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**Piedmont Chapter #14**

# Operation and Maintenance of Integrally-Geared Centrifugal Air Compressors

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# Operation

- Centrifugal Compressors use rotary continuous flow high speed impellers to impart velocity and pressure to a flowing medium.

- Impellers used in gear driven units are of the open type. A series of rotors are driven by a Bull Gear driven directly by an electric motor or turbine. Input speeds are usually 1800 or 3600rpm. The impellers are mounted on a rotor which includes a pinion gear and thrust collar. The rotor can either carry a single or double hung impeller.

- The fixed elements of the rotors include plane bearings, thrust bearings on single hung types, and air/oil seals either labyrinth or carbon ring types.

- The term centrifugal refers to the movement of the medium, in this case air, from an axial direction at the impeller inlet, to a radial direction by centrifugal force to the impeller discharge area. This is a 90º change in direction.

- After the air comes off of the tip of the impeller, its flow direction is changed by 90°a second time via the use of a diffuser. The air then passes through an intercooler and moisture separator. In some machines the air is then turned 180° and enters through the center of the next diffuser to the inlet section next impeller.

- 1ft$^3$ of air at standard conditions weighs .075lbs. When it is accelerated to a high speed, it applies force to a fixed element.

- Design condition requirements dictate the number of stages required. Most 100psi-150psi machines are typically 2-4 stages with inter-cooling.

- Rotor speeds on multistage machines increase from stage to stage. A typical 2500cfm compressor could use a 36” Bull Gear driving a 3” first stage pinion gear at 21,600rpm with 10” impeller. The tip speed of the impeller would be 942ft/sec.

- As rotor speeds increase, tip speeds remain constant by the reduction of the rotor impeller diameter. As an example; the rpm of the second stage could be 36,000 but the impeller diameter would be 6” with a tip speed of 942ft/sec, like the 10” first stage. As the number of stages increase, so does the rpm but the impellers tip speeds remains equal. As the air is forced from smaller stage to stage, its speed is increased and a proportionate rise in pressure is achieved.

- A multistage compressor is designed so that each stage shares the work equally. This means that each stage passes the same mass at the same compression ratio. A 4-stage compressor designed to operate at 139.7psia with an inlet pressure of 14.3psia has an overall compression ratio of 9.769/1. The compression ratio per stage would be the fourth root of 9.769 or 1.769. The discharge pressure of each stage would be:
  Stage 1 (1.767r) (14.3psia) = 25.268psia or 10.568psig
  Stage 2 (1.767r) (25.268psia) = 44.648psia or 29.948psig
  Stage 3 (1.767r) (44.648psia) = 78.893psia or 64.193psig
  Stage 4 (1.767r) (78.893psia) = 139.403psia or 124.703psig

- Since the same amount of work is being done there will be an equal rise in discharge temperature per stage. Since we can not achieve perfect inter-cooling, a typical 4-stage compressor will have about a 15° rise in air temperature per stage. This also means that the inter and after coolers all reject equal amounts of heat.

- A well designed 4-stage centrifugal air compressor will produce about 4.5scfm/bhp.

# Capacity Control

- The purpose of the capacity control system is twofold. The first is to insure that the available supply meets the flow and pressure demands of the plant. The second requirement is to insure that the compressor does not go into a surge condition due to a reduction in mass flow to the impellers or a change in overall compression ratio at one or more stages. Surge can be compared to cavitation.

- Centrifugal compressors respond to changes in plant demand by two means. An inlet guide vane or butterfly valve is located near the inlet to the first stage usually on the compressor casing. This valve is controlled by a signal from a control panel mounted near the compressor. A blow-off or Anti-surge valve is mounted after a check valve at the compressor discharge. Prior to the advent of micro processors, the valves were controlled by an electro-pneumatic system which sensed air pressure in a local air receiver tank. The butterfly valve changed position by the use of a pneumatic signal converter. This system was not very responsive or precise and therefore limited the ability of the machine to supply just the right amount of air at the correct rate. In other words the supply relative to the demand was rarely coordinated in an efficient manner. It also could not take advantage of the maximum turn down or inlet throttling. The blow-off valve is used to redirect air to atmosphere should the air demand be less than the maximum throttling capability of the inlet valve. It is also used to protect the machine in case of surge.

- More modern machines signal their respective valves by equating motor amps to mass flow and pressure.

- When air is moved through the compressor we are actually moving a certain weight of air per minute. Motor amperage increases at a constant compression ratio proportionate to the change in mass. As an example; a 2500cfm compressor on a standard day may have its inlet valve open at 90%. This means that at this valve position, 187.5lbs of air is being handled in 1 minute.

- If the ambient conditions change and there is a decrease in temperature or an increase in barometric pressure the weight of the air per $ft^3$ will increase. If the maximum allowable motor amps were set at 200amps = 187.5lbs of air/min, then the inlet valve would throttle to maintain the same mass flow. Its position would be something less than 90% open.

- This system allows for much more precise control and thus saves energy. Not only does the supply match the demand more closely, but increased throttling can be achieved, thus keeping the blow-off valve from prematurely blowing compressed air to atmosphere.

- It is extremely important to size the compressor so that the average plant demand stays within about a 70-100% of the compressors demand! If not, the consequences could be an extreme waste of energy. At $.04 per kWh the annual electric cost of a 500hp compressor is almost $133,000.00. If the blow-off valve is wasting 15% to atmosphere, the electrical waste is almost $20,000.00 per 8000hr year.

- An ideal scenario for plants with uneven demands is to add a smaller trim compressor to supplement the larger machine. In the above scenario one would be better served with a 2000cfm primary machine and a 500sfm trim machine.

# Surge

- When discussing centrifugal compressors, the understanding of a phenomena know as surge must be discussed. Surge is a limiting factor in the design, application and control of this type of machine. It is the point in which, at a given head pressure, compressor operation becomes unstable. By forcing the compressor to surge by dead heading at full capacity, the actual maximum flow capacity can be determined. Simply stated, the higher the surge point, the higher the flow! It takes more moving mass to created a higher surge. A deterioration of this “natural surge” point is directly proportionate to the reduction of flow capacity.

- Several conditions involving the operation or mechanical irregularities can cause the machine to surge. Remember that to compress the air, we must accelerate the mass to a sufficient speed to create work or produce pressure. In a constant speed machine, a surge condition occurs when for one reason or another, mass is reduced to the point at which the force created is less than the pressure on the outlet side of the impeller. This is the limiting factor in the amount of allowable throttling available. At this point of pressure equilibrium we have lost differential pressure and thus flow. At this point, the hot air at the outlet side of the impeller, leaks to the inlet side. As the pressure decreases below that of the inlet side, hot air tries to reverse and pass to the outlet side again! The cavitations or surge cycle has begun and unless checked, will continue in ever increasing intensity. The impeller disc can actually flex enough to cause contact with the face of the diffuser as pressure is applied alternately to the front and back side. This contact will cause excessive tortional loads thus causing damage to the plane bearings and seals. The thrust bearing and negative thrust bearings will fail. Finally the bull gear teeth could be damaged.

- Failure of the surge protection system to recognize and unload the compressor during surge can lead to one or more of the following damaged components.
    a) Impeller and diffuser/cover
    b) Thrust bearings and collars
    c) Plane bearings
    d) Air/oil seals
    e) Pinions/bull gear
    f) Main bearings
    g) Main oil pump

- Properly designed and maintained control systems can protect the machine from surge. A surge sensing device on older machines uses a differential pressure switch to sense surge. At the point of surge, the blow-off/anti surge valve opens and all air is directed to atmosphere. The internal pressure is reduced and the check valve closes to keep plant air from backwashing to the suction side of the compressor.

  More modern machines rely on the dramatic change of motor amps which is categorized during the control system programming and setup. The machine is purposely put into a very mild surge during commissioning with the surge parameters noted by the software.

# Failures

Mechanical failures usually start as uncontrolled surging or high vibrations. These issues can be the result of:

A. Improperly calibrated controls
    1) Over throttling can cause surge
    2) Under throttling can waste power
    3) Late blow-off can cause surge
    4) Early blow-off can waste power
    5) Poor valve response can cause surge
B. Fouled inlet filter
    1) Surge,
    2) High vibration
    3) Overheating
    4) Wasted power
    5) Worn impellers and diffusers
    6) Reduced flow
C. High inlet air temperatures
    1) Surge
    2) Reduced flow
    3) Overheating
D. Fouled intercoolers on air or water side
    1) Surge
    2) Overheating
    3) High inter-stage pressure changes
    4) Vibration
E. Worn impellers and or diffusers
    1) Reduce capacity
    2) Surge
    3) Overheating
    4) Vibration

F. Deposits on impellers, diffusers, moisture separators etc
    1) Vibration
    2) Surge
    3) Reduced capacity
    4) High inter-stage pressure changes

G. Momentary loss of electrical power
    1) Surge
    2) Vibration
    3) Loss or reduction of oil pressure causing bearing and seal failure

H. water carryover from condensate or cooling water leak
    1) Surge
    2) Vibration
    3) Impeller, pinion shaft, bearing/seal, diffuser damage

I. Improperly adjusted impeller to diffuser thrust clearance
    1) Surge
    2) Overheating
    3) Reduce capacity
    4) Vibration
    5) Impeller, pinion shaft, bull gear, bearing/seal, diffuser damage

J. Low or high cooling water flow
    1) Overheating
    2) Surge
    3) Reduce capacity
    4) Impeller, pinion shaft, bull gear, bearing/seal, diffuser damage
    5) Vibration

# Monitoring of Operating Parameters

Centrifugal Compressors typically produce more air per pound of machine weight than any other of the three major existing technologies, including double acting reciprocating and rotary screw types. This is due to their ability to run at very high speeds. In order to do this and avoid catastrophic failure, operating parameters must be closely controlled and monitored.

The following parameters are monitored and must be adhered too on today's machines. Here again, there are major differences in the way the data is gathered, displayed and stored.

A. Vibration

Most compressors have one or more vibration probes mounted at each pinion shaft. Newer machines monitor deflection on both the x and y axis by the use of an eddy current probe connected to a vibration monitor. Readouts are in mils. This device is used to show the average total movement of the shaft and send a warning signal prior to the critical point. Before damage occurs, an increase to a critical point shuts the machine down. In certain cases the machine will not even come up to full operating speed if the imbalance is too great. These systems are for machine protection but do not allow the operators to troubleshoot or trend potential problems. Serious damage can occur to the previously mentioned components even when this type of system is operating properly. In many cases the vibration increases during machine startup or coast down, as pinion speeds pass through the "critical". In other cases, a piece of dirt or other foreign material can separate from an impeller during coast down and not have any affect until restart. Since vibration typically climbs during the start as critical speeds occur, a timed delay is incorporated in the system to allow the machine to get up to full speed. Even with these systems in perfect working order, there is still a need for regular analysis with more sophisticated equipment. Most mechanical irregularities manifest themselves as vibration increases. I strongly recommend that vibration trending be a routine part of the normal maintenance schedule. This will be discussed in detail by Tim Irwin of M&B Engineered Solutions.

B. Motor Amps

Motor amps are what determines the air flow and protects the machine from surge on more modern machines. The control system also insures that the motor's maximum allowable full load current is not exceeded. This is done by limiting the position of the inlet valve so either the discharge pressure or the flow does not cause the motor amperage to become critical. At the maximum allowable amp reading the inlet valve positions itself to not exceed the maximum allowable mass flow or compression ratio of the compressor.

C. Inlet and Blow-off valve percent open

This is displayed by the control system and is simply for reference purposes. It is a relative number and is not an indication of actual capacity. The percentage will change with ambient conditions but the machine will do the same work at the same mass flow.

D. Cooling water temperatures

This is the temperature of the cooling water at the inlet and outlet sides of the inter and after-coolers. It is used along with the air out let temperatures, to determine the efficiency of the coolers. A cooler with a low differential temperature could indicate fouling on the air or water side or perhaps excessive water flow.

E. Discharge pressure

The actual system pressure located at the discharge of the compressor. It does not indicate actual pressure at the point of usage.

F. Inter-stage pressure

This is the pressure of the air at the outlet side of the impeller prior to the inter or after cooler(s). Changes in these pressures are an indication of degradation of an internal element as described above. As an example; an under performing impeller could cause inlet pressure to the following stage to decrease. If the pressure decreases enough due to the reduction in mass flow, that stage could surge.

G. Inter-stage temperature
This is the air temperature after an inter-cooler and before the next impeller. The same potential surge problems can exist due to a reduction in mass flow caused by increased temperatures.

H. Lube Oil pressure
This is the oil pressure produced by either the pre-lube auxiliary pump used for starting and stopping and the main oil pump used when the compressor is up to speed. A minimum pressure must be delivered an electric or air motor pump before the motor contactor will allow the main drive motor to be energized. Once minimum main oil pump pressure is achieved, the auxiliary pump will shut off. Pressure is maintained by the use of an oil bypass valve. Most machines have dual cartridge filters which can be changed while the machine is on line. A manual by-pass valve is incorporated. Filter integrity is determined by the ΔP across the filter.

I. Lube Oil Temperature
This is the oil temperature as it enter and exits the oil cooler.

J. Lube oil cooling water temperature
This is the cooling water temperature in and out of the cooler.

K. Seal air pressure
A separate air source is applied between the air/oil seal assembly to insure that pre-lube oil does not enter the compression area prior to start-up. Once the compressor loads, compressed air is supplied by the compressor and keeps the lube oil from passing through the oil seal. Worn or damaged seals show low seal air pressure with the machine off and a high seal air pressure with the machine running.

L. Inlet air filter ΔP
This is usually a magnehelic gauge on the compressor inlet to show filter degradation. It measures in inches of water column.

M. Drive motor winding temperature

This protects the motor windings and insulation from damage do to excessive heat. Larger motors also carry auxiliary lube oil pumps and can be water cooled. These larger motors will have instruments to monitor additional pressures, and temperatures of the oil and cooling systems.

# Maintenance

The following is a general description of maintenance requirements performed on a typical integrally geared centrifugal plant air compressor. It is general in nature and is for discussion purposes only. Follow the actual procedures suggested by the original manufacturer.

A. Inlet air filter(s)

Replace primary and secondary filter panels when indicated pressure drop exceeds recommended maximum. Insure that the inlet pipe is free of dirt and scale. Remove the pipe to clean if required. Cleaning in place may cause foreign material to enter compressor inlet.

B. Lube oil/filters

Based on an 8000hr/year cycle, send lube oil sample to be analyzed. Change only if recommended. Change oil filters at the first sign of fouling or once per cycle, which ever comes first. Insure auxiliary lube pump starts automatically below 15psi.

C. Controls

1) Calibrate all instruments including transducers, indicators, servos/valve petitioners, control panel, PLCs and vibration monitoring and protection devices every 16,000 operating hours or as required.
2) Perform diagnostic check of vibration trends on a bi-annual basis based on calendar time, not running hours.

D. Performance

1) Perform natural surge test every 8000 running hours to establish capacity decrease trend. When natural surge pressure is 15psi greater then design operating pressure take unit off line for running gear inspection, clean/balance and possible overhaul. Check wear on pinion/bull gear teeth.

E. Cooling system

1) Back-flush and chemically clean intercoolers, after cooler and oil cooler if air temps or oil temps can not be reduced to a CTD of 15° at full load as required.
2) Perform hydrostatic pressure test on all coolers while in place every 2000 running hours. Repair or replace immediately.
3) Test condensate removal system on a daily basis to insure no water carries over. Repair or replace immediately.

F. Instrument Air system

1) Check instrument air pressure with compressor off line every 8000 hours. Replace air and oil seals if pressure rises more than 25% when running loaded.

G. Drive Motor/Switch Gear

2) Align and grease coupling, megger motor, clean as required, inspect and check motor starter circuitry as required every 16,000 hours.

Thank you all for the opportunity to attend you meeting and to make my presentation. I hope that this brief presentation was interesting and informative. In the future if I can be of service to you or you company, please feel free to contact me.

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