Compressed Air Treatment (Dryers and Filters)

Chapter 3

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Compressed Air & Gas Institute

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To ensure the expected performance and reliability of a compressed air system, the selection of all components within a compressed air system must be considered carefully. The increased use of compressed air and the development of many new and more sophisticated devices and controls have accelerated the need for clean, dry air. This chapter will provide information on the importance of clean, dry air and the various air treatment technologies that are available to obtain it.

Applications Requiring Clean, Dry Air

Most compressed air applications require some air treatment. Following are some examples of the negative impact of moisture in a compressed air system and the reasons that applications require clean, dry air.

Plant Air

In almost every operation, clean, dry compressed air will result in lower operating costs. Dirt, water, and oil entrained in the air will be deposited on the inner surfaces of pipes and fittings, causing an increase in pressure drop in the line. A loss of pressure is a loss of energy used to compress the air, and a reduced pressure at the point-of-use results in a loss of performance efficiency.

Liquid water accelerates corrosion and shortens the useful life of equipment, and carryover of corrosion particles can plug valves, fittings, and instrument control lines. When water freezes in these components, similar plugging will occur.

Valves and Cylinders

Deposits of sludge formed by dirty, wet, and oily air act as a drag on pneumatic cylinders so that the seals and bearings need frequent maintenance. Operation is slowed and eventually stopped. Moisture dilutes the oil required for the head and rod of an air cylinder, corrodes the walls, and slows response. This results in loss of efficiency and production.

Moisture flowing to rubber diaphragms in valves can cause these parts to stiffen and rupture. Moisture also can cause spools and pistons to pit.

In high speed production, a sluggish or stuck cylinder could create costly downtime. A clean, dry air supply can prevent many of these potential problems.

Air Powered Tools

Pneumatic tools are designed to operate with clean, dry air at the required pressure. Dirty and wet air will result in sluggish operation and more frequent repair and replacement of parts due to sticking, jamming, and rusting of wearing parts. Water also will wash out the required oils, resulting in excessive wear.

A decrease in pressure at the tool caused by restricted or plugged lines or parts will cause a reduction in the efficiency of the tool.

Clean, dry air at the required pressure will enable the production worker to start operating immediately at an efficient level, with no time lost to purge lines or drain filters, and will help to maintain productivity and prolong tool life.

Instrument Air

Control air supplied to transmitters, relays, integrators, converters, recorders, indicators, or gauges is required to be clean and dry. A small amount of moisture passing through an orifice can cause malfunction of the instrument and the process it controls. Moisture and resultant corrosion particles also can cause damage to instruments and plug their supply air lines.

Pneumatic thermostats, which control the heating and air conditioning cycles in large and small buildings, also require clean, dry air.

Instruments and pneumatic controllers in power plants, sewage treatment plants, chemical and petrochemical plants, textile mills, and general manufacturing plants all need clean, dry air for efficient operation.

Preservation of Products

When used to mix, stir, move, or clean a product, air must be clean and dry. Oil and water in compressed air used to operate knitting machinery will cause the tiny latches on the knitting needles to stick. When used to blow lint and thread off finished fabrics, contaminants in the air may cause product spoilage.

If air is used to blow a container clean before packaging, entrained moisture and oil may contaminate the product. Moisture in control line air can cause the wrong mixture of ingredients in a bakery, the incorrect blend in liquor, water-logged paint, or ruined food products.

In some printing operations, air is used to lift or position paper which will be affected by dirty, wet air, and any water on the paper will prevent proper adhesion of the inks. In pneumatic conveying of a product such as paper cups or cement, dry air is essential for obvious reasons.

Test Chambers

Supersonic wind tunnels are designed to simulate atmospheric conditions at high altitudes where moisture content is low. These chambers use large volumes of air, which must be dried to a very low dew point to prevent condensation in the tunnel air stream.

Moisture Related Compressed Air Problems

Following is a summary of some of the problems that can be caused by moisture in compressed air:

1. Washing away required oils.
2. Rust and scale formation within pipelines and vessels.
3. Increased wear and maintenance of pneumatic devices.
4. Sluggish and inconsistent operation of air valves and cylinders.
5. Malfunction and high maintenance of control instruments and air logic devices.
6. Product spoilage in paint and other types of spraying.
7. Rusting of parts after sandblasting.
8. Freezing in exposed pipelines during cold weather.
9. Further condensation and possible freezing of moisture in mufflers whenever air devices are rapidly exhausted in applications like rock drilling and mining.

Compressed Air Quality

Compressed air leaving an air compressor is not normally of a quality suitable for the intended use. This is due to several factors:

- Atmospheric air, especially in an industrial environment, contains particulate matter, moisture and hydrocarbons.
- The inlet filter on an air compressor is a particulate filter, designed to protect the compressor rather than downstream equipment.
- The air compressor itself will contribute contaminants in the form of wear particles and compressor oil carry-over.
- The discharge temperature from the compressor may be too high for distribution and use.
- Cooling after compression results in condensation of moisture vapor and saturated air leaving the aftercooler. Moisture has a harmful effect on pneumatic tools, air operated equipment and processes.

Air Quality Classes

Compressed air quality classes are defined in the International Organization for Standardization (ISO) standard 8573-1. These classes are shown in Table 3.1A, Table 3.1B and Table 3.1C.

Air Quality Classes ISO 8573-1

Table 3.1A Maximum Particle Size and Concentration of Solid Contaminants

Class	Max particle size * microns	Max concentration **
		mg/m^3
1	0.1	0.1
2	1	1
3	5	5
4	15	8
5	40	10

* Particle size based on a filtration ratio $ß_{\mu} = 20$
** At 1 bar (14.5 psia), 20°C (68°F) and a relative vapor pressure of 0.6 (60%).

Table 3.1B Maximum Pressure Dew Point

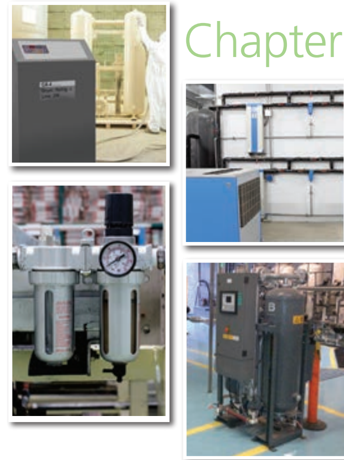
Class	Max pressure dew point	
	ºC	ºF
1	-70	-94
2	-40	-40
3	-20	-4
4	+3	+37.4
5	+7	+44.6
6	+10	+50
7	not specified	

Table 3.1C Maximum Oil Content

Class	Max concentration ***
	mg/m^3****
1	0.01
2	0.1
3	1
4	5
5	25

*** At 1 bar(14.5 psia), 20ºC(68ºF) and a relative vapor pressure of 0.6 (60%).

**** 1 mg/m^3 is a weight of oil in a volume of air and is approximately equal to 0.83 ppm by weight.



Moisture Content of Air

All atmospheric air contains water vapor. A rule of thumb is that for every increase of 20ºF in the temperature of air, its potential for holding moisture doubles. Tables at the end of this chapter show moisture content under various conditions:

Appendix Table 3.2 shows the water content in grains per cubic foot of saturated air at various temperatures.

Appendix Table 3.3 shows similar data in gallons per 1,000 cubic feet at various levels of relative humidity.

Appendix Table 3.4 shows the water content in gallons, of 1,000 standard cubic feet of saturated air at the temperature and pressure indicated.

Determination of the Water Content of Compressed Air Systems

A question of concern to the user of compressed air is, "How much water or condensate must be removed from the compressed air system?" Using Tables 3.3 and 3.4 permits the simple determination of the amount of condensate to be found in a compressed air system under a variety of operating conditions. The data presented, water content of saturated air at various temperatures and pressures, represent the worst possible condition. There is no guarantee that the water vapor content of compressed air will be any less than saturation at any given operating temperature and pressure; therefore, the vapor content at saturation should be used in all calculations.

The following example will illustrate the calculation of water content in a compressed air system:

Example: Calculating Moisture Content in a Compressed Air System

On a warm, humid day, the outdoor temperature is 90ºF and the relative humidity is 70%. This air is drawn into an air compressor intake and compressed to 100 psig. From the compressor, the air flows through an aftercooler and into an air receiver. The hot compressed air is cooled to 100ºF by the time it leaves the receiver. As it flows through the compressed air piping within the plant, it is further cooled to 70ºF. Suppose this compressed air system is in a medium-sized manufacturing plant utilizing a total of 50 air tools, each rated at 20 scfm. Also, assume that the tools are utilized 50% of the time. This makes an average air flow requirement of 20 x 50 x 0.5, or 500 scfm. Determine the amount of water collecting in the receiver and in the downstream piping.

From Table 3.3, the amount of water per 1,000 cubic feet of air at 90ºF and a relative humidity of 70% is 0.1970 gallons. From Table 3.4, the quantity of water per 1,000 cubic feet of air at 100ºF and 100 psig is 0.0478 gallons. The difference is 0.1970 - 0.0478 or 0.1492 gallons per 1,000 standard cubic feet of air. This is the amount of water which would condense in the receiver for every 1,000 cubic feet of air used. Every hour, 30,000 SCF (60 minutes x 500 scfm) of air will flow through the receiver. An excess of 4.476 gallons of water will collect in the receiver each hour. In an 8 hour shift, this amounts to 35.8 gallons.

In the compressed air piping, the temperature dropped to 70ºF. At that temperature and 100 psig, the compressed air can hold only 0.0182 gallons per 1,000 scfm of air. The air leaving the receiver has a moisture content of 0.0478 gallons per 1,000 scfm of air, therefore 0.0296 gallons per 1,000 cubic feet of air will condense in the piping system. Again, with 30,000 cubic feet of air each hour, the excess water will be 0.888 gallons. In an 8 hour shift the quantity will be 7.1 gallons which, if not removed, will be flowing through air tools, cylinders, paint guns and any other device using this air. Adding this amount to the 35.8 gallons collected in the air receiver makes a total of 42.9 gallons of water which will have condensed at some point in the compressed air system during an eight-hour shift.

Relative Humidity

Relative humidity is the ratio of the actual water vapor partial pressure to the saturation partial pressure at a constant temperature. Relative humidity is dimensionless and normally expressed as a percentage.

When air has 100% relative humidity is said to be water saturated or at its dew point. If air at its dew point – 100% relative humidity – cools, moisture will condense.

Air containing half of the water vapor than would be present at saturation, assuming constant temperature, is said to have 50% relative humidity. A rule of thumb says that air with 50% relative humidity has a dew point 20ºF lower than its temperature. Similarly, air with 75% relative humidity has a dew point 10ºF lower than its temperature.

When air is compressed, the space occupied by the air is reduced. For example, when atmospheric air has been compressed to 103 psig and cooled to its original temperature, the volume has been reduced to one eighth of its atmospheric volume. This is a compression ratio of 8:1. (The compression ratio is calculated by dividing the final absolute pressure by the initial absolute pressure: 103 psig + 14.7 psia)/14.7 psia.) If the final volume is 1 cubic foot, the original volume was 8 cubic feet. If the original volume of atmospheric air contained water vapor corresponding to 12.5% relative humidity, when compressed by a factor of eight, the final one cubic volume will be saturated, 100% relative humidity (12.5% x 8 = 100%). In most geographic areas, atmospheric air has a relative humidity well above 12.5%, and an 8:1 compression ratio will produce liquid water as the compressed air cools to its original temperature.

Figure 3.1 illustrates the ability of air to hold water vapor at various temperatures while maintaining constant pressure. It will be noted that as the temperature decreases, the quantity of water vapor that can be held also decreases but the relative humidity remains constant. When the volume is reheated, its ability to hold moisture is increased but since the excess moisture, in the form of condensate, has been drained off, no additional moisture is available. The relative humidity therefore decreases. The relative humidity can be approximated as follows: The 0.0858 gallons/1000 cu. ft. moisture content for saturated air can be determined from Table 3.4 at the intersection of the 120°F column and the 100 psig row. The moisture content for 80°F and 40°F also can be determined in this same manner. As the temperature is increased from 40°F to 120°F it again has the ability to hold 0.0858 gallons/1000 cu. ft. However, since the excess moisture has been drained off as condensate at the lower temperature, only 0.0061 gallons/1000 cu. ft. of moisture remain. The relative humidity, therefore, is reduced to 0.0061/0.0858 or 7%.

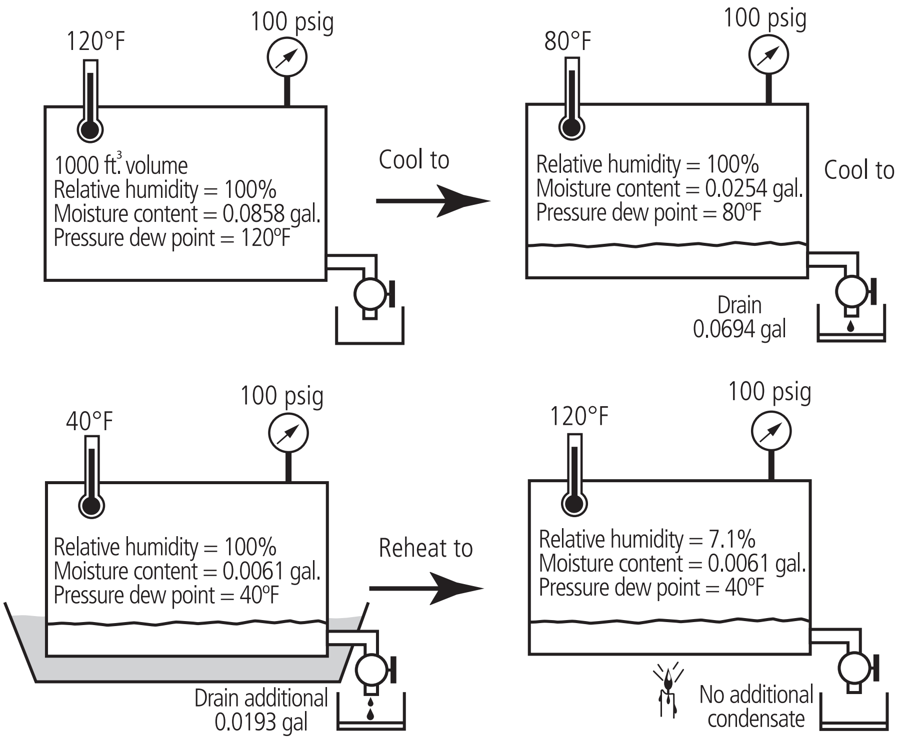
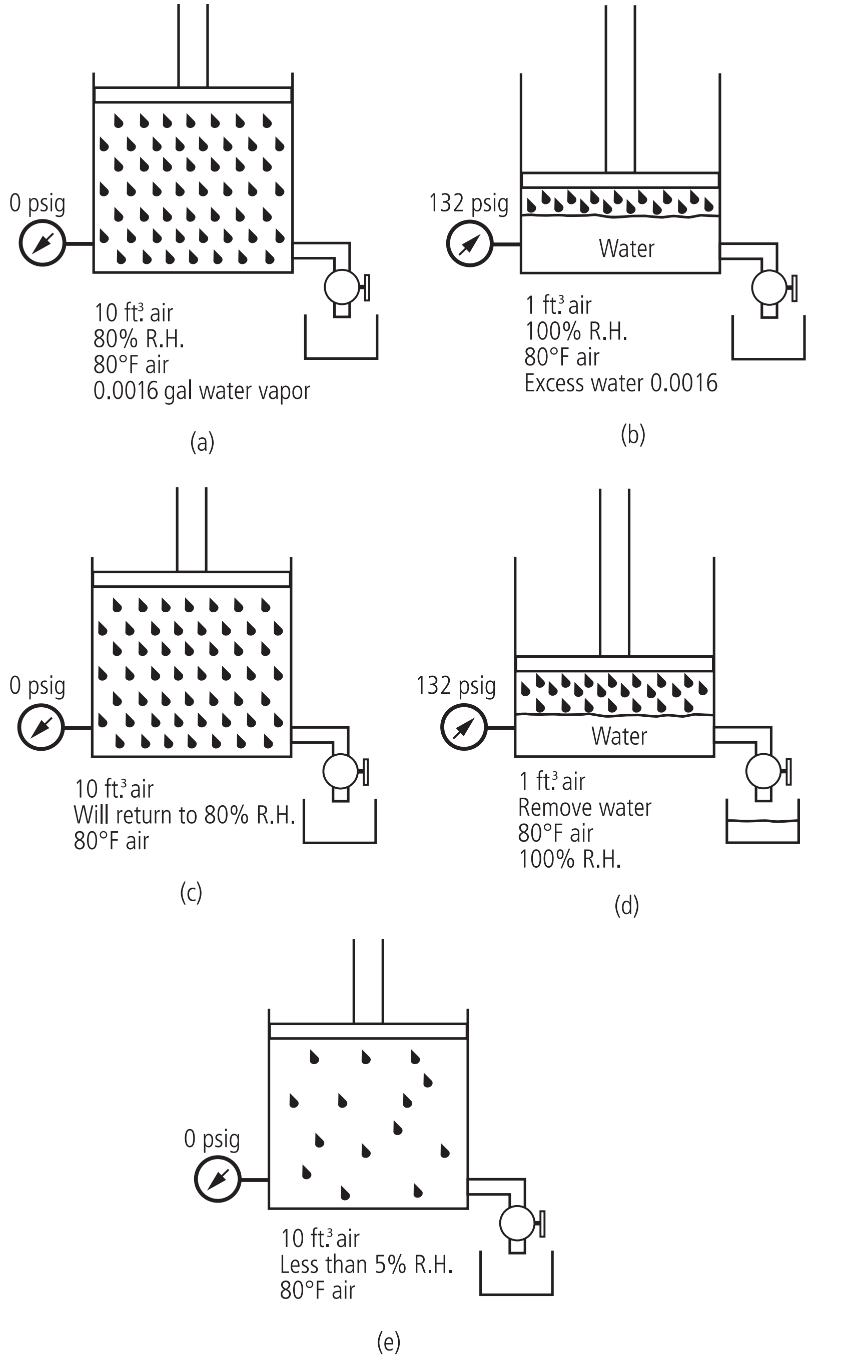


Figure 3.1 How temperature influences the capacity of air to hold water vapor, the pressure remaining constant.

An illustration of pressure effect on vapor content and relative humidity is shown in Figures 3.2a, 3.2b, 3.2c, 3.2d and 3.2e. The amount of water vapor in 10 cubic feet of air at 80% relative humidity and 80°F was determined from Table 3.3: 0.1625 x 10/1000 = 0.0016 gallons. See Figure 3.2.

Now, if air is compressed from 10 cubic feet to 1 cubic foot, the pressure is increased from atmospheric to 132 psig. [(132 psig + 14.7 psia) ÷14.7 psia]. At 132 psig and 80°F, the 1 cubic foot volume can hold only 0.00002 gallons of moisture. Since there were 0.0016 gallons in the 10 cubic feet of atmospheric air but as 1 cubic foot it now can hold only 0.00002 gallons, the excess moisture will condense. If the excess moisture is not removed, and the pressure is reduced to atmospheric, the excess water will gradually evaporate back into the air until equilibrium is established. This will happen because the air under this condition can again hold 0.0016 gallons of water vapor. If the condensed water had been removed at pressure, as shown in Figure 3.2d and the pressure again reduced as shown in Figure 3.2e, the excess water is no longer available to evaporate back into the air. The water vapor content of the 10 cubic feet then will be 0.00002 gallons, which is the maximum vapor content that 1 cubic foot of air can hold at 80°F and 132 psig. The 0.00002 gallons per 10 cubic feet thus determined is 0.002 gallons per 1,000 cubic feet. Referring to Table 3.3, it will be seen that 0.002 gallons per 1,000 cubic feet is less than any quantity listed for 80°F. Therefore, the relative humidity is less than 5%.



Figures 3.2a, 3.2b, 3.2c, 3.2d and 3.2e: reflect change in pressure affects moisture content of air at constant pressure.

Dew Point

A more useful term than relative humidity for indicating the concentration of water vapor in a compressed air system is dew point. The dew point is the temperature at which condensate will begin to form if the air cools at constant pressure. When the compressed air temperature and dew point are equal, the relative humidity of the compressed air is 100%.

In Figure 3.3 it will be noted that the dew point is equal to the saturated air temperature and follows the air temperature until it reaches its lowest point of 40°F. At this point, the air temperature was increased but the dew point remained at 40°F since the excess moisture had been removed. No further condensation would occur unless the temperature dropped below 40°F. This is further illustrated in Figure 3.33 in the appendix. If a refrigerant type air dryer set at +35°F were installed at point A, Figure 3.3, it would cool the air to +35°F and the moisture in the air would condense and be removed at this point. No further condensation would occur unless the temperature somewhere downstream was dropped below +35°F.

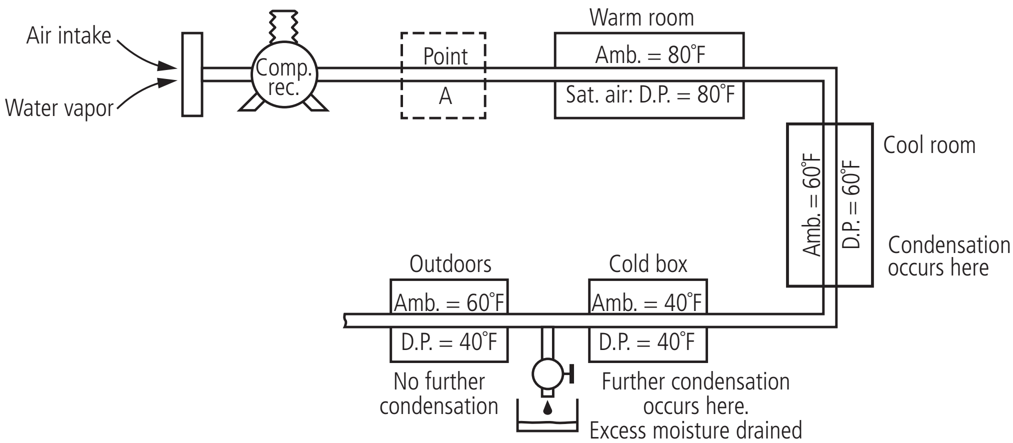


Figure 3.3: Effect of dew point on condensation

To obtain the dew point temperature expected if the gas were expanded to a lower – pressure see Figure 3.33 in the appendix.

It should be noted that as air leaves a compressor it is under both an elevated pressure and an elevated temperature. A delicate balance exists under this condition since the air under pressure has less capacity for water vapor, whereas air at an elevated temperature has a greater capacity for water vapor. The air leaving the compressor generally is cooled in an aftercooler causing water to condense and allowing saturated air to flow downstream. Any further cooling in the piping will result in additional condensation in the piping system.

Pressure Dew Point

A distinction must be made between the dew point at atmospheric conditions and the dew point under operating conditions at elevated pressure. The relationship between the atmospheric dew point and the pressure dew point is shown in the appendix, Figure 3.33. To convert the pressure dew point at 100 psig of 35°F to an atmospheric dew point, draw a horizontal line at +35°F from the scale on the right until it intersects the 100 psig pressure line, then draw a line vertically downward to the scale at the bottom where it shows approximately -10°F. This demonstrates that when water is removed from air under pressure, the resulting atmospheric dew point will be substantially lower. This demonstrates why dryers are normally located after the air compressor.

Compressed Air Treatment

A variety of equipment is used to treat compressed air so that it is suitable for use in many different applications with different requirements. The following material describes the different compressed air treatment equipment and provides guidance regarding purpose and use.

Aftercoolers

Hot compressed air could cause unsafe surface temperatures and thermal expansion in piping systems and could adversely affect gaskets, seals and other downstream components. An aftercooler normally is installed after the discharge of an air compressor and often as an integral part of the compressor package. An air cooled aftercooler uses atmospheric air for cooling and provides a final compressed air temperature within 15 to 30ºF of the ambient temperature. A water cooled aftercooler also can provide a final compressed air temperature in the range of 5 to 15°F above the cooling water temperature. The lower the temperature leaving the aftercooler, the more moisture will be removed from the air as condensate.

Adequate compressed air cooling is essential for the proper operation of compressed air treatment equipment. Dryers are normally designed for an inlet compressed air temperature of 100°F. If compressed air temperatures above 100°F cannot be avoided, a dryer may need to be oversized or otherwise modified.

Moisture Separators

A moisture separator is a mechanical device designed to remove condensate from an air stream. A moisture separator normally is installed immediately downstream of the aftercooler. It should be noted that no moisture separator is 100% efficient and that some condensate passes through the device. Also a moisture separator does not lower the compressed air dew point, meaning further cooling downstream will result in additional condensate in the piping system. Moisture separators require a drain valve for removing condensate from the pressurized system during operation.

Figure 3.4: Moisture Separator

Compressed Air Dryers – Selecting the Right Compressed Air Dryer

Many technologies and processes exist for drying compressed air. No one category of air dryer is suitable for all applications. Selecting the right air dryer involves understanding the dew point requirements, ambient temperature ranges, operating pressure and temperature ranges, available utilities, and other site specific conditions.

Know the Temperatures

To determine whether or not the compressed air will remain sufficiently dry, we must know the end use of the air and the temperature at which it must work. In an industrial plant where the ambient temperature is in the range of 70°F or higher, a dryer capable of delivering a pressure dew point 20°F lower than ambient, or 50°F, may be satisfactory.

Summer temperatures do not require a very low dew point whereas winter temperatures may dictate a much lower dew point. In winter, the temperature of the cooling medium, air or water, usually is lower than in summer, resulting in a variation of the air temperature to the dryer. This will affect the size of the dryer needed, since the same dryer must work in both summer and winter temperatures and humidity conditions.

Many chemical processing plants, refineries, and power plants distribute instrument and plant air within the facility with lines and equipment that are located outside the buildings. In such plants two different temperature conditions exist at the same time in the same system. Also, a dryer, which may be satisfactory for high daytime temperatures, may not be satisfactory for lower nighttime temperatures. In areas where freezing temperatures are encountered, a lower pressure dew point may be required. In general, the dew point should be specified 20°F lower than the lowest ambient temperature encountered in order to avoid potential condensation and freezing. To specify a winter dew point when only summer temperatures will be encountered, can result in over-sizing the equipment and increased initial and operating costs.

It is recommended that ISO 8573-1 be used by end-users and specifying engineers to communicate the moisture limitations of the compressed air system. Similarly, compressed air equipment manufacturers should reference this ISO Standard to convey the moisture removing capabilities of their drying equipment. With all parties subscribing to this ISO standard, the end user is assured that the drying equipment being considered is suitable for the application.

Know the Required Dew Point

Specifying a dew point lower than is required for an application can add to the capital and operational costs and is not good engineering practice. On the other hand, a dew point which is marginal may not meet requirements in varying operating conditions and could result in costly shutdown of a process and/or damage to the product or equipment.

It is recommended that the supplier of the end use equipment be asked to specify the dew point required for their equipment. One of the classes established in ISO 8573-1 should be selected. This will allow a dryer meeting that class to be chosen. The experience of the dryer manufacturer also should be drawn upon in this decision.

Typical pressure dew points from dryers are as follows:

Refrigerant Types:	38°F to 50°F
Regenerative Desiccant Types:	-40ºF to -100ºF
Single Tower Deliquescent Types:	20°F to 63ºF (below compressed air inlet temperature)
Membrane Types:	40ºF standard and lower

It is desirable to know the amount of moisture remaining in saturated air at various operating pressures. This can be seen in Figure 3.5.

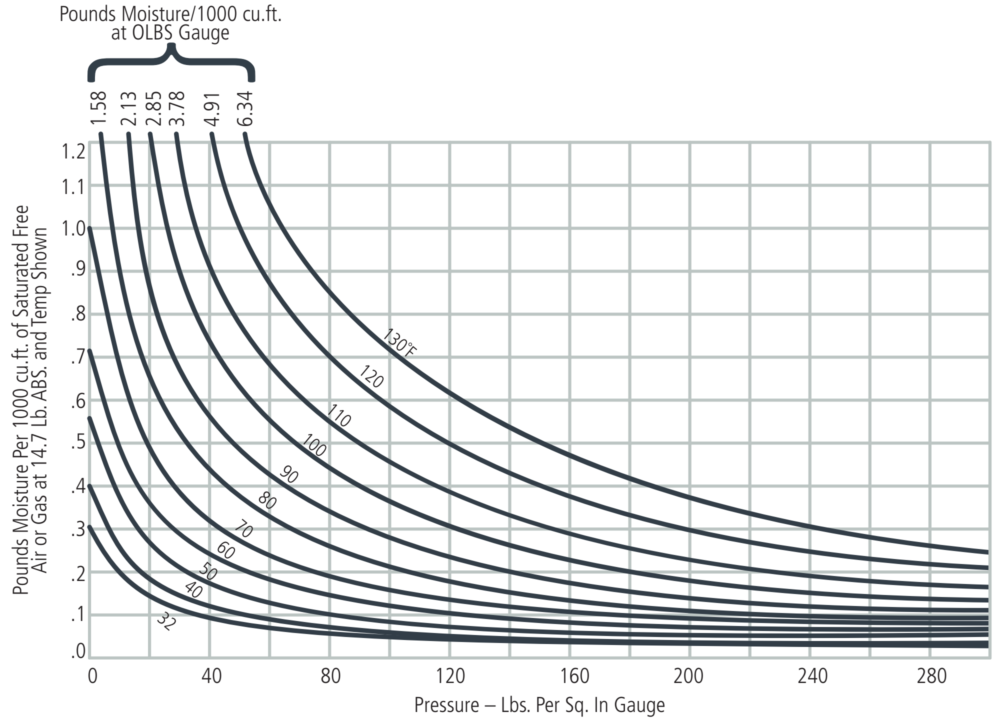


Figure 3.5: illustrates moisture remaining in saturated air when compressed isothermally to the pressure shown.

Process Air Applications

In addition to plant and instrument air applications, there are many cases where compressed air is used as part of a process that demands a low dew point. For example, railroad tank cars, which carry liquid chlorine, are padded (charged) with compressed air to enable pneumatic unloading. Chlorine will combine with water vapor to form hydrochloric acid; therefore, the compressed air must have minimum moisture content to prevent severe corrosion.

Droplets of moisture in wind tunnel air at high-testing velocities may have the effect of machine gun bullets, tearing up the test models.

Compressed air used as a feedstock for nitrogen or oxygen liquefaction must be virtually moisture free to prevent the formation of ice within heat exchangers.

For these and similar applications, compressed air must not only be free of liquid phase water but must also have a minimum content of vapor phase water. As such, a compressed air dryer delivering between -40°F to -100°F dew point is recommended.

Dryer Types

Different methods can be used to remove moisture from compressed air. Current drying methods include the following:

- Refrigerant
  - Cycling
  - Non-cycling
- Regenerative desiccant
  - Heatless (no internal or external heaters)
  - Heated (internal or external heaters)
  - Heated Blower
  - Heat of Compression
  - Non-regenerative Single Tower
- Deliquescent
- Membrane

Each of these dryer types is discussed below in greater detail.

Refrigerant Type Dryers

Refrigerant dryers provide compressed air quality that is acceptable in many general industrial plant air applications and is the most widely-used type of compressed air dryer. A refrigeration system similar to that found in a domestic refrigerator or home air conditioning system is used to cool the compressed air to approximately 35°F – 50°F. When cooled, moisture will condense and form liquid water droplets that can be separated from the compressed air stream. Collected liquid can then be discharged through a dedicated drain and the conditioned air used downstream. Note that since water freezes at 32°F, dew points lower than 32°F are not feasible with a conventional refrigerated dryer.

The simplest form of a refrigerant type dryer is referred to as a chiller or gas cooler. These dryers discharge air at a temperature equal to the outlet pressure dew point, providing the user with saturated air at temperatures between 35°F – 50°F. Most refrigerant dryers, however, include an air-to-air heat exchanger (also referred to as an "Economizer"), where there is a cross exchange between warm incoming air and chilled outgoing air. Note that since these dryers discharge air at a temperature higher than their pressure dew point, their warm outlet air temperature will prevent moisture from condensing on the surface of the compressed air piping downstream of the dryer.

In a non-cycling refrigerant dryer, the refrigerant circulates continuously through the system. Since the flow of compressed air will vary and ambient temperatures also vary, a hot gas bypass valve or unloader valve often is used to regulate the flow of the refrigerant and maintain stable operating conditions within the refrigerant system. In most designs, the refrigerant evaporates within the air to refrigerant heat exchanger (evaporator) and is condensed after compression by an air or water to refrigerant heat exchanger (condenser).

This design provides rapid response to changes in operating loads. While older refrigerant type air dryers have used CFC refrigerants such as R12 and R22, newer designs are in compliance with the Montreal Protocol and use chlorine-free refrigerants such as R134A and R407C or other environmentally friendly refrigerant blends. The properties of these newer refrigerants require careful attention to the refrigeration system design, due to differences in operating pressures and temperatures. Please note that all refrigerant type dryers should only be serviced by a licensed and trained technician to assure that the refrigerant material is properly handled.

Most compressed air systems do not operate at a continuous, full-load condition. Fluctuations in equipment usage, the use of variable-speed compressors, variations in inlet temperature and pressure to the dryer, result in highly variable demand. Non-cycling dryers do not have the means to respond to these system variations. Cycling dryers, however, incorporate a design that permits the refrigeration system to cycle on and off in relation to the varying demands of the compressed air system, resulting in potentially significant savings in operating costs.

Cycling type refrigerant dryers chill a thermal mass medium which in turn is used to cool the compressed air. This mass may be a liquid such as glycol or a metal such as aluminum block, beads or related substance, which act as a heat sink. The temperature of the thermal mass medium increases as heat is exchanged with the compressed air in an air-to-thermal mass heat exchanger. Conversely, the temperature of this medium decreases as it is cooled by the refrigeration system in a separate refrigerant-to-thermal mass exchanger. The operation of the dryer's refrigeration system is thermostatically controlled and enables the refrigeration system to cycle off during periods of reduced load. While cycling refrigerant dryers have typically higher acquisition costs than similar sized non-cycling dryers, over time they often make up for that difference in much lower operating costs.

Figure 3.6: Cycling Refrigerated Air Dryer

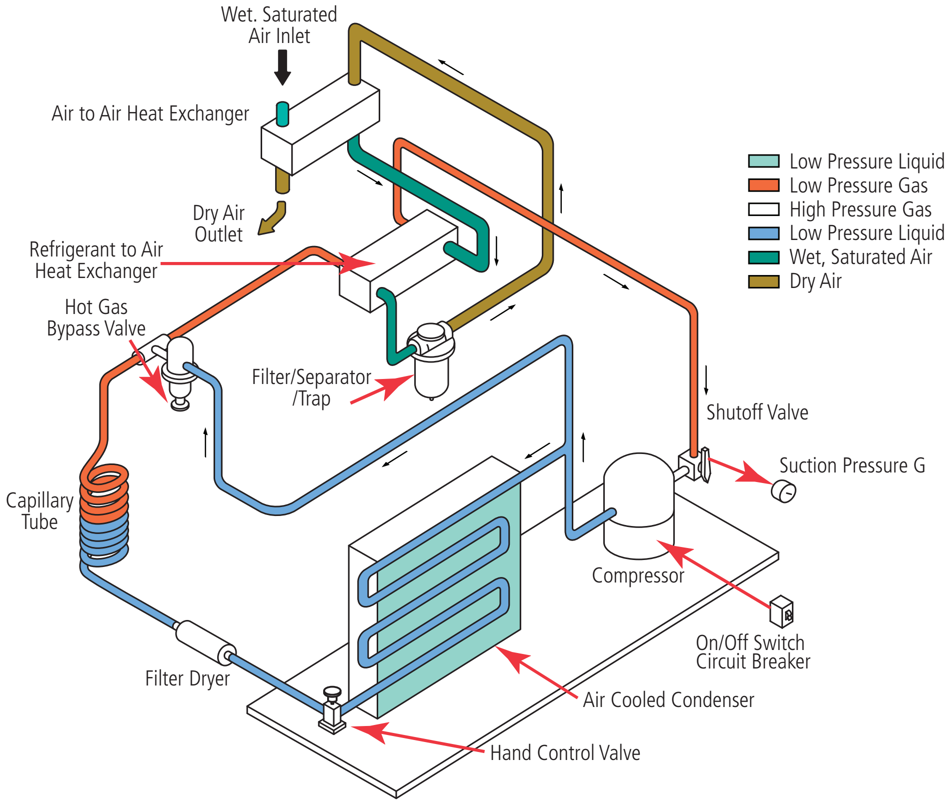


Figure 3.7: Typical Refrigerant Type Dryer with Hot Gas By-pass Valve

Figure 3.8: Non-cycling Refrigerant Dryer

Figure 3.9: High Temperature Refrigerated Dryer

Advantages / Disadvantages of Various Types of Refrigerant Dryers

Advantages of Refrigerant Type Air Dryers include:

- Low, initial capital cost.
- Relatively low operating cost.
- Low maintenance costs.
- Not damaged by oil in the air stream (Filtration normally is recommended).

Disadvantages of Refrigerant Type Air Dryers include:

- Limited dew point capability.
- Indoor use only in geographies subject to freezing ambient temperatures.

Advantages of Direct Expansion Control include:

- Minimal dew point swing.
- Refrigerant compressor operates continuously.

Disadvantages of Direct Expansion Control include:

- No energy savings at partial and zero air flow.
- Seasonal hot gas bypass adjustment.

Advantages of Cycling Control include:

- Energy savings at partial and zero air flow.

Disadvantages of Cycling Control include:

- Dew point swings.
- Increased size and weight to accommodate the heat sink mass
- Increased capital cost




Regenerative Desiccant Type Dryers

Regenerative desiccant dryers use a desiccant medium to adsorb water vapor present in the compressed air stream. Note that the term "adsorb" means that the moisture adheres to the desiccant, collecting in the thousands of small pores within each desiccant bead. The composition of the desiccant is not changed, and the moisture can be driven off during a process of regeneration. The term "absorb", which is not applicable to regenerative desiccant dryers, refers to the action where a material is dissolved in and used up by the moisture. Absorption takes place in a deliquescent type dryers and will be discussed later in this chapter.

Regenerative desiccant dryers normally are of twin tower construction. The desiccant in one tower dries the air from the compressor while the desiccant in the other tower is being regenerated. Regeneration can be accomplished using a time cycle or on demand by measuring the temperature or humidity in the desiccant towers or by measuring the dew point of the air leaving the on-line tower. Note that while drying takes place at line pressure, the regeneration process takes place by expanding air to atmosphere over the desiccant beads.

Heatless regenerative desiccant dryers do not incorporate internal or external heaters. These dryers apply the principle of pressure swing adsorption (PSA), where moisture is desorbed from the regenerating vessel through rapid depressurization plus a sweep of dry purge air. The purge air requirement can range up to 18% of the dryer's rated flow. The typical regenerative desiccant dryer at 100 psig has a pressure dew point rating of -40°F but a dew point down to -100°F can be achieved through modifications to purge volume, desiccant material and vessel cycle time.

Heat reactivated regenerative desiccant dryers use the principal of temperature swing adsorption (TSA) for desiccant bed regeneration. Heated atmospheric or heated dry process air is used to desorb water from the desiccant medium in the regenerating tower.

In externally heated regenerative desiccant dryers, the purge air is heated to a suitable temperature and then passes through the desiccant bed. The amount of purge air is approximately 5-10% of the air flow through the dryer. A variation of the externally heated regenerative desiccant dryers is a blower pure dryer. This type of dryer uses an external blower and heater to drive hot atmospheric air through the regenerating desiccant bed.

All regenerative desiccant dryers require protection from compressor lubricant. Lubricants can contaminate the desiccant which will prevent the adsorption of water. To protect downstream equipment from desiccant dust or "fines", a particulate filter should be installed downstream of any regenerative desiccant dryer.

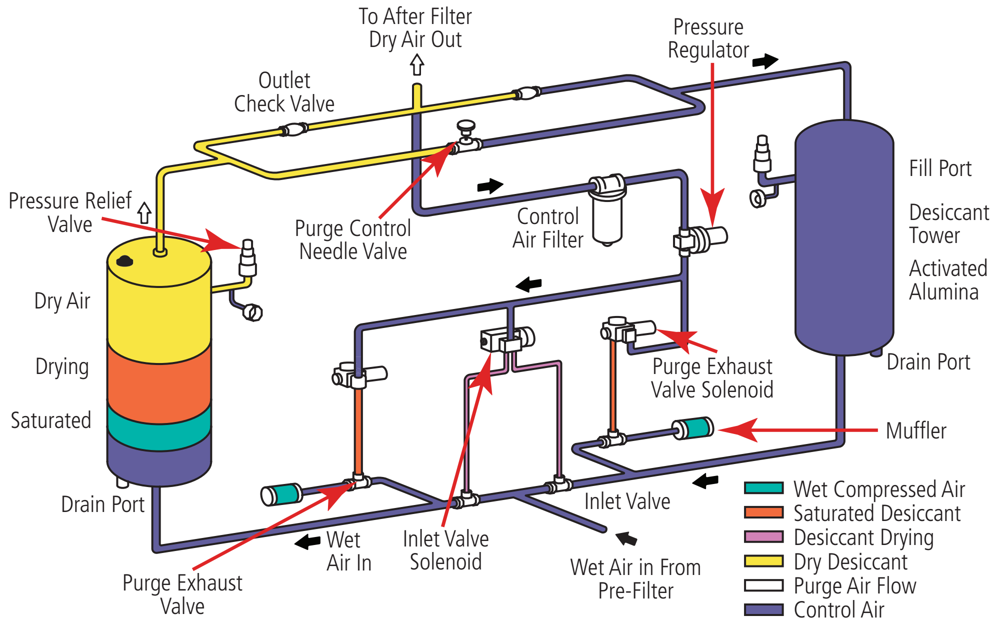


Figure 3.10: Typical Twin Tower Regenerative Desiccant Type Dryer

Figure 3.11: Externally Heated Regenerative Desiccant Dryer

Figure 3.12: Typical Twin Tower Regenerative Desiccant Type Dryer

Figure 3.13 : Blower Purge Regenerative Desiccant Dryer

Figure 3.14: Modular Dryers

Figure 3.15: Heated Zero Purge Regenerative Desiccant Dryer

Advantages / Disadvantages of Regenerative Desiccant Type Dryers

Advantages of Desiccant Type Dryers include:

- Very low dew points can be achieved without potential freeze-up.
- Moderate cost of operation for the dew points achieved.
- Heatless type can be designed to operate pneumatically for remote, mobile, or hazardous locations.

Disadvantages of Desiccant Type Dryers include:

- Relatively high initial capital cost.
- Periodic replacement of the desiccant bed (typically 3-5 years).
- Oil aerosols can coat the desiccant material, rendering it useless if adequate pre-filtering is not maintained.
- Purge air usually is required.

Heat of Compression Type Dryers

Heat of compression type dryers are regenerative desiccant dryers that make use of heat energy generated by the air compressor during the compression process. This heat source, which is typically considered waste heat, is used to regenerate the desiccant medium, eliminating the need for additional energy and the associated energy costs. There are two types of heat of compression dryers: the single vessel type and the twin tower type.

Single vessel heat of compression type dryers provide continuous drying with no cycling or switching of towers. This is accomplished with a rotating desiccant drum in a single pressure vessel divided into two separate air streams. One air stream is a portion of the hot air taken directly from the air compressor at its discharge, prior to the aftercooler, and is the source of heated purge air for regeneration of the desiccant bed. The second air stream is the remainder of the air discharged from the air compressor after it passes through the air aftercooler. This air passes through the drying section of the dryer rotating desiccant bed where it is dried. The hot air, after being used for regeneration, passes through a regeneration cooler before being combined with the main air stream by means of an ejector nozzle before entering the dryer.

The twin tower heat of compression type dryer uses the full hot outlet air volume from the air compressor to regenerate the desiccant medium in the regenerating tower. From there, the air is cooled in the dryer's aftercooler before entering the drying tower. Unlike most heat regenerative desiccant dryers, heat of compression dryers use little to no purge air to accomplish regeneration. Timing of the switching between of the two towers is similar to that of a typical heat reactivated desiccant dryer.

Advantages & Disadvantages of Heat of Compression Dryers:

Advantages of Heat of Compression Type Dryers include:

- Low electrical installation cost.
- Low power costs.
- Little to no loss of purge air.
- Single vessel type can be integrated into the compressor package due to small footprint.

Disadvantages of Heat of Compression Type Dryers include:

- Applicable only to oil free compressors.
- Applicable only to compressors having a continuously high discharge temperature.
- Inconsistent dew point with variable loads on single vessel type.
- High pressure drop and inefficient ejector nozzle on single vessel type.
- Booster heater required for low load (heat) conditions in twin tower type dryer.
- Desiccant material in single vessel (usually a cartridge type) has higher replacement cost than twin tower (usually activated alumina beads).

Figures 3.16: Twin Tower Heat of Compressor Dryer Single Vessel Heat of Compression Dryer

Single Tower Deliquescent Type Dryers

The deliquescent desiccant type dryer uses hygroscopic desiccant material, usually salt, which has a high affinity for water. The desiccant absorbs the water vapor and is dissolved in the liquid formed. These hygroscopic materials are blended with ingredients to control the pH of the effluent and to prevent corrosion, caking and channeling. The desiccant is consumed only when moist air is passing through the dryer. On average, desiccant must be added two or three times per year to maintain a proper desiccant bed level.

The single tower deliquescent desiccant type dryer has no moving parts and requires no power supply. This simplicity leads to lower installation costs. Dew point suppression of 15 to 63°F is advertised. This type of dryer actually dries the air to a specific relative humidity rather than to a specific dew point.

Figure 3.17: Single Tower Deliquescent Type Dryer

Advantages & Disadvantages of Single Tower Deliquescent Dryers

Advantages of Single Tower Deliquescent Dryers include:

- Low initial capital and installation cost.
- Low pressure drop.
- No moving parts.
- Requires no electrical power.
- Can be installed outdoors.
- Can be used in hazardous, mobile, dirty, or corrosive applications.

Disadvantages of Single Tower Deliquescent Dryers include:

- Limited suppression of dew point.
- Desiccant bed must be refilled periodically (2 to 3 times per year).
- Regular periodic maintenance.
- Desiccant material can carry over into downstream piping if dryer is not drained regularly and certain desiccant materials may have a damaging effect on downstream piping and equipment. Some desiccant materials may melt or fuse together (caking) at temperatures above 80°F.
- Desiccant material is hygroscopic salts which can accelerate corrosion.

Membrane Type Dryers

Membrane dryers are commonly used for air separation such as in nitrogen production for food storage and other applications. The structure of the membrane is such that molecules of certain gases (such as oxygen) are able to pass through a semi-permeable membrane faster than others (such as nitrogen) leaving a concentration of the desired gas (nitrogen) at the outlet of the generator.

When used as a dryer in a compressed air system, specially designed membranes allow water vapor (a gas) to pass through the membrane pores faster than the air, reducing the amount of water vapor in the air stream at the outlet of the membrane dryer, suppressing the dew point. The dew point achieved normally is 40ºF but lower dew points to -40ºF can be achieved at the expense of additional purge air loss.

Advantages & Disadvantages of Membrane Dryers:

Advantages of Membrane Type Dryers include:

- Low installation cost.
- Low operating cost.
- Can be installed outdoors.
- Can be used in hazardous atmospheres.
- No moving parts.

Disadvantages of the Membrane Type Dryers include:

- Limited to low capacity systems.
- High purge air loss (15 to 20%) to achieve required pressure dew points.
- Membrane may be fouled by oil or other contaminants.

Figure 3.18: Membrane Dryer

Dryer Ratings

When a compressed air system is started (for example, at the beginning of a shift, day or week), the lack of system pressure can result in excessive air velocities through moisture separators, dryers and filters with resultant moisture carry-over. This problem can be eliminated by having a "minimum pressure valve" located downstream of the primary treatment equipment, prior to distribution to the plant.

Oil injected rotary compressors have a similar valve to prevent excessive velocities through the air/oil separator but this does not protect treatment equipment downstream of the compressor.

The standard conditions for the capacity rating in scfm of compressed air dryers are contained in ISO 7183, *Compressed Air Dryers – Specifications and Testing and Performance Ratings*. These standard conditions in the US are commonly called the three 100s. That is, a dryer inlet pressure of 100 psig, an inlet temperature of 100°F, and an ambient temperature of 100ºF. If the plant compressed air system has different operating conditions, this will affect the dryer capacity and must be discussed with the supplier to ensure compatibility.

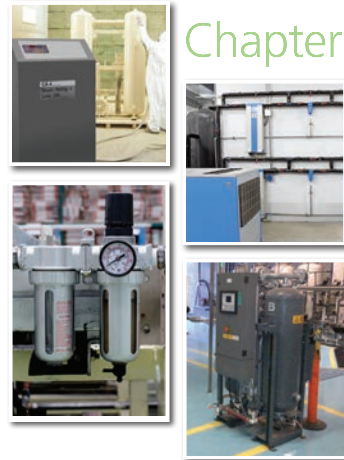
Know the Flow Capacity

The flow capacity of a dryer normally is stated in standard cubic feet per minute (scfm). The Compressed Air & Gas Institute and Pneurop now define standard air as 14.5 psia (1 bar), 68°F (20°C) and 0% relative vapor pressure (0% relative humidity). The capacity rating is also based upon inlet conditions to the dryer of saturated compressed air at 100 psig and 100ºF and an ambient temperature of 100ºF. An increase in inlet pressure raises the capacity of the dryer while an increase in inlet temperature or ambient temperature lowers it.

Generally a dryer is selected based on the capacity of the associated compressor. If the dryer is placed between the air compressor and an air storage vessel (air receiver), the flow through the dryer cannot exceed the output from the air compressor, even though air flow from the air receiver to the plant air system may be greater than the output of the compressor. If the dryer is placed downstream of the air receiver, the dryer could see a surge in demand which exceeds the capacity of the dryer. While the dryer benefits from radiant cooling of the air in the receiver and may be shielded from potentially harmful pressure pulsations associated with a reciprocating type compressor, the dryer may yield reduced dew point performance and high pressure drop if flowed beyond its rated capacity. Therefore, the user must consider the full flow potential on the dryer, which depending on the system, may be in excess of the capacity of the associated air compressor.

Know the Operating Pressure

The higher the inlet pressure to the dryer, the lower the moisture content at saturated conditions and the lower the load on the dryer. A higher operating pressure can result in a smaller, more efficient and more economical dryer but will require higher operating costs of the air compressor to produce the higher pressure. As a rule of thumb, an additional 1 psi above 100 psig increases compressor energy consumption by 0.5 %. The dryer design pressure must equal or exceed the maximum operating pressure of the air compressor.



Know the Operating Temperature

Knowing the operating temperature requires knowing the inlet temperature to the dryer, the variations in ambient temperature, and the temperature requirements at the points of use. Normally, the air dryer is downstream of the air compressor aftercooler and moisture separator and has a temperature close to that of the aftercooler outlet. It should be recognized that 15 to 20°F above inlet coolant temperature is the norm for aftercoolers. This means that with the most popular air cooled radiator types using ambient air for cooling, the compressed air temperature leaving the aftercooler will be 15 to 20 degrees above ambient. This also means that if a maximum ambient temperature of 100°F is anticipated, the compressed air inlet temperature to the dryer will exceed the dryer rating temperature of 100°F and will affect the dryer capacity. Water cooled aftercoolers with lower than ambient cooling water supply temperatures may provide a lower compressed air temperature from the aftercooler but the temperature of water coming from cooling towers generally will be above ambient air temperature.

Often the aftercooler is an integral part of the air compressor package and is installed indoors at a temperature above prevailing ambient temperature. Proper ventilation of the compressor room helps increase the efficiency of the aftercooler and lowers the inlet temperature to the dryer, improving performance.

Piping which distributes the compressed air to the plant system may pass outdoors and be exposed to ambient temperatures that are below freezing. The pressure dew point of the air must be below the lowest anticipated ambient temperature.

Know the Utility Requirements

Plant utilities generally available may include electric power, natural gas, cooling water, steam and compressed air. The type of location (e.g. hazardous or remote), the availability at the proposed location of each utility and its relative cost, will influence the selection of the type of dryer. Some dryer types require electric power while others do not.

More information on dryer selection can be obtained from the CAGI Air and Gas Drying selection guide, which is available on the CAGI web site. (www.cagi.org)

Compressed Air Filters

While the dryer is an integral part of achieving clean, dry air, additional treatment is often necessary to ensure proper system performance and good performance of dryers. Compressed air filters help protect equipment from dust, dirt, oil and water.

Particulate matter normally refers to solid particles in the air and it has been estimated that there are as many as 4 million particles in one cubic foot of atmospheric air. When compressed to 103 psig the concentration becomes over 30 million. Over 80% of these are below 2 microns.

One micron = One millionth of a meter
or = 0.04 thousandths of an inch

The inlet filter of a typical air compressor has a rating of about 10 microns and is designed for the protection of the air compressor and not any downstream equipment. In addition, wear particles from compressors and deposits from degradation of oils exposed to the heat of compression can add to downstream contamination.

The main mechanisms of mechanical filtration are direct interception, inertial impaction, and diffusion. These also may be enhanced by electrostatic attraction.

Direct interception occurs when a particle collides with a fiber of the filter medium without deviating out of the streamline flow. Usually this occurs on the surface of the filter element and affects mainly the larger sized particles (usually over 1 micron).

Inertial impaction occurs when a particle, traveling in the air stream through the maze of fibers in the filter element, is unable to stay in the streamline flow, collides with a fiber, and adheres to it. Usually this occurs with particles in the range from 0.3 to 1.0 microns.

Diffusion (or Brownian Motion) occurs with the smallest particles, below 0.3 microns. These tend to wander through the filter element within the air stream, with increased probability of colliding with a filter fiber and adhering to it.

Compressed air filters are a source of pressure loss within in the system. As a rule of thumb, 1 psi of pressure loss increases electricity consumption by 0.5%. Routine replacement of compressed air filter elements can reduce energy costs.

Particulate Filters

Particulate filter designs are such that some overlap occurs with the different mechanisms and the desired degree of contaminant removal. A higher degree of contaminant removal than is necessary will result in a higher pressure drop across the filter, requiring a higher pressure from the air compressor and additional energy costs. Particulate filters may have a pressure drop rating when new but the maximum allowable pressure drop before the filter element is changed must also be taken into account when determining the pressure at the air compressor discharge and downstream of the drying and filtration equipment.

A particulate filter is recommended downstream of the air dryer, ahead of any operational equipment or process.

Coalescing Filters

Small droplets of moisture or oil adhere to the filter medium and coalesce into larger liquid droplets. Flow through the filter element is from the inside to the outside where the larger diameter allows a lower exit velocity. An anti re-entrainment barrier normally is provided to prevent droplets from being re-introduced to the air stream. The cellular structure allows the coalesced liquid to run down by gravity to the bottom of the filter bowl from which it can be drained, usually by means of an automatic drain. The liquid may contain both oil and water.

The coalescing action should not result in any increase in pressure drop over the life of the filter. Pressure drop increase normally is due to the accumulation of particulate matter if the coalescing filter is not preceded by an adequate particulate filter. The normal pressure drop should be the "wet" pressure drop after the element by design has become saturated. The "dry" pressure drop before the element is properly wetted will be lower.

A coalescing filter is recommended ahead of any dryer with drying medium may be damaged by oil. The term oil includes petroleum based and synthetic hydrocarbons plus other synthetic oils such as di-esters which can affect materials such as acrylics in downstream equipment or processes.

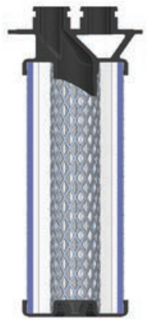


Figure 3.19: Coalescing Filter

Adsorption Type Filters

Particulate and coalescing type filters remove extremely small solid or liquid particles down to 0.01 microns but not oil vapors or odors. Adsorption is the attraction and adhesion of gaseous and liquid molecules to the surface of a solid. Normally the filter elements contain activated carbon granules which have an extremely high surface area and dwell time. The activated carbon medium is for the adsorption of vapors only. An adsorption filter must be protected by an upstream coalescing type filter to prevent gross contamination by liquid oil.

With the combination of all three types of filters downstream of a dryer, it is possible to obtain an air quality better than the atmospheric air entering the air compressor.

Dryer and Filter Arrangements

In the Air Quality Classes of ISO 8573-1, (see Tables 3.1A, B and C) the first class concerns particulate content, the second moisture content, and the third hydrocarbons.

A general purpose coalescing filter capable of removing particles down to 1 micron, and liquids down to 0.5 ppm (rated at 70°F), placed after an air aftercooler and moisture separator (Fig.3.20), will meet the requirement of Classes 1.-.3. That is Class 1 particulate, no rating for moisture and Class 3 for hydrocarbons.

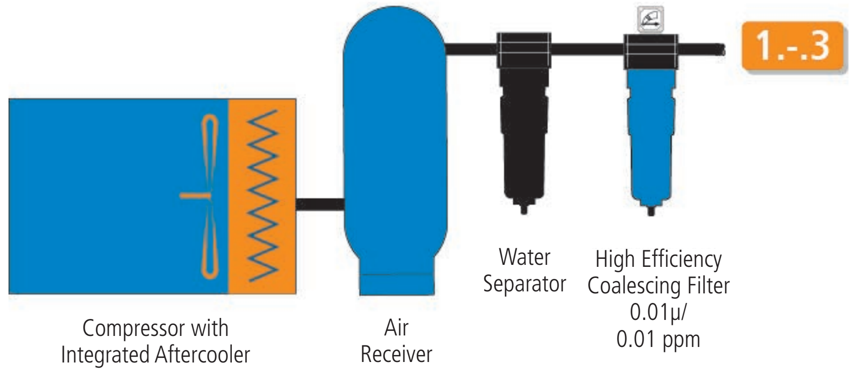


Figure 3.20: Typical Compressed Air Treatment Layout

The same general purpose coalescing filter used as a pre-filter followed by a high efficiency coalescing filter (Fig. 3.21) to remove liquid particles down to 0.01 microns, would meet Classes 1.-.2.

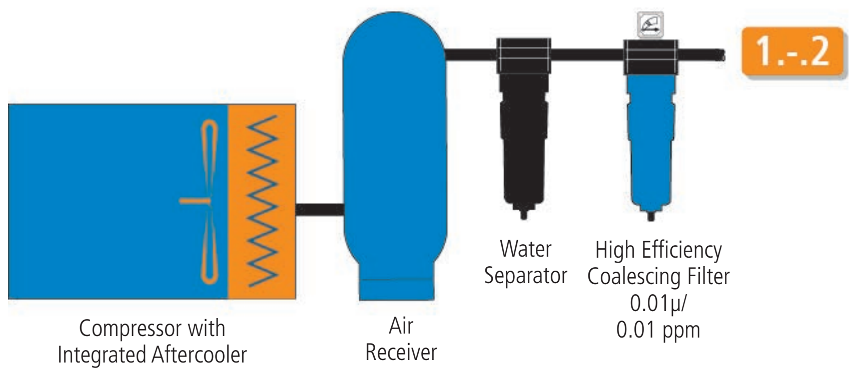


Figure 3.21

The same type of filter normally used in conjunction with a refrigerant type dryer (Fig. 3.22) will meet Classes 1.4.1.

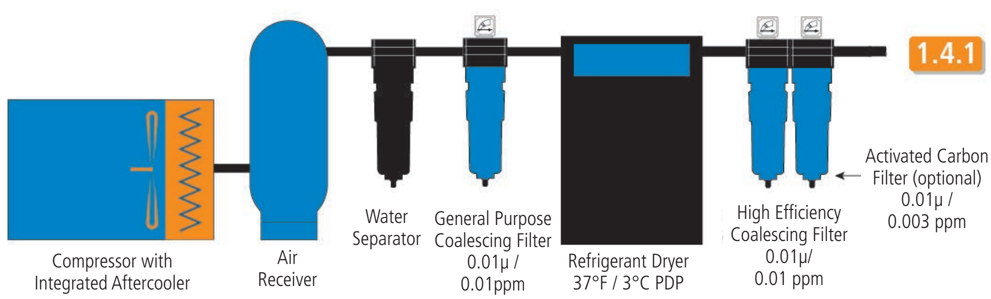


Figure 3.22: System, meeting Classes 1.4.1

In the case of a regenerative desiccant type dryer having a pressure dew point of -40°F, the high efficiency coalescing filter placed before the dryer to protect the desiccant bed and the same particulate filter placed after the dryer (Fig. 3.23) will meet Classes 1.2.2.

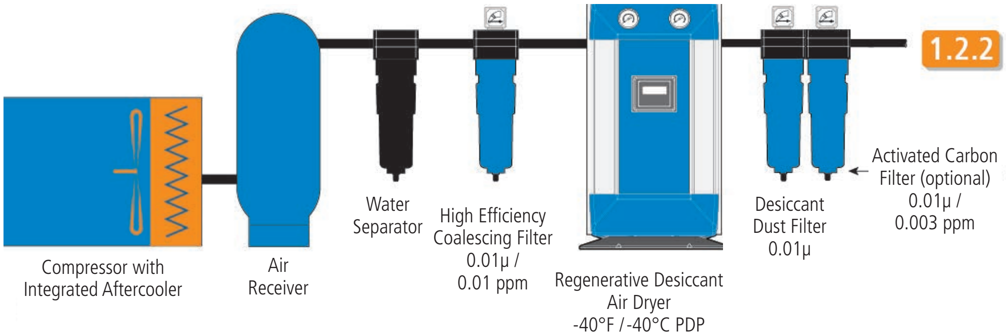


Figure 3.23

The combination of this latest arrangement followed by an activated carbon filter capable of removing oil content to 0.003 ppm, will then meet Classes 1.2.1 which may be claimed as "oil free", having less hydrocarbon content than a normal industrial atmosphere. If the regenerative desiccant type dryer had a pressure dew point rating of -100°F, the combination then would meet Classes 1.1.1. Substituting a refrigerant type dryer would still meet the "oil free" condition but with a higher (35 to 38°F) pressure dew point, or Classes 1.4.1.

Oil Free Air

Atmospheric air, particularly in industrial environments, contains condensable hydrocarbons from incompletely burned fuels exhausted by engines, heaters and other sources. It has been estimated that these can range from 0.05 to 0.25 ppm. Aerosols also atomize down to 0.8 to 0.01 microns. An oil free air compressor does not introduce oil into the compression chamber but the atmospheric air entering the compressor contains these atmospheric pollutants to a lesser or greater extent. For this reason, oil free compressors also require adequate drying and filtration after the compression process to meet Class 1.2.1 (Figure 3.24) or 1.1.1 air quality. Additional treatment is required to meet breathing or medical air requirements as listed under Table 3.2 Moisture Content of Saturated Air at Various Temperatures.

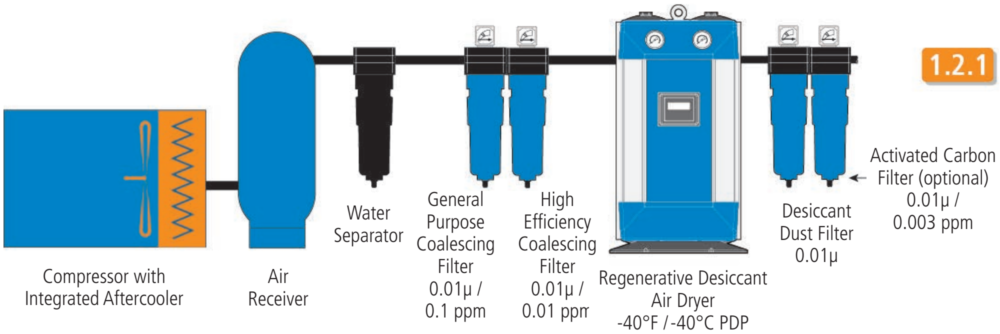


Figure 3.24

Condensate Management

Condensate management describes the removal of air system condensate and subsequent treatment for oil contamination. Condensate management products are typically defined as condensate drains and oil water separators.

Oil/Water Separators

Oil/water separators are devices for removing compressor lubricant from condensate produced in a compressed air system. Oily condensate is an environmental contaminant. Untreated condensate is generally not suitable for disposal into sewers or waterways. When selecting an oil/water separator consider the type of lubricant used in the air compressor(s), capital costs, operating costs, available utilities, and pertinent environmental regulations.

Gravity - Media Devices

The most common form of condensate treatment involves a device which utilizes gravity and/or a media to separate and remove the oil portion of emulsified condensate. Typically free oil naturally separates in the gravity separation chamber allowing the remaining condensate to flow to the media, which collects the remaining oil. Oil is both collected in the pre-separation chamber and retained in the media itself. The treated water can then be discharged to an appropriate drain. Advantages of this design include onsite treatment, a small footprint, and low initial costs. Disadvantages include consumable media costs and the need for ongoing operator inspections.

Figure 3.25: Gravity Media Oil Separator

Splitting Agent Device

This technology is used to treat stable emulsions where a gravity - media device will be ineffective. The splitting agent device typically uses a pre-separation tank to remove any free oils. The pre-treated wastewater is pumped into a reaction chamber where a non-toxic splitting agent is applied. The splitting agent encapsulates the oil particles which are then passed to a filter bag for easy collection. Purified water can then be discharged to an appropriate drain. Advantages include the ease of treating large volumes of condensate and difficult emulsions. Disadvantages include higher initial costs, a relatively large footprint, and consumable costs.

Figure 3.26: Splitting Agent Device Oil Water Separator

Evaporation

An open tank can be used to collect condensate. The waste liquid is heated to evaporate or boil off water, leaving an oily residue. Advantages include low initial cost and the ability to treat large amounts of condensate at one time with little concern for the type of mixture being processed. Negatives include high energy costs, fire risk, and the need for operator monitoring.

Offsite Disposal

Condensate is collected and then retrieved by a third party environmental waste handling company. Advantages include no capital equipment cost and third party validation of disposal. Disadvantages include condensate collection and storage issues along with a high cost for disposal.

Automatic Condensate Drains

Condensate accumulates at various points in the compressed air system, including bulk liquid separators, air receivers, refrigerated and deliquescent dryers, coalescing filters, and drip legs. This liquid must be regularly removed from the system to prevent harmful carryover. Automating this task improves system reliability. When selecting an automatic condensate drain, factors to consider are resistance to clogging or fouling, initial cost, utility requirements, and air loss (a measure of energy efficiency).

Internal Mechanical Float Drain

This drain fits within the housings of liquid separators and coalescing filters. When the liquid level within the housing rises to a set point, a float within the drain unseats from an orifice, allowing accumulated liquid to exit. As the liquid level decreases the float re-seats on the orifice, stopping further liquid from leaving the housing. These drains are generally low cost and do not purge compressed air. Their drain orifices are susceptible to blockage and require regular cleaning.

Figure 3.27: Internal Mechanical Float Drain

External Mechanical Float Drain

This drain attaches to the exterior of the device being drained. The drain contains a liquid reservoir and a float. When the liquid level within the reservoir rises to a set point the float lifts, either unseating from a drain orifice or releasing air pressure from a diaphragm allowing liquid to exit. These drains exhibit no air loss but do require consistent maintenance to prevent blockages.

Figure 3.28: External Float Drain

Solenoid Valve Timer Drain

This drain consists of an adjustable electric timer attached to a solenoid valve. Some compressed air is usually exhausted when the device actuates. A strainer should be installed ahead of the solenoid valve to reduce the risk of blockage.

Figure 3.29: Solenoid Valve Timer Drain

Ball Valve Timer Drain

This unit consists of an electric actuator with an adjustable timer and a ball valve. Compressed air is normally exhausted when the device actuates. A strainer is usually not needed.

Figure 3.30: Ball Valve Timer Drain

Electronic Level Sensing Drain

This device uses a capacitance senor within a liquid reservoir to control a solenoid and diaphragm valve. No compressed air is lost when the device actuates. Some models include an integral strainer to prevent blockage. Some models include fault and/or maintenance indicators.

Figure 3.31: Electronic Level Sensing Drain

Pneumatic Level Sensing Drain

This drain uses a mechanical float within a reservoir to control a pneumatic cylinder connected to a ball valve. No compressed air is lost when the device actuates. No strainer is required.

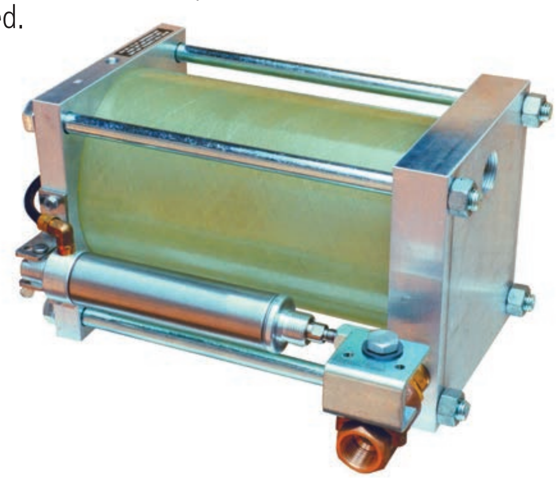


Figure 3.32: Pneumatic Level Sensing Drain

	Initial Cost	Air Loss	Power	Clog Susceptibility
Internal Mechanical Float	Low	No	None	High
External Mechanical Float	Low to Medium	No	None	High
Timer Drain – Solenoid Valve	Low	Yes	Electrical	High to Medium
Timer Drain – Ball Valve	Medium to High	Yes	Electrical	Low
Electronic Level Sensing	Medium to High	No	Electrical	Low to Medium
Pneumatic Level Sensing	High	No	Pneumatic	Low

Appendix:

To obtain the dew point temperature expected if the gas were expanded to a lower pressure proceed as follows:

1. Using "dew point at pressure," locate this temperature on scale at right hand side of chart.
2. Read horizontally to intersection of curve corresponding to the operating pressure at which the gas was dried.
3. From that point read vertically downward to curve corresponding to the expanded lower pressure.
4. From that point read horizontally to scale on right hand side of chart to obtain dew point temperature at the expanded lower pressure.
5. If dew point temperatures of atmospheric pressure are desired, after step 2, above read vertically downward to scale at bottom of chart which gives "Dew Point at Atmospheric Pressure."

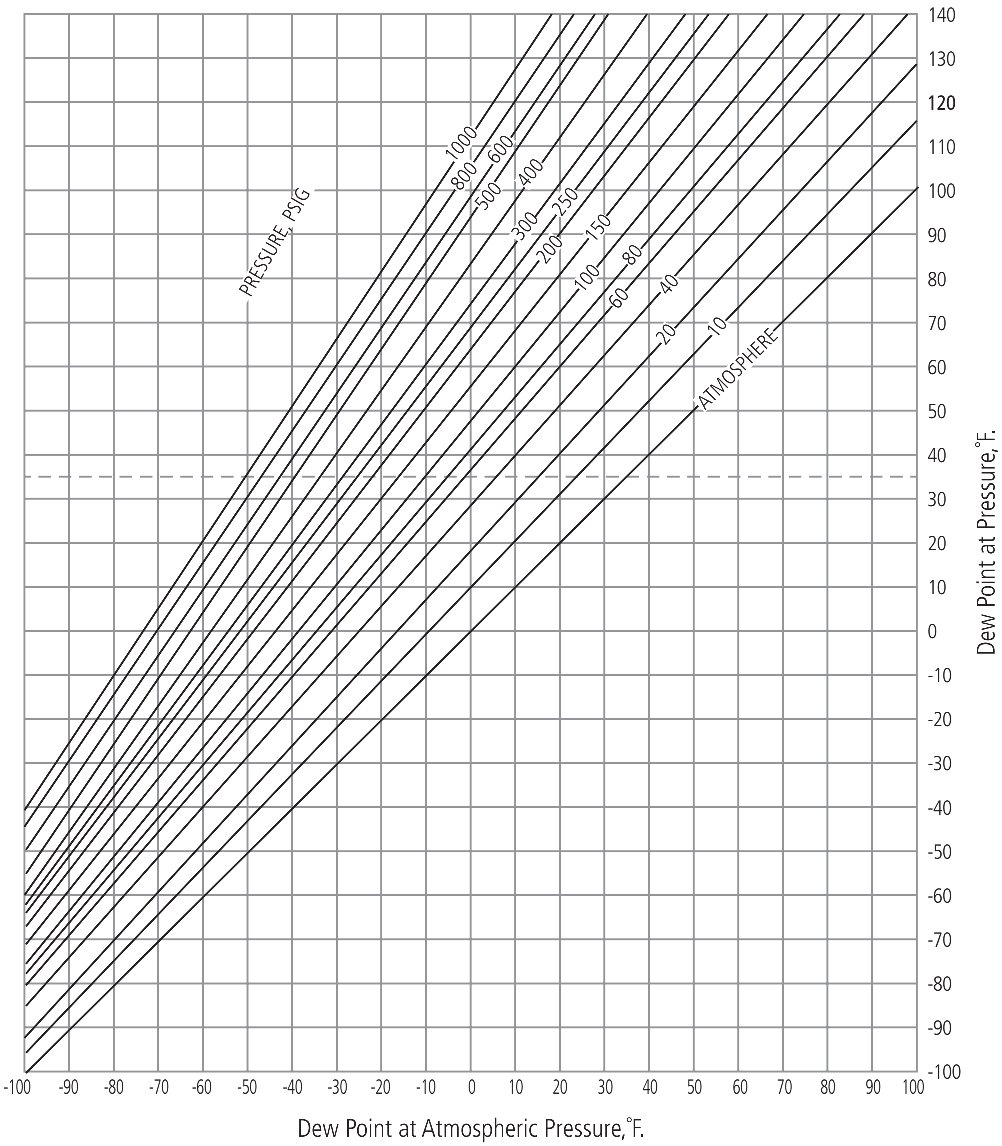


Table 3.1: Dew Point Conversion

°F	Grains per cu. ft.	°F	Grains per cu. ft.	°F	Grains per cu. ft	°F	Grains per cu. ft.
-60	.01470	-15	.218	+30	1.935	+75	9.356
-59	.01573	-14	.234	+31	2.023	+76	9.749
-58	.01677	-13	.243	+32	2.113	+77	9.962
-57	.01795	-12	.257	+33	2.194	+78	10.38
-56	.01914	-11	.270	+34	2.279	+79	10.601
-55	.02047	-10	.285	+35	2.366	+80	11.04
-54	.02184	-9	.300	+36	2.457	+81	11.27
-53	.02320	-8	.316	+37	2.550	+82	11.75
-52	.02485	-7	.332	+38	2.646	+83	11.98
-51	.02650	-6	.350	+39	2.746	+84	12.49
-50	.02826	-5	.370	+40	2.849	+85	12.73
-49	.03004	-4	.389	+41	2.955	+86	13.27
-48	.03207	-3	.411	+42	3.064	+87	13.53
-47	.03412	-2	.434	+43	3.177	+88	14.08
-46	.03622	-1	.457	+44	3.294	+89	14.36
-45	.03865	0	.481	+45	3.414	+90	14.94
-44	.04111	+1	.505	+46	3.539	+91	15.23
-43	.04375	+2	.529	+47	3.667	+92	15.84
-42	.04650	+3	.554	+48	3.800	+93	16.15
-41	.04947	+4	.582	+49	3.936	+94	16.79
-40	.05583	+5	.640	+50	4.076	+95	17.12
-39	.05583	+6	.639	+51	4.222	+96	17.80
-38	.05922	+7	.671	+52	4.372	+97	18.44
-37	.06292	+8	.704	+53	4.526	+98	18.85
-36	.06677	+9	.739	+54	4.685	+99	19.24
-35	.07085	+10	.776	+55	4.849	+100	19.95
-34	.07517	+11	.816	+56	5.016	+101	20.33
-33	.07962	+12	.856	+57	5.191	+102	21.11
-32	.08447	+13	.898	+58	5.370	+103	21.54
-31	.08942	+14	.941	+59	5.555	+104	22.32
-30	.09449	+15	.986	+60	5.745	+105	22.75
-29	.09982	+16	1.032	+61	5.941	+106	23.60
-28	.10616	+17	1.080	+62	6.142	+107	24.26
-27	.11258	+18	1.128	+63	6.349	+108	24.93
-26	.11914	+19	1.181	+64	6.563	+109	25.41
-25	.12611	+20	1.235	+65	6.782	+110	26.34
-24	.13334	+21	1.294	+66	7.069	+111	27.07
-23	.14113	+22	1.355	+67	7.241	+112	27.81
-22	.14901	+23	1.418	+68	7.480	+113	28.57
-21	.15739	+24	1.483	+69	7.726	+114	29.34
-20	.166	+25	1.551	+70	7.980	+115	30.14
-19	.174	+26	1.623	+71	8.240	+116	30.95
-18	.184	+27	1.697	+72	8.508	+117	31.79
-17	.196	+28	1.773	+73	8.782	+118	32.63
-16	.207	+29	1.853	+74	9.153	+119	33.51

7000 grains moisture = 1 pound.

Table 3.2: Moisture Content of Saturated Air at Various Temperatures

	Temperature, °F									
%RH	35	40	50	60	70	80	90	100	110	120
5	.0019	.0024	.0035	.0050	.0071	.0099	.0136	.0186	.0250	.0332
10	.0039	.0047	.0069	.0100	.0142	.0198	.0273	.0372	.0501	.0668
15	.0058	.0071	.0104	.0150	.0213	.0298	.0411	.0561	.0755	.1007
20	.0078	.0095	.0139	.0200	.0284	.0398	.0549	.0750	.1012	.1351
25	.0098	.0119	.0174	.0251	.0356	.0498	.0689	.0940	.1270	.1699
30	.0117	.0143	.0209	.0301	.0427	.0599	.0828	.1132	.1531	.2051
35	.0137	.0166	.0244	.0351	.0499	.0700	.0969	.1325	.1794	.2407
40	.0156	.0190	.0279	.0402	.0571	.0801	.1110	.1519	.2060	.2768
45	.0176	.0214	.0314	.0453	.0644	.0903	.1251	.1715	.2328	.3133
50	.0195	.0238	.0349	.0503	.0716	.1005	.1394	.1912	.2598	.3502
55	.0215	.0262	.0384	.0554	.0789	.1107	.1537	.2110	.2871	.3876
60	.0235	.0286	.0419	.0605	.0861	.1210	.1681	.2310	.3146	.4254
65	.0254	.0310	.0454	.0656	.0934	.1313	.1825	.2511	.3424	.4637
70	.0274	.0334	.0490	.0707	.1007	.1417	.1970	.2713	.3705	.5025
75	.0294	.0358	.0525	.0758	.1081	.1521	.2116	.2917	.3988	.5418
80	.0313	.0382	.0560	.0810	.1154	.1625	.2263	.3122	.4273	.5816
85	.0333	.0406	.0596	.0861	.1228	.1730	.2410	.3328	.4562	.6219
90	.0353	.0430	.0631	.0913	.1302	.1835	.2559	.3536	.4853	.6627
95	.0372	.0454	.0666	.0964	.1376	.1940	.2707	.3745	.5147	.7041
100	.0392	.0478	.0702	.1016	.1450	.2046	.2857	.3956	.5443	.7460

Table 3.3: Moisture Content of Air in Gallons per 1000 Cubic Feet

	Temperature, °F									
PSIG	35	40	50	60	70	80	90	100	110	120
0	.0392	.0479	.0702	.1016	.1450	.2046	.2857	.3956	.5443	.7460
10	.0233	.0283	.0416	.0600	.0854	.1200	.1667	.2290	.3119	.4217
20	.0165	.0201	.0295	.0426	.0605	.0849	.1176	.1612	.2186	.2939
30	.0128	.0156	.0229	.0330	.0469	.0657	.0909	.1243	.1682	.2256
40	.0105	.0128	.0187	.0269	.0383	.0536	.0741	.1012	.1367	.1830
50	.0089	.0108	.0158	.0228	.0323	.0452	.0625	.0853	.1152	.1540
60	.0077	.0093	.0137	.0197	.0280	.0391	.0540	.0737	.0995	.1329
70	.0068	.0082	.0121	.0174	.0246	.0345	.0476	.0649	.0876	.1169
80	.0060	.0074	.0108	.0155	.0220	.0308	.0425	.0580	.0782	.1043
90	.0055	.0067	.0098	.0140	.0199	.0279	.0385	.0524	.0706	.0942
100	.0050	.0061	.0089	.0128	.0182	.0254	.0351	.0478	.0644	.0858
110	.0046	.0056	.0082	.0118	.0167	.0234	.0323	.0439	.0592	.0789
120	.0043	.0052	.0076	.0109	.0155	.0216	.0298	.0407	.0548	.0729
130	.0040	.0048	.0071	.0102	.0144	.0201	.0278	.0378	.0509	.0678
140	.0037	.0045	.0066	.0095	.0135	.0188	.0260	.0354	.0476	.0634
150	.0035	.0042	.0062	.0089	.0126	.0177	.0244	.0332	.0447	.0595
160	.0033	.0040	.0058	.0084	.0119	.0167	.0230	.0313	.0421	.0561
170	.0031	.0038	.0055	.0080	.0113	.0158	.0217	.0296	.0398	.0530
180	.0029	.0036	.0052	.0075	.0107	.0149	.0206	.0281	.0378	.0503
190	.0028	.0034	.0050	.0072	.0102	.0142	.0196	.0267	.0359	.0478
200	.0027	.0032	.0048	.0068	.0097	.0136	.0187	.0254	.0342	.0455

Table 3.4: Moisture Content in Gallons of 1000 Standard Cubic Feet of Saturated Air at the Temperature and Pressure Indicated. Standard Cubic Feet Defined at 14.7 psia and 60°F.