COMPRESSED AIR SYSTEMS
AND
ENERGY SAVINGS

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Table of Contents

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1.0 Introduction

The advantage of using compressed air as an industrial power source is well known. Compressed air equipment is intrinsically safe and can be stalled without damage.

It is general practice to express compressed air flow as the flow at atmospheric pressure and is termed the "Free Air Flow" or "Free Air Delivered" (FAD) rather than the flow at the actual compressed air conditions because this avoids the need to state the pressure conditions each time.

It could be thought that the term free air may be misleading, however providing it is understood that it means the quantity of air that would flow or be delivered at normal atmospheric pressure, there should be no confusion.

A considerable amount of energy may be required to provide the compressed air in a factory and this depends on both the air pressure and the air volume required. Assuming a compressed air supply at about 7 bar gauge (100 psi), an installed motive power of at least 1 kilowatt is required to provide a free air flow of 3 litres/sec (FAD) or about 6 cubic feet per minute for a two stage compressor. For a single stage compressor, including losses, an installed motive power of at least 1 kilowatt is required to provide a free air flow of about 2.5 litres/sec (FAD) or about 5 cubic feet per minute

Assuming the cost of electricity is 10 cents per kWh, and that a factory works a 50 hour week, or 2500 hours per year, the energy costs of compressing 250 litres of air per second (about 500 CFM) at 7 bar (100 PSI) would be $25,000. Similarly, if the factory operated for 120 hours per week (3 shifts x 5 days) or had a FAD requirement of 600 litres per second (1200 CFM) at 50 hours per week, the annual energy cost for the air compressor alone would be $60,000.

Note that the above calculation included the compressor running costs only and did not take into account other costs such as compressor cooling or air drying. Also, there would be additional costs in providing the compressed air and these include the costs associated with the fixed equipment, maintenance repair and lubrication costs.

In general, the electricity running costs would be expected to be between 45-55% of total costs for a large plant, 50-65% of total costs for a small to medium sized plant, and 60-70% of total costs for a small sized plant - e.g. small works, town garages etc.

Clearly compressed air is not inexpensive and often represents a significant operational cost for many industrial enterprises.

2.0 The Physics of Compressing Air

For maximum efficiency of compressed air systems, there are many factors which should be considered. Firstly, it is worthwhile to briefly review some basic principles.

When air is compressed, some of the energy imparted to the air to force it into a smaller volume is taken in by the air in the form of heat. If the air could be compressed without a change in temperature, the process would be known as isothermal compression and it would be most efficient.

Compression under isothermal conditions may be expressed by the formula:

$$P_1V_1 = P_2V_2 = constant = RT(GasLaw)$$

where P = absolute pressure (gauge pressure + atmospheric pressure), V = specific volume, T = absolute temperature and R = universal gas constant (8314/MW N.m/kg.K).

The theoretical power required to compress a gas isothermally is as shown below (metric units):

$$kW = \frac{P_1 . FAD}{1000} . \ln\frac{P_2}{P_1}$$

where, kW is kilowatts, P is pressure in kPa, and FAD is the free air delivered in litres per second.

If the air is compressed adiabatically, i.e with no heat being lost or gained from outside sources, the process would conform to the following equation:

$$PV^{\gamma} = constant$$
$$where\ \gamma = ratio\ of\ specific\ heats\ at\ constant\ pressure\ and\ volume$$
$$= 1.4\ for\ air\ at\ normal\ temperatures$$

The theoretical power required to compress a gas adiabatically is as shown below (metric units):

$$kW = \frac{P_1 . FAD}{1000} . \frac{\gamma}{\gamma - 1} . \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]$$

where the symbols are as previously defined.

Compression under either adiabatic or isothermal conditions is not possible, but these models do establish theoretical efficiency limits in compressing air. To be expected, the actual air compression process is less efficient than either of these models. Friction losses in air systems, and leaks will add a significant amount of energy over and above the theoretical minimum.

Figure 1 shows the theoretical power required to provide 100 litres per second of FAD at various pressures under adiabatic compression and **Figure 2**, includes appropriate system losses.

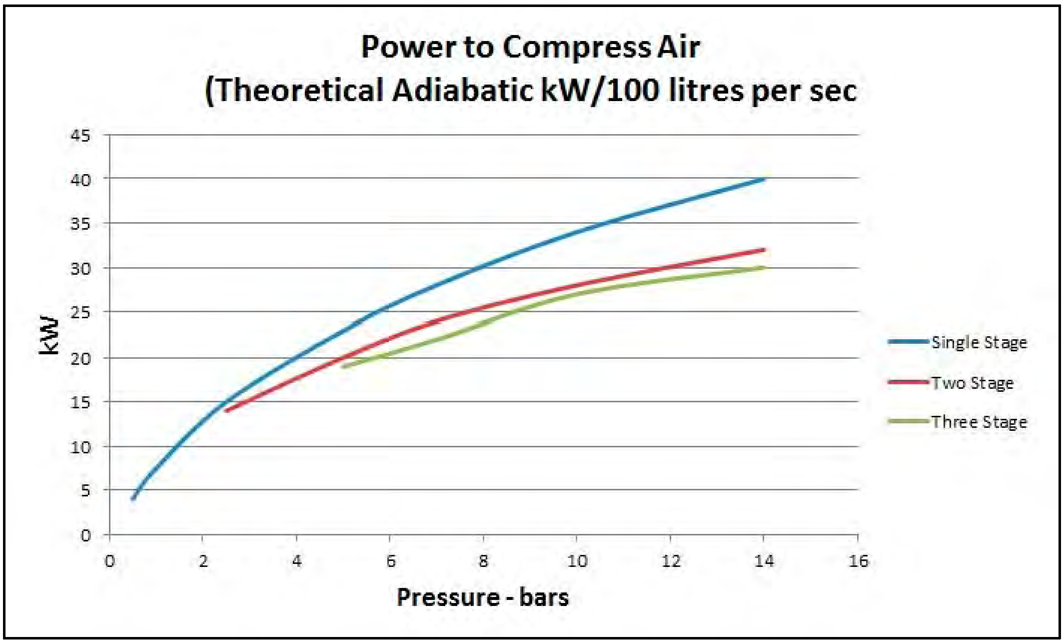

Figure 1

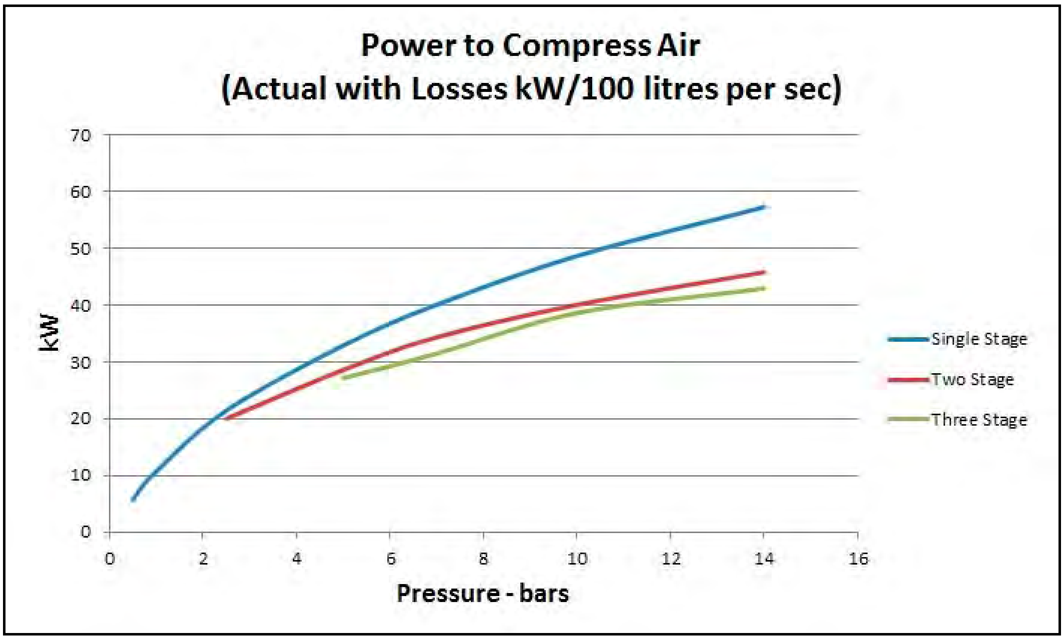

Figure 2

Now consider inflating a football by hand using a small hand pump with least effort for the desired output. The physical effort is the motor, the pump is the compressor. The input effort against friction can be lessened if the pump is clean, straight and lightly oiled. However, if the internal seal on the plunger is not in a good pliable condition, losses will occur around the seal. This may reduce the compression resulting in wasted effort and less Free Air Delivery. Typically, if the seal is stiff letting out most of the air the pump may deliver only a third of the pressure than when the seal is in good condition.

So a worn pump will only do a fraction of the work per stroke and produce even less air. The same sort of problems occur in real compressors.

With any compressed air system there is a choice to be made on the compressor sizing to suit the load. In the example of inflating a football, a large pump could be chosen for the work with a large effort required for a relatively short time. Alternatively, a small pump could be chosen for the work with a small effort required for a long time to inflate the football. The first choice would result in a heavy power use for a short time and excessive investment in the pump whereas the second choice of using a small pump would result in an excessive effort for a long time and considerable inconvenience, assuming that the pump was capable of meeting the load.

Unfortunately, the practice of mismatching the compressor to the required compressed air is not uncommon and this will result in using more energy than necessary. Often the mismatch is to oversize the compressor for the air needs.

Returning to the example of pumping up the football, if the pump or the connecting line leaks, the leak which may be a small hole may be enough to prevent most of the air getting into the football. However, the same amount of work is being done by the hand pump.

Alternatively, if the internal diameter of the connecting line is too small or is partially blocked, excess pressure and more work will be required to inflate the football. In a compressed air system this is equivalent to pumping to a higher pressure than required for the system. An extreme example would be to compress to a high level and utilise all the compressed air at a lower pressure through reducing valves.

Also, pumping with warm air will increase the effort required to inflate the football. This is so, because when air is warm it is lighter or less dense. Hence the same amount of work on the pump is used to compress less air which in turn inflates the cooler football less. For this reason excess heat in compressed air is undesirable. In a compressor it is essential to remove this unwanted heat by cooling both the compressor and the air.

Beyond this analysis, other considerations are required when compressed air is cleaned, cooled (to condense water vapour), drained, controlled, stored, transported, filtered, regulated and put to work under normal circumstances.

Conserving energy in air systems requires

1. *some understanding of what is happening in the system so that equipment is properly selected and installed and*

2. *a good maintenance program.*

3.0 Optimum Conditions for Efficient Compression

3.1 Compressor Plant

When new compressed air facilities are being installed, or existing capacity enlarged, particular opportunities for efficient energy use can arise:

1. the question of a central compressed air system versus a distributed system.

2. multi-stage compressors offer energy savings over single stage units and should be considered.

   There are many different types of compressors available - reciprocating, rotary vane, screw and turbine compressors. The reciprocating compressor or displacement type compressor may have one or more stages. The rotary vane compressor which is a dynamic compressor consists of a rotor with blades free to slide in radial slots, rotating off centre in a cylindrical chamber. This compressor works be centrifugal force throwing the blades out sweeping the compression chamber. It may have several stages. In the screw type compressor, two meshing helical rotors rotate in opposite directions causing the free air space between them to decrease axially in volume thus compressing the air trapped between the rollers.

3. a new installation provides the greatest opportunity for heat recovery.

3.2 Air Intake

Cool, clean and dry intake air leads to more efficient compression. A sheltered inlet protected from rain and heat is thus desirable. Dust will clog filters wasting energy. Ducting between air intake and the compressor should be short straight and a generous size.

For every kPa of pressure lost between the atmosphere and the entry of air to the compressor, an increase in power of 0.5% has to be provided to generate the same conditions and rate of compressed air. For a 7 kPa pressure loss, the flow rate of compressed air from the machine falls by as much as 3.5%.

An increase in the temperature of the intake air at entry to the compressor of 10^{o} C will require a power increase of 3.5% to deliver the same FAD output rate at the same pressure. Conversely, an intake of air 10 degrees cooler will improve the compressor's specific power performance by an equivalent amount.

3.3 Cooling

To maximise the efficiency in compressing air, it is necessary to cool the compressor. The cooling may be by air, water jackets and internal heat exchangers. Two stage units require particular cooling of air between the stages. Also, some machines require oil cooling.

The simplest type of cooling used on smaller machines is air cooling, and often a fan is added to supplement natural air flow across cooling fins. Compressors employing this type of cooling should be located in as cool a location as possible.

Water cooling can be by thermosiphon circulation or forced water circulation. Thermosiphon circulation is satisfactory for small single stage compressors and relies on convection to circulate the water which is heated by the compressor. The water circulates from the compressor jacket to a holding tank where the heat is lost. It is essential that the flow and return lines have a fall from the tank to the compressor to ensure good circulation. Preferably the tank should be placed in the open air. The drawback of this arrangement is that the tank could freeze in cold weather unless special precautions are taken (depending on climatic conditions).

For larger compressors, forced water cooling systems are used to extract the greater amount of heat generated.

It is good practice to cool the hot air leaving the compressor to prevent the carried over moisture from depositing through the air system as the air gradually cools. Moisture through the system could cause corrosion and damage to air tools. Sometimes refrigerant or chiller dryers are used for this purpose.

3.4 Air Receivers

The main air receiver is a key element in an efficient compressed air system. It serves the functions of:

- storing air to accommodate short heavy demands for air,
- allows the compressor to duty cycle (and cool down),
- assists in temperature equalisation through the system,
- assists in pressure equalisation through the system,
- avoids expensive short cycle time operations of the compressor.

Air receivers should be generously sized and an adequate practice is to install a receiver with a capacity of 8 litres for each litre/sec of FAD (compressor on full load).

3.5 Controls and Instrumentation

The control system which governs the running of the compressor should be matched to its duties and may need rematching if these change. Any arrangement which results in significant off-load running or an excessive number of stops and starts is likely to waste energy.

For small compressor systems, an automatic start/stop system operating on the pressure in the air receiver may be suitable. Under this type of system, the compressor is operated at full load for a given period until the pressure in the air receiver reaches a set point. This type of control is quite efficient but is not suitable for larger compressors because of the start up load that may occur.

For larger systems one control method is to keep the motor running and unload the compressor usually by short circuiting the cylinder head valves. With this type of control, the unloaded power consumption is still about 15% of the full load conditions. Although this method is less efficient than the on/off control method, it is a practical method of control for large machines.

On rotary screw and vane compressors capacity control is achieved by throttling the air flow at the inlet. If capacity is controlled alone, the unloaded power will still be about 70-80% of full power. Therefore some systems have been employed to reduce the oil reservoir pressure which lowers the oil flow to the compressor chamber resulting in air leakage across the rotors. The unloaded power on these systems is typically 15-30% of the loaded power.

Variable speed drives offer an efficient way of directly matching the compressor output to the air demand. Under some circumstances, soft starters with phase set back may offer an economic way of reducing energy usage. It is to be expected (or hoped) that manufacturers will offer standard air compressor package systems with these features when it is economical to do so.

Recommended instrumentation is as follows:

- pressure gauge on each receiver,
- pressure gauge on each branch line,
- water temperature gauge in compressor cooling jacket,
- coolant temperature gauge in aftercooler discharge,
- air temperature (compressor outlet),
- ambient air temperature,
- air temperature at receiver inlet,
- kWh meter for compressor.

3.6 Traps

Manual and automatic drain traps are essential for the correct and safe operation of any compressed air system. Moisture will accumulate in the lines and if not removed through traps, it could corrode the pipework and cause damage to air operated equipment.

Moisture may be removed from the air system through a system of traps. Where the moisture volume is likely to be greatest, e.g at the main air receiver, the trap should be automatic.

4.0 Air Leaks and other Wastage

4.1 Air Distribution System

The air mains and their associated branches, hoses, couplings and other accessories offer considerable opportunities for energy conservation and these include the following:

- excessive pressure loss,
- water accumulation and removal,
- blocked or partially blocked filters,
- leaks.

<u>Excessive pressure loss</u> due to inadequate pipe sizing, choked filters, improperly sized couplings and hoses represents energy wastage as do leaking pipe joints and couplings.

For the main distribution line,excessive energy loss can be avoided by restricting the air velocity to a maximum of 6 metres per second. Higher air velocities can be permitted in a shorter branch line of total length less than 15 metres.

Reference should be made to appropriate standards for maximum recommended air flow rates in pipes of various sizes.

Pressure loss can be reduced through the installation of ring mains which will allow the air to be distributed in two directions around the system.

<u>Water accumulation and removal</u> should be carried out in an efficient manner by:

- ensuring that all lines slope to strategic locations where automatic (or manual) drain valves are fitted.
- ensuring that branch lines and feeder pipes are fitted to rise from the top of air mains and branches (to avoid water blockage)
- ensuring that distribution lines are not subject to much cooling. Also excessive air line pressure losses will promote additional condensation.

<u>Blocked or partially blocked filters</u> must be:

- regularly serviced to clean or renew the elements which gradually become choked with dirt, thus causing excessive pressure drop and energy wastage.

<u>Air leaks can be quite expensive.</u>

Leaks frequently occur at the air receiver relief valves, pipe and hose joints, shut off valves, quick release couplings, tools and equipment. In most cases they are due to poor maintenance rather than improper installation, and repair of the leaks will be an economical exercise.

Figure 3 shows the air discharge through orifices of different sizes and at different pressures. For example the air leak through a 6 mm hole at 7 bar would be about 50 litres per second of FAD.

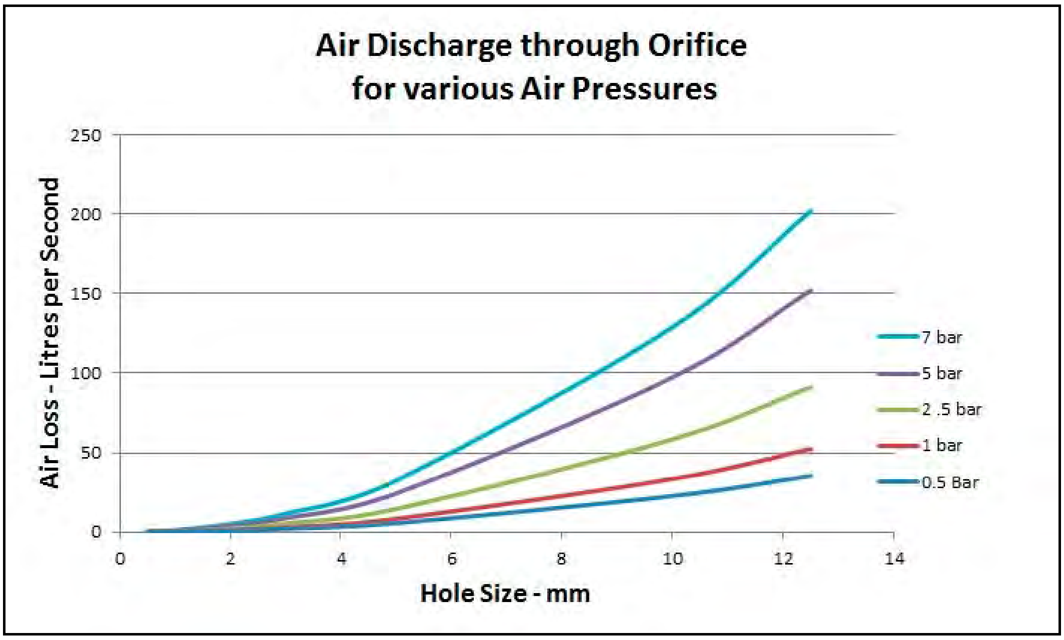

Figure 3

Referring to **Figure 2**, a single stage compressor would draw 30 kW to deliver 100 litres per second FAD, or 15 kW for 50 litres per second FAD. At 10 cents per kWh, a hole or leak equivalent to this size would cost $1.50 per hour, or $3,750 per annum for a plant operating 2500 hours per year. If the plant operated for 6,000 hours per year, the cost would be $9,000 per year.

A simple method of measuring the total leakage of the system is by making use of the known free air delivery capacity of the compressor and to time the compressor duty cycle. With all air operated equipment shut off, the air compressor should be run until the system reaches full line pressure and the compressor unloads. Due to air leaks, the system pressure will fall and the compressor will come on load again. The on-load and off-load times should be recorded several times and an average taken.

If T = the time on load in seconds , and t = the time off load in seconds, Q = the delivered free air capacity of the compressor in litres per second, and L = total system leakage in litres per second then the power wasted may be calculated from figures 2 and 3. For a system operating at 100 kPa, the power wasted may be calculated as shown below:

$$L = \frac{Q \cdot T}{(T + t)} \text{ litres per second}$$

$$\text{and Power wasted} \simeq \frac{L}{2.5} \text{ to } \frac{L}{3} \text{ kW}$$

From this calculation it can be seen that uncontrolled use of compressed air can be quite expensive.

For example compressed air should not be used as a broom to clean away waste material if other cleaning methods are available. Also it should be stressed that where air is used in blow guns, ejection nozzles etc discharged directly to the atmosphere, the operation causes energy wastage but is also *extremely dangerous*. The pressure to nozzles should be reduced to a safe and economic level or in the case of cooling air, fed by low pressure blowers or fans. Alternatively, cooling could be achieved through the use of pressure reducing valves.

5.0 Efficient Running of Air Driven Equipment

Unless air operated equipment such as pneumatic tools and directional control valves and cylinders are supplied with properly conditioned compressed air, wear of seals and other moving parts will occur, leading inevitably to loss in operating efficiency with possible leakage of compressed air and resultant energy wastage.

5.1 Filters

Filters should be installed close to the end use point to remove pipe scale, water and compressor oil thus preventing the formation of highly abrasive compounds. The degree of filtration should be related to the application. The finer the filter, the more dirt will be collected and the more readily it will become choked.

Ensure that a properly planned maintenance program is implemented for the whole system including final filters which service air tools and cylinders.

Filters should be regularly cleaned to avoid excessive pressure drops and energy wastage.

5.2 Correct Pressure

Equipment should not be operated above its correct rating as this can lead to excessive wear with further energy wastage.

The dangers of unrestricted air flow have been mentioned previously.

5.3 Lubricating Equipment

Attention should be given to proper lubrication of pneumatic equipment by installing appropriate equipment. Lubrication should not depend on disconnection of the device and manual injection if a quantity of lubricating oil.

Lubrication equipment should be properly maintained and regularly replenished with the recommended oil. This will reduce frictional losses, reduce wear of seals and overall will reduce energy consumption.

5.4 Item Checklist

A suggested checklist of items to check is as follows:

- perished hoses - replace,
- cracked drain cocks - close or replace with automatic drains,
- hissing couplings, pipe joints etc. - service and/or replace,
- leaking air tools - service,
- constant bleed devices - keep use to a minimum,
- consider regularly undertaking an ultrasonic survey to identify leaks.

6.0 Reduced Pressure

To reduce the pressure of the air system assumes that leaks generally have been contained and as a result the actual maximum pressure output of the compressor can be reduced.

This is not the same as saying that all air equipment can necessarily be operated at a reduced pressure.

A reduction in the delivery pressure of a compressor would reduce the power consumption as shown below:

Single Stage Compressor		Pressure reduction	Pressure reduction
Nominal Pressure	7 bar	10 percent	20 percent
Power Reduction		4 percent	9 percent

Two Stage Water Cooled Compressor		Pressure reduction	Pressure reduction
Nominal Pressure	7 bar	10 percent	20 percent
Power Reduction		4 percent	11 percent

Two Stage Air Cooled Compressor		Pressure reduction	Pressure reduction
Nominal Pressure	7 bar	10 percent	20 percent
Power Reduction		2.8 percent	6.5 percent

6.1 Operating Pressures of Individual Devices

Many items of equipment may be operating on a supply pressure greater than required for the particular operation, e.g. spray guns, cooling jets, pneumatic cylinders etc.

Considerable air consumption savings and hence energy savings can be achieved by fitting a standard type pressure regulator in these circumstances to keep the supply pressure to the equipment to a minimum.

Reference to the energy reduction tables in the previous section will provide an indication of the potential savings.

7.0 Waste Heat Recovery

Practically all the energy used by a compressor is converted into heat and in principle can be made available for other purposes. Heat recovery of more than 70% should be possible.

In all standard air compressor installations, the major part of the energy input is successful re-extracted by the compression stage cooling to maintain reasonable working temperatures, by the intercooler to improve efficiency and by the aftercooler to remove moisture from the compressed air.

The cooling medium is either water or ambient air and the heat extracted is generally *wasted*.

Although the heat is low grade, there may be some useful applications to which it could be put. Typically, for cooling water systems temperatures of about 40 - 70 C are obtained and for air cooled systems temperature of about 10 - 25 C above ambient are obtained.

Some useful applications for the waste heat from air compressor are as follows:

- space heating,
- water heating,
- pre-heating air to process dryers,
- pre-heating air to heat pump systems,
- pre-heating boiler feed water,
- any use of low grade heat in a process.

As an example, if a compressor operates with a 100 kW motor running with a 75 percent duty cycle and the heat recovery is 70 percent, the heat recovery is 0.75 x 0.7 x 100 = 52.5 kW.

REFERENCES

The following source material has been used in the preparation of this paper:-

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