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Energy conservation in compressed-air systems

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SUMMARY

In this paper, we evaluate and quantify the energy losses associated with compressed-air systems, and their costs to manufacturers. We also show how to reduce the cost of compressed air in existing facilities by making some modifications with attractive payback periods. Among the measures, we investigate to reduce the compressed air are: (1) repairing air leaks, (2) installing high-efficiency motors, (3) reducing the average air inlet temperature by using outside air (4) reducing compressor air pressure. We also illustrate the potential saving associated with each measure by using realistic examples. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: energy conservation; compressed-air systems; air leaks; air pressure; high-efficiency motor; outside air

1. INTRODUCTION

The production of compressed air can be one of the most expensive processes in manufacturing facilities. User should always consider more effective form of power before considering compressed air. For example, plants should use air conditioning or fans to cool electrical cabinets instead of compressed air vortex tubes, and should apply a vacuum system instead of creating a vacuum using compressed-air venturi methods that flow high pressure air past an orifice. As a general rule, compressed air should only be used if safety enhancements, significant productivity gains, or labour reduction will result. In spite of the fact that compressed air is one of the major utilities in manufacturing facilities. For example, the total installed power of compressed-air system in the U.S. is estimated to be more than 17 million horsepower (Talbott, 1993). Annual operating costs of air compressors, dryers and supporting equipment can account for up to 70% of the total electric bill (Risi, 1995). The compressors used range from a few

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kilowatts to more than 7500 kW in size. It is difficult to imagine a factory without a compressor. Failure of compressed-air system in some industries can shut down the entire manufacturing process (Cerci *et al*., 1995).

Manufacturers are quick to identify energy (and thus money) loses from hot surfaces and to insulate those surfaces. But somehow they are not so sensitive when it comes to saving compressed air since they view air as being free, and the only time the air leaks and dirty air filters get some attention is when the air and pressure losses interfere with the normal operation of the plant. However, paying attention to the compressed-air system and practising some simple conservation measures can result in considerable energy and cost savings for the plants (Cengel and Boles, 1998). The cost of electric power to operate an air compressor continuously for a year—about 8200 h—is usually greater than the initial price of the equipment. Seen from this perspective, any efforts to reduce energy consumption pay for themselves immediately and produce ongoing savings (Holdsworth, 1997).

There are many text and publications that describe the energy savings potentials of compressed-air systems (mainly Talbott, 1993; Cerci *et al*., 1995; Risi, 1995; Cengel and Boles, 1998; Holdsworth, 1997; Terrell, 1999; Cengel and Cerci, 2000; Kaya *et al*., 2001). In this study, we give an overview of such conservation measures complete with the analysis, the potential energy and cost savings, the implementation costs, and simple payback periods. The proposed measures are intended as a retrofit for existing facilities, and most of them can be implemented by maintenance personal of the facilities. In this paper, our goal is not to present something new, but rather, to raise awareness and to show the tremendous energy and cost-saving opportunities missed as a result of overlooking some simple and obvious conservation measures.

2. POTENTIAL ENERGY AND COST-SAVINGS POSSIBILITIES

2.1. Repairing compressed-air leaks

Air leaks are the greatest single cause of energy loss in manufacturing facilities associated with compressed-air system. The cost of compressed-air leaks is the cost of the energy required to compress the volume of lost air from atmospheric pressure to the compressor operating pressure. This cost is often very significant. The amount of lost air depends on the line pressure, the compressed-air temperature at the point of the leak, the air temperature at the compressor inlet, and the area of the leak. Air leaks, in general, occur at the joints, flange connections, elbows, reducing bushes, sudden expansions, valve systems, filters, hoses, check, valves, relief valves, extensions, and the equipment connected the compressed-air lines. Leaks often represent as much as 25% of the output of an industrial compressed-air system (Terrell, 1999). Eliminating the air leaks totally is impractical, and a leakage rate of 10% is considered acceptable (Cerci *et al*., 1995).

The cost of compressed-air leaks increases exponentially as the diameter of the leak increases, as shown in Figure 1.

Leaks should be repaired as soon as practical, and may be easily located by listening for their 'hiss' when other plant operations are idle. In some situations, it may be necessary to wait for a scheduled plant shutdown. Temporary repairs can often be made by placing a clamp over the leak.

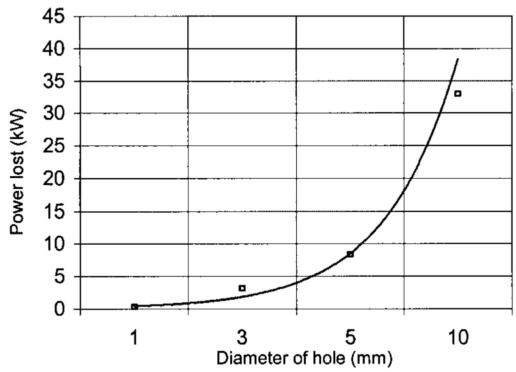

Figure 1. Dependency of power loss to hole diameter (at 600 kPa pressure).

The volumetric flow rate of free air, V_f, exiting all the leaks of a given size under choked flow conditions is calculated as follows (Cerci *et al.*, 1995):

$$V_f = \frac{\text{NL} \times (T_i + 273) \times P_l/P_i \times C_1 \times C_2 \times C_d \times \pi D^2/4}{C_3 \times \sqrt{T_l + 273}} \quad (1)$$

where V_f is the volumetric flow rate of free air, cubic metre per hour ($m^3\,h^{-1}$), NL the number of air leaks, no units, T_i the average temperature of the air at the compressor inlet, °C, P_l the line pressure at leak in question, kPa_a, P_i the inlet (atmospheric) pressure, kPa_a, C_1 the isentropic sonic volumetric flow constant, $7.3587\,m\,s^{-1}\,K^{0.5}$, C_2 the conversion constant, $3600\,s\,h^{-1}$, C_d the coefficient of discharge for square edged orifice, 0.8 no units, π the Pythagorean constant, 3.14159, D the leak diameter, mm (estimated from observations), C_3 the conversion constant, $10^6\,mm^2\,m^{-2}$ and T_l the average line temperature, °C.

The power loss from leaks is estimated as the power required to compress the volume of air lost from atmospheric pressure, P_i, to the compressor discharge pressure, P_o, power loss for each size of leak present for given conditions are calculated as follows (Cerci *et al.*, 1995):

$$L = \frac{P_i \times C_2 \times V_f \times k/(k-1) \times N \times [(P_o/P_i)^{(k-1)/(k \times N)} - 1]}{E_a \times E_m} \quad (2)$$

where L is the power loss from a given air leak, kW, k the specific heat ratio of air, 1.4, no units, N the number of stages, no units, P_o the compressor operating pressure, kPa_a, E_a the compressor isentropic (adiabatic) efficiency, no units and E_m is the compressor motor efficiency, no units.

2.2. *Installing high-efficiency motors*

Most industrial equipment in manufacturing facilities are powered by electric motors, and the electrical energy a motors draw for a specified power output is inversely proportional to its efficiency. Electric motors cannot convert the electrical energy they consume into mechanical energy completely, and the ratio of the mechanical power supplied by the motor to the electrical power consumed during operation is called the efficiency of the motor. Therefore, high-efficiency motors cost less to operate than their standard counterparts (Cengel *et al.*, 2000). Motor efficiencies range from about 70 to over 96% (MotorMaster, 1993).

The monthly kilowatt demand savings for the motor(s), $\mathrm{DS_i}$, and the annual kilowatt-hour usage savings, $\mathrm{US_i}$, which can be realized by installing high-efficiency motor(s), can be estimated as follows:

$$\mathrm{DS_i} = \mathrm{HP_i} \times N_\mathrm{i} \times \mathrm{LF_i} \times (1.0/E_\mathrm{c} - 1.0/E_\mathrm{p}) \tag{3}$$

$$\mathrm{US_i} = \mathrm{DS_i} \times H_\mathrm{i} \times U_\mathrm{fi} \tag{4}$$

where i is the motors to be considered, no units, $\mathrm{HP_i}$ the power of the motor, kW, N_i the number of motors of similar power and efficiency that operate under the same conditions, no units, $\mathrm{LF_i}$ the fraction of rated load at which the motor normally operates, no units, E_c the current efficiency for given motor, no units, E_p the proposed efficiency for given motor, no units, H_i the annual operating hours of the equipment operated by the motor, $\mathrm{h\,yr^{-1}}$ and $\mathrm{UF_i}$ the fraction of operating time that compressors are in use: (usage factor, estimated by plant personnel), no units.

2.3. *Using outside air intake*

Compressors are usually located inside the production facilities or in adjacent shelters specifically built outside these facilities. The intake air is normally drawn from inside the building or the shelter. But in many locations, the air temperature in the building is higher than the outside air temperature, because of space heaters in the winter and the heat given up by a large number of mechanical and electrical equipment as well as the furnaces year round. The temperature rise in the shelter is also due to the heat dissipation from the compressor and its motor. The outside air is generally cooler and thus denser than the air in the compressor room even on hot summer days. Therefore, it is advisable to install an intake duck to the compressor inlet so that the air is supplied directly from the outside of the building instead of the inside. This will reduce the energy consumption of the compressor since it takes less energy to compress a specified amount of cool air than the same amount of warm air.

The compressor work for the usual operating conditions in manufacturing plants is proportional to the absolute temperature of the intake air. Thus, the fractional reduction in compressor work, W_R, resulting from lowering the intake air temperature is estimated as

$$W_\mathrm{R} = (W_\mathrm{I} - W_\mathrm{o})/W_\mathrm{I} \tag{5}$$

$$W_\mathrm{R} = (T_\mathrm{I} - T_\mathrm{o})/(T_\mathrm{I} + 273) \tag{6}$$

where W_I is the work of compressor with inside air, kW, W_o the work of compressor with outside air, kW, T_I the average temperature of inside air, °C and T_o the annual average outside air temperature, °C.

The monthly demand savings, DS, can be estimated from the following relationship:

$$\mathrm{DS} = [\mathrm{HP} \times \mathrm{LF} \times \mathrm{WR}]/\mathrm{EFF} \tag{7}$$

The annual electric usage savings, US, in kilowatt-hours can be estimated from the relationship

$$\mathrm{US} = \mathrm{DS} \times H \times \mathrm{UF} \tag{8}$$

Care should be taken to ensure that the existing compressor fans can provide adequate air flow for compressor cooling when the additional ductwork is installed, as additional ductwork will cause a higher head loss on the compressor fans.

Where W_R is the fractional reduction in compressor work, no units, HP the power of the compressor motor, kW, LF the fraction of running time that the compressors are loaded (load factor), no units, EFF the compressor motor efficiency, no units, H the time-of-use hours of operation, $h\,yr^{-1}$ and UF the average fraction of operation time that compressor is running (usage factor), no units.

2.4. *Reducing compressor air pressure*

The lowest possible pressure level required to operate production equipment effectively is also typically determined. In many cases, system pressure can be lowered, thereby saving energy. Most systems have one or more critical applications that determine the minimum acceptable pressure in the system. In some cases, the application of dedicated storage or differential reduction on the critical applications will allow a reduction in overall system pressure.

The hissing of the air leaks can sometimes be heard even in high-noise manufacturing facilities. Pressure drops at end-use points in the order of 40% of the compressor-discharged pressure are not uncommon. Yet a common response to such a problem is the installation of a larger compressor instead of checking the system and finding out what the problem is. The latter corrective action is usually taken only after the larger compressor also fails to eliminate the problem. The energy wasted in compressed-air systems because of poor installation and maintenance can account for up to 50% of the energy consumed by the compressor, and it is believed that about half of this amount can be saved by practising energy conservation measures (Talbott, 1993).

The total annual usage savings, US, in kilowatt-hours can be estimated from the relationship:

$$\mathrm{US_i} = (1.0 - \mathrm{FR_i}) \times \mathrm{PL_i} \times H \times \mathrm{UF} \tag{9}$$

where $\mathrm{FR_i}$ is the ratio of proposed power consumption to current power consumption (used to represent a reduction in run time) based on maximum operating pressure, no units, $\mathrm{PL_i}$ the power draw of the compressors while loaded, kW, H the annual hours of operation, $h\,yr^{-1}$ and UF the average fraction of operation time when the compressor is running (usage factor), no units.

The following equation can be used to estimate FR, the horsepower reduction factor, based on current and proposed operating pressures (Compressed Air and Gas Handbook, 1961).

$$\mathrm{FR_i} = \frac{((P_{\mathrm{dp}} + P_{\mathrm{i}})/P_{\mathrm{i}})^{(k-1)/(k\times N)} - 1.0}{((P_{\mathrm{dc}} + P_{\mathrm{i}})/P_{\mathrm{i}})^{(k-1)/(k\times N)} - 1.0} \tag{10}$$

where P_{dp} is the discharge pressure at proposed operating pressure conditions, $\mathrm{kPa_a}$, P_{dc} the discharge pressure at current pressure conditions, $\mathrm{kPa_a}$, P_{i} the inlet pressure (atmospheric pressure), $\mathrm{kPa_a}$, k the ratio of specific heat for air ($k = 1.4$), no units, N the number of stages, no units.

3. SAMPLE CALCULATIONS AND RESULTS

3.1. *Example 1: Repairing compressed-air leaks*

At a production facility, 14 air leaks were found, among which five were estimated as 0.4 mm in diameter, two were estimated as 0.8 mm in diameter, six were estimated as 1.6 mm in diameter, and one was estimated as 3.2 mm in diameter. The volumetric flow rate of free air exiting the hole is dependent upon the extent to which the flow is choked. When the ratio of atmospheric pressure to line pressure is less than 0.5283, the flow is said to be choked (i.e. travelling at the speed of sound). There are three compressors present at this facility, two of which are used for backup purposes, and thus will not be accounted for in the following calculations. The main compressor at this facility operates at 689.76 kPa_g (790.829 kPa_a). Considering line losses, it is estimated that the line pressure is on average 620.528 kPa_g (721.9 kPa_a) throughout the plant. The ratio of 101.3 kPa_a atmospheric pressure to 717.055 kPa_a is 0.14 (101.3/721.9 = 0.14). Thus, the flow is choked. Average ambient temperature is 24°C. Rotary screw compressor isentropic (adiabatic) efficiency (E_a) is 0.82. Compressor motor efficiency (E_m) is 0.904.

3.1.1. Anticipated savings. This compressor is estimated to operate 100% of production hours; therefore, compressor operating hours is estimated as 4335 h/y^{-1}. The average usage cost is 0.053 $ kWh^{-1} and average demand cost is 1.95 $ kW^{-1} for this facility.

It is estimated that the average annual air temperature of compressor inlet is 32°C. This temperature is an estimation that the machine room housing the compressors is an average of 8°C above the average ambient temperature. This is used as the compressor inlet air temperature. Because of the long piping runs from the compressor to point use, the compressed air temperature is estimated to be the same as the outside temperature.

Data for factors affecting the cost of compressed air leaks were collected during the site visit, and are listed in Table I.

Using the compressor system data found during the site visit, the volumetric flow rate of air through the leak (Equation (1)), power lost (Equation (2)) due to the leak, and the savings possible from fixing leaks of various sizes were calculated (Table II).

The demand savings, DS, and the usage savings, US, due to repair of the air leaks can be estimated as

$$\mathrm{DS} = L,$$
$$\mathrm{US} = \mathrm{DS}\ (\text{compressor operating hours})$$

As an example, the demand savings, DS_1, for the 0.4 mm air leak is estimated as

$$\mathrm{DS}_1 = L_1$$
$$\mathrm{DS}_1 = 0.30\ \mathrm{kW}$$

It is assumed that demand reduction is constant throughout the day and will occur for each month of the year. In order to estimate the annual cost savings due to demand reduction, DCS, the following equation will be used:

Table I. Compressor system data.

Compressor type	Rotary screw
Number of stages	1
Compressor motor efficiency (%)	90.4
Compressor operating pressure (kPa_g)	689.476
Line pressure at point of leaks (kPa_g)	620.528
Air temperature at compressor inlet (°C)	32
Air temperature at point of leaks (°C)	24

Table II. Energy and cost savings from repair of air leaks.

Leak diameter (mm)	Number of leaks	V_f ($m^3 h^{-1}$)	L (kW)	DS (kW)	US (kWh)	DCS ($\$ yr^{-1}$)	UCS ($\$ yr^{-1}$)	CS ($\$ yr^{-1}$)
0.4	5	2.62	0.30	0.30	1300.5	7	69	76
0.8	2	4.19	0.48	0.48	2081	11	110	121
1.6	6	50.30	5.76	5.76	24969	135	1323	1458
3.2	1	33.53	3.84	3.84	16646	90	882	972
Total	14	90.64	10.38	10.38	44996.5	243	2384	2627

$$\text{DCS} = \text{DS (average demand cost, } 1.95\$ \text{ kW}^{-1}) \times (12 \text{ months yr}^{-1})$$

For the 0.4 mm air leaks:

$$\text{DCS} = 0.30 \text{ kW} \times 1.95\$ \text{ kW}^{-1} \times 12 \text{ months yr}^{-1}$$
$$\text{DCS}_1 = \$7 \text{ yr}^{-1}$$

Usage savings, US, are now determined as follows:

$$\text{US} = \text{DS (annual compressor operating hours, } 4335 \text{ h yr}^{-1})$$

For the 0.4 mm air leaks, the annual usage savings, US_1, are found as

$$\text{US}_1 = (0.30 \text{ kW month}^{-1}) \times (4335 \text{ h yr}^{-1})$$
$$\text{US}_1 = 1300.5 \text{ kWh yr}^{-1}$$

The usage cost savings, UCS, can then be estimated as

$$\text{UCS} = \text{US (average usage cost } 0.053\$ \text{ kWh}^{-1})$$

For the 0.4 mm air leak, UCS_1, is found as

$$\text{UCS}_1 = (1300.5 \text{ kW yr}^{-1}) \times (\$0.053 \text{ kW}^{-1})$$
$$\text{UCS}_4 = \$69 \text{ yr}^{-1}$$

Total cost savings, CS, for the 0.4 mm air leaks is now determined as

$$\text{CS}_1 = \text{DCS}_1 + \text{UCS}_1$$
$$\text{CS}_1 = \$6 \text{ yr}^{-1} + \$69 \text{ yr}^{-1}$$
$$\text{CS}_1 = \$76 \text{ yr}^{-1}$$

Table II shows total flow rate, V_f, power lost, L, demand savings, DS, usage savings, US, and cost savings, CS, calculations as a direct result of repairing the air leaks.

The total monthly demand savings are 10.38 kW and the annual usage savings are 44996.5 kWh yr^{-1}. The total annual cost savings after 14 air leaks are repaired are found as \$2627 yr^{-1}.

3.1.2. Implementation cost. Implementation of this energy conservation opportunities (ECO) may involve replacement of couplings and/or hoses, replacement of seals around filters, shutting off air flow during lunch or break periods, or repairing breaks in lines. Assuming that this work can be done by facility maintenance personnel, it is estimated that all 14 leaks in the plant can be eliminated for <\$280 (\$20 per leak). Thus, the cost savings of $\$2627\,yr^{-1}$ will pay for the implementation cost within approximately 2 months.

3.2. Example 2: Installing high-efficiency motors

At a production facility, the increase in efficiency for various power ranges is summarized in Table III below (Nadel *et al.*, 1991). The number of motors found in each range of power is also shown. Install high-efficiency electric motors to replace the existing standard motors currently used at this facility. It is recommended that the more efficient motors be installed only as existing motors wear out (Kaya *et al.*, 2001). The average usage cost is $0.053\$\,kWh^{-1}$ and average demand cost is $1.95\$\,kW^{-1}$ for this facility. Fraction of operating time that compressors are in use: for the air compressors 1, 2, and 5, factor 1 is used. For the air compressor 3 and 4, factor 0.5 is used (usage factor, estimated by plant personnel), no units. Fraction of rated load (L_{fi}) is 0.95. Annual operating (H_i) is $4335\,h\,yr^{-1}$.

3.2.1. Anticipated savings. The monthly kilowatt demand savings for the motor(s), DS_i, and the annual kilowatt-hour usage savings, US_i, which can be realized by installing high-efficiency motor(s), can be estimated as follows:

As an example the demand savings, DS_3, for the two air compressors (3) motors are estimated as:

$DS_i = HP_i \times N_i \times LF_i \times (1.0/E_c - 1.0/E_p)$
$DS_3 = (11.19 \times 2 \times 0.95) \times [(1.0/0.871)–(1.0/0.920)]$
$DS_3 = 1.30\,kW\,month^{-1}$

The annual usage savings for replacing the two 11.19 kW motors, US_3, are found as

$US_i = DS_i \times H_i \times U_{fi}$
$US_3 = DS_3 \times H_i \times UF_3$
$US_3 = 1.30\,kW\,month^{-1} \times 4335\,h\,yr^{-1} \times 0.5$
$US_3 = 2818\,kWh\,yr^{-1}$

The total corresponding cost savings, CS_3, are estimated as

$$CS_3 = [DS_3 \times (\text{average demand cost, } \$\,kW^{-1}) \times (12\text{ months } yr^{-1})] + [US_5 \times (\text{average usage cost, } \$\,kWh^{-1})]$$

Table III. Potential increase in efficiency.

Motor power (kW)	Number of motors in this range	Average efficiency new TEFC standard (%)	Average efficiency new TEFC EEM (%)
7.46	3	86.4	91.0
11.19	2	87.1	92.0
22.38	2	90.4	93.2
55.95	1	92.1	94.6
Total	8		

Note: Totally enclosed fan cooled (TEFC). Energy efficient models (EEM). Average efficiencies are based on full load nominal efficiencies of the motors supplied by eight different manufacturers.

Table IV. Motor energy savings.

Compressor number	HP_i kW	N	E_c (%)	E_p (%)	DS (kW)	US (kW)	CS ($)
1	55.95	1	92.1	94.6	1.53	6633	$387
2	22.38	2	90.4	93.2	1.41	6112	$356
3	11.19	2	87.1	92.0	1.30	2818	$180
4	7.46	2	86.4	91.0	0.83	1799	$115
5	7.46	1	86.4	91.0	0.41	1777	$104
Total		8			5.48	19139	$1142

$$\mathrm{CS}_3 = [1.30 \times (1.95\$\,\mathrm{kW}^{-1}) \times (12\ \mathrm{months\ yr}^{-1})] + [2818 \times (0.053\$\,\mathrm{kWh}^{-1})]$$

$\mathrm{CS}_3 = \$180\,\mathrm{yr}^{-1}$

3.2.2. Implementation cost. The price of high-efficiency motors is somewhat higher than that of standard motors. The simple pay back for these motors is based on the cost difference between the standard and premium motors, as found in Table IV.

Pay back = N(cost difference)/(CS_3/12)

Pay back = 20 months

These results are shown in Table IV for each motor observed in the plant.

The total monthly demand savings are 5.48 kW and the annual usage savings are 19139 kWh yr^{-1}. The total annual cost savings after all motors are replaced are found as \$1142 yr^{-1}.

3.3. Example 3: Using outside air intake

Table V lists the compressors in use at the facility with their respective operating values based on power measurements performed during the site visit.

The average air temperature at the intake of the compressor, as measured by the survey team, was about 35°C. The average outside air temperature for this region is estimated to be about 21°C. The compressors at this facility operate for a total of approximately 5000 h yr^{-1}. The average usage cost is \$0.0302 kWh^{-1} and average demand cost is 10.82\$ kW^{-1} for this facility.

3.3.1. Anticipated savings. The fractional reduction in compressor work due to lowering the compressor intake air temperature is calculated from Equation (6) as

$W_R = (35–21)/(35 + 273)$

$W_R = 0.045$

The annual reduction in power demand of the air compressor system is shown in the following example:

The annual electric demand savings, DS, in kilowatts is found from Equation (7) as

$\mathrm{DS}_1 = (18.65\,\mathrm{kW}) \times (0.95) \times (0.045)/0.89$

$\mathrm{DS}_1 = 0.90\,\mathrm{kW\ month}^{-1}$

$\mathrm{DS}_2 = (37.3\,\mathrm{kW}) \times (0.95) \times (0.045)/0.91$

Table V. List of compressors in use at facility.

Compressor number	Motor power (kW)	Usage factor (%)	Motor efficiency (%)
1	18.65	30	89
2	37.3	80	91

$DS_2 = 1.75\,\text{kW month}^{-1}$
$DS = DS_1 + DS_2$
$DS = 0.90\,\text{kW month}^{-1} + 1.75\,\text{kW month}^{-1}$
$DS = 2.65\,\text{kW month}^{-1}$

The annual electric demand cost savings, DCS, is

$DCS = DS\ (\text{average demand cost, }\$\,\text{kW}^{-1}) \times (12\ \text{month yr}^{-1})$
$DCS = (2.65\,\text{kW month}^{-1}) \times (\$10.82\,\text{kW}^{-1}) \times (12\ \text{month yr}^{-1})$
$DCS = \$344\,\text{yr}^{-1}$

The annual electric usage savings, US, in kilowatt-hours is found from Equation (8) as

$US_1 = (0.90\,\text{kW}) \times (5000\,\text{h yr}^{-1}) \times (0.3)$
$US_1 = 1350\,\text{kWh yr}^{-1}$
$US_2 = (1.75\,\text{kW}) \times (5000\,\text{h yr}^{-1}) \times (0.8)$
$US_2 = 7000\,\text{kWh yr}^{-1}$
$US = US_1 + US_2$
$US = 1350 + 7000$
$US = 8350\,\text{kWh yr}^{-1}$
$UCS = US\ (\text{average usage cost, }\$\,\text{kWh}^{-1})$
$UCS = (8350\,\text{kWh yr}^{-1}) \times (\$0.0302\,\text{kWh}^{-1})$
$UCS = \$252\,\text{yr}^{-1}$

The total annual cost savings, CS, can then be found as

$CS = DCS + UCS$
$CS = \$344\,\text{yr}^{-1} + \$252\,\text{yr}^{-1}$
$CS = \$596\,\text{yr}^{-1}$

3.3.2. Implementation cost. The most common material used for ducting outside air to the compressor intakes is plastic (PVC) pipe. One end of the duct is attached to the air cleaner intake or other appropriate intake port, and the other end is routed through a wall or ceiling to a cool, shady area on the outside. The total implementation cost for materials and labour to make these modifications to the compressors is \$560. Thus, the cost savings of \$596 yr^{-1} will pay for the implementation cost within 12 months.

3.4. Example 4: Reducing compressor air pressure

At a production facility, six Ingersoll-Rand rotary screw-type air compressors are operated over the facility air pressure requirement as shown Table VI.

Table VI. Operating parameters for compressors.

Compressor number	P_{dc} (kPa$_a$)	P_{dp} (kPa$_a$)	P_{rq} (kPa$_a$)	FR	HP (kW)	PL (kW)	EFF (%)
1	896.3	827.3	758.4	0.9578	74.6	76.59	92.5
2	861.8	827.3	758.4	0.9782	55.9	57.75	92.0
3	875.6	827.3	758.4	0.9698	22.4	23.75	89.5
4	875.6	827.3	758.4	0.9782	22.4	23.75	89.5
5	813.6	655	586	0.9378	22.4	23.75	89.5
6	792.8	655	586	0.9511	18.6	19.90	89.0

The amount of energy required for operating a compressor is related to the air pressure settings. Energy savings are thus possible from reducing the air pressure settings of the compressors. From discussions with plant personnel, it is estimated that 758.4 kPa$_a$ is a sufficient air line pressure for some buildings while others only require 586 kPa$_a$. Therefore, the set point of some of the compressors can be reduced to 827.3 kPa$_a$ and others can be reduced to 655 kPa$_a$, while still providing 758.4 and 586 kPa$_a$ to distant points from the compressors (P_{rq}) considering line losses. The average usage cost is \$0.05052 kWh^{-1}. Annual hours of operation is 7200 h yr^{-1} and average fraction of operation time that compressor is running (usage factor), 1 no units.

3.4.1. Anticipated savings. Using the Ingersoll-Rand 74.6 kW one stage ($N = 1$) rotary screw compressor as an example, FR1 is (from Equation (10)):

$$\mathrm{FR}_1 = \frac{((827.3 + 101.3)/101.3)^{(1.4-1.0)/(1.4\times 1)} - 1.0}{((896.3 + 101.3)/101.3)^{(1.4-1.0)/(1.4\times 1)} - 1.0} = 0.9578$$

Compressing the air to the proposed pressure requires less energy than is necessary to compress the air at the current pressure. The per cent energy savings, %ES, is that change divided by the total. Again, using 74.6 kW compressor as an example:

$$\%\mathrm{ES}_i = (1 - \mathrm{FR}_i)/1 \times 100$$
$$\%\mathrm{ES}_1 = 4.2\%$$

The annual usage savings, US, is then estimated as

$$\mathrm{US}_i = (1.0 - \mathrm{FR}_i) \times \mathrm{PL}_i \times H \times \mathrm{UF}$$
$$\mathrm{US}_1 = ((1.0–0.9578) \times 76.59 \times 7200 \times 1.0$$
$$\mathrm{US}_1 = 2328\ \mathrm{kWh\ yr}^{-1}$$

The annual usage cost savings, UCS, are found as

$$\mathrm{UCS}_1 = \mathrm{US}\ (\$\ \text{average usage cost}\ \mathrm{kWh}^{-1})$$
$$\mathrm{UCS}_1 = (2328\ \mathrm{kWh\ yr}^{-1}) \times (\$0.05052\ \mathrm{kWh}^{-1})$$
$$\mathrm{UCS}_1 = \$1176\ \mathrm{yr}^{-1}$$

The annual usage savings are 58891 kWh yr^{-1}. The total annual cost savings after lowering the set point of the compressors are found as \$2975 yr^{-1}.

Table VII. Calculated savings for compressors.

Compressor number	Energy savings (%)	Usage savings (kWh yr^{-1})	Usage cost savings (\$ yr^{-1})	Energy savings (kWh yr^{-1})
1	4.2	23280	1176	23280
2	2.2	9079	459	9079
3	3.0	5155	260	5155
4	2.2	3733	189	3733
5	6.2	10634	537	10634
6	4.9	7010	354	7010
Total		58891	2975	58891

Table VII Shows demand savings, DS, usage savings, US, and cost savings, CS, calculations as a direct result of reducing compressor air pressure.

3.4.2. Implementation cost. Assuming that these adjustments can be done by the maintenance crew in a few minutes, the implementation cost of adjusting the pressure settings are estimated as zero. Therefore, the energy cost savings is immediate.

4. CONCLUSION

In this paper, we have demonstrated that a considerable energy and money can be saved in compressed-air systems in industrial facilities by attractive common sense measures. These measures are: repairing air leaks, installing high-efficiency motors, reducing the average air inlet temperature by using outside air, reducing compressor air pressure. The calculation procedures are illustrated with realistic examples, and the potential savings and payback periods are evaluated. The payback period of these realistic examples approximately are: 2 months for repairing air leaks, 20 months for installing high-efficiency motors, 12 months for reducing the average air inlet temperature by using outside air, and immediate for reducing compressor air pressure. Most of them can be implemented by maintenance personal of the facilities. We hope these attractive measures will motivate manufacturers to implement and reduce their cost of energy usage.

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