## Module 2

# POSITIVE DISPLACEMENT COMPRESSOR OPERATION

## OBJECTIVES:

After completing this module you will be able to:

2.1 Explain how Isothermal and Adiabatic compression processes affect the work (energy) required to compress and deliver a given mass of air. *Page 2*

2.2 Explain the effect of clearances and valve leakage on compressor performance. *Page 3*

2.3 Explain, using a pressure–volume diagram, the effect of each of the following on compressor performance:

a) Jacket cooling, *Page 4*

b) Two–stage compression with intercooling. *Pages 4-5*

2.4 Explain three benefits of using an aftercooler on compressed air system operation. *Page 6*

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## INTRODUCTION

Various types of compressors are described in levels four and three mechanical equipment courses. This module will deal with the positive displacement compressors used in our stations.

As an introduction to this module, let's start by looking at the cycle used for the compression of the air that we use in our instruments, air tools, valve actuators, etc. Figure 2.1 shows a simplified air compression cycle as a pressure/volume diagram.

The shaded area in Figure 2.1 is representative of the work required to compress and deliver a particular mass of air, and for steady operation is representative of the power required. In this module, emphasis will be placed on how we compress and deliver air, and its effect on the work required.

NOTES & REFERENCES

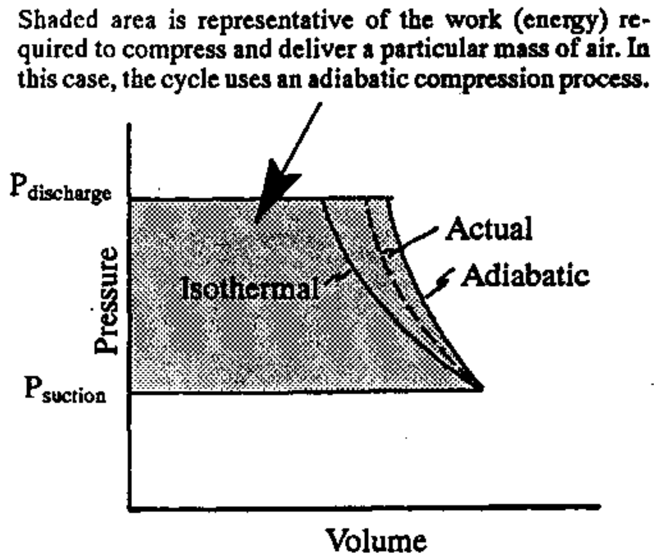


**Figure 2.1: Simplified Air Compression Cycle**

# THE COMPRESSION CYCLE

In theory, air may be compressed **adiabatically** (without the addition or removal of heat) or **isothermally** (at constant temperature).

It is difficult to compress gases at a constant temperature. The expense and size of heat removal equipment required for this makes the process impractical. Likewise, we cannot compress gases adiabatically, since some heat always escapes and friction heat generated during the compression process is added to the gas.

*Obj. 2.1*

These two compression processes are illustrated on pressure/volume axes in Figure 2.1. We can see that the area of the overall cycle, bounded by the adiabatic compression process, will be larger than an area bounded by the isothermal compression process. This means that the work required to compress and deliver the air using an adiabatic process is more than the work required using an isothermal process.

*These numbers are provided for illustrative purposes only. You are not expected to remember them or perform any calculations to derive these numbers.*

From the definitions of adiabatic and isothermal, we can deduce that an actual compression process lies somewhere between them (ie. some heat is lost during compression, but not all of it). The process will lie closer to adiabatic than to isothermal*, and a lot of heat is generated during the process. For example, air at 4°C if compressed from atmospheric pressure to 690 kPa (100psi), it will reach over 200°C *.

To keep the work needed per cycle (or power) as small as possible, we try to make our compression process as close to isothermal as possible (ideally, it is better to shift the process over even further, but again, this is not practical). Therefore, improvement to the cycle will involve removal of heat during the compression process.

NOTES & REFERENCES

*Obj. 2.2*

# THE EFFECT OF CLEARANCES AND VALVE LEAKAGE ON PERFORMANCE.

The diagram of Figure 2.1 (which is often called an indicator diagram), shows that in discharging the compressed air, cylinder volume is reduced to zero. However, clearances between moving and stationary components in the compressor, and the resulting internal leakage, cause a modification to the indicator diagram as shown in Figure 2.2. Looking at the model of a piston in a cylinder (at the top of Figure 2.2), we can visualize a small clearance between the piston and the cylinder head at the highest portion of the piston stroke. The high pressure air trapped in this space, plus any leakage past the discharge valve must expand to below atmospheric pressure on the suction stroke before a new charge of air can be drawn in. Expansion curve (CD) illustrates this characteristic and the "blips" at points B and D represent actions of the discharge and inlet valves respectively. Therefore, the actual volume of ambient air drawn in (referred to as "capacity") is less than the swept volume of the piston (referred to as "displacement"). The ratio of capacity to displacement is called the volumetric efficiency of the compressor (Figure 2.2). As the machine wears, air recirculation increases, volumetric efficiency decreases and the compressor tends to overheat.

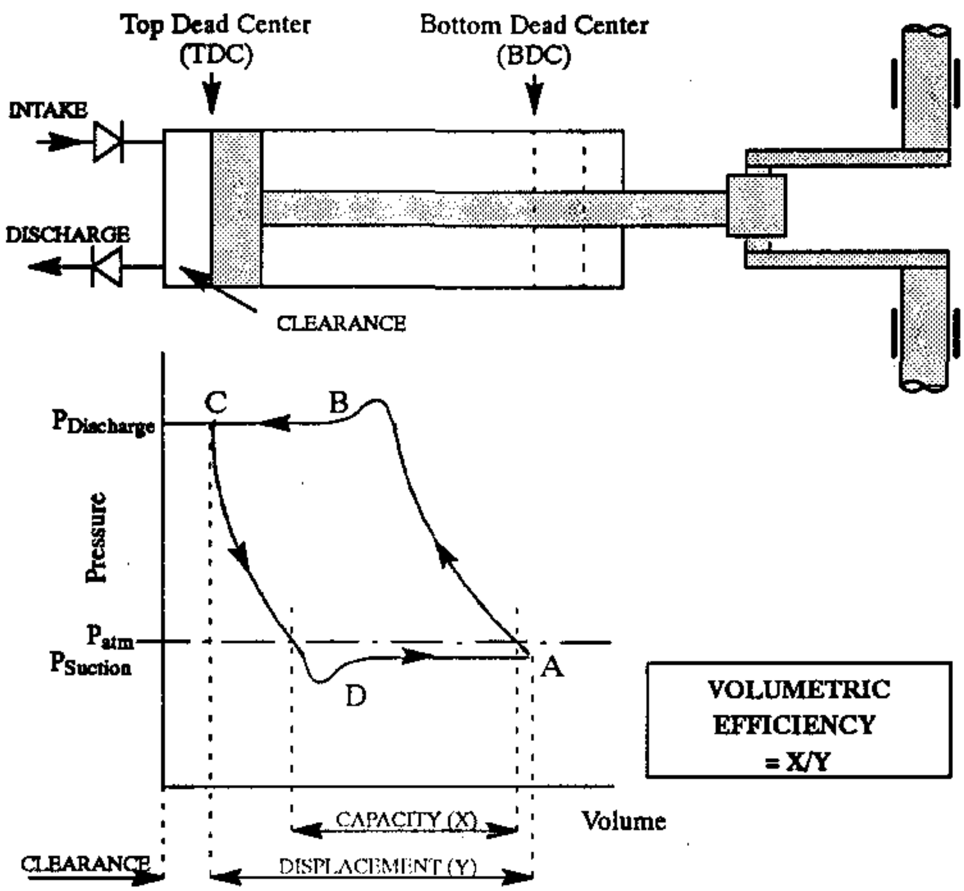


**Figure 2.2: Basic Piston Compressor Cycle Diagram**

NOTES & REFERENCES

The increased clearances caused by wear will allow more high pressure air to remain in the cylinder at the end of the compression process. Due to an increased amount of air remaining in the cylinder (which must expand during the suction stroke), the point at which the suction valve opens will now be delayed. This reduces the amount of air drawn in (shortening section DA on Figure 2.2), reducing capacity. Similarly, section BC on Figure 2.2 will be shortened due to the increased clearance volume.

# METHODS USED TO IMPROVE COMPRESSOR EFFICIENCY

To approximate an isothermal process, and therefore reduce the compressor power requirements, we remove the heat of compression in two ways:

i) By removing the heat during the actual compression process and,

ii) By compressing the air in two stages, and removing heat between stages.

Each of these will be discussed below.

*Obj. 2.3 a)*

## Jacket Cooling

The removal of heat during the compression process involves cooling of the cylinder or compressor element (rotary screw type) with a water jacket. This cooling jacket surrounds the compressing component, and removes some of the heat of compression and friction generated during the process.

Thus, the compression process is shifted toward the isothermal process (ie. shifted left on the pressure–volume diagram). The shaded area labelled in Figure 2.3 represents the energy (power) saved during the compression process with jacket cooling.

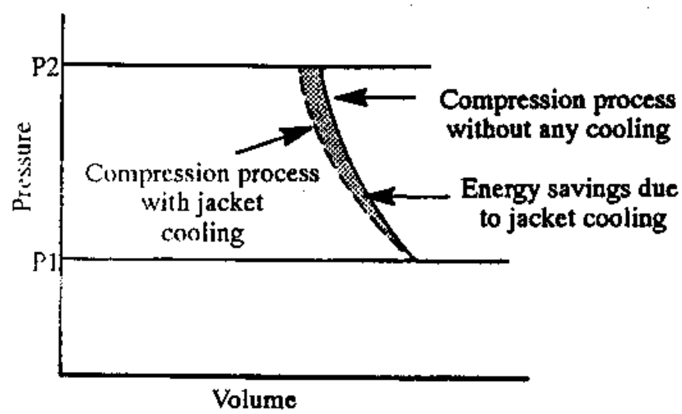


**Figure 2.3: Jacket Cooling Effects**

Jacket cooling, as with all other forms of compressor cooling, helps keep compressor metal temperatures at practical levels, prolongs lubricant life and consequently reduces machine maintenance.

NOTES & REFERENCES

## Two Stage Compression With Intercooling

*Obj. 2.3 b)*

The second method of heat removal is to compress the air part way to its final pressure, extract some of the heat then continue compression. This is done by **compression in two stages with cooling of the air between stages using an intercooler.** Intercoolers were discussed in your previous mechanical equipment courses.

Figure 2.4 shows a two stage compression process. The overall compression between pressure P1 and pressure P3 is done in two stages, with the intermediate pressure being P2. At P2, the intercooler will cool the air while its pressure remains constant*, causing the volume of the air to decrease. This moves the process line shown in the diagram horizontally toward the isothermal process (starting point for the high pressure stage (HP) is now cooler). The energy saved per cycle, as a result of intercooling, is represented by the shaded area in Figure 2.4.

* Pressure is maintained by steady state air flow through the compressor (otherwise, cooling would cause shrinkage and a corresponding pressure drop).

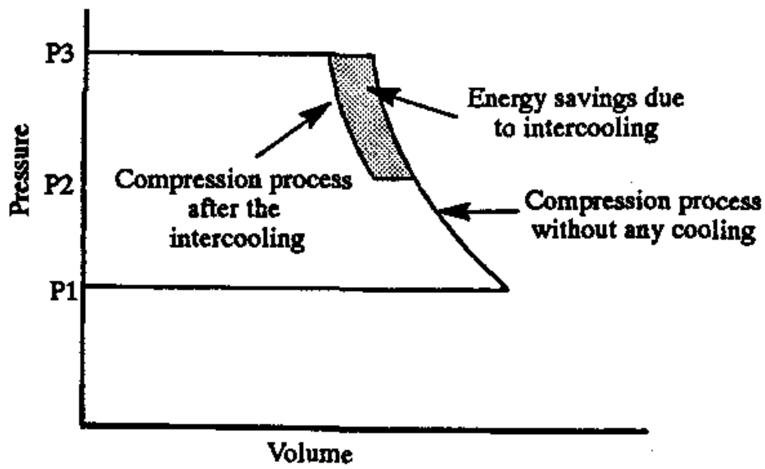


**Figure 2.4: Effect of Intercooling**

Figure 2.5 shows the overall energy saved (shaded area) using jacket cooling and intercooling on a pressure–volume diagram for a two stage compressor. As you can see, this combination more closely approximates an isothermal process.

NOTES & REFERENCES

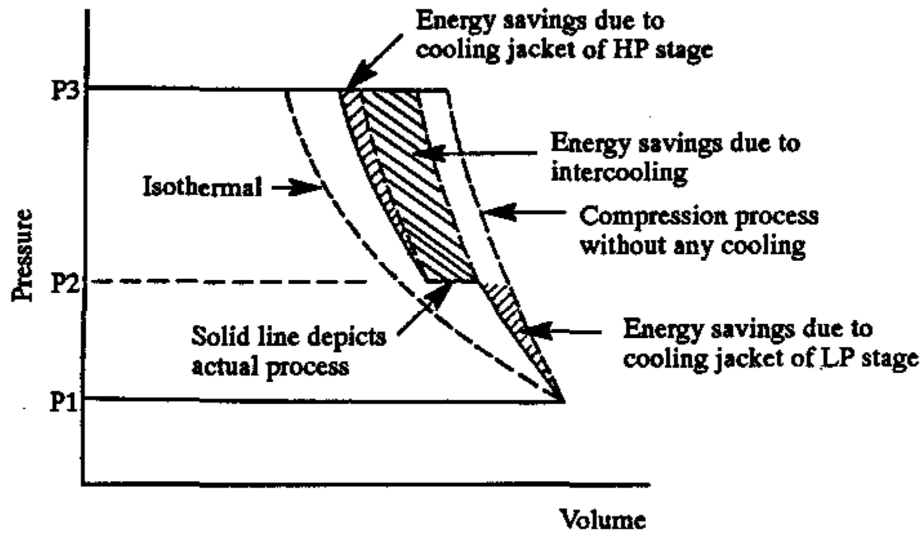


**Figure 2.5: Combined Jacket and Intercooling Energy Savings**

*Obj. 2.4*

# AFTERCOOLING

Recall from your previous mechanical equipment courses that the aftercooler removes heat from the air after it leaves the compressor. Heat removed after the compression process does not contribute to any savings in work required to compress and deliver the air. But, there are three major benefits obtained from the use of aftercoolers, and each will be discussed below.

## Minimize Storage Volume and Compressor Cycling

If we take air that has just been compressed after the last stage of compression, it will still be quite hot. If not cooled before entering the receiver, this hot air will cool in the receiver, and will **shrink in volume, causing its pressure to fall.** Aftercoolers cool the air before it reaches the air receiver, and hence **minimize compressor cycling** on and off.

*These numbers are provided for illustrative purposes only. You are not expected to remember them or perform any calculations to derive these numbers.*

The aftercooler cools the air, causing its volume to decrease, **allowing the receiver to hold more air mass.** For example, if the air is cooled from 200°C to 40°C, the volume will decrease to approximately 65% of its original volume (ie. an air receiver at 40°C will hold about 1.5 times more mass than if it was at 200°C)*. Thus, *air receiver temperature is a factor in the amount of air available after failure of the air compressor system* (ie. pressure drops due to usage, leakage and due to cooling/shrinking ).

NOTES & REFERENCES

## Moisture Separation

The second benefit for using aftercoolers is to **help reduce the moisture content of the air after compression.** By reducing the temperature of the air/water vapour mixture to below the **vapour's saturation temperature** (dew point), **water will be condensed** and then removed via a trap, before reaching the receiver. The resulting air will be saturated (ie. contain 100% of its water holding capacity) after cooling/condensation.

By removing moisture with the aftercooler and trap combination, less water will condense in the air receiver(s) and piping as the air cools further, and consequently reduce the corrosion problem*. If the air must be dried further (ie. for use as instrument air), moisture removal via aftercooling will reduce the load on the air driers.

* *Water will also be condensed during the intercooling process if temperature is reduced below the saturation temperature at the intercooler pressure.*

## Personnel Hazard Reduction

The **air temperature after a compression cycle can be high enough to cause serious burns.** By providing aftercoolers, the hot air is cooled immediately after the high pressure compression stage. This practice keeps piping and other system equipment at close to ambient temperatures, thus preventing injuries to personnel.

NOTES & REFERENCES

# SUMMARY OF THE KEY CONCEPTS

- For a given mass of air, an isothermal compression and delivery cycle will require the compressor to do less work. Compressors are cooled to more closely approximate an isothermal process.
- Clearances and valve leakage will reduce volumetric efficiency, and will tend to cause compressor overheating.
- Jacket cooling removes heat during the actual compression process.
- Two stage compression with intercooling will remove heat of compression between stages, at constant pressure.
- Aftercoolers reduce air storage volume and compressor cycling. They reduce the moisture content of the air and cool the air to prevent a thermal hazard to personnel.

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You can now do **assignment questions 1-5.**

NOTES & REFERENCES

## ASSIGNMENT

1. Explain how an isothermal compression and delivery process compares to an adiabatic compression and delivery process in achieving minimum work per cycle.
2. Explain the effect of valve leakage and clearances on compressor performance.
3. Explain, with the aid of the pressure–volume diagram, the effects of jacket cooling on compressor performance.
4. Explain, with the aid of the pressure–volume diagram, the effects of two stage compression with intercooling on compressor performance.
5. Explain three benefits of using aftercoolers on air compressors.

Before you move on to the next module, **review the objectives** and make sure that you can meet their requirements.

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