892

AUG 19 1940

[redacted]

[redacted]

[redacted]

[redacted]

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 949

THE MAXIMUM DELIVERY PRESSURE OF SINGLE-STAGE RADIAL SUPERCHARGERS FOR AIRCRAFT ENGINES

By W. von der Null

Luftwissen, vol. 7, no. 5, May 1940

Washington
August 1940

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 949

THE MAXIMUM DELIVERY PRESSURE OF SINGLE-STAGE RADIAL SUPERCHARGERS FOR AIRCRAFT ENGINES*

By W. von der Nüll

The subject under discussion was treated briefly by the author in 1937 (reference 1). The problem has since then frequently come up again as a result of the general tendency toward high-altitude flying in recent years. With the aid of simple considerations and test results, a further brief discussion will be given here and an attempt made to clear up some obscure points that still exist. The considerations will be restricted to those cases where it is in fact of advantage to "force" the large delivery heads required for high altitude and high supercharge with a single-stage supercharger.

The usual single-stage, centrifugal superchargers of airplane engines have simple radial impellers which are gear-driven by the engine crankshaft. The question as to where and how such superchargers are most conveniently mounted with respect to the engine must be decided by a compromise based on considerations of flow relations and shape of the supercharger. The greater the requirements imposed on the supercharger the more the flow considerations are the deciding factor. The importance of good axial air approach to the impeller for the attainment of optimum supercharger characteristics is generally recognized. The essential consideration as regards the axial approach is not so much attainment of a flow direction parallel to the axis as certainty with regard to the flow direction and uniform flow distribution at the impeller inlet. On account of the advantage of possible precompression through utilization of the kinetic energy at high flight speed, the air should be conducted to the supercharger with as little loss as possible and be received at a point at which full utilization of the dynamic pressure is assured under all flight conditions. No general

---

*"Überlegungen zur Frage der grösstmöglichen Förderhöhe einstufiger Radial-Lader an Flugmotoren." Luftwissen, vol. 7, no. 5, May 1940, pp. 174-180.

statement can therefore be made as regards the best arrangement of the supercharger with respect to the engine but the attempt should be made to satisfy the two requirements indicated above by using one structural shape for many mounting conditions. That no drastic changes should be made on the supercharger dimensions is obvious for "limiting superchargers," i.e., those of maximum delivery heads per stage and maximum efficiency. From experience with wind tunnel construction, it is known that right-angle deflections and limited variation in cross-sectional area may be attained with small losses. This experience may be successfully carried over to the air-passage design ahead of and behind the supercharger. The inlet velocity of the air in the supercharger impeller should not therefore be made to depend on the more or less accidental flight velocity, but should be governed by the condition that the impeller attain the maximum required performance values. Diameter ratio, inlet velocity, and rotational speed are strongly interconnected in a good supercharger and should not be considered as independent characteristics. Of what significance is the relatively large loss, for example, of 300 meters, in the case of a theoretical delivery head of 1400 meters (gas column) if thereby an air supply to the supercharger can be attained which leads to an increase of several percent in the efficiency of the latter, an increase which in some cases makes engine operation at all possible.

The question of the attainable delivery head is not the only factor to be considered. The deciding factor is rather the temperature rise in the supercharger. An engine operates without knock, depending on the fuel properties, only up to a certain supercharger temperature t_s. The critical maximum value, depending on the various operating conditions,

$\eta_{ad} = \frac{H_{ad}}{H} = \frac{H_{ad}}{J c_p (T_2 - T_1)}$; $T_2 - T_1 = \frac{A H_{ad}}{}$

$$t_s = \frac{A\ H_{ad}}{c_p\ \eta_{i-ad}} + t_I$$

"limits" the supercharger delivery head. The latter is generally expressed as a fraction of the theoretically possible delivery head for an infinite number of blades:

$$H_{ad} = q_{ad}\ H_{th\ \infty} \quad \text{i.e., for} \quad \alpha_0 = \beta_2 = 90^\circ$$

means rad'l blades

$$\underline{H_{ad} = q_{ad}\ \frac{u_2^2}{g}}$$

The value of the figure of merit q_{ad}, for which comprehensive test results are available (see, for example, reference 2, fig. 4) should not - as is shown in the following - be set equal to the internal supercharger efficiency η_{i-ad}.* The finite number of blades leads to a reduction from $H_{th\,\infty}$ to H_{th}. The relation between the two (reference 4) is given by $H_{th\,\infty} = m\,H_{th}$. Because of the internal friction losses in the supercharger, i.e., in the blades, the value H_{th} is further reduced to H (denoted as H_{ad} in the case of superchargers without intercooler). These losses H_{if} are accounted for by the efficiency η_h

$$\eta_h = \frac{H_{ad}}{H_{ad} + H_{if}} = \frac{H_{ad}}{H_{th}}$$

The figure of merit q_{ad}, by combining the two equations, is also given by

$$q_{ad} = \frac{\eta_h}{m}$$

A relation** can now be set up between η_h and η_{i-ad}. The internal specific work of compression H_i in the supercharger exceeds the theoretical blade work H_{th} by the impeller friction and backflow losses $H_f + H_{bf}$:

$$H_i = H_{th} + H_f + H_{bf}$$

Since $\eta_{i-ad} = \dfrac{H_{ad}}{H_i}$***, it is seen immediately that

---

*This assumption was apparently made by Kollmann in the determination of the values given in his table 1 of reference 3, p. 54, as is shown in table I of this article. The values in the upper row are those of Kollmann's table 1. The values of η_{i-ad} computed in the bottom row of table I were thus set equal by Kollmann to the ratios q_{ad} in setting up his table 1.

**In steam turbine theory, between η_u and η_i.

*** This expression is equivalent to $\eta_{i-ad} = \dfrac{\Delta\, t_{ad}}{\Delta\, t_w}$.

$\eta_h > \eta_i$.* It is therefore incorrect to set q_{ad} equal to η_{i-ad} since $\eta_h > \eta_i$ and furthermore $m \gg 1$.**

It has been pointed out that considerations of knocking limits the supercharger temperature. Assuming, for example, with a view toward future fuel improvement, $t_s = 115^\circ$ as a permissible value, then the supercharger pressure p_s from table II for the given required tip speeds of the supercharger impeller would be possible, provided that the assumed η_{i-ad} and q_{ad} values are realized.

The characteristic curves of several DVL superchargers (figs. 1 to 3) (designs of the years 1936, 1937, and 1938) show that the values on table II are entirely attainable or are partially realized already. These results show primarily, however, the continuous appreciable progress toward the goal of high efficiencies at large delivery heads.***

---

*This was pointed out elsewhere by the author in 1935. A detailed treatment of this question for centrifugal pumps will be found in reference 5.

**These relations can quite well be confirmed on the characteristics shown by Kollman - measured by the author a few years ago in the DVL on a DB supercharger. At $V_I = 0.85$, there is read off $\eta_{i-ad} = 0.68$ and there is computed $q_{ad} = 0.6$. Cautiously estimating $\eta = 1.10\ \eta_{i-ad}$, there is obtained $m = 1.25$. Computing now for the impeller of the investigated DB supercharger, the expected value of m by the method given in the literature m is found to be equal to 1.27. It thus appears, as emphasized by the author in his paper of 1937 (reference 1), that sufficiently accurate computations can be made, using the guide data available (reference 4).

***Kollmann is of the opinion that high η_{i-ad} values have until now been obtained only at low u_2 (peripheral speed) values < 220 m/s. In this connection, I should like to refer the reader to my paper (reference 2), which is also referred to by Kollmann in his Stuttgart paper, where in fig. 5 the contrary was proven. Fig. 2 shows one of these families of characteristics. Also, the test results presented by Dr. Kröner in the discussion to my Berlin paper (reference 6) indicated success in the desired direction.

These investigations can by no means be considered as concluded. Half-shrouded impellers have always shown less efficiency than shrouded impellers of the DVL type of construction. Figures 4 and 5 show a few results of the DVL tests carried out by the author for various values of u_2. According to these results, the value of η_{i-ad} for the shrouded impeller is evidently 1.05 times that of the otherwise fully equivalent half-shrouded impeller. The application of this result to the results given in figure 3 shows that at tip speeds up to 350 meters per second, efficiencies between 76 and 79 percent can be attained. Difficulties encountered in other directions that are met with in aiming toward the required high efficiencies can already largely be eliminated. Figure 6 shows, for example, that even with unusually small dimensions, large values ($\eta_{i-ad} = 0.8$; $q_{ad} = 0.66$) have been obtained through suitable computation and design. And the weight expenditure does not appreciably exceed present-day usual values. The weight of the DVL impellers, which are provided on both sides with walls lies considerably below the weight of the impellers of foreign engines (Rolls-Royce, Bristol, Farman) and exceeds only by a small amount those of present German engines. On figure 7 is shown an impeller of the Rolls-Royce Merlin on the left (impeller weight approximately 3 kg) and on the right a DVL impeller (weight approximately 1.3 kg). Both wheels are built for a tip speed of about 350 meters per second, but the DVL impeller* maximum efficiency is greater by 16 percent.** No fundamental difficulties in the operation of the impeller bear-

---

*The DB impeller for somewhat smaller values of u_2 weighs 0.88 kg. According to fig. 13 in Kollmann's paper, the charge taken in by this impeller at the design speed is about 0.8 m^3/s at $\eta_{i-ad} = 0.68$, whereas for the impeller shown in fig. 7 for equal H_{ad} (fig. 2), but for $\eta_{i-ad} = 0.78$ the intake volume is 1.4 m^3/s. The difference in weight between the DVL and DB impellers of about 0.4 kg, which in itself is extremely small, hardly enters into consideration.

**According to the personal communication of the Rolls-Royce designers, the Merlin impeller has been made so heavy because of several blade failures through backfiring of the engine.

ing arise through differences in weight of the above-mentioned magnitude, provided the bearing is properly designed. No absolute limits are as yet known. In the DVL supercharger constructions, the impellers run on one or two supports and operation even at 30,000 revolutions per minute leads to no fundamental difficulty.*

One of the advantages of the DVL impeller shape shows up clearly here, namely: that it is not difficult to balance the axial thrust by very simple means, either fully or to a degree sufficiently favorable for the bearing. (See for example, reference 4, fig. 45.) In the case of half-shrouded impellers, the back wall is often made with cut-outs between the blades to reduce the axial thrust (reference 5, p. 348 and fig. 233a). This procedure, which has been customary for about 20 years, has, owing to the increase in the value of u_2, given rise to many impeller failures (fig. 8).**

What about the "maximum possible" tip speed u_2? Quite generally it may be stated that with proper utilization of the existing materials and with skillful compromise between the flow and strength requirements this speed lies higher than is either desirable or permissible from the viewpoint of the charge condition. (See table II.) The tests conducted so far with DVL centrifugal superchargers have shown that it is possible, with the aid of very comprehensive literature on the subject, to make sufficiently accurate advance strength computations. In the case of complicated structural shapes, however, this computation involves considerable mathematical skill and is tedious. For a DVL impeller (similar to that of fig. 7, right) which for a centrifugal test was made of an elektron disk, it was computed*** that bursting would occur at about 520 meters per second peripheral speed, whereas bursting actually occurred at 540 meters per second ($n > 36,000$ rpm).

---

*DVL tests of my coworker, G. Getzlaff had previously been carried out up to bearing speeds $d_w\ n = 735,000$ mm/min. (See reference 7.)

**Half-shrouded impellers of the DVL type (like those of the Rolls-Royce) have never had such cut-outs, since a strength computation, somewhat uncertain, it is true, led to expected disadvantages. Such failures are reported by W. Kirsch in reference 8, fig. 3, where, however, no proof is given of the cause of failure.

***Computation of my coworker, H. Pfau.

An accuracy greater than this is not required.*

Impellers with cover disks on both sides naturally require rearrangement or extension of the manufacturing installations and will also be somewhat more expensive than half-shrouded impellers. Through suitable

---

*Kollmann concludes: "Unfortunately, there is no method at the present time for predicting the stresses arising in an impeller." Kollmann further considers the blade bending stresses which arise under the blade pressure as important. The magnitude of these stresses can readily be estimated. Between the delivery head, weight of discharge, and moment, there is the relation $H_{th} = \frac{M \omega}{\gamma V}$. For a pressure difference $\Delta p = \gamma \Delta h$ between the pressure and suction sides of the blade; for z blades of width b and radius r, we have

$$M = z \int_{r_1}^{r_2} \Delta p \, b \, r \, dr$$

Considering only a purely radial strip of the blade of width $b = \text{const}$ between r_1 and r_2, that is, a too unfavorable case, a simple relation is obtained between Δp and H_{th}, provided that the none too favorable assumption is made that Δp is constant over the blade surface (see reference 4, pp. 22 and fig. 24):

$$\Delta p = \frac{2 \gamma V H_{ad}}{z \omega b (r_2^2 - r_1^2) \eta_h}$$

Substituting the values from figure 13 of Kollmann's paper $H_{ad} = 8000$ m (gas column), $n = 27{,}000$ rpm and $\gamma V = 0.58$ kg/s, there is obtained, if all the blade parts with the inlet of the DB impeller is considered as cut away, a bending stress of $\sigma = 0.51$ kg/mm^2. The error made in entirely neglecting this stress is thus practically negligible. Difficulties in impellers due to dynamic stresses through vibration are not known to the author.

design and new-type devices, all "dreaded" difficulties may be eliminated, however. The inconvenient curved blade tips such as are usual with the half-shrouded impellers were avoided in the DVL impellers, as in many Junkers and Rolls-Royce impellers, through the separate mounting arrangement, as shown in figure 7. By this method not only is the shaping of the blades made independent of the manufacturing restrictions that are involved in subsequent blade curving but production methods are found which are rather simpler than the more difficult curving process. A slight increase in the cost of the impeller does not amount to much if as a result of the considerable improvement in efficiency the engine output and the permissible critical altitude are appreciably increased. Other viewpoints, of importance for the future, should also not be overlooked. The shape of the operating characteristic curves of half-shrouded impellers, as already communicated by the author, vary considerably with the clearance between the propeller blade edges and the housing wall (supercharger cover). Figure 9 shows a few results from the author's DVL tests. In the region of high delivery heads the smallest possible clearance feasible in the manufacture should be aimed for. The absolute size of the clearance in the warm operating condition of the supercharger is very difficult to determine even for single-stage superchargers since the necessarily light housing of the supercharger "breathes" somewhat, depending on the heating and the pressure inside. This effect will be of much greater importance, however, in the case of multistage superchargers when these become necessary. The required minimum clearances will then offer much greater difficulties. These considerations should be taken into account in any discussion of the most advantageous impeller shape since the abovementioned difficulties are met with in the DVL impeller as well as the previously introduced Junkers impeller. (See reference 2, p. 282, fig. 1, and reference 3, fig. 11.)

In summarizing, it is understandable that the introduction of the impeller with disks at both sides will receive lively discussion, since from the point of view of strength the tip speeds can be entirely realized and efficiencies may be attained which can assure operation without supercharger cooling with greater altitude performance. The half-shrouded impeller, while it is not "through," will always be at a certain disadvantage.

From the large complex of considerations with regard to supercharger design, a brief discussion, in concluding, will be given to the question of the most favorable design of the throttle regulation, at present required in almost all cases. It is known that superchargers with purely radial impellers start to pump with difficulty when the intake quantity goes below that corresponding to maximum delivery head. From centrifugal compressor operation it is known that this disturbance can be held partially in check if the throttle member is mounted very close to the impeller inlet. This fact, which, as far as is known to the author, has not been mentioned anywhere, is of great importance for the operation of the engine-driven supercharger. With fixed gear ratio between engine and supercharger, the inadmissibly high supercharge pressure must be throttled down, as is known, in the interval between starting and attaining the rated altitude. If the throttle arrangement is located ahead of the supercharger (on the suction side) the intake volume of the supercharger changes only with the absolute intake temperatures, i.e., extremely little. If the sea-level point of an engine lies in the operating region of the supercharger at B (fig. 10) then the latter for equal engine speed in the example chosen (7 km; p_s = 840 mm Hg) gradually travels with increasing altitude up to the nominal output point S. Delivery head and supercharger efficiency maintain their optimum values.* This, as may be seen on the upper left corner of figure 10, has a favorable effect on the engine output (curve S). (The ratio of net output N_{e-n} of the supercharged engine to the ground output N_{e-oo} of an unsupercharged engine of the same charge volume was plotted against the altitude.) If, for any reason, it is desired to place the throttle behind the supercharger, i.e., on the pressure side, account must be taken of the fact that the sea level point with smallest intake volume must again be chosen as the point B. The engine-operating point at altitude, for unavoidable and known reasons, moves toward D. The disadvantages that arise from this can be easily seen and become clearly evident on consideration of the engine output curve (curve D in upper left corner of fig. 10). In the example considered, the required supercharge pressure will no longer be attained at the rated altitude, although, as the comparison of these rotational speed curves (dotted in fig. 11) with

---

*The advantages of suction side throttling were first pointed out by Noack in reference 9.

those of the DB supercharger shows, the characteristic curves of figure 10 are not among the steepest. Pressure-side throttling* therefore is not the ideal throttling for centrifugal superchargers with radial impellers as regards its effect on the engine output, because the engine-operating point travels into the supercharger-characteristic field, the travel being farther the greater the critical altitude and supercharger pressure. In the case of suction-side throttling, the supercharger always operates at the maximum values of delivery pressure and efficiency.

In the ideal delivery pressure regulation through infinite speed variation, such as might be attained with

---

*With regard to this question, Kollmann expressed himself af follows: "It is not correct, in the comparison of pressure- and suction-side regulation, to consider the sea-level point for suction-side regulation to be the same as the sea-level point for the pressure-side regulation. A supercharger of this type will be absolutely incorrectly dimensioned..." On fig. 11, four engine-operating points are shown of the DB 600 in the range of characteristics given by Kollmann. B and D are sea-level and altitude points, respectively, for various engine speeds. The views expressed above correspond completely here, too, to the actual conditions. (The operating points indicated can be computed easily from the data in the literature and agree with corresponding measurements.) Kollmann further maintains that the sea-level point in the case of pressure-side throttling must lie so far to the left in the field of characteristics that the altitude point moves into the region of best supercharger values. Results in this connection on pressure-side-throttled superchargers with large efficiencies are as yet unknown, however. And even then, this method presents no ideal solution, since, in the large travel described by me above, the sea-level point would lie in the region of low supercharge efficiency, i.e., high supercharger temperature. A remedy could be found here in the simultaneous application of valving pressure regulation in the pressure pipeline. The same success, with regard to the position of the operating point in the supercharger characteristic field, would be met with as with suction-side throttling but, unfortunately, would be gained at the expense of the useful engine output.

good exhaust turbine drive, the engine operating points, in the example of figure 10, run through the range of supercharger characteristics along the curve R-S, the engine output varying with altitude according to the curve denoted by R. Superchargers which, also in the region of the smaller tip speeds, are intended to have the highest possible efficiencies, such as were attained for the first time in 1936 with a DVL supercharger (fig. 12, in Kollmann's paper) thus lead, with infinite speed regulation, also to large take-off and climb performance.

Summarizing, it may be stated that the limit to the critical altitude of engines for the present and probably for a long time will be set not by the maximum possible delivery head of the single-stage radial supercharger, but by the delivery head permitted by the increase in temperature determined by the work cycle in the engine cylinder, unless intercooling is used. The introduction of intercooling, however, leads again to fundamentally different considerations with regard to the supercharger design.* Besides, the introduction of intercooling naturally means no simplification either in the mounting or in the operation of the engine. It leads, moreover, to an additional harmful drag of the airplane. Increase in the supercharger efficiency, as far as possible, must therefore be one of the first requirements for the high-altitude engine. The important effect of the supercharger efficiency on the engine output is clearly shown in figure 12. In the upper part of the figure curves of equal density increase are plotted as functions of the supercharger efficiency and the pressure ratio, and in the lower part of the figure, curves of equal supercharger pressure are plotted as functions of the supercharger pressure ratio and the altitude. These curves indicate, if a first approximation is considered and side effects, including knocking, are not taken into consideration, a corresponding increase in the engine output. To attain a pressure $p_s = 1.4$ atmospheres at $H = 6$ km, the supercharger pressure ratio amounts to 2.91. If the supercharger has, for example, an efficiency $\eta_{i-ad} \sim 0.79$ instead of 0.54 the increase in the internal engine power as a result of

---

*A few of these questions were considered by the author at the VDI main session in 1938 (See reference 10.)

the increase in the density of supercharger air is about 14 percent. Such values as this certainly justify the added weight of the supercharger.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

1. von der Null, Werner: The Design of Airplane-Engine Superchargers. T.M. No. 839, NACA, 1937.
2. von der Null, Werner: Ladeeinrichtungen für Hochleistungs-Brennkraftmaschinen, insbesondere Flugmotoren. ATZ, Jahrg. 41, Heft 11, June 10, 1938.
3. Kollmann, K.: Grenzen zur einstufigen Verdichtung in Schleuderladern für Flugmotoren. Luftwissen, vol. 7, no. 3, March 1940, pp. 54-61. Also in Aircraft Eng, Oct. 1940, p 298
4. von der Null, Werner: Die Kreiselradarbeitsmaschinen. B. G. Teubner, Leipzig and Berlin, 1937.
5. Pfleiderer, C.: Die Kreiselpumpen. J. Springer, Berlin, 1932. (Second edition)
6. von der Null, Werner: Die Gestaltung von Flugmotorenladern. Jahrbuch 1937 der Deutschen Luftfahrtforschung, pp. II 143-155.
7. Getzlaff, Günter: Experiments on Ball and Roller Bearings under Conditions of High Speed and Small Oil Supply. T.M. No. 945, NACA, 1940.
8. Kirsch, W.: Suppl. to Flug und Werft of Jan. 16, 1939.
9. Noack, W. G.: Flugzeuggebläse. Z VDI, 1919, p. 995.
10. von der Null, Werner: Fragen der Regelung und des Antriebs von Flugmotorenladern in ihrer Beziehung zu Bau und Betrieb. Jahrbuch 1938 der Deutschen Luftfahrtforschung. II 203-209.

TABLE I

Kollmann's values	q_{ad}	0.60	0.60	0.75	0.75
Altitude (km)		6	10	6	10
$p_{II} = p_s$ (atm)		1.3	1.3	1.3	1.3
H_{ad} (m gas column)		8,370	12,940	8,370	12,940
$u_2 = \sqrt{g\ H_{ad}/q_{ad}}$ (m/s)		370	459	331	411
$\Delta\ t_{ad} = A\ H_{ad}/c_p$		81.6	126.2	81.6	126.2
$\Delta\ t_W$, according to Kollmann		136	210	110	168
$\Delta\ t_{ad}/\Delta\ t_W =$	η_{i-ad}	0.600	0.602	0.742	0.752

TABLE II

Altitude (km)	η_{i-ad}	$\Delta\ t_{ad}$	H_{ad} (m. gas column)	p_s (atm)	q_{ad}	u_2 (m/s)
0	0.80	80	8,200	2.44	0.63	357
2	.78	88	9,000	2.13	.62	378
4	.76	96	9,850	1.87	.61	397
6	.74	103	10,600	1.62	.60	416
8	.72	109	11,200	1.37	.59	432
10	.70	115	11,800	1.16	.58	447

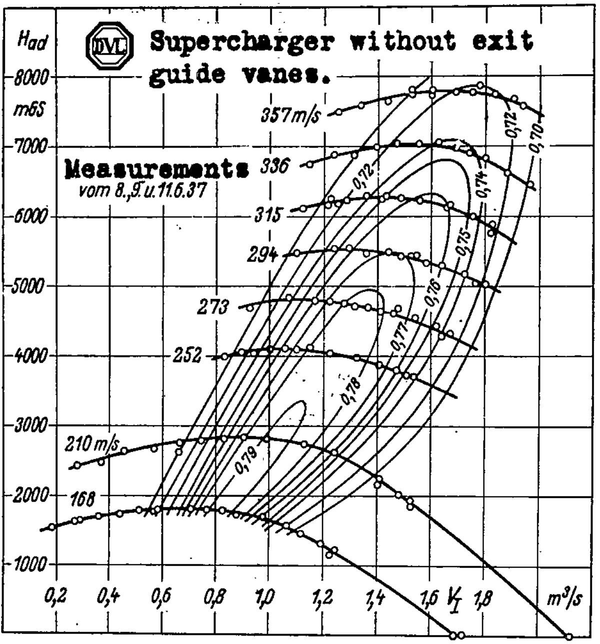
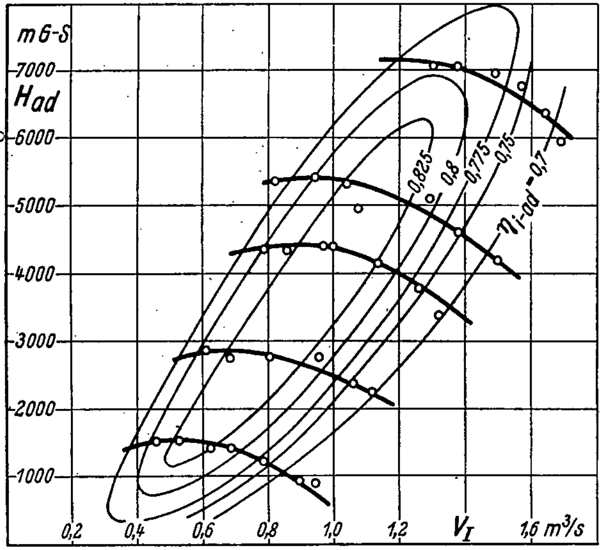


Fig. 1.



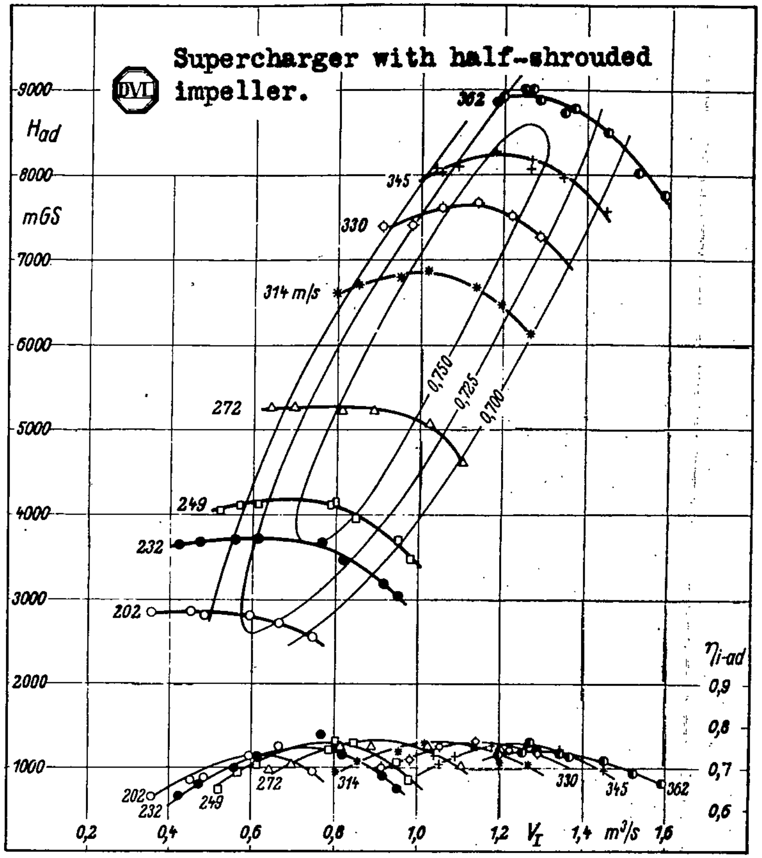


Figure 3.- Characteristics of a DVL supercharger.

Figures 1 and 2.- Characteristics of various DVL superchargers.

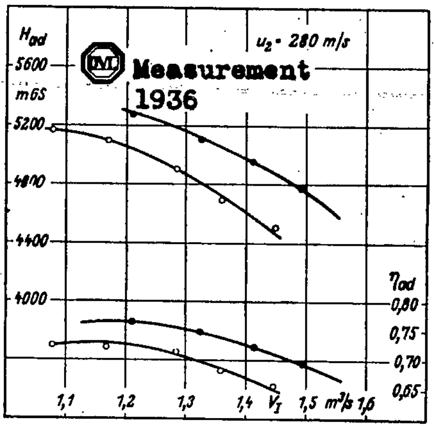
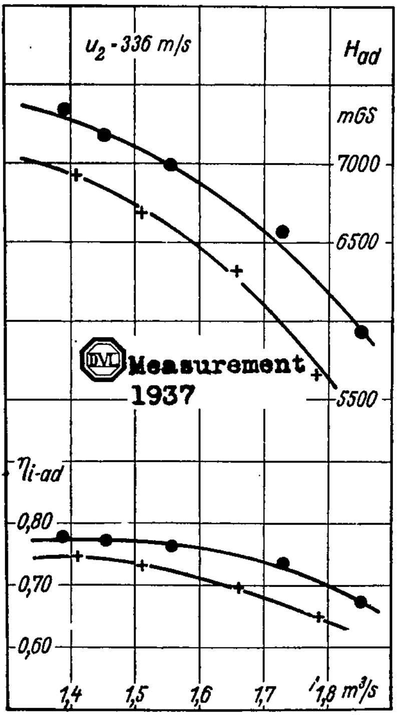


Figure 4.

- • • Shrouded DVL impeller.
- ○ ○ Half-shrouded DVL impeller with equivalent dimensions.



Figures 4 and 5.- Comparison of half-shrouded with shrouded impeller.

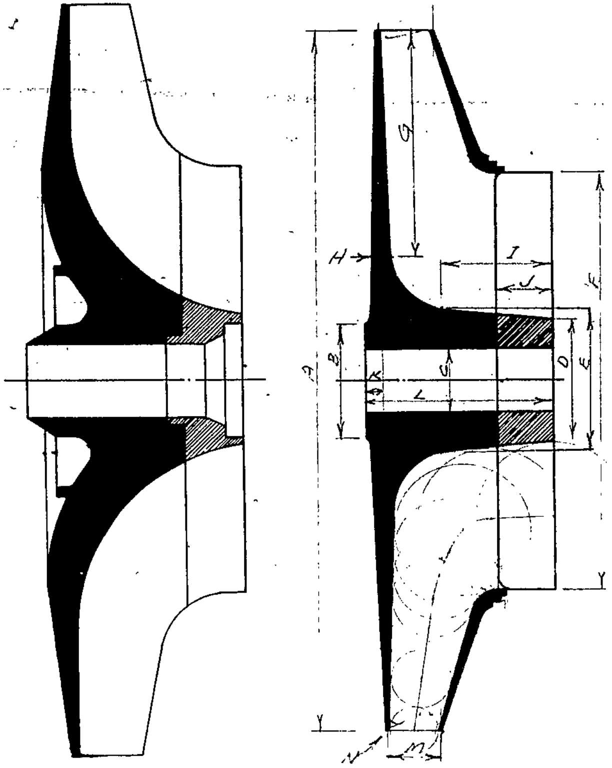


Figure 7.- Impellers: left, Rolls-Royce(3 kg), right, DVL (1.3 kg).

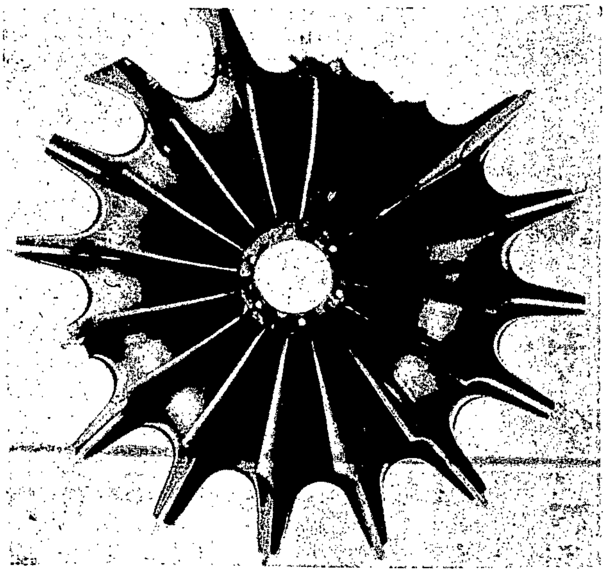


Figure 8.- Impeller failures with impeller wall cut-outs.

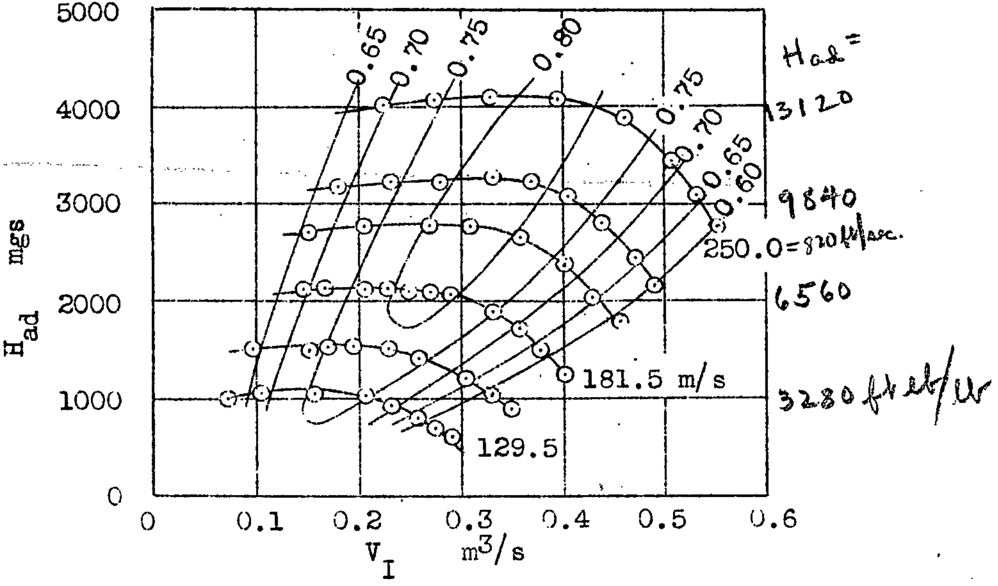


Figure 6.- Characteristics of a small DVL supercharger.

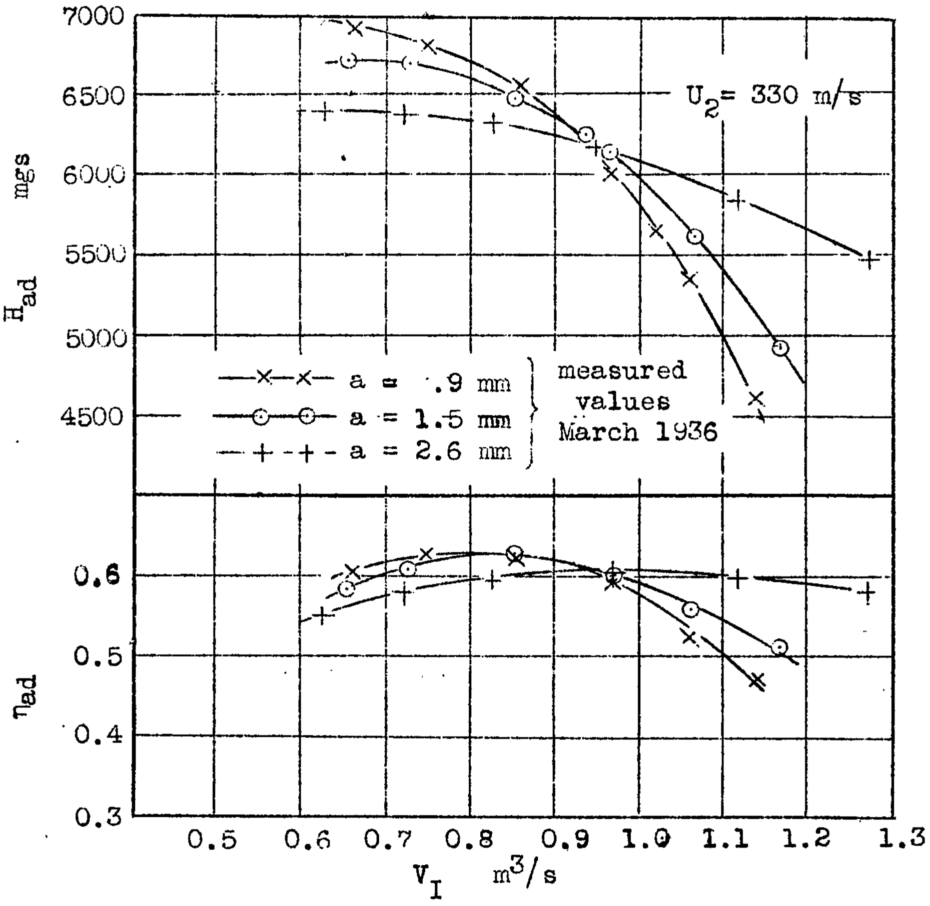


Figure 9.- Effect of cover clearance.

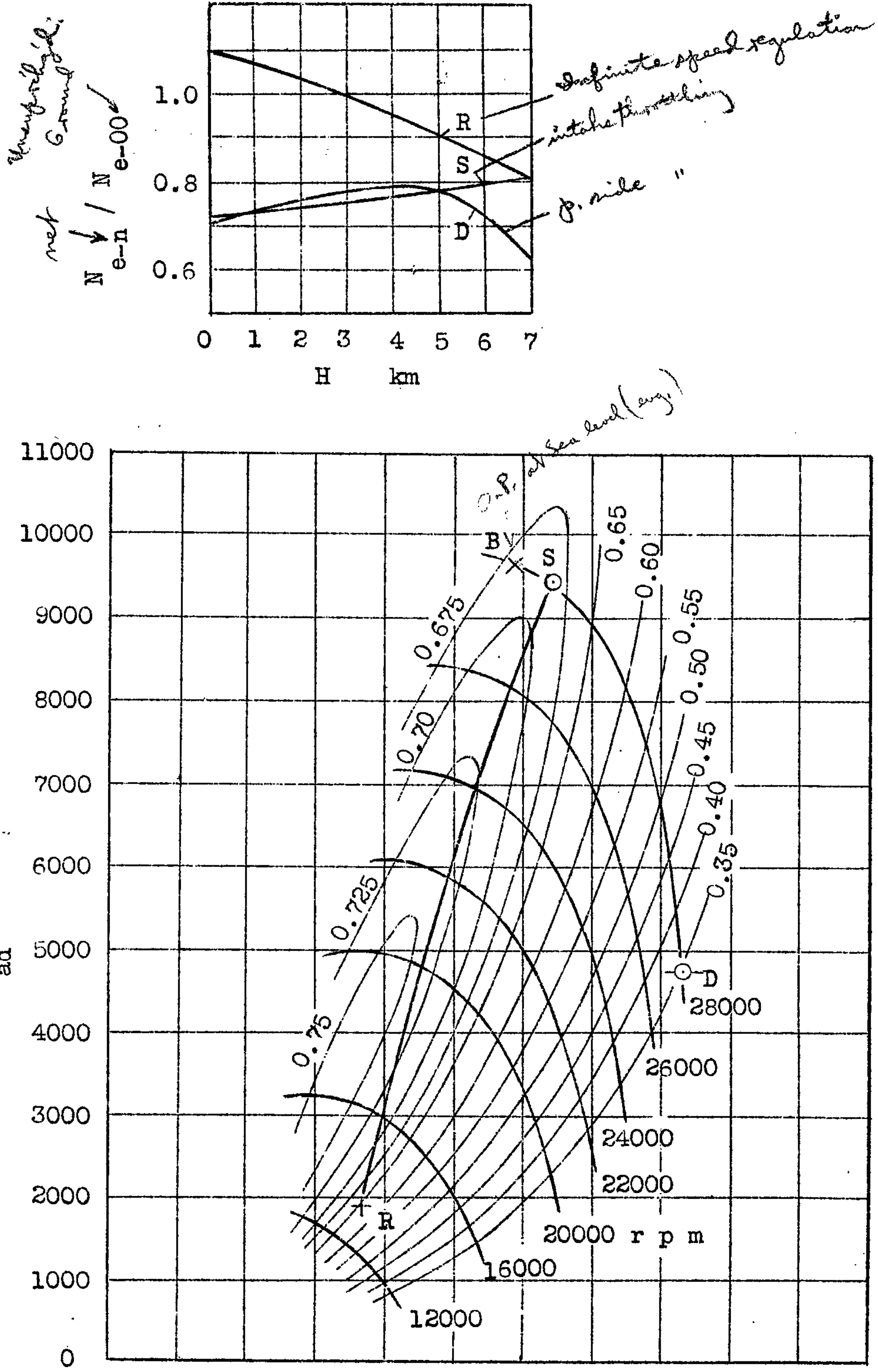
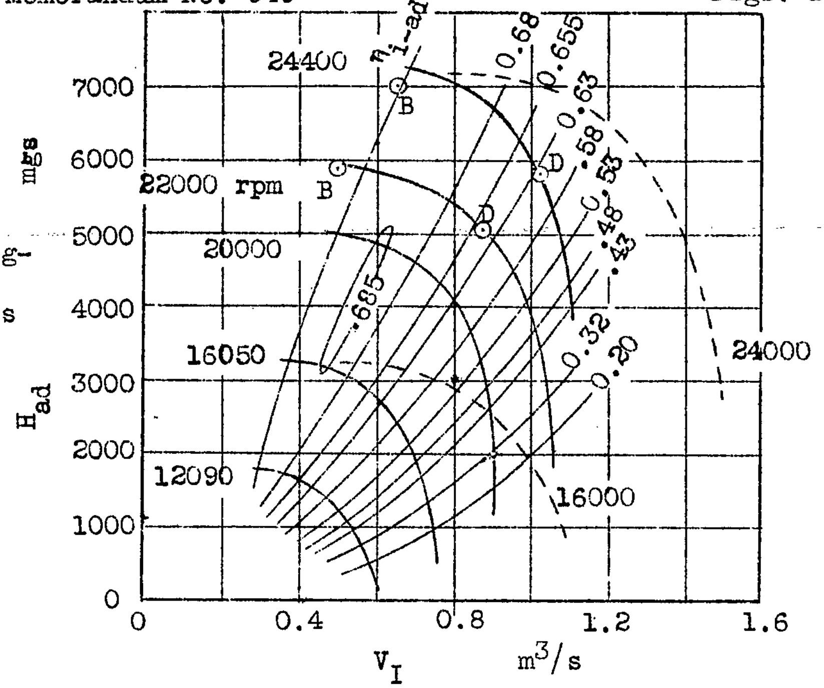


Figure 10.- Engine operating points in the region of supercharger characteristics and engine powers (in graph above).

Figure 11.-

Characteristics of DB supercharger with engine operating points and comparison characteristics.



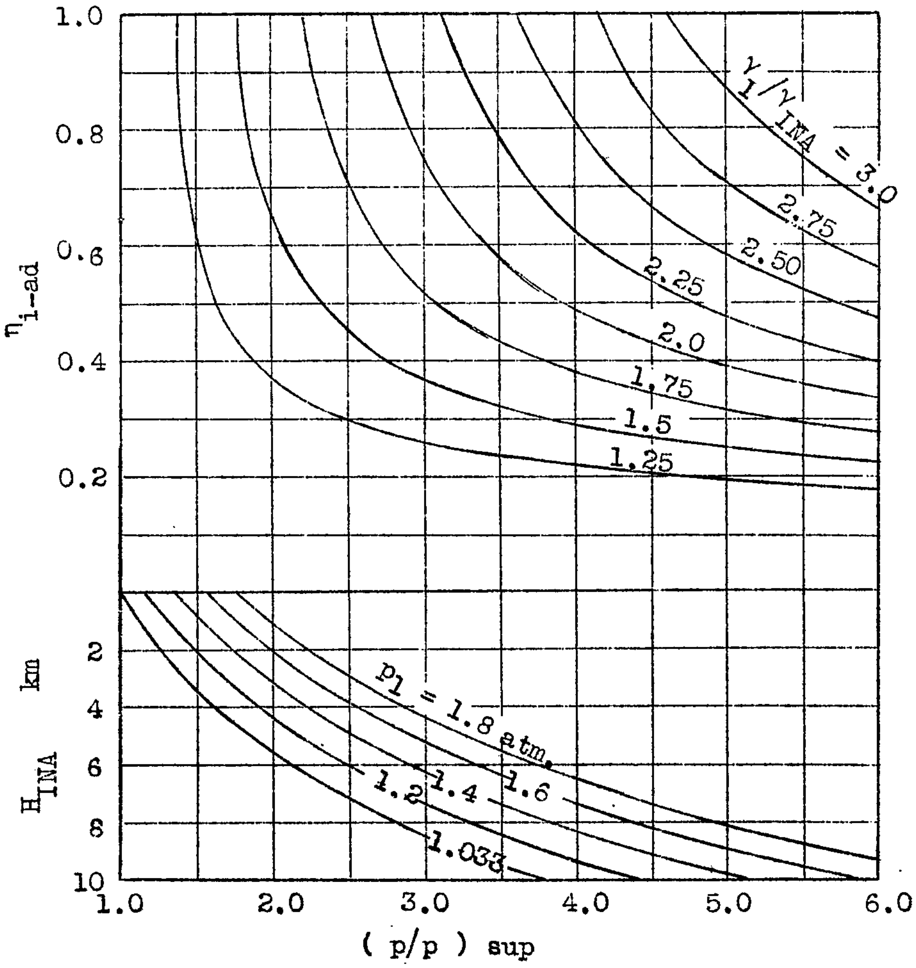


Figure 12.- Effect of supercharger efficiency on the increase in density.