All You Ever Need To Know

About:

General Aviation Exhaust Systems

Courtesy Of: Power Flow Systems, Inc., Daytona Beach, FL

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INTRODUCTION

If you're like me and most other pilots, you probably spend more time thinking about the cotter pin securing the castellated nut on the far outboard aileron pulley than you do about the exhaust system that is bolted to your aircraft's engine – which is to say: "Not Very Much."!

And, for the most part, that would seem to be a sensible allocation of (in my case, at least) limited mental resources. After all, how big of a deal can a bunch of inert steel pipes be?

This apathy is widespread among the aviation community - even among aircraft and power-plant designers, who should know better. It turns out, however, that the design and construction of the exhaust system can have a VERY big impact on the performance, efficiency and reliability of the entire aircraft. This is particularly true in the case of single-engine General Aviation aircraft where the efficiency of that single engine and the amount of power it is able to produce have a "singularly" profound effect on the performance and safety of the aircraft.

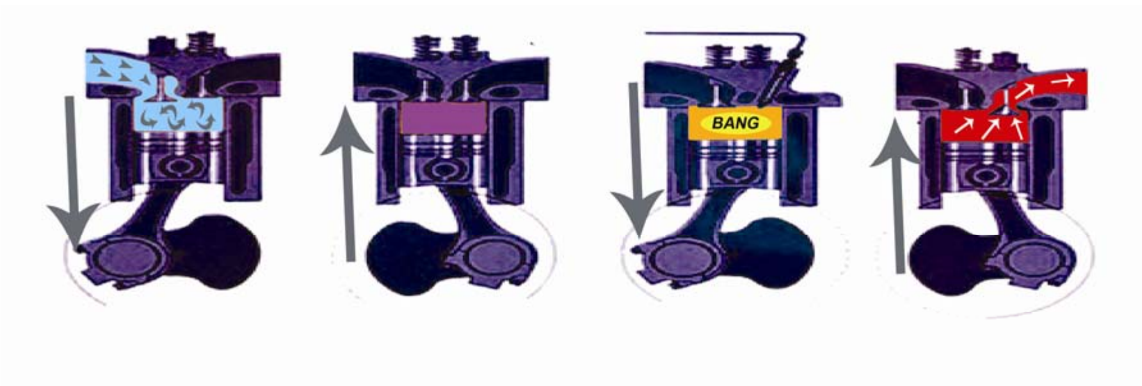
Firm in our belief that an educated pilot (Customer or not) is our best advocate, Power Flow Systems is pleased to offer this discussion of the various exhaust system designs found on current GA aircraft, together with the pro's and con's of each design.

I - EXHAUST SYSTEM BASICS

Let's get started with a brief discussion of the source of the exhaust:

The basic workings of the four cycle piston engines which power our aircraft are familiar to most pilots. The maximum horsepower that any piston engine can produce is a function of the internal volume of the engine's cylinders which determine the size of the fuel/air charge that can be burned during the power stroke. In the "ideal scenario", when the exhaust valve opens, the piston pushes spent exhaust gases out of the cylinder so that a fresh fuel/air charge can enter during the next intake stroke:

INTAKE **COMPRESSION** **COMBUSTION** **EXHAUST**



Although we're only looking at one cylinder here, in a small aircraft engine at least three other cylinders are going through the same process about 1,000 times per minute, generating over 200 cubic feet of hot, expanding exhaust gas in the process. Where does all that exhaust go? That is where, for the purposes of this discussion, things start to get interesting.

From an engineer's point of view, the primary purpose of any exhaust system is to remove ***all*** that exhaust gas from the cylinder as quickly and efficiently as possible. Not surprisingly, high performance aircraft engines have some of the simplest and highest performance exhaust systems as illustrated below:

Appropriately known as “Stub Stacks” these simple metal tubes with minimal bends and no internal obstructions fulfill that primary purpose admirably well. So well, in fact, that when measuring the output of an engine to determine its horsepower rating, most manufacturers and testing facilities will use what they refer to as “Neutral” or “Test” Stacks (which are really just straight “Stub Stacks” with a standard length of 4”).

Since this design has no muffler, and requires no provision for either cabin heat or carburetor heat, the Stub Stack / Neutral Stack design allows the engine to develop very close to its theoretical maximum output.

As an interesting aside, the photo of the polished North American P-51 also perfectly illustrates another attribute of this iconic aircraft: you can clearly see the aerodynamic benefits of the Mustang’s unique Laminar Flow wing outlined by the discolored metal caused by the heat of the exhaust plume. No drag inducing airflow separation burble ***here!***

Back to the business at hand, though:

The simplicity and efficiency of this design are among the attributes which make it ideal for high-output engines, but somewhat less than perfect for the slightly more civilized engines we typically fly behind. Although the sound of an unrestrained 1,500 horsepower Merlin cruising past would be music to the ears of most pilots, your neighbors might not be quite so enamored of it.

And while most of us probably harbor at least a mild case of “Yeager Envy” somewhere in the secret recesses of our souls, we prefer to nurture it from the confines of a well ventilated, comfortably heated aircraft cabin, preferably with a more than adequate source of carburetor heat should the need for same arise.

These considerations serve to illustrate some of the secondary requirements of the exhaust system on a modern aircraft. In addition to emptying the cylinder of spent exhaust gasses, it must also:

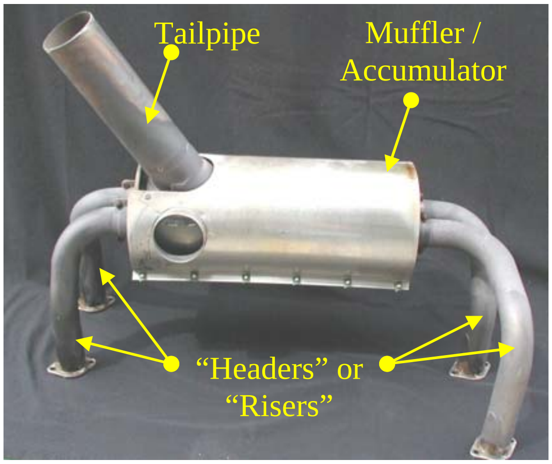
- Reduce &/or attenuate the engine noise,

- Ensure that noxious fumes do not enter the cabin area,
- Provide heating for the cabin, & (on carburetor equipped engines) –
- Serve as a heat source for the carburetor air intake when required.

Most current exhaust system designs fulfill these secondary requirements with varying degrees of success, but they do so at the expense of the unimpeded efficiency which is characteristic of the simple “Stub Stack” design discussed above.

II - ACCUMULATOR EXHAUST

Probably the most prevalent design, found on many popular airframes such as the Cessna 172 and 177 airframes as well as the Grumman AA5 series and the Mooney M20 B through J models is known (for reasons discussed below) as an “accumulator” exhaust.



Characterized by the four “header” or “riser” pipes which attach to the engine’s exhaust ports at one end and empty into one common muffler / accumulator on the other end, this type of exhaust system is inexpensive to fabricate with a minimal amount of tube bending and welding required.

The rolled sheet metal shroud encasing the muffler chamber serves as a source for both cabin heat and carburetor heat. On some versions, internal baffles (also referred to as “flame tubes”) are added inside the muffler to reduce the noise output &/or improve the cabin heat output.

As mentioned above, the primary benefit of this type of exhaust is its low cost. This is what accounts for its ubiquitous appearance on most mass produced GA airframes. That same ubiquity also yields a steady supply of reasonably priced repair facilities and replacement parts.

The biggest drawback of the design is revealed in its name: “accumulator”:

Remember in our initial discussion where we asked: “Where does all that exhaust gas go?” In an accumulator system, the header tubes route each blast of hot gas to the muffler/accumulator, which, as can be seen in the photo above, is a relatively small metal can with **four** inlets (one for each header tube), BUT usually only ***one*** outlet – the exhaust pipe.

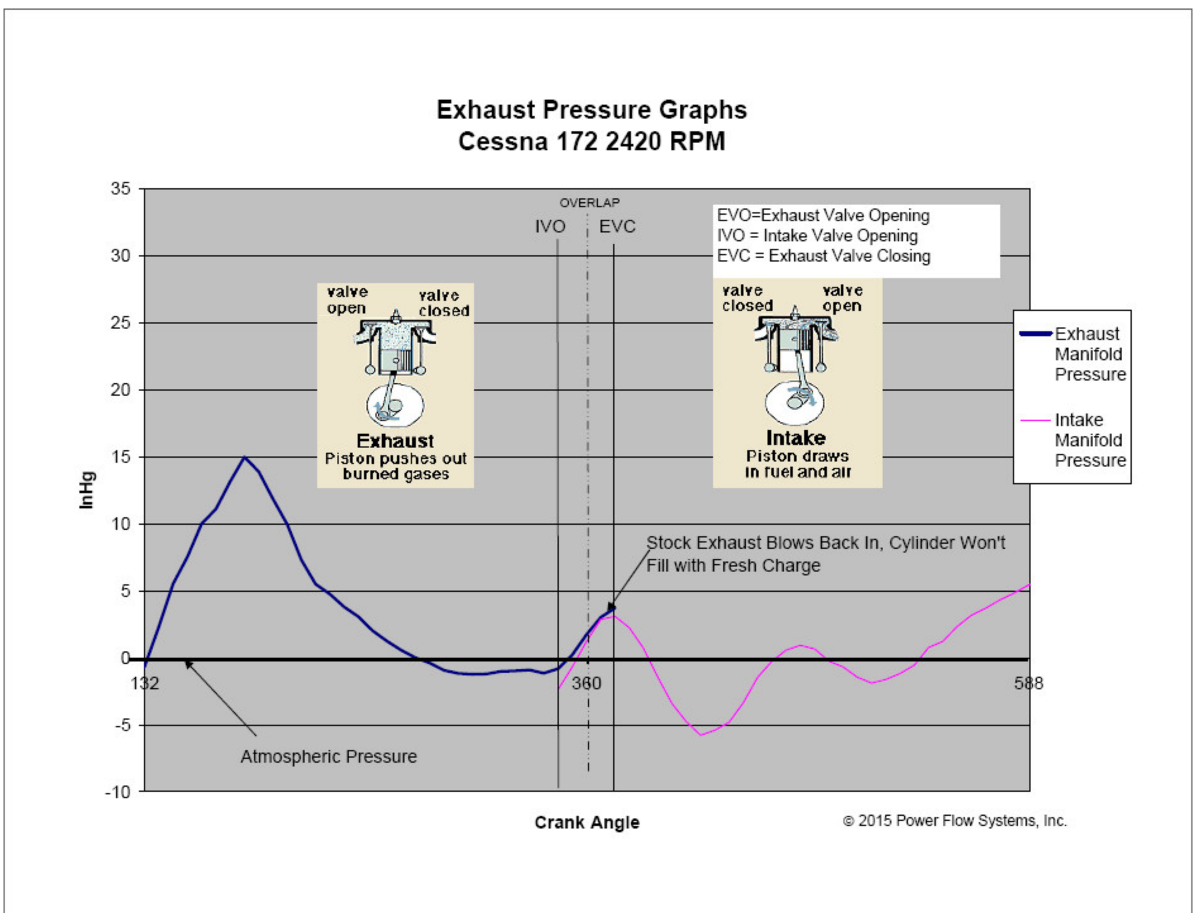
So, we have four cylinders blasting over 200 cubic feet of hot gas each minute into a muffler roughly the size of a large coffee can with only one “good” exit. But the laws of physics being what they are, the gas can’t flow out through that single tailpipe as fast as it is coming in from the four headers. So, the pressure inside the muffler / accumulator increases and then flows back up the headers to the exhaust ports on each cylinder.

Now, when the exhaust valve opens to expel the next pulse of combustion by-products, the piston has to push against the compressed exhaust gas from previous combustion cycles. This has two consequences, both bad:

#1.) The engine uses a portion of its available energy to push the spent gas out, generating excessive waste heat in the form of higher Cylinder Head Temperatures (by further compressing the latent exhaust gas) and leaving less energy to turn the propeller. The technical term for this wasted energy is "Pumping Loss".

#2.) The excessive back pressure in the header prevents the spent gas from completely evacuating the cylinder before the exhaust valve closes. So, when the intake valve opens there is less space in the cylinder for the fresh fuel/air charge. This undesirable effect also has a fancy technical name: "Reduced Volumetric Efficiency".

Using carefully instrumented engines we have determined that as much as 20% of each cylinder's volume can be wasted in this manner, significantly decreasing the available horsepower of a typical four cylinder Lycoming engine. The results of these tests are depicted in the chart below:



As a careful study of the chart will show (note the two solid Vertical Lines near the center of the chart), there is a brief period of time in each cylinder's combustion cycle when both the Intake Valve and the Exhaust Valve for that cylinder are open at the same time. Known (appropriately enough) as the "Overlap Phase" this feature is designed into the engine because it would be extremely difficult and inefficient for the engine to work against the near total vacuum that would result if the Intake Valve were to remain completely closed and sealed during the exhaust cycle.

The crucial parameters are shown by the purple line, depicting the measured pressure inside the Intake manifold and the dark blue line which shows the actual (and slightly higher) pressure inside the exhaust riser during the critical Overlap Phase. You may remember from High School Physics that "pressure flows from high to low".

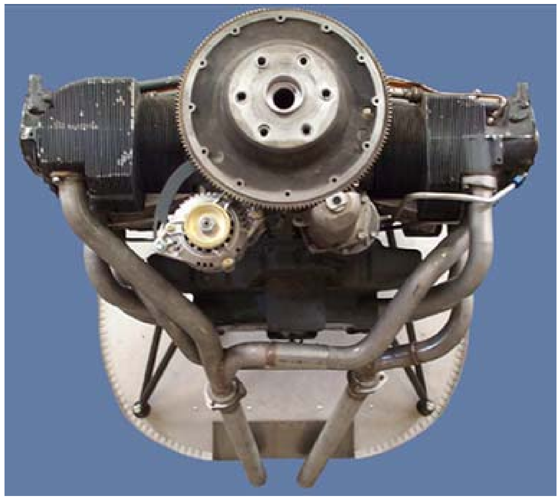
As documented above, with an accumulator design, the pressure inside the exhaust riser is higher than the pressure inside the Intake manifold during the brief period of time when both valves are open, thus physically preventing the cylinder from emptying completely and subsequently being filled completely with a fresh Fuel/Air charge.

How much power does this design actually end up wasting? Based on careful dynamometer testing of a four cylinder Lycoming O-320 engine, we know the answer to that one, too:

Although the engine we tested was nominally rated at 160 Horsepower at its operating redline of 2,700 rpm, with the accumulator exhaust installed the engine had a maximum attainable rpm of 2,563, and could therefore actually produce no more than 133.8 Horsepower. That represents a loss of 26.2 HP which corresponds to over 16% of the maximum output of that engine. Quite a performance penalty!

III – CROSSOVER EXHAUST

An effort to reduce that penalty lies behind another common exhaust system design: the Crossover type.



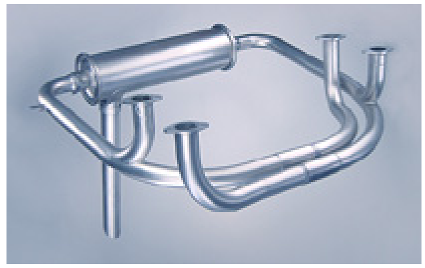
In a Crossover exhaust, the common muffler/accumulator is usually eliminated. Instead, the riser pipes connecting the two opposing cylinders in the engine's firing order are merged downstream from the cylinders and share a common tailpipe. In a Lycoming O-320, for example, with a firing order of 1 – 3 – 2 – 4, the riser pipes for Cylinders 1 and 2 share one tailpipe and Cylinders 3 and 4 share a second tailpipe.

The advantage behind this design is that with the two exhaust pulses spaced 180^{O} apart in the engine's combustion cycle, the chances of those two pulses interfering with each other to create power-robbing back pressure is greatly reduced. Since there is usually no muffler, there is no place for that back pressure to accumulate.

As a matter of fact, there can even be a slight performance benefit, since the momentum of gas from the first cylinder's exhaust pulse can actually help draw the exhaust gas from the second cylinder, IF the system is designed properly to take advantage of this possibility.

As can be seen in the photograph above, a Crossover exhaust is somewhat more complicated in both design and construction, making it more difficult and expensive to manufacture. With the greater number and complexity of both bends and welds, this design can be more susceptible to stress induced cracking and for the same reasons repairs can be more problematic.

The qualifier "usually" is applied liberally above, because one very popular aircraft, Piper's PA28-140, Cherokee, does utilize an exhaust system which incorporates elements of both the Crossover and the Accumulator designs. You can see in the photograph below that the two pairs of opposing cylinders each have merged riser pipes downstream of their respective exhaust ports:



Unfortunately, the resulting two merged risers then go into a single “Accumulator / Muffler” that still has but one tailpipe. This design delays the accumulation of engine stifling back pressure rather than eliminating it. The result is that this exhaust system is also a notorious choke point for the performance of the O-320 and O-360 engine’s powering the -140 as well as earlier (pre-1964 versions) of the PA28-150, -160 & -180 airframes.

Piper eventually discovered the error in their ways and on all 1964 and later model PA28 -150, -160, & -180 airframes, as well as all “Taper-wing” variants, they did away with the muffler entirely, yielding an immediate and noticeable improvement in the performance of each of these later models. In the field, these variants are easily distinguishable by the twin tailpipes protruding from the cowl.

For some reason known only to the designers (or maybe the marketers) Piper elected not to provide their best selling airframe at the time (the Cherokee -140) with this improved design.

IV – Maintenance & Repair Considerations

Some version of these two basic designs, the Accumulator or the Crossover, will be found as standard equipment on the vast majority of certified GA airframes powered by Lycoming's four cylinder O-320, O-360, I/O-360 or I/O-390 engines. This is probably an opportune time, therefore, to discuss the construction materials as well as the, inspection, maintenance and repair issues common to these two systems.

Most exhaust system components used on GA aircraft today are constructed from one of the three following materials:

- Mild Steel – Plentiful, relatively inexpensive, and easy to work with it is also very susceptible to both corrosion and cracking. Found primarily in "Stock" O.E.M. (Original Equipment Manufacturer) designs such as those from Cessna, Piper, Mooney, etc.

- Stainless Steel – Since it is corrosion resistant, light weight, and very durable, stainless is widely considered to be the perfect material for aircraft exhaust systems. It is more expensive than Mild Steel and also requires greater expertise to weld, form and drill properly. Widely used in upper end O.E.M. designs, such as the Cirrus SR22, and high quality aftermarket exhaust systems.

- Inconel – Also very light and durable, Inconel is an alloy of Nickel, Chromium and Iron. Able to withstand repeated cycles of extreme high and low temperatures, it is the material of choice for many jet engine components such as fan blades, exhaust nozzles, etc. Inconel is more expensive than either Mild Steel or Stainless and is also much more difficult / expensive to bend, form and drill than either of the other two materials. Its use in exhaust systems is therefore limited mostly to high-performance Custom Built / Experimental designs where money is no object.

The "back of mind / bottom of the list" mentality that has been the fate of exhaust systems in general also unfortunately extends to their maintenance and upkeep. Usually warranting no more than a brief glance during pre-flight (if that) and the occasional poke or prod during Annual, most pilots and their mechanics seem to have confused the well-proven maxim of "If it ain't broke, don't fix it" with the significantly more dangerous attitude of "If it ain't obviously broke or missing, don't inspect, maintain or repair it"!

This is a sentiment decidedly NOT shared by the F.A.A. Since 1983, through a series of Advisory Circulars and Special Airworthiness Inspection Bulletins, the

Agency has repeatedly warned against the misplaced complacency and neglect with which these crucial components are typically regarded.

In one of their more recent studies titled: *"Detection and prevention of carbon monoxide exposure in General Aviation Aircraft, Document No. DOT/FAA/AR-09/49"*, the results of which were released in October of 2009, the FAA concluded, after researching National Transportation Safety Board (NTSB) accidents related to carbon monoxide (CO) poisoning, that the muffler system was the top source of CO. For the CO-related cases where the muffler was identified as the source of the CO leakage, 92% had a muffler with more than 1,000 hours of service.

Although the Agency did not conclude that the safety concern rose to the level that required the issuance of an airworthiness directive, it did re-iterate several important and long standing recommendations:

1. Replace mufflers on reciprocating engine-powered airplanes with more than 1,000 hours on the muffler and at each 1,000-hour interval, unless the manufacturer recommends or FAA regulations require a more frequent replacement.
2. Review and continue to follow the guidance for exhaust system inspections and maintenance in SAIB CE-04-22, dated Dec. 17, 2003, and Aviation Maintenance Alert (AMA), All Powered Models, Carbon Monoxide Poisoning Potential, October 2006 issue of Advisory Circular 43-16A.
3. Use CO detectors while operating your aircraft as recommended by SAIB CE-10-19R1, dated March 17, 2010.
4. Continue to inspect the complete engine exhaust system during 100-hour/annual inspections and at inspection intervals recommended by the aircraft and engine manufacturers in accordance with their applicable maintenance manual instructions.

With these admonitions in mind, let's take a look at some of the more common failure points in the two traditional exhaust system designs described above.

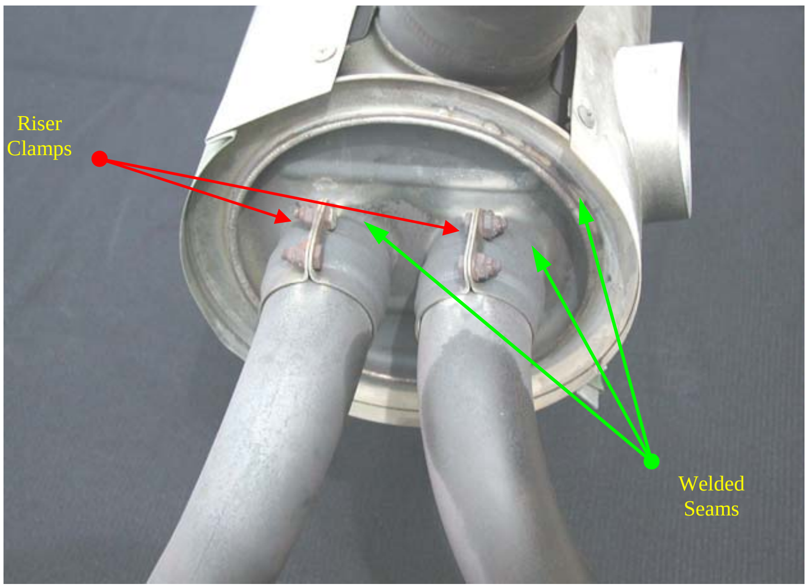
The root cause of several of these failures can easily be described by imagining the aircraft engine as a giant tuning fork weighing several hundred pounds and (during operation) vibrating at approximately 200 cycles per second at 2,500 rpm.

In addition to this constant vibration, the individual cylinders expand and contract at different rates during normal operation in response to several factors such as their location relative to the flow of cooling air, the relative richness or leanness of the mixture reaching each cylinder, any leaks or imperfections in the baffling, etc.

As long as the individual exhaust system components are free to move and reverberate in response to these various stressors and thus dissipate the resulting mechanical energy gradually, everything is fine. If we try to stop the dissipation and vibration in full force, all of that mechanical energy would of necessity be diverted elsewhere with less than desirable consequences.

If you look at the photo below you can see that most legacy exhaust system designs attempt to do precisely that. See how the two riser pipes are clamped tightly to the muffler flanges by nuts and bolts (the red arrows)? As a result, the constant and considerable vibration from the firing of the cylinders is transmitted directly to the welded seams on the muffler assembly (green arrows).

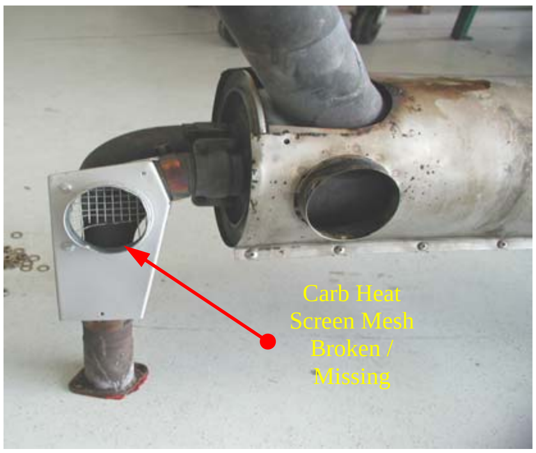
As the individual cylinders expand and contract at different rates, significant additional stress is continually applied to every flange, weld, and connection. Over time, that accumulated stress and vibration gradually fatigues the metal in these areas with stress cracks being the almost inevitable result.

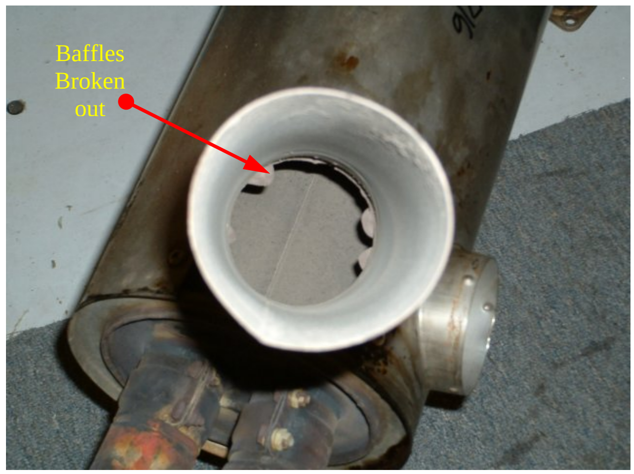


In addition to the external welds, this particular design (from a Cessna 172) has several welded seams located inside muffler's the rolled sheet metal shell. These welds are just as prone to cracking as the external welds but are, of course, a LOT harder to inspect regularly. Failure of the internal welds represents a very real danger of Carbon Monoxide entering the aircraft cabin, hence the FAA's concern.

Since, as we mentioned above, most original mufflers are constructed of mild steel, welding is a relatively quick and easy fix for those cracks that are visible. As illustrated below many older exhaust systems have more stitches, seams and scars than Dr. Frankenstein's monster!

The less visible (but perhaps far more crucial) internal components such as flame tubes, baffles, etc., are just as susceptible to cracking and failure but far less likely to be inspected and repaired as necessary:





In light of the all too common examples cited above, this is one instance where the FAA's abundance of caution mind-set seems to be well-founded.

What does this mean for you and your mechanic in the day to day operation, inspection and maintenance of your aircraft? The exhaust system is one component that you do NOT want to skim over during either pre-flight or annual inspections, particularly if your system has already seen several years &/or 200 - 300 hundred flight hours (or more) of service.

During your pre-flight take a good look at the visible components to check for leaks, cracking &/or corrosion, particularly around the welded seams. Exhaust leaks are often seen as a wispy, grayish white residue near the source of the leak. If you can see it on the outside, dollars to doughnuts says it's occurring on the inside as well.

If you see evidence of any of the failure modes described above DON'T just "let it slide". Have the system removed from the airplane at the earliest opportunity for a complete disassembly, inspection and repair as necessary.

At annual time, many A&P's think they are doing you a favor by not looking too closely at the exhaust system – they AREN'T. Make a thorough inspection of the system and its components a part of your work order. This means removal of the exhaust system from the aircraft, inspection of all components for the failure modes described above and repair or replacement of any defective components as necessary.

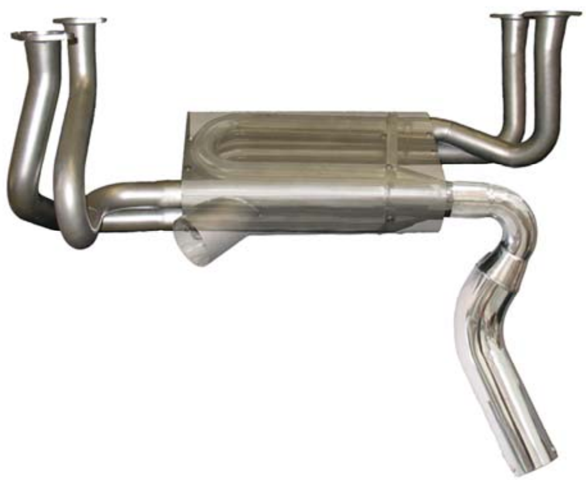
If all this seems like an awful lot of bother and expense, you're right – it IS.

Consider this, though: where and when do you think an exhaust system failure is cheaper and easier to deal with - In a heated hangar where your trusted A&P has the aircraft already disassembled for inspection and all the tools and materials necessary for an efficient repair are close at hand, or far from your home base after you (hopefully) discover the exhaust leak (or worse) in time to recover from it and safely land your now disabled aircraft?

Like any other aspect of aviation (or life in general, for that matter), ignoring a real problem does NOT make it go away. It just makes the eventual solution much more costly, time consuming and exasperating.

V – TUNED EXHAUST SYSTEM

Now that we've thoroughly explored the pro's and con's of the two most prevalent exhaust system designs, let's turn our attention to the third option available to many owners and pilots of certified aircraft powered by Lycoming four cylinder O-320, O-360, I/O-360 & I/O-390 engines – Power Flow's Tuned Exhaust System:

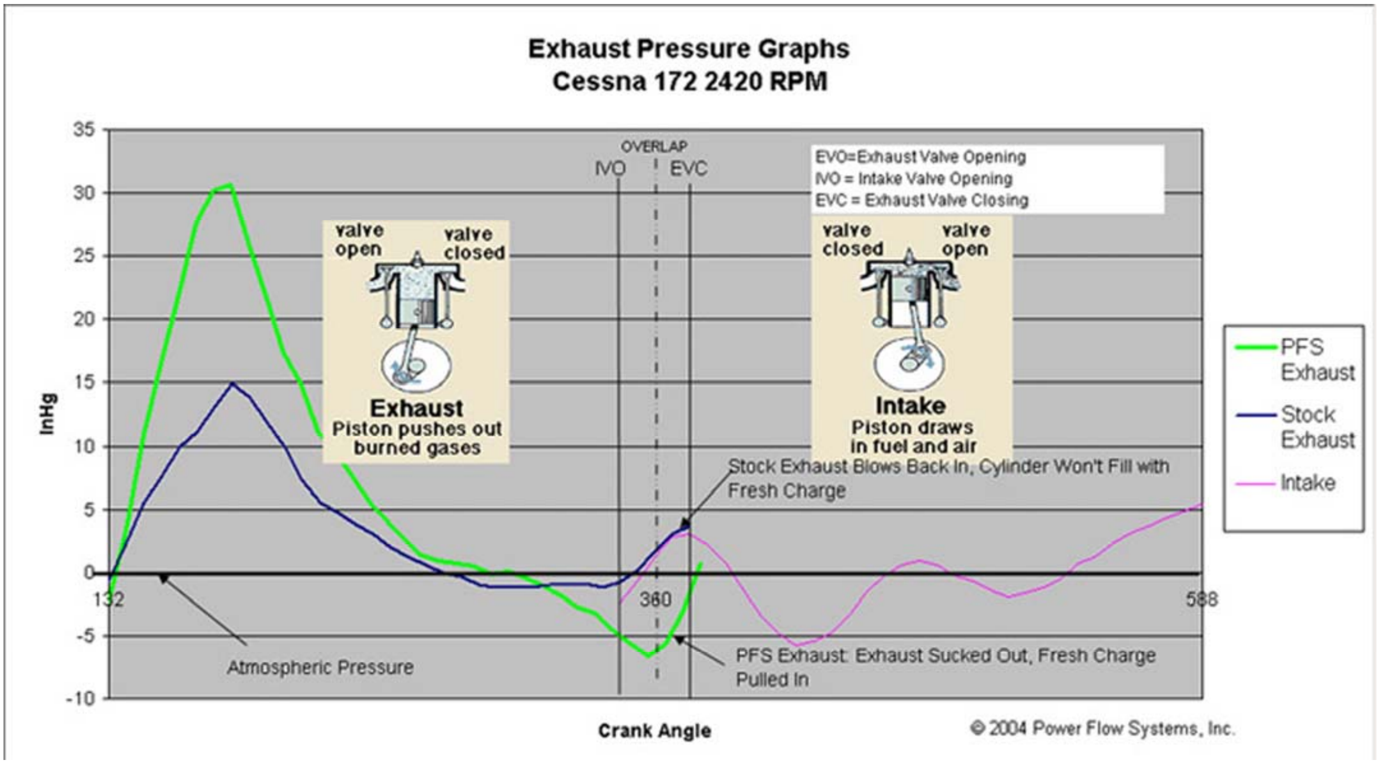


Let's start with a precise explanation of a true "Tuned Exhaust":

As you can see in the "X-Ray" view above, in a true Tuned Exhaust System, each header has a clear, unobstructed path from the exhaust port to the end of the tailpipe. There is no common muffler to accumulate power robbing back pressure. This feature alone does a lot to reduce internal friction / pumping loss and increase available power. To improve things even further, the headers in a Tuned Exhaust are all of a length that is calculated for each engine ("Tuned") to increase combustion efficiency and maximize horsepower.

The process is called "scavenging", and it works like this: As each pulse of exhaust gas blasts out of the cylinder and shoots down the header, there is a leading edge of high pressure in front of it and a trailing edge "wake" of relatively low pressure behind it, just like the slipstream generated by a fast moving vehicle.

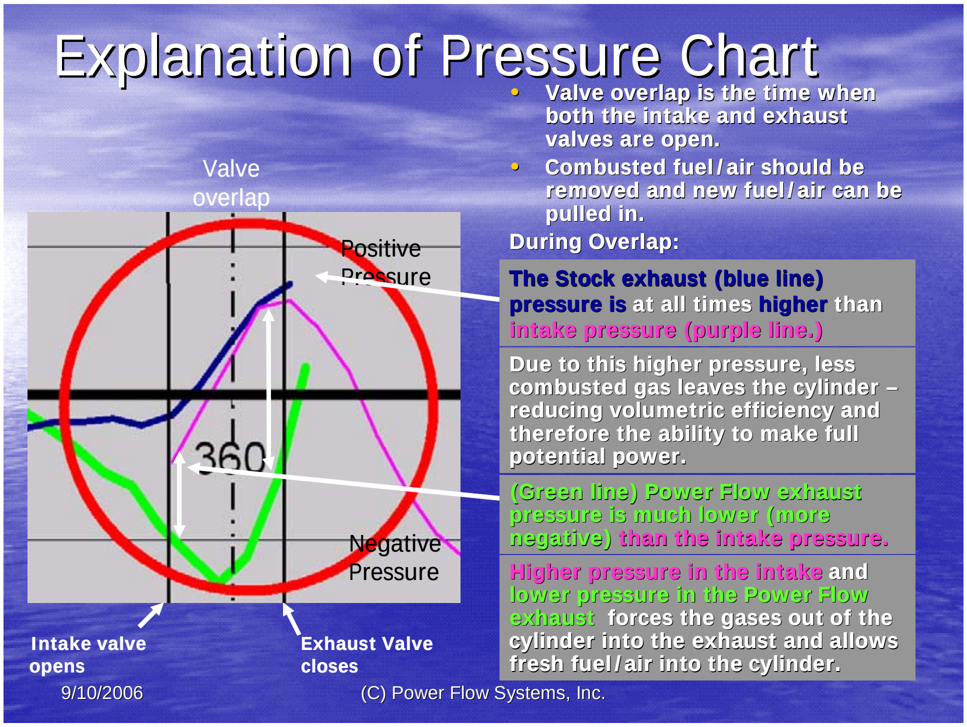
Let's take another look at that Exhaust Pressure Graph to see what happens next:



The exhaust pulse from the Tuned Exhaust System and the resulting pressure wave are shown by the green line on the chart above. Comparing the green line to the measured pressure wave from the "stock" 172 exhaust system (still shown in dark blue), you can see that in the Tuned Exhaust, the high pressure "peak" is higher and the low pressure "trough" is lower. That trough is also occurring just slightly later in the combustion cycle – by design it is right in the middle of the Overlap Phase denoted by the two solid vertical lines in the middle of the chart.

That's because in a Tuned Exhaust, the initial exhaust pulse is still racing down the (much longer) header pipe, with its low pressure wake trailing behind it, during the crucial Overlap Phase in the next combustion cycle when both the exhaust valve and the intake valve are open at the same time.

Now instead of slamming into high pressure interference flowing back upstream from the muffler/accumulator, the subsequent exhaust pulse is actually pulled ("scavenged") from the cylinder by the low pressure trough generated by the previous pulse. Note the difference in pressure between the Tuned Exhaust and the stock exhaust during the Overlap Phase when both the Exhaust Valve and the Intake Valve are open at the same time. As shown in the expanded chart below, this is the key to the improved performance available with a properly designed Tuned Exhaust System:



There is a secondary beneficial effect, called “Flow Momentum”, also at play in the process. Taking another look at the X-Ray view above, you can see that just upstream from the tailpipe connection, there is a point, called the 4:1, where the four exhaust risers are funneled into a single larger pipe that becomes the tailpipe.

At first glance you might think that this would be a perfect place for interference and efficiency robbing back pressure pulses to originate, and, in normal circumstances you would be right.

In addition to being “tuned” to facilitate the scavenging discussed above, though, the headers in a true Tuned Exhaust System are all of equal length (within an acceptable range of slight variation). Since each individual riser is essentially the same length, it takes each exhaust pulse (which have been emitted separately by the cylinders firing in sequence) the same amount of time to reach the point where it must merge with the other pulses.

By the time those separate exhaust pulses arrive at the 4:1, they are lined up in near perfect tandem order and merge smoothly into one unimpeded, steadily flowing stream. This effect is not unlike those traffic signals that sequentially meter merging automobiles onto a busy highway during rush hour. The resulting momentum of flowing gasses contributes significantly to the overall efficiency of this design.

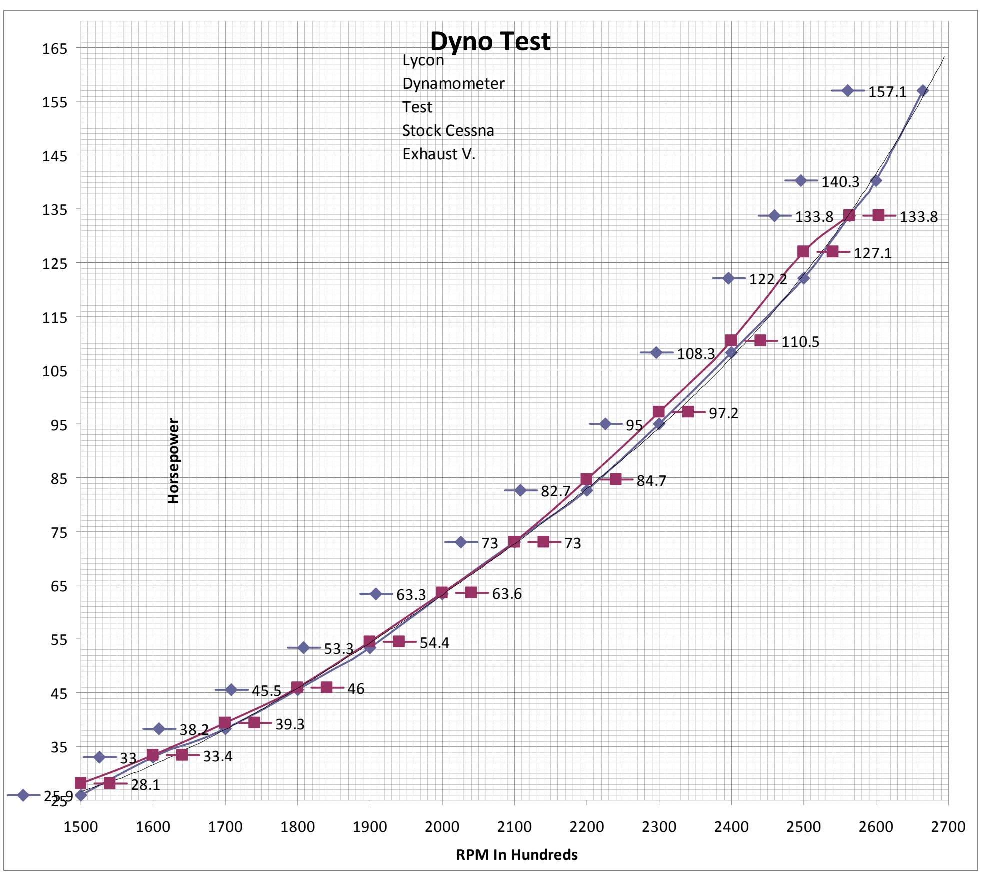
The net result is that instead of losing volume to residual exhaust gas, each cylinder is able to accommodate a significantly larger full fuel/air charge with every combustion stroke yielding a corresponding increase in power.

“Increased Volumetric Efficiency” is the technical term for this benefit, and the result is a smoother, cooler, more powerful engine. You get all of the benefits that you would expect from increased horsepower at a fraction of the cost of obtaining that horsepower by any other means simply by allowing the engine to generate a greater percentage of the power it was designed to produce.

Remember the dynamometer test we referenced earlier during which the 160 HP rated O-320 engine could develop no more than 133.8 HP when equipped with the Accumulator design exhaust system?

During that same test series, when the Accumulator System was replaced with Power Flow’s Tuned Exhaust System, the engine’s maximum attainable rpm increased by 102 (to 2,665 rpm) with a corresponding increase of 23.3 HP in actual power produced. This allowed the engine to develop 157.1 HP – very close to its rating of 160 HP.

These results are summarized in the graph below where the magenta data points and trend line illustrate the performance attained by the engine with the accumulator exhaust system and the blue points denote the power curve of the same engine with the Tuned Exhaust:



On an aircraft with a fixed-pitch prop, the benefits of this additional horsepower are most evident in take off and climb performance, when the engine is running at full power and you want all the horsepower you can get. In those situations, a Power Flow Tuned Exhaust System will shorten the aircraft's take-off roll by 100 - 300 feet and increase its rate of climb by about 100 – 150 fpm.

During cruise operations with a fixed pitch propeller and with the engine throttled back, the most obvious benefit of the system is the reduction in fuel burn (by about 1 – 2 gph) required to achieve the same rpm. A secondary benefit is a reduction in the CHT's by about 20^{O} – 30^{O}F, since the engine no longer has to push against and further compress the accumulated back pressure occurring in the original exhaust.

It is interesting to note, however, that on aircraft equipped with constant speed propellers, the prop automatically adjusts its pitch to take advantage of the higher torque available with the Tuned Exhaust System. In addition to the take-off and climb improvements noted above, these aircraft typically see increases of 5 – 7 knots in their cruise speeds at the same power setting and same, or very slightly higher (about .5 gph), fuel flow.

While still considered to be the most efficient design for an exhaust system, the Tuned Exhaust has been around for several decades. It was originally designed as a (relatively) inexpensive means to boost the output of high performance engines used in racing cars and motorcycles.

In the mid-1990's, Mr. Robin Thomas, well known in aviation circles as the President and founder of Laminar Flow Systems, a long-time designer and manufacturer of aerodynamic speed modifications for the PA-28, -32, & -34 series airframes, began a project to adapt this technology for the four cylinder Lycoming engines widely used in GA aircraft.

Power Flow Systems was formed in 1997 to manufacture the resulting products, with the first system, designed for Cessna 172 airframes powered by the Lycoming O-320 engine, obtaining an STC from the FAA in 1999.

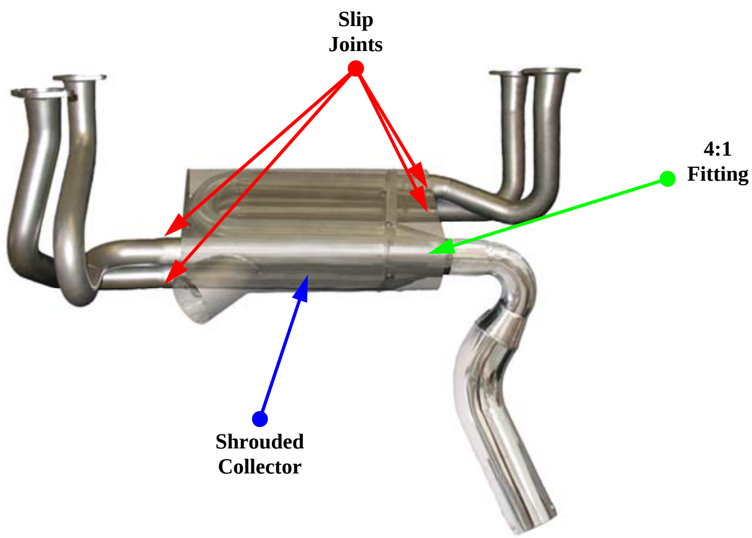
As part of the development project for the original system, Mr. Thomas and his design team took the opportunity to address several of the durability and reliability issues with the traditional aircraft exhaust systems described earlier. The innovative solutions they devised to remedy these shortcomings were incorporated into the original Power Flow System and have been used in every one of the fifteen STC'd Tuned Exhaust Systems that have been introduced by the company since 1999.

First and foremost, the decision was made early on to utilize Type 321 Stainless Steel in the construction of the new design rather than the prevalent and inexpensive mild steel used in the construction of most GA exhaust systems.

Type 321 is a stabilized stainless steel which offers as its main advantage an excellent resistance to intergranular corrosion (due to the addition of Titanium to the alloy) following exposure to temperatures in the range from 800° to 1500° F. To further enhance durability and reliability, the wall thickness of the tubing was specified to be .049" a full 40% increase over the "standard" .035" thickness used in most comparable systems.

While this decision dictated that the finished product would have to be priced higher than other options, it also meant that the corrosion problems plaguing legacy designs would largely be a thing of the past.

To better accommodate the vibration and thermal stress to which any exhaust system is subjected, "Slip Joints" were incorporated into the design between the exhaust risers and the shrouded collector assembly.



As the name implies, these joints, commonly used in turbo chargers and other high stress applications, are designed to "slip" or float. In so doing, they essentially act as independent shock absorbers to isolate the system's welded components from the considerable vibration of the engine. In addition, each cylinder on the engine expands and contracts at a different rate depending upon its location in relation to the flow of cooling air and other factors.

The slip joints allow the exhaust system to accommodate this differential in expansion and contraction rates (and the accompanying stress) better than any other method. As long as they are lubricated periodically (annually or every 500 flight hours, whichever comes first), with an appropriate high temperature anti-seize compound (rated at 1,600^{O} F or higher) they will perform as intended indefinitely.

Another advantage integral to the design is the minimal number of welds inside the shrouded collector. The risers are covered with a shroud (also constructed of stainless steel) allowing the four separate tubes to act as a radiant heat source for both cabin air and (where necessary) carburetor heat. Since each riser remains a single, separate tube until it merges with the others at the 4:1 fitting, there are very few welds within this heat source to act as potential sources for CO contamination of the cabin.

VI – INSTRUCTIONS FOR CONTINUED AIRWORTHINESS

The numerous improvements in both design and materials discussed above go a long way towards improving the durability and the reliability of the Power Flow system compared to any of the “legacy” designs discussed earlier. As a company, however, and in light of the potential consequences of a failure in this crucial component, we agree wholeheartedly with the FAA’s “abundance of caution” approach to exhaust systems in general.

As part of the Instructions for Continued Airworthiness furnished with every Tuned Exhaust System we produce, Power Flow stipulates that the system be removed from the aircraft at regular intervals (every 500 flight hours or 12 calendar months whichever occurs first) for a thorough inspection. The collector shroud enclosing the separate risers is designed to be easily removable by the use of stainless steel hardware and “Tinnerman” clips, greatly facilitating the inspection. This is, of course, also an ideal time to clean and re-lubricate the four slip joints referred to above.

In addition to the regimen of regular inspections recommended by the FAA, Power Flow strongly encourages the regular use of one other preventative maintenance protocol to assure the longest possible service life for the Tuned Exhaust System as well as almost any other accessory component bolted to the engine: a Dynamic Propeller Balance.

The computerized equipment required to accomplish this procedure is now widely available allowing the procedure to be performed by most A&P’s across the country (or by someone they know). It essentially spin balances the propeller on the aircraft and eliminates about 99.95% of the vibration resulting from any unbalanced components of the entire power plant. It is important to note that even if the engine seems smooth, there is a good chance that component damaging vibration IS occurring. The ONLY way to eliminate that vibration is by having the propeller dynamically balanced ON the airplane, WITH the engine running.

Having the test performed and the correcting weights applies (usually in the form of washers installed under the prop bolts) typically takes only a couple of hours and costs about $225.00. In light of the fact that the procedure will greatly increase the life span and the reliability of EVERY component that is bolted to the engine (not just the exhaust system), it is one of the cheapest and most cost-effective forms of insurance any pilot can buy.

Power Flow believes so strongly in the benefits of this procedure that if our Customers have this done within 25 flight hours of the installation of their new Tuned Exhaust, we will double the warranty on our system from 12 months to 24 months or 500 Flight hours, whichever occurs first. Doing so every two to four years thereafter will dramatically improve the useful life and reliability of every component that is bolted to the engine - including the Power Flow System.

So, that's what the "experts" have to say about the pro's and con's of various exhaust systems currently available for certified GA aircraft powered by four cylinder Lycoming O-320, O-360, I/O-360 or I/O-390 engines.

To gain a little perspective, it might be nice to end with the unsolicited and unedited thoughts and opinions we have received from a few of the more than 4,400 pilots who have actually flown with both the "legacy" designs discussed above and the Tuned Exhaust System currently available from Power Flow Systems.

VII – CUSTOMER TESTIMONIALS

"Improve performance for flying in Wyoming and Idaho mountains.
I now have the compatible performance of a 200 HP Husky.
This is an affordable increase in HP.

I have improved my POH takeoff distance by 367 ft .
I have improved my Manifold Pressure by 1-2 in for given power setting.
I have more confidence that my plane meets the challenges of mountain flying."

Mr. Stan Dardis, Aviat Husky A1B / N156AA / with Lycoming O-360 Power Flow Customer since: February 7, 2011

"I finally installed the system on my C23 Sundowner. WOW!! I saw a solid 125 rpm increase at static full power on the ground and 2700 rpm in flight. The airplane now has the feel of being "properly powered". We now have all 3 of our rental airplanes Powerflow equipped and the reviews from our customers who have seen the "before and after" performance results are impressive." **– Mr. Kenneth Hetge, Recover Your Cub / N273AM / 1978 Beech C23 / O-360**

"I purchased your PowerFlow short stack headers for my C-172N with the O-320-H2AD engine a little over a year ago and 'can now report "final" performance numbers:

- I now burn about 0.7 gal/hr less fuel . . . I am happy with the fuel savings, which more than cover the cost of the extra exhaust system inspection at annual time . . .
- I've added about 1,500' to my service ceiling. At STP, my aircraft has a book service ceiling of 14,200'. However, in the summer on a desert afternoon and with a full load, the "real" ceiling was more like 12,500'. . .
- the aircraft can generate a given power level at higher altitudes than previously, expanding my flight envelope . . .
- I noticed extremely efficient fuel burn at 50-60% power settings, < 6 gal/hr. This gives me the option of extra range if I need it . . .

Nice product. Thanks" - **Don Ferguson / N737EG / Cessna 172N w/ O-320**

“The power flow exhaust has met my expectations on fuel economy---and has greatly exceeded my expectations regarding power. As a CFI I gave a rental check to recently said, "I wouldn't have known it wasn't a 180hp if you hadn't told me. He had been flying 180hp Cessna 172s for the past year. So, as I mentioned to you, and you may quote me: With 20 thousand hours as a flight instructor and Designated Examiner, the power flow exhaust is the best $4,000 I ever spent on an airplane.” – **Mr. Sandy Reynolds / 172N / N6454G w/ O-320**

“It has added power, and thus speed at all altitudes. At full power down low (1800msl) it will pull the Mooney over red line speed. by about 3 kts. Before it wouldn’t reach red line.

It climbed to 16,500 feet with ease. I don’t know where it would stop. More power up there definitely helps. At altitude, it will easily do 150 kts true, (with light loads, 2060lb) with only nominal 2400 rpm. Thanks for developing a nice product.” – **Mr. Van Wadsworth / N2701W / 1966 M20E / I/O-360**

“Prior to the installation, at 13,000' the plane would climb at 50FPM and the stall horn would sing while the plane wallowed. Now, at 14,000' the plane climbs at 150FPM and indicates 110kts in the climb. I'd a gone higher, but it was cold up there. I call that a significant improvement. In fact, when I departed from Daytona after the installation of my PF, I was startled as the plane rotated off the runway in a much higher attitude than normal. I immediately rechecked the trim, but found all as it should be - except that there was nothing but blue in the windshield. My burn rate went from 10.5gph to 9.5gph. Even aggressively leaning the engine never causes pre-ignition now, and above 10,000' I routinely see 8.5 gph.” **– Mr. Tim Proksch / 1967 M20F / I/O-360 / N3463N**

“I have been very pleased with the improved performance I have experienced since installation . . . I was . . . looking for a way to wring some extra performance out of my airplane, particularly in climb, as that can be the most tedious phase of flight here in Texas, where temps can linger in the 90's well into October. My initial thought was to look into turbo-normalization, but couldn't justify the cost-benefit, particularly since I don't normally operate from high altitude airports. The Power Flow exhaust system has to be the best bolt-on performance modification for our airplanes and I have been happy with the results I'm seeing:

I am seeing 1100 ft/min rate of climb at 80 kts from my 1600 ft elevation home airport (KERV) on 90+ degree days. That is at least a 300 ft/min improvement.

Cruise speeds have improved 3-5 kts to 140 at 25/25 and 12 gallons per hour.

My experience as a new customer was very favorable and I am happy with the system and the additional performance I have observed in my airplane." - **David Wampler / 177RG / N52791**

"One of the best products, Performance/$ ratio I have ever applied on an aircraft. Nice job guys!

6000' msl take off. Identical aircraft. Mine had a power flow. 800ft higher coming around the pattern at the take off roll end of runway than stock exhaust.

We all hear about the "10% increase in power claims." After modifying automotive engines for years, most of us think this is baloney because anyone who makes a piece of plastic to smooth out your air intake claims it! Well, I bet the PowerFlow exhaust on my aircraft has increased the power at least 10% . . . Where this really hits home is my increased climb capability, living on the front range of the Rocky Mountains." - **Mr. Jeff Bursik / N29379 / 1968 C-177 / O-320**

"We just finished my first full annual after installing your amazing system. And we have performed the maintenance as instructed and my power flow exhaust looks as great as it performs!

I'm sure you hear these stories all the time, but it still amazes me every time I fly. I'm in southern Arizona where the ground is at 4,500 ft MSL and in the summer the density altitude can climb to 7,000+. Prior to installing the system I'd be lucky with a 50-100 FPM climb out. Now I'm 600-1,000 FPM depending on how heavily loaded. Everyone is sure I have a 360 tucked under the hood! I just finished flying back and forth to the local college to get my CFI and my 'little 140' out performs the college's Warrior 160s with ease. I'll be sure and send them the coupons as the director is considering installing the power flow systems onto their fleet aircraft to facilitate training during the summer.

I was skeptical about purchasing it in the begining (saving pennies as a new plane owner) but it has been the best performance booster to date and I always recommend it to everyone I fly with..

Thank you again for a great product!" -

Sincerely,
Jesse L. Brewington / N5575F / 1968 PA28-140B / Lycoming O-320

"I recently installed a Power Flow exhaust on my Tiger . . . I have noticed a huge difference in the performance of the airplane, especially with regard to climb.

It has been extremely hot and humid here in the Virginia Tidewater Region, with density altitudes of 2000 feet and more, yet my Tiger took off in a shorter distance (felt like it leaped off the tarmac), and demonstrated a 150+ foot increased rate of climb.

As you know, our planes are not know for being great climbers, and all else being equal, this is not only a big performance improvement, but an major safety factor increase considering taking off with a loaded aircraft and increased density altitudes. Not sure you can quantify or put a price on the safety factor. . . .

With respect to increased maintenance, the mechanic and I discussed the pros and cons before installation, and intend to disassemble and lubricate as recommended at annual time. I think will be a small price to play for the both the increased performance and safety margin." – **John Wrenn / AA5B / O-360 / N74636**

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