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Design, Manufacturing and Performance Testing of Hydrogen Gas Compressor

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Abstract

The importance of the design of reciprocating compressor for such critical application is apparent when we consider the unusually "high risk" environment the compressor operates in. This was performed in the Kirloskar Pneumatic Company Ltd., Pune.
Today Gas Compressor is one of the most rapidly growing sectors of the compressor industry. The present paper brings out some practical design considerations required for a successful design of the compressor besides following the suggestions covered in API standard. These considerations include a thorough analysis of the gas and its properties selection of suitable metallurgy for the wetted components, provision of suitable dynamic seals, type of lubrication as well as adequate designing of dampeners, intercoolers, After-coolers and separators or knock-out drum to take care of the condensate, sludge etc. Reciprocating compressors are ideally suited to this task and we offer practical solutions to meet this new environmental requirement.
The paper concludes with specific suggestions for the users for what they should look for making specifications for the hydrogen gas service. Gas turbines used in these power plants often require fuel gas boosters to fuel gas compression to increase the working pressure when the pipeline pressure is not enough. We offer standard and engineered solutions with reciprocating and centrifugal compressors, depending on the requirements of the customer.

Keywords: *Reciprocating compressor, Intercoolers, After-cooler, Seals, Dampeners, High risk, Engineered solutions.*

1. Introduction

Kirloskar Pneumatic Company Ltd. is the manufacturer of Air Compressors including Air Conditioning and Refrigeration systems, Marine HVACR, Process Gas systems and Hydraulic Power Transmission machinery.
We have in Air Compressor Division (ACD) received the order for H2 gas Compressor from one of the reputed client "Gujarat Flurochemicals Ltd." located in Dahej, Bharuch. The requirement is for Booster compressor with 50 Kg/cm^2 g discharge pressure and 1000 Nm^3/Hr flow with 200 (min. 100) mmWC suction pressure.
Till date in KPCL, we have not manufacture Compressor for Hydrogen Gas. Our target is to design, manufacture and commissioning the Compressor. And to achieve, Compressor sizing for above requirement, preferably by using existing cylinder combination is important task. As an Engineering function, initially we have identify the customer requirements, bottlenecks, define the scope, time, risk factors, performance criteria. Then will work on the control logic, safety interlocks, selection & sizing of equipment's, bought out items. In next step we have release the Engineering specifications, various manufacturing drawings and P & ID for procurement and manufacturing activities. Then will observe the assembly at shop floor and mechanical run testing. Last phase will be validation of the performance parameters after erection and commissioning at site.
Over the years, Kirloskar Pneumatic Company Ltd. has developed various sophisticated and high-tech products in the above categories to cater to the demands of various industrial sectors. KPCL has also established a number of joint ventures and technology partnerships with leading global companies. It has earned the distinction of developing a host of advanced products to suit Indian conditions and has been continuously updating them to maintain the highest standards of quality and reliability.

2. Literature review

Air compressors are used in a variety of industries to provide compressed and pressurized air for many applications. These devices are now even used to power construction and manufacturing equipment and to drive control system valves.
Although reciprocating compressors have recognized advantages such as excellent gas sealing behavior (-> high pressures), good capacity control ability and low tech manufacturing requirements, the reciprocating compressor has a couple of weak points, as:
Compared to rotating compressors the reciprocating compressor has a significantly lower capacity density (capacity vs. swept volume) which is mainly due to the low rated speed. The consequence is a large and

heavy compressor design.
A reciprocating compressor is build of many different parts. In addition, the number of parts increases with the variety of compressor designs.
The lifetime of some parts is limited, as for disk and reed valves and for piston rings.
The internal and mechanical efficiencies of reciprocating compressors are not sufficient, especially at part load.
The reciprocating compressor has an intermittent feed rate and its vibration behavior is unfavorable. (Haas, A., 2000),

One can easily visualize what the direct impact of heat transfer would be on material temperatures. Large material temperatures could be attributed to large discharge temperatures. This is indeed the case in vacuum pumps and other high pressure ratio reciprocating compressors resulting in isentropic temperaturesas high as at the end of the compression stroke. Even from the reliability point of view, high temperatures cause serious concern. For example, impact strength of a valve plate or the sealing effectiveness of a piston or packing ring depends on the temperature Vijaykumar F Pipalia1*, Dipesh D. Shukla2 and Niraj C. Mehta3, (December, 2015).

Air compressors were used for more than just metal working in those days; they were also used for mining and fabricating metals and providing ventilation to underground areas. During the 1857 construction of the Italy-France rail system, compressors were often used to move large air volumes into the 8-mile construction tunnel. Soon after, people conceptualized more ways to utilize the technology (Heinz P Bloch and John J. Hoefner, 2006)..

While dealing with gases involving high percentages of hydrogen it is important to provide a very good finish for achieving a perfect seal at all metal to metal sealing contacts, such as those between the cylinder head, liner and cylinder, valve sealing faces, stuffing box packing cups, etc. (S.N.Dwivedi, 1990).

Major assumptions made for the pressure drop analysis is, flow is steady and isothermal, and fluid properties are independents of time, Fluid density is dependent on the local temperature only or is treated as constant. The pressure at a point in the fluid is independent of direction & body force is caused only by gravity. There are no energy sink or sources along streamline; flow stream mechanical energy dissipation is idealized as zero (Sandeep K. Patel, Professor Alkesh M. Mavani).

Concept of air/gas compressors
In order for air to transmit power, it needs to be compressed or increased to a higher pressure. When air is compressed it is given energy that can provide power for machinery, usually through the use of pistons pushing the compressed air back and forth. Boyle's law indicates that the volume of gas (such as air) increases when the pressure is decreased at a constant temperature. Because of the nature of compressed air, it is inevitable that some energy will be lost in the process. This loss of pressure is caused by the friction of air as it travels through pipes or hoses, therefore making the size of the pipe/hose a primary factor in maximizing energy.
Several air compressors are usually used in conjunction with one another to create a distribution system that carries the compressed air as power to different points. The air is then conceived as energy for a mechanical tool.
It is important that all the operating parameters involved in the particular service are well specified in the beginning itself. Thorough knowledge of the properties and behaviors of the gas to be handled is most essential for the proper application of a compressor. The user should specify the exact gas Composition (S.N.Dwivedi, 1990).

"Applications do vary but the sole aim of the this compressor designing is to endeavor to achieve the required operating parameters by a judicious combination of designs, thermal, materials and processing for individual compressor components so as to ensure highest economically and practically feasible, trouble-free working life for the compressor. This ultimately helps the refinery maintain or even increase their processing capabilities over a longer duration".

3. Work Carried Out and Equipment Set-Up

Design and manufacturing of Hydrogen gas compressor for high pressure.
Since this gas is very light gas, therefore the only thing to be kept in mind is the leakage which should be prevented by, Piston ring should be made in pairs so that the end gaps do not align, finish of the flange & the sealing faces should be very good. Also Copper and aluminium gaskets are to be used. We have considered the additional compartment distance piece with packing at its end is normally sufficient. Gland packing should be fully floating type and especially design for this application. As well testing of all parts should be done with helium or hydrogen under water with pressure not more than design pressure.

The main objective is to size & design effective, less power consumption with better volumetric efficiency compressor for such high pressure requirement.

a. Design of multistage compressor for 50 Kg/cm^2g pressure.
b. Thermal design of Intercooler for each stage.
c. Development of Compressor with inter-cooling system.
d. Development of control system for safety and regulations of operating parameters.
e. Performance testing of compressor.

Following methodology need to be adopt while carrying out this work,

a. Study to compressor sizing and selection of various existing gases like, CO2, N2. – Helps to defining the cylinder sizes, MOC to be used for rings & pickings, compact sizing.

b. Heat transfer and pressure drop calculations.
c. Mechanical design of pressure parts like coolers, knockout drum, dampeners.
d. Identify the safety parameters and prepare the control login for smooth operation.
e. Preparation and release of manufacturing drawings within budget.
f. Observer the manufacturing activity, assembly and verify the accuracy.
g. Witness the Mechanical run test at shop floor.
h. Validation of performance parameters by comparing with actual readings.
i. Determination of scope for future development.

4. Mathematical modelling

Piston displacement (API 618, 2007)

Piston displacement is the actual volume displace by the piston as it travels the length of its stroke from piston bottom dead canter, to position top dead canter. Piston displacement is normally expressed as the volume displaced per minute or cubic feet per minute.

Data
Dia. Of 1st cylinder (DLP) = 0.425 m
Piston rod dia. (DROD) = 0.050 m
Piston stroke (L) = 0.2 m
Compressor speed (N) = 450 RPM
No. of cylinders in 1st stage (n) = 1

Piston displacement

$$PD = [\frac{\pi}{4}[(DLP)^2 + (DLP^2 - DROD^2)] \times L \times N$$

Sr. No.	Parameters	Unit	Value
1	Piston Diameter	mm	425
2	Stroke	mm	200
3	Single acting / Double acting	--	Double
4	Piston Rod Diameter	mm	50
5	Speed	rpm	450
6	Piston Displacement	m^3/min	25.36

Table 1 Compressor parameters

Volumetric efficiency calculation (ηv)

Overall volumetric efficiency (η_v) =

$$= [1 - C \times \{(Pd1/Ps1)^{1/k} - 1\}] \times Lf$$

Free air delivery calculation

FAD = Piston displacement x Volumetric efficiency

Heat load estimation (manually):

Suction pressure at I stage = P1
Discharge pressure at I stage = P2
Vapour pressure at suction = Pv
Relative humidity = RH

Formulae Used

a) Factor for Wt1 & Wt2 (F) =

$$= \frac{\text{Molecular Weight of water vapour}}{\text{Molecular Weight}}$$

= 8.938

b) Specific Humidity (Wt1) = $\frac{F \times (Pv \times RH)}{P1 - (RH \times Pv)}$

c) Specific Humidity (Wt2) = $\frac{F \times (Pv \times RH)}{P2 - (RH \times Pv)}$

d) PV = mRT
Where,
P = Pressure (Kg/cm²A),
V = Volume of the gas (m^3/min),
m = Gas mass flow rate (Kg/hr),
R = Universal gas constant
T = Absolute temperature.
e) Mass of vapour in (mv1) = m x Wt1
f) Mass of vapour out (mv2) = m x Wt2
g) Condensation = Mass of vapour in – Mass of vapour out

5. CAD Model

A simplified CAD model of fifth stage cylinder is shown below.
Fifth stage cylinder is 145 mm dia. & is single acting Cylinder. As fifth stage is the higher pressure stage, cylinder is designed for 55 Kg/cm^{2}g design pressure. 070M20 as per BS 970 (Part 3) or EN-3A (Forged) MOC is used to suit the requirement of 50 Kg/cm^{2}g working pressure.

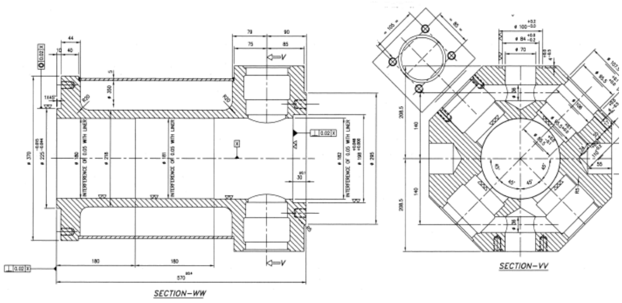

Fig.1 Ø 145 Cylinder

6. Expected outcomes

To get the desire pressure and flow at outlet as per requirement as per IS: 5456 standard.
Power consumption shall be within limit as per IS: 5456 standard.
Vibration and noise limit shall be as per standard.
Compressor Model: 5EHB4GT.

Stages	Pressure (Kg/cm^2g)	Temperature (ºC)	SRV Set Pressure (Kg/cm^2g)
Suction	200 (Min. 100) MM of WC	40	
1^{st} Stage Outlet	1.04	109	2.04
2^{nd} Stage Outlet	3.83	130	4.83
3^{rd} Stage Outlet	9.02	116	10.02
4^{th} Stage Outlet	20	119	22
5^{th} Stage Outlet	50	144	55
Suction of all stage	-	40	-
Cooling water in	3	34	-
Cooling water out	-	40	-
Cooling water flow	55 M^3/Hr		
Compressor Capacity	1226.9 M^3/Hr or 1000 NM^3/Hr		

Table 2 Experimental procedure parameters

7. In house testing set up

Photo 1 Experimental setup

Above photo shows the experimental setup of hydrogen gas compressor for mechanical run test (MRT) and performance of system with air. The highlights of the same are as under,

a. 80 Nos. new Drawings were released.
b. There is no problem in assembly, please refer attached photograph.
c. New cylinder group diameters 145 & 425 mm, Tandem arrangement for 145 mm Dia. on 200 mm Dia., Hoerbiger valves, gland packing etc,
d. Tungsten carbide coated piston rods, Diaphragm Unloader etc. released.

This set up is consisting with the five stage cylinders and five stage coolers.

8. Mechanical Run Test (MRT) of compressor

As a regular practice we are conducting the in-house shop floor testing for all air compressors. However for gas compressor we are performing the mechanical run test of the gas compressor for four hrs. duration.
The purpose of this testing is to ensure that all components like cylinders, coolers, gas, water & oil piping, all valves like Gate, Ball, SRV etc. are assembling as per the requirement. At the same time it will insure that all pickings, rings, valves are properly fitted and not leaking.
In MRT test compressor is running with air instead of hydrogen gas and QA will insure the all necessary readings.

Mechanical Run Test Readings
It was observed that 5EHB4GT compressor was run for four hours as per KPCL procedure.

Following parameters observed during Mechanical run test.
Start time – 10:45 AM Stop time – 03:00 PM

Sr. No.	Parameters	11:45 AM	12;45 PM	02:00 PM
1	Compressor oil pressure (Kg/cm2)	2.9	2.9	2.7
2	Compressor RPM	592	591	591
3	Crank case oil temp.	41.0	43.4	46.4
4	Abnormal noise observed	NIL	NIL	NIL
5	Leakage observed	NIL	NIL	NIL
6	Suction temp. (1st stage cylinder)	37.8	38.0	39.0
7	Discharge temp. (1st stage cylinder)	11.0	118.0	118.0
8	Suction temp. (2nd stage cylinder)	40.0	41.0	41.0
9	Discharge temp. (2nd stage cylinder)	106.0	108.0	108.0
10	Suction temp. (3rd stage cylinder)	40.0	41.2	40.0
11	Discharge temp. (3rd stage cylinder)	44.8	45.0	44.0
12	Suction temp. (4th stage cylinder)	36.0	36.2	36.0
13	Discharge temp. (4th stage cylinder)	38.0	38.8	38.8
14	Suction temp. (5th stage cylinder)	36.0	36.4	36.0
15	Discharge temp. (5th stage cylinder)	38.0	39.2	39.0

Table 3 MRT readings

Vibrations – At Crankcase foot

Velocity specified: 17.8 mm/sec Standard: As per ISO 10816-6 Vibration severity grade: 18	
LHS (L.P.) mm/s	RHS (H.P.) mm/s
V-2.1	V-2.8
H-6.1	H-5.7
A-3.2	A-3.2

Vibrations – On Cylinders (Stage wise)

Cylinder Stage	Vertical (mm/s)	Axial (mm/s)	Horizontal (mm/s)
1	8.8 mm/s	21.9	7.9
2	22.2	15.9	7.8
3	16.5	23.9	7.4
4/5	5.9	13.5	24.6

Note

Testing conducted with no load condition.
Compressor was tested on temporary bed arrangement.
All cylinders supports were not provided.
RPM also higher than the specified.

Noise level: 90-95 dBA.

Conclusions

1. Rod load of 9500 kgf and cylinder capacity are acceptable for this machine.
2. Optimum configuration of reciprocating compressors for Hydrogen gas regarding component design and manufacturing, commercial points, auxiliary and accessories, performance and reliability are addressed.
3. Apart from the high flow, coolers size is less due to low molecular weight.
4. Reciprocating compressors are used widely in industry due to their ability to deliver high pressure compressed gas.
5. Various interactions are required in between process designers & compressor designers to achieve the desirable goal.

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