Volumetric Efficiency and Engine Airflow

In a four-stroke naturally aspirated engine, the theoretical maximum *volume* of air that each cylinder can ingest during the intake cycle is equal to the swept volume of that cylinder (0.7854 x bore x bore x stroke).

Since each cylinder has one intake stroke every two revolutions of the crankshaft, then the theoretical maximum volume of air it can ingest during each rotation of the crankshaft is equal to one-half its displacement. The actual amount of air the engine ingests compared to the theoretical maximum is called volumetric efficiency (VE). An engine operating at 100% VE is ingesting its total displacement every two crankshaft revolutions.

There are many factors which determine the torque an engine can produce and the RPM at which the maximum torque occurs. However, the fundamental determinant is the **mass of air** the engine can ingest into the cylinders. The mass of ingested air is directly proportional to (a) the air density and (b) the volumetric efficiency. There is a remarkably close relationship between an engine's VE curve and its torque curve.

For contemporary naturally-aspirated, two-valve-per-cylinder, pushrod-engine technology, a VE over 95% is excellent, and 100% is achievable, but quite difficult. Only the best of the best can reach 110%, and that is by means of extremely specialized development of the complex system comprised of the intake passages, combustion chambers, exhaust passages and valve system components. The practical limit for normally-aspirated engines, typically DOHC layout with four or more valves per cylinder, is about 115%, which can only be achieved under the most highly-developed conditions, with precise intake and exhaust passage tuning.

Generally, the RPM at peak VE coincides with the RPM at the torque peak. And generally, automotive engines rarely exceed 90% VE. There is a variety of good reasons for that performance, including the design requirements for automotive engines (good low-end torque, good throttle response, high mileage, low emissions, low noise, low production costs, restrictive form factors, etc.), as well as the economically-feasible tolerances for components in high-volume production.

For a known engine displacement and RPM, you can calculate the engine airflow at 100% VE, in sea-level-standard-day cubic feet per minute (scfm) as follows:

100% VE AIRFLOW (scfm) = DISPLACEMENT (ci) x RPM / 3456

(Equation 3)

Using that equation to evaluate a 540 cubic-inch engine operating 2700 RPM reveals that, at 100% VE, the engine will flow 422 SCFM.

We have already shown (Equations 1 and 2 in **Thermal Efficiency**) how to calculate the fuel flow required for a given amount of power produced. Once you know the required fuel flow, you can calculate the mass airflow required for that amount of fuel, then by using that calculated airflow along with the engine displacement, the targeted operating RPM, and the achievable VE values, you can quickly determine the reasonableness of your expectations. Here's how.

Once you know the required fuel flow, you can determine the required airflow. It is generally accepted (and demonstrable) that a given engine (of reasonable design) will achieve its best power on a mixture strength of approximately 12.5 parts of air to one part of fuel (gasoline) by weight. (Other fuels have different best-power-mixture values. Methanol, for example, is somewhere around 5.0 to 1.)

Using that best-power air-to-fuel ratio, you calculate required airflow:

MASS AIRFLOW (pph) = 12.5 (Pounds-per-Pound) x FUEL FLOW (pph)

(Equation 4)

But airflow is usually discussed in terms of volume flow (Standard Cubic Feet per Minute, SCFM). One cubic foot of air at standard atmospheric conditions (29.92 inches of HG absolute pressure, 59°F temperature) weighs 0.0765 pounds. So the volume airflow required is:

AIRFLOW (scfm) = 12.5 (ppp) x FUEL FLOW (pph) / (60 min-per-hour x 0.0765 pounds per cubic foot)

That equation reduces to:

REQUIRED AIRFLOW (scfm) = 2.723 x FUEL FLOW (pph)

(Equation 5)

OK, hang on. The really useful bit is next.
If I solve Equation 2 (explained back in **Thermal Efficiency**) for FUEL FLOW, I get:
FUEL FLOW (pph) = HP x BSFC

Replacing "FUEL FLOW" in Equation 5 with "HP x BSFC" from Equation 2, produces this very useful relationship:

REQUIRED AIRFLOW (scfm) = 2.723 x HP x BSFC

(Equation 6)

Now, using Equation 6 you can estimate the airflow required for a given amount of horsepower, and using Equation 3, you can calculate the 100% VE airflow your engine can generate at a known RPM.
Combining those two equations yields one equation which enables you to evaluate the reasonableness of any engine program by knowing just a few values:

1. Required HP,
2. Operating RPM,
3. Engine displacement (cubic inches),
4. An assumed reasonable BSFC.

Here it is:

REQUIRED VE = (9411 x HP x BSFC) / (DISPLACEMENT x RPM)

(Equation 7)

Here is an example of how useful that relationship can be. Suppose you decide that a certain 2.2 liter engine would make a great aircraft powerplant. You decide that 300 HP is a nice number, and 5200 RPM produces an acceptable mean piston speed (explained **HERE**). How reasonable is your goal?
The required VE for that engine will be:
Required VE = (9411 x 300 x .45) / (134 x 5200) = 1.82 **(182 %)**
Clearly that's not going to happen with a normally aspirated engine. Supercharging will be required, and you can use the 1.82 figure to calculate the

approximate Manifold Absolute Pressure (MAP) needed (1.82 x 29.92" = 54.5" MAP, or 24.6 inches of "boost") for that power level.

Here's another example. Suppose you want 300 HP from a 540 cubic inch engine at 2700 RPM, and assume a BSFC of 0.45. Plugging the known values into equation 7 produces:

Required VE = (9411 x 300 x .45) / (540 x 2700) = 0.87 **(87 %)**

That is a very reasonable, real-world number. (If you recognized those figures as being for the 300-HP Lycoming IO-540 discussed above, well done.)

Manifold Absolute Pressure (MAP)

We mentioned this term (MAP) in the preceding discussion, and it is used regularly in discussing engine performance, but just in case it is unfamiliar, here is a clarification.

First, the term *Absolute Pressure* means the pressure above a zero reference (a perfect vacuum). Ambient atmospheric pressure at sea level on a "standard day" is approximately 14.696 psi absolute (or 29.92 inches of mercury, "HG, explained below).

Manifold Absolute Pressure, then, is just what it says: The absolute pressure which exists in the inlet manifold, usually measured in the plenum (if one exists). The MAP in an engine which is not running is equal to atmospheric pressure. If, on a "standard day", an engine is idling at a measured manifold "vacuum" of *14 inches,*, the MAP is actually 15.92 "HG (29.92 - 14 = 15.92).

The term "inches of mercury", as used to express a pressure, can be a bit confusing. One common unit of measurement for MAP, barometric pressures, and other precise pressure measurements is "inches of mercury". Mercury is a heavy metal that is in the liquid state under conditions of standard temperature and pressure. Mercury is commonly used in manometers and barometers (a special application of a manometer) because of its high density and its liquidity. Recalling from high school chemistry, "HG" is the chemical symbol for the element Mercury, derived from the Greek word **HYDRARGERIUM**, literally *silver water*.

In a mercury-filled barometer, the vertical distance between the two manisci, at sea-level, standard conditions, is 29.92 inches, hence the term *inches of mercury, "HG*, or for the lazy, just *inches*.

Source:

http://www.epi-eng.com/piston_engine_technology/volumetric_efficiency.htm