Bristol Engine Tests at the Royal Aircraft Establishment: Work Carried Out by Beatrice Shilling ca. 1941

by Robert J. Raymond

Original - August 2015; Revised - 14 March 2017

Preface

The work referred to in the title was carried out on three Bristol engines, a poppet valve Mercury VI, a sleeve valve Perseus VIII and a sleeve-valve Perseus XII. The paper summarizing these tests is noted in Reference 1. The purpose of the tests was to calibrate the engines' air flow characteristics as a function of operating conditions in anticipation of advanced fuel control system adoption. The information contained in this paper makes possible a direct volumetric efficiency comparison of sleeve and poppet valve engines at the stage of development they had reached in about 1940.

In a previous paper (Ref. 2) comparing the characteristics of sleeve and poppet valve engines I was unable to settle definitively the question of volumetric efficiencies because I had discovered only anecdotal comment on the subject at that time. Based on flow tests of a Hercules cylinder and sleeve (Ref. 3) I had concluded that there was probably not much difference between the two as regards volumetric efficiency. Shilling's work makes it possible to resolve this question as well as some other aspects of sleeve valve engine performance characteristics.

I have chosen to use Shilling's name in the title of this paper as a way of recognizing an extraordinarily competent engineer who seems to be remembered chiefly for solving the Merlin engine's carburetion problem in the early years of WW2. This important accomplishment is usually referred to in an inappropriate manner so perhaps this paper will add a little more perspective to her career.

Introduction

The reader is referred to Reference 2, page 17, on the AEHS web site for a discussion of the design factors that determine the air capacity of an engine. It will be noted that a number of dimensionless groups are used to compare performance between engines. Besides volumetric efficiency these include the ratio of intake to exhaust pressure and an intake system "Mach number" that includes piston speed. This number is referred to as "Z" and is defined in Table 4 of reference 2. Determining Z requires knowledge of valve (or port) areas and flow coefficients for the valves or ports. This information is not available for the Bristol engines we are dealing with here so I have used piston speed as the independent variable in my plot of volumetric efficiency versus engine speed.

Shilling's data is presented as air flow per cycle versus operating conditions that included engine speed, intake pipe pressure and temperature, exhaust pressure, fuel-air ratio, and cylinder head temperature. Fortunately, the data taken was included in the report so that it could be analyzed without having to extract information from her plots. I used the raw data to put everything in terms of volumetric efficiency rather than air flow per cycle.

Comparable tests were carried out by the NACA on two American engines (Refs. 4 and 5) a few years after Shilling's work and these results are used to augment the poppet valve data since the Bristol Mercury was a rather old design by 1941.

The effect of the sleeve valve on weight per horsepower and frontal area for a given displacement is easily discernible from the engine specifications and has been described and discussed in Reference 2. The performance factors that influence these characteristics are:

- Volumetric efficiency versus piston speed
- Detonation limits
- Friction
- The effect of the extra thermal resistance of the sleeve on volumetric efficiency

The sleeve valve engines of Bristol had higher detonation limits than their poppet valve counterparts and the reasons for this are discussed in Reference 2. There have been claims made both pro and con for the remaining three questions but most have been anecdotal without hard data to back them up. Shilling's data gives results for the first and fourth questions that appear to be very sound and consistent. The anecdotal claim for equal friction between sleeve and poppet was shown to be feasible, based on an analysis of the friction characteristics of the two types, and is given in Reference 2.

At the time this data was taken the Bristol sleeve valve engines were in their early adolescent years relative to poppet valve engines and development on them continued until production ended in the 1970s. Therefore the results presented here can only be regarded as a snapshot of where things stood in the 1940s. I still have not seen any Hercules or Centaurus data that would allow comparisons to be made of the two valving system types at the climax of large piston engine development.

Volumetric Efficiency

The Effect of Exhaust to Intake Pressure Ratio

The set of curves in Figure 1 were done as a check on the consistency of the data. This set is for 2,200 rpm and plots at other speeds gave similar results. The volumetric efficiency is normalized at a ratio of exhaust to intake pressure of one and corrected to a manifold temperature of 150°F. The correction factor is based on actual data taken for each engine and not on some general "rule", such as a square root factor.

The curves for the "ideal cycle" are based on a square pumping loop with no valve losses or heat

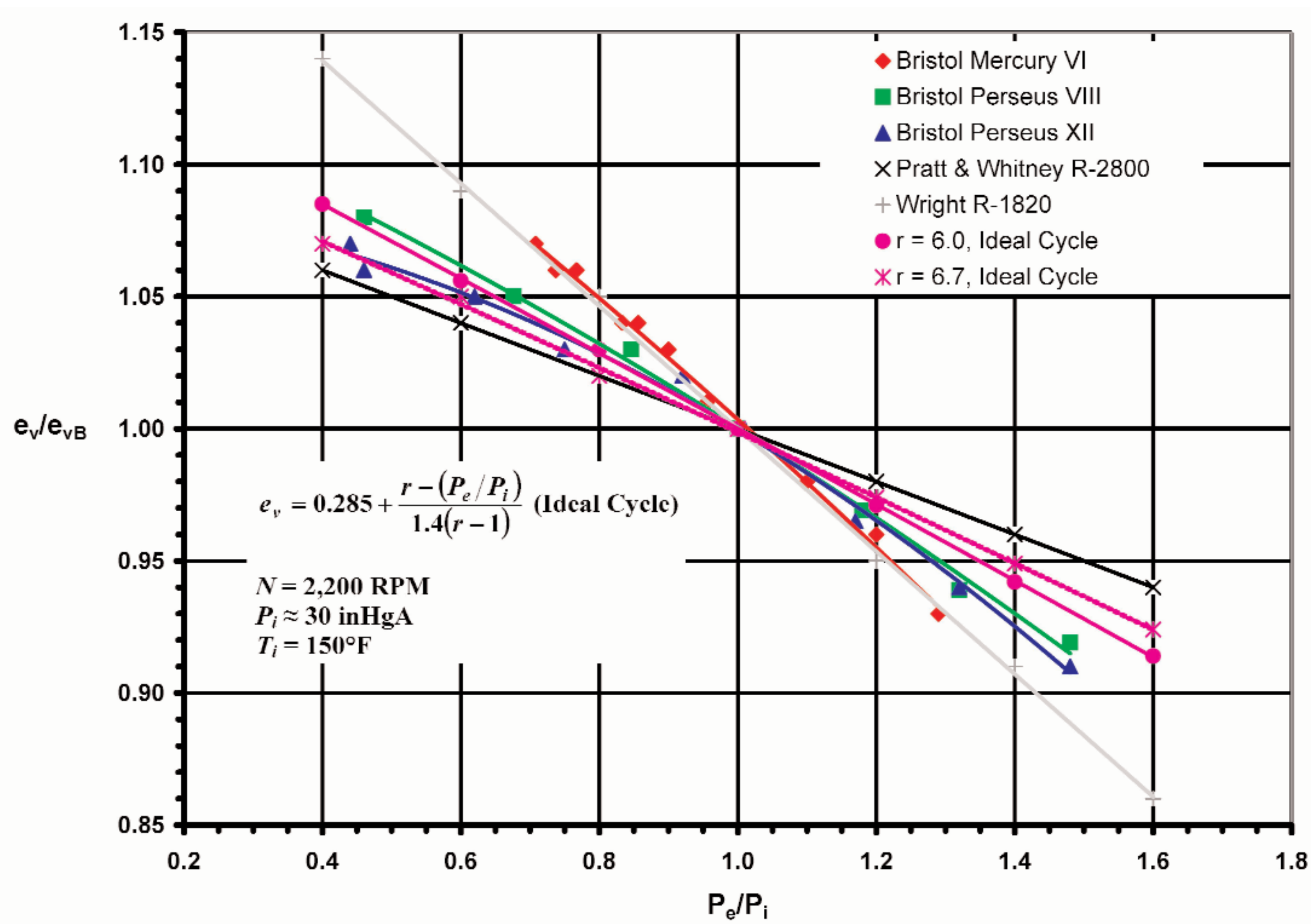

Fig. 1. Volumetric Efficiency Versus Exhaust to Inlet Pressure Ratio Normalized to $P_e / P_i = 1$.

Table 1
Engine Characteristics

	Valve Type	Bore (in)	Stroke (in)	Compression Ratio	Clearance Volume (in^3)	Spark Advance (BTDC)	Intake Opens (BTDC)	Intake Closes (ABDC)	Exhaust Opens (BBDC)	Exhaust Closes (ATDC)	Valve Overlap
Bristol Mercury VI	Poppet 2 Inlet 2 Exhaust	5.750	6.500	6.00	33.8	30°	29°	47°	76°	40°	69°
Bristol Perseus VIII	Sleeve	5.750	6.500	6.75	29.4	13°	15°	55°	55°	15°	30°
Bristol Perseus XII	Sleeve	5.750	6.500	6.75	29.4	13°	15°	55°	55°	15°	30°
Pratt & Whitney R-2800	Poppet 1 Inlet 1 Exhaust	5.750	6.000	6.65	27.6	20°	36°	60°	70°	26°	62°
Wright R-1820	Poppet 1 Inlet 1 Exhaust	6.125	6.875	6.70	35.5	20°	15°	44°	74°	25°	40°

transfer to the incoming charge. The equation for these lines at the two relevant compression ratios is shown on the plot. The differences between engines can be attributed to valve losses, valve timing, compression ratio, heat transfer, etc.

Table 1 gives the pertinent characteristics of all the engines.

The Effect of Piston Speed

Figure 2 shows volumetric efficiency versus

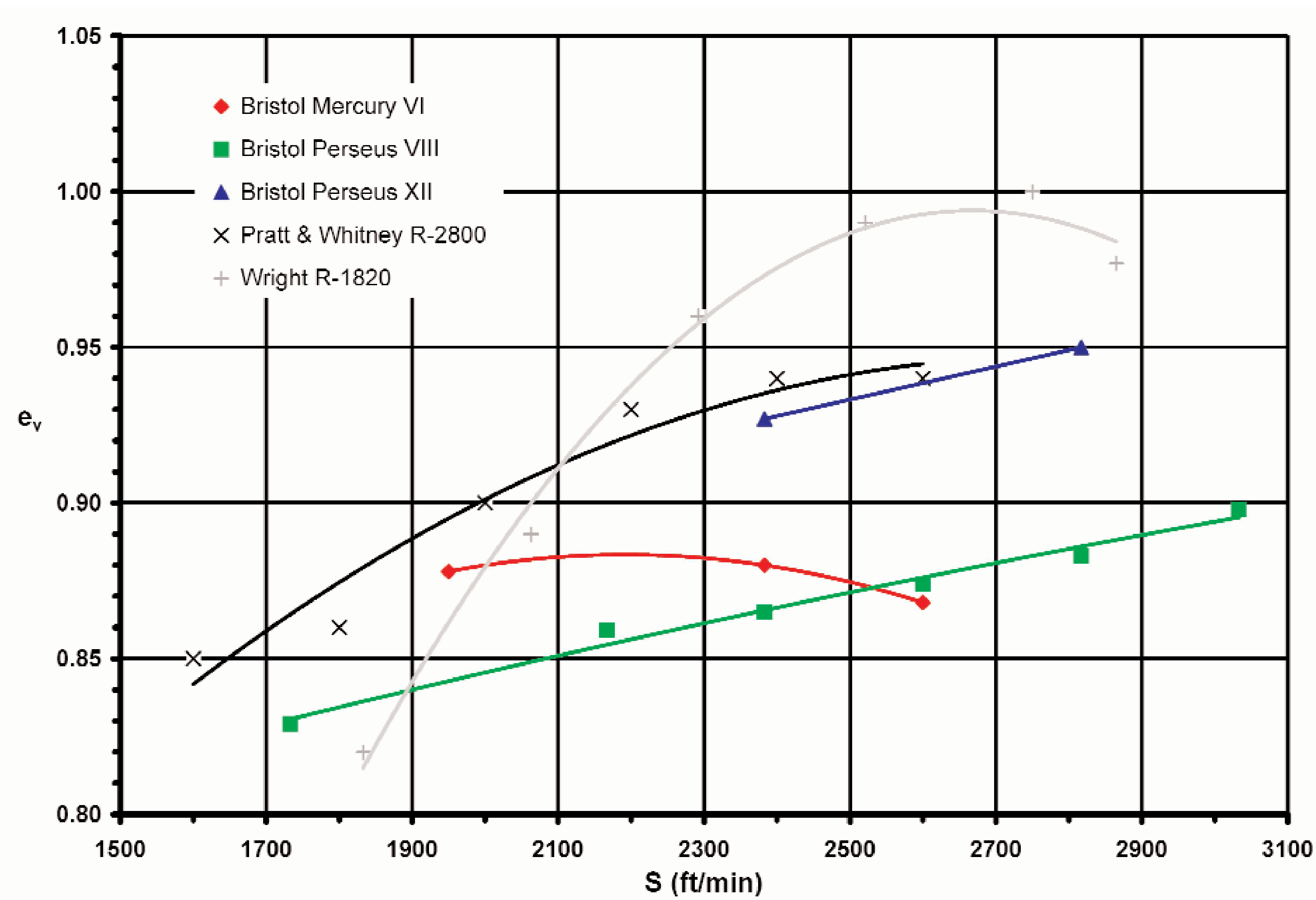

Fig. 2. Volumetric Efficiency Versus Piston Speed. $P_e / P_i = 1$; $T_i = 150°F$

piston speed for five engines. Again, the data has been corrected to an intake pipe temperature of 150°F and an exhaust to intake manifold pressure ratio of one.

The first question that comes to mind when looking at this plot is why was the Perseus XII six points better than the Perseus VIII? Shilling postulated that it had something to do with the longer induction pipes on the XII but gave no details as to their design or relative lengths. An inquiry to the Rolls-Royce Heritage Trust, Bristol Branch, resulted in dimensions of the pipes of the two Perseus models and photographs of the engines showing the induction pipe arrangements (Figs 3 and 4). The Perseus VIII induction pipes were six inches to the center of the manifold belt around the ports and the XII were 14 inches long. Both had an outer diameter of 3 inches. My estimate of the effect of the difference in pipe length would only account for two points out of the six point difference in volumetric efficiency at the higher piston speeds. It is possible that the difference was more heavily influenced by the transition from circular pipe to the manifold belt. The earlier arrangement appears to have had a much more abrupt elbow and sudden expansion to the

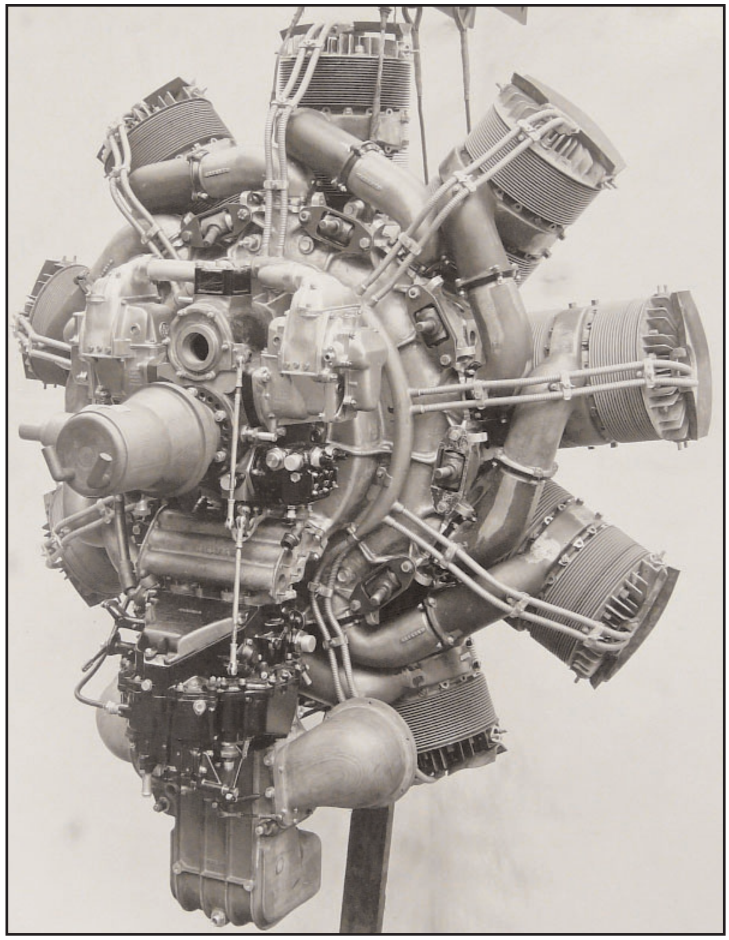

Fig. 4. Persius XII. Note the longer, still smoother intake pipes. (R-RHT, Bristol Branch)

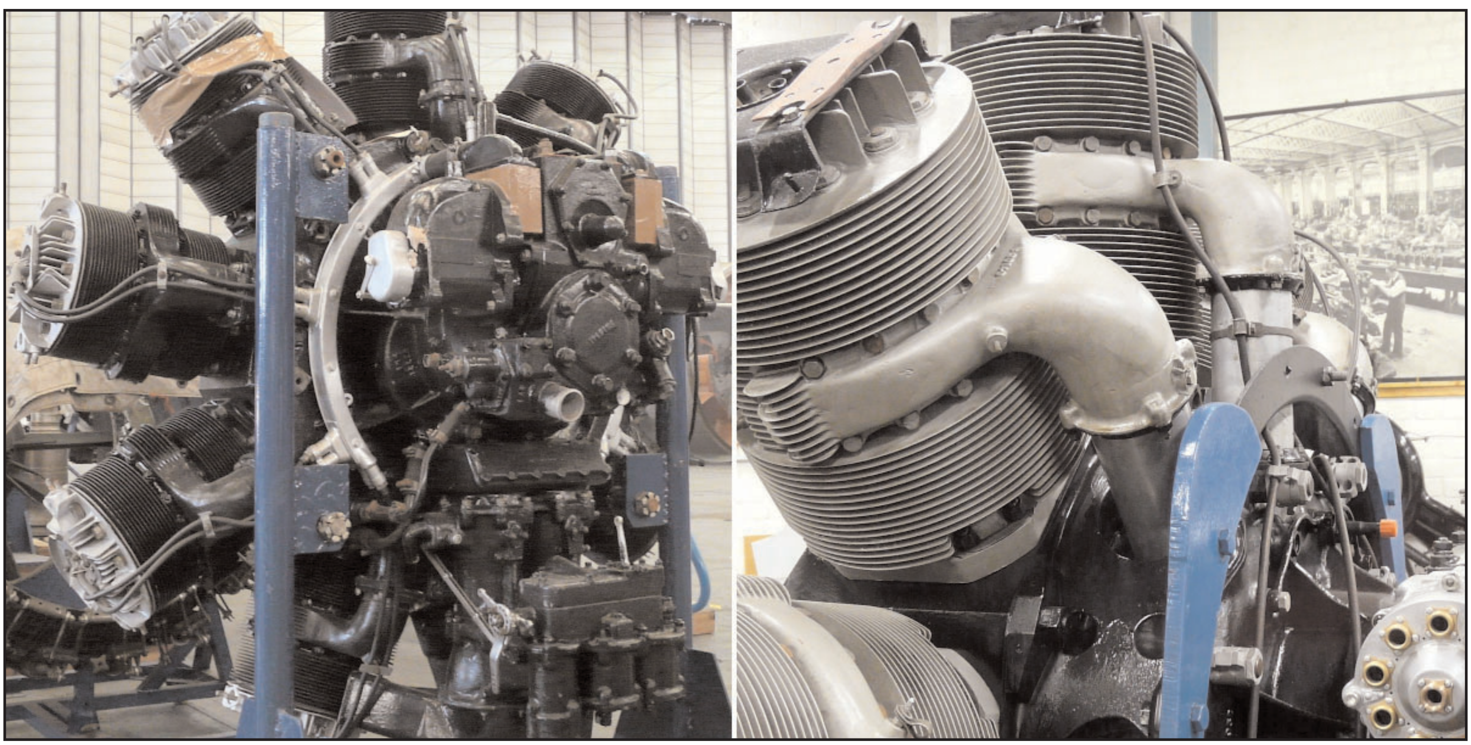

Fig. 3. Two Bristol Persius VIII Versions.
Note the short, angular, abrupt induction pipes on the left, smoother transitions right. (R-RHT, Bristol Branch)

Fig. 5. Much Improved Centaurus Induction Pipes

manifold belt. Figure 5 shows an induction pipe from a late model Centaurus which appears to be even more aerodynamic than the Perseus XII pipes.

The information in Figure 2 indicates that, at the stage of development attained in the early 1940s, sleeve valve engines were no better than poppet valve in terms of volumetric efficiency as exemplified by the two American engines. Similar data for two other Wright engines, the R-3350 and R-2600, show higher volumetric efficiencies than the Pratt & Whitney R-2800. It is obvious that Bristol was hard at work given the big jump from the VIII to the XII and it seems likely that they may have closed the gap with respect to the Wright engines by the end of the era. Could they have surpassed them? Perhaps some data as good as Shilling's will turn up one day for the Hercules or Centaurus.

I also wondered why the Mercury showed up so poorly in Figure 2. There is nothing in the valve timing that would make one think it would be worse than the R-2800. I have no information on the size of the intake valves or details of the intake ports so speculation on this subject is not worthwhile.

The Effect of Cylinder Head Temperature

Ricardo's early work with sleeve valves in liquid cooled engines indicated that the additional thermal barrier of the sleeve and extra oil film did not result in higher piston temperatures. Later work at Rolls-Royce and Bristol indicated higher piston temperatures in air cooled sleeve valve aircraft engines by as much as 50°C (see Ref. 2, page10). This should have shown up in the volumetric efficiency but I was unaware of any hard data on the subject until Shilling's work.

Figure 6 gives the effect of cylinder head temperature on volumetric efficiency for the two

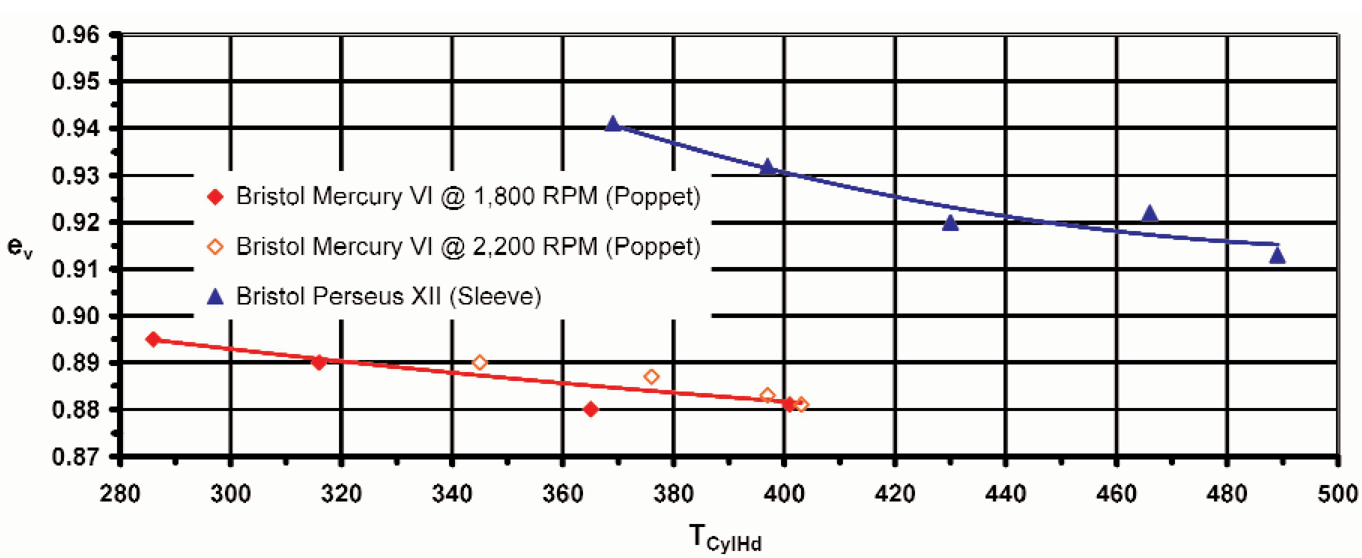

Fig. 6. Volumetric Efficiency Versus Cylinder Head Temperature. $P_e = P_i$; $T_i = 150°F$

Bristol engines. It is clear that the sleeve valve engine is more sensitive to cylinder head temperature rise than the poppet valve engine by about a factor of two. This would account for some of the difference seen in Figure 2 between the two types of engines.

Shilling noted the difference in air consumption per cycle versus cylinder head temperature and attributed it to a "characteristic of the sleeve valve design."

Miscellaneous Results

In this section I will discuss other information I was able to glean from Shilling's report. The absence of any information about the superchargers used on the engines and the pressure rise across them limits what can be inferred about the relative friction losses and efficiency losses of the two engine types. The temperature rise from engine intake to induction pipe was recorded and I attempted to establish which of the supercharger characteristics used on these engines best fit the data. This resulted in the conclusion that there wasn't much difference between the Mercury and Perseus superchargers used in these tests. A 9.84-inch diameter impeller and 7:1 gear ratio fit the data best for both engines.

I made some assumptions about the indicated efficiency relative to the fuel-air cycle efficiency and calculated the imep for a number of cases for all three engines. The only conclusion I was able to reach was that the difference in brake efficiency was more than can be attributed to the difference in compression ratio. When looking at the difference between imep and bmep which ran about 20 psi, there was always about a 5psi difference between the Mercury and Perseus in favor of the sleeve. Shilling attributed the higher brake efficiency of the sleeve engines to "superchargers, compression ratio and indicated efficiency." I wonder at the absence of friction in this list. Was it an oversight or did she believe the claims or have access to motoring data?

Table 1 lists the spark advance used in the

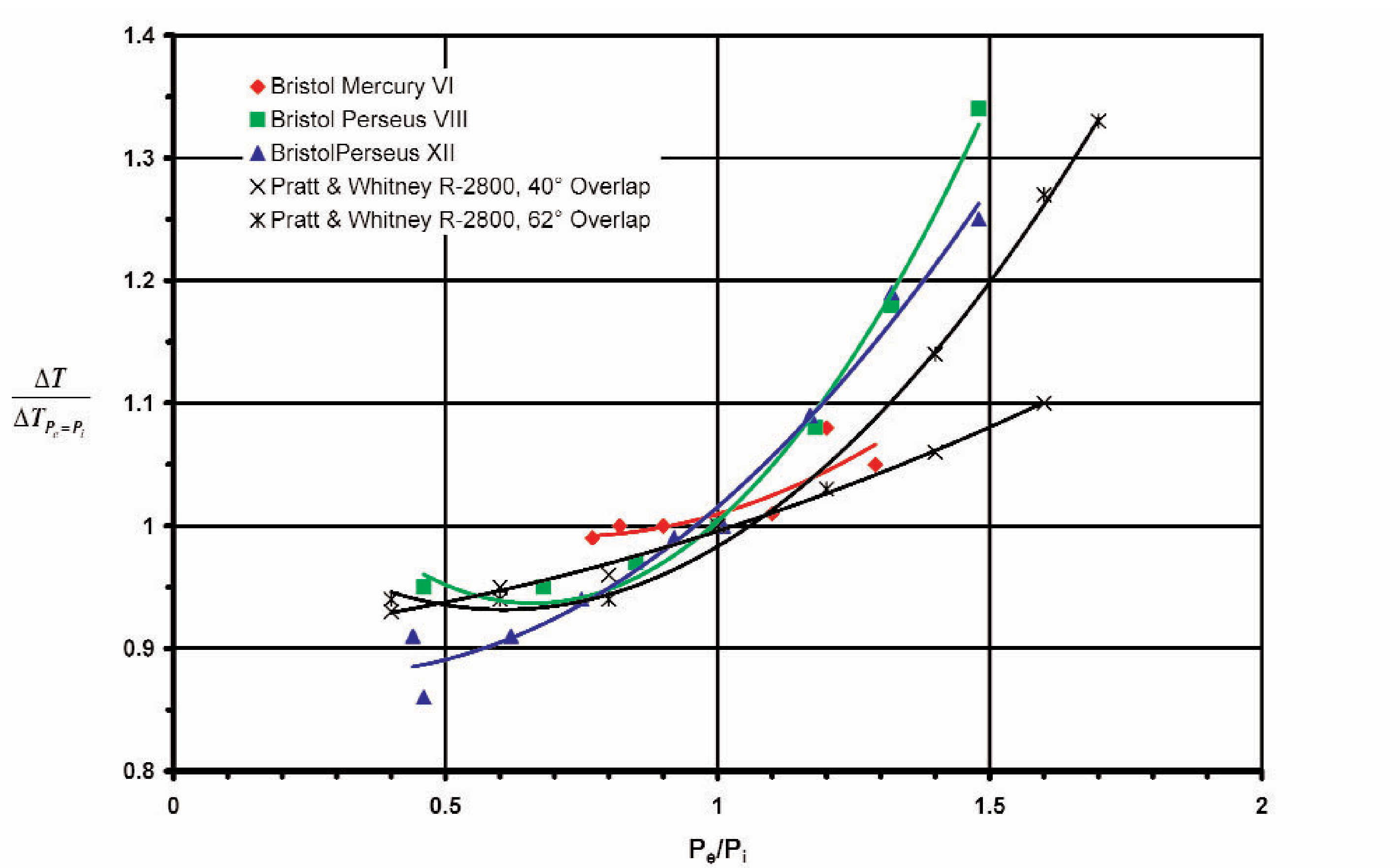

Fig. 7. Temperature Rise, Carburetor to Inlet Pipe Versus Exhaust to Intake Pressure Ratio. Normalized to $P_e / P_i = 1$; N = 2,200 RPM

Bristol tests and the difference clearly supports the higher flame speed of the sleeve valve engines and consequent higher detonation limits.

Another aspect of the sleeve valve performance which was noticeably different from poppet valve was the temperature rise from carburetor to intake pipe as a function of exhaust to intake pressure ratio. This is shown in Figure 7, where the temperature rise is normalized to a pressure ratio of one.

Despite the very small overlap relative to the poppet valve engines, the sleeve valve engines exhibit a relatively high temperature rise when the pressure ratio is greater than one. With no leakage from exhaust to intake, one would expect the temperature rise to be a function of the overlap and clearance volume and the poppet valve engines in this plot seem to bear this out. Both of these values are on the low side for the sleeve valve engines as seen in Table 1. The only explanation I can come up with for this phenomenon is leakage from the exhaust back into the inlet belt and pipe. This could be circumferential between the sleeve and cylinder, from the volume contained in the port which is common to intake and exhaust, and past the piston rings in the cylinder head which are closer together than the height of the ports, allowing a momentary short-circuit. This is a rather academic question since very little operational time is spent with exhaust to intake pressures greater than one. Some fresh charge could leak into the exhaust when the situation is reversed but if it were significant it would show up as increased fuel consumption, but the data given here does not indicate this is significant.

Summary

The results given here indicate that ca. 1941 the volumetric efficiency of the Bristol Perseus sleeve valve engine was better than the poppet valve Bristol Mercury engine and comparable to the Pratt & Whitney R-2800. It was not as high as that of the Wright R-1820 and other Wright engines of that period. The later version of the two Perseus engines tested showed a marked improvement in volumetric efficiency which apparently was due to changes made to the intake system. Continued efforts in that area could have closed the gap between sleeve and poppet valve with the Bristol Hercules and Centaurus engines, unfortunately that data has not, to my knowledge, surfaced.

The results also show that the extra thermal barrier of the sleeve and oil film did act to reduce the volumetric efficiency of the sleeve valve engine as compared to the poppet valve. It is not likely that this characteristic would have been overcome in later model Bristol engines.

Acknowledgements

I am indebted to David Robinson for bringing the Shilling paper to my attention and providing me with a copy. David was also helpful with his comments on a draft of this paper and information regarding Mercury and Perseus supercharger dimensions and gear ratios.

Patrick Hassell of the Rolls-Royce Heritage Trust, Bristol Branch provided intake pipe dimensions and the photos shown here as Figures 3 and 4. I am very grateful for his help.

Kim McCutcheon provided information on Bristol superchargers for the period of interest here.

References

1. Shilling, B. “Measurements of the Air Consumption of a Poppet and Sleeve Valve Air Cooled Radial Aircraft Engines with Varying Exhaust Back Pressure and Intake Temperature, Report No. E 3800” Royal Aircraft
Establishment, Farnborough, United Kingdom, February 1941.
2. Raymond, R. “Comparison of Sleeve Valve and Poppet Valve Aircraft Engines” AEHS http://www.enginehistory.org/members/articles/Sleeve.pdf, April, 2005.
3. Thomson, Mark R. “Flow Tests of a Bristol Sleeve Valve Engine Cylinder” M.I.T. Archives, Massachusetts Institute of Technology, Cambridge, Mass., 1951.
4. Shames. S. and Howes, W., “Determination of Air-Consumption Parameters for Two Radial Aircraft Engines” NACA Memorandum Report
MR No. E5H21, August 21, 1945.
5. Humble, L.V., et. al., “Effect of Exhaust Pressure on the Performance of an 18 Cylinder Air-Cooled Radial Engine with a Valve Overlap of 62°” NACA Technical Note TN No. 1232, January 2, 1947.