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WEAR TESTS METHODOLOGIES OF RECIPROCATING HERMETIC COMPRESSORS: AN OVERVIEW

Igor Marcel Gomes Almeida
Federal Institute of Rio Grande do Norte. Av. Salgado Filho, 1559, Tirol. Natal-RN. Brazil.
igor.almeida@ifrn.edu.br
Cleiton Rubens Formiga Barbosa
Francisco de Assis Oliveira Fontes
João Telesforo Nóbrega de Medeiros
Department of Mechanical Engineering. Federal University of Rio Grande do Norte. Av. Salgado Filho, S/N, Lagoa Nova. Natal-RN. Brazil.
cleiton@ufrnet.br; franciscofontes@uol.com.br; joaotelesforo@yahoo.com

Abstract. *The refrigerants being used in vapor compression processes have specific thermodynamic properties, which are decisive for the performance of the compressor of the system. The Montreal and the Kyoto protocols initiated a discussion of alternative refrigerants, which lead to new requirements of the compressor. The reliability of reciprocal compressors has become a leading field for compressor research. One of the main tools in the reliability field is accelerated life testing (ALT). These tests are designed to provide life estimates or to define lower bounds of product/parts reliability at shortened periods of time. The objective of this paper is to discuss the literature on accelerated life testing of reciprocating hermetic compressors, focusing on the wear of mechanical components. Several test methodologies are discussed as well as the procedures used to wear quantification. It is noted that there are numerous test methodologies. This fact can be attributed to the lack of standardization updated. Most authors directs the tests development to assess the scuffing occurrence in components. The evaluation of wear (qualitative and quantitative) is carried through optical microscopy techniques, scanning electron microscopy, surface roughness, physical-chemical analysis of the oil and electric power consumption. Test methodologies are presented based on critical analysis of the existing literature and the current scenario of refrigerants and lubricants development.*

Keywords: *hermetic reciprocating compressor, wear, accelerated life test*

1. INTRODUCTION

The refrigerants being used in vapor compression processes have specific thermodynamic properties, which are decisive for the performance of the compressor of the system. The Montreal and the Kyoto protocols initiated a discussion of alternative refrigerants, which lead to new requirements of the compressor (Suess et al., 2000).

The last two decades are characterized with various pressures on synthetic refrigerants from the point of their environmental effects. The first wave was due to ozone depletion when excellent-performing and easy-to-work-with CFCs were replaced with HFCs. The recent pressure is due to the global warming impact of HFCs (Hrnjak, 2010).

The request of new low GWP options based on either synthetic (man made) refrigerants or natural (naturally occurring) materials have to offer high efficiency in addition to environmental friendliness and safety for people and property. That situation will open new possibilities for drop in of synthetic refrigerants.

As conventional refrigerants phased out, isobutane (R600a) emerged as the main alternative in refrigeration industry. Hydrocarbons (HCs) such as R600a are viable substitutes as they possess favorable refrigerants properties. However, their compatibility and performance with compressor oils are being investigated (Sariibrahimoglu et al., 2010). In the operating conditions of domestic refrigerators, the R600a COP (at the optimized charge) is superior to both R134a and R12, however the long term wear and durability of equipment using this refrigerant is unknown.

As an example of how complicated our world can be, let's just look at compressor tribology (that is, lubrication of pistons, cylinders and bearings), with that of other machinery. Unlike changing the oil in your car, which is done often during the life of a vehicle, compressor oil for automobile and residential air conditioning, which is used under much more severe and extreme conditions, is rarely replaced. This fact alone speaks for a major technical accomplishment from Tribology perspective.

Although better COP values are achieved with HC refrigerants, wear life related issues need to be resolved since limited literature is available. Possible problem areas include motor/crankshaft journals; crank pin/connecting rod bearings, piston/cylinder sliding interface and the inlet/exhaust flapper valves (Na et al., 1997).

It is no exaggeration to suggest that simple, low cost, and precise bearings along with tribological capabilities are the critical force in supporting the advancement of today's compact and high-performance compressor (Nishioka, 1998).

The reliability of reciprocating compressors has become a leading field for compressor research. Quality control techniques are now known and have been shown to be efficient means to ensure quality at a short time horizon, allowing customers to focus on long term product quality features. Such features may be defined as product reliability measures. One of the main tools in the reliability field is accelerated life testing (ALT). These tests are designed to provide life estimates or to define lower bounds of product/parts reliability at shortened periods of time.

Compressors are designed to last for several years. The fast changing world and demand for new and improved products urges the use of design techniques that help to reduce the product development cycle time without jeopardizing the quality of the design process. This makes ALT an essential part in the compressor design cycle (Feldhaus and Coit, 1998).

The objective of this paper is to discuss the literature on accelerated life testing of reciprocating hermetic compressors, focusing on the wear of mechanical components. Several test methodologies are discussed as well as the procedures used to wear quantification. Test methodologies are presented based on critical analysis of the existing literature and the current scenario of natural refrigerants and lubricants. The aim is to strengthen the reliability study of the compressors with a view to using natural refrigerants and development of an more consistent theory of the mechanical parts degradation (wear), focusing in the systematic approach.

2. TRIBOLOGY AND TERMODYNAMIC RELIABILITY

Life and degradation tests of various forms are used to establish assurance that the compressor will perform over an extended period to satisfy the guarantee. They may be used to determine a possible weakness in design or the effect of surface variations on the life of the moving parts.

The modes of failure for a hermetic refrigeration compressor can be grouped into three general categories. These are, 1) electrical, 2) mechanical and 3) chemical. The mechanical group should be such failures as broken valves, broken connecting rods, broken suspension springs, assembly screws or bolts loosening with use, seized bearings or shafts, etc. Design techniques having advanced as they have, combined with good material and manufacturing control makes this group a small portion of the field returns (Erdman, 1972).

The tests with hermetic compressors are not run until failure. Their fundamentals for valuation are the physical and chemical changes determined after completion of the tests in the testing periods given or in the course of the test (Lorenz and Rochhausen, 1976). Accelerated degradation tests (ADT) has widely been used by manufacturers and testers for qualitative explanation of a degradation process, and comparative analysis. The degradation process obtained for different design aspects could be used to predict the most robust design to tolerate service stresses.

In reliability testing, most global companies focus on the accelerating life test (ALT). This method can help shorten the product development cycles, costs less money, and clarify diverse design faults. However, there are some caveats of using ALT: any failures after ALT may not represent those occurring under field conditions. This problem usually arises because of the inconsistency of the direction and magnitude of the load, such as force or pressure in system dynamics. Moreover, the number of test samples and the test times are insufficient to uncover infrequent failure modes. ALT should be performed with sufficient samples and test time, and ALT equipment can and should be designed to match product loads (Woo and O´Neal, 2006).

Refrigerator reliability problems in the field often occur when the refrigerator parts cannot endure the repetitive stresses due to internal or external forces over a specified period of time. When the energy flow in the refrigeration system can be expressed as the product of an effort and a flow variable, forces may be generally expressed as efforts. Efforts and flow in the hermetic compressors are represented by the pressure differential (ΔP) and refrigerant volume flow rate (Woo et al., 2011).

2.1. Scuffing wear context

A few among many otherwise highly successful lubricated sliding components fail catastrophically and without warning. This sudden mode of failure is often called scuffing. The phenomenon of scuffing has been known for many years and numerous attempts have been made to define it (Yoon and Cusano, 1999).

Scuffing is another tribological failure, which is of major concern for compressor manufactures as it occurs abruptly, leading to complete destruction of the sliding pair, thus rendering the device non-functional (Demas et al., 2005 *apud* Mishra and Polycarpou, 2011).

In the context of air conditioning compressor surfaces, the understanding of the scuffing mechanism can provide insight to avoiding detrimental component failure and result in an increase in operational lifetime (Suh et al., 2006).

Previous studies have shown the piston pin/connecting rod bearing to be the most susceptible since, for the domestic refrigerator compressor, only the gudgeon pin/small end bearing operates within the boundary lubrication condition, the others being hydrodynamic journal bearings. Figure 1 shows the friction parts of reciprocating compressors.

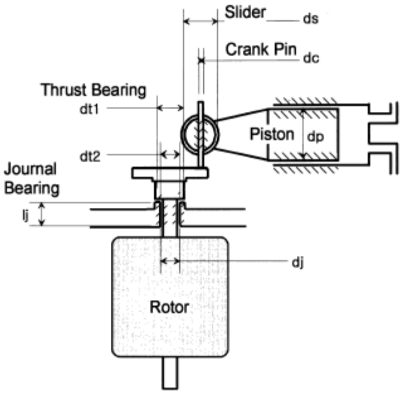

Figure 1. Friction parts of reciprocating compressor (Adapted from Na et al., 1997).

One such contact in a reciprocating compressor is the conforming connection between the die-cast aluminium alloy connecting rod and the hardened steel gudgeon pin. Under normal operation, conditions are similar to hydrodynamic lubrication, but at stop/start, condition is similar to boundary lubrication (Ciantar et al., 1999).

Scuffing causes catastrophic damage on tribological surfaces, mainly affecting the topmost surface layers at depths ranging from sub-micron to micron. Factors influencing scuffing include contact pressure, sliding velocity, contact temperature, lubricant and lubrication regime, surface topography, material composition and structure, and film coatings of surfaces in contact (Suh et al., 2006).

The reason why scuffing remains a poorly understood phenomenon is that it involves various damage mechanisms such as mechanical, chemical, metallurgical, and thermal reactions (Cho and Lee, 2011).

Recently, it has been suggested that the main cause of scuffing is associated with subsurface failure. Tests has been developed under dry sliding conditions and starved lubrication. Figure 2 presents the tribo-contact structure and levels of interaction.

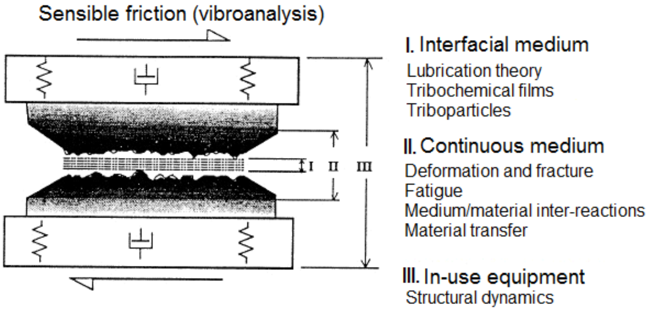

Figure 2. Heterogeneous real tribo-contact interactions. (Bulnes et al., 2012)

Scuffing failure originates at the internal parameters level (level I), however catastrophic aspects are late detected (*post-mortem*) on the external level (levels II and III). Scuffing prevention can be carried through the reliability based on tribology (RBT) focused on surface texture topology optimization (level II), certainly the texture affects the lubrication regimes. That is, ultimately, affects the friction, but only in boundary lubrication regime, where there is partial metal-metal contact.

Thus, it is evident that a RBT involves many complex issues that has to do mainly with the internal parameters, external to a lesser extent, and certainly unexpected parameters that affect what we mean by friction. The relationship between these parameters results in a complex problem, it is not possible to establish application limits of the concepts involved. You can only establish probable "tribological behaviour" of the system (Bulnes et al., 2012).

However, in addition a certain fascination with wear processes exists based on the idea that since wear is such a universally observed process it may be directly related to the fundamental nature of materials and processes (Klamecki, 1980).

There are many different methods and standards which are used for wear evaluation, besides a branch between methods used for experimental research on wear, friction and lubrication of the compression mechanism. Many authors use specific standards for wear tests on metallic specimens used in compressors (phenomenological) by using of tribometers and machines for evaluating lubricity of oil/refrigerant blend. These authors are concerned with the development of new materials and surface coatings (Yoon et al., 1998; Garland and Hadfield, 2005; Sariibrahimoglu et al., 2009; De Mello et al., 2009).

Moreover, some authors focusing on the compressor evaluation as a component of the overall refrigeration system. This favors obtaining a result more consistent with the actual situation of the component application. These authors apply different methodologies for accelerating the compressor life for tribological analysis purposes, based on the actual load parameters (Safari and Hadfield, 1998; Ciantar et al., 1999; Ciantar, 2000, Woo and O'Neal, 2006; Woo et al., 2011).

2.2. Accelerated life tests

Accelerated testing is a powerful tool that can be effectively used in two very different ways: in a qualitative or in a quantitative manner. Qualitative accelerated testing is used primarily to identify failures and failure modes while quantitative accelerated testing is used to make predictions about a products life characteristics (e.g., MTTF, B10 life, etc.) under normal use conditions.

Overstress testing (is the most common form of accelerated testing) consists of running a product at higher than normal levels of some accelerating stress(es) to shorten product life or to degrade product performance faster. Typical accelerating stresses are temperature, voltage, mechanical load, thermal cycling, humidity, and vibration (Nelson, 1992).

The stress loading in an accelerated test can be applied various ways. They include constant, cyclic, step, progressive, and random stress loading, according to Figure 3.

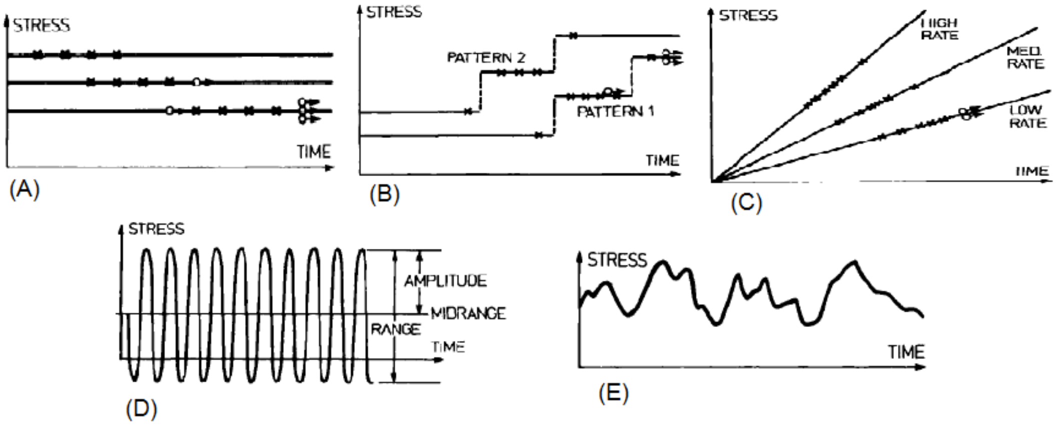

Figure 3 – Load stresses in accelerated tests: (A) constant, (B) step, (C) progressive, (D) cyclic e (E) random (Nelson, 1992).

Actually in the compressor, most of the contact of moving parts is through areas to make hydrodynamic lubrication. A compressor's working condition is not as severe compared to the standardized point or line contact test methods. Most of the wear occurs at the start and stop conditions in the compressor. The contact pressure between piston and slider is much less then pressure acting in the top face of the piston. So that this contact is not important and can be neglected (Na et al., 1997).

The contact area of the crank pin-slider (CP-S) is smaller than that of the piston journal-slider (PJ-S). Thus, the contact pressure of the CP-S is higher than that of PJ-S. Table 1 shows the typical stress factors for compressor testing.

Table 1. Summary of most common hermetic compressors ALT procedures: items, stress factors, and typical life period for the occurrence of a failure (Feldhaus and Coit, 1998).

Item	Typical Stress Factor(s)	Typical Life Period(s) of a Failure Occurrence
Bearings and moving parts (piston, wrist pin, valves, crankshaft, etc.)	Temperature (oil viscosity) Pressure differential (equivalent to mechanical load) Rotation	Constant failure rate phase Wear-out phase
Suction/discharge systems	Temperature Humidity Pressure differential Vibration	All phases of operational life
Oil	Temperature Humidity	Wear-out phase

The test under cyclic stress is configured as more consistent with the reality of hermetic compressors operation, since this component operates under the permanent cycling regime (on-off) in actual conditions. The stress (or life) of the compressor depends on the pressure difference suction pressure, P_{suc} , and discharge pressure, P_{dis}. Turning a system on and off will sometimes generate a failure mode (e.g., due to thermal cycling) that will not be seen in continuous testing.

The setting of the stresses applied to accelerated testing of hermetic compressors presents well divided in the literature. Some authors and standards (GOST 17240-1971, McAllister, 1972; Hansen and Finsen, 1992; Sekiya et al., 1998; Ciantar et al., 2000; Woo and O´Neal, 2006) apply the cyclic stress configuration, e.g. the compressor must operate intermittently. Another authors and standardization group (Lieding et al., 1972; DIN 8978, 1983; Iizuka et al., 1996; Sunami et al., 1996; Sunami et al., 1998; Sekiya et al, 1998; Slayton and Spauschus, 1998; Ciantar et al., 1999) apply the constant stress configuration, that is, the compressor should operate under a continuous regime.

2.3. Statistical approach

A statistical model for an accelerated life test consists of 1) a life distribution that represents the scatter in product life and 2) a relationship, between life and stress. A model depends on the product, the test method, the accelerating stress, the form of the specimen, and other factors.

Increasing the level of acceleration variables like temperature, humidity, voltage, or pressure can accelerate the chemical or other degradation processes related to specific failure mechanisms. If an adequate physically based statistical model is available to relate failure time to levels of accelerating variables, the model can be used to estimate lifetime or degradation rates at product use conditions (Meeker et al., 1998).

A more refined model employs a statistical distribution to describe the scatter in life. Thus the model here consists of a combination of a life distribution and a life-stress relationship. Commonly used theoretical life distributions include the exponential, lognormal, and Weibull distributions.

The relevant acceleration models that should be considered include: Arrhenius Temperature Acceleration for temperature and chemical aging effects, Inverse Power Law for any given stress, Miner's Rule for linear accumulated fatigue damage, Coffin-Manson non-linear mechanical fatigue damage, Peck's Model for temperature and humidity combined effects, Eyring/Black/Kenney models for temperature and voltage acceleration.

Many accelerated tests use elevated temperature to increase the rate of a chemical reaction or diffusion process and thereby reduce the life of the component. The data are then typically analyzed using the Arrhenius model relating life and temperature. A common yet dangerous practice is to presume that the effective activation energy fot the Arrhenius model is known instead using experimental data to estimate this quantity (Meeker et al., 2012).

Unfortunately, the mechanism of scuffing (severe adhesive wear) is so complicated that it is not easy to predict time to scuffing failures, because the process involves mechanical, chemical, metallurgical and thermal reactions. There is no developed literature in a statistical life and degradation model that considers sliding wear of metals.

A cumulative distribution function F (t) represents the population fraction failing by age t

$$F(t) = 1 - e^{-t/\theta}, t \geq 0 \tag{1}$$

$\theta > 0$ is the mean time to failure (MTTF). θ is in the same measurement units as *t*, for example, hours, months, cycles, etc. In some applications, life *t'* under design use is expressed in terms of life *t* at an accelerated test condition as

$$t = AF \cdot t' \tag{2}$$

Here *AF* is called the acceleration factor and is assumed known. As above, one can calculate equivalent times *t'* from accelerated times *t* and estimate the life distribution under design conditions. Typically, different failure modes have different acceleration factors. This is especially so for complex products consisting of assemblies of diverse components. With high overloads not being permissible additional failure mechanisms occur which are not in accordance with the actual failure behaviour (Lorenz and Rochhausen, 1976). Table 2 presents acceleration factors used for compressors testing available in the literature.

Table 2. Main acceleration factors for hermetic compressors wear tests stablished in literature.

Acceleration factor	Compressor type
Differential pressure at suction and discharge	Reciprocating, rolling piston, scroll
Rotational speed (rpm)/sliding velocity	Scroll, rolling piston
Liquid return (flooded cycle)	Rolling piston
Compressor housing temperature	Reciprocating
Number of cycles	Reciprocating, scroll, rolling piston

Woo and O´Neal (2006) presented a sequence of reliability testing, including ALT, they evaluated the compressor reliability with the new failure rate and B_x (shape parameter in a Weibull distribution) life. Authors have proposed the Arrhenius model (elevated temperature acceleration) to describe the time to failure. For medium stress, the life-stress model (LS model) has been proposed

$$T_f = A(S)^{-n} \exp\frac{E_a}{kT} = A(\Delta P)^{-n} \exp\frac{E_a}{kT} \tag{3}$$

where A and S are constants and are characteristics of the particular chemical reaction, T_f is the time to failure, k is Boltzman's constant, E_a is the activation energy, T is the absolute temperature and n is the quotient. The authors consider that the pressure differential (ΔP) develop by the compressor is the stress factor, inducing a chemical reaction (temperature elevation) at the friction parts.

The acceleration factor (AF) is given by:

$$AF = \left(\frac{S_1}{S_0}\right)^n = \left(\frac{\Delta P_1}{\Delta P_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \tag{4}$$

where S_1(or ΔP_1) is medium stress (or pressure difference), and S_0 (or ΔP_0) is normal stress.

Tribo-systems are in essence energy driven systems that are subject to thermodynamic constraints. Such constraints, represented in both entropy generation and transport, decide the state of integrity of the materials involved. That is, the degradation of the rubbing materials is also a thermodynamically driven process. The Arrhenius relationship is a simple model that will not adequately describe the effect that temperature has on all chemical reactions (Meeker et al., 2012).

3. WEAR TESTS OVERVIEW

3.1. Cycles architectures

Dirlea et al. (1996) proposed the hot (fully) gas cycle layout for compressors testing. A test point for refrigeration compressors is obtained by imposing three physical variables: pressure at compressor supply (P_{suc}), temperature at compressor supply (T_{suc}) and pressure at compressor discharge (P_{disc}). It can be concluded that the method is particularly suitable for long live tests and quality control of compressors. Due to the low charge of refrigerant (absence of condenser, evaporator, liquid receiver and accumulators), the method can be a useful tool in investigating compressors behaviour when using alternative refrigerants for which refrigerant charge of the plant is submitted to prescriptions, hydrocarbons for example. Figure 4 shows the cycle layout and the P-h diagram.

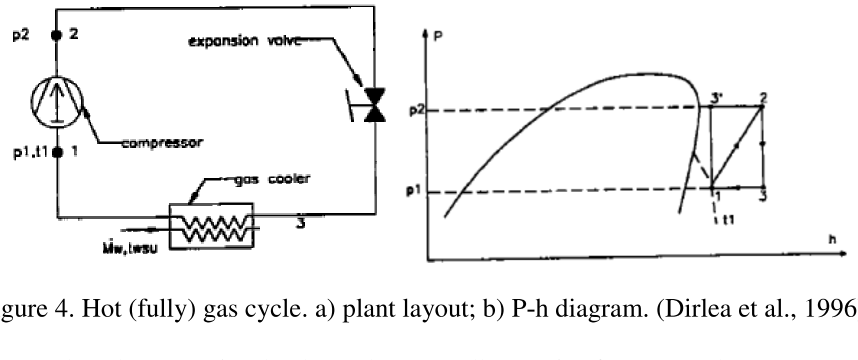

Figure 4. Hot (fully) gas cycle. a) plant layout; b) P-h diagram. (Dirlea et al., 1996)

Convention compressor bench tests using load stands, generally require from 2000 hours to 4000 hours (12 to 24 weeks). Slayton and Spauschus (1998) have proposed a short-term (200 hours), accelerated test protocol has been developed initially for rotary compressors used in air-conditioning and small heat pump applications. Figure 5 presents the cycle developed for the tests.

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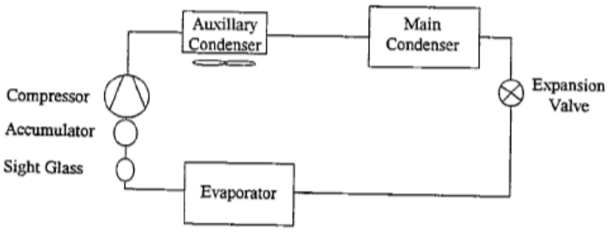

Figure 5. Floodback refrigerant circuit (Slayton and Spauschus, 1998).

At operating test pressures, a certain level of liquid floodback is provided and monitored by sight glass observations. The level of liquid floodback to provide appropriate test acceleration, within the 200 hour test period, was developed from designed experiments and correlated to actual field return compressor cut-apart analyses, to ascertain that the bearing wear modes were consistent with field experience.

Standard wear tests for hermetic compressors (DIN 1973) specify the use of test equipment which operates only in the vapor phase (hot gas). However, to evaluate the electric power required for hermetic compressors, using a vapor-liquid bench test comes closer to the actual refrigerator condition (Hansen and Finsen, 1992; Iizuka et al., 1996; Ciantar et al., 1999; Ciantar and Hadfield, 2004).

Ciantar and Hadfield (2004) designed a test rig (liquid/vapor phase) to evaluate the in-use power requirements of a hermetic compressor operating with a variety of working fluids. Tribological characteristics on concentrated contacts within these tested compressors were then studied to interpret any relationship between friction and wear and fluctuations in the monitored power. Figure 6 shows the test rig.

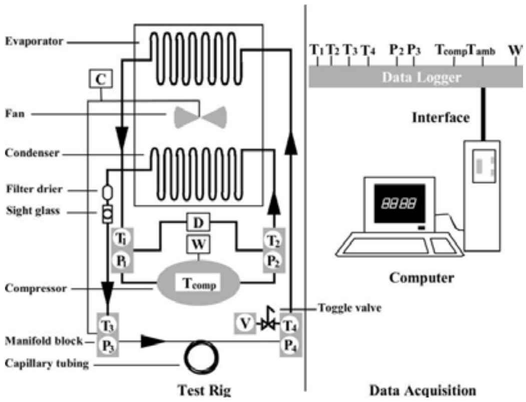

Figure 6. Schematic of compressor test rig (Ciantar and Hadfield, 2004)

3.2. Wear tests protocols

Table 3 shows a compilation of the major studies to wear evaluation of hermetic compressors. The table shows the compressor type, refrigerant used, the test rig and experimental methodology developed and techniques which are used to wear quantification on the components.

Table 3. Summary of wear tests protocols for hermetic compressors.

Author	Refrigerants/Lubricants	Compressor type/application	Test conditions	Evaluation
			- Standard vapor-liquid refrigeration cycle	Wear depth of reciprocating mechanical

Hansen e Finsen (1992)	R12, R134a, HCFC-22/HFC-152a/HCFC-124 blend Lubricants: AB, POE	Reciprocating/Domestic refrigerator	- P_{disc} = 2.16 MPa - P_{suc} = 0.26 MPa - Winding motor temperature = 150°C - Intermittent operation = 27 min (*on*)/3 min (*off*); - Duration = 2000-4000 hours;	components. Deposits in valves. Copper platting;
Iizuka et al. (1996)	R407C Lubricant: POE	Scroll/Air conditioner	Standard vapor-liquid refrigeration cycle High velocity P_{suc} = 0.40 MPa P_{disc} = 1.57-1.87 MPa Speed = 8250 rpm High load P_{suc} = 0.59 MPa P_{disc} = 2.85-2.94 MPa Speed = 5700 rpm Duration = 90 days (2160 hours); Continuous operation;	Surface roughness (Ra); Wear quantification of superior and inferior bearings;
Sunami et al. (1996)	R12, R134a, R22 Lubricants: AB, POE, Mineral oil.	Rolling piston/Air conditioner	- Fully gas cycle; - P_{suc} = 0.157 e 0.098 MPa; - P_{disc} = 2.94 e 1.67 MPa; - T_{disc} = 110 e 150°C; -Duration = 2000 hours; - Continuous operation;	Surface roughness (Ra) of sliding components: shaft, bearings, etc. Wear depth (mm).
Sunami et al. (1998)	R22, R407C Lubricants: AB, POE, Mineral oil.	Rolling piston/Air conditioner	- Fully gas cycle; - P_{suc} = 0.379 MPa; - P_{disc} = 2.85 MPa; - T_{disc} = 100°C; - T_{suc} = 6-17°C; - Duration = 500, 1000, 2000 e 5000 hours; - Continuous operation;	Surface roughness (Ra): sliding components; Physical and chemical lubricant analysis;
	R22, R410A		- Standard vapor-liquid refrigeration cycle; - P_{disc} = 4-4.5 MPa - P_{suc} = 0.7-1.0 MPa	Capillary tube clogging; Wear volume

<table>
<tr><td>Sekiya et al. (1998)</td><td>Lubricants: AB, POE, Mineral oil.</td><td>Rolling piston/Air conditioner</td><td colspan="3">- T_{disc} = 100-120°C
- Speed = 7200 rpm;
- Duration: 4000 hours;
- Continuous operation;
- Flooded compressor cycle (Intermittent = 3000 duty cycles)</td><td>quantification of sliding components;
Bearings wear depth (μm), in flooded starting test.</td></tr>
<tr><td>Slayton e Spauschus (1998)</td><td>R22
Lubricants: Mineral oil</td><td>Rolling piston/Air conditioner</td><td colspan="3">Flooded compressor cycle;
P_{suc} = 0.86 MPa
P_{disc} = 3.44/2.75 MPa
Duration: 200 hours;
- Continuous operation;</td><td>Surface roughness (Ra and Ry): rolling piston, bearings;</td></tr>
<tr><td rowspan="2">Safari e Hadfield (1998)</td><td rowspan="2">R134a
Lubricants: POE10, POE22, POE32</td><td rowspan="2">Reciprocating/Domestic refrigerator</td><td colspan="3">Standard vapor-liquid refrigeration cycle without evaporator;</td><td rowspan="2">Superficial damage and roughness analysis of polished surfaces: connecting rod, gudgeon pin and piston.</td></tr>
<tr><td colspan="3">P_{disc} = 2.76 MPa
P_{suc} = 0.14 MPa
Duration: 500 hours;
Continuous operation;</td></tr>
<tr><td rowspan="3">Ciantar et al. (1999)</td><td rowspan="3">R134a
Lubricants: POE10, POE22, POE32</td><td rowspan="3">Reciprocating/Domestic refrigerator</td><td colspan="3">Standard vapor-liquid refrigeration cycle;
T_{suc} = -10°C
T_{disc} = 90°C</td><td rowspan="3">Superficial damage and metal transfer in connecting rod e gudgeon pin: optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS).
Lubricant *debris* analysis.</td></tr>
<tr><td>POE10
P_{disc} = 2.66 MPa
P_{suc} = 0.08 MPa
$T_{housing}$ = 74.6°C
T_{room} = 21.36°C
Duration: 360 hours</td><td>POE22
P_{disc} = 2.7 MPa
P_{suc} = 0.114 MPa
$T_{housing}$ = 74.6°C
T_{room} = 21.4°C
Duration: 366 hours</td><td>POE32
P_{disc} = 2.49 MPa
P_{suc} = 0.087 MPa
$T_{housing}$ = 73.1°C
T_{room} = 21.4°C
Duration: 332 hours</td></tr>
<tr><td colspan="3">Continuous operation;</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">Standard vapor-liquid refrigeration cycle;</td><td></td></tr>
</table>

<table>
<tr><td rowspan="2">Ciantar et al. (2000)</td><td rowspan="2">R134a
Lubricants: PVE, POE</td><td rowspan="2">Reciprocating/Domestic refrigerator</td><td>Normal pressure test
P_{disc} = 14.9 bar
P_{suc} = 0.7 bar
T_{shell} = 100.7^{o}C
Duration = 972 hours</td><td>High pressure test 1
P_{disc} = 26.9 bar
P_{suc} = 1.2 bar
T_{shell} = 71.5^{o}C
Duration = 300 hours</td><td>High pressure test 2
P_{disc} = 24.6 bar
P_{suc} = 1.1 bar
T_{shell} = 69.9^{o}C
Duration = 311 hours</td><td rowspan="2">SEM and EDX at the connecting rod (top of the small end/bottom of the large end of the connecting rod in contact with the driveshaft) and gudgeon pin (top in contact with the small end of the connecting rod);
Deposits on the valve plates using XPS;
Analysis of wear debris;</td></tr>
<tr><td colspan="3">Continuous operation;</td></tr>
<tr><td rowspan="3">Woo e O´Neal (2006)</td><td rowspan="3">R134a
Lubricant: POE</td><td rowspan="3">Reciprocating/Domestic refrigerator</td><td colspan="3">Standard vapor-liquid refrigeration cycle;</td><td rowspan="3">Optical microscopy at the suction reed valves, crankshaft/bearing.
SEM in the suction reed valves.
Statistical reliability model based on Weibull distribution.</td></tr>
<tr><td colspan="3">P_{disc} = 30 kgf/cm^2 (AF = 5.5)
P_{suc} = 0.0 kgf/cm^2
$T_{housing}$ = 120^{o}C (AF = 3.9)</td></tr>
<tr><td colspan="3">Intermittent operation: 39000 cycles;</td></tr>
<tr><td rowspan="2">Woo et al. (2011)</td><td rowspan="2">R600a
Lubricant: POE</td><td rowspan="2">Reciprocating/Domestic refrigerator</td><td colspan="3">Standard vapor-liquid refrigeration cycle;</td><td rowspan="2">Vibration analysis;
Statistical reliability model based on Weibull distribution;
Investigation and correction of internal gaps in structure;</td></tr>
<tr><td colspan="3">P_{disc} = 1.39 MPa (AF = 12.6)
P_{suc} = 0.4 MPa
T_{shell} = 110^{o}C (AF = 2.31)
Intermittent operation: 9300 cycles;
On: 3 min
Off: 4 min</td></tr>
</table>

4. CONCLUSIONS

The objective of this paper is to discuss the literature on accelerated life testing of reciprocating hermetic compressors, focusing on the wear of mechanical components. Several test methodologies are discussed as well as the procedures used to wear quantification. Test methodologies are presented based on critical analysis of the existing literature and the current scenario of refrigerants and lubricants development.

A critical analysis of scientific literature provides the following notes:

a) Reliability/durability studies of compressors that use natural refrigerants (hydrocarbons, CO_2) are very incipient.
b) Although R600a is extensive refrigerant in use actually, there are no consolidated studies on long term tribological behaviour of compressors.

c) Phenomenological studies (development of new materials and surface coatings) are well established. It is important to compressor evaluation as part of a system. This basic principle of classical science can be applied analytically in a variety of directions, e.g., resolution of causal relations into separate parts (Czichos, 1978).
d) The correlation of wear reliability through a statistical life model is not yet established. Only Woo and O´Neal (2006), Woo et al., (2011) show statistical correlation (Weibull distribution) with the Arrhenius degradation model. Many authors are limited to empirical/qualitative assessment methods based on micrographic structure observation.
e) Lack of wear evolution and quantification based on the contact mechanics criteria and entropy production model. That is, the degradation of the rubbing materials is also a thermodynamically driven process involving complex theories, such as self-organization and self-healing of materials.
f) Standardization scarcity for wear tests (durability) in hermetic compressors.
g) Inconsistency in determining the tests duration. The authors stipulate random periods without reference to the acceleration factors. Testing at levels of the accelerating variable(s) that are too extreme can result in activating failure modes that would not be experimental at use conditions.
h) Need to set acceleration parameters for the scuffing failure. It is important to understand the physics of failure for the mechanism(s) that will be accelerated.
i) Most accelerated tests have been accelerated life tests (ALTs), in which the response is time to failure. For compressors, important is the domain of the mechanical assembly degradation process, e.g., wear. For the same amount of test time, degradation data always contain more information than the failure-time data and thus provide more precise estimates.
j) It is necessary to advance in the wear mechanisms of materials (physics of failure in order to obtain a reliability model more effective

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