The Impact of the VDI Screw Machines Conferences

A Personal Perspective

J. Sauls, Ingersoll Rand (Retired), La Crosse, WI USA

Abstract

This report contains a collection of observations and thoughts on the value of the *Screw Machines* conference series. It will be entirely from my perspective as a practicing engineer in the field of screw compressor design for air-conditioning applications – the business of Trane where I worked from 1973 until my retirement in 2013. My impressions are overall positive and I hope this assessment will be useful to others considering participating in this or other conferences and related events.

Introduction

The first *Screw Machines* conference was held at TU Dortmund in 1984 [1]. Seven more followed in 1987, 1990, 1994, 1998, 2002, 2006 and 2010 [2] – [8]. I have attended all but the first of these conferences, although after getting a copy of the 1984 program, I arranged to get the full proceedings (Figure 1). I had not been aware of the work being done at TU Dortmund until seeing this. However, during my introduction to screw compressors as Trane began to look into this technology, I had discovered that there was much other interesting work published in German. As a result of all of this, I began to learn the language in order to read the papers provided.

Fig. 1: 1984 *Screw Machines*

Also during this time, I discovered Professor Rinder's book, *Schraubenverdichter* [9]. I was trying to develop a thermodynamic simulation (chamber model) for screw compressors. It would be based on a simulation I had written for scroll compressors, so the biggest challenge was defining the geometric characteristics of the screw. *Schraubenverdichter* had such a clear and complete description of all of the issues I was working on – profile form, volume characteristics, leakage paths including blowhole size, and forces and torques on the rotors – that I felt it was almost too good to be true.

Not too long after I began studying the book, which provided a great boost in the development of Trane's screw compressor simulation, I met Professor Rinder in Vienna. Then, in 1983, he spent time at Trane, teaching the basics of screw compressor rotor design.

All of this led to my introduction to the *Screw Machines* conferences. When Professor Rinder was making plans to attend in 1984, he wrote, asking if I would be interested in attending. Due to the distance, the short duration of the conference and uncertainty over how useful attending might be, I decided not to go. But, as noted above, I soon saw that the potential value of the program content and the chance to meet many respected engineers in the field of screw compressors. So, I concluded that it would be more than worth the effort of traveling to Dortmund and continuing to work on my German language skills.

In the remainder of this report, I will offer some thoughts on the conference series, how I think these conferences are generally of value to industry. I will also provide specific examples of the value they have provided me and my company during my career. In the *Overview* section, I will look at the conferences "by the numbers." In *General Impressions* I will point out some papers in each of the conferences I attended that caught my attention as being use in my work at the time. This section also includes stories about meeting people and learning about different views on and approaches to screw compressor design over the years. Then, in *Specific Results*, I will describe some particular aspects of Trane's use of design tools that came directly from information and contacts from the conferences. Finally, I will offer some concluding observations and suggestions in the *Closing Comments* section.

Overview

In the eight conferences that have been held prior to this one, there have been 212 papers included in the proceedings. All of the papers at the 1984 conference were written in German; use of English grew slowly with the greatest number of such contributions in 2002 when there were 17 which represented 61% of the contributions. The number of English language papers fell to nine (31%) in 2010. However, English becomes the official language at this conference and, based on the abstracts accepted, for 24 of the 25 papers. Figure 2 illustrates this information.

There have also been 204 authors and co-authors involved in the contributions. The nine authors with the highest number of papers in the proceedings are Kauder, Rinder, Sauls, Benes, Brümmer, Janicki, Pucher, Stosic, and Svigler; five authors are tied for tenth on this list. Not surprisingly, Professor Knut Kauder from the Technical University (TU) Dortmund has contributed far and away the greatest number of papers – 42 in all.

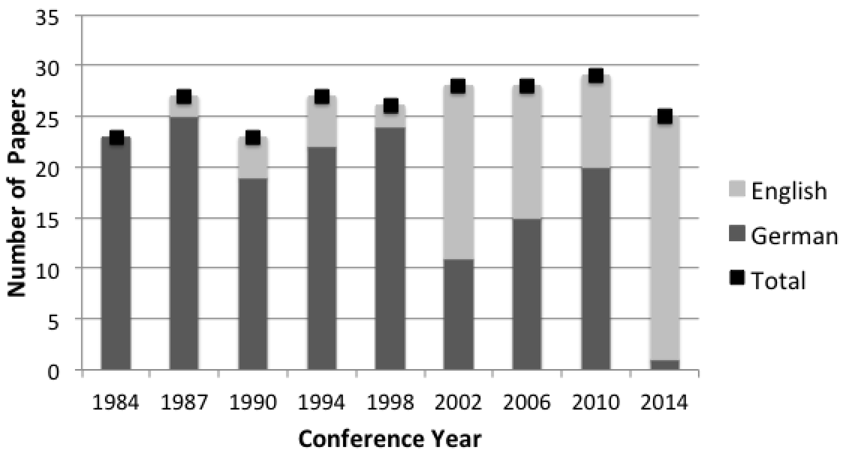


Fig. 2: Papers presented at the *Screw Machines* conferences since 1984

The conference has been reporting results from the many programs carried out at TU Dortmund in Fachgebiet Fluidenergiemaschinen (FG FEM) and Fachgebiet Fluidtechnik. There are 52 papers in this category representing 25% of all of the contributions between 1984 and 2010. In addition, a number of graduates from TU Dortmund continue to contribute to the conference as representatives of the companies at which they are now employed. These papers are one example of how the developments made in the university environment are transferred to benefits for industry. The section *Specific Results* in this paper will include other examples of this benefit which can come directly or indirectly from regular attendance at conferences such as the *Screw Machines* series.

One intent of this and other conferences is to collect contributions in particular technologies and make them available to the engineering community. Citations included in the papers provide some indication of the impact of previously published results on the work being reported. Looking at each of the 212 papers in the nine conference proceedings shows that there are 1,260 separate citations which papers refer to as sources of supporting information. Figure 3 shows some of the information collected from this brief analysis of citations.

In this figure, solid round symbols show the total number of citations from all papers in the conferences from 1984 – 2010. The columns show some selected sources for the citations.

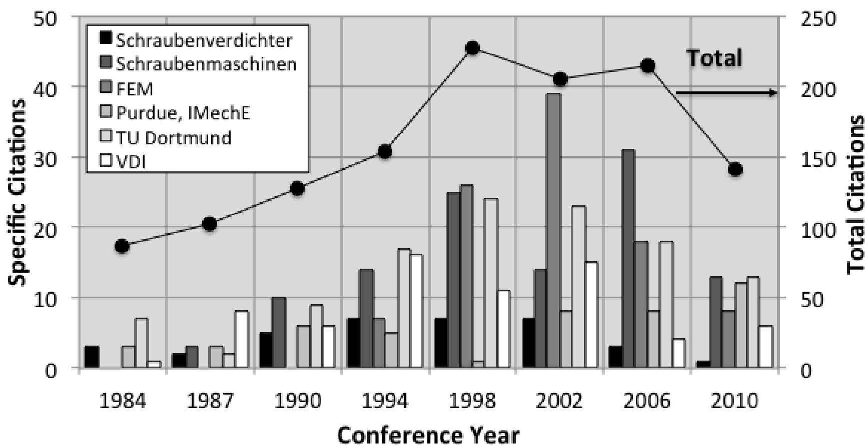


Fig. 3: Citations from papers presented at the Screw Machines conferences since 1984

Schraubenverdichter refers to the book by Professor Rinder [9]; **Schraubenmaschinen** is the collection of proceedings of the VDI Screw Machines conferences [1] – [8]; here we see conference contributions referring to earlier conference papers. **FEM** denotes an annual reporting of projects from TU Dortmund, Fachgebiet Fluidenergiemaschinen / Fluidtechnik. There have been 14 publications, entitled *Schraubenmaschinen Nr. 1*, *Schraubenmaschinen Nr. 2*, etc., released since 1993. These collections are available by subscription from the University. The **Purdue, IMechE** series represents the combined total of contributions from two other popular, compressor-focused conferences, the *International Compressor Engineering Conference at Purdue* and the *International Conference on Compressors and Their Systems*. The **TU Dortmund** data is a count of dissertations from the university that are referenced by authors and the **VDI** item shows the number of *VDI Fortschrittberichten* that are cited.

The total number of citations rose steadily during the first five conferences; the number of papers in each conference varies only within the range from 23 to 29 and for the totals shown in the figure, the average number of citations per paper follows nearly the same trend.

Technical conferences provide engineers opportunities to connect and share information. Conferences proceedings then provide a record of what was shared formally; access to this record allows others to build upon work by others rather than investing in re-invention.

Data in Figure 3, shows how this looks for the *Screw Machines* conferences. For example, *Schraubenverdichter* [9] is referenced in all of the proceedings; three of the proceedings have seven citations to this work. For me, the book was a good starting point for developing better understanding of many aspects of screw compressors; furthermore, I continue to use it as a reference in on-going work. It appears this is the case with others as well.

There is, of course, the obvious connection of this conference series to TU Dortmund. If we look at the total number of citations to TU Dortmund dissertations, the annual reports from FEM and proceedings of earlier screw machines conference (included as the venue has always been the university), we get the results in Figure 4. There has been a steady increase in citations in this category. That is not much of a surprise since every conference adds about 25 papers which can then be cited in the future. The FEM annual reports, quite often cited in the last five conferences, were not published until 1993. All in all, these TU Dortmund related citations represent from 5% (1987) to 37% (2002) of the total number of citations in all of the papers in the proceedings.

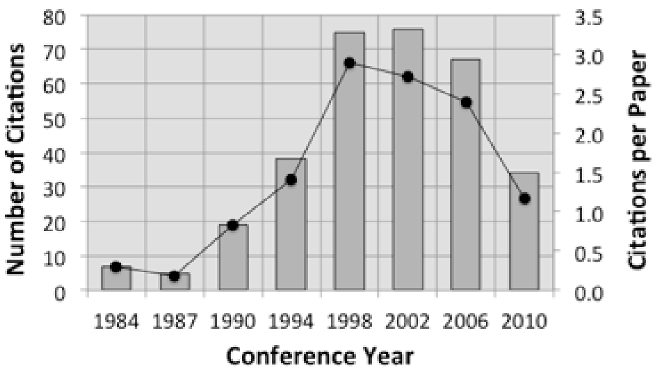


Fig. 4: TU Dortmund related citations

Finally, there are fewer references to works published in the Purdue and IMechE compressor conference proceedings. As of 2013, there have been 254 screw compressor related papers published in these two conferences, 20% more than in the *Screw Machines* series. But there are only 46 citations to papers in these other two conferences, fewer than half of the 110 citations to papers published in the *Screw Machines* proceedings. Nonetheless, there is a clear interaction between the works at the separate conferences.

General Impressions

My first impression of the *Screw Machines* conferences came from the proceedings of the 1984 conference [1] which I acquired shortly after the event was held. Many of the papers addressed issues that we at Trane were dealing with. While there were no detailed solutions to specific problems we faced, there were many general ideas regarding compressor design. In particular, were papers by Mente on rotor machining methods [pg. 93]; Peveling on rationalizing compressor design to specific operating environment factors [pg. 163]; Potz on the influence of discharge porting on noise and pulsation [pg. 203]; and three papers by Fister, Buthmann and Neumann on analytical procedures for compressor design [pgs. 271, 299, 329]. Finally, there was an appendix outlining research at TU Dortmund. This was more than enough to set me on the path to becoming a regular participant in the conference.

Every conference I have attended has had papers I found interesting and either directly useful or providing benefits after adaptation to the specifics of the issues with Trane's compressors and systems. Table 1 contains a list of what I found to be interesting papers in each. While these are highlights for various reasons, there are many more contributions I have found useful.

Table 1: Highlights of the conferences I attended from 1987 through 2010

Year	Page	Author(s)	Description
1987 [2]	11	Kauder, Piatkowski	Oil injection effects
	107	Benes	Design under consideration of noise
	209	Peveling	Effect of wrap angle
1990 [3]	1	Rinder, Moser	Distribution of oil in compression chamber
	185	Mosemann, Kolberg	Volume ratio control for fishing ship systems
	269	Holmes, Munro	Measurement of rotor pair clearances using light
1994 [4]	1	Kauder, Dreifert, et al	Finite element modelling (thermal effects)
	63	Fleming, You, et al	Efficiency, bearing loads with slide valve control
	357	Lorenz	Methods of screw rotor manufacturing
1998 [5]	107	Kauder, Sachs	Visualization of leakage flows
	279	Stošić, Smith, et al	Lubrication of involute contact rotors
	365	Kauder, Janicki	Simulation of transients (thermal effects)
2002 [6]	1	Kauder, Janicki, et al	Thermodynamic simulation (chamber model)
	29	Kauder, Helpertz, et al	Screw rotor optimization
	83	Kauder, Sachs	Leakage flow calculation
2006 [7]	3	Kauder, Janicki	Effect of leakage flows
	69	Zaytsev	Pressure pulsation in oil injected compressors
	363	Steinmann	CFD analysis of flow in screw compressors
2010 [8]	67	Hauser, Brümmer, et al	Rotor design for industrial compressors
	245	Kovačević, Kethidi, et al	Turbulence capture in CFD for compressors
	345	Švigler, Machulda	Analysis of rotor contact under load

In addition to the papers, summaries of research at TU Dortmund included in several of the conference proceeding provided more detail of the projects being carried out.

Many of the papers above relate to Trane's on-going commitment to improving design tools and adopting new and improved methods. The papers on oil injection led to discussions with TU Dortmund on applying lessons they learned to refrigeration compressors. Work on various optimizations reported over the years, while not specifically relevant to refrigeration compressors, gave us ideas for similar studies and led to deeper understanding of the effects of various design parameters.

Some of the papers report part of a larger body of work for which we were able to find more complete reports. The papers by Peveling contain information similar to what is found in a VDI Fortschrittberichte [10]. And, as noted in the Overview section, the annual reports from the FG FEM, first published in 1993, provided more information on work summarized in conference papers. Trane subscribed to this series and we made good use of the reports.

In addition to content in the papers and presentations, the conferences have provided an opportunity to meet a large number of talented, experienced engineers and to share information with them. There are many such occurrences, but one that stands out happened at the 1987 conference. One particular author had presented three papers in the 1984 conference as a student. He was back in 1987, now graduated and working in industry. I was quite happy to meet him and ask about his work; I found him during a break and introduced myself. As we were talking, another delegate from his company came up. After hearing I was from Trane, he suggested we not talk. Our companies were not really competitors, so it was not so clear as to why this should be. However, the next day, the author approached me and said the papers he was presenting all came from his university dissertation. There was no connection between that body of work and his current position; as a result, I was given a copy – a nice bonus to my first visit to the *Screw Machines* conference.

Of course getting the chance to meet Professor Kauder, and more recently, Professor Brümmer, and the many TU Dortmund students and FG FEM associates was of great benefit to us. The department has consistently built on earlier work and publications at the conferences provide access to the results. Projects of various sorts arose from our access to the publications and the personal contacts established by attending the conferences.

My personal opinion is that the meetings and exchanges such as these are extremely beneficial. While some care needs to be taken regarding privileged information, the exchanges around the engineering issues, analytical problems, and the like can provide real benefits. This benefit of conferences is no secret and is often cited in opening addresses.

The next section provides some details where Trane developed design methods based directly on information first encountered at the *Screw Machines* conferences.

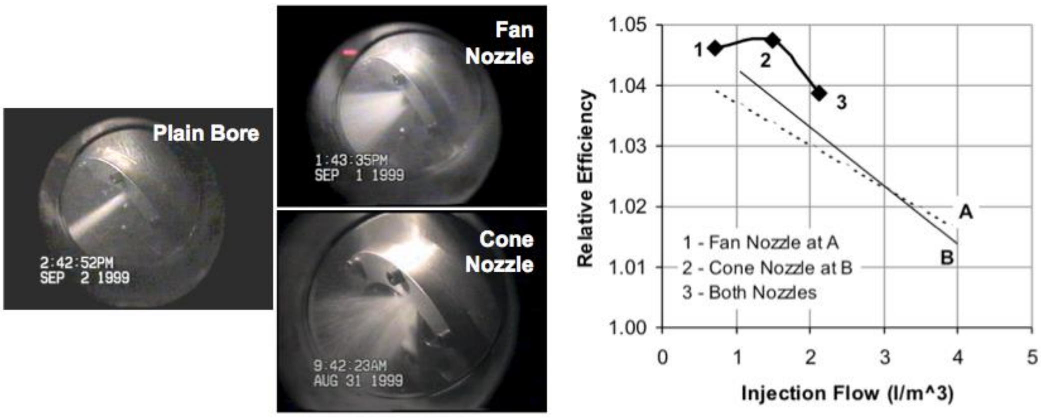
Specific Results

There are three important parts of Trane's design system in place today resulting from attending Screw Machines conferences. These are in the areas of oil injection, transient thermal analysis of compressor assemblies and calculation of the three-dimensional clearance between rotors with arbitrary surface deviations from nominal form.

<u>Oil Injection</u> A number of papers at the earlier conferences dealt with the issue of oil injection, these mostly related to air compressors. Our own tests showed that there were certainly ways to provide the injected oil in refrigeration compressors for better performance, so we felt a more complete, systematic study of effects would be beneficial, providing us with greater certainty in design decisions and better models for our simulation. We reached an agreement with the FG FEM for Dr. Deipenwisch to provide a report on the work in some detail. His work was reported in one of the FEM annual reports [11]; this included some studies with a variety of spray nozzles which we found interesting. The report prepared for us addressed some of the issues with refrigeration compressors and was the basis for planning an experimental program. During the course of this work, we consulted with Dr. Deipenwisch on a regular basis and shared results as they were acquired.

We executed a variety of tests in a specially modified compressor where we could study effects of oil flow rate, oil temperature and location of the injection port(s). We also built a test rig connected to the discharge side of the compressor which we used to visualize the flow from various nozzle options. The reason for this was our concern that the flashing of refrigerant dissolved in the oil would change the nature of the nozzle flow patterns. Results of this work were reported at this conference in 2002 [12]. Figure 5 shows some of the results from the tests. As shown in Figure 5(a), we saw that the fan and cone nozzles created the appropriate flow patterns even with the refrigerant flashing as a result of the very high pressure drop.

The chart in Figure 5(b) shows the effects of flow rate, location of the injection port (A or B) and nozzles; for the **Both Nozzles** test, the fan nozzle was set at location A (lower pressure) and the cone nozzle at location B (nearer the discharge port).



(a) (b)

Fig. 5: Results of oil injection tests [12]

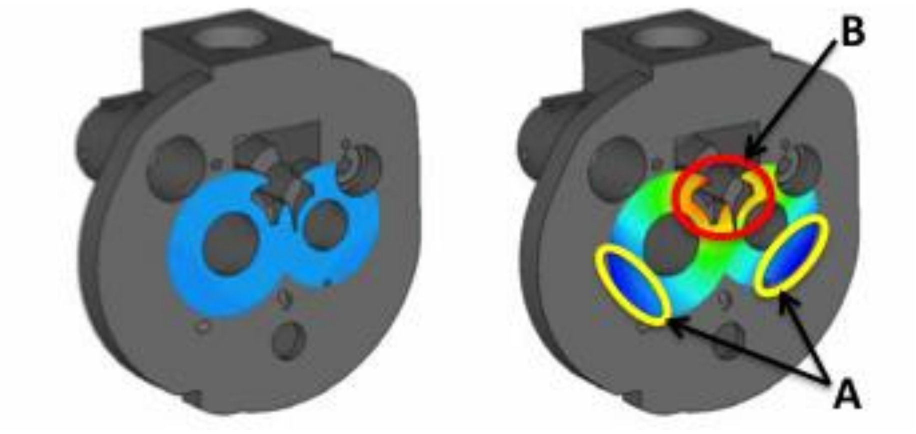
The tests showed we could realize a nearly 5% improvement in performance if all of the appropriate factors could be used. While it was difficult to incorporate the findings into production compressors at the time, improvement projects and introduction of new products have allowed us to realize the benefits of this work.

Thermal Analyses The 1994 paper by Kauder, et al [13] showed a method for computing the effects of temperature on screw compressors. In their 1998 report at this conference, Kauder and Janicki [14] showed a well developed process for using finite element analysis in prediction of transient thermal characteristics. Trane had established a process for measuring all parts of compressors tested in our laboratories for the purpose of determining the actual clearances in each sample; this process is described in [15]. Among other things, this was to avoid finding compressors with unacceptably small clearances by having them fail on the test stand. In spite of this, there were a few unexpected problems and we sought to get more details into our analyses. Thermal effects were a major concern. We had developed a fairly simple process for estimating these effects, but knew the situation was more complex. The work at TU Dortmund was a good model for the next level of simulation.

As a result, we arranged with the FG FEM for a special workshop on the issues of transient thermal analysis. We had an in-depth discussion of all of the processes used in their modelling, including details of the finite element modelling and the methods used to extract temperature and heat transfer coefficients from results of a chamber model simulation. The development of our analyses based on the work at TU Dortmund is reported in [16].

Validation of the model's capabilities was achieved during an extensive test program where both rotors and housings were instrumented. This work is reported in [17]. Key findings in these studies were: (a) the clearance between rotors and housings at steady state operating conditions were nearly the same as the as-built, cold clearance; (b) there was a significant reduction in clearance during transients as the conditions went from pre-start to final, steady state operation.

It was this second result that provided an explanation for the unexpected issues that occasionally appeared during our tests. In these cases, it was almost always a contact of the discharge face of the rotors with the discharge end bearing housing in the region around the axial discharge port. The transient analysis showed that clearance in this region decreased by almost 25 microns during the transient, then increased to a level of about five microns below the pre-start clearance built in at the time of assembly. Figure 6 shows some results.



(a) (b)

Fig. 6: Results from transient thermal analysis [17]

In this figure, the colors represent magnitude of the clearance between the bearing housing (shown) and the discharge end face of the rotors (not shown). The medium blue area in Figure 6(a) shows the uniform clearance state of the compressor before start. The point in time during the transient where the minimum clearance over the surface is at its lowest level is shown in Figure 6(b). Region **A** has clearances that are higher than the cold state and region **B** is where the clearances are below that level; in this particular case the bright red around the edges of the discharge port are where rotor and housing contact was known to occur. As a result of this, we have developed procedures to design the housing and bearing system in a way that eliminates this loss of clearance in operating transients.

<u>Rotor Intermesh Clearance</u> At the same time that we were developing the thermal transients, we acquired a computer program named IMC (<u>I</u>nter<u>m</u>esh <u>C</u>learance) for the calculation of rotor-to-rotor clearances. Janicki published information about this program and its methods in [18].

This program calculates actual clearance along the entire length of the sealing line for a rotor pair defined by its nominal profile form plus any number of arbitrary deviations from this form. In addition, the program allows for changes in the relative orientation of the centerlines of the two rotors. With this tool, we were easily able to see the effects of thermal and pressure load induced deformations, and manufacturing variations in the rotors and housings.

Use of this program to quantify the effects of thermal deformation on rotor clearance is documented in [17]. The program has also been used to assess manufacturing variation effects to provide input into decisions on manufacturing process development. In addition, we undertook a study of rotor transmission error using this program to calculate the changing rotor-to-rotor contact conditions as influenced by rotor profile deviations and changes in rotor shaft alignment. This work is reported in [19]. Typical results from this are shown in Figure 7.

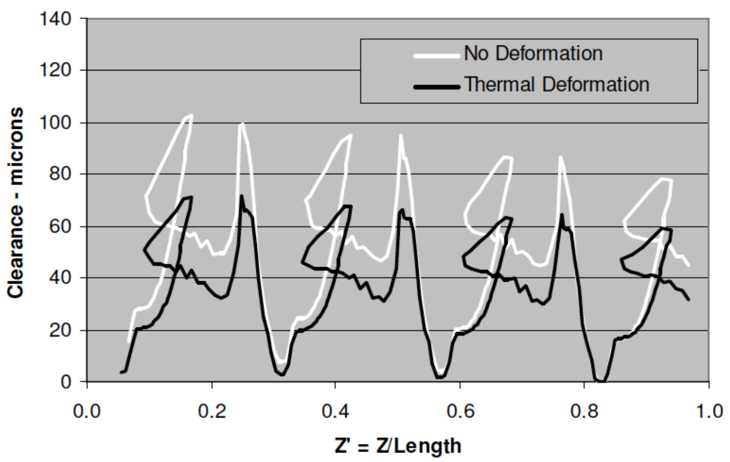


Fig. 7: Effect of thermal deformation on rotor-to-rotor clearance and contact [19]

This example shows the clearance and state of contact for a single angular orientation of the rotors. The rotor axes were misaligned, resulting in only a single contact at 80% of the distance along the length of the rotor. In order to compute the transmission error, the analysis is repeated for other angular orientations. At each orientation, the program reports the incremental change in the female rotor angular orientation required for the rotor pair to be in contact. This deviation is the source of the transmission error, a contributor to overall sound levels of screw compressors. Use of the thermal analysis and clearance program together gave us verification of rotor modifications that were introduced to minimize the transmission error in production compressors.

Closing Comments

The series of *Screw Machines* conferences has proven to provide the advantages one would expect from such an event – a collection of technical presentations that are relevant to the viewers' interests and an opportunity to meet and converse with outstanding engineers in the field. I have regularly attended other compressor conferences, namely the *International Compressor Engineering Conference at Purdue* and the IMechE *International Conference on Compressors and Their Systems* at City University London, where these benefits are evident as well.

A particular appeal of the VDI *Screw Machines* conferences, however, is the focus on screw machines. There have been very few papers directly related to my particular interests – refrigeration screw compressors for commercial air conditioning applications. However, the conference has had much to offer in the areas of analytical techniques and design ideas, some of which can be taken directly to the refrigeration compressor problems and others which can be adapted to that end.

In this paper, I hope I have conveyed the value of active participation in this conference and others like it and my appreciation for the many engineers I have met and worked with. It is not always easy to invest in the development of technical excellence under the pressure of current business requirements. But it is a worthwhile investment. I would expect the *Screw Machines* conferences to continue to provide support for this effort in the years to come.

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My thanks to Trane, Ingersoll Rand for providing the opportunity to present this paper. And to the too many to mention excellent engineers that I worked with at Trane over the years who made the analyses and design definitions come to life in world class designs. Thanks also to the remarkable contributions of the manufacturing teams who helped rationalize the designs and the processes used to make them and who execute the processes so effectively. Finally, a special thanks to Professor Knut Kauder, Professor Andreas Brümmer and the many associates we have worked with for building and maintaining excellence in screw machine technology at TU Dortmund.

And to Professor Laurenz Rinder, a special thank you for your book, your counsel, your friendship and for introducing me to the *VDI Screw Machines* conferences.

References

[1] **VDI-Berichte 521**: Proceedings of the conference *Schraubenmaschinen; Schraubenverdichter, Schraubenmotoren*; VDI-Verlag, Düsseldorf, 1984.

[2] **VDI-Berichte 640**: Proceedings of the conference *Schraubenmaschinen '87; Schraubenmotoren, Schraubenverdichter*; VDI-Verlag, Düsseldorf, 1987.

[3] **VDI-Berichte 859**: Proceedings of the conference *Schraubenmaschinen; Schraubenkompressoren, Schraubenlader, Schraubenmotoren '90*; VDI-Verlag, Düsseldorf, 1990.

[4] **VDI-Berichte 1135**: Proceedings of the conference *Schraubenmaschinen '94; Schraubenkompressoren, Schraubenlader, Schraubenmotoren*; VDI-Verlag, Düsseldorf, 1994.

[5] **VDI-Berichte 1391**: Proceedings of the conference Schraubenmaschinen '98; Schraubenkompressoren, Schraubenmotor, Schraubenlader, Schraubenspindel-Vakuumpumpen; VDI-Verlag, Düsseldorf, 1998.

[6] **VDI-Berichte 1715**: Proceedings of the conference *Schraubenmaschinen 2002*; VDI-Verlag, Düsseldorf, 2002.

[7] **VDI-Berichte 1932**: Proceedings of the conference Schraubenmaschinen 2006; Kompressoren, Lader, Motoren, Vakuumpumpen; Compressors, Superchargers, Engines, Vacuum Pumps; VDI-Verlag, Düsseldorf, 2006.

[8] **VDI-Berichte 2101**: Proceedings of the conference Schraubenmaschinen 2010; Kompressoren, Lader, Motoren, Vakuum- und Flüssigkeitspumpen; VDI-Verlag, Düsseldorf, 2010.

[9] **Rinder, L.**: *Schraubenverdichter*; Springer-Verlag, Berlin/Heidelberg/New York, 1979.

[10] **Peveling, F.**: *Ein Beitrag zur Optimierung Adiabater Schraubenmaschinen in Simulationsrechnungen*; VDI Fortschrittberichte, Reihe 7: Strömungstechnik, Nr. 136; VDI Verlag, Düsseldorf; 1988.

[11] **Kauder, K. and Deipenwisch, R.**; *Öl als Konstruktionselement in Schraubenmaschinen – Einsatz nicht newtonscher Öle –Teil 1*; Forschungsberichte des FG Fluidenergiemaschinen Schraubenmaschinen Nr. 6; Universität Dortmund, 1998.

[12] **Sauls, J.**; *Some Effects of Injection Oil on a Screw Compressor for Application in Refrigerant R-134a Air-Conditioning Systems*; VDI-Berichte Nr. 1715, Schraubenmaschinen 2002; VDI Verlag, Düsseldorf, 2002.

[13] **Kauder, K., Dreifort, Th., Keller, G., and Rofall, K.**; *Probleme der Anwendung der Finite-Elemente-Methode in Schraubenmaschinen*, VDI Berichte Nr. 1135, Schraubenmaschinen '94; VDI Verlag, Düsseldorf, 1994.

[14] **Kauder, K., Janicki, M.**; *Simulation instationärer Betriebszustände von Schraubenkompressoren*, VDI Berichte Nr. 1391, Schraubenmaschinen '98; VDI Verlag, Düsseldorf, 1998.

[15] **Sauls, J.**; *The Influence of Leakage on the Performance of Refrigerant Screw Compressors*; VDI-Berichte Nr. 1135, Schraubenmaschinen '94; VDI Verlag, Düsseldorf, 1994.

[16] **Sauls, J., Powell, G., Weathers, B.**; *Transient Thermal Analyses of Screw Compressors; Part I – Development of Model*; VDI-Berichte Nr. 1135, Schraubenmaschinen 2006; VDI Verlag, Düsseldorf, 2006.

[17] **Sauls, J., Powell, G., Weathers, B.**; *Transient Thermal Analyses of Screw Compressors; Part II –Application*; VDI-Berichte Nr. 1135, Schraubenmaschinen 2006; VDI Verlag, Düsseldorf, 2006.

[18] **Janicki, M.**; *Ein Programm zur Profileingriffsspaltberechnung von verformten Schraubenmaschinen*; Forschungsberichte des FG Fluidenergiemaschinen - Schraubenmaschinen Nr. 13; Universität Dortmund, 1996.

[19] **Sauls, J.**; *Thermal Deformation Effects on Screw Compressor Rotor Design*; Proceedings of the 2007 International Conference on Compressors and Their Systems; Chandos Publishing, Oxford, UK, 2007.