Truth and Compression*

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Written on the occasion of the 75th anniversary of the founding of Pneumofore, in Turin, Italy, the following paper describes several technological considerations and the personal experience of the head of the company, who played a key role in shaping the destiny of Pneumofore for more than 40 years. Various types of compressors are compared with a view not only to their performance characteristics but also to their adaptability to new challenges such as saving energy and protecting the environment.

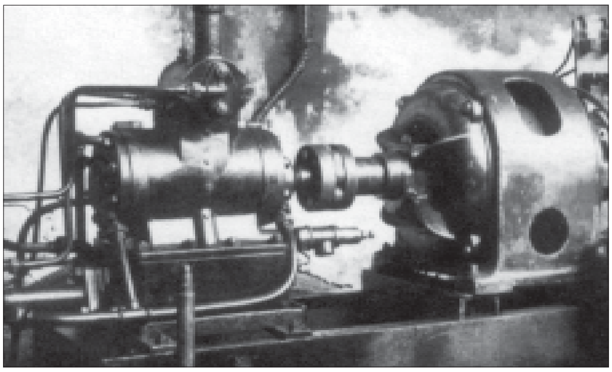

Image 2 - The world's very first single-stage rotary compressor with oil-injection cooling (1927, Pneumofore model A12, 27 PS)

The Development of Compressor Design

The first piston compressors were single-stage with a nearly isentropic compression process. They were replaced by dual-stage compressors with intermediate cooling achieving a higher efficiency (see annexed entropy diagram, **Img. 1**, in which the area under the lines corresponds to the work performed). However, their mechanical design was complex, causing problems such as troublesome vibrations and expensive maintenance. For these reasons, today, dual-stage piston compressors are manufactured almost exclusively for special applications.

Numerous piston compressor manufacturers existed in all of the early industrialized countries. At the time, rotary compressors were synonymous with rotary vane compressors. The first rotary compressors were dual-stage compressors equipped with drip feed lubricators and intermediate cooling systems. Later, single-stage rotary compressors with closed-circuit lubrication systems were developed. Only few manufacturers developed rotary compressors further and reached the production stage.

Approximately 35 years ago, single-stage screw compressors with oil injection appeared. They were considered to be the successors of the piston compressor. From the standpoint of energy conservation, however, this development was not one, but two steps backward. Why? Piston compressors with elastic piston rings, similar to the combustion motor, have an active cylinder sealant. The rotors in the screw compressor, in contrast, must not come into contact with the external wall - which is equivalent to a passive sealant that leads to the loss of power and return of air to suction. The situation grows even more problematic as soon as the radial play of the roller bearings increases due to wear. As a result of this design, the lifetime of a screw compression unit amounts to a mere 25,000 hours of operation, which is a considerable disadvantage.

For customers, it appears more economical to purchase screw compressors than to bear the cost of continously developed rotary compressors. And this is why most screw compressor suppliers assemble standardized components today. Customers are left to discover the exact origin of the various components of his screw compressor at their cost.

Only rotary compressors, which have been continually updated and improved, were able to survive on the market. Along with Pneumofore, other active and successful manufacturers of rotary compressors in Europe included Wittig, Hydrovane and Mattei.

The Development of the Rotary Vane Compressor

Ninety years ago, Wittig invented the rotary vane compressor, a dual-stage compressor with intermediate cooling that reached 7 atm. A dozen companies adopted the principle and for decades produced dual-stage rotary compressors with drip feed lubricators and 24 steel blades.

In 1927, in Turin, Italy, Pneumofore developed the world's very first single-stage rotary compressor with oil-injected cooling, featuring only 15 blades made of Aluminium. (**Img. 2**, Compressor A12, 156 m³/h, 25 PS).

As early as 1930, Pneumofore was awarded

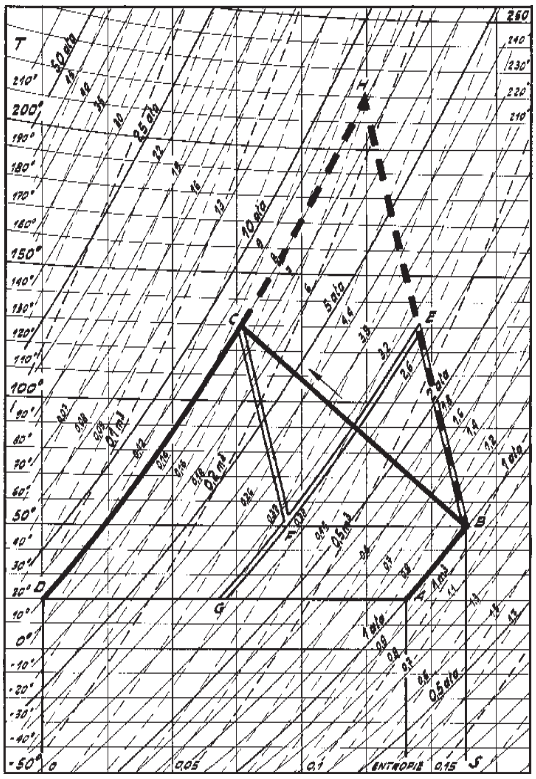

Image 1 - TS Diagram showing a single-stage piston compressor, dual-stage intermediate cooling and single-stage compressor with oil-injection cooling.

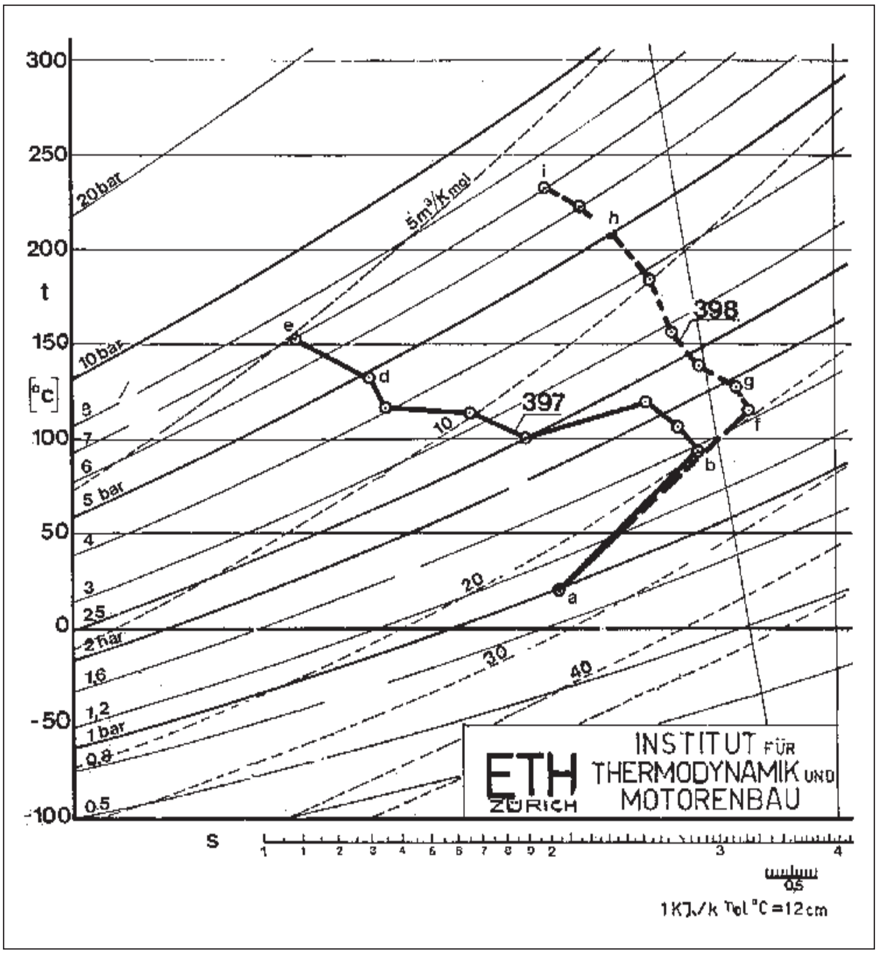

Image 3 - TS Diagram. Measurements with piezoelectric quartz crystals; 398 = traditional oil injection; 397 = intensive oil-injection cooling.

German Imperial Patent 510603 for the oil separation system that had been developed in-house. During the following years, the manufactured models grew steadily in size until units reached 400 kW power. These compressors have been running for decades and have outlived dual-stage piston compressors.

More than 60 years ago, a new air-cooled rotary vane compressor was developed for military applications in England. It had 8 cast-iron blades and continuous flow control.

The basic research carried out jointly by Pneumofore and the Swiss Institute of Thermodynamics brought revolutionary innovations to the world of compressors. The Intensive Oil Injection System is the only invention during the last few decades that has had a positive impact on the thermodynamic compression process. (**Img. 3**, entropy diagram). The Intensive Oil-injection cooling System is aptly described by the term "Brush Spray," in which oil is injected in a brushlike, capillary way. In this process, many fine streams of oil cool the air in the compressor area where the effective pressure increase is greatest.

In most screw compressors, oil is injected through axial holes that are 6 to 8 mm in diameter. In this case - despite assertions to the contrary - spray is not possible, because pressure is too low. The oil therefore functions mainly as a sealant and lubricant between the rotors and cools the compressed air only slightly.

Additional basic research established, among other things, that larger rotary vane units are more reliable than the large air-ends in screw compressors units. This can be explained on the basis of the geometrical and thermal processes involved. In the case of the rotary vane compressor, air is drawn in evenly and perpendicularly to the axis of rotation. The same principle applies to the expulsion of compressed air. The activity of the vanes also compensates to a degree for the linear thermal expansion. In the compression unit of the screw compressor, air intake is at one end and expulsion directly opposite at the other end of the cylinder. The diagonal flow of compressed air heats up and warps the cylinder unevenly. Additional power is lost through radial leakage and blow holes in this process.

Pneumofore's Contribution to the Development of the Rotary Vane Compressor

The decrease in electricity consumption between Pneumofore's single-stage rotary compressor and the dual-stage piston compressor was a significant challenge for Pneumofore. After many years of basic research in cooperation with the ETH (Swiss Federal Institute of Technology) in Zurich, the aforementioned Intensive Oil Injection was developed and implemented (**Img. 5**).

Repeated measurements show that compression is isothermal in the oil injection area. Even to the individual with only a basic understanding of thermodynamics, the considerable energy savings are apparent. The low temperature of compressed air at the cylinder exit, the large cooler with above-average oil cooling ability and the exceptional success in pre-separation are the basic prerequisites for optimal oil separation. Low temperatures result in large drops of oil, and therefore no aerosol. The fact that compression is nearly isothermal in the area subject to the brushlike oil injection is clearly demonstrated by the ensuing energy savings.

Today, Pneumofore manufactures compressors only of the single-stage, air-cooled, rotary vane type with units ranging from 5,5 to 315 kW. Large cooling areas make full load operation possible even at ambient temperatures exceeding 40° C (**Img. 6**). In everyday use, the energy-efficient Pneumofore System offers proven advantages over conventional screw compressors.

The vertical design on some of Pneumofore's air-cooled compressor model, which has been in use continually since 1970, was also a breakthrough. In addition to the more compact footprint - a growing requirement over the past years - the vertical layout makes it possible to use a large oil cooler and aftercooler. As a spin-off, the preliminary separation of oil through gravity is optimized, which means another step forward in improving the quality of delivered air.

In 2006 Pneumofore is far from its 80th anniversary. Throughout the eight decades since its inception, Pneumofore has continued to improve its rotary vane compressors and is well known for being ahead of the general requirements of the time.

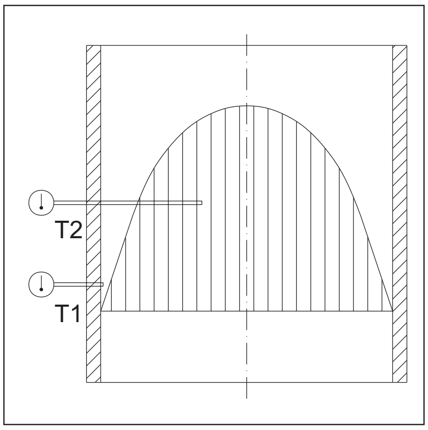

Image 4 - Laminar flow distribution in round cylinder; T1 measurement at wall, T2 measurement in center of flow.

Image 5 - Cutaway model of UR26, 160 kW air compressor; the intensive oil injection system is visible on the left cylinder wall

Befuddling Instead of Informing

The first compression units in screw compressors had asymmetrical profiles and were lauded for having 16% higher efficiency. In reality, there was 16% more intake volume - far from an improvement in the overall efficiency to the extent claimed.

Another type of obfuscation often takes place when a value is given for the volume of delivered air: measurements are taken directly at the compressor outlet - a practice established over decades.

In the case of piston compressors, this standard was correct, of course, due to the pulsating flow of air. According to German standard DIN 1952, effective air delivery is equivalent to the intake volume, because air delivery is measured at atmospheric pressure. The measurement at the compressor exit, as prescribed by the Pneurop and ISO norms, requires a calculation with several coefficients, multipliers, divisors, and so forth.

What, then, is the problem? The pressure is distributed evenly across the diameter of the air outlet pipe and can be precisely measured, i.e. almost with the precision of a barometer reading. In laminar flow, the temperature is distributed parabolically inside the pipe section, proportionate to the air speed. (**Img. 4**). Along the pipe wall, for example, 40°C may be measured (T1), but in the center of the pipe the temperature may well be over 70° - 80°C (T2). Under isobaric conditions, the air volume fluctuates by 1% per 3 degrees change in temperature. Therefore, if the temperature of the outflowing air is given as 40°C at the compressor outlet, but the temperature in reality is approximately 70°C, 10% more volume, for whichever norm, is being simulated. After the fact, such measurements must be converted and adjusted downward to atmospheric pressure using formulas and factors, during which process additional factors can be introduced for "cosmetic" purposes.

The Inverter Compressor Boom

When installing any compressor, the parameters are adjusted and adapted so that in each case the highest possible efficiency is achieved during full operation. With higher and lower rotation speeds, i.e. operating pressures, the specific energy requirement increases.

Why are inverter compressors nonetheless so highly praised? For screw compressors, the inverter solves two problems at once:

a) Due to its design, the compressor can be turned on and off only 6 – 8 times per hour.

b) When idling, the specific energy requirement reaches and exceeds the full load performance of most screw compressors and some rotary vane compressors by 30 to 40%.

Regarding a): In the case of oil-injected screw compressors, the main rotor drives the stator through direct contact. The difference in the number of flutes and cogs leads to axial movement between the rotors. When starting, the main rotor hits the stator quite forcefully, which is somewhat muffled by the film of oil. The compressor can be turned on and off only 6 to 8 times per hour, in order to limit much as possible the number of times the rotors collide. Even to someone with only a basic understanding of the technology, it is clear that such repeated impact must have consequences for the compressor's mechanical operation.

Regarding b): The handling in idle cycle clearly distinguishes the newcomers (screw) from the more modern variants of old-timers (rotary vane). Thanks to the lower number of rotations for inverter screw compressors in idle cycle, the specific energy requirement drops from 40% to 25% of full load performance. (Modern rotary vane compressors still only require half of this figure: 12%).

Another solution to points a) and b) is the turn valve. It gradually reduces the volume of delivered air, limits the number of interruptions, but does not have a negative impact on overall efficiency.

With their active oil seal, vacuum pumps are usually rotary vane machines, which have a high vacuuming intensity. When idling, rotary vane compressors become vacuum pumps and thus circulate oil as required. In this area, Pneumofore can draw on many years of comprehensive experience.

Screw compressors and some rotary vane compressors never actually idle, but rather continue to compress air to approx. 2 bar, in order to guarantee that the rotating components remain lubricated. This is why they still perform at 30% or 40% when idling. In idle cycle, the oil pressure must also compensate for any remaining axial thrust.

When the rotation speed changes, the oil circuit flow stays constant, casing either too little or too much oil flow into the displacement chamber. Too much oil leads to oil squeezing, i.e. a higher energy requirement, and vice versa, too little oil results in higher compression temperatures.

It is clear, however, that turning machines on and off 20 times an hour, for example, may damage contactors and electrical motors. In the case of the rotary compressor, though, no mechanical difficulties arise. By regulating the rotation speed accordingly, the operating pressure can be kept almost constant, which is important in some applications. Saving energy is nevertheless a wish far removed from reality.

What Environmental Protection Means

Everyone talks about environmental protection, but only few take action. This principle also applies to compressor manufacturers. An excellent example was the 1994 Hannover Trade Fair, where many water injected screw compressors were presented for the first time. Why didn't Pneumofore come up with this idea? Because water injection is "an old hat with a lot of holes in it." That is why this "innovation" had disappeared by 1997's Hannover Trade Fair. Presenting trendy solutions that are not yet ready for the market requires less effort than developing new approaches based on fluid mechanics, thermodynamics and pertinent experience. Inexpensive, compact units usually perform poorly in terms of oil separation. Quality entails more effort and higher costs.

Today, most compressors are oil-cooled. The issue is now the art of separating the oil from the compressed air to the greatest extent possible with few, simple means. Oil flows as large or small drops and as vapor. Vapor results when compressors have poor cooling systems, small oil coolers, and when the radial play of the rotors increases (i.e. doubling or tripling the amount of vapor). Low compression temperatures require high density in the compression area, e.g. dual-stage compression with efficient intermediate cooling and optimal oil injection for cooling purposes in the compressor. It must be taken into consideration that the thermometer at the compression unit exit does not measure the air temperature but rather the oil temperature, because oil sticks to the sensor while air flows past.

As mentioned already, Pneumofore was carrying out intensive research into oil separation in oil-cooled compressors as early as 1930, accumulating vast experience that has made Pneumofore a leader both then and today. The intensive oil injection system was a great step forward for oil separation. Temperatures that

Image 6 - Compressor UR9, 35 - 55 kW

are approximately 50°C lower result in larger oil drops, which can be caught much more easily than a vapor of small droplets or aerosol. Larger drops of oil can be separated using centrifugal and gravitational forces. The elevation required for optimizing this process led to the vertical design. This layout makes more cooling space available as well.

Environmental protection also requires saving energy, and not only on paper. Intensive oil injection is the only known way of influencing the compression process thermodynamically. As can be seen on the entropy diagram, (**Img. 3**), compression is isothermal in the area subject to intensive oil injection.

The direct, coaxial coupling of the motor and the compression unit increases the cost of the unit, because each unit requires a different motor size. The advantage is efficiency and trouble-free power transmission.

The belt drive used in screw compressors up to 400 kW allows the assembler to build several units using only one compression unit, merely by adjusting the transmission ratio. The loss of energy (2 – 4%) through the belt drive is the disadvantage, which has a greater impact in the case of larger units and leads to replacement after about 5000 hours of operation.

When the same compressor unit is used for range of 3,000 to over 6,000 rpms, it is often forgotten that the compression unit (energy waster!) also has an ideal speed at which the specific energy requirement is smallest.

Saving Energy—Our Expertise!

Energy conscious compressor manufacturers use only electric motors with direct coupling, produce only air-cooled units and efficient control systems. In these areas, Pneumofore has clear environmental and energy savings goals. Only few manufacturers are able to fulfill this series of objectives.

Belt vs. Direct Coupling

Belt drives provide greater flexibility in manufacturing, because by changing the belt gear diameter, the same compression unit can be used for quantities of delivered air ranging from 1 to 3. Through optimized belt drive systems, slippage can be reduced. But since some slippage remains - although it has been reduced - and the V-belts are not all the same length, approximately 4% of total output is lost through transmission. Those who do not believe this should touch such belts after they have been in use for a longer period of time. If the belts are warm, energy loss has occurred. This does not play a major role for 4 kW units, but it is all the more important for 250 kW units: 4% of 250 kW is 10 kW!

Water or Air Cooling Systems?

"It comes from the sky and returns to the sky." We continue to live with the same water that was formed millions of years ago. The number of inhabitants on earth has increased many thousand fold, but the same amount of water remains with us and it is increasingly polluted. Cleaning dirty water is a very expensive procedure. It is the duty of humankind to conserve water and energy. Too often we hear the mindless comment, "Why save energy? After all, we have outlets ... ".

For this reason, Pneumofore has made a commitment to manufacturing only air-cooled compressors up to 315 kW and vacuum pumps up to 3240 m^3/h. It is very clear that air cooling systems for industrial compressors running at full capacity entail higher costs for radiators than small water/oil heat exchangers. In addition, the treatment of cooling water, which may contain oil and metal residues, is also expensive.

Water containing calcium carbonate leads to residue and overheating. When water is softened, corrosive free ions may be released result. Cooling towers distill water, which forms calcium carbonate residue, and salt water is corrosive. The already high cost of water treatment continues to increase.

These are all arguments in favor of air cooling. This solution requires large-scale oil coolers, however. For cost reasons, oil coolers are often installed that are too small. In the summer, or in warm or hot climates, air cooled compressors often run in rooms where doors are left open. Modern air-cooled compressor units are easier to manage and service, because temperatures are self-regulated thermostatically. (**Img. 6** Mod. UR9, 35 - 55 kW).

Control Systems

Various types of control systems are used to attempt to save energy, i.e., through turn valves, lowering operating temperatures, avoidance of long idle times, and use of the smallest compressor for a given application. Nevertheless, all of these measures are secondary solutions; they do not solve the root cause of the problem. Why not study primary energy consumption in detail during compression and control the compression process thermodynamically? Expensive basic research does not necessarily lead directly to results; what is required is harmonious cooperation between theory and years of practical experience. This is easily said, but difficult to carry out (**Img. 5** Cutaway Mod. UR26).

Eighty years of research, design, and production at Pneumofore have laid the foundation for further development in reducing energy consumption and provinding the highest possible purity of compressed air. The ongoing improvement of Pneumofore products and satisfaction of customer needs will remain the mission, however challenging, of the firm's next generation.

Robert Hilfiker was trained as an engineer at the ETH (Swiss Federal Institute of Technology) in Zurich and completed an apprenticeship abroad before joining Pneumofore, the company founded by his father, in Turin, Italy. As the Managing Director of Pneumofore, Mr. Hilfiker has led our company through growth and success for over 50 years. He passed away on June 2006 and is succeded by his son Daniel Hilfiker, who actively joined the firm in 1995.

* Translator's note: The German title "Verdichten und Wahrheit" refers to Johann Wolfgang von Goethe's early literary work Dichtung und Wahrheit [Poetry and Truth].

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