

# Turbocharger Compressor Calculations

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## Introduction

The purpose of this little paper is to show the reader how to calculate the volume and mass of air moving through his engine, and how to size a turbochargers' compressor to move that quantity of air. It should also offer some enlightenment of the effects of temperature, pressure, and intercooling on the engine's performance.

## Engine Volumetric Flow Equation

This equation is for finding the volume of air going into the engine. The displacement on our cars is 231 cu.in. We have a four stroke engine; the intake valve on a cylinder opens once every 2 revolutions of the engine. So, for every 2 revs the engine takes in 231 cu.in. of air. How many pounds of air is that? That depends on the pressure and temperature of the air in the intake manifold. But the volume is always 231 cu.in. every 2 rpm.

$$\text{volume of air (cu ft/min)} = \frac{\text{engine rpm} \times \text{engine cid}}{(1728 \times 2)}$$

## Ideal Gas Law/Mass Air Flow

The Ideal Gas Law is a handy equation to have. It relates the air pressure, temperature, volume, and mass (ie, pounds) of air. If you know any three of these, you can calculate the fourth. The equation is written:

$$PV=nRT$$

where P is the absolute pressure (not the gauge pressure), V is the volume, n is related to the number of air molecules, which is an indication of the mass (or pounds) of air, R is a constant number, and T is the absolute temperature.

What are absolute temperature and pressure? Do we care? Of course we do!

Absolute pressure is the gauge pressure (measured by a gauge that reads 0 when it is open to the outside air) plus atmospheric pressure. Atmospheric pressure is about 14.7 psi at sea level.

**Example:** a boost gauge reads 0 psi before it is hooked up. Hook it up, boost the car, and it reads 17 psi. 17 psi is the gauge pressure, the absolute pressure at sea level is 14.7 + 19 = 33.7.

A pressure reading is marked psia or psig. The "a" stands for absolute, the "g" for gauge. (The psi stands for Pounds per Square Inch). As we just showed, 17 psig = 33.7 psia. A perfect vacuum is 0 psia, or -14.7 psig.

The absolute temperature is the temperature in degrees F plus 460. This gives degrees Rankine, or deg R. If it is 80 deg F outside, the absolute temperature is 80 + 460 = 540 deg R.

The *Ideal Gas Law* can be rearranged to calculate any of the variables. For example, if you know the pressure, temperature, and volume of air you can calculate the pounds of air:

$$n=PV/(RT)$$

That is useful, since we know the pressure (boost pressure), the volume (which we calculate as shown in the first section "Engine Volumetric Flow"), and we can make a good guess on the temperature. So

we can figure out how many pounds of air the engine is moving. And the more pounds of air you move, the more power you will make.

Here is the Ideal Gas Law rearranged to the two handiest forms, with the required constants:

### To get pounds of air:

$$n(\text{lbs}/\text{min}) = \frac{P(\text{psia}) \times V(\text{cu. ft.}/\text{min}) \times 29}{(10.73 \times T(\text{deg R}))}$$

### To get the volume of air:

$$V(\text{cu. ft.}/\text{min}) = \frac{n(\text{lbs}/\text{min}) \times 10.73 \times T(\text{deg R})}{(29 \times P(\text{psia}))}$$

## Volumetric Efficiency

If life was perfect, we could fill the cylinders completely with air. If we had 17 psi boost in the intake manifold, we would open the intake valve and get 17 psi in the cylinder before the intake valve closed. Unfortunately, this doesn't usually happen. With some exhaust remaining in the cylinder and the restriction offered by the intake ports and valves the actual amount of air that flows into the cylinder is somewhat less than ideal. The amount that does flow divided by the ideal amount is called the volumetric efficiency.

For your basic stock small block chevy, I think this number is around 0.85 (or 85%). Things like big valves, big cams, ported heads, tunnel rams, etc... get this number closer to 1.0 (or 100%). With tunnel rams some normally aspirated cars can get over 100% at certain rpms due to the ram effect.

To take this into account when we calculate flow into the engine, we multiply the ideal amount of air by the efficiency to get the actual amount of air:

$$\text{actual air flow} = \text{ideal air flow} \times \text{volumetric efficiency}$$

### Example

Time for an example. Lets calculate the pounds of air flowing into an engine for two different cars, an intercooled '87 and a nonintercooled '85. For both cars we will use a volumetric efficiency of 0.85. For both cars the engine is turning at 5000 rpm. What is the volume of air it is using?

$$\text{volume, in cu.ft per minute} = \frac{5000 \times 231}{1728 \times 2} = 334.2 \text{ cfm}$$

This holds true for both cars, both intercooled and nonintercooled will be moving 334.2 cfm of air into the cylinders at 5000 rpm. As we will see however, the mass of air flowing is not the same.

Suppose the car an '85, so it isn't intercooled. The temperature in the intake manifold is about 250 deg F. The car is running 19 psi boost. What is the mass of air the engine is using?

$$\text{Absolute temperature} = 250 \text{ deg F} + 460 = 710 \text{ deg R}$$

$$\text{Absolute pressure} = 19 \text{ psig} + 14.7 = 33.7 \text{ psia}$$

$$n(\text{lbs}/\text{min}) = \frac{33.7 \text{ psia} \times 334.2 \text{ cfm} \times 29}{10.73 \times 710 \text{ deg R}} = 42.9 \text{ lbs of air per minute (ideal)}$$

$$\begin{aligned} \text{lbs air per minute actual} &= \text{lbs}/\text{min ideal} \times \text{vol. eff.} \\ &= 42.9 \times 0.85 \\ &= 36.4 \text{ lbs air}/\text{minute} \end{aligned}$$

What if the car is an '87, it **IS** intercooled, so the temperature in the intake manifold is only 130 deg F. This car is running 17 psi boost.

$$\text{Absolute temperature} = 130 \text{ deg F} + 460 = 590 \text{ deg R}$$

$Absolute\ pressure = 17\ psig + 14.7 = 31.7\ psia$

$n(lbs/min) = \frac{31.7\ psia \times 334.2\ cfm \times 29}{10.73 \times 590\ deg\ R} = 48.5\ lbs\ of\ air\ per\ minute\ (ideal)$

$lbs\ air\ per\ minute\ actual = 48.5 \times 0.85 = 41.3\ lbs\ air/minute$

Notice that the '87 car is getting **MORE** lbs/min of air (41.3 for the '87 to 36.4 for the '85) even though the boost pressure is lower. This is because the intake manifold temperature is so much lower. And more pounds of air means more power!

## Compressor

The compressor is the part of the turbocharger that compresses air and pumps it into the intake manifold. Air molecules get sucked into the rapidly spinning compressor blades and get flung out to the outside edge. When this happens, the air molecules get stacked up and forced together. This increases their pressure.

It takes power to do this. This power comes from the exhaust side of the turbo, called the Turbine. Not all of the power that comes from the turbine goes into building pressure. Some of the power is used up in heating up the air. This is because we lowly humans cannot build a perfect machine. If we could, all of the power would go into building pressure. Instead, because of the design of the compressor, the air molecules get "beat up", and this results in heat. Just like rubbing your hands together will warm your hands due to the friction between your hands, the friction between the compressor and the air and between the air molecules themselves will heat up the air.

If you divide the amount of power that goes into building pressure by the total power put into the compressor, you get the efficiency of the compressor.

For example, if the compressor is 70% efficient, this means that 70% of the power put into the compressor is used in building air pressure. The other 30% of the power is used heating up the air. That is why we like high efficiency compressors; more of the power is being used on building pressure and less is used heating up the air. Turbos, Paxtons, and Vortechs are all centrifugal superchargers. They are called this because the centrifugal force of flinging the air molecules from the center of the housing to the outside edge is what builds air pressure. The maximum efficiency of these kinds of superchargers is usually between 70% and 80%. Roots blowers, like the 6-71, work differently and have much lower efficiency, like about 40%! With those, when you try to build lots of boost you have to put in a lot of power and more than half of it gets used heating up the air instead of raising pressure.

If the temperature goes up a lot when you increase the boost you can end up with fewer pounds of air going into the engine, so you lose power. That's why a Roots blower is bad if you want lots of boost. Screw compressors, like the WhippleCharger for the 5.0, have good compression efficiency. That's why the Top Fuel guys are starting to try them out, and getting good gains from them.

## So? How Hot is the Air Coming out of the Compressor?

Well, I'm glad you asked. The equation used to calculate the discharge temperature is:

$$T_{out} = T_{in} + \frac{T_{in} \times [-1 + (P_{out}/P_{in})^{0.263}]}{efficiency}$$

Example: the inlet temperature is 70 deg F, the suction pressure is -0.5 psig (a slight vacuum), the discharge pressure is 19 psig, and the efficiency is 72%. What is the discharge temperature?

$$T_{in} = 70\ deg\ F + 460 = 530\ deg\ R$$

$$P_{in} = -0.5\ psig + 14.7 = 14.2\ psia$$

$$P_{out} = 19\ psig + 14.7 = 33.7\ psia$$

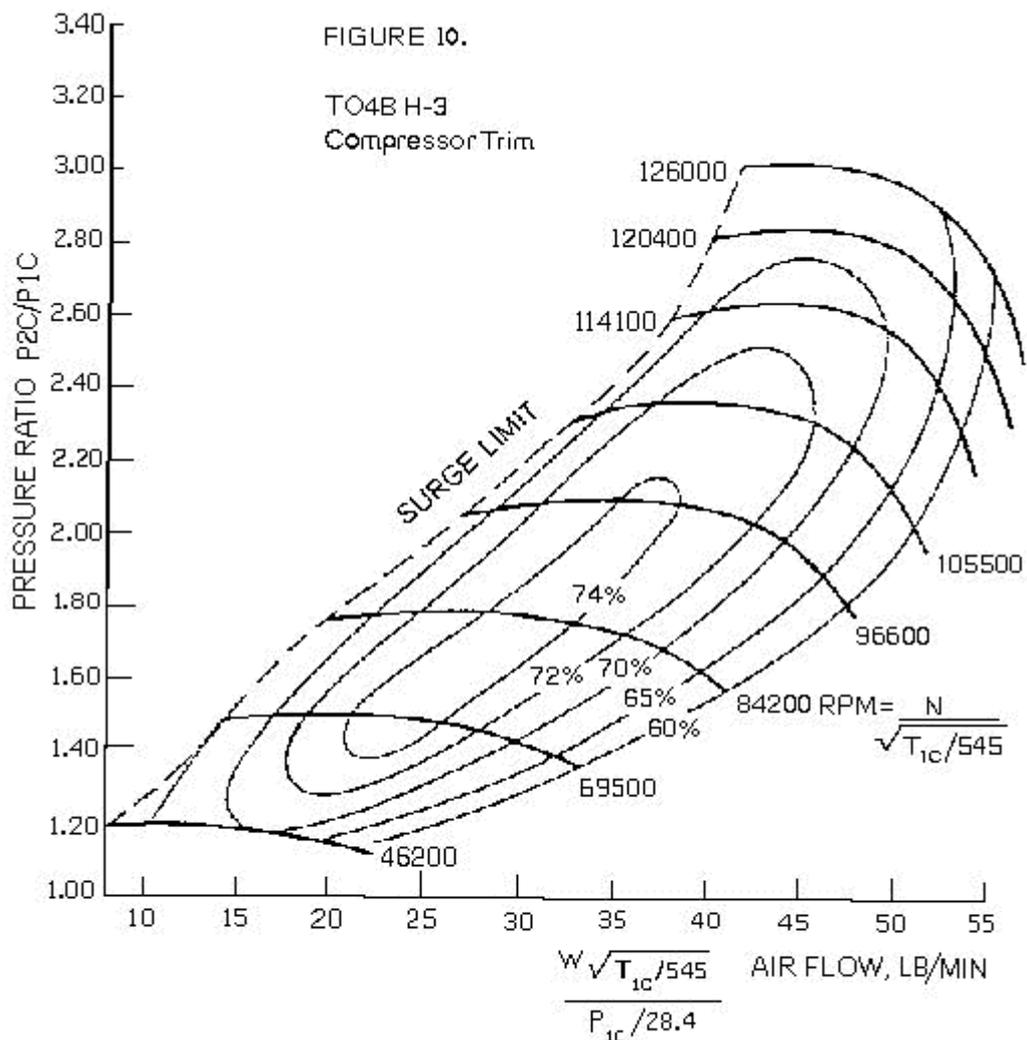
$$P_{out}/P_{in} = 33.7/14.2 = 2.373\ (this\ is\ the\ compression\ ratio)$$

$$T_{out} = 530 + \frac{530 \times (-1 + 2.373^{0.263})}{0.72} = 717.8\ deg\ R - 460 = 257.8\ deg\ F$$

So the theoretical outlet temperature is **257.8 deg F**. I sure would like to have an intercooler to cool that hot air down before it goes into my engine!

Compressors do not always operate at the same discharge pressure. The discharge pressure that the compressor produces depends on the volumetric flow into it (not the pounds of air, but the CFM of air), and the rpm that it is turning. The performance of a compressor can be shown on a graph by a series of curves. Below is a [compressor map](#) from the **Turbonetics** catalog attached, it is the file called [H-3.JPG](#). [The graph is included here, and is available for download via

the hotlinks provided....Ed.]



This is for their Cheetah turbo; take a look at it. The bottom of the graph shows the lbs/min of air that the compressor is moving, corrected to a standard temperature and pressure. The standard industry practice is to put this part of the graph in actual volumetric flow (such as ACFM) since the compression is constant for a given volumetric flow and compressor speed, NOT for a given mass flow. Unfortunately they didn't do their curves that way, and to use the Turbonetics curves we have to figure out the pounds of air moving and correct it from the actual inlet temperature and pressure to their standard temperature and pressure.

The left side of the graph shows the outlet pressure to inlet pressure ratio.

There are two different sets of curves in the graph; **efficiency curves** and **rpm curves**. The area where there are lines drawn is the operating envelope. It is best to operate the compressor within its envelope. It will still run if you go to the right of the envelope, just not well. To the left of the envelope, where it is marked "**surge limit**", the flow through the compressor is unstable and will go up and down and backwards unpredictably. This is surging. Do not pick a turbo that will operate in this area! It can be very damaging.

The Turbonetics catalog says to pick a turbo that is close to the peak turbo efficiency at the engine's torque peak while still maintaining at least 60% efficiency at the maximum rpm of the engine.

**Here's how to read the graph.**

Figure out the pounds of air that you are moving through the engine. In our '87 example, we were passing 41.3 lbs/min of

air, at inlet conditions of -0.5 psig and 70 deg F. Now correct that flow to the standard temperature and pressure.

$$\text{Corrected flow} = \frac{\text{actual flow} \times (T_{in}/545)^{0.5}}{(P_{in}/13.949)}$$

Note that I am using 13.949 because we are measuring everything in psia instead of in inches of mercury, which Turbonetics assumes.

*13.949 psia = 28.4 inches mercury absolute.*

*29.92 inches mercury is atmospheric pressure at sea level, so 29.92 - 28.4 = 1.52 inches mercury vacuum.*

That is their standard suction pressure.

Their standard temperature is 545 deg R, or 545 - 460 = 85 deg F.

So we are correcting the flow from 70 deg F and -0.5 psig to 85 deg F and -0.75 psig (or 13.949 psia, or 0.75 psi vacuum, or 1.5 inches mercury vacuum, or however you want to look at it.)

Again, temperature and pressure have to be absolute.

$$T_{in} = 70 + 460 = 530 \text{ deg R}$$

$$P_{in} = -0.5 + 14.7 = 14.2 \text{ psia}$$

$$\text{Corrected flow} = \frac{41.3 \times (530/545)^{0.5}}{(14.2/13.949)} = 40.0 \text{ lb/min}$$

So we mark that point on the bottom of the graph, and draw a straight line upward from that point.

An alternate and better way of getting airflow at less than full throttle is the use of a scan tool. The scan tool (such as TurboLink(tm)) reads the mass air sensor output. TurboLink(tm) gives this in grams per second. To convert that to pounds per minute just multiply by 0.1323. For example, if TurboLink(tm) says 18 gm/sec @ 45 mph, 18 x 0.1323 = 2.4 lb/min of air.

Correct that to standard conditions and plot that on the compressor map. Unfortunately the MAS will only read to 255 gm/sec. If you are moving more air than that, the MAS won't show it. That is why you need to go through the above calculation for full throttle air flow.

The next step is to figure out the compression ratio, using absolute pressures. Using our example, we had 17 psi boost in the intake manifold. Let's suppose the pressure drop from the turbo outlet to the manifold is 3 psi; so the actual compressor outlet pressure is **3+17=20 psig**. The air pressure is 0 psig, but since the turbo is sucking air to itself the pressure at the inlet is lower than that.

Let's say it is **-0.5 psig** at the inlet. Then the compression ratio, Pout/Pin is :

$$P_{out}/P_{in} = \frac{(20 + 14.7)}{(-0.5 + 14.7)} = 2.44$$

So then we find about where 2.44 is on the left side of the graph and draw a line horizontally from that point. Where the two lines meet is where the turbo will operate.

Look at the efficiency curves, which look like circles. Our point is just a little inside the 72% curve, so when we are running at 5000 rpm and 17 psi boost with 70 deg air outside and 130 deg air in the manifold then the compressor efficiency is a fraction over 72%.

The other curves are rpm curves. Our point is above the **105,500 rpm** curve, so the turbo has to spin about **108,000 rpm** to get the pressure up to 20 psig from -0.5 psig. The Turbine has to provide enough power to spin it that fast.

Change any of these numbers, and the point at which the compressor runs at changes. More engine rpm means more air flow, so the operating point moves to the right. Colder intake temperatures means more pounds of air which moves our point to the right. Raising the boost probably means more air into the cylinders, but also the compression ratio goes up so our point definitely moves up and should move right. And so on.

## Summary

So, how do tie all this together? Well, suppose you are in the market for a new turbo. Which one to buy?

- **First, I would pick about 4 different operating scenarios. Highway cruise, part throttle acceleration (say 2/3**

@ 2700 rpm), full throttle acceleration at 3500 or 4000 rpm, and full throttle acceleration at 5500 or 6000 rpm sound like 4 good points to me.

- Second, calculate the volumetric flow for each one of those cases. Then, making estimates of the intercooler outlet temperature (or turbo outlet temperature if nonintercooled), turbo discharge pressure, volumetric efficiency, manifold pressure, etc.. calculate the mass air flow for each case. You may also want to check the difference between summer and winter, ie air temps at maybe 90 deg F and 40 deg F. This will affect the manifold temperature and so the air flow. Note that when cruising and at idle, even though the manifold pressure is at a vacuum the turbo discharge pressure is not. It has to pump up the air some, even if it is only to 0.5 psig or so. You can check it out by moving your boost gauge to some point upstream of the throttle body. Besides the mass air flow, calculate the  $P_{out}/P_{in}$  for each case.
- Third, and this is the hard part, find the compressor maps for the turbos you are interested in. Turbonetics has maps for their Cheetah, 60-1, and 62-1 in their catalog. The other vendors may not want to let you have the maps for theirs. Plot the points from the 4 cases on the compressor map.
- Fourth, evaluate the proposed compressors performance. Are the idle/cruise operating points to the left of the surge line? Then this turbo will surge and isn't a good choice. Is the 5500 rpm point so far out to the right that it is off the map? Then this turbo doesn't flow enough for your application. You want all the operating points within the map, and preferably at as high an efficiency as you can get.

If you are trying to choose between 2 turbos, pick the one with the better efficiency where you do most of your driving.  
**Good luck!**