



ENVIRONMENTAL PROTECTION AGENCY

APTI 413: Control of Particulate Matter Emissions

Student Manual:

Chapter 1

APTI: 413 CONTROL OF PARTICULATE MATTER EMISSIONS, 5TH EDITION

Student Manual



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**The National Association of Clean Air Agencies (NACAA) represents air pollution control agencies in 53 states and territories and over 165 major metropolitan areas across the United States.*

State and local air pollution control officials formed NACAA (formerly STAPPA/ALAPCO) over 30 years ago to improve their effectiveness as managers of air quality programs. The associations serve to encourage the exchange of information among air pollution control officials, to enhance communication and cooperation among federal, state, and local regulatory agencies, and to promote good management of our air resources.

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Chapter
1

This chapter will take approximately 2.5 hours to complete.

Basic Concepts

This chapter distinguishes the basic concept used to regulate particulate matter emissions by examining various control concepts and methods.

OBJECTIVES

Terminal Learning Objective

At the end of this overview chapter, the student will be able to understand basic science concepts necessary for the control of particulate matter emissions.

Enabling Learning Objectives

- 1.1 Distinguish between two types of gas temperature.
- 1.2 Distinguish between three types of gas pressures.
- 1.3 Calculate the molecular weight of gas mixtures.
- 1.4 Identify the five parameters in the Ideal Gas Law.
- 1.5 Distinguish between the two types of viscosity.
- 1.6 Define two types of Reynolds Number.
- 1.7 Calculate Dew Point

Checks on Learning
End of Chapter Review

1.1 Gas Temperature

There are several scales available for measuring temperature. The Fahrenheit scale and the Celsius or Centigrade scale, both of which are based on the properties of water, are the two most commonly used scales for measuring temperatures. As shown below in Figure 1-1, the Fahrenheit scale separates the freezing and boiling points into 180-degree units. The Fahrenheit scale sets the freezing temperature of water at 32°F, and the normal boiling temperature of water at 212°F. The Celsius scale separates the freezing and boiling points into 100-degree units. The Celsius scale sets the freezing temperature of water at 0°C and the normal boiling temperature at 100°C. The following relationships convert one scale to another:

(1-1)

$$^{\circ}F = 1.8^{\circ}C + 32$$

(1-2)

$$^{\circ}C = \frac{^{\circ}F - 32}{1.8}$$

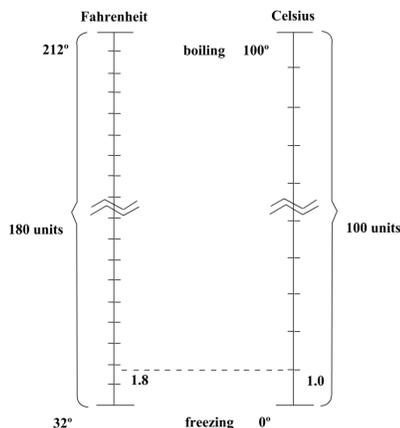


Figure 1.1 In this course, the USEPA standard temperature of 68°F will be used

Absolute Temperature

Fahrenheit and Celsius scales can be used in daily practices, but both create difficulties when forming temperature ratios or when taking roots and powers of negative temperatures. The best resolve to these situations is an absolute temperature scale, which is a scale with zero set as its lowest value. Experiments with ideal gases have shown that, under constant pressure, for each change in Fahrenheit degree below 32°F the volume of gas changes 1/491.69. Similarly, for each Celsius degree below 0°C the volume changes 1/273.16. Therefore, if this change in volume per temperature degree is constant, then theoretically the volume of gas would become zero at 491.69-Fahrenheit degrees below 32°F, or at -459.69°F. On the Celsius scale, this condition occurs at 273.16-Celsius degrees below 0°C or at a temperature of -273.16°C.

Absolute temperatures determined by using Fahrenheit units are expressed as degrees Rankine (°R). Absolute temperatures determined by using Celsius units are expressed as Kelvin (K). As shown below in Figure 2-2 the following approximate relationships convert one scale to the other:

(1-3 & 1-4)

$$^{\circ}\text{R} = ^{\circ}\text{F} + 460$$

$$\text{K} = ^{\circ}\text{C} + 273$$

Standard Temperature

There is not a common temperature that is recognized by all groups. One particular temperature of interest is standard temperature. USEPA has *two* standard temperatures, one for air monitoring, and one for all other applications. The standard temperatures used by various groups are listed in Table 1-1.

Table 1-1 Standard Temperatures	
Group	Tstd
USEPA (General)	68°F (20°C)
USEPA (Air monitoring)	77°F (25°C)
Industrial hygiene	70°F (21.1°C)
Combustion	60°F (15.6°C)
Science	32°F (0°C)

Example 1-1

The gas temperature in the stack of a wet scrubber system is 130°F. What is the absolute temperature in Rankine and Kelvin?

Solution Absolute Temp. °R = 460°F + 130°F = 590°R

 Absolute Temp. K = $\frac{590^{\circ}\text{R}}{1.8} = 327.8\text{K}$

1.2 Gas Pressure

A body may be subjected to three kinds of stress: shear, compression, and tension. Fluids are unable to withstand tension stress; therefore, they are subject only to shear and compression stress. Unit compressive stress in a fluid is termed pressure and is expressed as force per unit area (e.g., lb_f/in² and Newtons/m²). Pressure is equal in all directions at a point within a volume for fluid and acts perpendicular to a surface.

Barometric Pressure

Barometric pressure and atmospheric pressure are synonymous. These pressures are measured with a barometer and are usually expressed as inches or millimeters of mercury (Hg). Standard barometric pressure is internationally recognized and is the average atmospheric pressure at sea level, 45°N latitude and at 35°F. Standard barometric pressure is equivalent to a pressure of 14.696 pounds force per square inch exerted at the base of a column of mercury 29.92 inches high. Other equivalents to standard pressure are listed in Table 1-2. Weather and altitude are responsible for barometric pressure variations.

Table 1-2. Standard Pressure	
Units	Value
Atmosphere (atm)	1
Pounds force per square inch (psi)	14.70
Inches of mercury (in Hg)	29.92
Millimeters of mercury (mm Hg)	760
Feet of water column (ft WC)	33.92
Inches of water column (in WC)	407
Kilopascals (kPa)	101.3
Millibars (mb)	1013

Gauge Pressure

The pressure inside an air pollution control system is termed the gauge or static pressure and is measured relative to the prevailing atmospheric pressure, as shown in Figure 1-2. If the system pressure is greater than the atmospheric pressure, then the gauge pressure is expressed as a positive value. If the system pressure is smaller, then the gauge pressure is expressed as a negative value. The term vacuum designates a negative gauge pressure. Gauge or static pressures in air pollution systems are usually expressed in inches of water column (in WC).

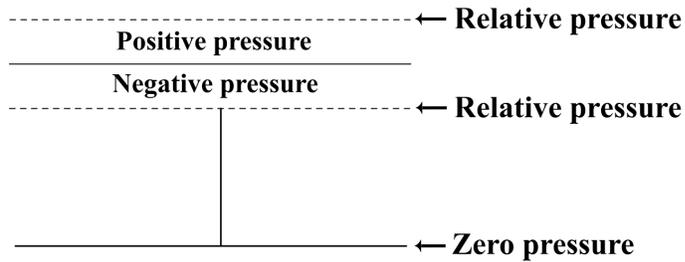


Figure 1-2. Definition of positive and negative gauge pressures.



Absolute pressure is the algebraic sum of the atmospheric pressure and the gauge pressure.

Absolute Pressure

The gauge pressures commonly used in reference to air pollution control systems share an attribute that causes difficulties in the use of normal temperature scales—they can have negative values. As a result, calculations involving pressure ratios and roots and powers of pressure must use absolute pressure. Absolute pressure is the algebraic sum of the atmospheric pressure and the gauge pressure:

(1-5)

$$P = P_b + P_g$$

Where

P = absolute pressure

P_b = barometric or atmospheric pressure

P_g = gauge pressure

Example 1-2

An air pollution control device has an inlet static pressure of -25 in WC. What is the absolute static pressure at the inlet of the air pollution control device if the barometric pressure at the time is 29.85 in Hg?

Solution

Convert the barometric pressure units to in WC :

$$P_b = 29.85 \text{ in Hg} \left(\frac{407 \text{ in WC}}{29.92 \text{ in Hg}} \right) = 406 \text{ in WC}$$

Add the barometric and gauge (static) pressures :

$$P = 406 \text{ in WC} + (-25 \text{ in WC}) = 381 \text{ in WC}$$

1.3 Molecular Weight and the Mole

The molecular weight of a compound is the sum of the atomic weights of all the atoms in the molecule. The atomic weight of an atom is based on an arbitrary scale of the relative masses of the elements, usually based on a carbon value of 12. The chemical identity of an atom is determined by the number of protons in its nucleus and is called the atomic number. Values of atomic number and atomic weight can be found in a Periodic Table of Elements.



Periodic Table

<http://education.jlab.org/beamsactivity/6thgrade/tableofelements/stu01.1.html>

Mixtures of molecules do not have a true molecular weight; however, they do have an apparent molecular weight that can be calculated from the composition of the mixture:

(1-6)

$$MW_{\text{mixture}} = \sum_{i=1}^n \chi_i MW_i$$

where χ_i is the mole fraction of component i and MW_i is its molecular weight. Properties of a contaminated gas can be approximated by the properties of air, which is itself a mixture of molecules. The apparent molecular weight of air is 28.95, or approximately 29.



Moles can be expressed in terms of any mass unit: gram-moles, kilogram-moles, ounce-moles, pound-moles and ton-moles

A mole is a mass of material that contains a certain number of molecules. Moles can be expressed in terms of any mass unit; thus, e.g., there are gram-moles, kilogram-moles, ounce-moles, pound-moles and ton-moles. The relationship between the different types of moles is the same as the relationship between the corresponding mass units. Thus, there are 1,000 gram-moles in a kilogram-mole, 453.6-gram-moles in a pound-mole, 16 ounce-moles in a pound-mole and 2,000 pound-moles in a ton-mole.

The gram-mole is the mass of material that contains Avogadro's number of molecules, approximately 6.023×10^{23} . The mass of a mole is numerically equal to the molecular weight. For oxygen, which has a molecular weight of 32, there are 32 grams per gram-mole, 32 kilograms per kilogram-mole, and 32 pounds per-pound mole. However, only the gram-mole contains Avogadro's number of molecules. The kilogram-mole contains 1,000 times Avogadro's number of molecules; the pound-mole contains 453.6 times.

1.4 Equation of State

Equations of state relate the pressure, volume, and temperature properties of a pure substance or mixture by semi-theoretical or empirical relationships. Over the range of temperature and pressure usually encountered in air pollution control systems, these values may be related by the ideal or perfect gas law:

(1-7)

$$PV = nRT$$

Where

- P = absolute pressure
- V = gas volume
- n = number of moles
- R = gas constant
- T = absolute temperature

Here, R is referred to as the universal gas constant, and its value depends on the units

of the other terms in the equation. Values of R include:

$$10.73 \text{ psia} \cdot \text{ft}^3/\text{lb} - \text{mole} \cdot ^\circ\text{R}$$

$$0.73 \text{ atm} \cdot \text{ft}^3/\text{lb} - \text{mole} \cdot ^\circ\text{R}$$

$$82.06 \text{ atm} \cdot \text{cm}^3/\text{g} - \text{mole} \cdot \text{K}$$

$$8.31 \times 10^3 \text{ kPa} \cdot \text{m}^3/\text{kg} - \text{mole} \cdot \text{K}$$

Volume Correction

A useful relationship can be developed from the ideal gas law by noting that $PV/T = nR$, and that, for a given number of moles of a gas, nR is a constant.

Thus, at two different conditions for the same gas, we may write equation 1-8.

Equation 1-9 allows volumes (or volumetric rates) to be corrected from one set of temperature and pressure conditions to another. One common calculation (1-10) is to convert volumetric flow rate from actual conditions to standard conditions, or vice versa (1-11).



SCFM = standard cubic
feet per minute

ACFM = actual cubic
feet per minute

(1-8)

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

(1-9)

$$V_1 = V_2 \left(\frac{P_2}{P_1} \right) \left(\frac{T_1}{T_2} \right)$$

(1-10)

$$\text{SCFM} = \text{ACFM} \left(\frac{P_{\text{actual}}}{P_{\text{std}}} \right) \left(\frac{T_{\text{std}}}{T_{\text{actual}}} \right)$$

(1-11)

$$\text{ACFM} = \text{SCFM} \left(\frac{P_{\text{std}}}{P_{\text{actual}}} \right) \left(\frac{T_{\text{actual}}}{T_{\text{std}}} \right)$$

Example 1-3 A particulate control system consists of a hood, ductwork, fabric filter, fan, and stack. The total gas flow entering the fabric filter is 8,640 scfm. The gas temperature in the inlet duct is 320°F and the static pressure is -10 in WC. The barometric pressure is 28.30 in Hg. If the inlet duct has inside dimensions of 3 feet by 4 feet, what is the velocity into the fabric filter?

Solution

Convert the static pressure to absolute pressure:

$$P = 28.30 \text{ in Hg} \left(\frac{407 \text{ in WC}}{29.92 \text{ in Hg}} \right) + (-10 \text{ in WC}) = 375 \text{ in WC}$$

Convert the gas temperature to absolute temperature:

$$T_{\text{actual}} = 320^{\circ}\text{F} + 460^{\circ} = 780^{\circ}\text{R}$$

Convert the inlet flow rate to actual conditions:

$$Q_{\text{actual}} = 8,640 \text{ scfm} \left(\frac{780^{\circ}\text{R}}{528^{\circ}\text{R}} \right) \left(\frac{407 \text{ in WC}}{375 \text{ in WC}} \right) = 13,853 \text{ acfm}$$

Calculate the velocity:

$$V = \frac{13,853 \text{ ft}^3/\text{min}}{3\text{ft} \cdot 4\text{ft}} = 1,154 \text{ ft}/\text{min}$$

Molar Volume

The ideal gas law can also be rearranged to calculate the volume occupied by a mole of gas, called the molar volume:

(1-12)

$$\frac{V}{n} = \frac{RT}{P}$$

Example 1-4

What is the molar volume of an ideal gas at 68°F and 1 atm? At 200°F and 1 atm?

Solution

At 68°F and 1 atm:

$$\frac{V}{n} = \frac{RT}{P} = \frac{\left(0.73 \frac{\text{atm} \cdot \text{ft}^3}{\text{lb} \cdot \text{mole} \cdot ^{\circ}\text{R}} \right) (528^{\circ}\text{R})}{1 \text{ atm}} = 385.4 \text{ ft}^3/\text{lb} \cdot \text{mole}$$

At 200°F and 1 atm:

$$\frac{V}{n} = \frac{RT}{P} = \frac{\left(0.73 \frac{\text{atm} \cdot \text{ft}^3}{\text{lb} \cdot \text{mole} \cdot ^{\circ}\text{R}} \right) (660^{\circ}\text{R})}{1 \text{ atm}} = 481.8 \text{ ft}^3/\text{lb} \cdot \text{mole}$$

or

$$\frac{V}{n} = 385.4 \left(\frac{660^{\circ}\text{R}}{528^{\circ}\text{R}} \right) = 481.8 \text{ ft}^3/\text{lb} \cdot \text{mole}$$

Gas Density

DESIGN CUSTOMIZATION

Finally, we can use the ideal gas law to estimate gas density. Density is the ratio of the mass of a material to the volume that material occupies. For accurate values, gas densities should be determined from reference texts. However, an estimate of the gas density can be determined from the ideal gas law. Recognizing that the number of moles is given by mass (m) divided by molecular weight (MW), the ideal gas law may be written:



(1-13)

$$PV = \left(\frac{m}{MW} \right) RT$$

Gas Viscosity
increases with an
increase in
temperature.

The gas density (ρ) can then be estimated from:

(1-14)

$$\rho = \frac{m}{v} = \frac{P \cdot MW}{RT}$$

Density can also be estimated from the molecular weight and molar volume:

$$\rho = \left(\frac{MW}{385.4} \right) \left(\frac{528}{T} \right) \left(\frac{P}{29.92} \right)$$

Where

P = absolute pressure (in Hg)

T = absolute temperature ($^{\circ}R$)

1.5 Viscosity

Viscosity is the property associated with a fluid resistance to flow. Viscosity is the result of two phenomena: (1) intermolecular cohesive forces and (2) momentum transfer between flowing strata caused by molecular agitation perpendicular to the direction of motion. Between adjacent strata of a moving Newtonian fluid, a shearing stress, σ , occurs that is directly proportional to the velocity gradient or shear rate, Γ (see Figure 1-3). This is expressed in the equation:

(1-16)

$$\sigma = \mu \Gamma = \mu \frac{dv}{dy}$$

Where

σ = shear stress

μ = proportionality constant

Γ = shear rate or velocity gradient (dv/dy)

The proportionality constant, μ , is called the coefficient of viscosity, the absolute viscosity or merely viscosity. It should be noted that the pressure does not appear in Equation 1-16, indicating that the shear stress and viscosity are independent of pressure. Actually, viscosity increases very slightly with pressure, but this variation is negligible in most engineering calculations.

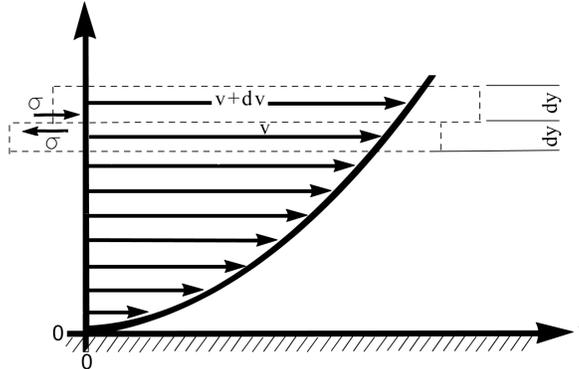


Figure 1-3. Shearing stress in a moving fluid



Liquid Viscosity
decreases with an
increase in
temperature.

Liquid Viscosity

In a liquid, transfer of momentum between strata flowing at slightly different velocities is small compared to the cohesive forces between molecules. Hence, viscosity in liquids is predominantly the result of intermolecular cohesion. Because forces of cohesion decrease rapidly with an increase in temperature, liquid viscosity decreases with an increase in temperature.

Gas Viscosity

In a gas, the molecules are too far apart for intermolecular cohesion to be effective. Thus, the viscosity in gases is predominantly the result of an exchange of momentum between flowing strata caused by molecular transfer. Since molecular motion increases as temperature increases, gas viscosity increases with an increase in temperature.

The viscosity of air at any temperature may be estimated from:

(1-17)

$$\frac{\mu}{\mu_{\text{ref}}} = \left(\frac{T}{T_{\text{ref}}} \right)^{0.768}$$

Where

- μ = absolute viscosity
- μ_{ref} = absolute viscosity at reference temperature
- T = absolute temperature
- T_{ref} = reference absolute temperature

The viscosity of air containing other gases important in air pollution control applications can also be estimated from:

(1-18)

$$\mu = 51.05 + 0.207T + 3.24 \times 10^{-5} T^2 - 74.14x + 53.417y$$

Where

- μ = absolute viscosity (micropoise)
- T = absolute temperature
- x = water vapor content (fraction)
- y = oxygen content (fraction)

The viscosity of air at 68°F is 1.21×10^{-5} lb_m/ft · sec or 1.8×10^{-4} g/cm·sec



Dimensionless numbers

<http://www.earthmatrix.com/extract83.html#temperature>.

http://en.wikipedia.org/wiki/Dimensionless_numbers

Kinematic Viscosity

The ratio of the absolute viscosity to the density of a fluid, known as kinematic viscosity, often appears in dimensionless numbers, such as the Reynolds Number. Kinematic viscosity is defined according to the following relationship and is used to simplify calculations:

(1-19)

$$v = \frac{\mu}{\rho}$$

Where

- v = kinematic viscosity
- μ = absolute viscosity
- ρ = density viscosity



Reynolds Number

Is the ratio of inertial forces to viscous forces in a flowing fluid.

Reynolds Number

Reynolds Number is the ratio of inertial forces to viscous forces in a flowing fluid. A typical inertial force per unit volume of fluid is $\rho v^2/L$. A typical viscous force per unit volume of fluid is $\mu v/L^2$. The first expression divided by the second provides the dimensionless ratio known as the Reynolds Number:

(1-20)

$$Re = \frac{Lv\rho}{\mu}$$

Where

- Re = Reynolds Number
- L = characteristics system dimension
- v = fluid velocity
- ρ = fluid density
- μ = fluid viscosity

The linear dimension, L , is a length characteristic of the flow system. It is equal to four times the mean hydraulic radius, which is the cross-sectional area divided by the wetted perimeter. Thus, for a circular pipe, L is the pipe diameter, D , and the Reynolds Number (sometimes termed the *Flow Reynolds Number*) takes the form:

(1-21)

$$Re = \frac{Dv\rho}{\mu}$$

Reynolds Number in this form is used to distinguish between laminar and turbulent flow. In laminar flow, the fluid is constrained to motion in layers, or laminae, by the action of viscosity. These layers of fluid move in parallel paths that remain distinct from one another. Laminar flow occurs when the Reynolds Number is less than about 2,000. In turbulent flow, the fluid is not restricted to parallel paths but moves forward in a random, chaotic manner. Fully turbulent flow occurs when the Reynolds Number is greater than about 3,000. Between Reynolds Numbers of 2,000 and 3,000, the flow may be laminar or turbulent, depending on the flow system conditions. Pipe or duct vibration, for example, can cause turbulent conditions to exist at Reynolds Numbers significantly below 3,000. It is worth noting that, primarily because of the size, flow in air pollution control equipment is always turbulent. Laminar conditions are present only in the very thin boundary layers that form near surfaces.



Particle Motion

Most particle motion in air pollution control devices occurs in the Stokes and Transitional Regions.

A form of Reynolds Number that is of greater interest in this course is the *Particle Reynolds Number*. Here, the characteristic system dimension is the particle diameter, d_p , and the velocity, v_p , is the particle velocity relative to the gas stream:

(1-22)

$$Re_p = \frac{D_p v_p \rho}{\mu}$$

Particle Reynolds Number is used to characterize flow conditions when particles move through or with a flowing fluid. Particle Reynolds Numbers less than about one indicate laminar conditions and define what is commonly termed the *Stokes Region*. Values over about 1,000 indicate turbulent conditions and define what is commonly termed the *Newton Region*. Particle Reynolds Numbers between 1 and 1,000 indicate transitional conditions. Most particle motion in air pollution control devices occurs in the Stokes and Transitional Regions.

Example 1-5 Calculate the Particle Reynolds Number for a $2\mu\text{m}$ diameter particle moving through 10°C still air at a velocity of 6 m/sec.

Solution From Appendix B, the density of air at 20°C is $1.20 \times 10^{-3} \text{ g/cm}^3$ and the viscosity is $1.80 \times 10^{-4} \text{ g/cm(sec)}$

Estimate the gas density at 10°C.

$$\rho = 1.20 \times 10^{-3} \left(\frac{293\text{K}}{283\text{K}} \right) = 1.24 \times 10^{-3} \text{ g/cm}^3$$

Estimate the gas viscosity at 10°C.

$$\mu = 1.80 \times 10^{-4} \left(\frac{293\text{K}}{283\text{K}} \right)^{0.768} = 1.75 \times 10^{-4} \text{ g/cm} \cdot \text{sec}$$

Calculate Particle Reynolds Number :

$$\text{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(2 \times 10^{-4} \text{ cm})(6 \times 10^2 \text{ cm/sec})(1.24 \times 10^{-3} \text{ g/cm}^3)}{1.75 \times 10^{-4} \text{ g/cm} \cdot \text{sec}}$$

Example 1-6 Calculate the Particle Reynolds Number for a gas stream moving through a 200 cm diameter duct at a velocity of 1,500 cm/sec. Assume that the particles are moving at the same velocity as the gas stream and are not settling due to gravity. Assume a gas temperature of 20°C and standard pressure.

Solution Since there is no difference in velocity between the gas stream and the particle, the Particle Reynolds Number is zero.

The Flow Reynolds Number is:

$$\text{Re} = \frac{Dv\rho}{\mu} = \frac{(200\text{cm})(1,500\text{cm/sec})(1.20 \times 10^{-3} \text{ g/cm}^3)}{1.80 \times 10^{-4} \text{ g/cm} \cdot \text{sec}} = 2.00 \times 10^6$$

1.7 Calculation of Dew Point

Many gas streams that must be treated for particulate emissions may also contain significant amounts of water vapor or another condensable component. In most cases, for example, if particulate control is to be accomplished using fabric filters, it is necessary that the gas stream be maintained at a temperature sufficient to prevent the water or other component from condensing as condensation will cause the particulate matter to collect on the filters as a paste that cannot be easily cleaned.

The temperature at which condensation occurs is also known as the dew point temperature. At the dew point temperature the partial pressure of the condensable component is equal to its vapor pressure



Why is Dew Point important?

This condensate can form paste on fabric filters making them unusable

$$P_i = P^* = y_i P$$

Where

P_i = partial pressure of the condensable component
 P^* = vapor pressure of the condensable component
 y_i = mole fraction of the condensable component in the gas
 P = total pressure

Vapor pressure as a function of temperature can be obtained from the Antoine equation.

$$\log_{10} P^* = A - \frac{B}{T + C}$$

Where

P^* = vapor pressure, $\mu\text{m Hg}$
 T = Temperature, $^{\circ}\text{C}$
 A , B , and C are unique constants for each component

Tables of Antoine constants may be found in numerous standard references and is offered in Appendix C.

For water, values of the vapor pressure as a function of temperature may be obtained directly from Vapor Pressure Tables (available widely on the internet).



Example 1-7 The mol fraction of water in the stack gas from a combustion process contains 14 mol% water vapor. What is the dew point temperature if the total pressure is 1 atm? The Antoine constants for water are:

$$\begin{aligned} A &= 8.10765 \\ B &= 1750.286 \\ C &= 235.000 \end{aligned}$$

Solution At the dew point temperature:

$$P^* = P_i = y_i P = 0.14 (1) = 0.14 \text{ atm or } 106.4 \text{ mmHg}$$

From the Antoine equation:

$$\log_{10} P^* = 8.10765 - \frac{1750.286}{T + 235.000}$$

Solve for T to obtain:

$$T = 53^{\circ}\text{C}$$

Where to see
Steam Tables
<http://pye.dyndns.org/freesteam/>

Review Questions



1. How does the particle Reynolds number change when the gas temperature is increased?
 - a. Increases
 - b. Decreases
 - c. Remains unchanged

2. How does the gas viscosity change as the temperature is increased?
 - a. Increases
 - b. Decreases
 - c. Remains unchanged

3. Flow in air pollution control equipment is always turbulent, and Laminar conditions are only present in the very thin boundary layers that form near surfaces.
 - a. True
 - b. False

4. When Particle Reynolds Numbers indicate laminar conditions that exist within the
 - a. Flow Reynolds Region
 - b. Newton Region
 - c. Stokes Region
 - d. Viscous Region

Review Question Answers

1. How does the particle Reynolds number change when the gas temperature is increased? (see page 10)

b. Decreases

2. How does the gas viscosity change as the temperature is increased? (see page 9)

a. Increases

3. Flow in air pollution control equipment is always turbulent, and Laminar conditions are only present in the very thin boundary layers that form near surfaces. (page 10)

a. True

4. When Particle Reynolds Numbers indicate laminar conditions that exist within the

c. Stokes Region



Review Problems

1. The flows from Ducts A and B are combined into a single Duct C. The flow rate in Duct A is 5,000 scfm, the gas stream temperature is 350°F and the static pressure is -32 in WC. The flow rate in Duct B is 4,000 acfm, the gas stream temperature is 400°F and the static pressure is -35 in WC. What is the flow rate in Duct C? Assume a barometric pressure of 29.15 in Hg. (see page 6)
2. Calculate the Particle Reynolds Numbers for the following particles. Assume a gas temperature of 20°C and a pressure of 1 atm. (see page 10)
 - a. 10 μm particle moving at 1 ft/sec relative to the gas stream
 - b. 10 μm particle moving at 10 ft/sec relative to the gas stream
 - c. 100 μm particle moving at 1 ft/sec relative to the gas stream
 - d. 100 μm particle moving at 10 ft/sec relative to the gas stream

Review Problem Solutions

1. The flows from Ducts A and B are combined into a single Duct C. The flow rate in Duct A is 5,000 scfm, the gas stream temperature is 350°F and the static pressure is -32 in WC. The flow rate in Duct B is 4,000 acfm, the gas stream temperature is 400°F and the static pressure is -35 in WC. What is the flow rate in Duct C? Assume a barometric pressure of 29.15 in Hg. (see page 6)

Solution

Calculate the absolute pressure in Duct B :

$$P = 29.15 \text{ in Hg} \left(\frac{407 \text{ in WC}}{29.92 \text{ in Hg}} \right) + (-35 \text{ in WC}) = 361.5 \text{ in WC}$$

Convert the flow in Duct B to standard conditions :

$$Q_B = 4,000 \text{ acfm} \left(\frac{528^\circ\text{R}}{860^\circ\text{R}} \right) \left(\frac{361.5 \text{ in WC}}{407 \text{ in WC}} \right) = 2,181 \text{ scfm}$$

Combine flows :

$$Q_C = 5,000 \text{ scfm} + 2,181 \text{ scfm} = 7,181 \text{ scfm}$$

2. Calculate the Particle Reynolds Numbers for the following particles. Assume a gas temperature of 20°C and a pressure of 1 atm. (see page 10)

- 10 μm particle moving at 1 ft/sec relative to the gas stream
- 10 μm particle moving at 10 ft/sec relative to the gas stream

Solution a & b

$$Re_p = \frac{d_p v_p \rho}{\mu} = \frac{(10 \times 10^{-4} \text{ cm}) \left((1.0 \text{ ft/sec}) \left(\frac{30.48 \text{ cm}}{\text{ft}} \right) \right) \left(1.20 \times 10^{-3} \frac{\text{g}}{\text{cm}^3} \right)}{1.80 \times 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{sec}}} = 0.203$$

$$Re_p = \frac{d_p v_p \rho}{\mu} = \frac{(10 \times 10^{-4} \text{ cm}) \left((10.0 \text{ ft/sec}) \left(\frac{30.48 \text{ cm}}{\text{ft}} \right) \right) \left(1.20 \times 10^{-3} \frac{\text{g}}{\text{cm}^3} \right)}{1.80 \times 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{sec}}} = 2.032$$

- 100 μm particle moving at 1 ft/sec relative to the gas stream
- 100 μm particle moving at 10 ft/sec relative to the gas stream

Solution c & d

$$\text{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(100 \times 10^{-4} \text{ cm}) \left[(1.0 \text{ ft/sec}) \left(\frac{30.48 \text{ cm}}{\text{ft}} \right) \right] (1.20 \times 10^{-3} \text{ g/cm}^3)}{1.80 \times 10^{-4} \text{ g/cm} \cdot \text{sec}} = 2.03$$

$$\text{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(100 \times 10^{-4} \text{ cm}) \left[(10.0 \text{ ft/sec}) \left(\frac{30.48 \text{ cm}}{\text{ft}} \right) \right] (1.20 \times 10^{-3} \text{ g/cm}^3)}{1.80 \times 10^{-4} \text{ g/cm} \cdot \text{sec}} = 20.3$$



References

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