ADVANCED TECHNOLOGIES IN RECIPROCATING COMPRESSOR WITH RESPECT TO PERFORMANCE AND RELIABILITY

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Abstract

Reciprocating compressors are most common type of compressor and most flexible machine to handle wide capacity and condition swings. They offer a most efficient method of gas compressing. They are vital machines in various units of industrial plants. In this paper advanced technologies and latest configurations and methods regarding condition monitoring, performance, flow management, capacity control system, inter-stage arrangement, low suction pressure opertaion, lubricated cylinder, machine optimum speed, compressor valve, lubrication system, piston rod coating, liner material, barring device, pressure drops, rod load, pin reversal, discharge temperature, cylinder coolant system, coupling, flywheel, special tools, commercial points, delivery, pulsation and acoustic conditions are presented.

Keywords: Reciprocating Compressor, Performance, Reliability.

1. Introduction

In this paper latest and advanced technologies in reciprocating compressor design, component selection and performance monitoring and management are presented and discussed. Reciprocating compressors are the most common type of compressors [1,2,3,4]. Reciprocating compressors can generate high head independent of density. They are only option for many applications such as very high pressure and light gases (for example hydrogen, etc). Worldwide installed reciprocating compressor horsepower is approximately three times that of centrifugal compressors. Maintenance costs of reciprocating compressors are approximately three and half times greater than those for centrifugal compressors [3]. Design, evaluation, selection and purchasing a reciprocating compressor shall be done with respect to latest available technologies. Otherwise purchased reciprocating compressor may not be suitable machine for expected performance, safety and reliability level.

2. Performance

2.1. Load Step Curvature

Advanced design technology recommendation is to avoid steep load curve. A review of the steepness of the load curves can quickly identify which load steps (and where) are quite steep in nature, and thus small changes in pressure can have significant changes in load and flow. Often, steep load curves may indicate improper sizing of cylinders. Units with steep load step curves can also prove difficult to automate and tune [1].

2.2. Advances in Machine Shop Run Test

Shop mechanical run test is the first test after manufacturing of machine and last test before delivery. Shop test results, including vibration, may seem to have limited usefulness because supporting structure and operating condition of the machine are different with final site installation. However this test is a unique opportunity to find defects in design and manufacturing phases while machine is still in fabrication shop. Generally the larger the power per compressor throw leads to higher the dynamic forces and 370 KW or more per throw is a high risk machine. Latest method is to record and analyze shop run test measurements (Kalman Filter can be used to optimally evaluate machine dynamic characteristics based on measured data).

2.3. Advances in Pressure Drop Prediction

Latest recommendation for prediction of pressure drop values for basic design stage is as follows: pulsation dampeners: 1% pressure, intercooler: 0.70 bar. The use of orifice plates, especially on high-speed single-act, can contribute to significant pressure drops [1].

2.4. Rod load and Pin Reversal Details

Maximum Rod Load is recommended be less than 80% of allowable rod load. Duration and peak magnitude load of rod reversal shall not less than 15° of crank angle and 3% of the actual combined load in the opposite direction, respectively and shall be checked for all possible operating cases [1] (especially low suction and part load).

2.5. Highest Expected Discharge Temperature

High discharge temperatures cause problems with lubrication cooking and valve deterioration. It shall be reviewed at least for average and maximum suction temperatures [1]. The maximum predicted discharge temperature [1,2,3,4] shall not exceed 150ºC and not exceed 135ºC for hydrogen rich service (MW of 12 or less). Latest technology is to limit gas discharge temperatures below 118ºC to extend life of wearing parts.

2.6. Performance Curves

Required performance curves for latest control system design to safely and reliably control the unit across its defined operating range [1] are as follows: 1- Suction Pressure vs. Load. 2- Suction Pressure vs. Flow. 3- Discharge Pressure vs. Load. 4- Discharge Pressure vs. Flow 5- Suction Pressure vs. Discharge Pressure, per load step.

2.7. Advances in Flow Performance Management

Latest flow management methods require flow details as flow curves from unit’s minimum achievable flow rate to its
maximum achievable, in specified increments [1]. Alternative may be flow versus discharge pressure plots of specific suction pressures (more compact and common when suction pressure variation is limited).

3. Advances in Compressor Design

3.1. Advances in Inter-stage Pressure Arrangement

Discharge pressure of each stage is normally protected by pressure relief valves, high pressure discharge switches are seldom seen [2]. Based on latest optimization methods and experiences, inter-stage pressures can be obtained by formulation and optimization of performance and investment for compressor and inter-stage facilities. Some vendors are intended to change inter-stage pressures, generally higher pressures at early stages and lower pressure ratio at last stages. Vendor offered inter-stage pressures based on just compressor without respect to inter-stage facilities, are not justified. Inter-stage pressures are going to increase during part load operation and high suction pressure. If not tolerate-able, additional clearance pocket on first stage cylinder and part load operation inhabitation by the controlling logic can be studied. Generally it is compromise to fix inter-stage facility design pressure based on vendor recommended PRV set points (around 10-15% higher due to common ranges of part load operation and suction pressure variations).

3.2. Advances in Low Suction Pressure Design

Sometimes, due to process requirements, reciprocating compressors shall be capable to operate at lowest suction pressure and full design flow at normal discharge pressure. It can have strong effect on compressor sizing especially frame rating and motor power (more than 35% power increase for 20% suction below normal). Latest experiences recommend respecting this condition as design point in basic design to avoid costly future changes.

3.3. Advances in Capacity Control System

Step-less capacity control system uses finger type unloader, is pneumatically actuated, and unloads the suction valve for only a portion of compression cycle to achieve adjusted capacity [2]. Finger type unloaders have potential for damaging the valve sealing elements and require more care for maintenance [2]. Valves and unloaders cause around 44% of unscheduled reciprocating shut down [5,6] and this selection has a strong effect on reliability [5,6,7,8]. For small machine, 100% spill back is latest recommended solution, because power is low. For big machine best and latest configuration is selection of part load steps based on plug/port unloader and clearance pocket.

3.4. Advanced Condition Monitoring

Condition monitoring [9,10,11,12,13] shall be particularly effective and include necessary items to identify malfunctions at an early stage (lower maintenance costs and lower risk of accidents). Advanced vibration monitoring: 1- Vibration – continuous monitoring (Shut down). Velocity transducers are preferred over accelerometers due to better signal to noise ratio [9]. Advanced configuration: each end of the crankcase about halfway up from the base plate in line with a main bearing [9]. 2- Each cross head accelerometer (Alarm). 3- Electric motor vibration (Shut down). Advanced temperature monitoring: 1- High gas discharge temperature - each cylinder (Alarm and Shutdown). 2- Pressure packing case - piston rod temperature (Alarm). 3- High cross head pin temperature (Alarm). 4- High main and motor bearing temperature (Alarm). 5- Valve temperature (Monitoring). 6- Oil temperature out of frame (Alarm). 7- High jacket water temperature - each cylinder (Alarm). Optimum implementation is properly set trip levels that are just high enough over the normal operating levels to reach to mechanical failures, but not so high as to miss the failure prior to catastrophic release [9]. Proximity probes are typically located under the piston rods [9] and used to measure the rod position and determine wear of the piston and rider bands, malfunction e.g. cracked piston rod attachment, a broken crosshead shoe, or even a liquid carryover to a cylinder. Latest method: just for alarm and not for shut down. Latest operation experiences recommend cold run outs and normal conditions operating run outs are about 50 microns (2 mils) and on the order of 50 to 150 microns (2 to 6 mils) peak to peak, respectively [9]. All shutdown functions shall be 2 out of 3 voting to avoid unnecessary trip. Usually it can be deviated for compressor frame vibration and temperature related trips.

3.5. Advance Technology in Valve Selection

Cylinder valves are the most critical components of reciprocating compressors and strongly influence the reliability and efficiency [5-8,10]. Valve defects are obviously responsible for most of the unscheduled maintenance events [5-8,10]. Three main valve types: ring type, ported plate and poppet. For big machines (generally low speed and high pressure ratios) and small machines (relatively higher speeds) ring type valves and plate type valves are best choice respectively. Optimum valve size shall be obtained with respect to efficiency, reliability and performance requirements including minimum clearance volume. Lift is the distance travelled by the valves moving elements. The higher the lift, the higher the valve flow area, lower the valve pressure drop, less consumed power, higher moving elements impact velocities and lower valve durability. Acceptable compromise should be found. Optimum valve spring stiffness is also important. Too stiff spring can lead to valve flutter (more compressor power and considerable wear rate) or early closing of valve (reduce capacity). Too light spring cause valve late closing and the reverse flow (higher velocity, less reliability and reducing capacity). Nonlinear partial differential equations describing the valve differential pressure and the valve element motion (such as [14]) can be used in optimization process to estimate optimum valve lift, spring stiffness and gas velocity for each machine and application.

3.6. Advances in Piston Rod Coating

Piston rod seal is second important area for reliability of reciprocating compressor and most likely path for potentially hazardous process gas leakage [8]. Packing life could be improved three times by adding the proper tungsten carbide piston rod coating [10]. It is latest technology.
3.7. Advances in Cylinder Liner Material

Cylinder liner is used to provide a renewable surface to the wearing. The liners made by Ni-Resist cast iron (high Nickel content) are not recommended due to problems such as permanent distortions. Latest researches recommend grey cast iron [8] for all applications except very high pressure or extremely high corrosive applications.

3.8. Advanced Passive Vibration Reduction System

Sometimes odd number of cylinders is avoidable. In this case dummy crosshead shall be used to reduce vibration. Also state of art spring-mass-spring system shall be studied for passive force counter balance and more reduction in vibration, where dummy crosshead is, on the one hand, attached to a movable piston assembly by flexible member and on the other hand, to the stationary compressor casing using auxiliary mechanical springs.

3.9. Future Expansion

Future expansion planning can save money and time if process changes (capacity increase, molecular weight increase due to catalyst change, etc) are foreseen [12]. Optimum selection is sizing cylinders for economical operation at the present rate. The frame can be sized for future applications. When the future conditions become a reality, the cylinders can be changed while keeping the same frame. Latest design method is to over size the journal diameter include margins for future development, thus ensuring that crankshaft size would never become the first important limitation of the design [15].

3.10. Minimum speed lubricated Cylinder

Reliable machine is involved low speed (around 350 RPM) and lubricated cylinder. Optimum piston speed is 3-4.4 m/s. Most advanced configuration: horizontal cylinder(s), discharge nozzle on the bottom side. For small compressors some vendors intend to deviate lubricated cylinder or low speed. Optimum option is lubricated cylinder with available lowest speed machines. Probably less than 20% of all reciprocating compressors are designed for non-lubricated operation just because of process demands (oxygen, high pressure air, etc) [2].

4. Advances in Commercial Management

4.1. Commercial Conditions and Negotiations

It is absolutely necessary to receive at least three proposals and have minimum two technically accepted machines. It is completely justified to extend proposal dead time, clarification time, accept optimum configuration, reasonable deviations and attend extensive clarification meetings to have at least two clarified and technically accepted proposals.

4.2. Advances in Delivery Methods

Small and medium machines shall be delivered fully fabricated as one skid mounted package. For very big machine, latest and optimum figure is to deliver machine prefabricated (including crankcase, distance pieces, etc) while cylinders are dismantled. Assembled cylinders are delivered to site separately and installed. Vendor to advice to offer all site supervision work for cylinder installation as closed price.

5. Advances in Compressor Auxiliaries and Packaging

5.1. Advances in Flywheel and Irregularity

For all reciprocating compressors, flywheel is mandatory to regulate variable reciprocating torques. Irregularity degree for mechanical component reliable operation is maximum 2%. This value is minimum requirement for all compressors. Generally in accordance with specific requirements of driver (especially current pulsation for electric motors), torsional vibration results, etc, lower irregularity value is required. It is recommended to obtain 1% for special purpose units. Latest studies and designs recommend irregularity value between 1-1.5%.

5.2. Barring Device

When compressor stopped for an extended time, turn it around a quarter turn every week by barring device. Manual barring device is for small compressor. Pneumatic is for compressor rated over 750 KW, without area classification problem or intermittent power availability and preferred technically [11].

5.3. Special Tools

Latest recommended check list for special tools [11] for big machines: 1- bearing extractor 2- piston extractor 3- valve extractor 4- piston fit up tool 5- hydraulic tightening system 6- crosshead assembling tool, 7- special lifting tools 8- partition plate assembling tools 9- mandrels for wear bands. For special tools, tool boxes required and they shall be delivered with main machines, in separate and tagged boxes.

5.4. Advanced Lubrication System

API 614 is typically applied only to reciprocating compressor trains involving a large turbine driver and gear unit [11]. Optimum oil system shall include two oil pump (for special purpose machine as per API 676), both sized at least 20% over (Two motor driven identical with run down tank, or well known crank shaft driven main oil pump, supplying UPS power for one pump is not acceptable alternative), dual removable bundle shell and tube oil coolers (TEMA C) and double oil filters with removable element and stainless steel piping.

5.5. Advances in Coupling Selection

For reciprocating machine because of special design, the potential exits for torsional resonance and torsional fatigue failure [2]. Coupling is best available option for modification to tune the system. Coupling configurations: 1- high torsional stiffness coupling (it is best option if allowed by torsional analysis). 2- flexible coupling (more elasticity and damping and more maintenance). 3- direct forged flanged rigid connection (no coupling), with single bearing motor. Coupling for big machines shall be as per API 671.
5.6. Advanced Coolant System

Liquids should never form inside the cylinder [10,11,12]. Liquid contributes to poor reliability, can cause high impact velocities, can lead to stressing of valve moving elements (slugging) and reduce the lubrication effectiveness. For any application, a good sized suction drum with a drain provision shall be in order [12]. It may be a part of pulsation control, if properly done. Cylinder cooling system must be monitored and controlled. Coolant inlet temperature between 6 °C and 16 °C above inlet gas temperature [12]. For exotic gases or operations near critical areas, much care needs to be taken. Also make sure the thermodynamic model is proper.

5.7. Advances in Pulsation Control

Advanced technique trends to dissipate less energy than reliance on special solutions such as orifices to control pulsation levels [16]. Acoustic reviews shall be performed for design and guarantee points as well as all other operating cases and combinations of pressures, speeds and load steps. Pulsation can also alter the timing of the valve motion and decrease efficiency and reliability [5].

Based on latest optimization processes, for design stage, pulsation limit is recommended around 95%-85% of API 618 (Approach 3) limits to have some margin (around 5-15%) to mitigate risk during construction and installation periods as well as unpredicted deviations and problems.

5.8. Pulsation Shaking Forces

Reduction of pressure pulsation can be accompanied by an increase in shaking forces (or unbalanced forces) [17]. It illustrates that shaking forces shall be determined and controlled and piping and vessels properly supported. The margin of separation between the mechanical natural frequency (MNF) of system (including piping and bottles) and excitation frequency is 20% and MNF shall be greater than 2.4 times maximum run speed [11,18]. If not meet limits, the force response (including stress analysis) is required. The cylinder gas forces (also called frame stretch or cylinder stretch force) can be significant source of excitation (can cause high frequency vibration on the bottles and piping close to the compressor) and lead to excessive pulsation bottle vibration even if the pulsation shaking forces meet limits. Flow induced pulsation is rarely seen [17]. API 618 Design Approach 3 and less rigorous analysis, to control pulsation and shaking (unbalanced) force levels and avoiding mechanical resonance can result in an optimized design [17].

Pulsation and vibration analysis report shall include Time Domain (TD) and Frequency Domain (FD) simulations, Time Domain (TD) plots of key forces and pressure pulsation, dynamic pressure drop, models including mounting details (mounting plate, bolts, localized skid, etc) and shell flexibility (nozzle connection flexibility), calculated cylinder stretch forces, mode shape of bottles and piping and compressor stiffness assumption (compressor frame modelled as flexible support) [18].

5.9. Advances in Inter-state Facilities

Inter-stage facilities and coolers and after coolers shall be sized carefully. Undersized lines, facilities and coolers can cause excessive pressure drop and power loss. Pulsation and shaking force studies are necessary to avoid vibration problem in inter-state facilities. Increased cross section area, especially in coolers, to decrease pressure drop can cause significant increase of shaking force and equipment (cooler) vibration. Secondary volumes may be studied to reduce this vibration however in some cases this solution can not reduce vibration and modifications to recycle line are required to significantly lower shaking [17].

5.10. Advances in Torsional Analysis

Typically, for reciprocating compressor, lateral natural frequencies will be positioned well above significant torsional natural frequencies, so lateral critical studies are not required. A stress analysis shall be performed if the torsional excitation falls close to the torsional natural frequency to ensure that the resonance will not be harmful for the system [18,19]. The torsional vibration analysis report shall include data used in mass elastic system, display of force vs. speed, torsional critical speeds, deflection (mode shape diagram), worst case design, upset condition results (such as valve failure, start up, short circuit, electrical network faults, etc) and how the input data variance will affect the results (sensitivity analysis) [18]. Continuous operation at torsional resonance shall be avoided. Changing the load sequence could help reduce torsional vibration. Avoid full load shutdowns. Measure and verify torsional vibration during performance test. Synchronous motor or system started on a frequency basis need more care (definitely need a transient torsional start up analysis). Electric machine (driver) shaft diameter to be equal to or greater than the reciprocating compressor crankshaft diameter.

5.11. Advances in Dynamic Package Analysis

The dynamic package analysis shall include modeling and simulation of the foundation at the same time. The accuracy of this analysis is strongly influenced by the design of the foundation especially for pile installation [18]. It is even more important for packages mounted on offshore platforms, FPSO (Floating Production Storage Offloading Vessels) [20], modules mounted on steel structure, new and unproven skid design and where the local soil conditions are suspect. Skid lifting study (including lifting lug details and calculations review) is necessary. Transit study and environmental loading analysis are also recommended [18].

5.12. Advances in Package General Arrangement

Layout is often complex and compromise must be made between the support requirements, process requirements, vibration/pulsation conditions, access and maintenance. Optimum configuration is to install local panel near compressor package (around 200 mm away from package) but on separate skid (frame) which is installed on foundation, to avoid vibration damage. For maintenance, consider spool removal and avoid support removal. Access required in front of cylinder for cylinder piston dismantling and non-drive end of compressor. Pay attention to minimum elevation requirement of pulsation bottle suction flange to keep suction line, no pocket.
5.13. Advances in Piping Analysis

The thermal piping design often requires that flexibility be added to the system which is counter to requirement for more support and increase stiffness to meet vibration design. These analyses shall be conducted by same party to optimize design iteration and result in an overall optimized system. Piping thermal analysis is necessary especially when the coolers are off-skid, multiple compressors on a common header, extremely cold ambient temperature, or operation over a very wide range of conditions.

5.14. Advanced Cylinder Lubrication System

Using the proper type of lubricant as well as establishing the proper lubricant rates to the cylinder and packing can be most important for machine reliability [10]. The life of the compressor valves, piston rings, rider bands, and pressure packing can all be significantly affected by the type and quality of lubrication used. Too much or wrong type of lubrication can increase the effects of valve stiction (viscous adhesion) and reduction in reliability. Reliable lubrication system with optimum type and rate of lubrication shall be selected [10].

6. Conclusion

Latest technologies, recommendations and configurations for reciprocating compressors regarding component design and selection, commercial points, auxiliary and accessories, performance and reliability are addressed in this paper.

References