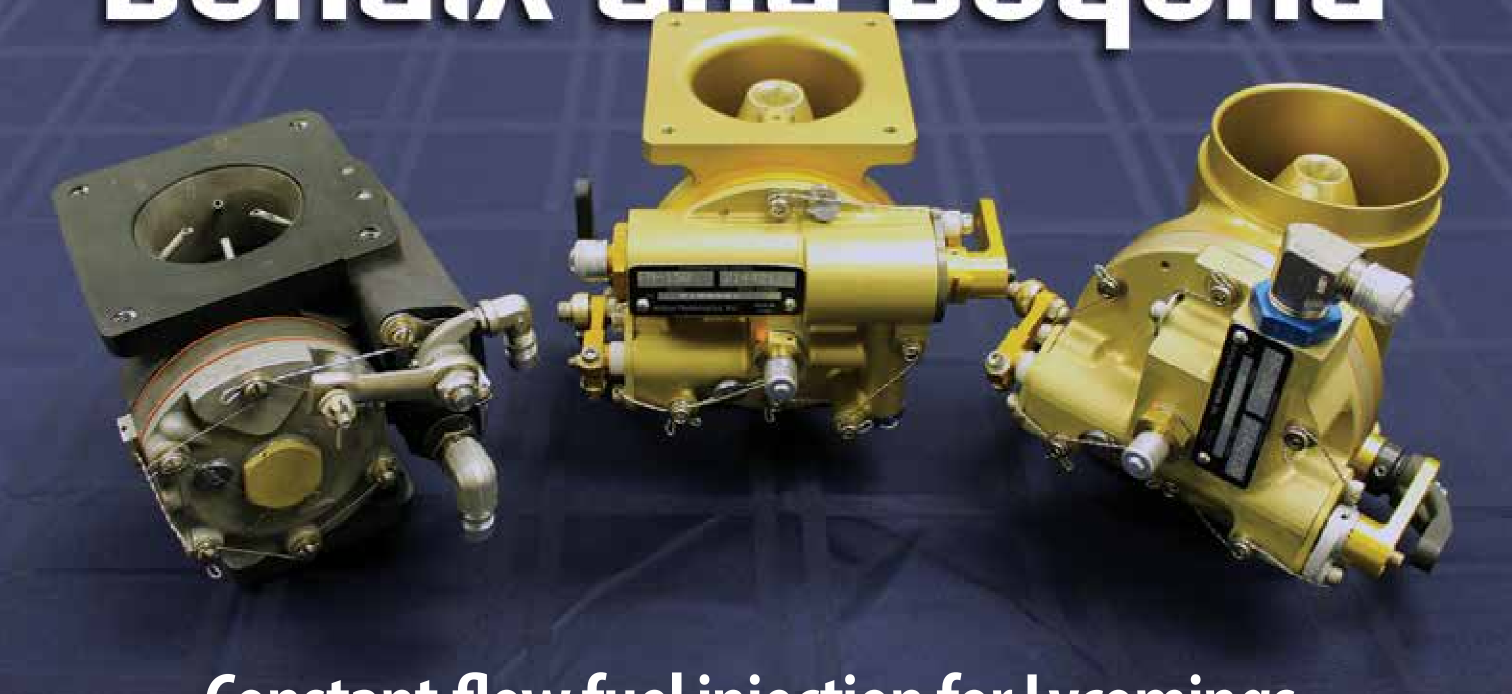
Bendix and Beyond



Constant-flow fuel injection for Lycomings.

BY DAN HORTON

The *Wright Flyer's* 12-hp 4-cylinder had nothing like a carburetor. Gravity supplied fuel, which was regulated with a valve. The fuel dripped directly into the intake manifold, where it was vaporized by heat and intake air. Although far more precise, constant-flow port fuel injection remains fundamentally similar. A device meters a steadily flowing, partially atomized cylindrical fuel stream from a small brass nozzle. The nozzle, one for each cylinder, is mounted just upstream of the intake valve. The hot cylinder head raises the fuel temperature, and the sudden pressure drop when the valve opens causes it to flash into vapor.

The Diaphragm Tug-of-War

The fuel injection type most often seen on a Lycoming engine has its roots in the work of a prolific design engineer named Elmer A. Haase. After graduation from Valparaiso University in 1935, Haase joined The Bendix Corporation in South Bend, Indiana, where he was first a draftsman and development engineer working with pressure carburetors, then a production liaison, turning out very large pressure carbs for combat aircraft. After the war he was assigned to missile work, then in 1950 was transferred to the jet engine fuel controls section, where he was granted six patents in eight years, all for turbine engine and afterburner fuel controls. Returning to piston engines, he and his team first developed the Bendix RS fuel control, then a refined design, the familiar Bendix RSA. (Interested readers can look up Haase patents online; the publication numbers related to RS and RSA development seem to be US3007684A, US3140324A, and US3114359A.) Today, the two best known fuel injection lines, Precision Airmotive and Airflow Performance, still follow the Haase pattern. A recent addition to the market, AvStar Fuel Systems, manufactures a PMA replacement.

The key similarity shared by all these systems is the use of opposing fuel and air diaphragms to control a fuel valve (Figure 1), a concept Haase borrowed from previous Bendix pressure carburetor designs. A large air diaphragm is subjected to dynamic pressure on one side, and venturi pressure on the other, which generates a variable force proportional to engine intake velocity and density. A stem connects the center of the air diaphragm to the center of a smaller fuel diaphragm located in an adjacent chamber, and to a ball valve seated in the fuel outlet. One side of the fuel diaphragm is exposed to inlet pump pressure, while the other side sees only the pressure remaining after the fuel passes through a metering jet. As a result, the fuel diaphragm acts in opposition to the air diaphragm.

The linked diaphragms always find a position of equilibrium, and in doing so, move the ball valve in relation to its seat. The ball valve does not itself directly meter fuel. Rather, by controlling the exit from the metered fuel chamber, it controls the pressure drop across the metering jet.

Imagine the pilot adding power in order to climb. Opening the throttle butterfly increases air velocity into the engine, raising dynamic pressure and lowering venturi pressure. As a result, the air diaphragm pulls the ball valve farther off its seat. The increased valve area causes a decrease in pressure in the metered fuel chamber, which increases fuel flow through the metering jet restriction. The increased pressure differential between pump pressure and metered pressure causes the fuel diaphragm to oppose the air diaphragm with greater force, and the two again reach equilibrium. The response time from airflow change to new equilibrium is about 1/20 of a second.

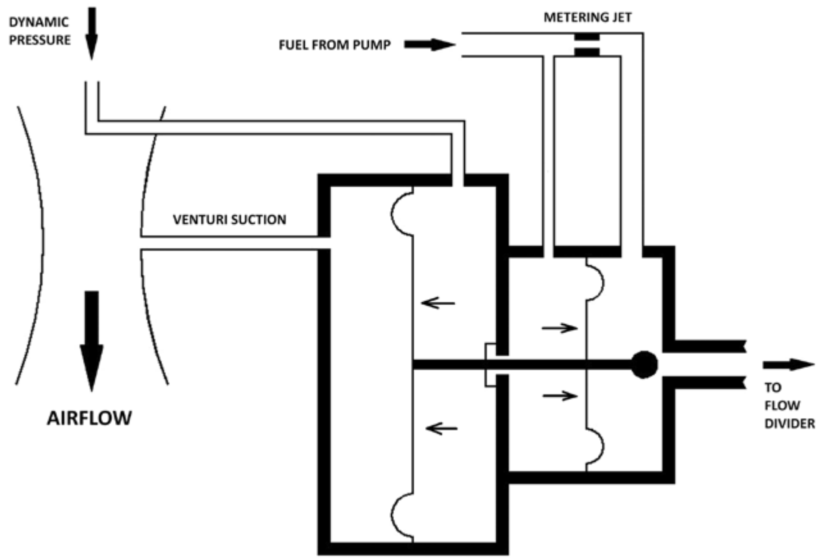


Figure 1: Dual diaphragm regulator.

The dual-diaphragm system also responds to changes in air density due to altitude. The ram and venturi pressures are both a function of the fundamental "1/2 rho V_2" aero equation, where rho is air density, and V is velocity. A change in density has the same practical effect as a change in velocity, increasing or decreasing air diaphragm force.

Consider a climb to cruise altitude, at a fixed rpm. An engine is a volumetric pump, always inhaling the same air *volume* regardless of density. The volume calculation is easy:

[Displacement in cubic inches (rpm / 2)] / 1728 = cubic feet per minute

However, our goal is to introduce fuel molecules to air molecules in correct proportion, by *weight*. So, we're actually interested in the *mass* of the air entering the engine, not its volume. Determining mass flow is also easy; it's just volume x density:

Cubic feet per minute x local density x 60 = mass flow in pounds per hour

Scientists long ago developed models of the Standard Atmosphere, so we can look up the standard air density for any altitude. One common model gives it as 0.0765 lbs per cubic foot at sea level. At 15,000 feet, it is 0.0481 lbs per cubic foot, or roughly 63% of sea level density. The perfect metering device would automatically reduce fuel flow in lockstep with the density reduction.

ALT	FF GPH	rho lbs ft^3
2000	17.8	0.0721
3000	17.6	0.07
4000	17.1	0.0679
5000	16.9	0.0659
6000	16.5	0.0639
7000	16.3	0.062
8000	15.9	0.0601
9000	15.6	0.0583
10000	15.4	0.0565
11000	14.9	0.0547
12000	14.6	0.053
13000	14.2	0.0514
14000	14.2	0.0497
15000	13.7	0.0481

FUEL FLOW VS DENSITY

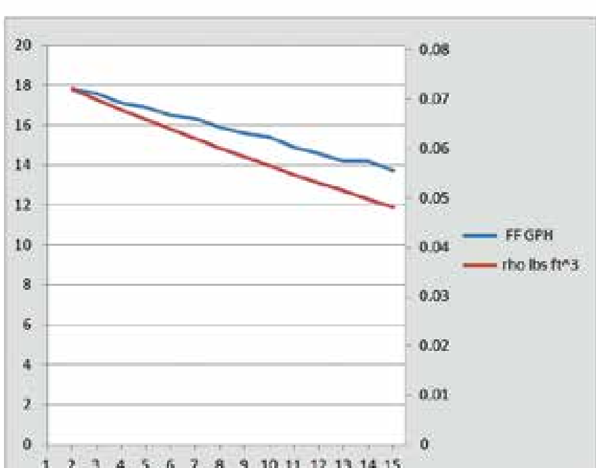


Figure 2: Fuel flow vs. Standard Atmosphere density (rho), 2000 through 15,000 feet, IO-390.

The dual diaphragm system isn't *perfect*, but it does a remarkably good job. Figure 2 is a flight of my IO-390 powered RV-8; fuel flow is plotted against standard air density while climbing from 2000 feet through 15,000 feet, running WOT, full rich, and 2700 rpm. The fuel control is an Airflow Performance FM-200.

Density at 15,000 is 67% of the 2000 foot density (0.0481/0.0721), while fuel flow declines to 77% (13.7/17.8). The result is a small overall enrichment of Fuel/Air ratio, although it is nothing like the enrichment we would see if fuel flow remained constant. How much richer? The answer can be derived from the previous mass calculations, or from exhaust gas temperature. Here the average EGT drop for the whole climb was approximately 200°F. The relationship of F/A ratio to EGT is known to be near linear in this part of the rich-of-peak operating region, so consulting Lycoming data says the ratio shift is a bit more than 0.02, here from 0.08 to roughly 0.10 F/A, or 12.5:1 to 10:1 air-fuel. A plot of peak power vs. mixture is fairly flat in this F/A range, so the power loss due to enrichment is less than 5% if the pilot does nothing. All in all, it's a good performance from a device with no power requirement, and only a few moving parts.

Of course, the pilot may wish to lean in the climb. As seen in Figure 2, only

Photos: Dan Horton

Figure 3: AFP FM-150 showing straight throat and mast-mounted high gain venturi.

Figure 4: RSA-5 looking through the intake end. Tubes in air-stream sense dynamic pressure.

minor tweaking is needed with any Bendix-style fuel control. These days, most pilots seem to be using the "target EGT" method, noting full rich EGT shortly after takeoff, and adjusting mixture in the climb to maintain that approximate value. It's a simple and effective way to climb faster while burning a little less fuel. What's not to like?

There is one more interesting detail about the dual diaphragm system; it is relatively insensitive to pump delivery pressure. The fuel diaphragm counterforce is based on the *difference* between supplied fuel pressure and metered fuel pressure, so the system will meter with reasonable accuracy given a supply pressure starting at roughly 20 psig, and extending all the way up to the limits of the internal seals. The maximum varies between manufacturers, but it is generally assumed to be 80 to 90 psi.

A Tour of the Hard Parts

Precision Airmotive bought the RSA product line from Bendix in 1988, and they still build the RSA-series fuel control in nine different models for certified aircraft. The RSA-5 is generally used on 4-cylinder and low-output 6-cylinder engines, while the much larger RSA-10 is used on high output sixes and the rare eight-cylinder Lycoming. Precision also builds their Silver Hawk line of fuel controls in two sizes for aircraft licensed in the Experimental category. The Silver Hawk EX-5 series is basically an RSA-5 without certification paperwork.

Airflow Performance occupies a unique niche. Founders Don and Colleen Rivera were both Bendix employees, and Don worked with Mr. Haase, first as the new kid, and later as the engineer responsible for the Bendix RSA product line. When Don left Bendix to found AFP in 1984, he designed his own line of fuel controls based on what were obviously familiar operating principles. However, the AFP FM-100, 200, 300, and 400 systems were not Bendix copies. They were originally intended for racing applications, and as such needed a very wide metering range to accommodate fuels other than gasoline. (Methanol, for example, requires more than twice as much fuel flow for the same quantity of air.) They were also designed to exhibit less carb loss (the reduction in manifold pressure due to venturi restriction), an important detail when hp is everything.

The most obvious visual difference between the RSA control and its

Figure 5: Airflow Performance mixture valves, early drum type on left, later disk valve on right.

Figure 6: Control body fuel diaphragm with bleed fitting and ball valve.

equivalent Airflow Performance FM control is directly related to carb loss improvement. The FM incorporates a high-gain modular signal venturi suspended in the center of the throat. That means the throat itself has no significant taper. The older RSA control uses a constricted throat insert to form the venturi (Figure 3 and Figure 4).

Note the four ram (dynamic pressure) tubes in the RSA throat. The FM dynamic pressure tap is the small hole seen in the venturi mast. The larger hole in the center is the high-gain venturi.

The RSA mixture control valve is a slotted disk that covers and uncovers fuel flow holes in order to vary fuel supply to the main jet. The early AFP FM designs (FM 100, 200, 300) use a simple drum-style valve, which is easy to machine and shrugs off dirt. More recent AFP designs (FM-150, and 250) have a disk valve conceptually similar to the RSA valve (Figure 5).

The drum mixture valve is responsible for another well-known feature of Airflow fuel injection, the purge valve. You'll generally find it on top of the engine, plumbed between the fuel control body and the flow divider. Although generally thought of as a hot-start aid (see below), its fundamental purpose is to re-route pressurized fuel back to an aircraft tank at shutdown. Why? The disk-style valves have a very low bleed rate, and cleanly cut off fuel supply to the flow divider and injector nozzles. The drum valve has a 1- to 3-pound-per-hour leak rate, and consequently may not always shut down the engine cleanly when the mixture lever or knob is moved to the idle cut off position. Following shutdown, a drum valve may also allow the flow of fuel held in a pressurized state by the engine driven pump's spring. The purge valve sends it all to a tank, rather than through the flow divider and injectors, flooding the engine.

For most users, mixture valve bleed issues are invisible. They love the purge valve because it can be used to circulate cool fuel through a hot system prior to a re-start, without a single drop entering the engine. All the fuel vapor bubbles are flushed out, the components are cooled, and when the engine is cranked, it starts and runs normally, rather than the spit-and-sputter, or throttle-wide-open starts so often seen. Although considered standard equipment with the drum valve FM models, it is possible to install a purge valve with *any* Bendix-pattern constant-flow FI system, regardless of brand or mixture valve type.

The brands have different filtration requirements. Rivera recommends a large area 125-micron filter early in the flow path to protect the electric boost pump as well as the FI system. The AFP FM fuel controls are themselves

On the Bench

The original Bendix design and all subsequent versions use the same general operating principle, so is there a real difference in performance? We went to the flow bench for the answer.

Airflow was set at 1560 pounds of air per hour, an approximation of a 540 Lycoming running 2700 rpm on a 70°F day at Reno. The numbers below represent *carb loss* in inches of water…the loss of manifold pressure due to intake restriction. Each control was fitted with a standard intake bell mouth before measurement.

RSA-5	12.75 inches
FM-150	10.0 inches
FM-200	4.0 inches
RSA-10	4.9 inches
FM-300A	2.6 inches

The RSA-5 and FM-150 compare directly, as they have the same installation dimensions. The carb loss performance appears to demonstrate the primary design difference, a throat venturi vs. a pedestal-mounted center venturi. These two controls fit the majority of Lycoming-powered homebuilts with 320s, 360s, and low output 540s. The FM-200 and RSA-10 are the performance choices for larger 4-cylinder engines (IO-390, Superior 400, etc.) and 540s above 260 hp. The FM-300A is one of Rivera's lesser-known specials. It's used on seriously hot-rodded 540s and pumped-up M-14 radials.

—D.H.

Original Bendix RSA-5 on the Superflow bench.

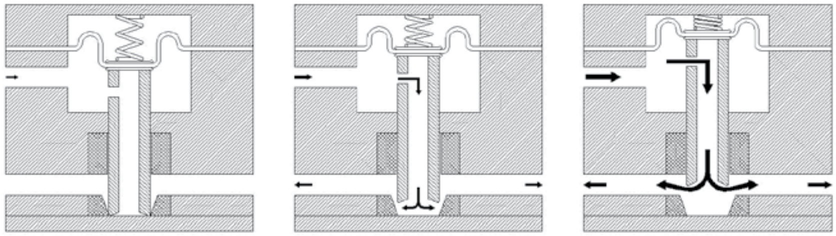


Figure 7: Flow divider schematic. (Left) No fuel flow; valve closed, all outlets isolated. (Center) Idle and low cruise power; fuel pressure pushes against diaphragm, partially raising valve piston. Fuel is regulated evenly through progressively increasing valve outlet areas. (Right) WOT and high cruise power; pressure fully retracts valve piston. Flow is unrestricted by divider area.

Figure 8: Flow divider insert showing metering slots and unrestricted outlet holes in valve piston passage.

equipped with a small 75-micron inlet filter, plus a 75-micron filter in the flow divider. The Bendix RSA-5 has a physically larger 75-micron inlet filter with a bypass spring; it will push off its seat and allow unfiltered fuel flow in the event of a blockage. Unfortunately, that usually dumps a load of garbage into the fuel control, flow divider, and injector nozzles. The Precision Silver Hawk units require a very fine 32-micron filter prior to the servo inlet. Such a fine filter should not be installed upstream of the boost pump.

Note an interesting fuel diaphragm detail: Next to the outlet valve ball there is a small fitting with a tiny little bleed hole (Figure 6). Take another look at Figure 1, and you'll see how it is possible for vapor bubbles to accumulate on the pump pressure side of the diaphragm. The bleed ensures trapped vapor is released to the metered fuel chamber. It works because it otherwise merely acts as a secondary (but tiny) metering jet, subject to the same forces as the primary jet.

Some of the best high-precision machining is found in the lowly flow divider. The divider (aka the "spider") has a two-fold purpose. The primary task is to ensure even distribution of fuel to the cylinders when fuel flow is too low to regulate evenly with injector nozzle size alone. In a system with typical 0.028-inch diameter restrictors in the nozzles, that means total flow below 6 or 7 gph. As a secondary task, the flow divider's internal valve closes when fuel flow from the control drops to zero at idle cut off, isolating all the outlet passages. The closure prevents one cylinder sucking fuel from another cylinder's fuel passage, the result being a cleaner shutdown.

AFP "Fuel Injection 101" School

I admit to enjoying some mild debauchery on the weekend…you know, a bottle of beer, the company of good friends, perhaps even staying awake until 10 p.m. However, an airplane guy can't spend all his time immersed in such revelry. Sometimes we need to mix education with the recreation. It is, after all, why Uncle Sam lets us build our own airplanes.

One of the more interesting weekend schools is found in a hangar at the far west end of the Spartanburg Downtown Airport (KSPA). It's the home of Airflow Performance, a small firm entirely dedicated to the design, manufacture, and overhaul of mechanical fuel injection components.

The AFP "Fuel Injection 101" class starts with a Friday afternoon arrival. There's a lot of hand-shaking, a few cold beverages, a shop tour, and dinner. The Friday meet and greet is a lot of fun, as classmates come from every corner of the airplane world. The class I attended was a nice mix of A&Ps, engineers, and pilots. All were homebuilders, Experimental owners, or worked on them every day.

The AFP hangar and shop is very much like what you might find at any small fly-in community. The office, the assembly and overhaul areas, and the lab spaces are built into the main hangar, along with a kitchen, which (of course) is where folks tend to congregate.

Class fired off at 8 a.m. Saturday morning around a big table. The Riveras have the program nailed; Don teaches, Colleen takes care of everyone, and the students soak up the collective goodness. The atmosphere is relaxed, partly due to Don's style, and partly because of the small class size. The morning session is devoted to operational theory. Don uses actual Bendix and Airflow fuel injection parts to illustrate, and passes them around the room. Most of the PowerPoint images are presentations of data, with a few illustrations here and there. The pace allows for questions, and Don cheerfully expands on any detail. It's definitely *not* a one-way lecture class, and the morning passes quickly. Lunch is again a social bonanza centered around the kitchen.

With all tanks topped, the class split into two groups for the afternoon session. One group stayed with Don for a discussion of practical maintenance, installation, and troubleshooting issues, while the other went with Kyle Day, AFP's all-around indispensible right-hand man, for a live session in the test and calibration lab.

The lab is the heart of the operation, no surprise given that the whole point is precise control of fuel and air ratio. The key tools are flow meters based on fundamental physics, one for air and the other for liquid. The airflow meter is the same classic Superflow SF-600 flow

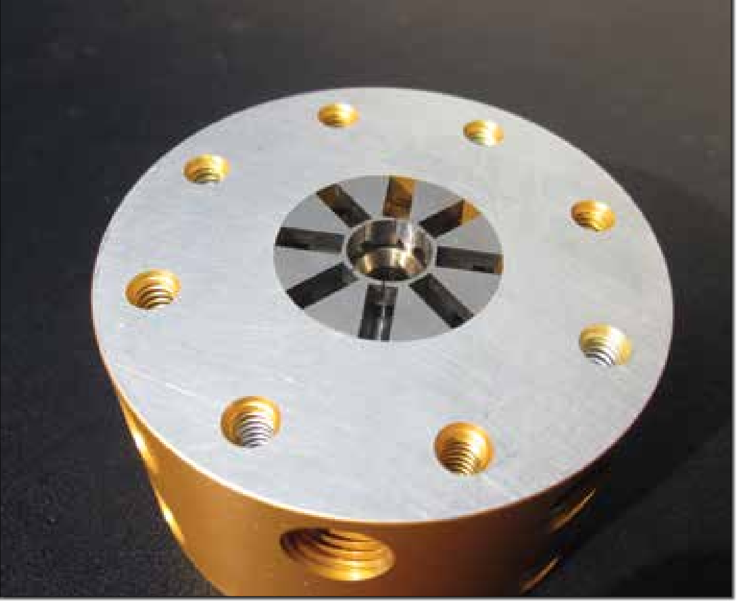


Figure 9: Insert in body with piston. Divider is upside down with bottom plate removed. Piston is retracted beyond metering slots, enough to uncover holes allowing unrestricted flow. At this point fuel division becomes a function of injector nozzle area.

Figure 10: Injector nozzles. (Top) Current two-piece nozzle with swappable restrictor insert. (Bottom) Older Bendix nozzle with pressed insert. Note air bleed passage through the side wall of the nozzle body at the bottom of the photo.

A flow divider (Figure 7) is conceptually simple. A tubular valve piston slides up and down in the center of the body. A diaphragm is attached to the top, so that pressure against the diaphragm raises the piston. A light spring opposes the diaphragm pressure. When fuel pressure (starting around 2 psi) is applied to the upper chamber, the piston is raised, exposing small slots in a metering insert which surrounds the base of the piston (Figure 8 and Figure 9). More pressure raises the piston progressively farther, exposing more slot length. Since the slots are all *exactly* the same width, fuel quantity is equally divided between each injector outlet.

The injectors are really quite simple, just brass nozzles with precision inserts (Figure 10). The restrictor insert was pressed into early nozzles, which meant they could not be separated for cleaning or tuning. Current nozzles incorporate restrictor inserts, which can be removed without tools. A whole set may be exchanged with grossly larger or smaller sizes for different engine displacements, or any individual restrictor may be exchanged with a very slightly smaller or larger size. Doing so allows exact matching of fuel flow to the particular

bench so often seen in cylinder head shops, but the liquid bench is custom built. They can be connected to the same fuel control at the same time, so that for any given quantity of air, the precise quantity of delivered fuel can be measured. The tools are often configured in different ways for different purposes. For example, flow divider output can be measured to ensure individual nozzle lines are receiving exactly the same quantity of fuel.

Airflow Performance is an FAA-approved Repair Station; they check and rebuild certified Bendix controls as well as their own FM-series products. *Everything* is calibrated before it goes out the door, and it is fascinating to see how it is done.

We spent about two hours in the lab and overhaul shop, then swapped instructors so the other group could have a turn. Saturday evening wrapped up with a barbeque and more social time. After packing so much into the day, no one stayed up late.

We were back in the conference room bright and early. Sunday morning is catch-all time; Don takes questions and invites discussion. It really works well, as each attendee has had time to think about the previous day's lessons, and identify the things he or she may not fully understand. Listening to the other questions jogs minds, and the result is a lively exchange. When conversation runs out, it is time

Custom-built liquid metering bench.

to go home, notebook and Airflow Performance manual in hand. A weekend well spent!

Airflow Performance "Fuel Injection 101" classes are generally held in the spring and fall. To inquire about the next available class weekend, contact Colleen Rivera at 864-576-4512.

—D.H.

Figure 11: Classic FM-200.

Figure 12: FM-200A with disk mixture valve.

airflow capacity of an individual cylinder. The tuning process has become known as "adjusting the GAMI spread," as General Aviation Modifications, Inc. of Ada, Oklahoma, has done a great job spreading the gospel of flow balancing. Any knowledgeable owner can do the work, and the small-increment restrictor inserts are available from Airflow Performance as well as GAMI.

In Figure 10, note the air bleed hole through the side of the nozzle body. Air is drawn into the chamber around the tip of the insert, where it is entrained in the fuel as it is squirted from the restrictor tip into the drilled nozzle passage. At small throttle openings, manifold suction is quite high, so the air drawn into the nozzle body has velocity and breaks up the low volume, low pressure idle fuel flow into smaller, more atomized droplets. The effect of the atomizer air is less pronounced at high fuel flows and lower manifold suction (i.e. higher manifold pressure). The effect is still there, but not needed so much, as the heat and violence of the intake port at high power settings is more than enough to vaporize the fuel.

Times Change

Some readers may be confused about the many different models of AFP fuel controls. First, there are two entirely different families, the earlier FM-100, 200, 300, and 400 line (Figure 11), and the later FM-150 and 250 models. In general, the "100-series" controls have longer bodies than a similar Bendix unit, which may be a packaging consideration in some tight cowls. In addition, they use a

Fuel Injection, Family Style: Don and Colleen Rivera

So how do you get to Carnegie Hall? Practice, of course. It's how Don and Colleen Rivera became the best known names in aircraft fuel injection. They've been working with fuel systems most of their adult lives.

Don and Colleen Rivera, founders of Airflow Performance.

Don's father was a field representative for Bendix, so his early exposure to fuel metering went way beyond the typical carburetor. In fact, young Don fuel injected his high school ride (a Corvair) using a cast off RSA-5, a feat worthy of bragging rights in teenage car culture. Next stop was A&P school, and a turn in aircraft maintenance. When he started thinking about what he really wanted to do, Don returned to college for an engineering degree...after which he got a chance to go to work at Bendix, in South Bend, Indiana. The die was cast.

Don's first big professional project rarely achieved an altitude of more than a few feet; he was assigned to the development of a gas turbine fuel control intended for a US Army main battle tank. When that project reached production, Don was reassigned to the Carburetor Group. In a huge stroke of luck, he soon found himself under the wing of Elmer Haase, inventor of the RS and RSA line of Bendix fuel controls.

It wasn't Don's only stroke of luck. Colleen was a Bendix test technician, mostly working in the hot, cold, and dirt test programs for military fuel systems. One day she decided to fix up her best girlfriend with the Rivera guy from down the hall. The girlfriend was interested, but

Figure 13: FM-150.

Figure 14: Lightweight AFP FM-150L.

clamp ring at the intake end, rather than a bolt flange. They have drum-type mixture valves, so in a Lycoming application they are almost always installed with a purge valve next to the flow divider. "Almost" is the operative word, because Rivera has recently introduced an FM-200A (Figure 12), a classic FM-200 body with a disk-type ("A") mixture control. There's no *need* for a purge valve with the FM-200A; purge or no purge is a customer choice.

The FM-150 and 250 (Figure 13) are newer designs. They too have a low-bleed disk mixture valve (and no purge valve), but their primary feature is packaging that makes them a bolt-in replacement for a Bendix unit installed on an E/A-B aircraft. They have the same overall dimensions as the equivalent Bendix, and the same flanges and bolt pattern at each end. They do, however, retain a straight bore with a mast-mounted high-gain venturi, a signature AFP feature.

One of the more recent developments is the FM-150L (Figure 14), a featherweight version in limited production for an airframe OEM known to be fanatical about weight. The body was slimmed, internal parts were lightened, and the front flange was eliminated. As a result, it's about 25% lighter than its direct competitor.

Because the original FM series controls were designed to be highly adaptable, it's possible to get an AFP control in almost any configuration to fuel almost anything. You can try to stump Rivera with a new engine, but there's a pretty good chance the parts list is already in his notebook. ✈

a little hesitant about a blind date. Colleen agreed to come along and make an introduction, but at the appointed meeting place, her friend was a no-show. Colleen and Don decided to make the best of it. . .and today they still do.

Don eventually became the Bendix project engineer for the RSA line. In 1984, he and Colleen left to start Airflow Performance. At the time they had no intention of competing with Bendix in aircraft fuel systems; AFP's original focus was fuel injection for racing, mostly sports cars and drag boats. The business moved to Spartanburg in 1987 in order to be more centralized in the Southeast's racing market. They shared space in a building with a race car engine shop.

Racing was fun, but given their backgrounds, the Riveras were never very far from airplanes. A few high-performance aircraft engine builders had discovered that AFP's FM-series fuel control throttle body exhibited less manifold pressure loss than the certified Brand B unit, and the word began to get around. Things really took off in the early 90s, when Kenny Tunnell (of Ly-Con Aircraft Engines) called to ask if Airflow might be interested in sponsoring a former California crop duster (and U.S. Aerobatic Champion) named Sean Tucker. Don said yes, and it turned out to be a great choice. Tucker, ever the professional, worked hard at creating value for sponsors. Almost overnight, everybody in the airshow business wanted to know more about AFP injection.

Don has now been designing fuel controls almost 40 years, with Colleen there every step of the way. Key man Kyle Day has been working alongside them for 19 of those years, and will no doubt carry Airflow Performance well into the future. Colleen stills answers the phone, while Don and Kyle provide technical help to pretty much anyone who asks. The three arguably know more about Bendix/Precision and their own FM-series fuel controls than anyone alive. . .and they are all genuinely nice people. It's good to see nice people finish first.

—D.H.

Fuel injection expert Kyle Day offers service with a smile.