M311 Gas Laws and Calculations

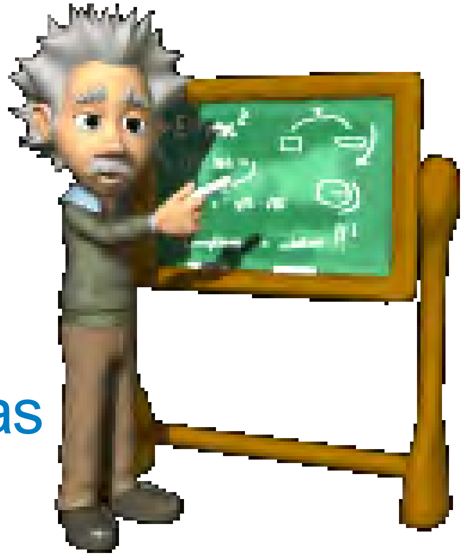
Patrick (Pat) J. Hardock, P.Eng.
Measurement and Regulatory Specialist
Gas and Liquid Flow

Objectives

1. Basic units of measure important in gas measurement

2. Laws governing gas
    1. Boyle's law
    2. Charles's law
    3. Gay-Lussac's law
    4. Combined gas law(s)

3. Identify the following properties of natural gas
    1. Combustion
    2. Composition percentages
    3. Heating value



Basic Units of Measure Important to Gas

- Composition of Natural Gas
- Temperature
- Pressure
- Energy content

Components of Natural Gas

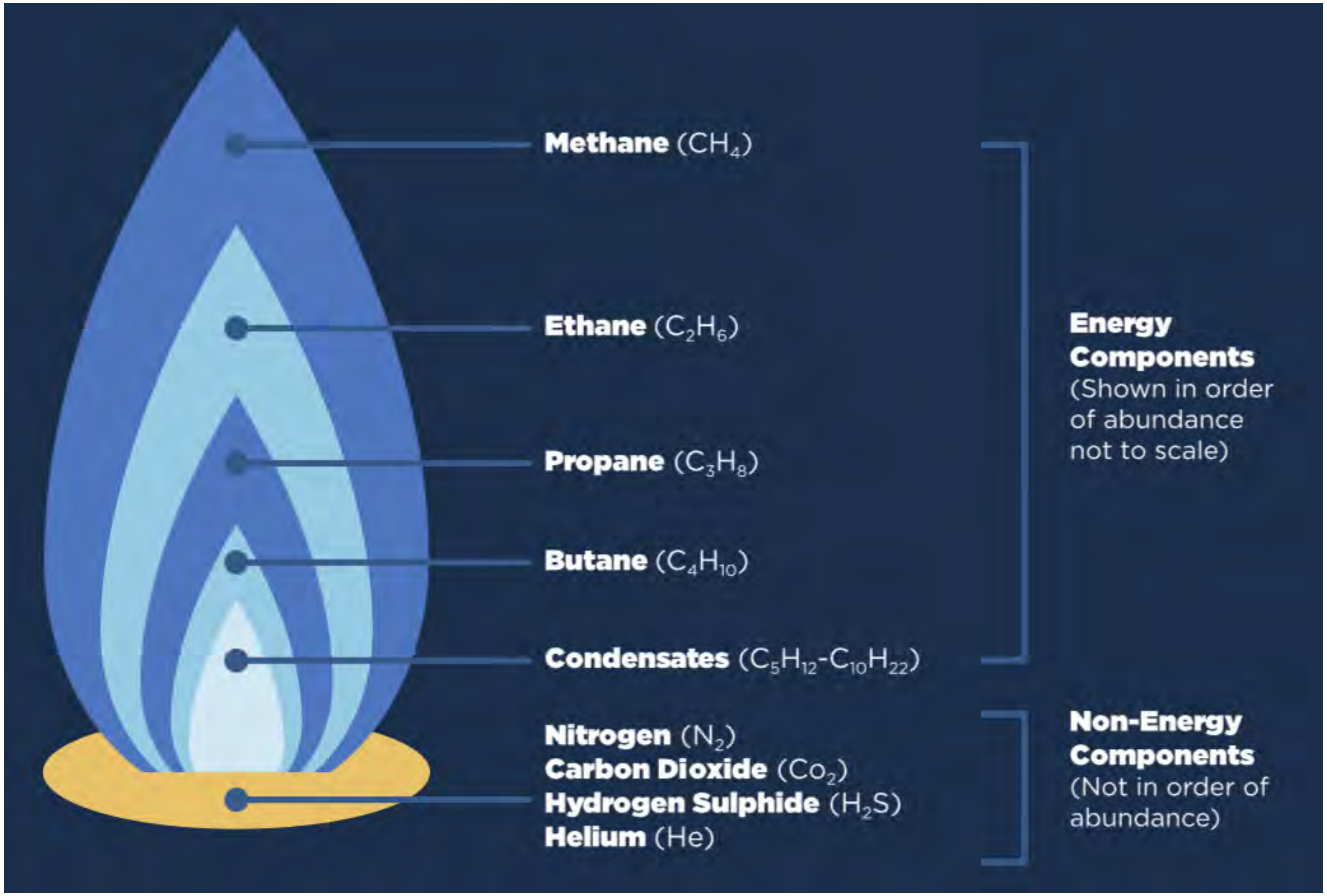


Figure from 2023 Natural Gas Playbook - CGA Website.

Components of Natural Gas

- Composition is an overall system average and may vary from the typical value listed below by location.
- * The gross heating value is the total heat obtained by complete combustion at constant pressure of a unit volume of gas in air, including the heat released by condensing the water vapor in the combustion products (gas, air, and combustion products taken at standard temperature and pressure).

Information from ENBRIDGE

Component	Typical Analysis (mole %)	Range (mole %)
Methane	94.6	93.1 - 96.1
Ethane	4.4	3.1 -5.7
Propane	0.2	0.09 - 0.2
iso - Butane	0.01	trace - 0.02
normal - Butane	0.01	trace - 0.03
iso - Pentane	0.003	trace - 0.007
normal - Pentane	0.002	trace - 0.005
Hexanes plus	0.002	trace - 0.004
Nitrogen	0.4	0.3 - 0.45
Carbon Dioxide	0.3	0.19 - 0.51
Oxygen	0.005	trace - 0.51
Hydrogen	0.01	trace - 0.01
Specific Gravity	0.58	0.57 - 0.59
Gross Heating Value (MJ/m^3), dry basis *	38.9	38.5 - 39.3
Wobbe Number (MJ/m^3)	50.9	50.7 - 51.3

Components of Natural Gas

Composition is important in determining the physical properties of the gas mix.

Each component contributes a portion (based on its percentage in the mix) of its value to the mix total.

From this, the gas compressibility, speed of sound, gas density and heating values are calculated.

Typically, the composition is measured using a gas chromatograph.

Units of Measurement - Temperature

Temperature describes how hot or cold a gas is. The temperature of a gas relates to the kinetic energy (of motion) of its atoms and molecules.

Units of Temperature

Temperature may be expressed in either Imperial units - degrees Fahrenheit (^oF), or Metric units - degrees Celsius (^oC).

To convert from ^oC to ^oF the formula below is used:

$$^oF = (^oC \times 9/5) + 32$$

To convert from ^oF to ^oC the formula below is used:

$$^oC = (^oF - 32) \times 5/9$$

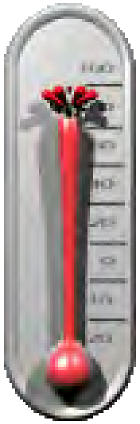
Units of Measurement - Absolute Temperature

Measured in Degrees Rankine (°R)

°R = °F + 460 (Rounded)

Measured in Kelvin (K)

K = °C + 273 (Rounded)



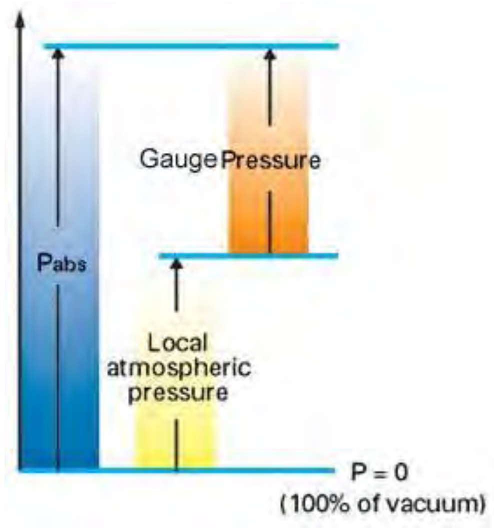
Why is this important? All gas calculations for temperature are in degrees Rankine of Kelvin.

Absolute Pressure

Pressure measured or calculated on an absolute scale, the zero of which represents the pressure exerted by a total vacuum.

Absolute Pressure = Gauge Pressure + Atmospheric Pressure

Pabs = Pg + Patm



Why is this important? All gas calculations for pressure are in absolute units (psia or kPa (absolute))

Atmospheric or Barometric Pressure

The pressure exerted by the earth's atmosphere at any given location.

Atmospheric pressure decreases with increased elevation (inversely proportional) since the mass of air decreases as you go higher.

The Electricity and Gas Inspection Regulations use a mathematical equation to define the relationship between atmospheric pressure and elevation above sea level. Commonly used in gas billing and PFM installations.

37 (1) The atmospheric pressure shall be calculated for a meter location by using the following equation, namely,

(a) in the International system of units,
$P_a = 101.560 - (0.0113 \times M)$ kPa, or

(b) in the Imperial system of units, P_a
$= 14.73 - (0.0005 \times F)$ psia

Gauge Pressure

Gauge pressure is measured on a scale the zero of which is atmospheric pressure at the time and place the measurement is taken.

Often in measurements, a gauge is used to record the pressure difference between the system and the atmospheric pressure.

This is called gauge pressure.

Gauge pressure is represented by Pgauge in applicable formulae and units expressed on the gauge pressure scale are followed by the symbol g, ie. psig

Units of Measurement - Pressure

Pressure is the result of force exerted over a given area.

$$P = F / A$$

The table below shows common units of pressure used in gas measurement in Canada and applicable conversion factors

	psi	kPa	in. Hg @32°F	in. w.c. @60°F	in. w.c. @68°F
1 psi =	1	6.8948	2.03602	27.70726	27.729767
1 kPa =	0.14504	1	0.2953	4.018598	4.021863
1 in. Hg @32°F =	0.491154	3.38639	1	13.60854	13.619596
1 in. w.c. @ 60°F =	0.03609	0.24884	0.073483	1	1.000812
1 in. w.c. @ 68°F =	0.03606	0.24864	0.073424	0.999188	1

Units of Measurement - Energy

Energy - British Thermal Unit (BTU)

The amount of heat required to raise one pound of water one degree Fahrenheit at sea level.

Energy - Joule

A Joule is the amount of energy required to raise 1 gram of cool, dry air by 1.0°C (1.8°F).

Important to note that the heat content of natural gas depends on its composition.

Gas Laws

A number of fundamental gas laws are used to define the relationship between various thermodynamic properties of gas such as volume, pressure and temperature.

We will review the relationships covered by the following gas laws:

1. Boyle's law
2. Charles's law
3. Gay-Lussac's law or Amonton's law
4. Combined gas law (ideal gas)
5. Combined gas law (real gas)

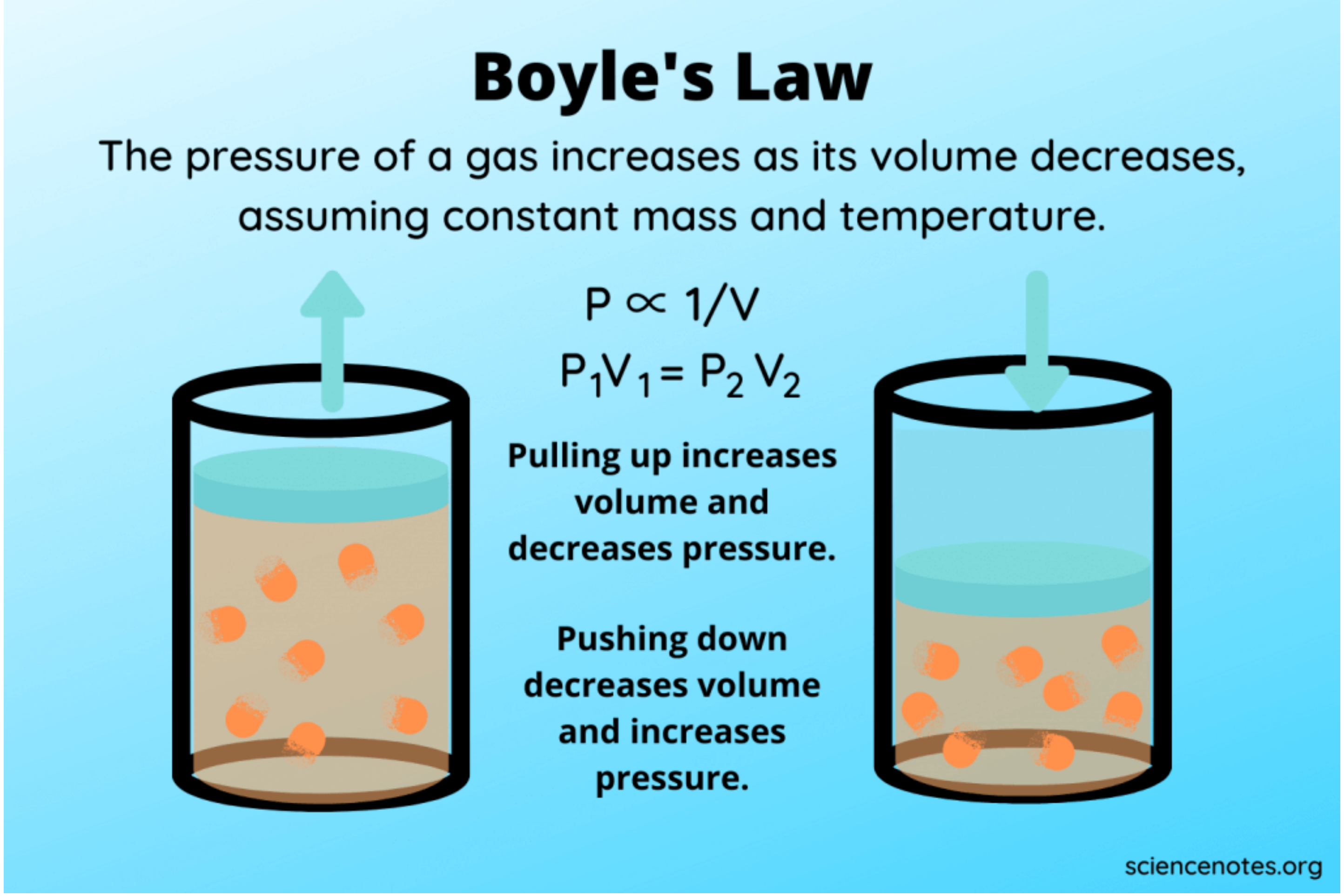
Boyle’s Law

Boyle’s law was put forward by the Anglo-Irish chemist Robert Boyle in the year 1662.

*“Boyle used a closed J-shaped tube and after pouring mercury from one side he forced the air on the other side to contract under the pressure of mercury. After repeating the experiment several times and using different amounts of mercury he found that under controlled conditions, the pressure of a gas is inversely proportional to the volume occupied by it.”

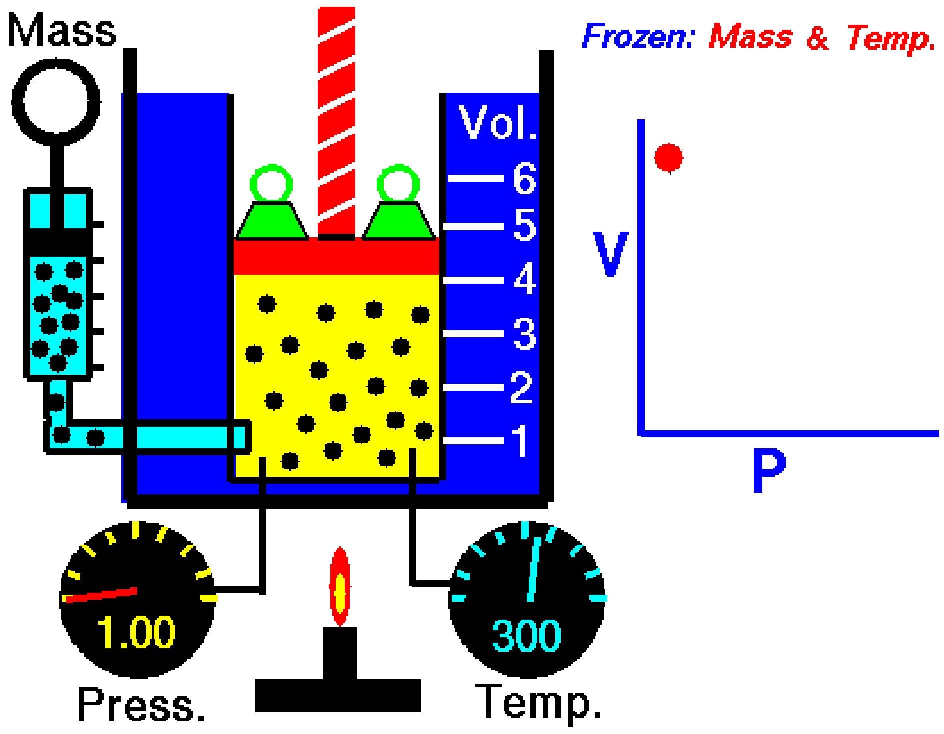
*Wikipedia

Boyle's Law



Boyle's Law
The pressure of a gas increases as its volume decreases, assuming constant mass and temperature.
$P \propto 1/V$
$P_1V_1 = P_2V_2$
Pulling up increases volume and decreases pressure.
Pushing down decreases volume and increases pressure.
sciencenotes.org

Boyle's Law



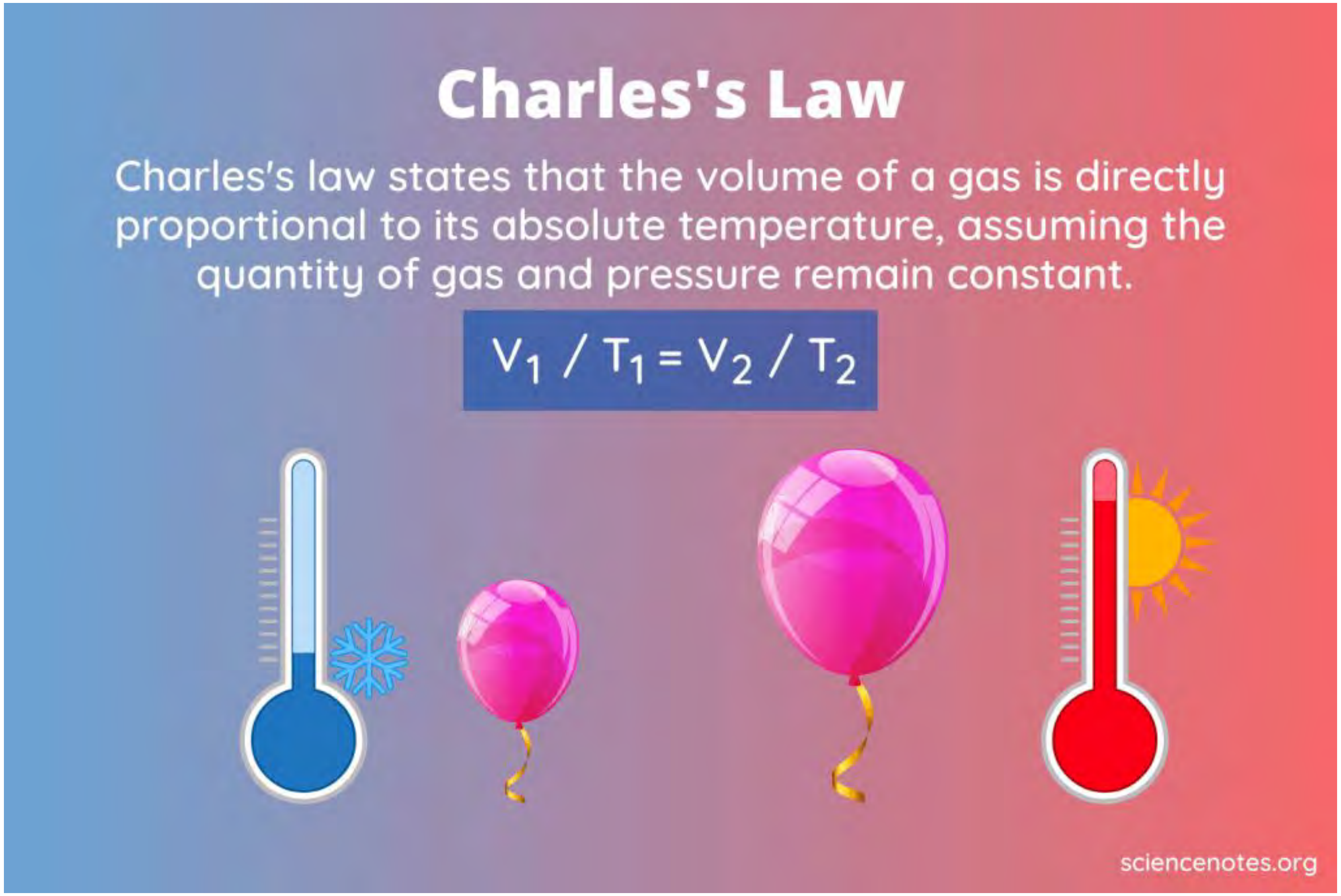
Volume of a fixed mass of gas at a constant temperature varies inversely with a change in *absolute* pressure.

Figure from NASA

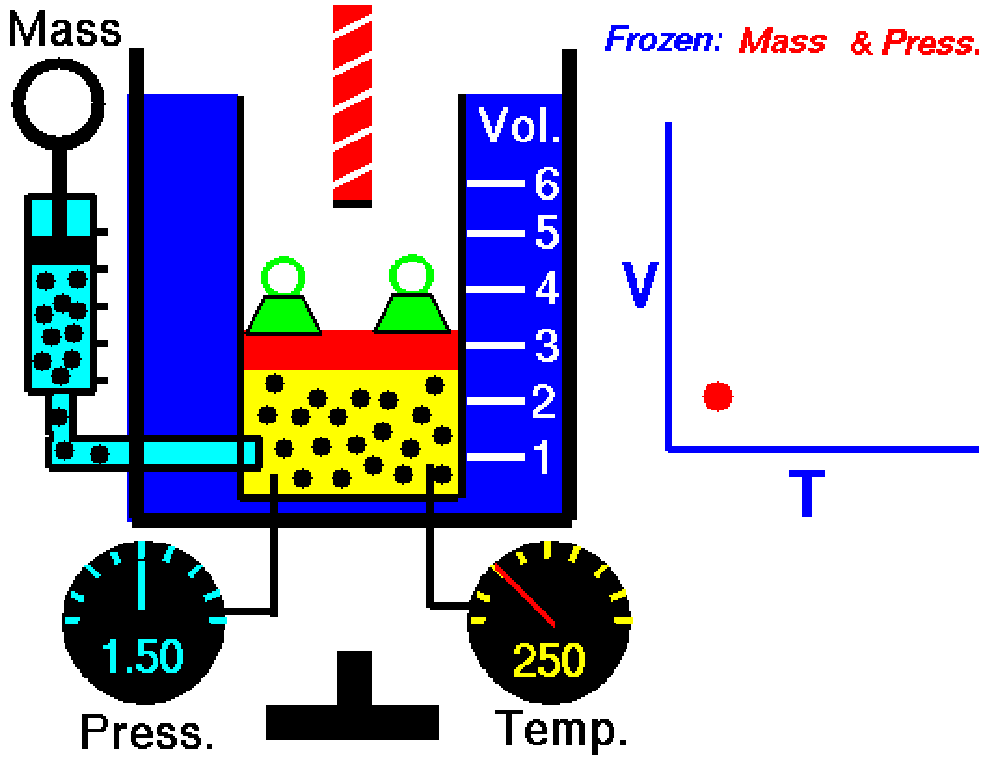
Charles's Law

Also known as the law of volumes, The Law resulted from experiments begun around 1787 by Jacques Charles but was properly established only by the more accurate results published in 1802 by Joseph Gay-Lussac.

Charles's Law



Charles's Law



Volume of a fixed mass of gas at a constant pressure varies directly with a change in *absolute* temperature.

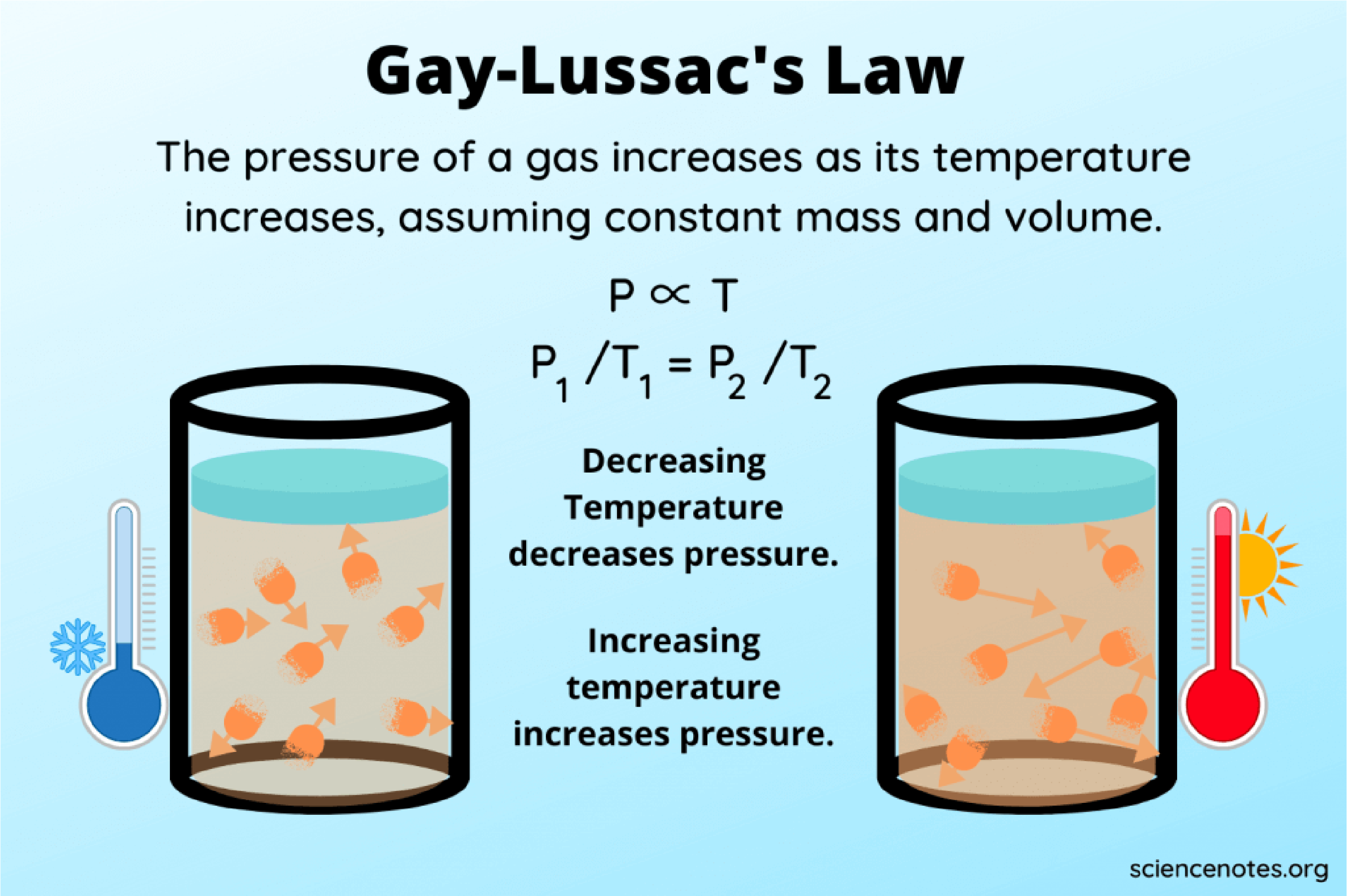
Figure from NASA

Gay-Lussac’s law or Amonton’s law

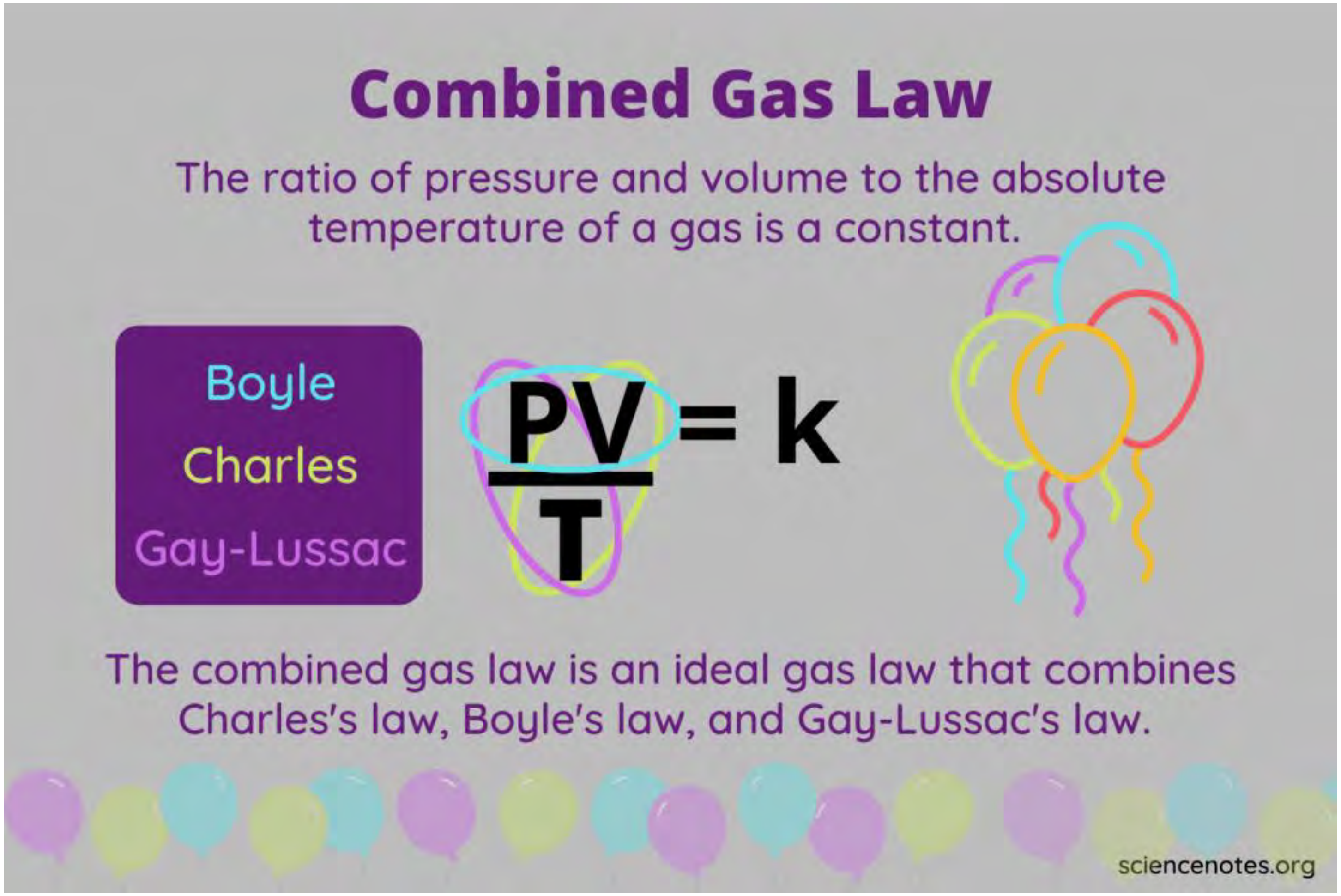
Incorrectly attributed to Gay-Lussac rather than to Guillaume Amonton.

Formulated the law in 1802 and states that the absolute temperature and pressure of an ideal gas are directly proportional, under conditions of constant mass and volume.

Gay-Lussac's Law or Amonton's Law

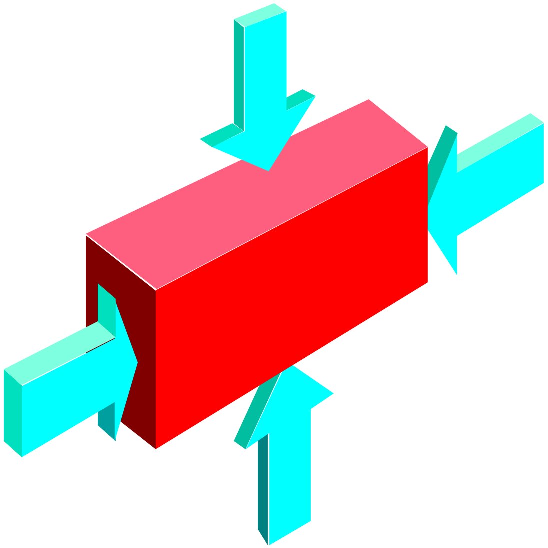


Combined Gas Laws



Combined Gas Laws

Boyle's law: PV = k
Charles's law: V/T = k
Gay-Lussac's law: P/T = k
Combined gas law: PV/T = k



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

(Common form of Combined Gas Law)

The combined gas law holds true for ideal (perfect) gases.

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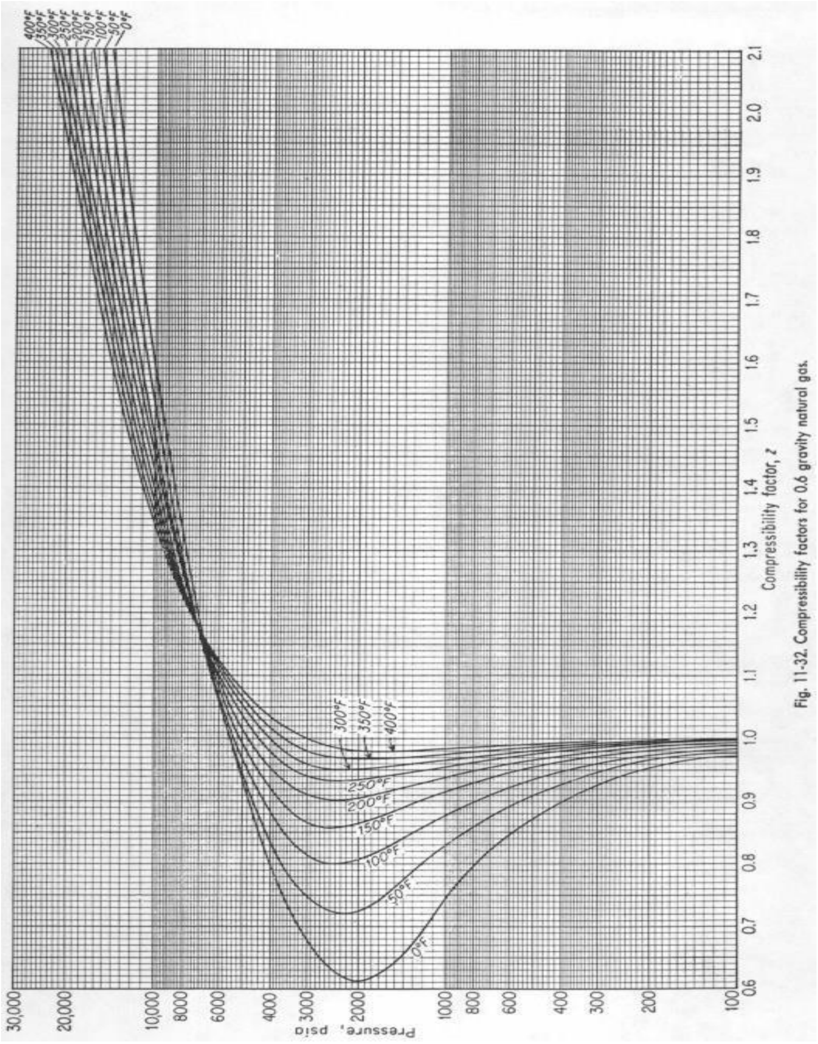
Real Gases and Compressibility

Compressibility Factor (Z) for 0.6 specific gravity natural gas.

Compressibility (Z) varies for a real gas with changes in pressure, temperature and composition.



Real Gases and Compressibility

Real (imperfect) gases deviate from the Ideal Gas Law. This deviation is related to the compressibility factor Z, of the gas.

$$\frac{PV}{kT} = Z$$

Z = 1 for an ideal gas at all P & T values

Z varies for a real gas with changes in pressure, temperature and composition

$$\frac{VP}{TZ} = k$$

$$\frac{V_1 P_1}{T_1 Z_1} = \frac{V_2 P_2}{T_2 Z_2}$$

$$V_2 = V_1 \; x \left(\frac{P_1}{P_2}\right) x \left(\frac{T_2}{T_1}\right) x \left(\frac{Z_2}{Z_1}\right)$$

This equation holds true for real (imperfect) gases such as natural gas.

Real Gases and Compressibility

$$V_2 = V_1 \; x \left(\frac{P_1}{P_2}\right) x \left(\frac{T_2}{T_1}\right) x \left(\frac{Z_2}{Z_1}\right)$$

$$\left(\frac{P_1}{P_2}\right) = Pressure\ Correction\ Factor$$

$$\left(\frac{T_2}{T_1}\right) = Temperature\ Correction\ Factor$$

$$\left(\frac{Z_2}{Z_1}\right) = Compressibility\ Correction\ Factor$$

This special case of the equation holds true for real (imperfect) gases where P1,T1 and Z1 are at some base reference conditions.

This is the equation built into most electronic correctors.

Supercompressibility

Supercompressibility Factor (*Fpv*)

A factor applied to volume measured in orifice metering to compensate for the deviation from the Ideal Gas Law and is generally assigned the symbol, Fpv.

$Fpv = (Z_2 / Z_1)^{0.5}$

Supercompressibility Ratio (s)

The term used for the squared supercompressiblity factor applied to non-orifice metering applications.

$Fpv^2 = Z_2 / Z_1$

"Gas Measurement Law"

$$V_B = V_{Meter}\, x \left(\frac{P_M}{P_B}\right) x \left(\frac{T_B}{T_M}\right) x\, (F_{pv})^2$$

V_{Meter} = Metered Volume (Uncorrected)

P_M = Absolute Metering Pressure

P_B = Base Pressure

T_B = Absolute Base Temperature

T_m = Absolute Metering Temperature

F_{pv} = Supercompressibility Factor

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Simple Metering Equation

$$V_2 = V_{meter} \ x \ (M_f) \ x \left(\frac{P_{meter}}{P_2}\right) x \left(\frac{T_2}{T_{meter}}\right) x \left(\frac{Z_2}{Z_{meter}}\right)$$

If we add in a meter performance correction factor (M_f), determined during a meter's calibration, we get the most common form of equation for turbine, rotary and diagram meters.

Orifice plates and other differential producers use a different model.

Compressibility Standards

Some Standards that publish equations to calculate compressibility factors are:

1. A.G.A. Transmission Measurement Committee Report No. 8,1992 (1994 Rev)
   - Adopted by American Petroleum Institute as A.P.I. Chapter 14.2
   - AGA Report #8 (1994) Detail Method
   - AGA Report #8 (1994) HV/RD/CO2 (Gross Method 1)
   - AGA Report #8 (1994) RD/N2/CO2 (Gross Method 2)

2. A.G.A. Transmission Measurement Committee Report No. 8, 1985
   - AGA Report #8 (1985) Primary Method
   - AGA Report #8 (1985) Gravity/HV/CO2 Method
   - AGA Report #8 (1985) Gravity/HV/CO2/N2 Method
   - AGA Report #8 (1985) Gravity/CO2/N2 Method
   - AGA Report #8 (1985) HV/CO2/N2 Method
   - AGA Report #8 (1985) Gravity/Methane/CO2/N2 Method

3. A.G.A Report NX-19, 1962
   - Developed for calculations of supercompressibility factors
   - Uses specific gravity, % N2 composition and %CO2 composition

Relative Density & Specific Gravity

Specific Gravity

The ratio of the molecular weight of a gas (or a gas mixture) to the molecular weight of dry air, where the molecular weight of air is taken to be 28.9644.

Relative Density

The ratio of the weight of a volume of gas (or a gas mixture) to that of an equal volume of dry air not containing in excess of 0.003% by volume of CO_2, where both the air and the gas are at equal pressure and temperature conditions.

The basic difference between Specific Gravity and Relative Density is the effect of the deviation from the ideal gas laws due to compressibility.

Heating Value - Gross or Net

Gross (or high, upper) Heating Value

The amount of heat produced by the complete combustion of a unit quantity of fuel.

Assumes all water (H_2O) produced by combustion and/or entering with fuel and air leaves as condensed liquid.

Net (or lower) Heating Value

Obtained by subtracting the latent heat of vaporization of the water vapour formed by the combustion from the gross or higher heating value.

Assumes all water leaves as vapour or steam.

Heading Value - Dry, Wet or as Delivered Basis

Dry Basis

Gross or Net Heating Value of a volume of gas at reference conditions which contains no water vapour.

Saturated Basis

Gross or Net Heating Value of a volume of gas at reference conditions which is saturated with water.

As Delivered (Wet) Basis

Gross or Net Heating Value of a volume of gas at reference conditions which delivered with variable water content. The water content must be known in order to specify the wet-basis heating value.

Heating Value - Ideal or Real Basis

Ideal basis

Volume based heating value is established based on ideal gas equations of state.

Real basis

Volume based heating value adjusted for the compressibility of natural gas at the applicable reference conditions for pressure and temperature.

Heating Value Standards

1. AGA Report No. 5, *Natural Gas Energy Measurement**

2. GPA 2145, *Table of Physical Constants of Paraffin Hydrocarbons and Other Components of Natural Gas*

3. GPA 2172, *Calculation of Gross Heating Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis*

*AGA Report No. 5, *has been deemed obsolete by the North American gas industry and has been superseded by GPA2145 and GPA2172*

Heating Value Units

To be properly understood and applied the nature and units of a heating value need to be well defined.

- Mass and/or volume based units
- Gross (high) or net (low)
- Dry, saturated or as delivered basis
- Ideal or real basis

Mass based units

BTU$_{(?)}$ /lb
J/kg
kcal/kg

Volume based units

J/m^3
BTU$_{(?)}$/ft^3$_{(??)}$

(?) need to identify the specific BTU temperature reference component
(??) need to reference pressure and temperature conditions for the volumetric component

Thanks

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Questions / Comments?