# Chapter 5 Calculations

# 5.1 Example of dimensioning compressed air installations

Below follows some normal calculations for dimensioning a compressed air installation. The intention is to show how some of the formulas and data from previous chapters are used. The example is based on a desired compressed air requirement and result in dimensioned data, based on components that can be chosen for the compressed air installation. After the example are a few additions that show how special cases can be handled.

# 5.2 Input data

The compressed air requirements and the ambient conditions must be established before dimensioning is started. In addition to this requirement, a decision as to whether the compressor shall be oil lubricated or oil-free and whether the equipment shall be water cooled or air cooled must be made.

## 5.2.1 Requirement

Assume that the need consists of three compressed air consumers.
They have the following data:

| Consumer | Flow | Pressure | Dew point |
|---|---|---|---|
| 1 | 12 $Nm^3$/min | 6 bar(e) | +5°C |
| 2 | 67 l/s (FAD) | 7 bar(a) | +5°C |
| 3 | 95 l/s (FAD) | 4 bar(e) | +5°C |

## 5.2.2 Ambient conditions (dimensioning)

Dimensioning ambient temperature: 20°C
Maximum ambient temperature: 30°C
Ambient pressure: 1 bar(a)
Humidity: 60%

## 5.2.3 Miscellaneous

Air cooled equipment
Compressed air quality from an oil lubricated compressor is regarded as sufficient.

# 5.3 Component selection

It is a good idea to recalculate all input data from the requirement table under 5.2.1 so that it is uniform with regard to type before dimensioning of the different components is started.

Flow: In general the unit l/s is used to define the compressor capacity, which is why consumer 1, given in $Nm^3/min$, must be recalculated.

$12\ Nm^3/min = 12 \times 1000/60 = 200\ Nl/s.$

Insertion of the current input data in the formula gives:

$$Q_{FAD} = \frac{Q_N \times (273 + T_i) \times 1.013}{273 \times P_i} = \frac{200 \times (273 + 35) \times 1.013}{273 \times 0.74} \approx 309\ l/s\ (FAD)$$

**Pressure:** The unit generally used to define pressure for the compressed air components is overpressure in bar, i.e. bar(e).

Consumer 2 is stated in absolute pressure, as 7 bar(a). The ambient pressure shall be detracted from this 7 bar to give the overpressure. As the ambient temperature in this case is 1 bar the pressure for consumer two can be written as 7-1 bar(e) = 6 bar(e).

With the recalculations set out above the table for uniform requirement:

| Consumer | Flow | Pressure | Dew point |
|---|---|---|---|
| 1 | 225 l/s (FAD) | 6 bar(e) | +5°C |
| 2 | 67 l/s (FAD) | 6 bar(e) | +5°C |
| 3 | 95 l/s (FAD) | 4 bar(e) | +5°C |

### 5.3.1 Dimensioning the compressor

The total consumption is the sum of the three consumers 225 + 67 + 95 = 387 l/s. A safety marginal of approx. 10-20% should be added to this, which gives a dimensioned flow rate of 387 x 1.15 ≈ 445 l/s (with 15% safety marginal).

The maximum required pressure for consumers is 6 bar(e). The dimensioned consumer is the one, including the pressure drop, that requires the highest pressure.

A reducing valve should be fitted to the consumer with the requirement of 4 bar(e). Assume at the moment that the pressure drop in the dryer, filter and pipe together does not exceed 1.5 bar. Therefore a compressor with a maximum working pressure of 7.5 bar(e) is suitable.

### 5.3.2 Assumption for the continued calculation

A compressor with the following data is selected:

Maximum pressure = 7.5 bar(e)
State flow at 7 bar(e) = 450 l/s
Total supplied power at 7 bar(e) = 175 kW
Supplied shaft power at 7 bar(e) = 162 kW
The compressed air temperature out of the compressor = ambient temperature +10°C.

Furthermore, the selected compressor has loading/unloading regulation with a maximum cycle frequency of 30 seconds. Using loading/unloading regulation the selected compressor has a pressure that varies between 7.0 and 7.5 bar(e).

$Q_c$ = Compressor's capacity (l/s) = 450 l/s
$P_1$ = Compressor's intake pressure (bar(a)) = 1 bar(a)
$T_1$ = Compressor's maximum intake temperature (K) = 273 + 30 = 303 K
$f_{max}$ = maximum cycle frequency = 1 cycle/30 seconds
$(p_U - p_L)$ = set pressure difference between loaded and unloaded compressor (bar) = 0.5 bar.
$T_0$ = Compressed air temperature out of the selected compressor is 10°C higher that the ambient temperature which is why the maximum temperature in the air receiver will be (K) = 273 + 40 = 313 K.
Compressor with loading/unloading regulation gives the right formula for the air receiver volume:

$$V = \frac{0.25 \times Q_c \times T_0}{f_{max} \times (p_U - p_L) \times T_1} = \frac{0.25 \times 450 \times 313}{1/30 \times 0.5 \times 303} = \underline{6\,972\ \text{l}}$$

This is the minimum recommended air receiver volume.
The next standard size up is selected.

## 5.3.4 Dimensioning of the dryer

As the required dew point in this example is +6°C, a refrigerant dryer is the most suitable choice of dryer. When selecting the size of the refrigerant dryer a number of factors must be taken into consideration by correcting the refrigerant dryer's capacity using correction factors. These correction factors are unique for each refrigerant dryer model. Below the correction factors applicable for Atlas Copco's refrigerant dryers are used and are stated on the Atlas Copco's data sheet. The four correction factors are:

1. **Refrigerant dryer's intake temperature and pressure dew point.**
   As the compressed air temperature out of the selected compressor is 10°C higher than the ambient temperature, the refrigerant dryer's intake temperature will be maximum 30 + 10 = 40°C. In addition, the desired pressure dew point is +5°C.
   The correction factor 0.95 is obtained from Atlas Copco's data sheet.

2. **Working pressure**
   The actual working pressure in the compressor central is approx. 7 bar, which represents a correction factor of 1.0.

3. **Ambient temperature**
   With a maximum ambient temperature of 30°C a correction value of 0.95 is obtained.

Accordingly the refrigerant dryer should be able to handle the compressor's fully capacity multiplied by the correction factors above.
450 : 0.95 x 1.0 : 0.95 = <u>406 l/s</u>.

## 5.3.5 Assumptions for the continued calculation

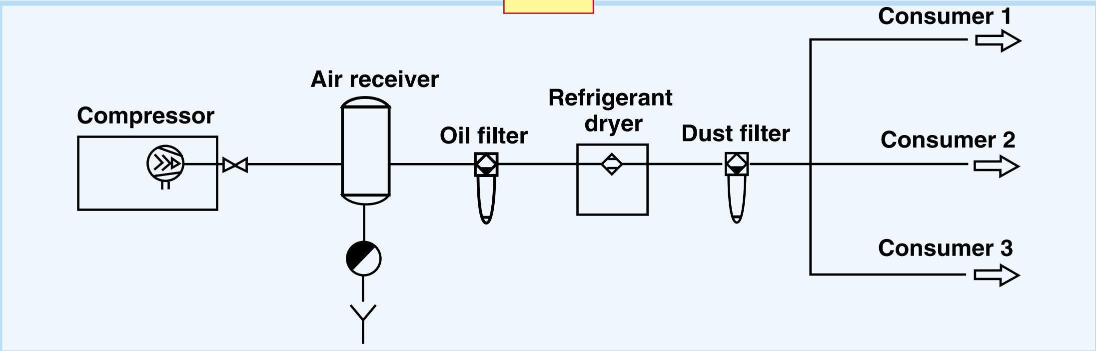
An air cooled refrigerant dryer with the followed data is selected:

Capacity at 7 bar(e) = 450 l/s
Total power consumption = 5.1 kW
Emitted heat flow to surroundings = 14.1 kW
Pressure drop across the dryer = 0.09 bar

When all the components for the compressor installation have been chosen, it should be checked that the pressure drop is not too great. This is done by adding together all the pressure drops for the components and pipes.

It may be appropriate to draw a schematic diagram of the compressed air installation as shown in fig. 5:1.

5:1




The pressure drop for the components is obtained from the component suppliers, while the pressure drop in the pipe system should not exceed 0.1 bar.

The total pressure drop can now be calculated:

| Component | Pressure drop (bar) |
|---|---|
| Oil filter (pressure drop when filter is new) | 0.14 |
| Refrigerant dryer | 0.09 |
| Dust filter (pressure drop when filter is new) | 0.2 |
| Pipe system in compressor central | 0.05 |
| Pipe system from compressor central to consumption points | 0.1 |
| **Total pressure drop:** | **0.58** |

The maximum pressure of 7.5 bar(e) and on-load pressure of 7.0 bar(e) for the selected compressor gives a lowest pressure at the consumers of 7.0 - 0.58 = 6.42 bar(e). You should add to this, the pressure drop increase across the filter that occurs over time. This pressure drop increase can be obtained from the filter supplier.

# 5.4 Other dimensioning

## 5.4.1 Condensation quantity calculation

As an oil lubricated compressor has been chosen, the water condensation separated in the compressor and refrigerant dryer will contain oil. The oil must be separated before the water is released into the sewer, which can be done in an oil separator. Information on how much water is condensed is needed in order to dimension the oil separator.

The total flow of water in the air taken in is obtained from the relation:
$f_1$ = relative humidity x the amount of water (g/litre) the air can carry at the maximum ambient temperature 30°C x air flow = 0.6 x 0.030078 x 445 ≈ 8.0 g/s.

The amount of air remaining in the compressed air after drying is subtracted from this quantity (saturated condition at +6°C).

$$f_2 = \frac{1 \times 0.007246 \times 445}{8} \approx 0.4 \text{ g/s}$$

The total condensation flow from the installation $f_3$ then becomes

$$f_1 - f_2 = 8.0 - 0.4 = 7.6 \text{ g/s} \approx \underline{27.4 \text{ kg/hour}}$$

With help of the calculated condensation flow the right oil separator can be chosen.

The principle that the supplied power to the room air shall be removed with the ventilation air is used to determine the ventilation requirement in the compressor room.

For this calculation the relationship for the power at a specific temperature change for a specific mass of a specific material is used.

$$Q = m \times c_p \times \Delta T$$

$Q$ = the total heat flow (kW)
$m$ = mass flow (kg/s)
$c_p$ = specific heat capacity (kJ/kg, K)
$\Delta T$ = temperature difference (K)

The formula can be written as:

$$m = \frac{Q}{c_p \bullet \Delta T}$$

where:

$\Delta T$ = the ventilation air's temperature increase; presuppose that an increase of the air temperature with 10K can be accepted $\Rightarrow \Delta T = 10$ K.
$c_p$ = specific heat capacity for the air = 1.006 kJ/kg x K (at 1 bar and 20°C)
$Q$ = the total heat flow (in kW) = (94% of the supplied shaft power to the compressor + the difference between the supplied total power to the compressor and the supplied shaft power to the compressor + the stated heat flow from the refrigerant dryer) = 0.94 x 162 + (175 - 162) + 14.1 ≈ 180 kW

which gives the ventilation air

$$m = \frac{Q}{c_p \times \Delta T} = \frac{180}{1.006 \times 10} \approx 17.9 \text{ kg/s}$$

which at an air density of 1.2 kg/$m^3$ is equivalent to 17.9/1.2 ≈ <u>15$m^3$/s.</u>

# 5.5 (Addition 1) At high altitude

Question: Presuppose the same compressed air requirement as described in the previous example at height of 2500 metres above sea level with a maximum ambient temperature of 35°C. How large compressor capacity (expressed as free air quantity) is required?

Answer: Air is thinner at altitude, which must be considered when dimensioning the compressed air equipment that has a compressed air requirement specified for a normal state (e.g. $Nm^3/min$). In those cases that the consumer's flow is stated in free air quantity (FAD) no recalculation is necessary.

As consumer 1 in the example above is given in the unit $Nm^3/min$ the requisite flow for this consumer must be recalculated. The state at which the compressor's performance is normally stated is 1 bar and 20°C, which is why the state at 2500 metres above sea level must be recalculated into this state.

By using the table the ambient pressure 0.74 bar at 2500 metres above sea level is obtained. If the flow is recalculated to Nl/s (12 $Nm^3/min$ = 12000/60 Nl/s = 200 Nl/s) and is set in the formula the following is obtained:

$$Q_{FAD} = \frac{Q_N \times (273 + T_i) \times 1.013}{273 \times P_i} = \frac{200 \times (273 + 35) \times 1.013}{273 \times 0.74} \approx 309 \text{ l/s (FAD)}$$

The total compressor capacity demanded is then 309 + 67 + 95 = 471 l/s (FAD).

# 5.6 (Addition 2) Intermittent output

Question: Presuppose that in the calculation example above there is an extra requirement from consumer 1 of a further 200 l/s for 40 seconds on the hour. It is accepted during this phase that the pressure in the system drops to 5.5 bar(e). How large should the receiver volume be to meet this extra requirement?

Answer: It is possible, during a short period, to take out more compressed air than what the compressor can manage by storing the compressed air in an air receiver. However, this requires that the compressor has a specific over capacity. The following relation applies for this:

$$V = \frac{Q \times t}{P_1 - P_2}$$

where

$Q$ = air flow during the emptying phase = 200 l/s
$t$ = length of the emptying phase = 40 seconds
$P_1 - P_2$ = permitted pressure drop during the emptying phase = normal pressure in the system - minimum accepted pressure during the emptying phase = 6.46 - 5.5 = 0.96 bar

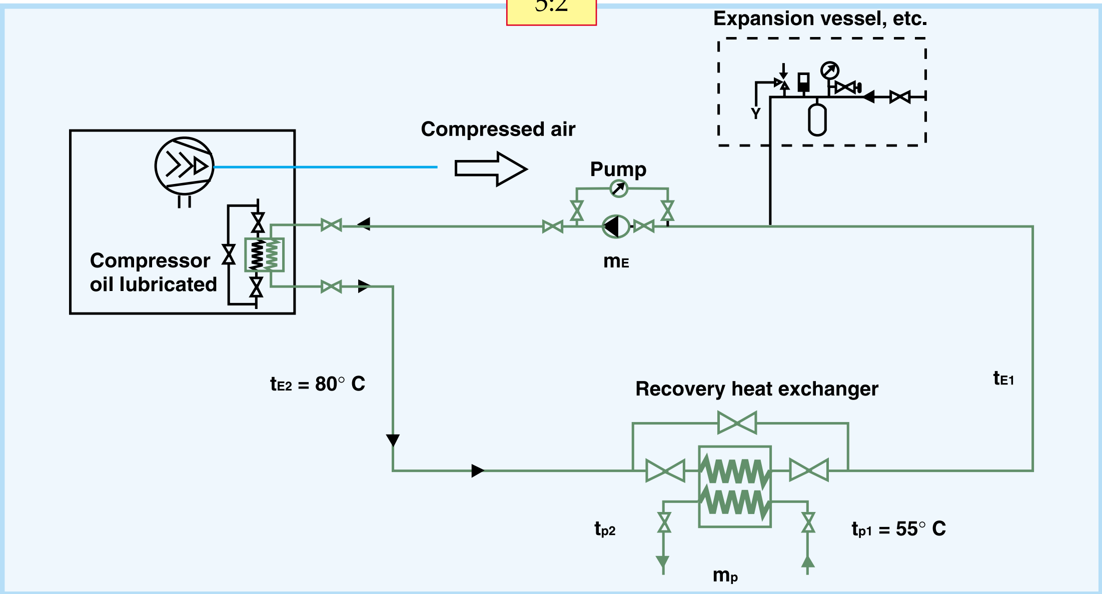
Inserted in the formula to give the requisite air receiver volume:

$$V = \frac{Q \times t}{P_1 - P_2} = \frac{200 \times 40}{0.96} = 8\,340 \text{ l}$$

In addition, it is required that the compressor has a specific over capacity, so that it can fill the air receiver after the emptying phase. The selected compressor has an over capacity of 5 l/s = 18000 litres/hour. As the air receiver is emptied once per hour the compressor's over capacity is more than sufficient.

# 5.7 (Addition 3) Water borne energy recovery

5:2




**Question:** A water borne energy recovery circuit is to be built for the compressor in the example. Presuppose that the water to be heated is in a warm water return (boiler return) with an ingoing return temperature of 55°C. Calculate the flow required for the energy recovery circuit and the power that can be recovered. Also calculate the flow and outgoing temperature for the boiler return.

**Answer:** Start be drawing the energy recovery circuit and name the different power, flow and temperatures. Now follow the calculation below.

$Q_E$ = power transferred from the compressor to the energy recovery circuit (kW)
$Q_P$ = power transferred from the energy recovery circuit to the boiler return (kW)
$m_E$ = water flow in the energy recovery circuit (l/s)
$m_P$ = water flow in the boiler return (l/s)
$t_{E1}$ = water temperature before the compressor (°C)
$t_{E2}$ = water temperature after the compressor (°C)
$t_{P1}$ = ingoing temperature on the boiler return (°C)
$t_{P2}$ = outgoing temperature on the boiler return (°C)

### 5.7.1 Assumption

The following assumption has been made:

A suitable water temperature out of the compressor for energy recovery can be obtained from the compressor supplier and is assumed to be in this example $t_{E2}$= 80°C.
Assumption for the water circuit through the energy recovery heat exchanger:

$$t_{E1} = t_{P1} + 5°C$$

$$t_{P2} = t_{E2} - 5°C$$

In addition it is assumed that the pipe and heat exchanger have no heat exchange with the surroundings.

### 5.7.2 Calculation of the cooling water flow in the energy recovery circuit

$$Q = m \times c_p \times \Delta T$$

$\Delta T$ = temperature increase across the compressor = $t_{E2} - t_{E1}$ = 80°C - 60°C = 20°C
$c_p$ = specific heat capacity for water = 4.18kJ/kg x K
$Q = Q_E$ = the power that can be taken care of = 70% of the supplied shaft power = 0.70 x 162 = 132 kW.
This is the power possible to recover for the selected compressor.
m = mass flow in the energy recovery circuit = $m_E$.

The formula can be written as:

$$m_E = \frac{Q_E}{c_p \times \Delta T} = \frac{113}{4.18 \times 20} = \underline{1.35\ kg/s}$$

## 5.7.3 Energy balance across the recovery heat exchanger

For the recovery heat exchanger applies:

$$Q_E = m_E \times c_p \times (t_{E2}-t_{E1})$$

$$Q_p = m_p \times c_p \times (t_{P2}-t_{P1})$$

However, as it has been presupposed that no heat exchange shall take place with the surroundings, the power transferred to the energy recovery circuit from the compressor will be equal to the power transferred in the recovery heat exchanger, i.e. $Q_P = Q_E = 113$ kW.

The formula can be written as:

$$m_P = \frac{Q_P}{(t_{P2} - t_{P1}) \times c_p} = \frac{113}{(75 - 55) \times 4.18} \approx \underline{1.35 \text{ l/s}}$$

## 5.7.4 Compilation of the answer

It can be established from the calculation that the power which can be recovered is 113 kW. This requires a water flow in the energy recovery circuit of 1.35 l/s. An appropriate flow for the boiler return is also 1.35 l/s with an increase of the boiler temperature by 20°C.

# 5.8 (Addition 4) Pressure drop in the piping

**Question:** A 23 metre pipe with an inner diameter of 80 mm shall lead a flow of 140 l/s. The pipe is routed with 8 elbows that all have a bend diameter equal to the inner diameter. How great will the pressure drop across the pipe be if the absolute initial pressure is 8 bar(a)?

**Answer:** First the equivalent pipe length for the 8 elbows must be determined. The equivalent pipe length of 1.3 metres per elbow can be read off from the table 3:36. The total pipe length is then 8 x 1.3 + 23 = 33.4 meters. The following formula is used to calculate the pressure drop:

$$\Delta p = 450 \frac{Q_c^{1.85} \times l}{d^5 \times p}$$

Insertion gives:

$$\Delta p = 450 \frac{140^{1.85} \times 33.4}{80^5 \times 8} \approx 0.0054 \text{ bar}$$

Accordingly, the total pressure drop across the pipe will be 0.0054 bar