2013 Western Gas Measurement Short Course
Reno, NV

# INTRODUCTION TO THE BASIC GAS LAWS

ROBERT BENNETT
FIELD SERVICES
ELSTER METER SERVICES

## INTRODUCTION

Science interprets nature in terms of matter and energy. Energy is defined as the capacity to do work. There are many types of energy such as heat energy, electrical energy, chemical energy, kinetic energy (energy of motion), and potential energy (intrinsic energy of an object due to the position of the object).

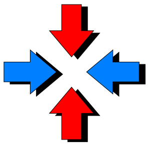
Matter is the material of which the universe is composed and is defined as anything that occupies space and has mass. There are three normal states of matter - solid, liquid, and gas. Under certain conditions, most substances can be made to exist in any of the three states, i.e. water as steam, liquid, or ice.

Solid matter is rigid, generally crystalline, and will exhibit a definite shape. Liquids will flow, assume the shape of the container they are stored, and considered to maintain a constant volume and density. Gaseous matter is much more difficult to qualify since it consists of widely separated molecules in rapid motion. The comparatively large distances between the molecules make it possible for one gas to accommodate molecules of another gas or be compressed to force the individual molecules closer together. Since the molecules are in constant motion, they will expand to fill any container and strike the walls of the vessel. These myriad impacts result in a pressure.

## NATURAL GAS

Natural gas is a mixture of different types of gases whose final composition is dependent on the area where the gas originated and how it has been scrubbed and mixed with other sources.

## BOYLE’S LAW



Robert Boyle first gave the quantitative relationship between the volume and pressure of a gas in 1662. Boyle's Law states:

If the constant temperature remains constant, the volume of a given mass of gas is inversely proportional to the pressure.

This means that doubling the absolute pressure on a given amount of gas will decrease its volume by half. Mathematically the law is written:

V is proportional to 1/Pressure

Therefore

$$V = k/P$$

$$P \times V = k = \text{Constant}$$

which means:

$P_1 \times V_1 = \text{Constant} = P_2 \times V_2$

where:

$V_1$ = Original Volume

$P_1$ = Original Pressure (psia)

$V_2$ = New Volume

$P_2$ = New Pressure (psia)

For example: Assuming the gas temperature remains constant, what will be the volume of gas at a base pressure of 14.73 psia if the volume of the gas is 10,000 cubic feet at 100 psig? Assume an atmospheric pressure of 14.4 psig.

Using Boyle's Law

$V_1$ = 10,000 cubic feet

$P_1$ = 100 psig + 14.4 psia

= 114.4 psia

Note: Pressures used in any of the Gas Law Equations must always be in psia (Absolute Pressure). To get this pressure, simply add the atmospheric pressure to the gauge pressure. In this case, the atmospheric pressure = 14.4 psia and the gauge pressure is 100 psig, therefore the absolute pressure is the sum of the two or 114.4 psia

$P_2$ = 14.73 psia

Note that this is already an absolute pressure.)

$V_2$ = ?

Boyle's Law $V_1 \times P_1 = V_2 \times P_2$

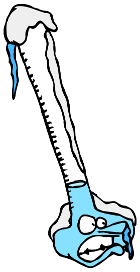
Solving for $V_2$

$V_2 = (V_1 \times P_1)/P_2 =$

$(10{,}000 \times 114.4)/(14.73)$

$V_2$ = 77,665 cubic feet

## CHARLES' LAW



Boyle's Law describes the behavior of gases under conditions of constant temperature. Studies to determine the effect of temperature on the volume and pressure of a gas sample were first undertaken by Jacques Charles (1787) and this work was considerably extended by Joseph Gay-Lussac (1802).

Charles' Law states:

If the pressure remains constant, the volume of a given mass or weight of a gas varies directly with the absolute temperature.

This means that if the absolute temperature is doubled, the volume is also doubled with the pressure remaining constant.

Mathematically expressed, the law is:

V is proportional to T

or $V = k \times T$
Therefore:

$V_1/T_1 = k = \text{Constant} = V_2/T_2$

where:

$T_1$ = Original Temperature

$V_1$ = Original Volume

$T_2$ = New Temperature

$V_2$ = New Volume

As an example: Assuming the pressure remains constant, what will be the volume of gas at $60^0$F if the volume of the gas is 10,000 cubic feet at $50^0$F?

Using Charles' Law:

$T_1 = 50^0F + 460^0 = 510^0R$

Note: As with pressure, the temperatures used in the Gas Laws must be in absolute degrees. To obtain this value, add $460^0$ to any temperatures given in degrees Fahrenheit. This will convert the temperatures to degrees Rankin.

$T_2 = 60^0F + 460^0 = 520^0R$

$V_1$ = 10,000 cubic feet

$V_2$ = ?

Charles Law: $T_1/V_1 = T_2/V_2$

Solving for $V_2$

$V_2 = (V_1 \text{ X } T_2)/T_1 =$

(10,000 X 520)/510

$V_2$ = 10,196 cubic feet

## IDEAL GAS LAW

By combining Boyle's and Charles' laws, it is possible to solve problems in which all three variables - volume, pressure, and temperature - change.

Mathematically expressed:

V is directly proportional to the absolute temperature and inversely proportional to the absolute pressure.

$V = kT/P$

Therefore:

$P_1V_1/T_1 = k = \text{Constant} = P_2V_2/T_2$

Where $P_1$, $V_1$, $T_1$, $P_2$, $V_2$, and $T_2$ have the same significance as before.

Example: 10,000 cubic feet of gas measured at 100 psig and $50^0$F. What would be the volume of this gas at standard conditions of 14.73 psia and $60^0$F? Atmospheric Pressure is 14.4 psia.

$P_1$ = 100 psig + 14.4 psia

= 114.4 psia

$V_1$ = 10,000 cubic feet

$T_1 = 50^0F + 460^0 = 510^0R$

$P_2$ = 14.73 psia

$T_2 = 60^0F + 460^0 = 520^0R$

$V_2 = ?$
Ideal Gas Law:

$(P_1 \times V_1)/T_1 = (P_2 \times V_2)/T_2$

Solving for $V_2$

$V_2 = V_1 \times (P_1/P_2) \times (T_2/T_1) =$

$10{,}000 \times (114.4/14.73) \times (520/510)$

$V_2 = 79{,}187$ cubic feet

## KINETIC THEORY

The Ideal Gas Law correlates observed facts concerning the behavior of "ideal" gases. Real gases obey these laws reasonably well over certain temperatures and pressures depending on the molecular properties of the specific gas being considered.

The theory that offers a model to explain these laws and observations is known as the kinetic theory of gases. This theory postulates the following for an ideal gas:

1. Gases consist of molecules widely separated in space. The total volume of the molecules is negligible in comparison to the volume of the gas as a whole.

2. Gas molecules are in constant, rapid, straight-line motion colliding with each other and their container. The collisions are perfectly elastic with energy being transferred from molecule to molecule but with no net decrease in kinetic energy.

3. Gas molecules translate heat energy into kinetic energy. Although different molecules have different kinetic energies, the average kinetic energy of the molecules depends upon the temperature and increases as temperature increases. The molecules of any gas have the same average kinetic energy at a given temperature.

4. No attractive forces exist between the molecules of an ideal gas.

## IDEAL GAS VERSUS REAL GAS

At higher pressures and lower temperatures, real gases do not quite follow the Ideal Gas Law and another factor must be considered. The reason for the variance from ideal behavior comes from some inaccuracies in the assumptions of the Kinetic Theory.

1. As the pressure is increased, the molecules are forced closer together and the volume of the individual molecules becomes significant when compared to the total volume. Therefore at high pressures, the volume of a real gas is materially larger that that predicted for an ideal gas. There is in effect a repulsive force set up between the individual molecules that comes into bearing as they become closer together.

2. There are some attractive forces between the molecules that tend to draw them closer together than the Ideal Gas Law would indicate. At high temperatures, the molecules move so fast that the attractive forces between the molecules is effectively overcome. But at low temperatures, the forces of attraction pull the molecules together so that the volume observed is less than that indicated by the ideal gas law. The gas becomes more compressible.

Note that these two forces act in opposition to each other and the net result is dependent on the pressure, temperature and composition of the gas.

To compensate for this variance, another factor must be added to the Ideal Gas Laws

$(P \times V)/T = Z \times k$

where Z is a Compressibility Factor.

The Gas Law with Compressibility Factors becomes:

$(P_1xV_1)/(T_1xZ_1) = (P_2xV_2)/(T_2xZ_2)$

Solving for $V_2$:

$V_2=V_1 \times (P_1/P_2) \times (T_2/T_1) \times (Z_2/Z_1)$

To simplify this equation, $Z_2/Z_1$ is defined as the supercompressibility ratio (s). Natural gas is assumed to have a Z factor equal to 1 at 14.73 psia and $60^0$F. Therefore the supercompressibility ratio (s) = $1/Z_1$ where $Z_1$ is the compressibility factor for the gas at flowing conditions.

The equation now becomes:

$V_2 = V_1 \times (P_1/P_2) \times (T_2/T_1) \times s$

The more common term is Supercompressibility Factor which is the Square Root of s, so s = $F_{pv}{}^2$.

Appendix A shows the Supercompressibility Factor ($F_{pv}$) for a 0.6 Specific Gravity Hydrocarbon natural gas versus pressure at constant temperature of 50 Degree F.

Notice how the factor increases as the pressure increases as a result of the molecules being closer together which increases the attractive forces between the individual molecules. The factor increases until the molecules become too close and the repulsive forces start to overcome the attractive forces.

Lower temperatures increase the supercompressibility factor as the molecules are not moving as fast and therefore the attractive forces do not have to overcome the kinetic energy coming from heat.

In the gas industry the gas law equation is normally written as follows

$V_b= V_m \times (P_m/P_b) \times (T_b/T_m) \times (F_{pv})^2$

where:

$V_b$ = Volume of gas at base temperature and base pressure

$V_m$ = Volume registered by metering device

$P_b$ = Absolute Base Pressure (Usually 14.73 PSIA)

$P_m$ = Absolute Metering Pressure (Gauge + Atmospheric Pressures)

$T_b$ = Absolute Base Temperature, = ($60^0$F) + 460 = 520 R)

$T_m$ = Absolute Gas Temperature = Gas Temperature ($^0$F) + 460

$F_{pv}$= Supercompressibility Factor

= $s^{1/2}$

Example: A meter registers 10,000 cubic feet of gas volume at an average pressure of 100 psig and an average temperature of $50^0$F for a period of one month. Calculate the corrected volume of the gas at a base pressure of 14.73 psia and base temperature of $60^0$F. Assume an atmospheric pressure of 14.4 psia.

$V_m$ = Meter Volume = 10,000 cubic feet

$P_b$ = 14.73 psia

$P_m$ = 100 psig = 114.4 psia

100 psig (Gauge pressure) + 14.4 psia (atmospheric pressure) = 114.4 psia

$T_b = 60^0F = 520^0R\ (60^0 + 460^0)$

$T_m = 50^0F = 510^0R\ (50^0F + 460^0)$

$F_{pv}{}^2$ = 1.0171 for natural gas at 100 psig, 0.6 specific gravity and a temperature of $50^0F$

$V_b = 10{,}000 \times (114.4/14.73) \times (520/510) \times (1.0171)$

$V_b$ = 80,539 cubic feet

## MEASUREMENT COMPONENTS

Natural gas measurement centers around solving the Basic Gas Law Equation(s) correctly

$$V_b = V_m \times (P_m/P_b) \times (T_b/T_m) \times (F_{pv})^2$$

In order to accomplish this, there are 4 separate components that need to be considered:

Rate Structure – How will the gas used be billed and under what conditions; i.e. cubic feet, base pressure, and base temperature. This is where $P_b$ and $T_b$ are set.

Metering – Determining the volume used by some means of metering device; i.e. diaphragm meters, rotary meters, turbine meters, ultrasonic meters, orifice meters, etc. These provide the $V_m$.

Regulation – What is the pressure being delivered to the customer and how accurate is that pressure being maintained over the whole range of flows going through the meter. This provides the $P_m$.

Instrumentation – What is the nature of the gas being delivered; i.e. its heating value, its specific gravity, odorization, etc.

## CONCLUSIONS

An understanding of the basic gas laws is essential if a working knowledge is to be obtained in the area of gas measurement. It becomes evident that significant errors can result if gas law principles are not applied to large volume consumers or to those who are delivered gas at high pressures.

# APPENDIX A – SUPERCOMPRESSIBILITY RATIO

Base Date = 0.6 Specific Gravity Hydrocarbon Gas