Two Stage Air Compressor Test

Dhuha Radhi Nayyef

E-mail: dhuha.radhi @uomus.edu.iq

Target

Getting to know the two-stage compressor device and checking the type of process done in compressors and the effect of intermediate cooling

Introduction

Compressors, like pumps and fans, are devices that increase fluid pressure. Work is applied to the compressor by an external source through a rotating shaft. Therefore, the term of work for compressors is negative because work is done on the fluid. The process performed in compressors is assumed to be isentropic compression theory. In reality, we assume that this process is close to isentropic (Pϑ^k=c) and we calculate the polytropic n power of each compressor and compare its value with k=1.4.

To reduce the work input to the compressor, it is necessary to cool the gas while it is being condensed. For this purpose, multi-stage condensation with intermediate cooling is usually used. Multi-stage condensation with an intercooler is especially useful when a gas is to be condensed to a very high pressure.

Description of the device

Figure 1: Two-stage compressor test device

The test device is shown in Figure 1. This device consists of the following main components.

Two-stage compressor, intercooler, inlet air tank, intermediate tank, compressed air tank and temperature, pressure and flow measurement devices.

In the figure, various sensors installed on the device are shown along with their names.

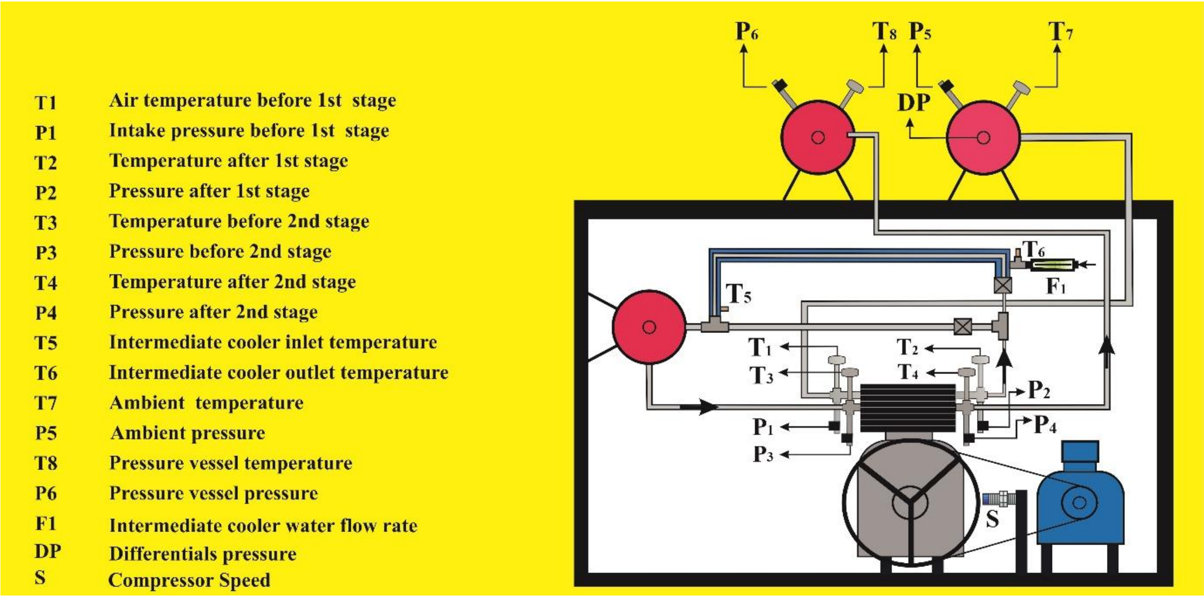

Figure 2: Sensors installed on the two-stage compressor device

The ambient air enters the inlet tank (the tank on the right side of the figure) through a venturi nozzle and then enters the first stage compressor, and its pressure rises to the middle pressure. After that, it enters the intermediate cooler and storage tank, and then it enters the second stage compressor. Finally, the compressed air enters the final tank and the required amount is stored in this tank and the rest is discharged. The final air pressure can be adjusted by discharging part of the compressed air through the final tank discharge valve.

The venturi nozzle installed at the inlet of the air intake tank is used to measure the air flow rate of the device. Figure (3) shows the inlet air tank and its nozzle along with changes in nozzle pressure.

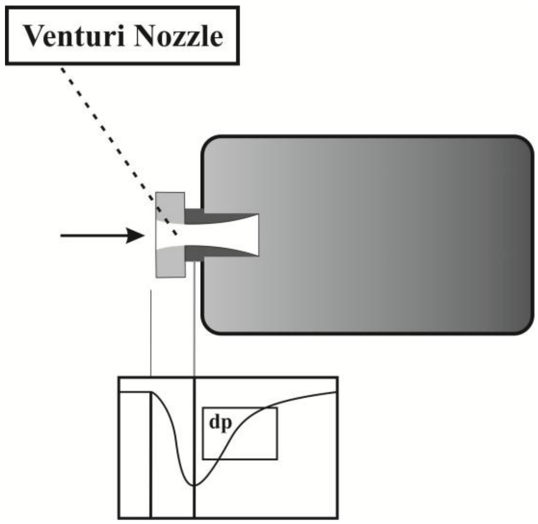

Figure 3: Inlet tank nozzle and its pressure change curve

The created pressure difference is related to the difference between the ambient air pressure and the pressure in the smallest cross-sectional area, and it is displayed as dp on the screen in millibars, and it can be used to calculate the air flow rate.

The power consumption of the motor is displayed in the form of voltage and amperes on the screen, which can be obtained according to the 80% efficiency of the motor, the power consumption of the compressors.

Test method

Setting up the device

1. To prevent the device from moving, lock the front wheels of the chassis.
2. Connect the device to the power source and supply the required water to the device.
3. While the engine is off, check the device oil.
4. Put the valve (Pressure Switch) in the Auto position.
5. Turn on the device

   First stage: without intercooler
6. Close the water inlet valve to the intercooler.
7. Turn on the compressor.
8. By means of the valve, adjust the final tank pressure to the specified value and keep it constant during the test.
9. After about 10 minutes, write down the numbers in the test table.

10. Note that although the intermediate cooler has been removed from the circuit, there is still some intermediate cooling due to the presence of the intermediate tank and heat transfer through it.

    The second step: with an intermediate cooler

11. Open the water inlet valve to the middle cooler and adjust the water flow in both coolers.
12. Insert the intercooler into the circuit.
13. In two separate steps, keep the final tank pressure constant at the specified pressures and note the desired numbers after about 10 minutes in each step.

Questions

What is the first law of thermodynamics for a compressor? Write down your assumptions.

Draw the theoretical cycle of the two-stage compressor with an intermediate cooler on the P-V and T-S axes and specify the thermodynamic processes in each one.

Using mathematical relationships (integral relationship for compressor work), explain why in a compressor, cooling the gas reduces the work input to the compressor?

In a two-stage compressor, in order to minimize the input work, what should be the relationship between the values of the pressure ratio of the input air and the output of the compressors? Prove with mathematical relations.

Explain the reason for using an intermediate cooler in a two-stage compressor.

Draw the actual P-V curve for one of the test steps.

Compare and discuss the observations and results of different stages of the experiment. In your discussion, mention the following:

a) Changes in the inlet air temperature to each of the first and second compressors.

b) The actual process performed in each of the compressors and its comparison with the theoretical process.

Test theory

The p-v diagram for a cylinder and piston is according to figure (1).

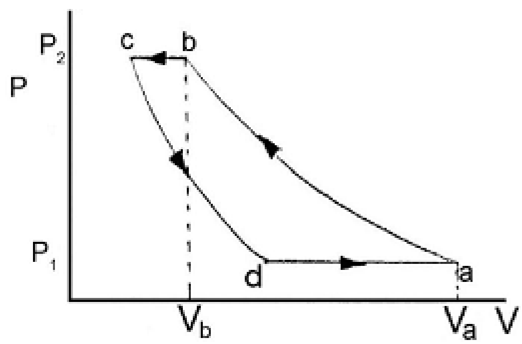

Figure 4: Ideal p-v diagram of a cylinder and piston

In this diagram, the following 4 main processes can be seen.

Suction course $d \rightarrow a$

Compression course $a \rightarrow b$

Discharge course $b \rightarrow c$

Expansion course $c \rightarrow d$

The value $r = \frac{p_2}{p_1}$ is called compressor cycle pressure ratio.

V_c is the space above the piston at top dead center.

$v_s = v_a - v_c$: Piston displacement volume

$v = v_a – v_d$: Suction volume

The polytropic process is a process with variable entropy in which we will have heat transfer. Because normal reciprocating compressors have a relatively low rotation speed, the thermodynamic evolutions of compression and expansion are neither adiabatic nor isotherm, and the index of polytropic expansion and compression is n, It is a number between 1 and 1.4.

$$pv^n = cte \Rightarrow P_1 v_1^n = P_2 v_2^n \Rightarrow n_1 = \frac{ln(P_2/P_1)}{ln(v_1/v_2)}, n_2 = \frac{ln(P_4/P_3)}{ln(v_3/v_4)}$$

$$pv^n = cte \Rightarrow \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^n \Rightarrow r_p = r_v^n \ , \quad r_v = r_p^{1/n}$$

$$Pv = RT \Rightarrow \frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} = R \Rightarrow \frac{v_1}{v_2} = \frac{P_2 T_1}{P_1 T_2} \Rightarrow \frac{P_2}{P_1} = \left(\frac{P_2 T_1}{P_1 T_2}\right)^n \Rightarrow (\frac{P_2}{P_1})^{1-n} = (\frac{T_2}{T_1})^{-n}$$

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}} \Rightarrow r_p = r_t^{\frac{n}{n-1}}$$

The polytropic work done is equivalent to the area under the p-v curve:

$$W_t = \oint Pdv = RT_1 \left(\frac{n}{n-1}\right) [r_{p_1}^{\frac{n-1}{n}} - 1] = RT_1 \left(\frac{n}{n-1}\right) \left[r_{t_1} - 1\right]$$
$$= R \left(\frac{n}{n-1}\right) [T_2 - T_1]$$

Therefore, the work done by the compressor in each stage and the hydraulic power of the whole device are obtained from the following relationships.

$$W_1 = \frac{n_1}{1 - n_1} R(T_2 - T_1)$$

$$W_2 = \frac{n_2}{1 - n_2} R(T_4 - T_3)$$

$$P_{hydr} = \dot{m}_a (W_1 + W_2)$$

Specific volume of air at different stages for points 1 to 5 assuming that air is a complete gas.

$$P\nu = RT \qquad , \qquad R = 287 \ \ J/kg.K$$

Figure (5) theoretically shows the processes related to the two-stage compressor. The process performed in compressors is assumed to be isentropic compression, and the ideal process of the compressor is a constant temperature process in which the work of the compressor reaches the minimum possible value.

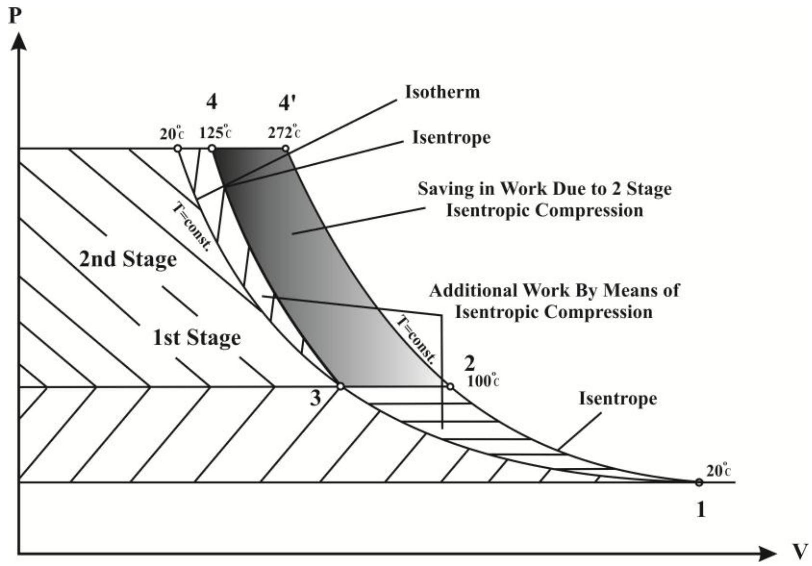

Figure 5: Two-stage compression in a compressor

As can be seen, the use of an intermediate cooler brings the overall process of the device closer to the constant temperature process (ideal process of the compressor) and reduces the work of the compressor to the level of 2-3-4-4'. As a result, the efficiency of the compressor increases.

Using the previous relation for two compression cycles, we can write:

$$W_p = RT_1\left(\frac{n}{n-1}\right)\left(r_{p_1}{}^{\frac{n-1}{n}} - 1\right) + RT_I\left(\frac{n}{n-1}\right)\left(r_{p_2}{}^{\frac{n-1}{n}} - 1\right)$$

$$W_p = R\left(\frac{n}{n-1}\right)\left[T_1\left(r_{p_1}{}^{\frac{n-1}{n}} - 1\right) + T_I\left(r_{p_2}{}^{\frac{n-1}{n}} - 1\right)\right]$$

The two-stage compression reduces the total volumetric efficiency and the total consumption of electric power. To get the minimum work consumption, we solve the following equation:

$$\frac{dW_p}{dp_I} = 0$$

Assuming that TI is not a function of PI and using derivation, the following results are obtained

$$P_I = \sqrt{(\frac{T_I}{T_1})^{\frac{n}{n-1}} P_1 P_2}$$

In order to reduce the heat at the output of the two-stage compressor, an intermediate cooler is usually used to cool the air between the two stages. If T1=TI, the minimum power consumption of the compressor is when:

$$P_I = \sqrt{P_1 P_2} \Rightarrow \frac{P_I}{P_1} = \frac{P_2}{P_I} \Rightarrow r_{P_1} = r_{P_2}$$

It means that the pressure ratio of both compressors is equal. For T1<TI values, the intermediate pressure increases.

The air flow is obtained from the following relationship:

$$\dot{m}_a = A_d \sqrt{\frac{2dp}{\nu_1}} \quad , \quad A_d = 1.16 \times 10^{-4} (m^2)$$

In the above relationship, A_d is the venturi nozzle cross-section and dp is the pressure difference of the venturi nozzle, which should be placed in m^2 and pa respectively in the above relationship to obtain the air flow rate in kg⁄s.

The efficiency of the device is obtained from the following relationship.

$$\eta = \frac{P_{hydr}}{P_{electric}}$$

Calculation of cooling capacity

The intermediate cooler is a water-to-air tubular heat exchanger that cools the air coming out of the first stage compressor.

Converter losses are very low and negligible. So:

$Q_a = Q_w$

Since:

$$Q_w = C_{pw} \rho F (T_{out} - T_{in}) \rightarrow Q_a = C_{pw} \rho F (T_{out} - T_{in})$$

In the above relationship, Cpw, F, ρ, Tin, Tout are, respectively, the specific heat capacity of water, cooling water flow rate, water density, water temperature entering the cooler and water temperature leaving the cooler. The values of density and specific heat capacity of water at 20°C are as follows.

$$\rho = 1.22 \text{ kg/m}^3 \quad , \quad C_{pw} = 4180 \text{ J/kg.°C}$$

Psychometric definitions

Ambient air in normal conditions has some water vapor. The amount of water vapor in the air changes according to atmospheric conditions, and in a process such as condensation, which is accompanied by cooling, the usual ratio of air to water vapor changes.

Specific humidity is defined as follows:

$$\omega = \frac{\text{Water vapor mass}}{\text{Dry air mass}} = \frac{m_v}{(m_a)_{dry}} = \frac{(v_v)_{dry}}{v_a}$$

v_a and v_v are specific volumes of air and water vapor.

Assuming that water vapor behaves like a perfect gas, using Dalton's law for partial pressures, we can write:

$$P_v.v = m_v.R_v.T_v$$

Also for dry weather:

$$P_a.v = m_a.R_a.T_a$$

and because $T_v = T_a$ so:

$$\omega = \frac{P_v.R_a}{P_a.R_v} = 0.622\frac{P_v}{P_a} = 0.622\frac{P_v}{P - P_v}$$

Because we have:

$$\text{Gas constant for air:} \quad R_a = 0.2871\frac{kj}{kg.k}$$

$$\text{Gas constant for water vapor:} \quad R_a = 0.4615\frac{kj}{kg.k}$$

$P = P_a + P_v$

Relative humidity at temperature T1 is defined as follows:

$$\phi = \frac{\text{Partial pressure of water vapor}}{\textit{Partial pressure of water vapor in saturated air}} = \frac{P_v}{(P_v)_{SAT}} = \frac{m_v}{(m_v)_{SAT}} = \frac{(v_v)_{SAT}}{v_v}$$

Dew point

The thermal degree at which, if the air becomes dry or cold to that degree, water vapor distillation takes place (the air becomes saturated), is called the dew point of the air.

Psychometric analysis of air compressor

By using dry bubble and wet bubble thermometers that are installed in the air inlet of the first stage compressor and the air outlet of the second stage compressor, it is possible to obtain the amount of water vapor flow in entering and leaving the test device.

It can be seen that the water flow rate at the inlet of the compressor is higher than the flow rate at the outlet, and this is due to the water sitting in the system. In a single-stage compressor, water vapor is distilled at its inlet, while in a two-stage compressor, most of the steam is distilled in the intermediate cooler. The reason for the distillation of water vapor after condensation, after the air cools down to the ambient temperature either in the compressor inlet or in the intercooler, is justified by using the specific humidity relationship.

$$\omega = 0.622\frac{P_v}{P - P_v}$$

In the condition of saturated steam, P_v is only a function of temperature, so if the gas pressure of the air-water vapor mixture, i.e. p, increases, according to this relationship, the percentage of water vapor will decrease. This decrease is due to the distillation of water vapor

Quantity	Description	No Intercooler	With Intercooler	
		P=	P=	P=
P1 (bar)	Intake pressure before 1st compressor stage			
T1 (°C)	Air temperature before 1st compressor stage			
P2 (bar)	Pressure after 1st compressor stage			
T2 (°C)	Temperature after 1st compressor stage			
P3 (bar)	Pressure before 2nd compressor stage			

T3 (°C)	Temperature before 2nd compressor stage			
P4 (bar)	Pressure after 2nd compressor stage			
T4 (°C)	Temperature after 2nd compressor stage			
P5 (bar)	Ambient pressure			
T5 (°C)	Intermediate cooler inlet temperature			
P6 (bar)	Pressure vessel pressure			
T6 (°C)	Intermediate cooler outlet temperature			
T7 (°C)	Ambient temperature			
T8(°C)	Pressure vessel temperature			
F1 (lit/min)	Intermediate cooler water flow rate			
dp (mbar)	Differential pressure across venture nozzle			
P (W)	Electric motor power consumption			

Computational quantity	Definition	without cooling	with cooling	
		P=	P=	P=
n_1	Polytropic power n for the first stage compressor			
n_2	Polytropic power n for the second stage compressor			
W_1 (J/kg)	First compressor work			
W_2 (J/kg)	Second compressor work			
P_{hydr} (W)	Hydraulic power of the device			
η (%)	Compressor efficiency			
P_K (W)	Cooling capacity of the intermediate cooler			