Using a Pressure Gauge with a Propane Cylinder

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Introduction

One approach to anticipating when a propane cylinder is nearing depletion is the use of an accessory pressure gauge. However, the full benefit of using a pressure gauge can only be gained by applying knowledge of the liquid-vapour equilibrium occurring in the cylinder, and the gas law. This article provides background information and discusses the theory relating to the use of a pressure gauge with a propane cylinder. It provides everyday-life examples that could be useful in teaching many topics, including: changes of state; liquid-vapour equilibrium; thermochemistry; the gas law; unit conversion; safety.

The article is based on the popular '20 lb' propane cylinder that many consumers use for their outdoor grill. Other cylinder sizes differ only in scale. Many engineering and other common units are used in this area; conversions have been made using Professor Wildi's *Visualization of Units* reference pages (1). In the article, values in engineering and other traditional units are accompanied by values in SI units, e.g. the pressure units atm and inches of water are converted to kPa, and the power unit Btu / h is converted to kW.

Pre-Article Questions (Answers at the End of the Article)

1. The correct order for connection of a pressure gauge in a propane cylinder grill is:
   (a) Cylinder - regulator - pressure gauge - burner(s);
   (b) Cylinder - pressure gauge - regulator - burner(s);
   (c) Neither of the above.

2. A full '20 lb' propane cylinder can supply 20,000 Btu / h (5.86 kw) of heat energy for about 20.6 hours. When the cylinder is full, at 20 °C, the attached pressure gauge reads 8.4 atm (850 kPa). After 10.3 hours of cooking at 20,000 Btu / h the pressure gauge, at 20 °C, will read:
(a) 8.4 atm; (b) 4.2 atm; (c) Neither of the previous answers.

3. A propane cylinder can supply fuel to a grill at an ambient temperature of − 50 °C. True? / False?

Physical and Chemical Properties of Propane

The Table below contains some properties of propane relevant to its use as a fuel gas. The data are for the chemical substance propane, from the CRC Handbook (2) and Wikipedia (3a). Commercial propane, however, is not pure propane. A petrochemical, it has variable composition and properties, and depending on the source and processing history, contains varying small proportions of other alkanes with similar physical properties (3b, 4). Commercially as a fuel it is bought and sold by its heat content.

Physical States of Propane

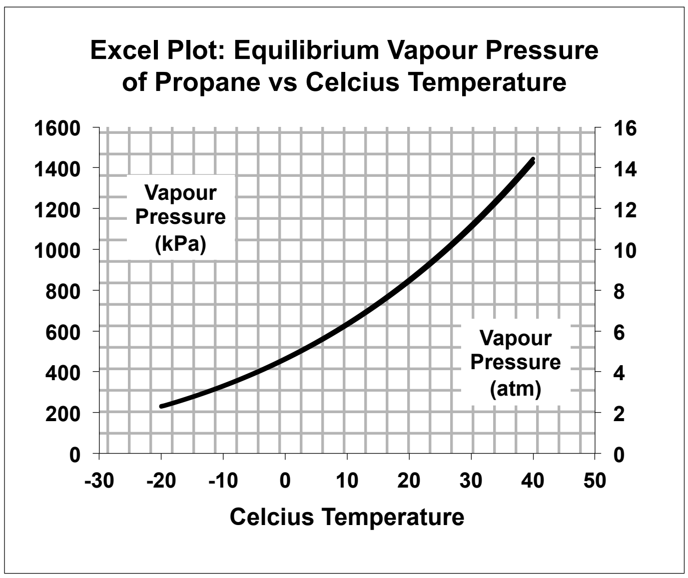
Propane cannot be used as a compressed gas. To be used as a compressed gas, the gas must be above its critical temperature (3c). The critical temperature of propane is 96.8 °C. If propane vapour is compressed at ordinary temperatures, it condenses to a liquid. Propane is bought and used domestically as a volatile, pressurized liquid, called 'Propane' in some markets or 'Liquefied Petroleum Gas' (LPG) in others (3b). It is dispensed as a liquid under pressure through valves into pressurized cylinders or tanks, or through valves into pressurized vehicle tanks.

Table: Selected Physical and Chemical Properties of Propane	
Chemical Formula	C_3H_8
Molar Mass	**44.10 g / mole**
Normal Boiling Point	**− 42.1 °C**
Critical Point	**96.8 °C, 42 atm**
Density of Liquid	**0.51 kg/L**
Flammability Limits	**2.2 % - 9.6 %**
Ignition Temperature	**493 °C - 604 °C**
Flame Temperature	**1980 °C**
Heat of Vaporization	**20.1 kJ/mol**
Heat of Combustion (product water as a gas)	**2.044 MJ/mol 46.35 kJ/g**
Specific Heat Capacity	**1.67 kJ/kg.°C**

The Propane Liquid – Vapour Equilibrium

The important point to note is that propane fuel in a cylinder is not a compressed gas. Propane in a cylinder or tank at ordinary temperatures is a highly volatile liquid in equilibrium with its vapour at a pressure, the equilibrium vapour pressure (3d), that varies only with temperature, as shown in the Excel® plot. This curve is a function known in thermodynamics as the Clausius-Clapeyron equation (3e). The 1974 edition of the CRC Handbook (5) gives the required equation and coefficient data to calculate values of the vapour pressure at any temperature.

Excel functions were used to calculate the vapour pressure at every integral temperature from − 20 °C to + 40 °C, and to convert the values to both **atm** and **kPa** units. These values were plotted with the two pressure units shown as the two scales on the plot. The values rise from about 2 atm at − 20 °C to above 14 atm at + 40 °C. A propane cylinder in the sun on a hot summer day will have an internal pressure well above 10 atm.



As propane vapour is drawn from a cylinder to be burned in a grill, the pressure in the cylinder drops and liquid propane vaporizes according to Le Châtelier's Principle (3f) to restore equilibrium.

This requires heat energy since the evaporation of liquid propane is endothermic. Heat energy must flow in from the surroundings. The temperature of the liquid drops as this happens because heat flow from the surroundings is not instantaneous:

$$C_3H_8\,(l) + 20.1\text{ kJ} \rightleftarrows C_3H_8\,(g)$$

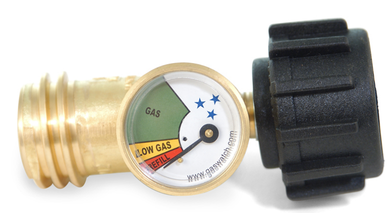
At 20 °C the equilibrium vapour pressure of propane is 8.41 atm (852 kPa). A pressure gauge (3g) connected to the cylinder will indicate this 'absolute' pressure reading when the tank is full, and will stay at this reading at 20 °C as propane is removed, until all of the liquid phase is depleted. After this, the pressure of the propane and the gauge reading will drop until it reaches slightly above atmospheric pressure, when no further propane can be supplied. The behaviour of the propane vapour during this phase may be approximated, by using the ideal gas law (3h).

Propane Cylinders

A common propane cylinder type used for grills is the '20-lb' cylinder (3i). The valve guard of the cylinder is stamped with various data, including the tare mass 8.4 kg (18.5 lb), the 'water volume' 21.6 L (5.7 US gal) and the date of manufacture (6). The maximum fill volume allowed is about 85 % of the water volume, or about 18.4 L, which translates as about 9.4 kg of propane, or about 20.6 lb. Cylinders are filled by mass to avoid overfilling, hence the term '20-lb' cylinder. Cylinders may be used for 10 years from the date stamped on the guard ring, after which time they may be re-qualified by a visual inspection for a further 10 years (6), although this is not a simple process.

Overfilling greatly increases the possibility of dispensing liquid propane when the valve is opened. In addition to the hazard of fire or explosion, liquid propane evaporates so rapidly in contact with skin that it is a severe frostbite hazard. Propane is also a CNS toxin. To avoid this, all cylinders sold now must be fitted with a valve with an OPD or overfill protection device which closes the valve when the liquid propane reaches a set level in the cylinder (7). The OPD prevents excessive inflow, but does not block outflow of gas or of liquid, allowing use of the cylinder when full. Cylinders must be secured upright when used to prevent outflow of liquid propane.

Pressure Gauges for Propane Cylinders



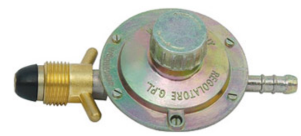
Accessory pressure gauges for propane cylinders are available at many retailers (8). The one shown here is typical: there is no indication of pressure units on the gauge, but rather a large green segment (gas OK), a small yellow segment (gas low), and a small red segment (refill needed). The one I have is embossed with the legend **MWP250PSI** which means 'maximum working pressure 250 lb / in^2 (17.0 atm; 1720 kPa).

An equilibrium pressure of 1720 kPa is not reached in a cylinder until somewhere above 40 °C. At 20 °C, the pressure is 852 kPa, where the gauge needle will be roughly at its mid-point position, in the green area.

This type of gauge display is intended to simplify life for the consumer with limited knowledge of science. When used in warm weather or roughly above 10 °C, the needle will be in the green as long as there is some liquid propane remaining in the cylinder. If the consumer opens the cylinder valve and finds the needle in the yellow or red, then a refill is advisable before use. If the needle begins to drop during use of the propane, then depletion of the cylinder is nearing, and action may be required.

The gauge is much more difficult to use and interpret in cold weather. Use below 0 °C is not easy, because the equilibrium vapour pressure is so low, even a full cylinder shows a yellow or even a red indication. Alternative and complementary approaches to determining the fill state of the cylinder are examined later in the article.

Gas Supply Pressure Regulation



The most common gas pressure regulator system is the diaphragm + spring type (9). This is a very rugged and dependable regulator that uses the movement of a diaphragm to open or close a valve. When there is excess pressure in the gas line to the burners, the regulator valve shuts, and when the pressure in the supply line drops too low, the regulator valve opens. In this way, by negative feedback (3j), the pressure of fuel gas flowing to the burners is maintained at the specified ‘gauge’ pressure (3g) above atmospheric pressure. A normal gauge pressure for propane burners is 10.5 inches of water (2.6 kPa; 0.026 atm) (10).

Notice that when a propane cylinder runs out of propane, the regulator valve will be fully open, and air and water vapour will be able to enter the cylinder. Water could cause corrosion of the cylinder or regulator, or freeze to block the cylinder valve or the regulator valve. To prevent this, the cylinder valve must be closed if the propane is exhausted.

When the cylinder valve is shut after cooking and the burners are allowed to burn off the gas in the supply line, then the regulator valve will be in the open position. The next time the cylinder valve is opened, there will be a sharp snapping sound heard as the regulator valve closes.

Propane Burners

The control and burner assembly of a grill is designed to control the fuel gas flow and mix the fuel gas with an appropriate amount of air, within the flammability limits (3k), such that the mixture can be easily ignited and completely burned in safety. Resistance to blowing out in a gusty wind is also a consideration. The air is drawn into the burner by a carburetor effect (3l) based on Bernoulli’s principle (3m). The combustion reaction is exothermic (3n):

$$\mathbf{C_3H_8\ (g) + 5\ O_2\ (g) \rightarrow 3\ CO_2\ (g) + 4\ H_2O\ (g) + 2.044\ MJ}$$

Burn Rate of a Propane Grill and Burn Time of a Full Cylinder

In North America gas appliances, grills and air conditioners are rated in the unit Btu / h, e.g. Weber E310 grill rated at 38,000 Btu / h (11a). What is the burn rate of propane required to produce **20,000 Btu / h** (**5.86 kW**)? In cooking, the product water is a gas; the appropriate value of the heat of combustion as given in the Table above is 46.35 kJ / g of propane. To produce 5.86 kW (5.86 kJ / s) requires the combustion of **0.1264 g / s** of propane.

How long does a full ’20-lb’ cylinder (9.4 kg) of propane burn at this rate? Answer: 74,500 s = **20.6 h**. Every user of propane will have a different pattern of consumption, so this value is just an approximate guideline.

How Much Cooking Time is Left After the Liquid Propane is Used Up?

When there is no longer any liquid propane and the pressure gauge needle begins to drop, how long have you got before the vapour in the cylinder is used up? Let's assume the burn rate is 20,000 Btu / h and answer this question at (a) **25 °C** and (b) **0 °C**.

First, use the Excel plot above to roughly estimate the vapour pressure of propane in the '20 lb' cylinder when the liquid propane has just run out at each temperature: (a) 980 kPa and (b) 465 kPa. Assume that the grill will continue to function until the propane pressure drops to 2.6 kPa above atmospheric pressure, 103.6 kPa. As noted above, the cylinder volume is 21.6 L. Use the ideal gas law (3h) as an approximation to determine how much burnable propane is in the cylinder in each case, and from that, the burn times: (a) 7.64 mol, 340 g, **45 min** and (b) 3.44 mol, 150 g, **20 min**.

When to Refill a Propane Cylinder - Alternatives

For propane users, running out of propane while grilling is at least very inconvenient, and at worst a culinary and social disaster. But refilling a cylinder is all-or-nothing and you pay a set cost even if you only need half a cylinder of propane. There are various possible strategies to avoid refilling too soon or too late:

1. Add an accessory pressure gauge between the cylinder and the regulator as described above.

2. (Not while cooking!) Check the mass of the cylinder frequently, or gently tilt the cylinder and listen or feel for the liquid propane to splash about. This works very well, but is not easy unless you are physically strong. At least one manufacturer of 'high-end' propane grills now has a weight-based indicator of cylinder fill level on its grills (11b). The cylinder has to be lifted up under the grill and suspended from a spring. The small downward movement of the spring is magnified into a cylinder fill reading by a very clever Vernier scale (3o) effect. This system would appear to be extremely useful, but only if the user is physically able to lift the cylinder into place on the scale. A full '20 lb' cylinder has a total mass of 17.8 kg (39.2 lb).

3. Use the temperature drop of the evaporating liquid propane to locate the surface level. At the burn rate of 0.1264 g / s calculated above, each minute (60 s) about 7.58 g of propane must evaporate to replenish the gas taken from the cylinder, and this translates to 3.46 kJ of heat needed. The top 1 kg of propane in the tank if thermally isolated would drop in temperature by about 2 °C in losing this heat. (Relate this to the danger of frostbite when liquid propane is spilled on skin surfaces.)

The temperature of the liquid propane does drop significantly while grilling. The location of the liquid surface level is easily detected by hand on the steel case of the cylinder at moderate temperatures, but the effect is lost at very high or very low outdoor temperatures, or if the cylinder is in the sun. A strip of tape containing a thermochromic (3p) dye may be a useful aid (12). The tape may be glued to the cylinder, or attached magnetically to the steel of the cylinder wall.

4. Have a second filled cylinder on hand. Anyone who uses propane in a remote location uses this strategy. The valve on the exhausted cylinder must be closed as soon as possible, and the extra full cylinder requires safe, secure storage. Remember that a cylinder may not be refilled after it is 10 years old, adding to the cost of this strategy.

Acknowledgement

This article is an expanded version of part of the article 'Natural Gas (Methane) and Propane as Fuel Gases' that has been submitted to the University of Waterloo's Chem 13 News (13) for publication.

Questions for Students

1. What is the lowest ambient temperature at which a propane grill can be operated? Explain your answer. (Answer: Down to slightly above the normal boiling point temperature, **− 42.1 °C**, below which the equilibrium vapour pressure drops below that required to supply vapour to the burners.)

2. Verify the unit conversions in the article.

3. Verify the gas law calculations in the article.

4. Verify the thermochemical calculations in the article.

5. Propane may be used as a furnace fuel in either low- or high-efficiency furnaces. A low efficiency furnace does not condense the product water vapour, while a high efficiency furnace condenses the product water vapour in the combustion gases by the use of a heat exchanger (3q). Calculate the percentage increase in the heat energy obtained from the propane by condensing the water. (Answer: The molar heat of combustion increases from 2.044 to 2.202 MJ / mol, because 4 mol of water vapour are condensed. The increase in heat energy obtained is about 7.7 %)

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   Pressure: http://www.wildi-theo.com/fichiers/documents/contenu/charts/pressure_and_stress.pdf;
   Power: http://www.wildi-theo.com/fichiers/documents/contenu/charts/power.pdf.

2. CRC Handbook, CRC Press, 54th edition, 1973-74.

3. http://www.wikipedia.org for: (a) propane; (b) liquefied petroleum gas (LPG); (c) critical point (thermodynamics); (d) vapor pressure; (e) Clausius-Clapeyron; (f) Le Châtelier's Principle; (g) pressure measurement; (h) gas laws; (i) gas cylinder; (j) negative feedback; (k) flammability limits; (l) carburetor; (m) Bernoulli's principle; (n) heat of combustion (o) Vernier scale; (p) thermochromism; (q) heat exchanger.

4. Engineering Toolbox: http://www.engineeringtoolbox.com/chemical-composition-gaseous-fuels-d_1142.html;
   Union Gas: http://www.uniongas.com/aboutus/aboutng/composition.asp.

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13. Chem 13 News, University of Waterloo: https://uwaterloo.ca/chem13news/

Answers to the Pre-Article Questions

The correct answers to the questions are 1. (b); 2. (a); 3. False.