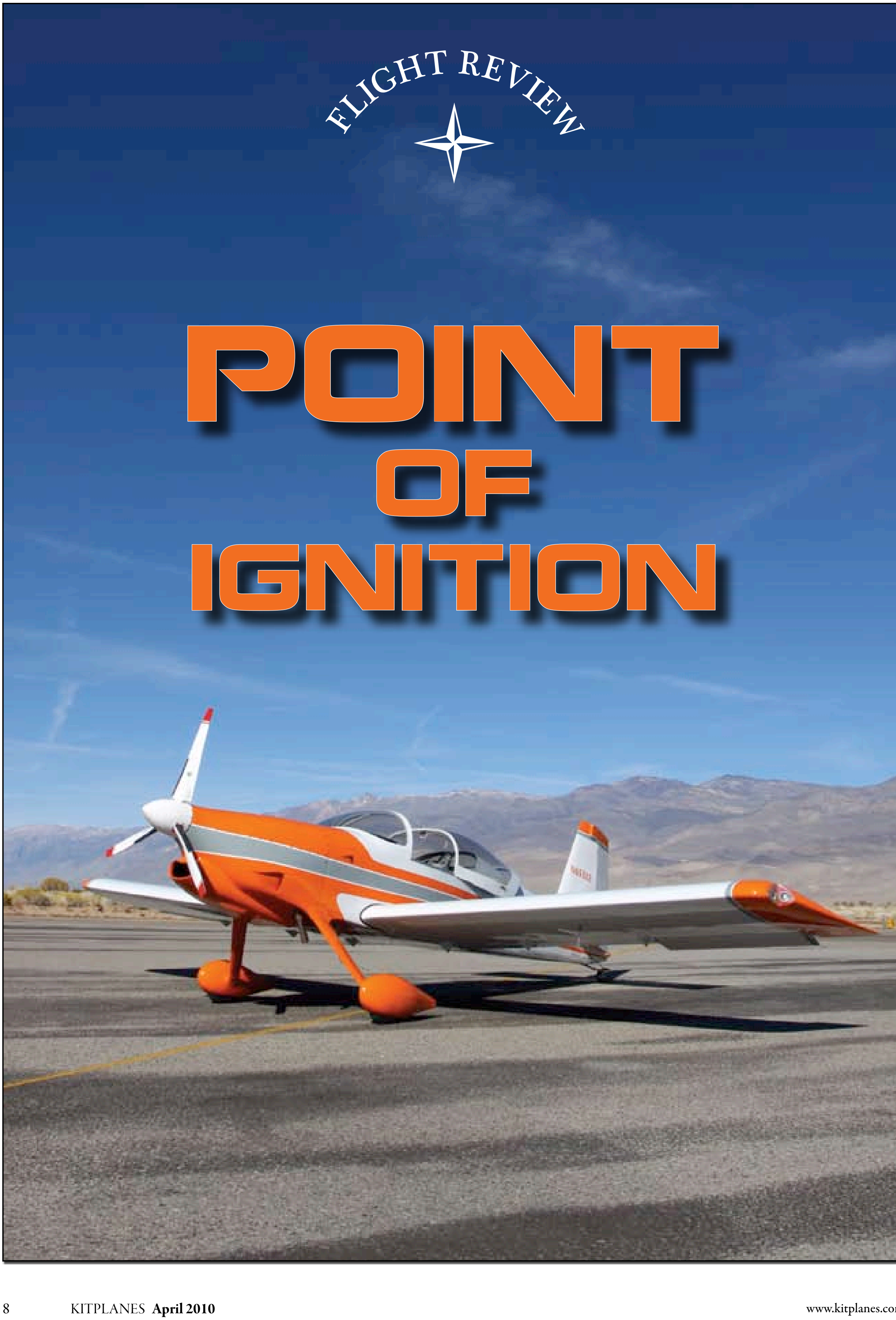
FLIGHT REVIEW

POINT OF IGNITION



The Wilksch WAM-120 engine is, for many, one of the most promising compression-ignition engines. *We get hands-on with the first installation in the U.S.*

BY KEN KRUEGER

Editor's note: Here is the rare opportunity to watch the engineer in his natural habitat. We met RV-9 builder Kurt Goodfellow the same day as Van's Aircraft Chief Engineer Ken Krueger was undertaking test flights of the Wilksch-powered RV-9 and the factory's own Lycoming-powered RV-9A. We were hoping to piggyback onto some of Krueger's results, but when he offered to write a full evaluation for us—something we'd expected he'd keep inside the walls at Van's—we said, "Heck, yeah."

As the chief engineer for Van's Aircraft, I have been following the development and maturation of the Wilksch Airmotive (WAM) diesel engines with more than passing interest. The size, weight and horsepower range of the WAM engine made it a possible candidate for installation into one of my favorite aircraft, the RV-9. While visiting the U.K. in 2006, I had a chance to see a Thorp T211 with a WAM-120 engine installed, but until October of 2009 I had never flown behind one. When Kurt Goodfellow, a builder from Boulder City, Nevada, called offering to let me look at and fly in his WAM-120 powered RV-9, I was eager to seize the opportunity.

For those not familiar with the WAM engine, it is a direct-drive, two-stroke, liquid-cooled, forced-induction diesel engine. Three inline cylinders reside beneath the high-mounted crankshaft; the propeller thrust line is close to where it is with the Lycoming despite the lack of a gearbox. (For a more complete description of the engine and the thought process that spawned it, see the sidebar on Page 11.)

Side by Side by Side

It didn't take a lot of time before the idea came of using the Van's Aircraft RV-9A demonstrator to conduct a series of comparison flights with Goodfellow's RV-9. By flying the two aircraft side by side, using GPS to measure speed and carefully accounting for the fuel consumed, we could eliminate a lot of variables and get a fairly good idea of the performance difference between the two with only a few flights. Because the aircraft were flying "same way, same day," any atmospheric instability that affected one aircraft would equally affect the other. After digesting the data recorded during the comparison flights, it is possible to infer the "real-world" power output with the propeller efficiency and cooling drag accounted for.

Goodfellow earns his flying money by operating a rock-crusher business, and this alone makes him no stranger to diesel-powered equipment. But diesel power has been a hobby all of his adult life, and it includes several diesel conversions and a diesel-powered Bonneville streamliner. By his own admission, Goodfellow really likes diesel engines; in fact, it could be said that he is mad about diesels.

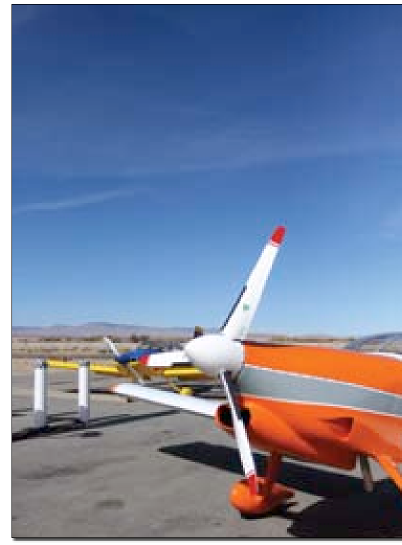
Knowing this, it is not surprising that his RV-9 has a WAM-120 powerplant. Mating the WAM-120 engine to an airframe designed for a Lycoming is quite a challenging task, and judging from the results, Goodfellow has met the challenge. The engine-mount design had already been worked out by Wilksch, and there are some WAM-120 RV-9As flying in the U.K., but Goodfellow felt some improvements could be made. Prior WAM installations had placed the two heat exchangers (radiators) stacked in series and placed low in front

Photos: Ken Krueger, Marc Cook

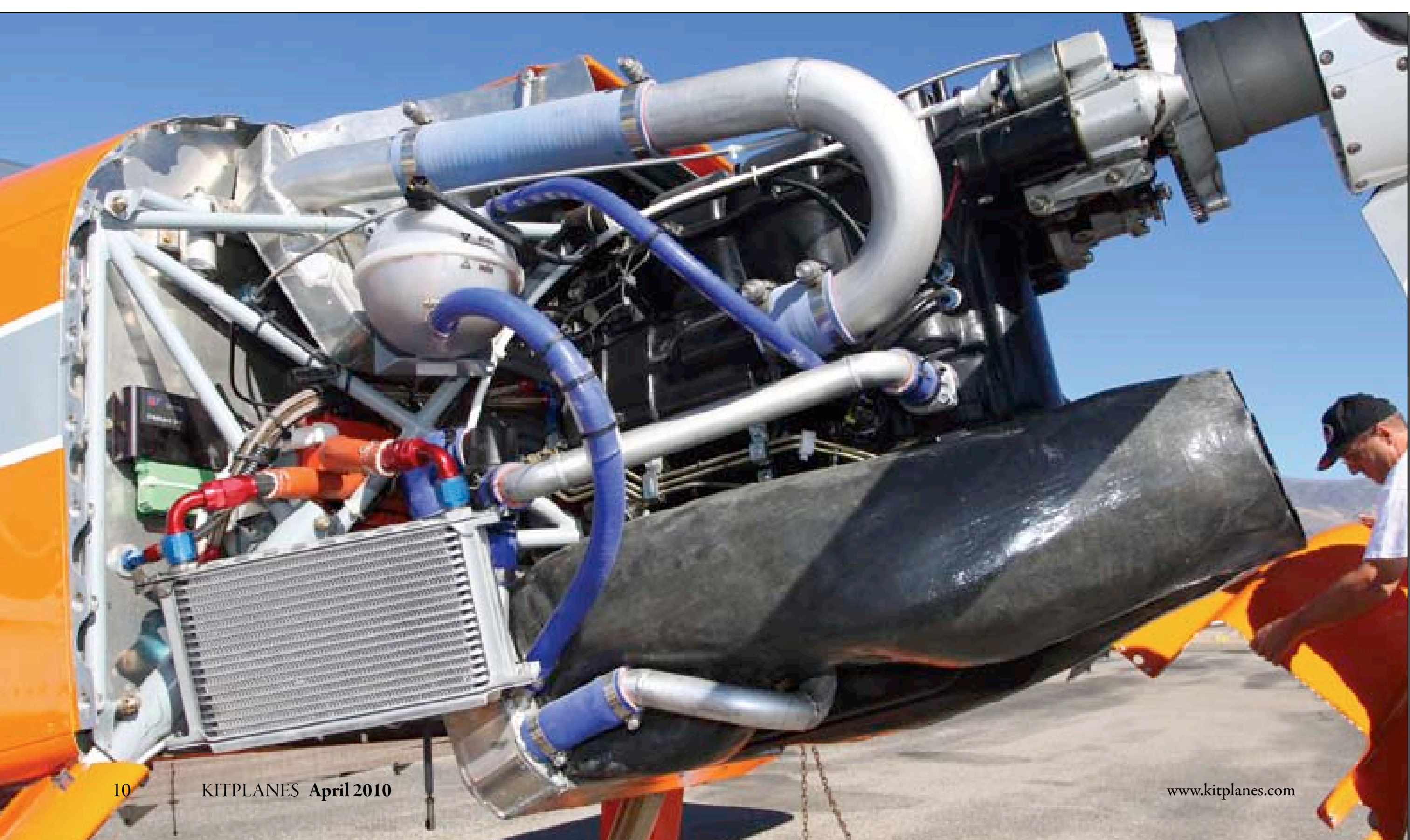
of the engine. This results in a short and almost certainly inefficient inlet duct. Goodfellow's installation places the coolant radiator at the rear of the engine and low in the cowl, and the air-to-air intercooler is also placed at the rear of the engine but high in the cowl. Two cowl flaps are used. One is at the top with a forward-facing opening; it captures more inlet air, directing it through the intercooler. The second cowl flap on the bottom allows exiting air to be drawn through the coolant radiator. A single electric actuator powers the linkages that move the two cowl flaps simultaneously. He elected to install an MT three-blade, hydraulically actuated constant-speed propeller, which is typical of other WAM installations.

The comparison flights originated at Bishop, California. This location proved to be nearly ideal, as it was geographically convenient for both Goodfellow and me, the weather is consistently good, the airspace is uncongested—and there is a really good Thai restaurant in the terminal building. Additionally, the airport elevation is 4120 feet, and con-

At the end of each flight, both aircraft were refueled and their consumption compared. In each case, the Wilksch consumed fewer gallons of fuel than the Lycoming.



The diesel RV-9 sports a three-blade MT prop. The Van's Aircraft factory RV-9A, in the background, features a Lycoming O-320 and a two-blade Hartzell constant-speed prop.



The Man Behind the WAM Discusses Aero-Diesels

Wilksch Airmotive was founded in 1994 in the U.K. with private equity backing topped up with a government technology grant. When laying out the WAM inverted two-stroke modular concept I was mindful of the need to achieve a power/weight ratio at least equal to established aircraft engines.

I chose the inverted two-stroke arrangement because it gives a modular engine family with direct drive and favorable packaging. I had always admired the Lycoming range for its modularity and use of common parts—far more important in a low-volume market like GA than in, say, the auto industry.

A traditional flat-four/six arrangement is not favorable using a two-stroke, as the flat-four variant has large unbalance. In the WAM, the "primary reverse" balance weights, which rotate at crank speed, are nearly the same for two-, three-, four- and five-cylinder variants—a big help with modularity.

The WAM engines achieve installed power/weight equal to or better than equivalent Lycomings, with the WAM-120 weighing the same as an O-235 and a WAM-160 coming in at about 10 pounds lighter than an O-320. Attempts at aero conversions of auto engines such as the Thielert and Austro have resulted in much heavier and more complex installations.

However, the WAM still requires a radiator and intercooler, and a constant-speed prop is almost essential to get the best out of the torque curve. So the installation (while not heavier) is more complex than a Lycoming. A big plus with the all-mechanical WAM is that engine operation is simple and completely independent of aircraft electrics.

While the diesel's efficiency is high, the heat dumped to coolant tends to be higher than a gasoline engine, so cooling drag and hot-day temperature limits can be an issue, but the overall result in terms of speed/economy is a win as we can see from the RV-9 numbers.

Because liquid-cooled diesel engines are a new idea, the definitive simple installation has not yet developed as it has for the Lycoming. Kurt Goodfellow's RV-9 is particularly good, but further simplification is desirable if diesels are to make it in volume-produced GA aircraft.

In 2005, I moved on from WAM to study further diesel options including all-mechanical DI [direct injection] engines and air cooling. During 2007-2008, I assisted TCM with its diesel study and worked on weight reductions plus the new sump design of the O-200-D for the SkyCatcher. I am now assisting Ilmor Engineering in the U.K. with further studies on aero-diesels. One of these is a WAM derivative with DI and an expected SFC reduction of around 15%. Beyond that I am studying an air-cooled diesel aimed at a return to Lycoming-like simplicity.

I take the view that global success will most likely follow success in the U.S. market; hence, there should be little downside compared to a Lycoming, and the engine should "wash its face" with U.S. fuel prices, thereby assuring follow-on success globally.

—Mark Wilksch

ducting the comparison flights at high altitude allowed the forced induction WAM engine to really shine.

The Test Plan

Preflight preparation involved fueling both aircraft, after which we could

Started and ready for taxi, the Wilksch-powered RV-9 does sound like a miniature big-rig with a propeller.

weigh each fully fueled as well as each pilot. The aircraft with the lighter pilot would carry ballast to make up for the difference in pilot weights.

Because the aircraft in this comparison use different density fuels, it is also necessary to account for the difference in fuel weight and add ballast to the aircraft carrying the lower-density fuel. This approach is preferred to partially fueling one aircraft, because it eliminates variation due to estimation when partially filling a fuel tank. 100LL Avgas (at 6.02 pounds/gallon) is less dense than Jet A (at 6.76 pounds/gallon). Given that the

Author Ken Krueger (left) and builder Kurt Goodfellow discuss the flight plan.

Riding Shotgun

Confidence to take a flight in an uncommon aircraft—particularly where the powerplant is the unusual element—is easier to achieve the more confident the owner. And I don't mean brash or boastful. Instead, Kurt Goodfellow is quiet and modest, yet he clearly has pride in his work. He should. His installation of the WAM-120 is close to artwork, despite the fact that this was the first of its kind, at least in this configuration. (Other WAM-120s are flying, even in RV-9s, but the cooling system and accessory layout is unique to Goodfellow's airplane.)

In the main story, you will get a thorough, objective picture of this engine/airframe combo. But I was after one answer: Will pilots accustomed to standard aircraft engines find the Wilksch attractive or weird? Well, we start with, er, not weird but different. The Wilksch uses glow plugs to help initiate combustion during the start process. In Goodfellow's machine, you turn the key to the first position and wait a few seconds while the glow plugs get hot. If you've driven an older diesel automobile, this turn-and-wait sequence will be familiar. (More modern direct-injection diesels are ready to run almost instantly, and, anyway, the engine computer will figure out when it's OK to crank the engine no matter how hard you turn the key.)

The WAM-120 starts with a burble and a definite "ball bearings in a can" sound, but it's smooth and responsive. Goodfellow notes that the alternator runs at crankshaft speed, so you'll need to boost the idle up a bit to get a charge. From the tiedown spot to the end of the runway, the only clue is the idle sound and the long, beak-like nose blocking your forward view. There's no runup per se, but the pre-takeoff checklist includes opening the cowl flaps and turning on the electric boost pump.

During the takeoff, the noise level increases markedly, but the engine remains smooth with a characteristic three-cylinder growl. The exhaust is muted thanks to the small turbocharger. (It's also visible: A gout of smoke trails the RV-9 at high power settings.) After 5 minutes at 2750 rpm and full throttle, you're supposed to pull back to 2575 rpm and reduce manifold pressure. The instruments supplied with the engine provide readings in percentage of maximum, so pulling each back to 83% or less gets you close to the 100-hp maximum continuous rating. In our flight, the coolant temp held at 95° C (203° F) and the oil at 98° C (208° F). According to Wilksch, the engine's fuel specifics are 0.49 pounds per horsepower hour at maximum, 0.45 pph/hp at 100 hp and 0.43 pph/hp at the economy cruise setting of 67 hp (67% of max continuous, 56% of maximum takeoff power). Those fuel specifics don't sound great until you remember to take into account the heavier fuel; converted, those values are 0.44, 0.40 and 0.38. Run lean-of-peak EGT, the very best avgas-burning aero engines can achieve 0.39 pph/hp, but also have portions of their operational profile where they require 0.50-0.60 pph/hp to remain cool.

Setting the Wilksch up for cruise is a matter of selecting prop rpm and manifold pressure, closing the cowl flap and retrimming. That's it. A sensation of a fast-turning engine remains, a quirk of the two-stroke cycle not the engine's actual speed; twice as many combustion events fool the ears. On the descent, pull the power back all you want; the liquid cooling takes care of itself. The Wilksch is responsive enough that you can approach and land conventionally. Finally, on the shutdown—no clankety-clank gearbox noise—it dawned on me that if you hadn't caught a whiff of Jet A, it would be easy to forget you'd just flown a diesel-powered homebuilt. Years of development by Wilksch and many hours of effort by Goodfellow make it seem so easy and natural that you have to believe they're onto something.

—Marc Cook

It's a beautiful day in Bishop, California. This shot is taken from the following Lycoming-powered RV-9A, which shadowed the Wilksch airplane out and back.

RV-9 fuel-tank volume is 36 gallons, the Lycoming-powered RV-9A had to carry 27 pounds of ballast to compensate for the denser fuel carried by Goodfellow's RV-9. The total ballast carried by the Lycoming RV-9A was 58 pounds: 31 for the pilot and 27 for the fuel.

The test takeoff weight for the Lycoming-powered RV-9A was 1522 pounds (1083 pounds empty plus 217 pounds avgas plus 164 pounds pilot plus 58 pounds ballast). The test takeoff weight for the Wilksch-powered RV-9 was 1465 pounds (1027 pounds empty aircraft plus 243 pounds jet fuel plus 195 pounds pilot).

The Flights

Three specific test flights were conducted to look at particular aspects of the Wilksch-powered RV-9's performance.

Flight No. 1: This was a side-by-side flight comparing takeoff distance, climb rate and maximum speed at three different altitudes. The two aircraft take off side by side, accelerate to a preselected

To be sure about weights, the Van's factory RV-9A is placed on electronic scales; the Wilksch was weighed immediately after. The diesel aircraft is actually 57 pounds lighter overall.

IAS, and climb at that speed to a preselected altitude. The elapsed time from brake release to target altitude for each aircraft is recorded.

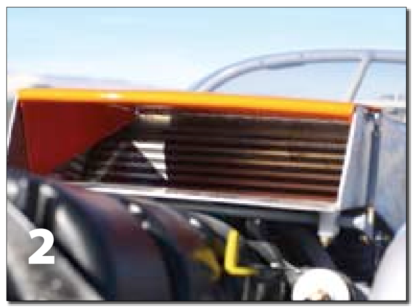
With both aircraft at altitude, the aircraft achieve stable side-by-side flight at preselected cruise speed. Once established in steady side-by-side flight, both aircraft go to full power and full rpm while holding heading and altitude. Allowing 2 minutes for speeds to stabilize, the GPS ground speed (GPS GS) and indicated airspeed (IAS) for each aircraft are recorded. This test was conducted at 8000, 10,000 and 12,000 feet MSL. After recording data, both aircraft return to base and refuel. Fuel required to fill each aircraft is recorded as well as total flight time.

Flight No. 2: Another side-by-side flight but made into a short cross-country of approximately 1 hour total time. In this test, the two aircraft fly the entire time side-by side with the slower aircraft setting the pace. For the sake of fairness, the aircraft with the non-standard engine is allowed to select the flight profile (climb speed, cruise altitude, cruise power setting). This gives the non-standard aircraft the maximum advantage, or stated another way, does not inadvertently put it at a disadvantage. Again, because they are in the same atmosphere at the same time and altitude, the variables are greatly reduced.

After the flight, both aircraft are fueled and the amount of fuel consumed by each aircraft is recorded along with the flight time. Because the flight was to a selected point and back, the distance flown is also recorded. For this

The oil cooler is fed air from a side-mounted NACA duct.

DETAILS



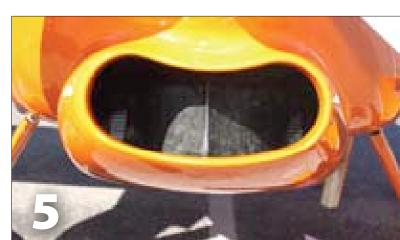
1. This Wilksch installation is very tidy. Humps to clear the crank throws are visible on the top side of the engine; the configuration is a direct-drive, inverted three-cylinder.

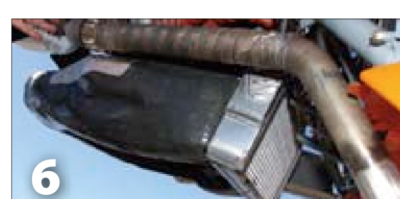
2. The air-to-air intercooler is visible through the duct. Reducing inlet-air temperature is key to obtaining good power and reliability.

3. A single turbocharger helps preserve high-altitude performance, while a separate supercharger keeps the induction pressure in a range that will support combustion in the cylinders.

4. The inverted design places the crankshaft line properly for aircraft intended to use flat-opposed engines. Notice the standard prop governor and balance weight integrated into the starter ring gear.

5 & 6. Cooling is a big deal. Goodfellow constructed this cowl opening and carbon-fiber splitter to deliver cold air to the main radiator below and just ahead of the firewall.





In flight, the Wilksch is calm, cool and collected. Not quite FADEC, though; while there's no mixture, you have to manage the prop.

comparison the two RV-9s flew from Bishop, California, 83 miles north to Hawthorne, Nevada, (overflight only, no landing) and then back to Bishop.

Flight No. 3: This was a subjective, "overall impressions" evaluation of the Wilksch-powered aircraft. In addition, we also performed two timed power-off descents so that the difference in drag between cowl flaps open and cowl flaps closed could be calculated. (By appearances, the Wilksch installation appears to have more cooling drag, particularly with the larger upper cowl flap open. This test would allow us to assess the degree of that penalty.)

Diesels are reputed to be heavy, but this was not the case here. The WAM-120 engine/MT prop RV-9 is 57 pounds lighter than the RV-9A with the Lycoming O-320/Hartzell two-blade, constant-speed prop. That's a big difference in empty weight, but it's not surprising. The WAM-120 engine is best compared to the Lycoming O-235 both in terms of power output and weight.

Performance Comparison, Flight No. 1

Rate of climb: Taking off from 4120 feet MSL, accelerating to 90 mph IAS, and climbing to 12,000 feet. For this test, the WAM RV-9 required 9 minutes 9 seconds versus 7 minutes 30 seconds for the Lycoming RV-9A. Average climb rate was 861 fpm for the WAM RV-9 versus 1051 fpm for the Lycoming RV-9A.

Cruise speed: At 12,000 feet the WAM-120 RV-9 was 16 knots (true) slower than the Lycoming RV-9A. At 10,000 feet, that difference was 13 knots, and at 8000 feet, the Wilksch was 19 knots slower. This difference in speed is not surprising, as not only does the Lycoming RV-9A have more horsepower, it also has a more efficient two-blade propeller. Because the WAM engine has forced induction and can make its continuous rated power at practically any altitude, it is expected that the speed disadvantage would diminish with increasing altitude, and that's pretty much what we saw. The surprise was that there was a greater difference in speed at 12,000 feet than at 10,000 feet, attributable to experimental error. Welcome to the real world!

Fuel Consumption

Because most RVs have engines that make shaft power by burning gasoline, the comparison of fuel consumption generally ends at the number of gallons. In this instance where we have an RV with an engine that burns jet fuel, we consider two additional ways of comparing fuel consumption: fuel energy content and fuel cost. For this comparison, the energy content of 1 gallon of 100LL is assumed to be 120,000 BTU compared to the 135,000 BTU assumed to be in 1 gallon of Jet A. At the Bishop Airport on the day of the comparison flights, 100LL cost $4.387 per gallon and Jet A cost $3.752 per gallon. Comparing the number of BTUs consumed is the best way of measuring efficiency, but the comparison that hits closest to home is fuel cost. (See Table 1 for details.)

Cowl Flap Drag

For this test the total weight of the WAM aircraft, fuel, pilot and passenger was 1615 pounds. Power-off glide at 100 mph IAS with cowl flaps closed resulted in an average descent rate of 817.5 fpm. Given the gross weight of 1615 pounds,

Table 1.

Flight No. 1							
Aircraft	Fuel Volume	Fuel Energy Content	Fuel Cost	Rate of Climb, Avg	Speed Delta, 8000 feet	Speed Delta, 10,000 feet	Speed Delta, 12,000 feet
WAM RV-9	5.6 gallons	751,950 BTU	$20.90	861 fpm	-19 mph TAS	-13 mph TAS	-16 mph TAS
Lycoming RV-9A	6.2 gallons	744,000 BTU	$27.20	1061 fpm			

Flight No. 2			
The cruise altitude for the 166-s.m. roundtrip from Bishop to Hawthorne was 9000 feet, and it took 1 hour 7 minutes from takeoff to touchdown, resulting in an average ground speed of 149 mph.			
Aircraft	Economy by Volume	Econ by Energy	Econ by Cost
WAM RV-9	33.2 statute mile/gallon	4066 BTU/statute mile	$0.113/statute mile
Lycoming RV-9A	23.9 statute mile/gallon	5017 BTU/statute mile	$0.183/statute mile

this tells us that the aircraft requires approximately 40 thrust horsepower to maintain level flight at 100 mph IAS.

Power-off glide at 100 mph IAS with cowl flaps open resulted in an average descent rate of 990 fpm. Assuming the same gross weight as during the cowl flap closed glide, approximately 48.5 thrust horsepower is required to maintain level flight at 100 mph IAS with cowl flaps open. This means that at a typical climb speed the open cowl flaps are costing 8.5 thrust horsepower or, assuming an 80% efficient propeller, 10.6 shaft horsepower.

Overall Impressions

The WAM-120 engine is a very good match to the RV-9 airframe, arguably better than the O-320 because it is very light but with adequate power. The aircraft can cruise fairly fast and because of forced induction, the fuel economy at altitude is excellent. The constant-speed prop yields good operational flexibility by allowing the engine to make its rated horsepower during takeoff and climb. The cabin noise and vibration levels are comparable to that of a Lycoming-powered aircraft.

Operating the engine is simple, as there is no manual mixture control. However, this is offset slightly by having to open and close the cowl flaps. The additional drag of the open cowl flap is measurable and would explain why the climb rate of the WAM RV-9 was not as good as might otherwise be expected. (For perspective, consider that the climb rate of many "high-performance" certificated aircraft is comparable to that of the WAM RV-9. It's just that the "big engine" Lycoming RV-9A with the constant-speed prop has climb performance most people only dream about.)

I describe the engine as being built on a solid foundation. As a direct-drive powerplant it elimi-

Q&A with Martin Long of Wilksch Airmotive Ltd.

KK: Is the WAM-120 available for a homebuilder to purchase?

ML: Yes, the WAM-100 and WAM-120s are currently available to homebuilders. We increased the price partly to dissuade less serious kit builders so we can focus on developing new products and looking more for OEM customers including certification paths.

What is the price and lead time?

The current price for a WAM-120 is £15,000 [$23,900 in January 2010] plus VAT and delivery. This price can be negotiated for more than one-offs and OEMs, etc. We currently have a couple in stock, so delivery could be within a couple of weeks, though this can change on a weekly basis.

Does Wilksch Airmotive have (or plan to offer) a product that replaces the WAM-120?

We are developing a bigger-bore engine. It will be the same physical size and similar weight but with up to 140 hp. The new engine uses the same external casings but a different combustion system and a more conventional piston and pin arrangement. We plan to release it probably at 125-hp rating, going up to 140. We have run it on test at around 155 hp, but this would not be a durable rating. It's difficult to know when we will release this variant, but we will be starting the durability phase soon.

What does the near future hold for Wilksch Airmotive? Who do you see as the primary market for your engines? Homebuilders? Light Sport Aircraft manufacturers? Retrofit onto existing "certificated" aircraft?

Longer term primary markets are LSA and fully certificated once we can take advantage of the new ELA 1 and 2 regulations. Although even once we enter into these markets, I imagine we will still supply the homebuilder market. I would like to get away from the one-off types and get more into the serious kit planes with a standard installation like the Van's series.

—K.K.

Two views of the intercooler's top cowl flap: closed on the ground (left) and open during climb. The drag of the necessary flap is measurable.

A stunning skyline and a huff of dark smoke: The Wilksch, being a two-stroke diesel, definitely leaves a visible trail, particularly on takeoff.

nates all of the compromises associated with gearing, uses a hydraulic constant-speed prop to get the most output from the engine regardless of flight condition, and it has the simplicity of all-mechanical systems, thereby eliminating the need for electronics (or even electricity) to keep running optimally.

Goodfellow's mating of the WAM engine to the RV-9 airframe builds on the engine's solid foundation in that the installation includes reasonable size and length ducts for cooling air, has effective cowl flaps for regulating engine temperatures and is a handsome installation with the cowling on *and* off. This good foundation shows through in the aircraft's good looks, efficiency and simplicity of operation. By starting with the well-proven RV-9 airframe and then installing the light and efficient WAM engine, Goodfellow has crafted an amazingly capable aircraft. ✈

For more information, visit www.wilksch.com. Find a direct link at www.kitplanes.com.

KEN KRUEGER

A pilot, aircraft owner, builder and aerospace engineer, Ken has been enthralled with flying machines since childhood. Joining the Van's engineering team in 1996, he has contributed to the detail design of the RV-7, RV-8, RV-9, RV-10 and RV-12.