THE USE OF VORTEX GENERATORS TO ENHANCE PUSHER AIRCRAFT COOLING

David G. Ullman, Sept 2014, david@davidullman.com

Introduction

The cooling air for the IO-360 engine in my Velocity SEFG comes through two NACA style ducts in the top of the fuselage as seen in the first two photos The air then down-flows through the cylinders and is exhausted out the rear of the fuselage about 2" in front of the propeller as can be seen in the photo on the next page. I have flown the plane for about 3 years and it has always run hot.

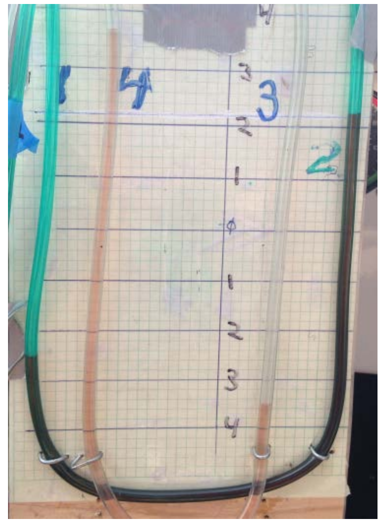
I added external scoops on the rear edge of the NACA ducts and that helped but looked crude and not very elegant as the NACA ducts were supposed to be a low drag, internal scoop. When I painted the airplane, after 3 years in primer (a color I called "blotch white") I took the scoops off. The combination of no external scoops and a smooth paint surface made the NACA ducts very ineffective. My engine was overheating (above 425^{o}F on the cylinder head temperatures (CHTs)) on climb out and cruise.

This led me to a study of different methods to get more air through the engine. First, I tried to see how much air was going through the NACA ducts by putting smoke oil on the top and flying around the pattern. Traces (Figure 2) showed that air was indeed flowing into the ducts, but this gave no indication of how much.

Early efforts to make the engine run cooler were based on the suggestions of flying colleagues, latter efforts based on studying the literature to find a good engineering solution. I call these the "hacking" phase and the "engineering" phase, respectively. In this paper I will document what I tried and also detail the engineering solution. To give away the ending, I knocked 55^{o}F off the CHTs with a simple fix. It just took a while to find it.

The Initial Situation and Experimental Set Up

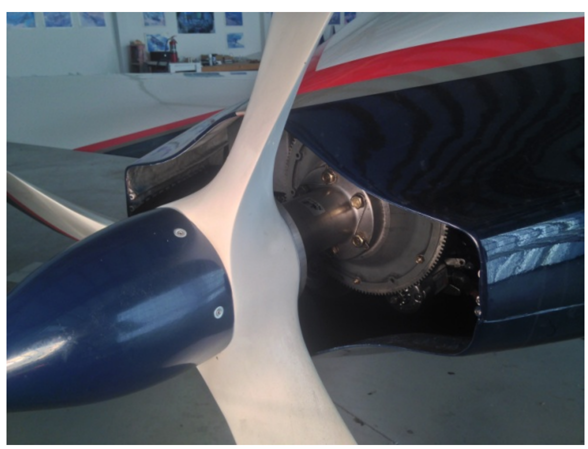
One check to learn more about the airflow through the engine was to measure the pressure drop across the cylinders. Lycoming specifications state that there should be a drop of 6” H_2O for adequate cooling. To measure this and to better understand the pressures created by the NACA ducts and the changes, two manometers were used. These were made of long lengths of clear tubing and some water with red dye and drop of dish soap in it (Figure 3). The first manometer measured the pressure difference between the static pressure and the plenum above the cylinders (labeled 3 and 4 in the figure). One end was plumbed directly into the static system in the airplane. The other end was secured to the fuel injection spider in the plenum above the cylinders. The end of that tube was blocked off and holes were drilled around the periphery of the last inch of the tube so that it was clearly sensing static pressure. The second manometer measured the difference in pressure across the cylinders labeled 1 and 2 in the figure). One end was mounted in the upper plenum next to tube from the first manometer. It too was plugged and drilled. The other end was mounted just below the cylinders under the engine and was plugged and drilled.



The manometers themselves were mounted on a board in the cockpit so that a copilot could photograph them for later data reduction. The example shown is from late in the experiments and at high velocity. It shows 4.6” of H_2O across the cylinders and 7.2” of static pressure in the plenum above the cylinders. Initially, before any additions, the pressures were 2.0” H_2O and 3.0” H_2O.

The Hacking Phase

There were two schools of thought on what to do, push more air into the NACA ducts or pull more air out the back of the fuselage. Most of the advice came builders with front engine experience where often the problem is that not enough air is being pulled. Hacks were tried that pushed more air into the NACA ducts with scoops, louvers on the bottom of the cowl that pulled more, and vortex generators in front of the NACA duct to force more air in.



Some said the opening to pull air out was being blocked by the propeller. But, this area was quite large. None-the-less louvers on the bottom of the cowl were tried.

The figure below shows many of the ideas tried, many in combination.

Name	Description	
Small Scoops	The small scoops protruded 1.5” above the fuselage surface. The Large Scoops (not shown) were 3” high.	
Small Louvers	On bottom rear of the cowl to help draw air out.	
Large Louver	Large Louvers placed over the same holes as the small louvers but with much more projection into the slipstream.	

4 Vortex Generators	The 2 VGs in front of the NACA duct were tried first and then the other 2 added later to help bring flow in when at a high angle of attack. These vg, the same as used on the wing and canard are .43” tall.	
8 Vortex Generators	This was an effort to mix all the air in front of the NACA scoops.	

The results of testing these configurations and a few more are shown in the following figures. Three test conditions were used:

	Velocity
climb	115 kts (104 ft/sec). Note that Vx is 95 knots, but I generally climb out at this higher speed.
Low cruise	125 kts (114 ft/sec)
High cruise	170 kts (155 ft/sec)

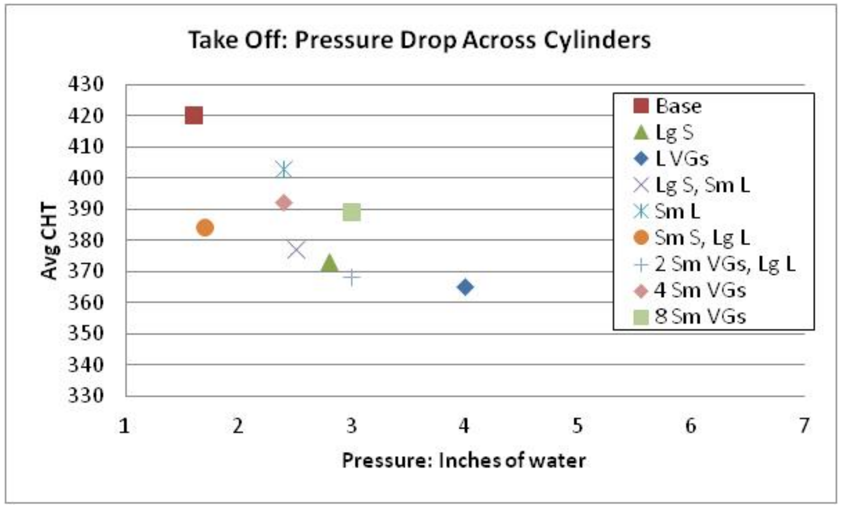
Data was taken from the manometers and the average cylinder head temperature. The engine was run full rich for all test points to be consistent. All temperatures were corrected for the outside Air Temperature (OAT) by normalizing them to a 60deg Fahrenheit day. The results are plotted in the following figures. The points are for:

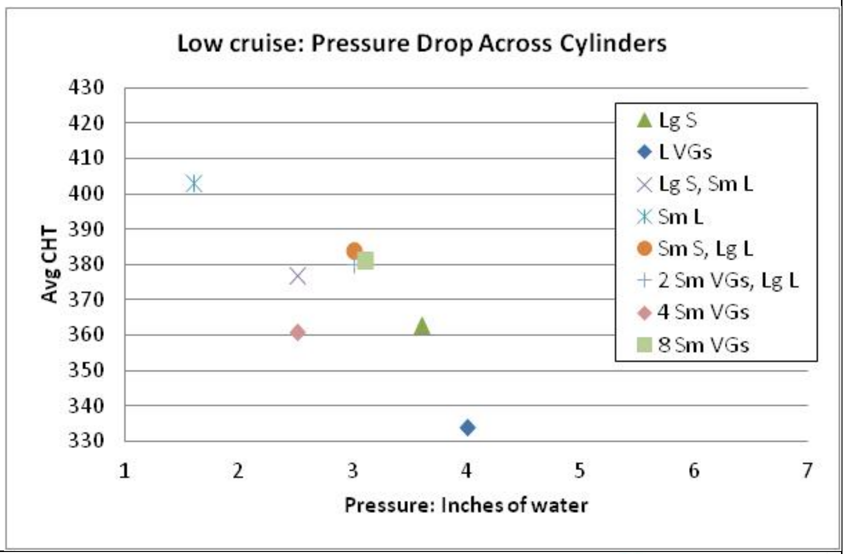
Lg S	Large Scoop (no photo of this is shown above, but it stuck up 3” above the fuselage surface
Sm S	Small Scoop – Stuck up 1.5” above the fuselage surface.
Sm L	Small Louvers
Lg L	Large Louvers
Sm VGs	Small vortex generators - These are the same vortex generators used on the wings and canard. They are 0.43” tall
L VGs	Large Vortex Generators – the engineering solution described later in the paper.

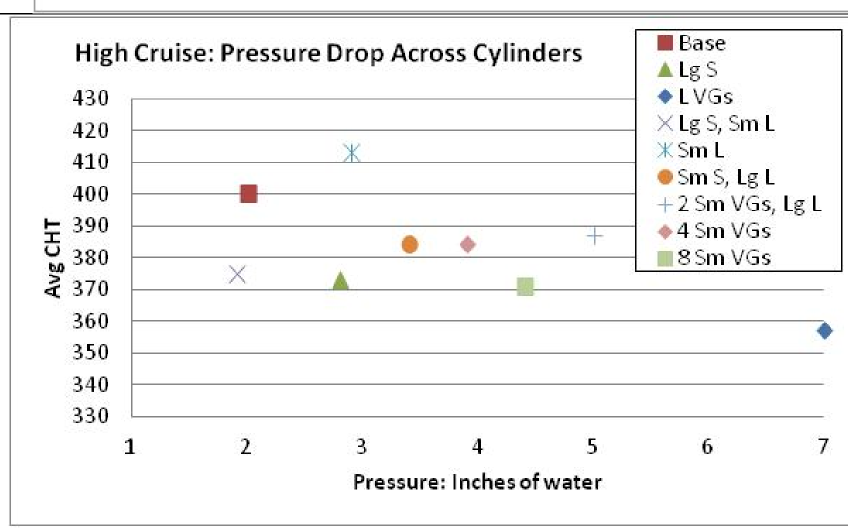
The results are shown for each of the three conditions. Data for the Base condition, just the NACA scoops as built, are in the upper left corner of the Take Off and High Speed Cruise plots. No data was taken at the low speed cruise condition. These points are all worse than they appear as the temperature was still climbing when I throttled back. I did not take data for this condition for Low Speed Cruise. Note that besides high temperatures the pressure drop across the cylinders was only 2" or less. No wonder the engine was overheating.

The results in the lower right corner are for the final configuration, Large VGs as will be developed. Here the temperatures are acceptable and pressure drops 4" – 7", much closer to the Lycoming 6" spec.

The other configurations are scattered between these two extremes. Some key points that can be taken away from these are list below.







Note that not all combinations were tested as: 1) that would have been too many runs, and 2) this was trial and error so the options were not all known before hand.

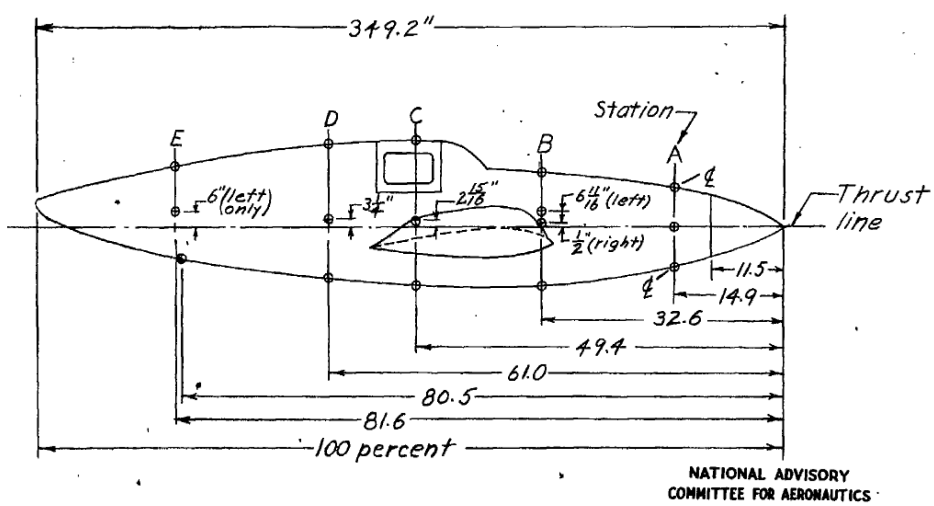
- The Large Scoop (Lg S) helped on Take Off and High Speed Cruise, but not as well on Low Speed Cruise. But this was both ugly and increased the drag (no firm data on this).
- The Louvers on the bottom did not make significant difference.
- Small VGs helped some, but it was unclear how many to use and where to put them. See discussion on VGs later.

The Engineering Solution

Parallel to the hacking phase, I worked to understand the physics of what was happening. It became clear that even though air was flowing into the NACA duct as shown with the oil traces, there was not enough. The boundary layer which increases in thickness on the fuselage was keeping air out of the NACA ducts.

To explain what the boundary layer was doing and why it is important, some basics. These are all worded from the viewpoint of the surface with the air moving past it, as it makes easier reading. The boundary layer is the region of air near the surface that, at the surface is not moving at all, and at some distance out is moving at the speed of the air flowing over the body. We usually think of the boundary layer as quite thin. It isn't!

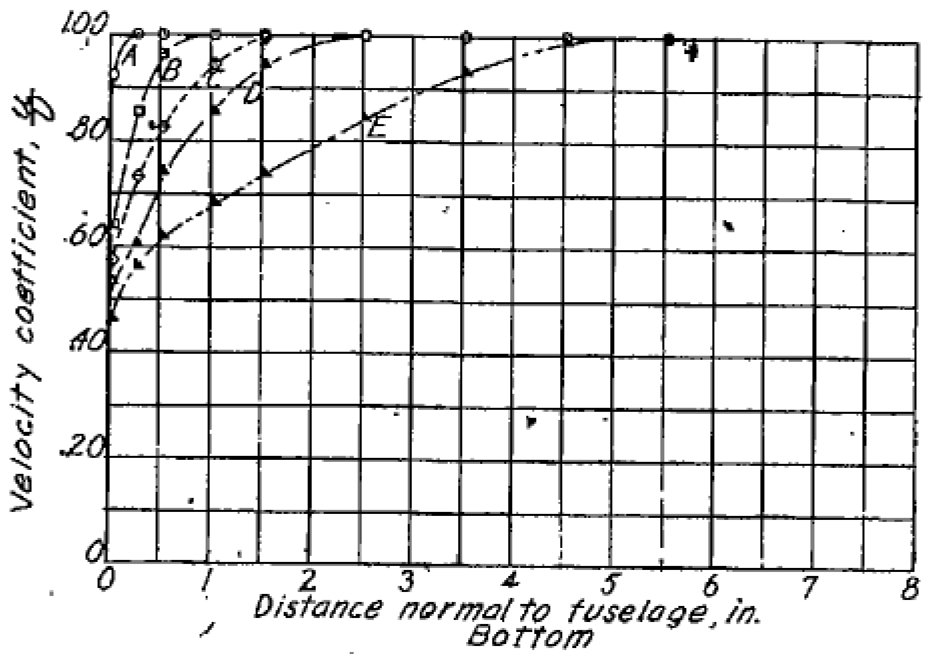
The actual thickness of the boundary layer can be seen from the results of an experiment described in a NACA Technical Note[i]. In this note, the authors measured the velocity of the air near the fuselage of an unidentified fighter shown in the figure below. They had removed the propeller, antennas and other protuberances, and sealed all ducts. They measured the velocities in the boundary layer on the top, bottom and sides at various angles of attack.



(a) Locations of pressure rakes on the fuselage of the model.

Figure 3.- Details of pressure-rake locations and fuselage contours.

Typical of what they found is shown in the figure below. Here, the vertical axis is the ratio of the speed of the air in the boundary layer divided by the speed of the air in the free stream (u/U) for the various stations along the fuselage bottom. This bottom image is the clearest in the report, so it is used here. It is typical of the airflow on the top and sides. The edge of the boundary layer is generally defined as when u/U = .99 (air moving at 99% of the free stream velocity). So, here the boundary layer on the bottom, at station E (81.6% the length of the fuselage) is about 5" thick!



Note further that the air near the surface is moving at only 50% of the free stream velocity, The NACA engineers could not get all the way to the surface with their pitot tube where the velocity actually goes to zero.

What is important here is that on top of the test plane, behind the cockpit, the boundary layer thickness (δ) was measured at 3.0" with the airplane in a dive; 4.0" in cruise; and 5.5" in a climb. No wonder my NACA ducts don't work as they should.

To make sure that these results make sense consider a simple explanation of the boundary layer theory. Theoretically, boundary layers start off laminar and, after a distance, become turbulent. Think of smoke coming off a match that has just been blown out. The smoke leaves the match as a smooth column and then, after a few inches becomes a turbulent jumble. The first part is called laminar and the second, turbulent. On a fuselage, with it long distance, most of the boundary layer is turbulent. For a turbulent boundary layer, the thickness over a flat plate is:

δ = x * .16 /(Re)$^{1/7}$ (see Stern 2010[ii])

where:

x = the distance from the front in feet
Re = Reynolds number which for standard conditions is = 6,350 * U * x

The Reynolds Number is a non-dimensional number that can be used to determine if the flow is laminar or turbulent. If below about 1 x10^6, the flow is laminar and above this value, turbulent (note that the exact value depends on many secondary affects).

Note that the formula above is for a smooth flat plate. The shape of the fuselage and the surface smoothness affects this in complex and second order ways. Assuming this is adequate, then for the fighter in the NACA report, x = 23.7' (81.6%) and the tests were run with U = 63 mph or 92 ft/sec. Thus,

δ = 23.7 * .16 / (6350 * 92 * 23.7) $^{1/7}$ = .36' = 4.34"

This result is close enough to that measured at the cruise condition to give comfort that it is OK to use on the Velocity.

Then, for the Velocity, the NACA ducts are about 11' from the nose and thus:

δ = 11 * .16 / 6350 * U *10) $^{1/7}$= .36 / U $^{1/7}$

	U	δ
climb	115 kts (104 ft/sec)	.185' (2.2")
Low cruise	125 kts (114 ft/sec)	.183" (2.2")
High cruise	170 kts (155 ft/sec)	.175' (2.1")

As can be seen, the speed has little effect and the boundary layer is about 2" for all conditions. It is then no surprise that the small vortex generators tried earlier (.43 inches tall) had so little impact. They were only stirring the bottom layers of air, those with low velocity as detailed in the next section.

Vortex generators

I put vortex generators on the wings and canard of my Velocity from the beginning. My test pilot strongly encouraged this as I was a low time pilot. They make the handling very docile. I know this because; just before I painted my plane I took off the inner ¼ of the VGs on both the wing and canard. The plane was much looser at low speed. After painting I put all of them back on, but I did not really understand what they did to the airflow.

The VGs I used on the lifting surfaces were .43" tall and at about 22% of the chord. Since the airfoils on the Velocity have the maximum thickness at 35% and the boundary layer is still laminar (Re < 1 x10^6). A really good article on vortex generators on certificated airplanes is at Avweb. This gives a good overview of the basics for use on wings and tails.

A well designed VG stirs the free stream into the boundary layer. This brings higher energy air (more velocity) into the boundary layer at the cost of a slight increase in drag. There are two design variables: the height of the VG relative to the height of the boundary layer and orientation of the VG to the free steam air and adjacent VGs.

To be effective the VG must reach into the free stream air or near to it. For the Velocity cooling problem, the boundary layer is a little over 2" thick. Thus, the VGs need to be nearly that high to stir in free stream air. The VGs tried during hacking were only .43" tall and, even at that height, they did some good, but there was more to be had. Note that some literature claims that VGs that reach 20% into the boundary layer are just as effective as those reaching into the free stream. It will be shown that this was not the case here.

The position and orientation of the VGs is also important. Typically VGs are oriented at 15-20 deg from the flow direction. Thus they are like little wings at high angle of attack with a vortex rolling off of them as shown in the figure below. This figure is from the most definitive (and somewhat obscure) writings on vortex generators; a section of a chapter from the second volume of a 1961 book[iii].

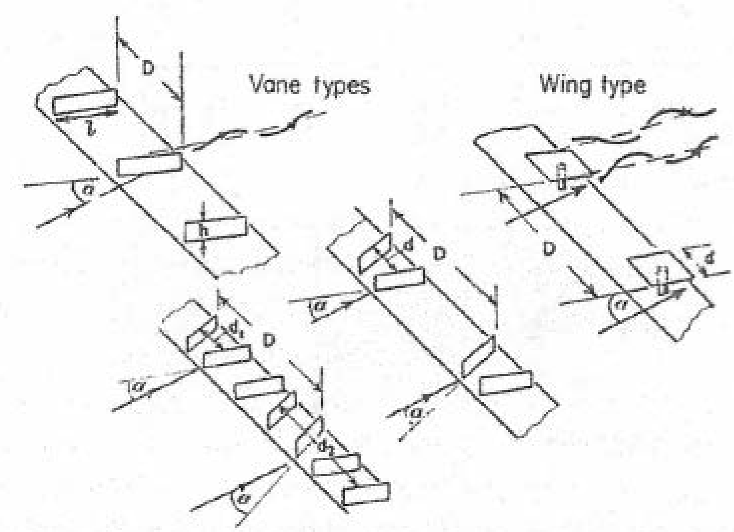


FIG. 87. Types of vortex generators, and notation.

This figure shows the foure styles of VGs, parallel vanes, also called co-rotating (upper left), biplane (lower left), counter-rotating (center) and wing style (upper right. Parallel vanes are often seen on commerical jets and . Biplane (pairs of parallel vanes with every other set anlgled in the opposite direction) are seldom used. Counter-rotating are most common and will be further explored. Finally, the wing type are not much used but are a signicant feature on some Glasair Glastar planes.

Co-rotating vanes set up vortices that all rotate in the same direction, whereas counter rotating vanes reinforce each other driving air from the free stream down in the area between VGs.

The effect of co-rotation can be seen in the following figure, from the same report. This shows the pressures downstream of the VGs. The dashed line in each figure is the height of the 95% boundary layer upstream of the VGs and the faint circles in the middle of each circular pattern is the top of the vg. "D" is the distance between the center of each pair as in the figure above and "X" is the distance downstream. The lines shown are lines of equal pressure. These are equivalent to velocities. As can be seen immediately after the VGs (X/D = 1.6) the 95% pressure line is nearly at the surface and remains there at least until X/D = 6.4. Not shown in these diagrams, but important here is that the air between the VG is being forced downward, the two vortices off of each pair rolling air down between them.

Not reflected here is that the NACA duct is inset into the fuselage, affecting these results.

Based on this information I designed a set of VGs to hopefully force the air into the ducts.

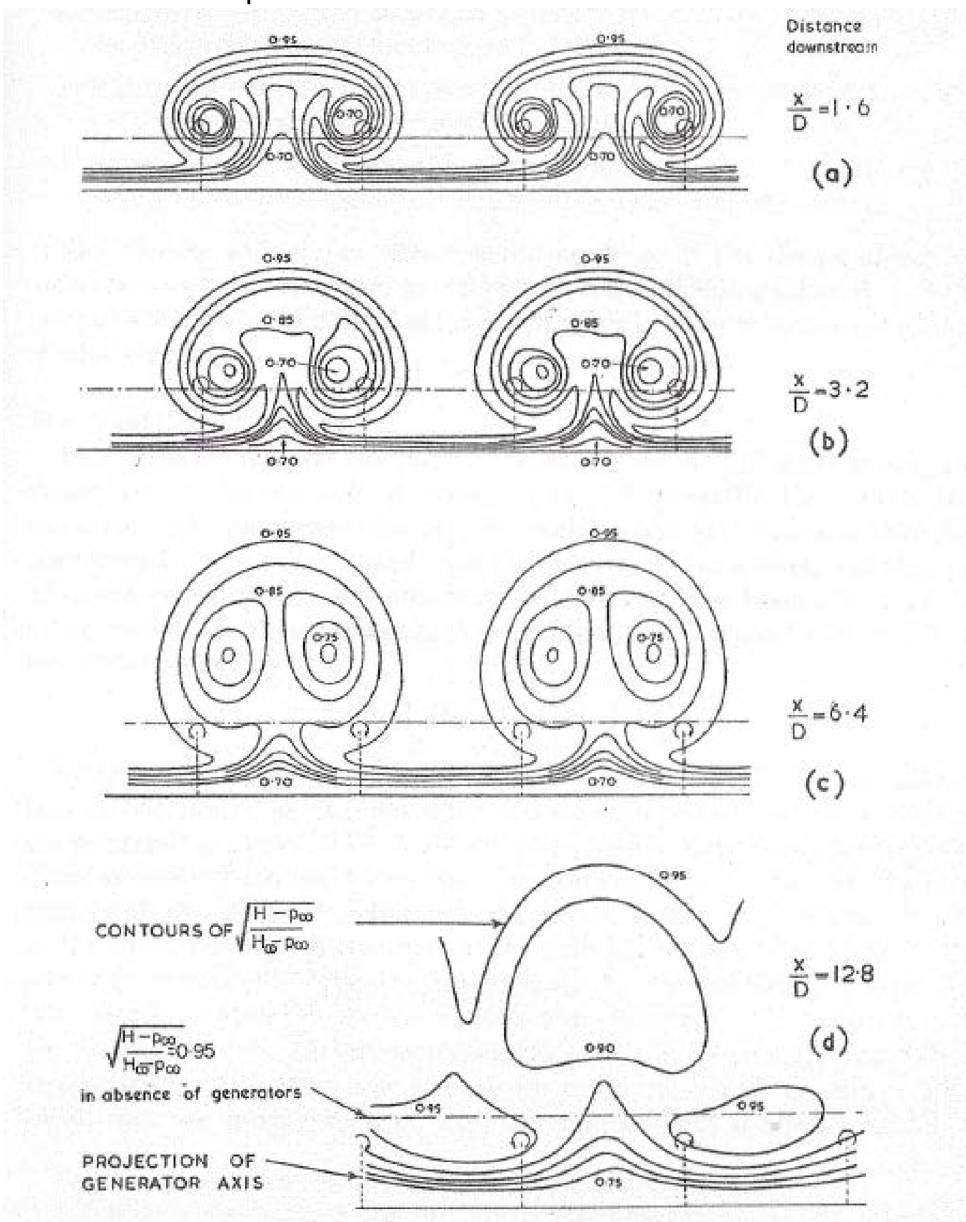
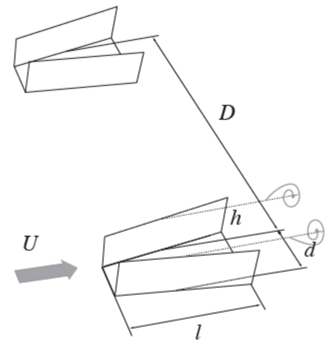


FIG. 93. Contours of pitot pressure for counter-rotating vortices that are initially equally spaced. (Variation of pattern with distance downstream.)

The design rules for counter-rotating VGs are generally accepted to be:

- h = .95 * boundary layer height
- D = 10 * h
- d = D / 4
- l = 2.5 * h



Thus I designed the VGs for cooling to be:

- h = 2”
- l = 5”
- D = 20”
- d = 5”

I Put them about 15” in front of the start of the scoop and at 15 deg from the center line. I would have liked them further forward, but wanted to stay away from the door opening.

At first I bent some aluminum VGs, pop-riveted them on, and tested those. When the data showed them effective, I replaced them with fiberglass as shown in the photograph. The table below shows the results. The values in the table are the same as in the plots earlier with two exceptions. First, data is also shown for the change in the static pressure in the plenum. Second, I did not take data for Low Cruise in the Base condition. Thus I have used the Small Louver data instead as it was near (actually slightly better) than Base for the other conditions.

The plenum static pressure is an indication of how well the NACA ducts are working. As can be seen, the addition of the scoops increased the pressure there dramatically (between 2.3” and 6.2”). Even the Large scoop only increased this pressure to 2.9” on Takeoff and 6.1” at high cruise.

Note that all data was taken with a payload of 480 – 520 lbs (pilot, co-pilot and 10-15 gallons of fuel).

	Delta P across cylinders, inches H_2O			Plenum static pressure relative to static port, inches H_2O			CHT corrected to and OAT of 60° F		
	Base	Final	Difference	Base	Final	Difference	Base	Final	Difference
Takeoff	1.6	4.0	2.2	2.1	4.4	2.3	420+	365	55
High Cruise	2.0	7.0	5.0	3.0	9.2	6.2	400	357	43
Low Cruise	1.6	4.0	2.4	2.0	5.2	3.2	403	334	69

Conclusion

The VGs work well. The 6 inch of H_2O across the cylinders is only achieved at the High Cruise, but the 4” at Takeoff and Low Cruise is more than double the Base values. Most importantly, the average CLT is down an average of 55°, just by the addition of four VGs. The data in the table above is even better than I hoped for. I probably could improve on this further by moving the VGs to another location, but this is good enough.

I like the final solution. It is elegant, simple and effective. I do not know for certain, but as best I can measure there is no speed penalty. Another plus is that it gives yet another area for people to ask questions about. Now it is off to the next thing I want to improve.

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[i] TN 1087, Langley Full-Scale-Tunnel Investigation of the Fuselage Boundary Layer on a Typical Fighter Airplane with a Single Liquid Cooled Engine, June 1946).
[ii] Stern 2010, http://user.engineering.uiowa.edu/~me_160/lecture_notes/ch7fall2010-2.pdf
[iii] Shock Induced Separation and its Prevention by Design and Boundary Layer Control, H.H. Pearcy, in Boundary Layer and Flow Control V2, edited by G. V. Lachmann. Pergamon press; specifically Section 4.5, Vortex Generators.