Managing Compressed Air Energy

Part III: Supply Side Issues

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Eleven factors that affect a system's energy requirements.

Energy management in compressed air systems can be divided into two sectors: demand side and supply side. Once the energy constituents of demand in the system have been determined we must determine how effectively we are using energy to support the usage. In most systems, much of the demand usage is a constituent of the supply energy.

There are a number of ways that energy is consumed in an industrial air system besides the obvious. Some of these are very interactive and difficult to isolate, but they must be addressed in a typical plant compressed air system. Remember that air systems are extremely dynamic.

In auditing most systems, there is a common problem that always surfaces in the supply side of the system. The issue is ownership. Responsibility in the system is broken up between supply and demand, often with no one responsible for the demand side of the system. Preventive maintenance normally is performed by maintenance personnel. Overhaul and annual maintenance often is contracted to compressed air service organizations. It is assumed that these personnel are adjusting the equipment for its efficient operation. Often, this is not the case. The following problems are typical.

Problem: **A service contract is issued with no discussion or understanding of the objectives of the owner.**
Preventive Action: **Establish service objectives.**

Problem: **The owner, out of a lack of knowledge, assumes that the right things will be done. Neither party understands that the way the system operates must be owned by someone.**
Preventive action: **Designate a compressed air system manager.**

Problem: **The equipment is adjusted to factory-recommended set points and signals when it is installed. This has nothing to do with either how the system will work or efficient operations. In most cases the equipment is never readjusted for its useful life unless the controls are replaced.**
Preventive action: **Periodically audit system performance and adjust set points as needed.**

Problem: **No one, including the service vendor and the operators, has any records of how the equipment was originally adjusted. No discussion occurred about how the system should work, other than meeting a minimum acceptable pressure.**
Preventive action: **Document system history.**

Problem: "Keep the equipment running" is a vague protocol that assures energy waste and high operating cost.

Preventive action: Establish a rational approach to system management that can allow unused equipment to be taken off line and adjust signals, set points, and control philosophy accordingly.

These preventive measures must be revisited each time demand changes or a piece of supply equipment is added, deleted, or replaced, and the operating approach adjusted appropriately. If not, the system energy efficiency and system effectiveness will suffer.

The following 11 items are issues that affect supply energy in the tyical system.

1. **Demand Usage:**

   Demand usage is the amount of energy necessary to support consumption assuming no inefficiency in the system. Factors affecting demand were discussed in previous articles.

2. **Temperature and Relative Humidity of Intake Air:**

   Using standard conditions as a normalized value, higher temperatures at the inlet of a compressor provide less dense air and result in less compressed air mass. Because the compressor produces less results in terms of mass or work energy, more energy is required to produce the identical results systemically achieved at lower temperatures. Dynamic and positive displacement compressors respond differently, but the systemic results are comparable. When the inlet air represented is based on volume with no regard to density, one can easily overlook this issue and the corresponding energy required.

   When the temperature drops, the air is denser and the compressors will produce more mass to the system using more energy. As work energy in the system is our objective, inlet density or mass is a necessary component of determining the power required and the number of compressors to support all conditions relative to the system. At 0 F without the effect of relative humidity, you will produce close to 12 percent more air by mass and an equivalent amount of energy than at standard conditions. At 100 F without the effect of relative humidity, you will produce at least 7 percent less air by mass and an equivalent amount of energy.

   Higher relative humidity implies that there is more water present in the air at the compressor intake. Because water does not compress, it reduces the amount of net air that can be compressed. Relative humidity can influence the net result by as much as 3.5 percent less displaced mass.

   When effects of temperature and relative humidity are combined, there can be as much as a 22.5 percent swing in performance on the compressors in the system from 0 F at 1 percent relative humidity to 100 F at 100 percent relative humidity.

   When you compare the demand requirements including trim and conditional loads against the inlet condition profile, the amount of energy needed will be a function of the size of the compressors used. The larger the compressors as a percentage of the total requirement, the

more part loaded a large unit will be depending on conditions and load. The smaller the compressors are, as a percentage of the total requirement, the less part loaded any one compressor can be. When properly controlled, the arrangement and size of the units vs. the needs profile can represent as much as 33 percent less power systemically at the lowest temperature and load.

3. Compressor Optimization:

The primary objective of compressed air system management is to get the most mass per kilowatt of electricity. The more mass you can achieve in any one compressor in the system, the fewer compressors you will need to accomplish the same results. Throughout this article, mass refers to pounds mass (volume at density).

On positive displacement compressors, the volume is fixed within the operating pressure of the compressor. As you elevate the pressure within this range, the volume will remain constant as the pressure and power increases. This is an increase in mass. As you exceed optimum, the mass will become constant and/or the motor efficiency will begin to drop. The pressure and energy will increase, but the mass will remain constant. In our experience, optimum will be achieved within a compressor frame range at a higher pressure in the bottom of the frame and at a lower pressure in the top of the frame. This is a result of packaged losses that increase in the top of a frame.

On centrifugal or other types of dynamic compressors, optimum is achieved in a slightly different manner. There are zones on the performance curve. A portion of the curve will produce constant mass. This implies that as the pressure rises and falls the volume will change inversely and maintain the amount of mass.

Above and below this zone of performance, either the pressure will drop faster than the increase in volume or the volume will diminish faster than the rise in pressure. Both of these zones will produce less mass. The power does not diminish as quickly as the mass in these zones. You would have to determine at what pressure you would displace the most mass per kilowatt of electricity by carefully examining the curve of the compressor at the typical and extreme inlet conditions of intended operation.

The confusing issue with centrifugal and dynamic compressors is that the performance curve moves with changes in inlet temperature. It will drop and move to the left as the inlet temperature increases, and rise and move to the right as the inlet temperature drops. This would require adjusting the operating pressure and the current limit adjustments on temperature change to stay within this optimum range. If the curve is generous enough for your conditions, you may be able to operate at relatively little performance change despite conditions.

The number of stages and the design will determine at what range of pressure this can be achieved. Optimum is normally achieved at the lowest pressure in the constant mass zone of the curve, which uses the least amount of input power for the mass achieved. We have found that factory-supplied curves only show performance between maximum stable flow and the surge pressure of the unit. More than half of the compressors of this type that we

evaluate are operating at least a portion of the year below the pressure and temperature where you will find maximum stable flow (not mass).

If you continue down the curve from this point, the volume will become constant as the pressure drops and the energy either remains constant or diminishes. This is referred to as the choke zone. In the choke zone, you lose the advantages of this type of compressor. Further down the curve the volume will diminish as the pressure drops. This more-than-linear loss of mass is called stonewall where you will achieve sonic velocity through the unit.

Neither the choke zone or stonewall are shown on factory-supplied charts. We would suppose that this is not shown because you should not operate in this manner. Nevertheless, we frequently find compressors that have set points of operation below maximum stable flow and well below optimum. We also seldom find compressors operating on the curve. Most of the time they are operating in modulation or throttle. If the curve were extremely vertical, where there is very little volume turndown on the curve, you would have to operate at a low relative pressure in throttle to prevent surge. It should be obvious that examining the curves in terms of mass at pressure including minimum stable mass at various pressures and inlet conditions is the only way to determine the best operating set points for efficient performance.

You also should request that the curves show throttled performance at pressure and power at these various pressures and inlet conditions. Despite this need, we did not encounter one facility in the past 250 audits that had enough information to determine the best way of operating the compressor. In fact, most owner/operators have never seen curves, even during the selection process. Since this information is obviously needed and has never been produced, one must be curious how factory required service technicians adjust the units in the field. Our experience is that keeping them running is the approach taken, not optimization. Factories need to train their service personnel and the operators in performance optimization of both the individual equipment and the system using actual performance data and curves rather than typical factory set up suggestions.

4. Compressor Cooling Temperature:

All compressor performance is influenced to some extent by the temperature at which the unit is cooled. There is a considerable difference in types of compressors. The displacement can be influenced by 0.5 percent to 3.5 percent of rated capacity for every 10 deg F increase over rated cooling media temperature. The inherent inefficiency, combined with the range of cooling media temperature and the maintenance condition of the coolers on the compressor, can effect the displacement efficiency by as much as 25 percent on the most temperature-sensitive types of compressors. Centrifugal compressors should be tested for natural surge and throttle surge at least twice a year to determine the performance decay of the unit as a result of cooler fouling.

You must record the inlet conditions during these tests so you can compare actual performance against theoretical performance for these conditions. Factory service personnel should either teach operating personnel how to perform these tests or provide this test data to maintenance personnel on a regular basis if you wish to minimize onboard energy and perform maintenance as required.

5. **Systems Storage vs. Rate of Flow of the Largest Event in the System vs. Loading Time Required for the Next Available Compressor:**

The more storage capacity in the system, the less the pressure will fluctuate on any demand event. This will allow you to maintain all of the compressors that need to be operating closer to optimum. The slower the speed that it takes to turn on the motor and load the next compressor, the more the pressure will drop. You should be able to add trim compressors to the system with a minimum delay and pressure drop. When this process doesn't work well, and the pressure fluctuates too much, the normal reaction is to put all compressors in modulation and keep them on line regardless of demand. This will avoid the fluctuation or pressure decay, but not without a considerable increase in energy and operating cost.

Another anomaly is that as demand increases, the supply pressure drops. When the pressure drops on all of the compressors that are base loaded, there is a loss of isothermal efficiency proportional to the decay in the density of the compressed air. In most systems, as the demand increases and you require more mass, the compressors that are operating produce less mass. This causes the pressure to drop exponentially. As you need more, you can become less efficient with pressure decaying at an accelerated rate.

Careful design of control storage and thoughtful selection of set points, signal locations, and operating logic is necessary to achieve any relative efficiency from the system. Single set point, rate of change automation is the best approach to maintaining optimum system performance.

6. **Resistance to Flow in the System's Piping and Downstream Point of Use Components:**

The highest point of use pressure requirement is determined by the highest article or inlet pressure on the air-using equipment plus the highest installation differential across the point of use transmission components such as filters, regulators, lubricators, disconnects, hose, and fittings.

Original equipment manufacturers install smaller transmission components with high differential pressures to control manufacturing costs. The user of the equipment must compensate by providing high initial pressures from the plant air system. The tradeoff between high operating costs and the price of equipment with lower operating pressures or differentials is an important but rarely considered issue. Typical pressure drops across accessories on air-using equipment have increased substantially in the past 15 years. As long as this is a non-issue among the purchasers of this equipment, you may be assured that manufacturers will continue to use differential pressure as a tool for controlling manufacturing costs.

The highest differential is achieved at the highest flow, highest inlet temperature, and the lowest pressure. All specifications should incorporate this information in performance queries and specifications with maximum differential being the desired response. Compressor manufacturers report that elevating the pressure 1 psig will increase power by 0.5 percent of the total connected onboard energy. If you are operating with the

compressors in load-no load mode and the elevation of pressure does not increase the demand in the system, then this is true.

Unfortunately, most systems are in modulation and do not have a demand control or expander. The elevated pressure then will cause demand to increase. The demand increase will be a function of the percentage of unregulated demand including leaks and points of use with regulators adjusted to the maximum setting. The power will increase proportional to the pressure increase adjusted for the percentage of unregulated demand plus the 0.5 percent per 1 psig rise. If the increased demand does not require an added compressor, the influence on energy will be between 0.5 percent to 1.575 percent of the total connected brake horsepower (bhp) from 100 percent regulation at the point of use and no leaks in the system, to 0 percent regulation plus leaks respectively per 1 psig rise in operating pressure.

If you are in modulation, and must add another compressor in order to increase the pressure, the new compressor will support a portion of the added load, but the total volume will be shared across all modulating compressors. This can be so inefficient, depending on the degree of part load prior to the add, that the effect of a pressure increase can be 25 percent or more for a 1 psig pressure increase if another compressor must be added. We haven't seen a system without leaks, nor 100 percent regulated below the lowest compression pressure. Compressor manufacturers do not field test how their units are influenced in systems, only packaged results. So much for the 0.5 percent per psig of pressure rise.

7. **Differential Pressure Across Supply Components Downstream of the Compressor Control Signal Location:**

   Differential pressure influences system energy in the same manner as in item 6. Filters that degrade will cause the downstream pressure to drop. Typical of these components would be aftercoolers, separators, filters, and dryers when the compressor signal is located upstream of the aftercooler. Specified performance never includes the influence of differential. This must be determined at the highest flow, lowest pressure, and highest temperature as with point of use equipment. What is unique is that the differential will ride on the system's pressure and drive backwards into the compressor's operating pressure signal.

   If the operating philosophy is to turn on compressors to maintain a system pressure of 100 psig, the pressure drop across the clean-up equipment will drive the control signal up accordingly. If the clean up differential pressure is 10 psig, the signal pressure would have to be maintained at 110 psig to maintain a system pressure of 100 psig. As you need more air, the differential will increase at a higher rate of rise than the dropping system's pressure.

   The more you need, the harder it will become to satisfy the demand, and the more likely you will turn on the next available compressor to share the load.

8. **Higher internal pressures resulting from differentials across components upstream of the compressor control signal**

   This is where the compressor control signal is downstream of all or some of the components as in item 7. In this case, the differentials increase the internal pressure in the compressor.

In this case only, the compressor energy will increase 0.5 percent of the total connected bhp per psig for this internal pressure rise.

The same would be true of an air to lubricant separator on a rotary screw compressor. As the filter/separator dirt loads, the upstream internal pressure rises, increasing the motor bhp. The separator is upstream of the control signal. The increase in energy we are discussing is only true as long as there is motor capacity available. Once you have consumed all of the available energy, either the displacement will diminish, the motor will overload depending on the compressor type, or you will have to add another compressor. The differential and the energy will rise and fall with the change in the compressor volume, but the system will not see the effect of this, only the drive motor.

9. **Resistance to flow on inlet filters and their effect on reduced inlet pressure to the compressors**

   As the inlet filter becomes loaded with dirt, the dry inlet throat pressure drops proportionately. If the compressor is not fully loaded, it will increase in load to achieve the desired result as a consequence of the controls set point at the reduced inlet pressure. The effect will be different depending on how the compressor is operating.

   In load-no load mode, the increase will be in more load time. The energy increase will be proportional to the ratio of the atmospheric pressure divided by the added differential. This particular differential is measured in inches of water and needs to be corrected to pounds/sq in. for the ratio (27 in. static pressure water gauge equals 1 psi).

   If the compressor is in modulation, the effect on energy can be more or less than linear depending on the load on the compressor at the time that the inlet pressure reduction occurs. Power is anything but linear in modulation. Based on manufacturers' recommendations for filter changes, most systems will increase power by 2.3 percent to 3 percent during the time between when the inlet filter is clean and when it is sufficiently dirty to require change. If this causes the need for another compressor, the influence increases the power dramatically.

10. **Inefficiencies resulting from how the compressor controls are set up and their effect on unit performance**

    The effect of improperly set controls can increase energy consumption by a modest amount to as much as 33 percent of the total connected kilowatts. A system control setting is a very complex matter requiring a great deal of understanding. Previous discussion outlined the general effects of the demand system and the supply components on energy usage. This actual influence is specific to the interrelationship between the compressors, their signals, set points, and differentials within the system. This complex subject is outside the scope of this article but is covered fully in a 90-page section of the author's "Compressed Air Systems Solution Series.

11. **Fouling of internal components on the air path of the compressor**

Fouling of internal compressor components is specific to dynamic compressors such as centrifugal and axial types. The dirt and condensibles from the inlet loading on impellers and diffusers can cause considerable performance losses. As this occurs, the surge pressure usually drops in the compressors. Natural surge testing can assist in determining whether this condition exists. You can also observe whether the unit is performing in terms of mass at pressure and power comparing test results against rated performance on its curve.

Measuring and Managing Energy:

For the most part, compressors have no power monitoring equipment on them. In the infrequent case where there is, the compressor is monitored with an amp meter measuring current to the motor. Current is not an accurate means of monitoring power on a compressor because of the relationship between mass and input power.

Monitoring and trending total and individual input power is perhaps the best means of trending operating cost and predictive maintenance issues. The only accurate method we have observed is using kilowatts, relative to full and part load performance.

Compressors and systems do not usually fail. They degrade. If you trend individual compressor input power vs. status and system efficiency, you can easily avoid an interruption without the extravagant application of power as an alternative. You need to monitor the total mass at pressure on the demand side of the system and trend the demand mass divided by the total input kilowatts.

Although many of the individual compressed air energy issues have been understood for some time, it has only been in the past five or six years that the interrelationship of a system's supply and demand has begun to be understood. The improvement in and quality of information applied and trended systemically has provided the best basis for separating the theoretical from the actual. The commercial emphasis in compressed air has always been with the equipment. Much more emphasis must be placed on systems and their operations at all levels including system operations, production usage, sales engineering, contract field service, and equipment manufacturing.

The remarkable opportunities available for operating cost reduction and quality improvements in production are a strong indication that there is much work that needs to be done in this area of plant asset management. Many of the poor decisions that are made are out of fear of not satisfying production. Fear is only present in the absence of knowledge. Education, ownership, and the application of information are the beginning of more effective plant air systems.

R. Scot Foss is president of Plant Air Technology, Charlotte, N.C., a company specializing in system auditing and designing. This series of articles is based on his book, "Compressed Air System Solution Series". A portion of the proceeds from sales of the book is donated to children's charities. The book can be ordered through Southern Corporation.