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JANUARY 2009

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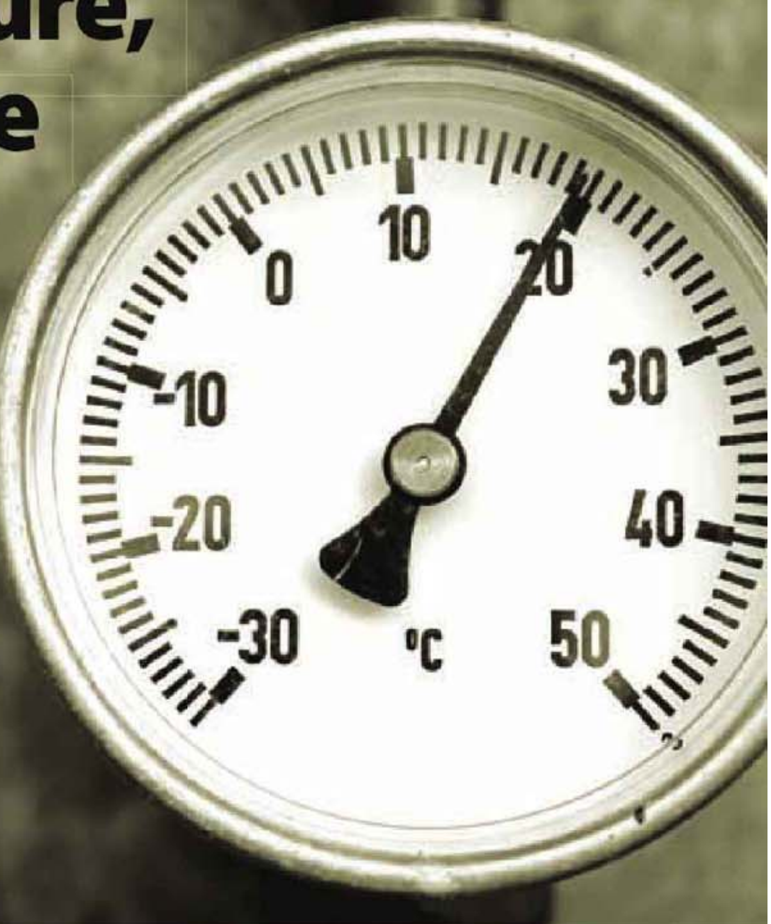
Part One

Inlet Temperature, Outlet Pressure and Storage



Don't let misapplied rules of thumb become your compressed air rules of dumb

BY HANK VAN ORMER

Will reducing the inlet air temperature to a compressor increase its efficiency? In a world of sound bites, people become obsessed with simple, easy answers. The oft-quoted rule about inlet air temperature goes something like this: Each 5°F reduction in inlet air temperature nets a 1% gain in efficiency. How many times have you heard statements like this? Others include:

A big difference

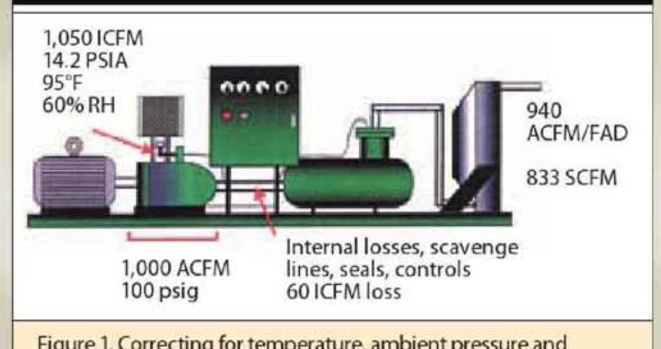


Figure 1. Correcting for temperature, ambient pressure and moisture content can have a large effect on the measured air volume.

- Install the air intake on the north side in the shade.
- Pre-cooling the inlet air always increases efficiency.

The unvarnished truth is this: The temperature rule holds true for some compressors, but not all compressors.

Before you ask why, you need to know what we mean by an increase in efficiency. Efficiency doesn't mean operating longer between overhauls or running smoothly. Efficiency means delivering more compressed air output per unit of input electrical power. Throughout the industry, this measurement often is denominated as bhp per 100 cfm of compressed air delivered. People like me, who want things simple and easy, use cfm per input kW – the amount of air delivered per input kW of power. We call it specific power.

Weight versus volume

Another concept that affects the math is the difference between the actual volume of inlet air (acf) and the standard volume of inlet air (scf). The most valid efficiency measure is scfm delivered at full-load input power. The actual cubic feet per minute, also called free air delivered (FAD), is based on air at the inlet conditions. There are no corrections made for temperature, pressure or relative humidity.

Psychrometric data

Air temp, °F	Water vapor PP (psia)	Air temp, °F	Water vapor PP (psia)	Air temp, °F	Water vapor PP (psia)
32	0.08854	60	0.2563	86	0.6152
34	0.09603	62	0.2751	88	0.6556
36	0.10401	64	0.2951	90	0.6982
38	0.11256	66	0.3164	92	0.7432
40	0.1217	68	0.339	94	0.7906
42	0.1315	70	0.3631	95	0.8153
44	0.14199	72	0.3886	96	0.8407
46	0.15323	74	0.4156	98	0.8935
48	0.16525	76	0.4443	100	0.9492
50	0.17811	78	0.4747	102	1.0078
52	0.19182	80	0.5069	104	1.0695
54	0.20642	82	0.541	106	1.1345
56	0.222	84	0.5771	108	1.2029
58	0.2386	85	0.5961	110	1.2748

Table 1. Water vapor partial pressure at 100% RH as a function of temperature.

The standard cubic feet per minute measurement, on the other hand, is a function of those variables. Remember:

- A fixed volume of cold air weighs more the same volume of warm air.
- A fixed volume of air at a higher ambient pressure weighs more than the same volume at lower ambient pressure.
- Water vapor at the inlet is compressed and removed in the air dryer, and represents a reduction in the weight of air compressed and delivered to the systems.

In short, inlet conditions affect the density and weight of the air delivered to the users in the plant (Figure 1).

Measuring in scfm requires that the inlet air conditions be corrected to 60°F, 14.5 psia and 0% relative humidity, the standard conditions established by the Compressed Air and Gas Institute (CAGI) and Pneurop, its European counterpart. Most, if not all, manufacturers of air compressors and dryers use these standard conditions. Unfortunately, production machinery manufacturers and flowmeter manufacturers don't always use this standard. You can use the following equation to connect the inlet and outlet conditions for a compressor:

$$scfm = acfm \times ((p_1 - p_w) \times (460°F + 60°F))/(14.5 \times (460°F + t_1))$$

where:

p_1 = inlet ambient pressure (psia)

p_w = water vapor partial pressure at inlet (psia)

t_1 = inlet air temperature (°F)

You can find the water vapor partial pressure in Table 1, which is sufficiently accurate for informed decisions about equipment selection. Multiply the saturated values given there by the percent relative humidity at the inlet conditions. Whatever water vapor the cleanup equipment removes represents a reduction in inlet air pressure to the compressor.

For example, assume an ambient temperature of 90°F and 50% relative humidity. If the air was fully saturated, the water vapor partial pressure, according to Table 1, would be 0.6982 psia. But, with 50% RH, the partial pressure is 0.6982 x 0.50 = 0.3491 psia. Deduct this value from the recorded inlet pressure (psia) to compensate for the water vapor to be lost. This effectively reduces the weight of the compressed air.

Measure inlet pressure with a vacuum gauge. A reading below 14.5 psia increases the volume of the air required for the target flow rate. But, weight and volume also are functions of inlet filtration, inlet piping and weather. Hence, compressed air is dynamic, so be aware of the effect the inlet filter size and condition, and the piping size and length have on performance. Any inlet condition variable that makes the air denser increases the scfm delivered per unit of acfm (inlet air at inlet conditions).

That background is preparation for answering the original question: Will reducing the inlet air temperature to a compressor increase its efficiency? It seems kind of simple now, doesn't it? The hotter the air, the lower its density. The colder the air, the more a unit volume will weigh, thereby producing greater scfm. And, in a positive-displacement compressor, the actual swept volume of inlet air has more effect on power draw than does the scfm or weight of air. As the temperature falls, delivered air scfm increases at a much greater rate than the power. The net result leads to a relatively accurate guideline: Every 5% of cooling leads to a 1% improvement in specific power or efficiency.

Reducing inlet temperature or otherwise increasing the air density is equivalent to increasing the mass flow when the volume displacement (icfm/acfm) remains constant. The input power remains the same or about the same. This rule is fairly accurate for reciprocating and oil-free rotary compressors (vane, screw, lobe, scroll, etc.)

A new ballgame

What about lubricant-injected cooled units (rotary screw and vane)? Generally, compressed-air representatives are going to give you one of two answers: "Sure, the 1% per 5°F rule applies," or, "No, it doesn't apply." The facts are these:

- The rule certainly doesn't apply in its entirety.
- Compressor manufacturers have invested many hours of laboratory testing unsuccessfully trying to establish an accurate guideline.

Positive-displacement, lubricant-cooled, rotary screw or vane compressors inject lubricant (at 150°F to 160°F) into the compressed air, either at the inlet or immediately after seal-off. The oil acts as a coolant and absorbs most of the heat of compression. Regardless of design, some of this hot coolant/lubricant finds its way back to the inlet, where it can have a significant effect on the temperature of the air entering the rotary compression element(s). This localized heating of the inlet air can greatly reduce the beneficial effect of a colder inlet air temperature.

Over the years, we chased all over trying to find a universally appropriate way to quantify this effect. Finally, we gave up, accepting the test result for what it was: a normal change in inlet air temperature had no consistent measurable effect on efficiency. The methods for injecting lubricant/coolant into rotary-screw compressors have evolved from the old-style standard injection ports located after the seal-off point to methods such as:

- Female rotor injection on the inlet side to enhance sealing
- Rotor inlet oil injection

Both approaches probably warm the inlet air significantly, so the net result is that you can't count on colder inlet air to increase performance (more scfm/kW) from a lubricant-cooled rotary screw or vane compressor.

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The centrifugal story

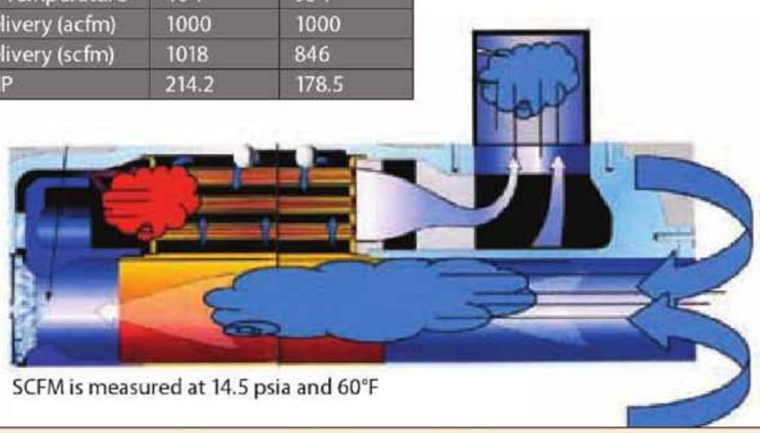
Because they're mass-flow units, the required input power to centrifugal compressors is a function of the weight/density or mass flow of the air. When the inlet air is colder (Figure 2), these compressors deliver more air using a commensurate increase in driving power. This doesn't improve efficiency, but if you require the extra air and have the power available to produce it, it might help keep an additional unit offline. If you don't have the power available or haven't reset the current or power limiters, then the centrifugal compressor will just blow off sooner.

This rule of thumb can become a rule of dumb. When someone takes things out of context and says, "My inlet air is 100°F now. When it goes to 30°F this winter, I'll increase my air flow by 14% (1% per 5°F) so now my 1,000 cfm unit will deliver 1,140 cfm and I can add another bench." Real life doesn't work that way.

Most of the guidelines in use were developed for 100-psig-class compressors, which operate between 80 psig and 135 psig. Keep this thought in mind when applying them.

Temperature and power

Conditions		
PSIA	14.2	13.1
Air Temperature	40°F	95°F
Delivery (acfm)	1000	1000
Delivery (scfm)	1018	846
BHP	214.2	178.5



SCFM is measured at 14.5 psia and 60°F

Figure 2. Air temperature has a large effect on centrifugal compressor power consumption, but not necessarily on its efficiency.

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Next month, Part 2 addresses the relationship between pressure and input power, load control and storage, and recommendations for effective storage volume.