The first units went into the field in March of 2001, and were sold to the University of Southern California, Stanislaus. They have since brought several more Turbocor driven chillers.

In the initial stages we could not just sell compressors, so we had to build a dozen chillers and sell the entire package.

In 2004 Turbocor formed a 50/50 joint venture with Danfoss, and in 2005 it was decided, for commercial reasons, to move the business one more time to Tallahassee, Florida.

The product that we ended up with did not meet the original specification, but it did come pretty close. The dream was an impossible dream, but then again, like the word problem, it doesn't really exist, so the almost impossible became possible.

Ignorance is sometimes a great tool, and not knowing that it can't be done sometimes end up a big help.

Not one person in the development team had ever designed a compressor before and the only person that had any compressor experience was me with my rebuilding work. I did not want people on the team that had any pre conceived ideas, or knew enough to doubt that we could do it.

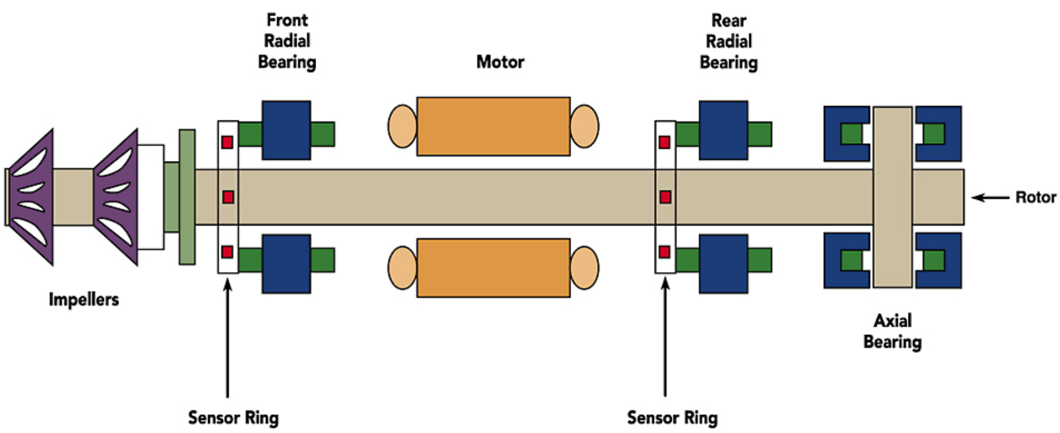
Design Features

What we ended up with is a 200-300 kWR direct drive, 2 stage, oil-free centrifugal compressor suited for the HVAC market. It is fully integrated with digital homopolar magnetic bearings, synchronous high speed P.M brushless Dc motor, inverter, pressure and temperature transducers and has an intelligent digital control system. The compressor is the most efficient, light weight, environmentally friendly, compact and quiet and vibration free compressor in the world.

- magnetic bearings

We decided to use magnetic bearings, after spending considerable time and money investigating all of the options in parallel. Once we had exhausted our investigations, we finally chose to go the magnetic bearing route because they have no mechanical or friction losses, have no oil-related heat transfer losses, were able to eliminate the oil management system, were able to increase the life of the machine because there was no wearing surfaces, and because we found them to be more durable than hydrostatic, foil or air bearings.

The bearing system we developed is a homo-polar design, which means that the permanent magnets do the bulk of the work, and the active magnets trim the shafts position. The sensors measure the shafts position to within 0.0005mm which is about 1/80th of a human hair. The shaft itself is repositioned a staggering 100,000 times every second; this means that the shaft is physically moved back into position 6 million times every minute. If oil bearing were used, we would have used 10,000



watts of energy, if we had used foil bearings, we would have used 2,500 watts, but with this system we use around 50 watts (maximum 180 watts).

Another question often asked is, what happens to the bearings if the power goes out? Well the incoming A/C current is turned into a DC current and then is converted back into a varying AC frequency, this is what varies the motor speed. The bearing and controls get the power from the DC buss, and in the event of a power failure, the capacitors on the DC Buss feed the bearing and control system, however within a half of a micro second, the motor turns into a generator, and the energy that is stored in the shaft, is turned back into electrical power and is fed back into the DC buss. This way, a power failure is treated as a normal shutdown.

- variable speed motor

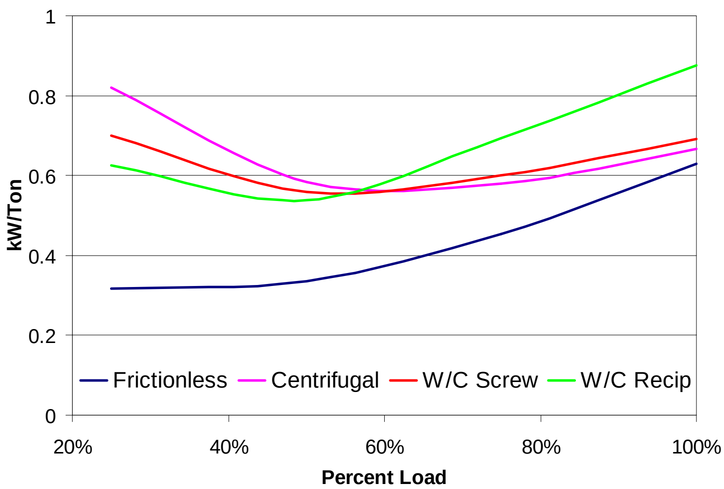
One of the main advantages that the variable speed motor has, besides its infinitely variable capacity control, is the impact that the unloading has on its efficiency. Operating without oil allows the system to be able to run with very low pressure ratios, and therefore very low speeds. The power increases by the cube as you double the speed, and reduces in the same manner. The motor can go as high as 48,000 RPM, but typically operates between 27,000 and 33,000 RPM, and can go as low as 18,000 RPM.

The motor in the smaller model (TT300) is a 120kW motor that is the same physical size as a 1.0kW motor and the larger model (TT500) has a 160kW motor that is the same physical size as a 1.5kW motor.

- centrifugal compressor

The compressor type is a two stage centrifugal compressor and each of the models fits into the same physical housing, from the outside, they all look the same. The impellor in the smaller model is an open shrouded design and the larger models all have a shrouded design.

The centrifugal design was chosen because of it efficiency and its ability to operate in an oil free environment. Reciprocating, scroll and screw compressors all need oil to lubricate the components.



- economizer

Being two stages allows for an economizer feature, this is especially useful in air cooled designs, and the compressor has been designed to operate on R134a. The compressor can withstand the occasional slug of liquid, because it is not a positive displacement compressor and because it has no oil.

- efficiency

The compressor is very efficient, especially at part load, and it offers exceptionally good IPLV (Integrated Part Load Value – Performance). Above is a graph, by one of the OEM's that use this technology, comparing it with other types of equipment that they use. The difference between the lines is the energy savings that can be achieved.

- elimination of oil

Eliminating oil has changed the way systems are designed and operated, this has a positive impact of piping configurations and application flexibility, no longer is oil return an issue, so multiple compressors can be installed into a common circuit and this eliminates the need for additional chillers needing to be installed for redundancy. It also increases the systems unloading capability and flexibility.

Axima 1800kWR Watercooled Chiller

Conclusion

Danfoss Turbocor is now the world's largest centrifugal compressor manufacturer, and there are now over 16,000 compressors operating worldwide, and are in applications varying from central air conditioning to process cooling. They are used in schools, universities, high rise buildings, apartment blocks, hospitals, theaters, shopping centers, large homes, naval and merchant ships, aircraft hangers, data centers, nuclear power plants and supermarkets.

They are suited for water cooled, air cooled applications, chillers, DX systems, condenser-less chillers and condensing units.

There are four models available, the TT300 – 200-300 kWR, TT350 – 300-400 kWR, TT400 – 400-500 kWR and the TT500 – 500-600 kWR.

I am often asked, what was the hardest part of the experience? Well developing the technologies had its fair share of challenges, but the hardest part, by far, was the raising of the necessary funds, this was by far the biggest pressure, however despite the fact that we almost didn't make it several times, we never missed payroll. We came close, but knew that if we did, then it was over. I went without any income myself many times, but I always made sure the employees' salaries were covered.

I must add, that if it were not for my partner's (Roger Richmond-Smith) positive attitude and ability to get it done and his belief in me, then we would not have made it. While I am on that topic, if it were not for my fabulous wife Denise's rock solid support, I would have given up and had a go at lying on the beach instead. She had absolutely no idea of what the compressor was about, but she supported me in every way possible.