The Performance Professor

Jim McFarland

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Air Flow & The Internal Combustion Engine

Without adequate and properly timed airflow, power from an internal combustion engine will be less than maximum. Following are some keys to making certain you know how to obtain horsepower from proper supply of air. Also included are some basic definitions of related and important terms.

Engine Airflow (Basic Information)

Engines operate in a “sea” of air pressure. This either takes the form of atmospheric influence or some artificial means of getting air inside an engine. If atmospheric pressure is the driving force that provides air, the engine is said to be “normally aspirated.” Should a mechanical means be added to atmospheric pressure, “super” air charging is the method of aspiration. Stated another way, an engine becomes “supercharged” with air pressure higher than atmospheric.

The downward movement of pistons creates an in-cylinder pressure that is less than atmospheric, causing air to be forced into the engine, either by atmospheric or some artificial means of providing pressure (supercharging is an example of “artificial” aspiration). The term “suction” is somewhat a misnomer, suggesting that air is pulled or “drawn” into cylinders rather than forced there by atmospheric or mechanically derived pressure. This difference in perspective of how air enters an engine is important to remember, particularly when considering the way carburetors operate. It will be a concept to which these “lessons” will refer as discussions unfold during following months.

> **“Of particular importance is the fact when a change in airflow is caused (typically an increase), it is necessary to make changes in fuel flow and ignition spark timing.”**

Cylinder Filling & Torque

The ability of an engine to ingest air is a measurement called “volumetric efficiency.” Although this term will be discussed in more technical depth a bit later, suffice that it is a means by which an engine’s physical capacity is compared to actual air intake. This is a dynamic measurement obtained as a function of engine rpm and load. If an engine accepts a volume of air that is equal to its physical volume (piston displacement), it is said to have a volumetric efficiency of 100%. It can be less or more, depending upon a variety of circumstances.

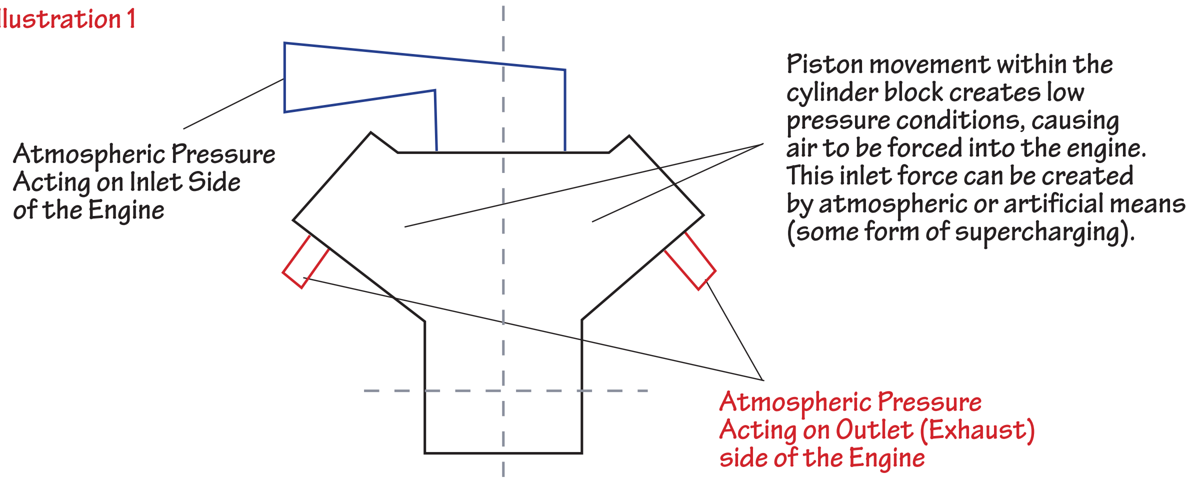
In reality, an engine’s volumetric efficiency at each rpm of measurement can be represented on a graph. Sample v.e. and torque curves are provided elsewhere in this lesson (see illustration #5). Interestingly, a volumetric efficiency curve closely approximates an engine’s torque curve, or the amount of torque produced at each rpm of measurement. From this, you might suspect that there is a specific relationship between a volumetric efficiency curve and a torque curve…and there is.

Generally speaking, increases or decreases in volumetric efficiency correspond to increases or decreases in torque. If an engine modification is made that increases airflow (or volumetric efficiency), the potential for an increase in torque is available. In fact, the majority of changes to a stock engine intended to increase power are associated with some form of airflow change.

Of particular importance is the fact when a change in airflow is caused (typically an increase), it is necessary to make changes in fuel flow and ignition spark timing. Historically, these changes have been made to “mechanical” devices (carburetors and ignition-point distributors). Today, on-

Illustration of External Air Pressure (Forces) Acting on an Internal Combustion Engine

Illustration 1



Front View of V-Type Engine

Note: Atmospheric pressure exists at an engine's exhaust outlet point at all times. If conditions within cylinders become lower than atmospheric pressure (as during valve overlap) outside air or exhaust gas can pass back intothe engine, causing fresh air/fuel mixture contamination and reduced combustion efficiency.

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board electronic controls, using various types of microprocessors of mini-computers, provide programmed fuel delivery and spark timing.

Methods of Cylinder Filling

If an engine receives air based on the force of atmospheric pressure, it is said to be "normally aspirated." In this case, atmospheric pressure changes with altitude, so engines must have their air/fuel mixtures and spark ignition timing adjusted to compensate for changes in atmospheric pressure. In today's computer-controlled engines, fuel and spark calibrations are adjusted by predetermined components in the microprocessor program that address a variety of environmental conditions…including atmospheric pressure.

Artificial means of supplying an engine with air include a variety of superchargers. Such devices provide pressure higher than atmospheric, virtually independent of geographical location (altitude). Some of these are belt or chain driven by an engine's crankshaft while others derive motive force from exhaust gas flow (turbo-superchargers). In any case, air pressure higher than atmospheric is provided, resulting in substantial increases in volumetric efficiency and torque. And in virtually every case of artificial aspiration, adjustments to fuel volume and ignition spark timing are required to optimize benefits of the additional air.

Besides artificial aspiration, it is possible to improve an engine's volumetric efficiency and torque by the addition of non-stock, bolt-on components. Included among these are special design intake and exhaust manifolds (or "headers"). Valve timing can also favorably affect volumetric efficiency by the exchange of a stock camshaft with one of non-stock valve events, typically directed to increased volumetric efficiency in a specific range of engine rpm. In addition, valve rocker arm ratios can be changed to effect improved v.e. Low-restriction air filters or elements can increase airflow, as can re-designed air inlet systems or ducting.

Essentially, air supplied to an engine is related to lower-than-atmospheric cylinder pressure. How this low-pressure condition is created and related to engine rpm and load will determine much of its ability to produce torque. Traditional modifications made to increase engine performance are directed to increased airflow and attending changes to fuel and ignition spark.

Illustration of Pressure Conditions During "Critical" Engine Cycles

Pressure Conditons During "Critical" Engine Cycles:

P1>P2<P3 - This is the intake cycle during which time air is forced into the cylinder.

P1=P2= or >P3 - This is at the moment of intake valve closing where cylinder pressure may be higher than atmospheric if a measure of "resonant tuning" (sometimes called "ram") has been accomplished.

P1<P2>P3 - At this point, the exhaust cycle begins and continues until...

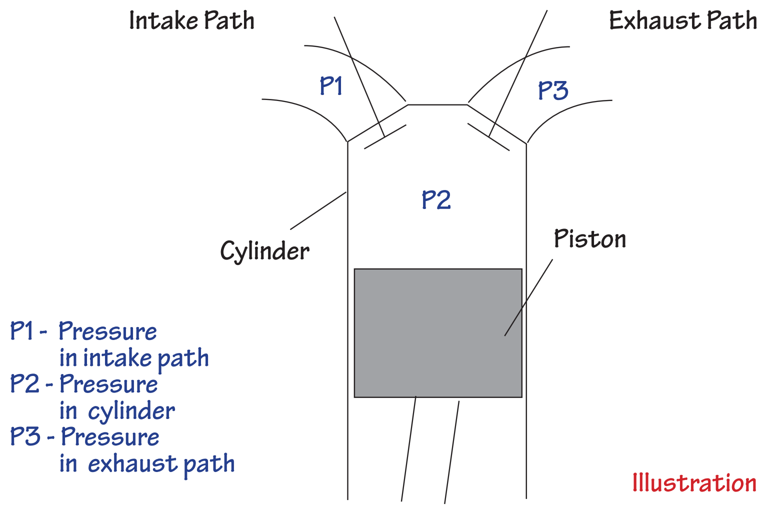

Illustration 2

P1>P2>P3 - This is the beginning of valve overlap, when the intake valve is beginning to open and the exhaust valve is about to close. Depending upon these pressure conditions, fresh air mixture may pass directly fromthe intake path, through the cylinder and out the exhaust path.

P1>P2<P3 - These condtions set up the beginning of the next intake cycle.

Special Case: When the intake valve first begins to open, it is possible that P2>P1, due to residual combustion pressure not reduced through the normal exhaust cycle. This causes exhaust gas to be passed back into the intake path, diluting fresh air/fuel mixture. The condition is often called "reversion".

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Engine Airflow (Advanced Information)

Today, the long-assumed status of engine airflow as a "black art" is changing. The evolution of precision air flow measuring equipment, computer modeling of engine functions, computational flow analysis of air movement to/within/from the combustion space and related technology development are rapidly increasing engine performance, efficiency and outright power.

Atmospheric Pressure as an Energy Source

Were it possible, especially when normally-aspirated, engines would be designed with intake and exhaust porting that provided direct, line-of-sight paths into and out of the combustion space. A plethora of conditions prevent this from happening. The result has become a complex engineering problem of designing the most effective and efficient paths that join an engine's cylinders with atmospheric pressure, on both sides of the combustion space (intake and exhaust).

Since atmospheric pressure is the primary energy source for cylinder filling, we need to know how it can be used to optimize volumetric efficiency and torque. In the future, when the combustion process is a lesson topic, ways airflow "quality" can influence the burn process will be discussed. Meanwhile, it's important to distinguish between airflow "quantity" and "quality," both of which are initially affected by the amount of atmospheric energy that's available during any intake or exhaust cycle.

Airflow "quantity" relates to the volumeof air present in an engine's air path. Most importantly, it deals with the quantity of air that traverses the inlet path and the quantity of air that reaches the combustion space. It is not a flow rate. So cubic feet per minute (cfm) doesn't equate to volume (or mass).

On the other hand, airflow "quality" describes the dynamic configuration of air. For example, how air pressure is distributed within a passage contemplates high and low pressure areas, typically related to flow velocity. (see illustration #6, showing a vectored "distribution of pressure" in a flow passage.) While airflow quality is critical in the conveyance of fuel to the combustion space, this aspect of flow dynamics affects even "dry flow" induction systems (fuel introduced at or near the combustion space).

As this instructional series unfolds over the coming months, we will discuss specific design components that affect engine airflow. These discussions will be directed to increased knowledge in the selection of parts as well as a more in-depth understanding of their functions. At this point, it will be helpful to expand upon the term "volumetric efficiency," particularly since it bears such a strong influence upon an engine's potential to produce torque.

Volumetric Efficiency

Generally, volumetric efficiency is defined as a ratio of induced air (for a given cylinder and at a specific rpm) to the swept volume (physical volume) of the cylinder. More exactly, "induced air" should be considered at ambient temperature and density, where "ambient" is taken to mean air conditions outside the engine at time of measurement. It should be understood that the temperature and density of induced air at the end of the intake cycle (including fuel charge density and temperature) are more specific to the calculation of v.e.

From a practical standpoint, there are variables that influence "net" volumetric efficiency, including the effects of mechanical compression ratio. But for purposes of discussion and understanding, suffice that volumetric efficiency is a measure of how effectively an engine is able to ingest volumes of air equitable to its physical piston displacement or total swept volumes. Volumetrically efficient engines typically produce v.e. in the range of 85-90% at peak torque (or peak v.e.). Engines fitted with tuned intake systems producing inlet pulses of pressures higher than atmospheric can produce v.e. in excess of 100%.

Factors Affecting Volumetric Efficiency

They are numerous. Of them, there are certain ones that should

Illustration of Basic Flow Passage Shapes for Engine Air Movement

See text for further explanation and examples

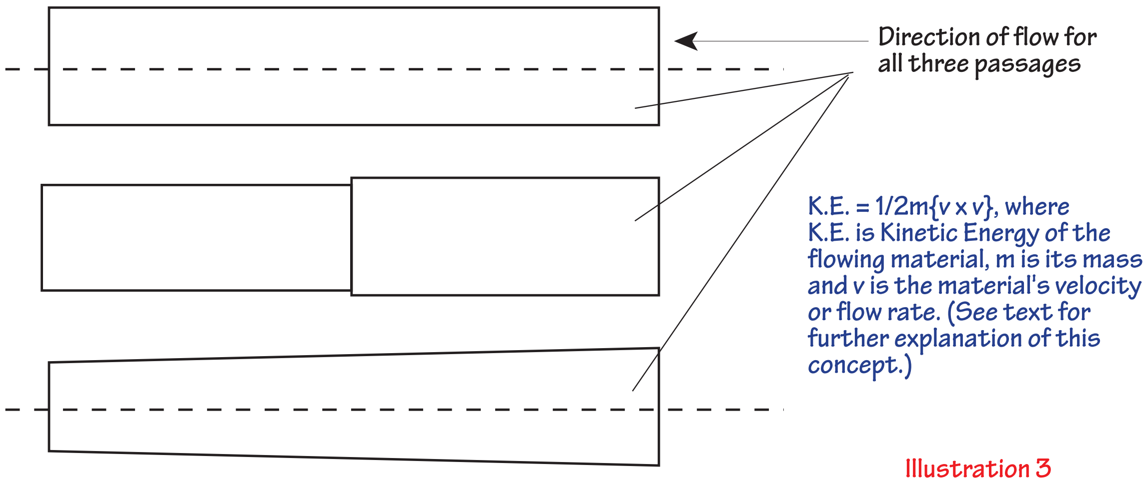

Illustration 3

Note: See text for further explanation of these illustrated pressure conditions. In particular, note that any point along the axis of passage #1, flow velocity is a constant (there is no change in crossection area). In passage #2, there is a constant change in flow velocity, caused by a continuous change in crossection area. Passage #2 is a "special case", discussed at length in the text. So-called "stepped" passages are commonplace in exhaust headers used for some high performance street and many race engine applications.

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be considered during the modification (or building) of an engine or its parts.

One consideration is the **effect of inlet air temperature**. There is a "balance" between low temperature inlet air that is more dense than higher temperature air and air that is heated along the inlet path into the cylinders. Higher density air is usually associated with increased oxygen content, and correspondingly higher power. What must be weighed against this possibility is that as heated engine parts add temperature to incoming air and its density is decreased, volumetric efficiency is reduced. Remember that volumetric efficiency is a comparison of air volumes by weight, and altering density by a temperature change affects air weight.

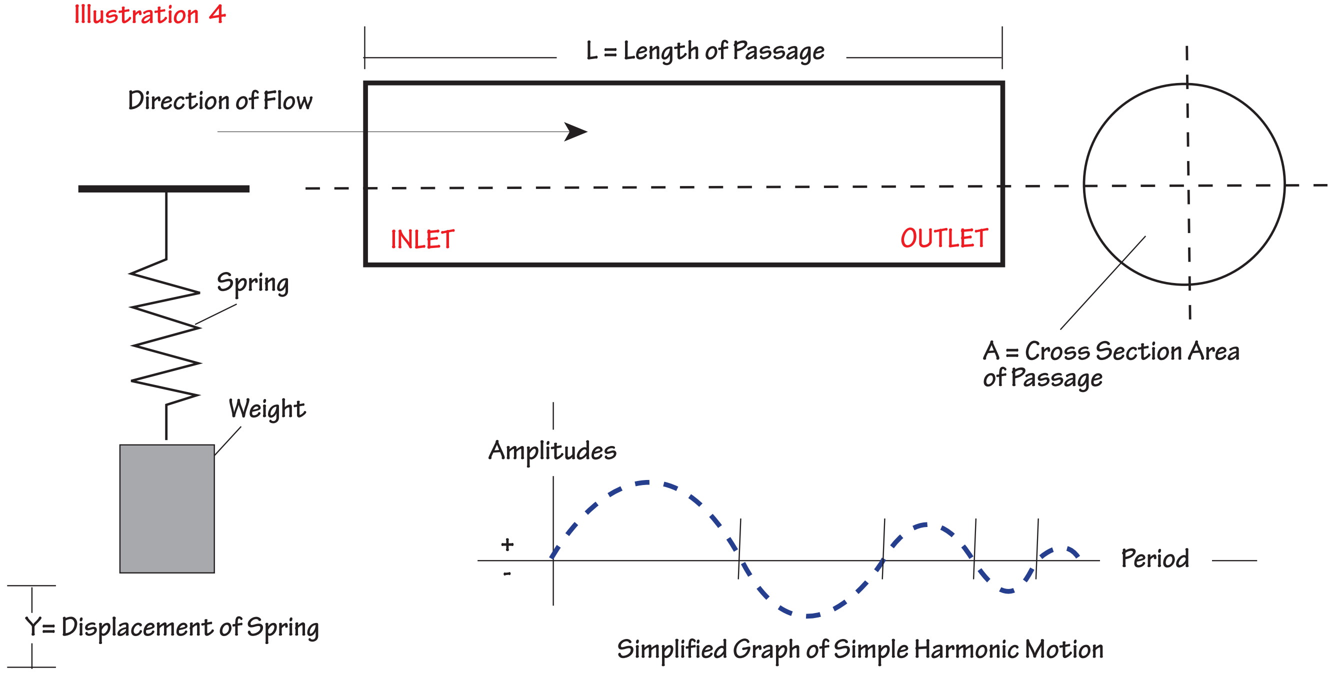
Here's the so-called "balance" issue. If intake air temperature is increased, the temperature **difference** between it and heated engine parts located along the inlet air path will be reduced. This reduction in temperature difference can lead to a v.e. increase, since the inlet air and in-cylinder air temperatures approach each other. In fact, if this notion is taken to extreme, it's possible that heated intake air could **lose** temperature to the inlet path and contribute to a net v.e. increase.

Bottom line, it's generally a good idea to reduce inlet air temperature and achieve an oxygen-increasing density elevation, resulting in a power gain…simply stated. And as these changes in final mixture density (from combined inlet and in-cylinder temperatures) are altered, both the amount of fuel delivered AND ignition spark timing should be evaluated for optimum performance. For example, increasing final mixture density tends to accelerate combustion flame travel. This opens the door for a slight reduction in ignition timing, leading to an opportunity to reduce the amount of work (negative) performed on a piston ascending TDC on the compression/power stroke.

There are also **dynamic** conditions that can affect volumetric efficiency. In fact, these factors play a part in differences between v.e. and its corresponding torque curve. Fluid friction and inherent inertia characteristics of the "working fluids" in an engine's intake or exhaust system (air, air/fuel mixtures or exhaust gas) when com-

Simplified Illustration of Pressure Wave Motion in an Air Flow Passage as Analogous to a Spring-Suspended Weight

Illustration 4



Note: Assumes flow is initiated in the indicated passage, from left to right (as veiwed in this illustration). If atmospheric pressure exists out the outlet end of the passage, a "return" wave will be directed back] to the outlet. Upon arrival at the inlet end, this wave will be re-directed back to the outlet end. Motion of wave travel can then be described as "simple harmonic motion", akin to that produced by a weight suspended by a spring. (See text for further explanation.)

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bined with improper valve timing can lead to reduced volumetric efficiency.

From a practical viewpoint, these poor results often accompany incorrect "matching" or integration of engine parts. There is a "symmetry" to the functional relationship among an engine's components. By avoiding this concept, the "whole" of an engine is not the sum of its parts. For example, failing to consider such basic elements as intake and exhaust port flow when selecting a camshaft can lead to the failure of all three components to fall short of their optimum performance.

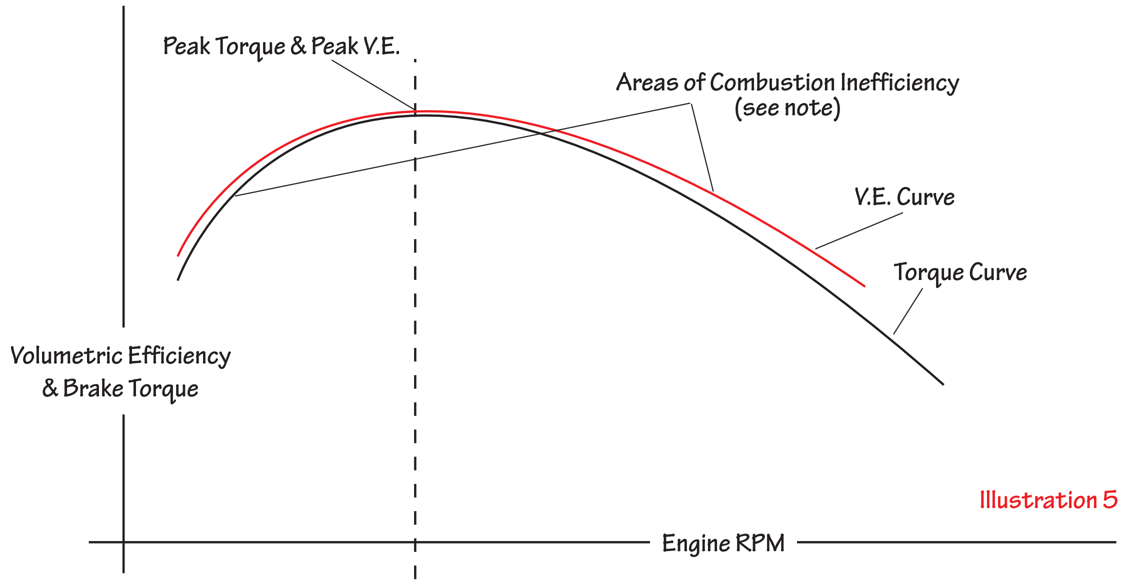
As this series of lessons continues to unfold, expect more in-depth discussion of how major engine components (or systems) should be viewed for proper functional integration.

Concluding thoughts on volumetric efficiency (for future reference)

Essentials to the improvement of an internal combustion engine's output include increased airflow, at varying rpm and conditions of load. Volumetric efficiency is a measure in determining these improvements. While the determination of quantitative degrees of volumetric efficiency are not the direct concerns of "hobby" or street performance engine builders, the fact that v.e. is linked to torque is important.

In order to make sensible decisions about changing camshafts, headers, mufflers, intake manifolds, carburetor, air valves, cylinder heads and an assortment of other power-enhancing parts or systems, the role of volumetric efficiency requires acknowledgment. The reason for this is basic: Given proper adjustment to factors affected by or affecting volumetric efficiency, increased torque should result. Clearly, bigger is not always better. In far too many instances, bigger is worse.

Illustration of Fundamental Relationship Between Peak Torque & V. E.



Note: Areas of "combustion inefficiency" show where the fact that air is present in the cylinders does not always translate into torque. Up to peak torque rpm, inefficient charge mixing decreases combustion efficiency. Above peak torque rpm, there is either insufficient time to combust the air/fuel charge or charge quality is reduced by air/fuel mixture separation or dilution with combustion byproducts, typically exhaust gas.

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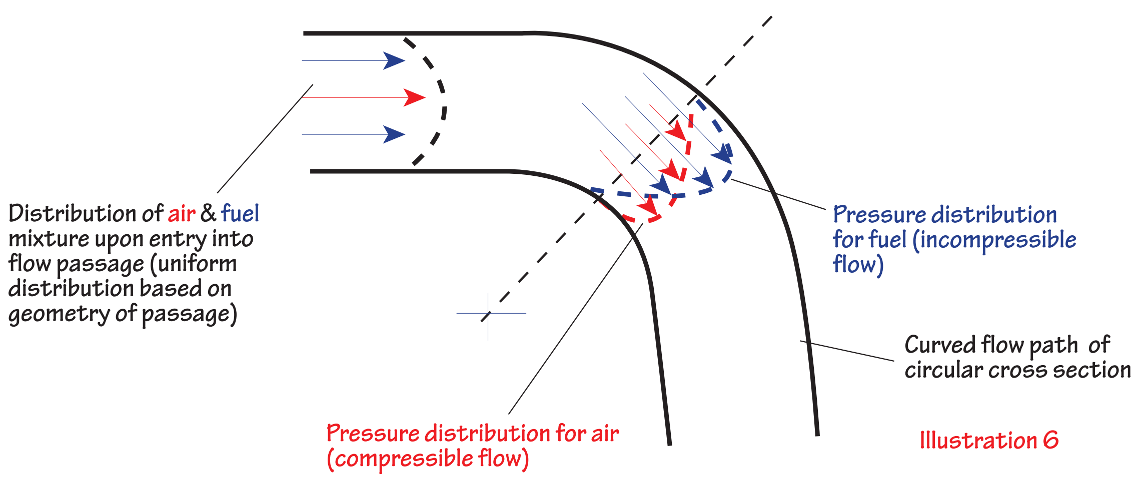
Illustration of Pressure Distribution During Changes in Flow Direction



Note: The geometrical configuration of flow passages, whether for dry (air only) or wet (air and fuel) can be designed to provide uniform distribution during flow directional changes. Essentially, these designs accommodate changes in direction as if none had occured...highly desireable in wet-flow environments and flow rates in excess of 300 feet/second which are common in racing engines.

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Glossary

Air Density
Basically, density refers to a substance's mass per unit volume. In the case of an internal combustion engine, air density usually refers to the total mass of an air sample as affected by the percentage of water (moisture) it contains, temperature and pressure at which it is measured.

Ambient
As this pertains to an internal combustion engine, the term applies to the temperature of air immediately surrounding the air inlet point.

CFM (cubic feet per minute)
This is a measure of engine airflow (by volume) as a function of time.

Combustion
This is a process whereby a rapid chemical reaction takes place between oxygen and a fuel, causing the liberation of heat, which is energy in a useful form.

Compression Stroke
The upward movement (stroke) of an engine's piston immediately following closing of the intake valve, causing a rise in cylinder pressure.

Compression Ratio
A numerical value that compares the volume above an engine's piston at its bottom dead center position to the volume above the same piston at its top dead center position.

Displacement
The physical volume of a piston or set of pistons determined by cylinder bore size and length of piston travel (stroke) from its bottom to top positions.

Dynamic
Applicable to engine functions or conditions that imply movement or energy (as opposed to static conditions).

Horsepower
The application of torque acting over a period of time, or the time-rate of performing work; e.g., 1 horsepower = 33,000 feet-pounds/minute or work/minute divided by 33,000.

Induction
A process whereby air or air and fuel is admitted to an internal combustion engine.

Inertia
A characteristic of an object or substance to resist a change in state of motion, either from at rest or in motion.

Net Power
A term applicable an internal combustion engine whereby all parasitic losses are considered to produce a final value of output.

Pressure
In automotive application, a measure of stress (typically expressed as force per unit area) that is uniform in all directions, including conditions whereby the distribution of such forces may vary with location.

Static
Applicable to conditions or functions whereby there is no motion or relationship with time.

TDC (top dead center)
The location of an engine's piston where there is momentarily no vertical motion and direction is changed from upward to downward.

Torque
The result of a force acting on a body that intends to produce rotation.

Vacuum
A condition that results when the pressure in a space or region is less than atmospheric pressure.

Velocity
In automotive applications, this is a measurement of the time rate of change of an object, system or working fluid. If velocity becomes variable, the subject experiences acceleration.

Volume
A space measured in cubic units pertaining to capacity.

Volumetric Efficiency
A measurement comparing the weight of a gas or a combined working fluid passing into an engine on its induction stroke compared to the weight of that gas or fluid that would occupy the engine's cylinders under standard conditions of atmospheric pressure and temperature (usually represented as a percentage).

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Guest Commentator on the subject of "Basic Engine Air Flow"

Ron Funfar, President
Hedman Hedders & TD Performance Products

"In the study of engine air flow, it is important to consider how air enters and leaves an engine's cylinders. Without this knowledge, the selection and matching of components that improve airflow will not be optimum. There are certain basic considerations in the choice and application of performance parts affecting engine air movement and, ultimately, net power.

"First, the engine's final application must be considered. Whether it's for high performance street use, racing or towing a trailer, how an engine will be used determines the method and extent of modifications to be performed.

"It's also critical to determine a specific range of rpm in which the engine will be used, most of the time. For example, an engine that makes good power and high rpm but is used on the street is a mismatch of components and application. Conversely, it's a waste of money and time to build a low- or mid-rpm engine that sees use primarily at high rpm.

"You can take this concept right to the selection process when choosing parts that affect air flow. In the case of exhaust headers, the installation of big-tube headers might allow efficient airflow at high rpm, but these same headers can decrease torque in the mid-rpm range and adversely affect street performance.

"Not only does rpm influence parts selection, so does an engine's size or piston displacement. The same size headers that make good high rpm power on a small displacement engine will improve power at a lower rpm on a larger displacement engine. It's simply a matter of how much air is displaced at each rpm, and the bigger the cylinder the more air it'll move…at the same rpm. We size our headers based on piston displacement and rpm, thereby addressing torque output based on these two conditions.

"Another area I believe needs to be understood by people learning about engines is that torque and horsepower are not the same. Torque is what makes a vehicle quick. Horsepower makes it fast. The ability for an engine to make torque depends on how fast it can get air. The faster it can 'breathe,' the quicker it can make torque. I think this is a subject talked about in this month's n2performance lesson, so I won't go into it further here. But it's very important to understand that an engine's ability to make torque depends on rapid, clean airflow…in and out of the engine.

"Overall, learning as much about the basics of engine air flow will lead to the ability to properly select and apply modified parts and systems. Knowing the basics is something that we often don't take the time to do, but in the case of understanding how engines work, we don't have a choice but to take the time to learn."

Review Questions — True or False

1. Atmospheric pressure acts only on the intake side of an engine, causing the exhaust system to operate in a partial vacuum.

2. Because of the rapid decrease in cylinder pressure during an engine's intake cycle, air (or air/fuel mixtures) are drawn or "sucked" into the engine.

3. When an engine is modified to increase net airflow, it is often necessary to make changes to fuel delivery and ignition spark in order to optimize power from the additional air.

4. Without some means of mechanically aspirating (supercharging) an engine, it is not possible to achieve volumetric efficiencies higher than 100%.

5. Airflow "quality" refers to the dynamic condition of engine air, particularly with regard to the distribution of pressure within a given sample and how this may affect air/fuel mixture conditions.

6. According to Hedman Hedders President, Ron Funfar, header selection should include consideration for total piston displacement and rpm in order to maximize torque from an improved exhaust system.

7. Changes in the temperature of an engine's inlet air have little or no effect on overall volumetric efficiency.

8. In the modification or building of a performance or racing engine, it is important to understand the relationship between and importance of volumetric efficiency and torque.

9. All else being equal, the reduction of air/fuel charge temperature (in an engine's cylinders) tends to increase mixture density and flame travel.

10. Generally speaking, "ambient" air temperature can be taken as the temperature of air surrounding an engine.

Answers

1. **False** – Atmospheric pressure surrounds an engine entirely, even if it is artificially aspirated.

2. **False** – An engine's cylinders are filled by the positive pressure (work performed by) either atmospheric or artificial pressure sources…as in supercharging. Engines operated below sea level experience a form of "supercharging."

3. **True** – Increased volume of air in an engine's cylinders, required to combust in the same period of time as before the increase, typically required a change in fuel volume and ignition spark timing.

4. **False** – By the use of certain intake system "resonant tuning" characteristics or phenomena, it is possible to achieve volumetric efficiency levels above 100%. This is commonplace in well-tuned racing engines.

5. **True** – The "construction" of airflow and its nature during combustion can be related to its quality, not quantity.

6. **True** – In both design and selection of exhaust headers, pipe size relates to total piston displacement and rpm because of how these two factors affect exhaust flow rate and tuning.

7. **False** – Air temperature and its density are related. And because changes in air density can affect volumetric efficiency, temperature changes can impact v.e.

8. **True** – Either directly or indirectly, one leads to the other.

9. **True** – Again, all else being equal, dense air/fuel charges burn more rapidly than do those less dense.

10. **True** – Even though air temperature differences are apparent in various areas on and within an operating engine, the initial temperature of air that passes the first point of entry can be considered ambient.