

Cylinder Head Design and Modification - Getting Started

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From Engine Builder Magazine, by Ken Weber

No one can teach you how to port heads in a single magazine article, because every job is unique to itself and its intended use. If you are serious about learning to do this combination of artwork and science called porting, I suggest you look into something like Joe Mondello's porting school. (805) 237 9185. They will teach you what tools are needed and how to use them, where to take metal out, and sometimes where to put metal in.

Using porting tools properly is essential to the quality of the finished part. A grinder is not as easy to use as it looks. With a can of spray paint, or a paint gun, if you keep your finger on the nozzle or trigger at the end of a stroke, you will have runs in your paint. And so it is with a grinder - except instead of runs, you have divots where the cutter takes too much material. If you've never done this, you should first of all, invest in the proper tools, and then practice on a junk part for a while. Although I've done it, I don't recommend you use an electric drill. Get a proper die grinder. I prefer a foot controlled, variable speed shaft grinder with interchangeable hand pieces such as one made by Fordham Tool Co. Air powered grinders turn too many rpm. Joe Mondello is also a source for porting supplies, and he has a catalogue that will get you started. Another source is CC Specialty in Lawrenceburg, Tennessee. (931) 762 6995. They have a catalogue and also sell the Fordham grinders.

There are books available, such as David Vizard's "How to Port Small Block Chevy Heads", and "The Theory and Practice of Cylinder Head Modification", and books on aerodynamics that are helpful. SAE sells books and engineering papers on the subject, and Motorbooks (motorbooks.com) has books available. You should start building a library, and get friendly with it.

If you have one, get out your high school physics book and study up on Bernoulli's equation. It describes the relationship between pressure and velocity in a fluid as it flows through a pipe, which changes in cross sectional area along its length. Bernoulli's equation translated, says that as you increase the velocity of the fluid, the pressure of the fluid at that point decreases, and if you slow the fluid down, the pressure of the fluid increases, and how much it increases or decreases. How do you change the speed of the air in a port? Simply by making the port bigger (slower) or smaller (faster). Also, any fluid, including air, does not like to change direction, and doing so causes it to lose velocity and energy which is hard to recover. To better understand your mission in porting heads, you should spend some time thinking about how all this works in an engine.

Cylinder Head Design

The cylinder head is the part of an engine that is most responsible for its performance characteristics. Once the basic geometry of an engine is established, there is no other part that has as much influence on the amount of power developed, and the shape of the power curve. All the other parts are merely supporting cast.

So, what determines the worth of one head over another? First, you must understand that any design is a compromise between what is desirable and what is possible. Engineers that initially design an engine rarely have free rein to make it the most powerful piece possible - and they may not want to either. Even in Formula 1, where engines are designed from scratch to make as much power as possible, there are compromises that are determined by the rules of the sanctioning body and the necessity to install the engine in the car. Like other vehicles, aerodynamics and handling requirements require compromises in size, shape and weight of the engine.

The vast majority of the aftermarket cylinder heads popular today are compromised because they adhere to the standard OEM port geometry. This is done so the supporting components designed to that geometry can be used on the new head. As engine builders, most of us have to work with parts that already exist. They may be production parts or aftermarket parts, but they all have compromises, and it's up to us as porters, to minimize the compromise.

How Airflow Is Measured

Most people interested in performance know that a flow bench is used to measure airflow, but lacking hands on experience, don't understand how it works, how it is used to measure flow in a cylinder head, or what the flow numbers actually mean.

You should know that a fluid flows from high pressure to low pressure. Air, being a fluid, follows that rule. If you turn on your vacuum cleaner, the motor creates a low pressure inside the cleaner, and atmospheric pressure, now being higher, pushes air in to fill the void. The rate of flow of the fluid is proportional to the difference in pressure. Seal the vacuum hose to the combustion chamber of a cylinder head, open the intake valve and turn the motor on. Air will flow through the port and into the cleaner. Add a valve in the hose to regulate how much pressure or suction you are using, and a means of measuring the suction and the amount of flow - usually done with manometers - and you have a flow bench.

All this flow bench does is move air through a port by creating a predetermined pressure differential, and then measure the quantity of air being moved. Tests can be done at any pressure you choose, up to the limit of the bench's capability. Most are done at 10", 25", or 28" of water, but the trend is to higher pressures, like 60 inches.

A cylinder head adapter is commonly used to mount the head to the bench (as opposed to the vacuum hose previously mentioned) so the effect of cylinder wall shrouding can be simulated. Either a radius-ed inlet guide or an intake manifold can be attached to the head to eliminate turbulence at the manifold flange, and if testing the exhaust side, a short length of appropriately sized exhaust tubing is mounted on the header flange. A rigid fixture that will open the valve in .001" increments is needed too. Mount the head on the head adapter, open the intake valve to the first increment of lift, say, .100". Turn on the motor, and set the control valve at a test pressure such as 25", and record the amount of flow. Open the valve to the next increment of lift, such as .200", and repeat the test, again at 25" of water. A similar test is done at each increment of lift you wish to test. You have now flow tested one intake port, and have some data telling you how much flow your port has at 25" of water, at each increment of lift you tested. To be meaningful, all tests should be done at the same pressure, and use the same inlet or outlet configuration, and the same test procedure. Simply using a different inlet radius, valve shape, or cylinder diameter can change the flow. In other words, sweat the small stuff and pay attention to the details to insure repeatability and make comparisons from one test to another valid.

To this, you can add tests for tumble and swirl in the cylinder, do localized testing within the port with test probes to determine velocity distribution and turbulent areas, try different valve and seat shapes, and even do wet flow testing if you have the capability. You can also reverse the head on the flow bench and check the flow characteristics around the valves in the combustion chamber (blow through the intake port and suck through the exhaust port).

A standard for maximum flow through a valve is 146 CFM per square inch of valve opening. This is used to rate the efficiency of a port. I use the valve curtain area - the circumference of the valve head ($3.1416 \times \text{Diameter}$), x valve lift, x 146 CFM, and then divide the result into the flow. This gives a percentage of the standard at each valve lift. If the port in the head can be made to flow up to the standard then it would in effect be achieving 100% efficiency. If it only flows half as much, then it would be 50% efficient. Another way to rate flow is to relate it to the area of the head of the valve. So now you have a means to test a port and a means to rate that port at each valve lift, relative to a standard. From that you can evaluate the efficiency of different heads based on valve size and lift.

Remember, a flow bench, like a dynamometer, is just a tool. It will give you data, but it will not tell you how to interpret that data, nor tell you what decisions you need to make regarding the suitability of the port you tested, nor will it tell you how to change the port to make it better. From this point, you must evaluate your data and make those decisions - and therein lies a large portion of the skill in modifying cylinder heads.

How Airflow Influences Engine Performance

Volumetric efficiency is the measure of how well the cylinder is being filled with air, as a percentage of what it would be if it were filled to the same pressure as the atmosphere outside the engine.

As the piston moves away from TDC, it creates a vacuum in the cylinder, which draws in the fresh charge of air and fuel. As the piston accelerates from TDC toward its point of maximum velocity at around 75 degrees after TDC, flow lags behind demand, creating a higher and higher vacuum in the cylinder. Then the piston slows down until at BDC it parks for a moment before starting back up the cylinder. As the piston nears BDC, the inertia of the air from its velocity causes flow to catch up with piston demand and then finally exceed it. After bottom dead center, the piston is going the wrong direction to pull in air, so even though we don't get 100% VE on the down stroke of the piston, we can achieve high overall volumetric efficiency by holding the intake valve open long after bottom dead center, to take advantage of the momentum of the intake charge (from its velocity) and the resonant tuning of the intake port, to keep filling the cylinder after the piston changes direction. This packing of the cylinder continues as the piston continues back up the cylinder until the valve closes. In a properly "tuned" intake system, a pressure wave will also arrive at the valve shortly before it closes, packing even more air in the cylinder. If it were not for the inertia of the incoming air, and resonant tuning of the

port, it would be impossible to achieve even 100% cylinder filling. Typical low performance production engines operate in the 60% VE range.

The demand on the intake port is partially a function of the piston speed, which is zero at top and bottom dead centers, and can reach 8000 ft/sec or more (about 5400 miles/hour) somewhere between 70 and 80 degrees after top dead center. For a 4" bore by 3.48" stroke 350 Chevy to achieve 100% volumetric efficiency at this point, the head would have to flow over 500 CFM. It is unlikely that we will find a head for a small block Chevy that will flow this much, and if we did size the port for the 500 CFM demand at this point in the cycle, it would be too big during the remainder of the cycle and have insufficient velocity to continue filling the cylinder after bottom dead center. Ports and valves that are too big don't generate sufficient velocity in this segment of the intake cycle, and therefore don't make as much power as a port that is properly sized. Bigger is not always better. With resonant tuning and high velocities, typical performance engines can operate close to 100%, while more highly refined engines can achieve 120% or more, especially engines with multiple intake valves per cylinder.

On the exhaust side, velocity is important too. The velocity of the exhaust pulse in the port and header creates a vacuum behind it, creating a pressure drop in the cylinder as the piston approaches TDC on the exhaust stroke. This pressure drop from the exhaust during valve overlap, gets the intake system started before the piston even starts down on the intake stroke.

The Kinetic energy in the air moving in and out of the engine is a function of the square of the velocity, so small changes in velocity make large changes in the energy of the flow.

Even though the conditions in a running engine are constantly changing throughout each intake and exhaust cycle, steady flow on a flow bench can give a good representation of the power available from the engine by approximating the average conditions in the engine. Tests done at 25" of water test pressure seem to closely approximate the *average* conditions that exist in an engine.

As I mentioned earlier, there is a trend to testing at much higher pressures. Peak velocities in a port can be over 600 ft/sec, but testing an intake port sized for high rpm power at 25" of water may only have 200 ft/sec on the flow bench. It may be very efficient at that velocity, but have high levels of turbulence at twice that velocity. The only way to determine the worth of a port at the higher velocities is to test it at those velocities, requiring higher test pressures.

When you increase the efficiency of a port in the normal direction, you also increase the efficiency of the port in the wrong direction. This makes the engine more sensitive to camshaft changes, and to intake and exhaust system tuning. An intake manifold or exhaust system that worked just fine before, may not work very well after the heads are done, not because it's a bad piece, but because it's the wrong piece.

So, what is the process to determine the correct cylinder head or head modifications needed? Whether you are dealing with a street rod or a serious race effort, the first thing to do is determine how the engine will be used, the rpm range it will see, the engine specs, and a power goal. I regularly deal with customers that have never answered those questions, they just want their heads ported because they believe it will make more power, but until they are answered, you have no way to determine the optimum port and valve sizes, and flow requirements. If you want a pair of heads for a rock crawler that mostly runs just above idle, but you ported them the same as you would for a 7000 rpm bracket racer, you would probably not be happy with the results. Once these things are known, you can proceed.

There are mathematical relationships that can predict the airflow requirements to reach a specific power - or predict the power potential of a known airflow - and the rpm at which peak power will be developed. This includes the intake manifold and carb or throttle body. These equations can be used to see if you are in the "neighborhood" of what you want to do. If the rest of the engine combination is complimentary, they will be pretty accurate. If you have the airflow desired, but the engine does not make the power it should, then you have another problem that needs fixing.

Horsepower per cylinder = .43 x airflow @ 10" of Water, .275 x airflow @ 25" of water, or .26 x airflow at 28" of Water. To find required airflow for a given horsepower, divide the horsepower per cylinder by .43, .275, or .26 respectively.

RPM at peak horsepower will be 2000 divided by the displacement of one cylinder x airflow @ 10" water. Use 1267 @ 25" of water, or 1196 @ 28" water. The more airflow available to the cylinder, the higher the rpm required to reach peak horsepower.

The maximum practical intake valve size in a two valve, wedge chamber head is about .52 x the diameter of the bore. In a hemi type chamber, .57 is about the maximum.

How to Improve Airflow

The vast majority of porting work can be described as merely cleaning up an existing port and doing a valve job for improved performance for a street rod, boat, or for sportsman level racing. No matter what the application, an understanding of what is needed and a methodical approach to the modifications will

usually result in a satisfactory level of performance. A flow bench is essential, because it's really easy to make things worse. It can be a commercial unit or home built, as long as it is repeatable.

The level of porting you wish to do will determine the approach taken. You can start with a good valve seat shape and blend it into the bowl under the valve and to the chamber and call it good, or you can get into a complete ongoing cylinder head development project, or somewhere in between.

The area from around the valve guide across the seat and into the chamber responds more to changes (both good and bad) than any other part of the port, especially the short turn, and the shape of the valve and valve seat is the single most critical part. The largest flow loss is in the expansion of the air as it exits the valve/valve seat into the chamber. Different valve shapes which sometimes include rolling or radiusing the margin area of the valve, different widths and angles on the back side of the valve, and different angles approaching and leaving the seat are some of the "tunable" things that make and otherwise ordinary job come to life. Many ports can be improved substantially by merely blending the seat cuts into the bowl under the valve and into the surrounding combustion chamber, frequently referred to as "pocket porting".

My approach to head work is to first determine a power goal as explained above, which determines the required flow and port and valve sizes.

Next, I flow the head to get a baseline flow curve, and decide what modifications are most likely needed to meet the performance goal. Depending on how much material has to come out, I may sonic test the ports for thickness to make sure I don't have a problem there.

If I'm to do a full porting job, I make a rubber mold of the port and slice the mold into segments $\frac{1}{2}$ to $\frac{3}{4}$ inch wide. I lay each segment on graph paper, draw around the circumference, and count the squares in the outline of each segment to obtain its cross sectional area. This gives me a diagram of the shape of the port. The silicone rubber I use is Dow Corning Silastic V base and curing agent. You can find a distributor near you at dowcorning.com. I have tried the Silastic M, but it is too hard, which makes it difficult to get out of the port once it cures. I have also used Blue Sil type G, from Perma Flex, 1919 Livingston Ave, Columbus Ohio. Expect to pay close to \$150 for a gallon of it.

If I plan to make radical changes to the port geometry, I will make an acrylic flow box as detailed in a previous article, and do the development work on that before moving to grinding on the real head. With the flow box, mistakes can be made and repaired much easier than on the real head. In developing valve shapes, I make valves out of aluminum, which is inexpensive compared to buying valves, and easy to make changes to. They can be ground in a valve grinder just like a normal valve if you use Pro Blend in the grinding oil. By making the stem from 11/32 or 5/16 material, and the head separate, time is saved and material waste is small.

From this point on, it's a matter of grind awhile, pour a mold, redraw the port shape, and evaluate the new shape. Once the port is close to the desired shape and size, the valve seat is cut and blended, and then the port is tested on the flow bench again. It may take a lot of attempts to get it right. Once I get the first port finalized, I make aluminum patterns of the shape of each side, the roof, and the floor of the port, and use them to shape the rest of the ports (assuming there is more than one cylinder). This helps make all the ports as nearly the same as possible. Finally, all the valve seats are cut and blended into the chambers and ports, the chambers are checked for size and the head surfaced as needed for the desired volume. It's not unusual to spend over 100 hours on a pair of aluminum V8 heads, so be patient. Cast iron heads take longer.

To the general automotive community, CNC porting is the hot item these days. CNC merely means that a computer controls the tool paths of a milling machine to take material out of a head. The main advantage to CNC porting heads is time and repeatability. In most cases, the port being CNC'd is a digitization of a port that was developed by hand porting using the methods described above, and the success of the port being CNC'd depends on how good the port is that was used to develop the program in the first place. If the original port wasn't too good, then all you have is a whole lot more ports that are also not too good. Even if it's an outstanding port, it may be wrong for your application. The key here is to find a good port that fits the application, and the only sure way I know to do that is to get your hands on one, make a mold to evaluate the shape, and flow test it, then decide if it's suitable.

As you can see, properly modifying a set of heads involves much more than merely picking up a grinder and polishing the surface to a high luster. I have only touched the surface of what is involved, but space is limited.

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