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Different Operational Modes for Refrigeration Twin-Screw Compressors

L. Sjoholm

DIFFERENT OPERATIONAL MODES FOR REFRIGERATION TWIN-SCREW COMPRESSORS

Lars Sjöholm

Svenska Rotor Maskiner AB (SRM)
Box 15085
S-104 65 Stockholm, Sweden

ABSTRACT

Three different operational modes for the refrigeration twin-screw compressor are discussed: oil-free, oil-reduced and oil-flooded.

By oil-reduced operation is meant the case when the oil/gas ratio is about 1 % by weight and the oil is circulated in the refrigeration system. In the oil-reduced mode the rotors work without timing gears - as in the oil-flooded mode. Advancements in profile design and rotor manufacture have made this possible.

Performance test results are shown and the different operational modes are also discussed from application point-of-view.

INTRODUCTION

Today's twin-screw compressor is the result of developments that started in the early 1930's.

It was first introduced into the refrigeration industry in the late 1950's. Since then it has been adapted to many other applications and the capacity range has been widened consideri-ably.

At present the twin-screw compressor is manufactured in capacities from 10 to 10 000 m^3/h (6 - 6000 CFM) for refrigeration and air-conditioning applications and up to 60 000 m^3/h (35 000 CFM) for general purpose.

BACKGROUND

The twin-screw compressor consists of two mating, helically grooved rotors "male and female" in a stationary housing with inlet and outlet ports. The flow of gas in the rotor grooves is mainly axial. Common lobe combinations are 4-6, 5-6 and 5-7.

Rotor Profiles

Helical rotor design has evolved over the years starting with an asymmetric, basically point-generated rotor profile 1935, used in compressors with timing gears (dry compression).

The symmetric "circular" rotor profile was introduced 1947, mainly because it was easier to manufacture than the preceding profile. Later, it proved to be possible to operate oil-flooded compressors without timing gears using this profile.

The asymmetric, point- and line-generated profile was introduced 1967, as the result of studies regarding profile optimization. Performance was improved and female rotor drive became feasible with this profile.

During the 1980's the helical rotor design has spread out to a large family of rotor profiles and lobe combinations, designated for different applications and manufacturing methods/rotor materials. The rotor profile is normally asymmetric and line-generated (Fig. 1). Lobe combination, rotor profile, "blowhole", length of sealing line, quality of the mesh seal, torque transfer between rotors as well as clearances can be optimized for each set of conditions, such as pressures, temperatures, speeds, operational mode etc. Optimum rotor tip speed is 15-40 m/s (50-130 ft/s) for oil-flooded operation, 25-70 m/s (80-230 ft/s) for oil-reduced operation and 60-120 m/s (200-400 ft/s) for oil-free operation.

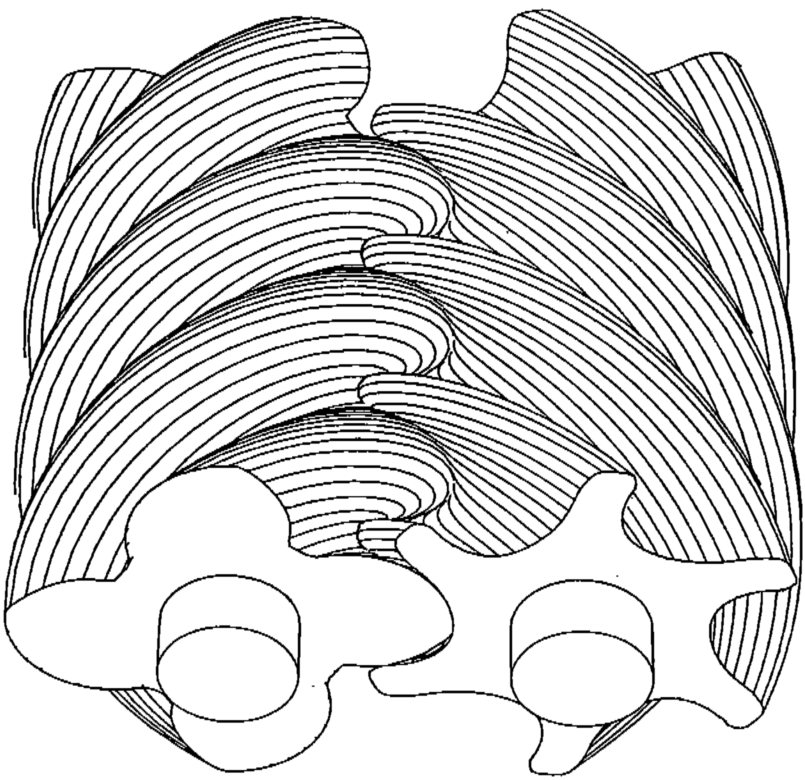

FIG. 1: ROTORS* TO A TWIN-SCREW COMPRESSOR

*ROTOR PROFILE: SRM D-2-B

Rotor Contact

The contact between non-synchronized rotors is mainly of rolling nature, at a contact band on each rotor's pitch circle. Very little sliding is encountered and virtually no rotor wear occurs. With the latest profile designs, with specially tailored contact conditions, oil-reduced operation has become possible.

Rotor Torque

On the male rotor, the internal gas forces always create a torque that acts in a direction opposite to the direction of rotation. This has been called "positive" or braking torque.

On the female rotor, the average torque can be chosen positive, negative or zero. Negative torque means that the internal gas forces tend to drive the rotor. If the average torque is near zero, the rotor is subjected to torque reversals when going through its phase angles, which under certain conditions can cause instability problems. This has to be avoided and a stabilizing female rotor torque of sufficient magnitude can easily be handled by the mesh, due to the good gear action.

Male rotor drive: The torque transmitted from male rotor to female rotor is normally 5 - 25 per cent of input torque.

Female rotor drive: The torque transmitted from female rotor to male rotor is normally 50 - 65 per cent of input torque.

Rotor Loads

The rotors are subjected to radial, axial and tilting loads. (Tilting loads: radial loads due to axial loads outside rotor centre line). The axial load is normally balanced with a balancing piston for larger, high pressure machines (rotor diameter above 150 mm (6 inch) and pressure above 1.1 MPa (160 psia)). The balancing force is created by high-pressure gas or oil.

Bearings

Radial: Sleeve bearings have been most common for larger compressors (male rotor diameter larger than 150 mm (6 inch)) but antifriction bearings are being used more and more, even for larger compressors; in compressors for oil-reduced operation, they are mandatory.

In smaller compressors, the antifriction type is most practical. Antifriction bearings in this context can mean cylindrical or tapered roller bearings as well as ball bearings.

Axial: Most common are angular contact ball bearings, but tapered or axial roller bearings are also used, mainly for smaller compressors.

General: Low-pressure compressors have long, large displacement rotors. The space available for the bearings is sufficient as the rotor loads are light. These compressors are normally designed without thrust balancing pistons.

High-pressure compressors have short and stiff rotors (shallow grooves) and therefore have space for large bearings. High-pressure compressors are normally designed with balancing pistons but smaller compressors can often get adequate bearing life without them.

Rotor Materials

The rotors are normally made of ferrous materials but also aluminum and plastics are feasible for certain applications.

OIL-FLOODED OPERATION

In oil-flooded screw compressors the oil is injected at a rate of about 1 % of the displacement volume flow. Part of this oil is used for lubrication of bearings and shaft seal prior to injection.

Historically, the large oil flow was needed for the following reasons:

1) Sealing - but with modern profiles and better rotor manufacturing methods the rotors can form an adequate seal without oil-flooding, at least for lower pressure ratios;
2) Cooling - but for refrigeration systems, liquid refrigerant injection can be used. The inevitable performance loss has with the latest rotor profiles decreased significantly;
3) Lubrication - but correct design of rotor contact and torque transmission as well as matched rotor materials make the compressor less dependent of rotor lubrication.

The type of lubricant is normally a naphtenic base mineral oil but synthetics like polyalphaolefines (PAO) are taking over more and more.

Oil is injected into intermediate pressure region through ports, either situated in a slide valve or through stationary ports in the casing.

The oil is separated out from the gas by gravity or centrifugal force. The oil carry-over is about 1 % by weight with those methods. If the refrigeration system does not allow any oil return, the oil carry-over is designed to be about 50 PPM and this is achieved with coalescing filters.

Figure 2 shows the oil-flooded twin-screw compressor in the refrigeration system.

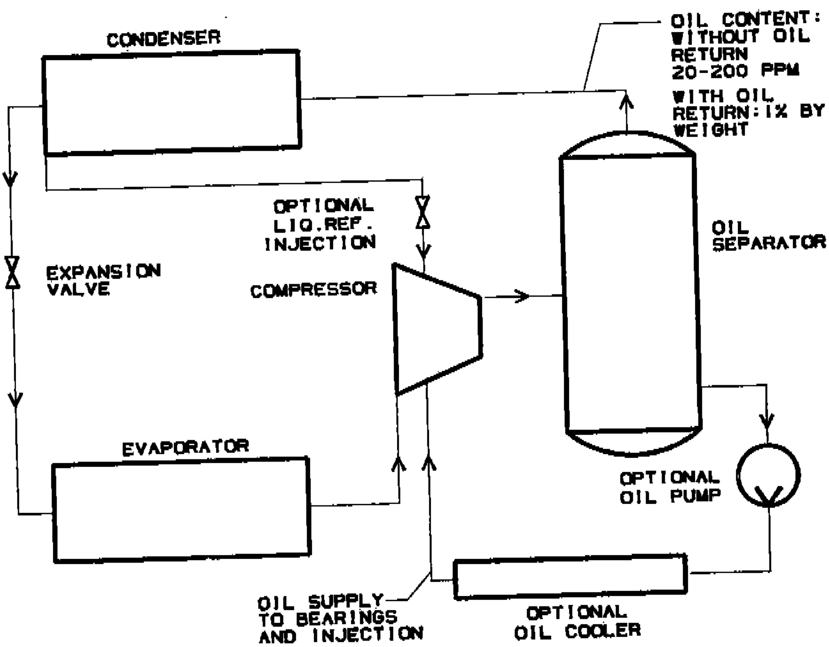

FIG. 2: THE OIL-FLOODED TWIN-SCREW COMPRESSOR IN THE REFRIGERATION SYSTEM

Performance Test Results

Smaller Compressor

Compressor: twin-screw*

Operation : oil-flooded

Rotors : 5-6 (male-female) lobe combination
Asymmetric, line-generated rotor profile**
Male rotor diameter: 113.4 mm (4.465 inch)
Male rotor material: steel
Female rotor diameter: 95.8 mm (3.772 inch)
Female rotor material: nodular iron
Rotor length: 150 mm (5.91 inch)

Clearances: discharge end: 0.04 - 0.07 mm
(0.0016 - 0.0028 inch)
interlobe: 0.005 - 0.04 mm
(0.0002 - 0.0016 inch)

Rotor shaping method: single-index milling to final shape

Bearings: Radial: cylindrical rollers
Axial: cylindrical rollers

Displacement: 175.3 m^3/h (103.2 CFM) at 3550 RPM

Male rotor tip speed: 21 m/s (69 ft/s)

Built-in volume ratio: optimal within 2.0 - 5.7

Lubricant: PAO ISO 200

Oil flow: 20 - 30 l/min (5.3 - 7.9 GPM)

Oil temperature: 45°C (113°F)

Performance for R22, see figure 3. (Definition of isentropic efficiency, see reference (1)).

* SRM K 318
** SRM D-3-13

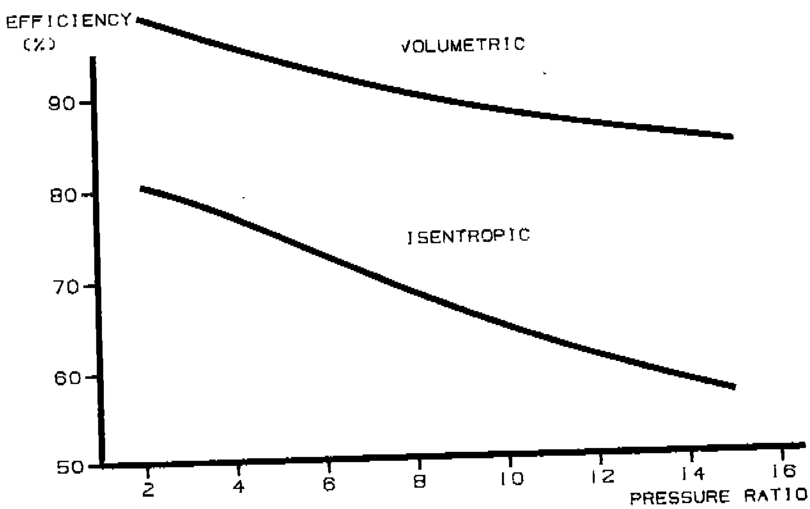

FIG. 3: OIL-FLOODED TWIN-SCREW COMPRESSOR,
TEST RESULTS
DISPLACEMENT = 175,3 m3/h (103,2 CFM) AT 3550 RPM
R22, COND.TEMP. = 40°C (104°F)

Larger Compressor

Compressor: twin-screw*

Operation: oil-flooded

Rotors: 4-6 (male-female) lobe combination
Asymmetric, line-generated rotor profile**
Male rotor diameter: 204 mm (8.03 inch)
Male rotor material: steel
Female rotor diameter: 204 mm (8.03 inch)
Female rotor material: steel
Rotor length: 336.6 mm (13.25 inch)

Clearances: discharge end: 0.05 - 0.06 mm (0.0020 - 0.0024 inch)
interlobe: 0.035 - 0.105 mm (0.0014 - 0.0041 inch)

Rotor shaping method: single-index milling to final shape

Bearings: Radial: sleeve
Axial: angular contact ball (with thrust balancing)

Displacement: 1222 m^3/h (719.2 CFM) at 3000 RPM

Male rotor tip speed: 32 m/s (105 ft/s)

Built-in volume ratio: optimal within 2.2 - 4.8

Oil flow: 115 - 138 l/min (30 - 36 GPM) for R717
82 - 93 l/min (22 - 25 GPM) for R22

Oil temperature: 45°C (113°F)

Performance for R22 with PAO ISO 68 lubricant, see figure 4.

Performance for R 717 with mineral oil naphtenic base ISO 66, see figure 5.

* SRM K 526
** SRM D-2-B

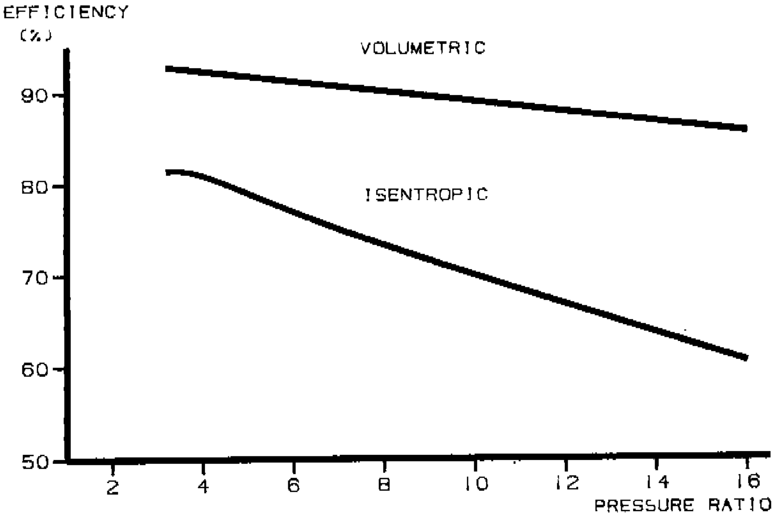

FIG. 4: OIL-FLOODED TWIN-SCREW COMPRESSOR.
TEST RESULTS
DISPLACEMENT = 1222 m3/h (714,2 CFM) AT 3000 RPM
R22, COND.TEMP. = 40°C (104 F)

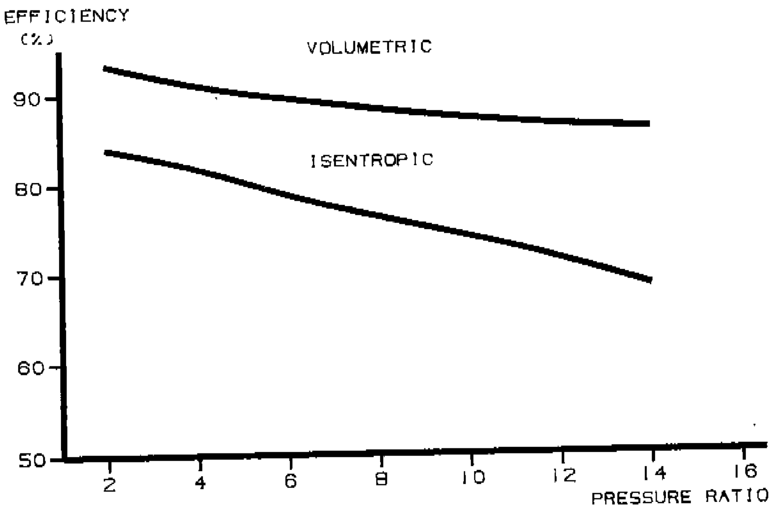

FIG. 5. OIL-FLOODED TWIN-SCREW COMPRESSOR,
TEST RESULTS
DISPLACEMENT = 1222 m3/h (714,2 CFM) AT 3000 RPM
R717, COND.TEMP. = 40°C (104°F)

OIL-REDUCED OPERATION

The operation can be called oil-reduced when the oil/gas ratio is about 1 % by weight, which corresponds to about 0.03 % of displacement volume. The oil is circulated within the refrigeration system. This means that the oil-reduced operation eliminates the need for the entire oil system typical for oil-flooded compressors.

Since there is no oil separator in an oil-reduced system, the lubricant selected can have high solubility/miscibility which gives good oil-return characteristics. Examples of such lubricants are alkylated benzenes and fluorocarbon lubricants.

The total amount of oil needed for an oil-reduced compressor system is normally 20 - 40 times less than for an oil-flooded system.This means that the money can be spent on a more sophisticated lubricant (longer life, better lubricity) when the compressor is oil-reduced.

The bearings are oil mist lubricated. Figure 6 shows the oil-reduced twin-screw compressor in the refrigeration system.

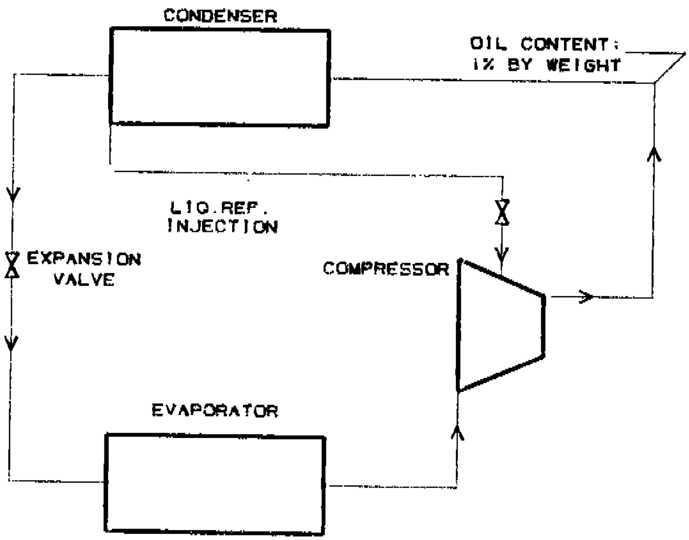

FIG. 6. THE OIL-REDUCED TWIN-SCREW COMPRESSOR IN THE REFRIGERATION SYSTEM

Oil-reduced operation without timing gears is possible if due attention is paid to the tribological conditions in the contact zone.

The performance achievable with an oil-reduced compressor is about the same as for an oil-flooded compressor up to a pressure ratio of 8. A rotor profile with very high sealing quality contributes to this. It should be pointed out that in this context the performance figures given are valid for the "bare" twin-screw compressor. In the refrigeration system, the oil-reduced compressor is not subjected to pressure drop losses over an oil separator, resulting in a corresponding increase in the overall efficiency.

In an oil-flooded compressor the main performance loss is due to a high content of refrigerant dissolved in the oil. This refrigerant-rich oil is returned to an intermediate pressure region by the external oil system and some of this oil leaks to regions with still lower pressure. When the oil is exposed to lower pressure some of the dissolved refrigerant evaporates. This type of loss is eliminated in the oil-reduced compressor.

The discharge temperature is limited by injection of high pressure liquid refrigerant when necessary. Two cases of liquid refrigerant injection can be observed:

1) Discharge temperature is above saturated condition. The amount of liquid refrigerant injected is normally less than 2 % of displacement volume. This type of discharge temperature control is also used for oil-flooded operation.

   Below a pressure ratio of 8 the quantity needed is small and the performance deterioration rather insignificant. Below a pressure ratio of about 4 there is no need to inject liquid refrigerant from temperature point-of-view. These values are valid for R22. R12 and R114 are even more favorable in this respect.

2) Discharge temperature is at saturation point. Here the compressor can be said to be flooded with liquid refrigerant and liquid refrigerant exists in the discharge gas. The amount of high-pressure liquid is normally 0.2 - 0.5 % of displacement volume.

A liquid-refrigerant-flooded compressor must be oil-reduced or completely oil-free because the oil separation system for an oil-flooded compressor cannot tolerate a saturated condition.

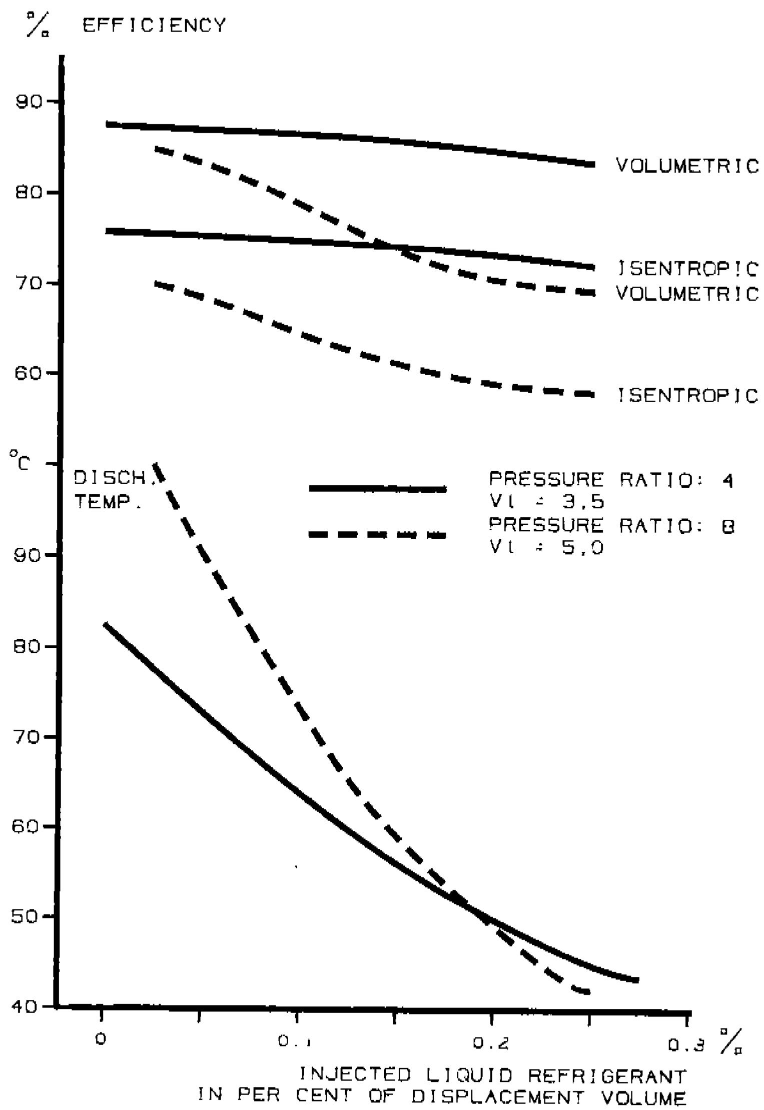

FIG. 7: PERFORMANCE VERSUS LIQUID REFRIGERANT INJECTION RATE
OIL-REDUCED TWIN-SCREW COMPRESSOR,
DISPLACEMENT = 517,5 m3/h (304,6 CFM) AT 2980 RPM
R22, COND.TEMP. = 40 C (104°F)

The liquid refrigerant has poor sealing qualities, since if it "seals" it leaks and when it leaks, it will evaporate and create losses. This is true unless the liquid refrigerant is subcooled to evaporator temperature, which cannot be done "free of charge".

Test results in figure 7 show that the performance always decreases with larger amounts of liquid refrigerant. These test results indicate that the oil-reduced compressor shows better performance with superheated discharge temperature than with saturated discharge temperature (liquid-refrigerant-flooded), especially at high pressure ratios.

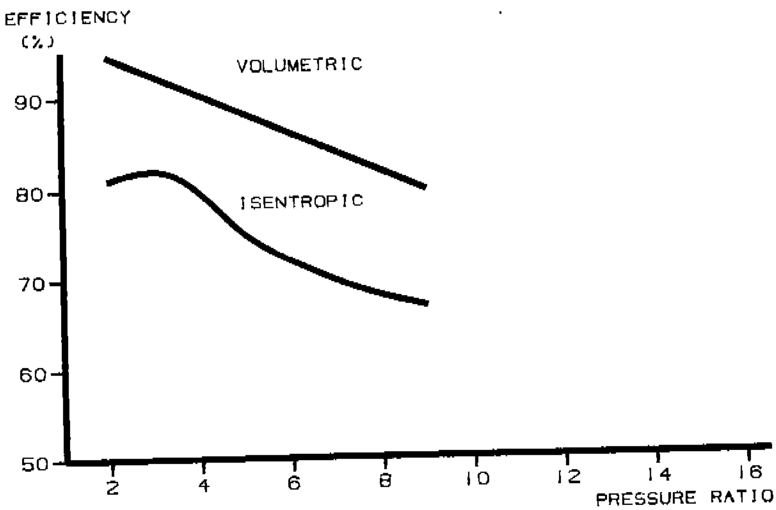

FIG. 8. OIL-REDUCED TWIN-SCREW COMPRESSOR,
TEST RESULTS
DISPLACEMENT = 517,5 m3/h (304,6 CFM) AT 2980 RPM
R22, COND.TEMP. = 40°C (104°F)

Performance Test Results

Compressor: twin-screw*

Operation: oil-reduced

Rotors: 4-6 (male-female) lobe combination
Asymmetric, line-generated rotor profile**
Male rotor diameter: 163.2 mm (6.425 inch)
Male rotor material: steel
Female rotor diameter: 163.2 mm (6.425 inch)
Female rotor material: nodular iron
Rotor length: 220 mm (8.66 inch)

Clearances: discharge end: 0.04 - 0.05 mm
(0.0016 - 0.0020 inch)
interlobe: 0.025 - 0.130 mm
(0.0010 - 0.0051 inch)

Rotor shaping method: single-index milling to final shape

Bearings: Radial: cylindrical rollers
Axial: angular contact ball

Displacement: 517.5 m^3/h (304.6 CFM) at 2980 RPM

Male rotor tip speed: 25.5 m/s (83.7 ft/s)

Built-in volume ratio: optimal within 2.2 - 5.0

Lubricant: alkylated benzene ISO 98

Oil/gas ratio: about 1 % by weight

Discharge temperature: 75 - 95°C (167 - 203°F)

Injected liquid refrigerant: 0 - 7 l/min (0 - 1.8 GPM)

Performance for R22, see figure 8.

* SRM K 314
** SRM D-2-8

OIL-FREE OPERATION

Since the rotors in a twin-screw compressor are parallel, timing gears are very practical and this was also the original design. The rotors run without contact and the compressor working chamber does not require any lubricant.

Synchronized twin-screw compressors are historically known as noisy, high-speed machines with a limited pressure ratio capability. However, the advancements also on the dry compressor scene may justify a renewed consideration for this type of machine, e.g. in cases where absolutely no oil can be tolerated in the refrigeration system.

With new rotor profiles and temperature-compensated clearances, lower tip speeds (resulting in lower noise levels) and higher pressure ratios can be achieved.

CONCLUSIONS

The versatility of the basic twin-screw concept has been demonstrated by the fact that quite different operational modes are possible. The compressor can be adapted to very specific needs without loosing its favourable characteristics as a heavy duty machine with high performance.

Based on this, an extrapolation into the future will indicate that:

- the oil-flooded twin-screw compressor will continue to have a given place for refrigeration, heat pump and air-conditioning applications;

- the oil-reduced twin-screw compressor will probably find its place in smaller heat-pumps and air-conditioning applications;

- the oil-free twin-screw compressor will continue to have its given place in larger process-refrigeration applications and has a chance in larger air-conditioning systems and in refrigeration booster applications.

REFERENCE

1) Lundberg, A and Glanvall, R.
A Comparison of SRM and Globoid Type Screw Compressors.
Purdue Compressor Technology Conference (1978).

SINGLE STAGE, OIL-FREE SCREW COMPRESSOR WITH A COMPRESSION RATIO OF EIGHT

Hidetomo Mori[1], Katsuhiko Kasuya[1], Mitsuru Fujiwara[1], Katsumi Matsubara[1], Akira Suzuki[2], and Masakazu Aoki[2]

[1]Mechanical Engineering Research Laboratory, Hitachi, Ltd.,Tsuchiura, Ibaragi, Japan
[2]Ebina Branch, Narashino Works, Hitachi, Ltd., Ebina, Kanagawa, Japan

ABSTRACT

The development of a series of single-stage, oil-free screw air compressors with a compression ratio of 8, previously obtainable only with two-stage compressors, is described. A new rotor profile, which reduces leakage loss to achieve higher efficiency, and designed for ease of manufacture,is detailed. Additionally, a new design method for the clearance between rotors, to compensate for rotor deformation due to thermal expansion, is also introduced. This oil-free, screw air compressor with a rating of 37-55 kW has been marketed since 1982 and 15-22 kW since 1984.

INTRODUCTION

Oil-free air compressors having a discharge pressure of approximately 0.8 MPa (8 ata), and widely used in electrical, food and chemical industries were traditionally reciprocating type compressors. Recently, however, the advantages of oil-free rotary screw compressors have been recognized. These include mechanical simplicity, high reliability,low noise and low vibration. Two-stage, oil-free screw air compressor use has predominated in the capacity range above 550 m^3/h (motor power above 65 kW).
Nevertheless, for compressor capacity below this range, where oil-free air is needed, this type of compressor was not available.