AER-56-6

Power Supplies for Suction-Driven Gyroscopic Aircraft Instruments

By C. S. DRAPER[1] and A. F. SPILHAUS,[2] CAMBRIDGE, MASS.

At the present time gyroscopic instruments constitute an essential part of the equipment in any well-equipped airplane. The "turn indicator," the "artificial horizon," and the "directional gyro" are three widely used gyroscopic aircraft instruments which have reached a very satisfactory state of development. However, in order that proper results may be attained in practise, it is necessary that some reliable and sufficient source of suction be provided. It is the object of this paper to present a study of the various devices used in operating the gyroscopic instruments.

Air Requirements for Instruments

As a preliminary to the problem of suction supply it is necessary to study the air-consumption requirements of the gyro instruments. Figs. 1, 2, and 3 indicate diagrammatically the gyro-wheel arrangements in the three instruments. In each case the wheel is supported on gimbals within a chamber which is closed except for an air entrance leading to a nozzle and a connection to the intake side of the source of suction. Air flowing through the nozzle into the evacuated chamber impinges on the wheel and produces the necessary driving torque.

Fig. 4 shows the experimentally determined relation between the pressure difference provided and the rotor speed for the three instruments. In a similar manner Fig. 5 indicates the variation of air consumption with pressure difference. Table 1 is a summary of the conditions for normal operation.

TABLE 1 NORMAL OPERATING CONDITIONS AT SEA LEVEL

Instrument	Pressure difference, inches of mercury	Rotor speed, rpm	Air consumption, cfm
Turn indicator...........	2 to 2.5	10,000	0.5
Artificial horizon.........	3.5 to 4	17,000	1.7
Directional gyro..........	3.5 to 4	12,000	1.0

Effect of Altitude. It is very interesting to note that for a constant pressure difference the curves indicate that the gyro wheel experiences an increase in speed with increasing altitude. A study of this phase of the problem has shown that the experimental results check nicely with the predictions of theory.[3] Physically this means that a considerable portion of the energy required to keep the gyro wheel in rotation is expended in the maintenance of eddies in the air around the wheel. The energy thus expended will decrease as the air density decreases.

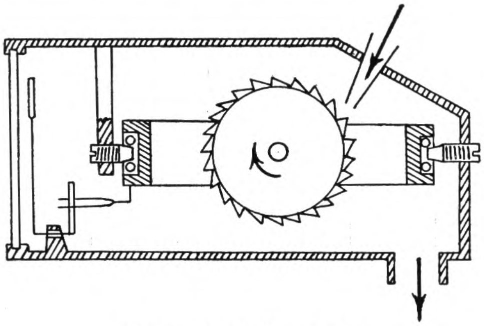

Fig. 1 Turn Indicator

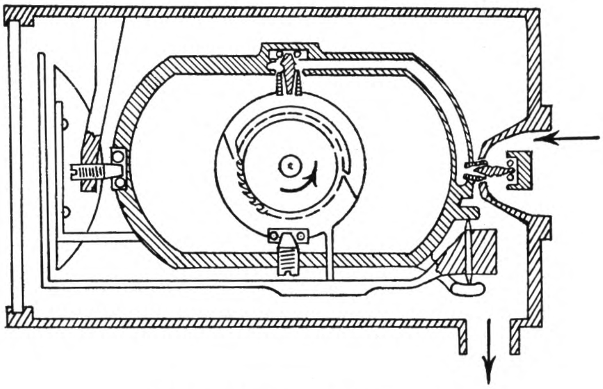

Fig. 2 Artificial Horizon

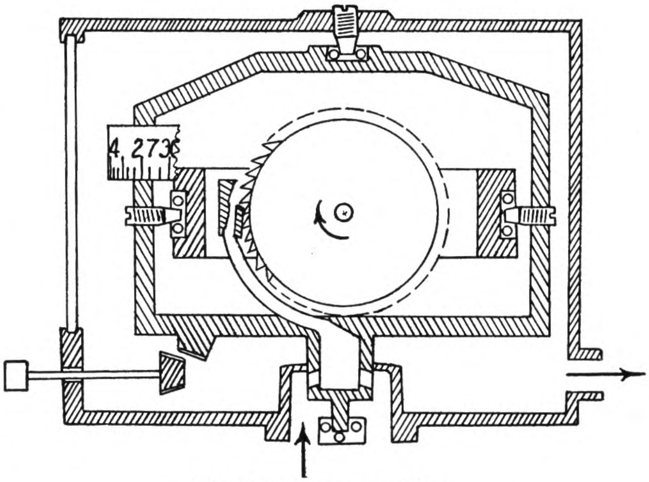

Fig. 3 Directional Gyro

---

[1] Member of Staff, Massachusetts Institute of Technology. Mr. Draper attended Missouri University in 1917, received the degree of A.B. from Stanford University and the degrees of S.B. and S.M. from the Massachusetts Institute of Technology. He is a commissioned officer in the Army Air Corps Reserve and holds a pilot's license from the Department of Commerce. Since 1928 he has been a member of the staff of the Massachusetts Institute of Technology engaged in internal-combustion-engine research and in charge of aircraft-instrument work at the Institute since 1930.

[2] Graduate Student, Massachusetts Institute of Technology. Mr. Spilhaus attended school in England and later the University of Cape Town, South Africa, where he received the degree of B.Sc. From the Massachusetts Institute of Technology he received the degree of S.M. in Aeronautical Engineering. Mr. Spilhaus' work on aircraft instruments was begun at M.I.T. and later continued for the Sperry Gyroscope Co. in Brooklyn, N. Y.

Contributed by the Aeronautic Division and presented at the Metropolitan Section Meeting, New York, N. Y., November 23, 1933, of The American Society of Mechanical Engineers.

[3] "Air Suction Methods in Driving of Gyroscopic Instruments for Aircraft." Thesis by A. F. Spilhaus, Mass. Inst. of Tech., 1933.

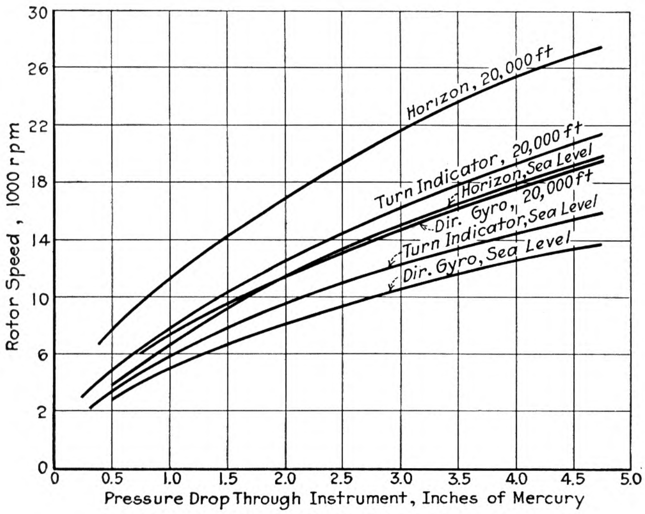

FIG. 4 ROTOR SPEED VS. PRESSURE DROP

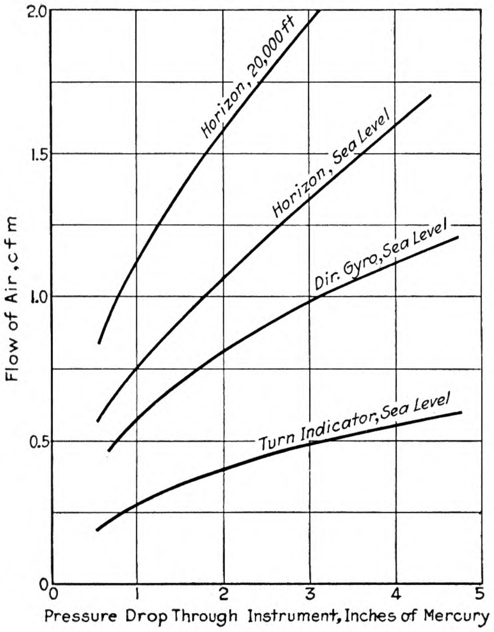

FIG. 5 FLOW OF AIR VS. PRESSURE DROP

Effect of Temperature. The three instruments are required to pass an operation test at minus 35 F. At sea level, the lowering of the temperature increases the density of the air and slows the wheels down slightly. However, as altitude is increased and the temperature decreased there is a net loss of density and therefore a small gain in rotor speed.

The only requirement that seems necessary, therefore, is to maintain a constant pressure difference for the instruments within ± 0.5 in. of mercury, because altitude and temperature changes do not have any marked detrimental effect. This conclusion applies to the air-driven wheel itself considered as free from the effects of bearing friction.

POWER SOURCES FOR OPERATING INSTRUMENTS

The source of power for gyro instruments, in order to be satisfactory, must have certain characteristics:

(1) It must be reliable and of reasonable efficiency
(2) It must handle the required air volume per unit time at the proper pressure difference under all flying conditions near sea level
(3) It must fulfil condition (2) at the ceiling of the airplane.

At present three types of suction supply are in common use for gyro instruments:

(1) Venturi with air introduced at the throat section
    (*a*) Single venturi for turn indicator
    (*b*) Double venturi for horizon and directional gyro
(2) Displacement air pump
    (*a*) Propeller driven
    (*b*) Mechanically driven
(3) Engine carburetor pressure drop.

VENTURI

In the past, specially constructed venturis have been in almost universal use for operating gyro instruments. These venturis have the advantage of being simple, reliable, and inexpensive. On the other hand, they have certain disadvantages:

(1) The suction supplied varies widely with flight conditions
(2) The efficiency of the venturi as a power supply is exceedingly low
(3) Ice formation renders the venturi inoperative.

As long as installations are confined to airplanes with cruising speeds of around 100 mph the advantages of a venturi installation somewhat outweigh the disadvantages.

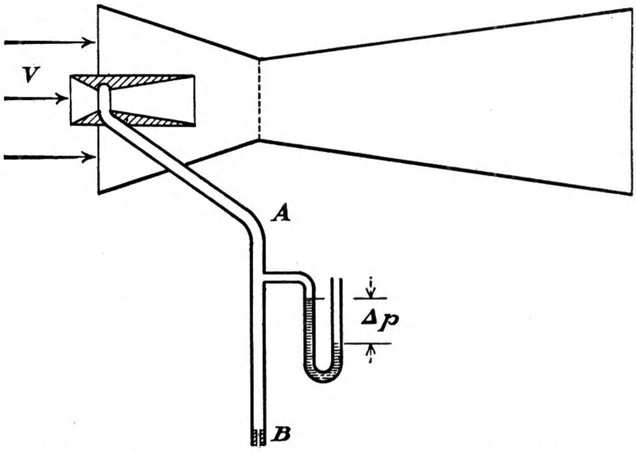

FIG. 6 ARRANGEMENT OF APPARATUS FOR VENTURI TESTS

However, for the modern high-speed airplane it becomes imperative that the problem be reconsidered. This section is devoted to a study of the performance of the venturi in this connection.

Suction Produced by Venturi. The essentials of the system used in the experimental work are indicated in Fig. 6.

In general, the pressure difference given by a venturi producing static suction, that is, with no flow through the line A, may be written.[4]

$$\Delta p = K(1/2\rho v^2) \qquad [1]$$

where Δp = pressure difference
ρ = mass density
v = relative velocity of the venturi and the air stream

---

[4] "The Theory of Pitot and Venturi Tubes," by Earle Buckingham. National Advisory Committee for Aeronautics, Technical Report No. 2.

K = constant (except for second order effects)[5]

Variation of Suction With Flow. Experiments made by the writers, with venturis drawing air through orifices of different areas, have shown that for any particular orifice the suction is given by the relation:

$$\Delta p_1 = K_1(1/2\rho v^2) \quad \text{..............} \quad [2]$$

Fig. 7 shows the variation of K_1 for a standard venturi as the effective orifice area is changed. The rapid decrease of K_1 as the orifice area is increased shows that the venturi is unsatisfactory for operating a load with other than a very small orifice area. In practise this means that a separate venturi is required for the horizon and the directional gyro. The turn indicator could be connected in with the directional gyro to even up the amount of air drawn in by each venturi (See Table 1).

Suction Affected by Airplane Speed. Equation [2] shows that the suction supplied by the venturi varies as the square of the relative air velocity v. This means that, if a venturi is to supply sufficient pressure difference at low airplane speeds, it will produce large suction values at high speeds. This may result in rapid deterioration of the gyroscopic instruments due to excessive rotor speeds. On the other hand, if the suction is adjusted to a proper value at high airplane speeds, at low speeds the instruments will not operate satisfactorily.

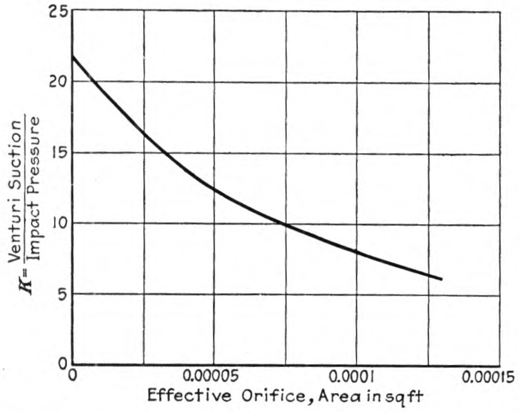

Fig. 7 Variation of Venturi Constant With Orifice Area for Double Venturi
(From wind-tunnel tests at Mass. Inst. of Tech.)

Fig. 8 shows the measured suction on a standard installation with the venturis mounted on the fuselage, in the slipstream, of an airplane with a cruising speed of 160 mph. It is evident that within the cruising range the suction supplied to the gyroscopic instruments was far too great. In such an installation some form of vacuum regulator certainly should be included in the system.

Suction Affected by Altitude. It is evident from Equation [2] that for the same air speed as indicated by a pitot-static meter, that is with $1/2\rho v^2$ constant, the pressure difference will be constant except for a second order variation with Reynold's number.[4] This means that if a venturi installation gives sufficient suction at stalling speed near sea level, it will give the same value for stalling speed at any altitude. In general, the suction supplied at a given indicated air speed will be the same for all altitudes. In other words, the venturi and instrument combination will operate satisfactorily at the higher altitudes providing the speed, as indicated by the air-speed meter, remains above the speed at which the instruments cease to function at sea level.

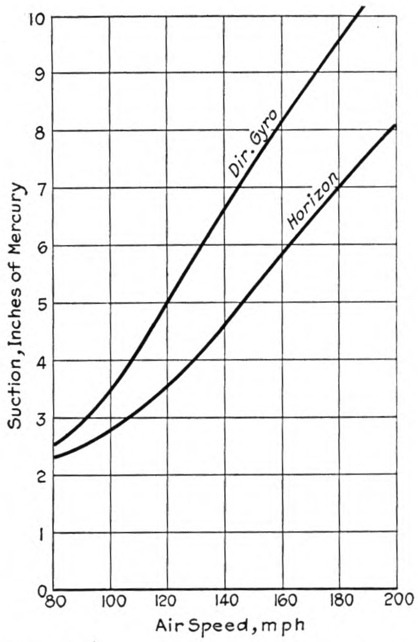

Fig. 8 Venturi Suction at High Speeds
(Venturi mounted on side of fuselage and operating an instrument.)

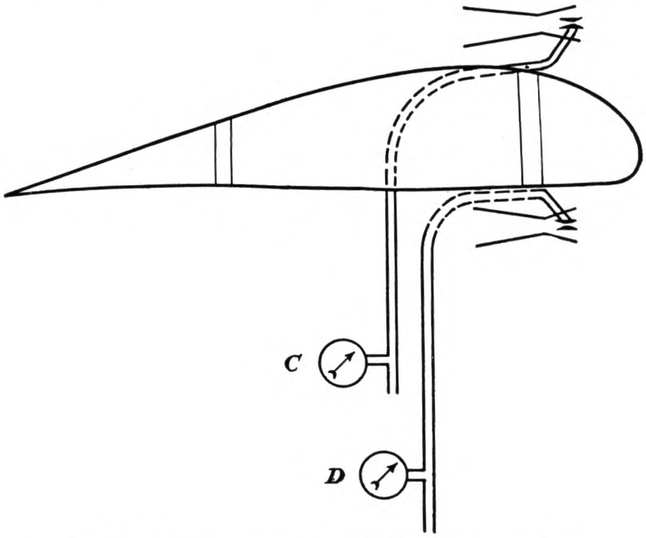

Fig. 9 Arrangement of Venturis for Flight Test

Effect of Location and Flight Conditions on Venturi Suction. Possible positions of venturi.

(1) On fuselage in slipstream
(2) On strut in slipstream
(3) Top of wing in slipstream
(4) Under wing in slipstream
(5) Above positions not in slipstream.

A series of flight tests were carried out by the writers with the cooperation of the Meteorological Department at the Massachusetts Institute of Technology. The purpose of these tests was to study the effect of various flight conditions on venturi operation. Two venturi positions were considered, one above the front wing spar and a second below the wing directly in line with the first. Both positions were well within the slipstream. Fig. 9

---

[5] "The Altitude Effect on Air Speed Indicators," by M. D. Hersey, F. L. Hunt, and H. D. Eaton. National Advisory Committee for Aeronautics, Technical Report No. 110.

is a diagram of the experimental arrangement. A moving picture camera was used to record instantaneous readings of the pressure gages C and D in addition to data supplied by the other instrument equipment of the airplane. The information used in plotting the curves of Fig. 10 was obtained by examination of the moving-picture-film record. Apart from influences of airspeed as discussed above, the effect of maneuvers on venturi performance may be analyzed into two components, one due to the slipstream and a second due to the effective yaw of the venturi with respect to the relative air velocity.

Slipstream Effect. The slipstream effect will be considered first. In general, the pressure difference supplied by the venturi will be:

$$\Delta p' = K' 1/2 \rho v_e^2 \qquad [3]$$

Where v_e is the effective velocity of the air past the venturi.

In practise v_e will be a function not only of slipstream velocity but also of local deviations of the air stream past parts of the airplane structure.

If the indicated velocity of the airplane is v the pressure difference furnished by a venturi without the slipstream and local effects would be:

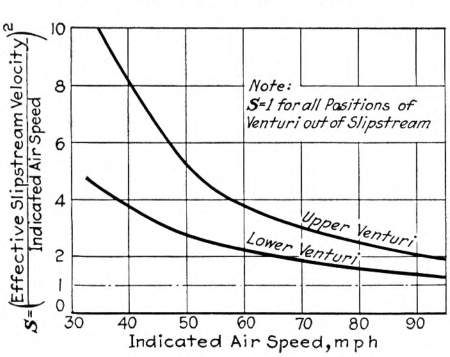

Fig. 10 SLIPSTREAM EFFECT ON VENTURI SUCTION
(Engine kept at constant throttle.)

$$\Delta p = K 1/2 \rho v^2 \qquad [4]$$

The ratio between $\Delta p'$ and Δp may be taken as a measure of the influence of slipstream and position on venturi operation, that is:

$$\frac{\Delta p'}{\Delta p} = \frac{v_e^2}{v^2} = \frac{\Delta p'}{1/2 K \rho v^2} = S \qquad [5]$$

Fig. 10 is a plot of S against indicated air speed for the tests mentioned above and from this it is immediately apparent that the venturi mounted above the wing profile is much better than that mounted below the wing. This result is readily understandable since air passing above the wing will be accelerated to a greater extent than the air which flows under the wing. The plot also shows the great advantage of a venturi mounted within the slipstream, since a pressure ratio of from 5 to 10 is obtained for a low speed climb where suction is especially valuable.

Effect of Yaw. Data taken from the motion-picture record indicated that slipping or skidding of the airplane has a pronounced tendency to reduce the venturi suction. A series of tests on a venturi was carried out in the wind tunnel at the Massachusetts Institute of Technology. This work showed that the suction for practical purposes is independent of yaw up to an angle of forty degrees.

It was found impossible to explain the flight results on the basis of the wind-tunnel tests. The authors feel that this difficulty may be cleared up easily by further flight tests. It is questionable, however, if this part of the problem is of sufficient importance to warrant the effort.

VENTURI DRAG

There remains to be considered the power required for the operation of the gyroscopic instruments by means of venturis.

Wind-tunnel tests showed that venturi drag increases with the square of the relative air velocity. This, of course, leads to the usual cube-law increase of power consumption with speed. Fig. 11 shows the power required by the venturi equipment for driving various combinations of the gyroscopic instruments as the airplane velocity is varied. The data used in plotting these curves are based on the assumption of venturis mounted within the slipstream.

Efficiency. It can be shown for the case of a venturi drawing air through a fixed orifice, that efficiency, on a basis of the ratio of power output to power required, is substantially independent of air velocity under conditions of constant density. This efficiency as experimentally determined lies in the range of from 1 to 2 per cent.

The considerable amount of power absorbed by a venturi is a serious disadvantage, especially for use on high-speed, long-range airplanes. For this reason, venturi installations for instrument operation should be limited to airplanes cruising at 120 mph or less. More efficient equipment is available, but the relatively small power loss (less than 2 hp) makes the desirability of added complication questionable.

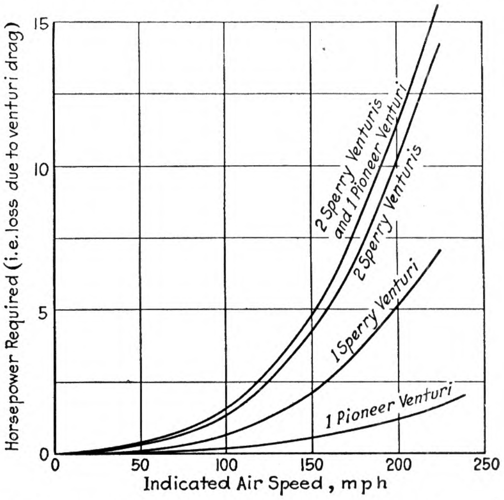

Fig. 11 HORSEPOWER REQUIRED VS. AIR SPEED

Ice Formation. During an extended series of flights carried out by the Meteorological Department at the Massachusetts Institute of Technology, it was found that under certain atmospheric conditions the venturi installation was rendered inoperative by ice formation. This problem is especially serious as it means that often the instruments will not be available when they are needed most.

It is possible to reduce the difficulties due to ice formation by mounting the venturis where they may receive heat from the engine exhaust. This may be accomplished by placing the venturis on the exhaust manifold itself or by allowing part of the hot gases to flow through the venturi throat. It was found in practise, however, that any simple arrangement for the use of exhaust heat did not prevent ice formation under severe conditions.

DISPLACEMENT PUMP

The problem of drawing air through a fixed orifice by means of a displacement pump has been studied theoretically. The pressure difference maintained by a displacement pump across the orifice is given by the formula[3]

$$\Delta p = \frac{\gamma p}{2} \times \left(\frac{1}{1 + \dfrac{(a\alpha)^2 \gamma R T}{(nv)^2}} \right) \cdots\cdots\cdots\cdots [6]$$

Where

Δp = pressure difference across orifice
p = atmospheric pressure
$a\alpha$ = effective orifice area
v = pump displacement per revolution
n = revolutions per second
T = temperature of atmosphere (absolute)
R = gas constant for unit mass of gas
γ = exponent of expansion process

This equation is valid for cases in which $(\Delta p)^2$ is small compared to p^2.

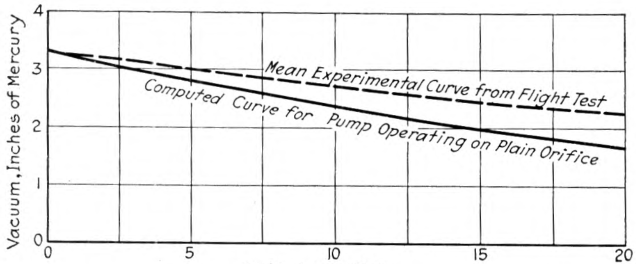

FIG. 12 RELATION BETWEEN VACUUM AND ALTITUDE FOR CONSTANT-SPEED, PROPELLER-DRIVEN, SINGLE-RECIPROCATING-VANE PUMP DRIVING DIRECTIONAL GYRO AND ARTIFICIAL HORIZON

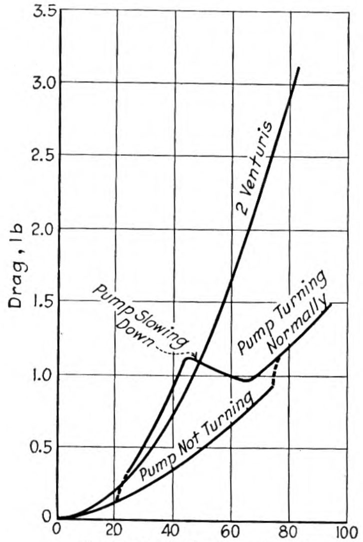

FIG. 13 COMPARATIVE DRAG CURVES FOR PROPELLER-DRIVEN, SINGLE-RECIPROCATING-VANE PUMP AND TWO VENTURIS

Experiment showed that this equation represents very closely the actual behavior of a pump-orifice system. In practise it was found that with γ equal to unity a good check was obtained. Physically this means that the expansion process was almost isothermal. This is the result to be expected in the case of a well-cooled pump and exposed copper-tube connections.

Types of Pumps and Pump Drives. The various types of pumps can be listed as follows:

(1) Piston pump
(2) Multiple rotating vane eccentric
(3) Single rotating vane
(4) Single reciprocating vane
(5) Gear
(6) Roots blower

The different methods of driving the pumps are:

(1) Propeller drive
(2) Electric motor drive
(3) Engine drive.

It is not the intention to discuss all the different types of pumps. Certain examples only will be considered below.

The pressure-altitude plot shown in Fig. 12 is a comparison of flight test results on a constant-speed, propeller-driven, single reciprocating vane pump with corresponding values calculated by formula [6]. In this case the pump was operating both an artificial horizon and a directional gyro. The theoretically predicted curve falls somewhat below the empirical points. This discrepancy has been shown to be due to a variation in effective orifice area of the instruments caused by the presence of the rotor.

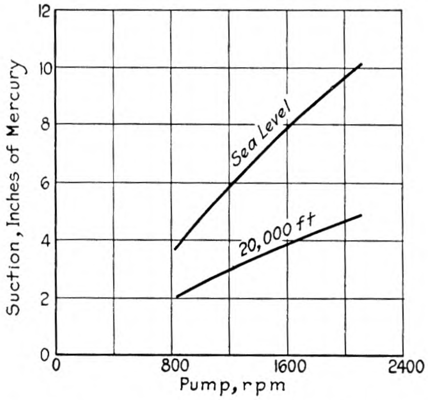

FIG. 14 RELATION BETWEEN PUMP SUCTION AND RPM FOR MULTIPLE-ROTATING-VANE ECCENTRIC PUMP
(Sea level and 20,000 ft altitude.)

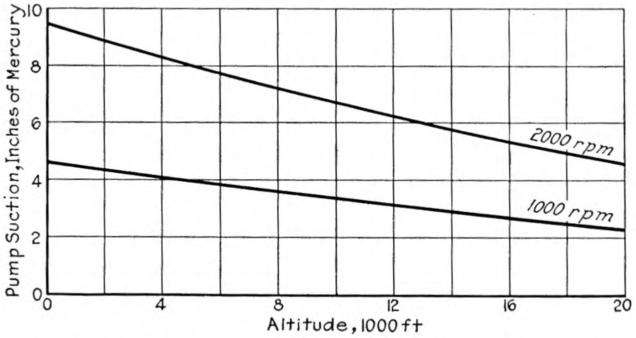

FIG. 15 RELATION BETWEEN PUMP SUCTION AND ALTITUDE FOR MULTIPLE-ROTATING-VANE ECCENTRIC PUMP FOR TWO ENGINE SPEEDS
(Pump operating on orifice equivalent to directional gyro and artificial horizon. Assumed volumetric efficiency = 70 per cent.)

If this effective orifice variation is taken into account,[3] a much better check is obtained but in the interest of brevity the data are omitted here.

Fig. 13 shows a comparison between the drag of a venturi installation and the drag of a propeller-driven pump. These tests were carried out in the Massachusetts Institute of Technology wind tunnels. It was found that the blade element contributed little to the drag. The mounting and the pump housing caused the major portion of the resistance at all air speeds above 65 mph.

Fig. 14 is a plot of the relation between pump suction and rpm at sea level and 20,000 ft altitude for a multiple rotating vane eccentric pump. A pressure release valve was furnished with this pump to limit the pressure to 4 in. of mercury. Fig. 15 shows the relation between suction and altitude for two engine speeds, the pump operating on an orifice equivalent to the directional gyro and the artificial horizon.

CARBURETOR DROP

One of the essential functions of an aircraft engine is that it must pump through itself the air required for combustion of the fuel. For any aircraft engine the total volume of air handled per unit time is very large compared to the quantity of air flowing through the gyroscopic instruments in the same time.

In general, for an engine with a brake thermal efficiency of 25 per cent, estimated on the basis of air consumption, and using a hydrocarbon fuel, the air requirement is about 1.8 cfm per hp. Thus the amount of air that an engine delivering 100 horsepower will draw through itself is about 180 cfm. The air flow through a complete set of gyroscopic instruments is about 3 cfm. These data show that the use of the carburetor drop for gyroscopic instrument drive will affect the air flow by less than 2 per cent for a 100-hp output and consequently less than 0.5 per cent on a 400-hp output. In any case, the air entering the manifold through the instruments may be easily compensated for by use of the carburetor adjustment.

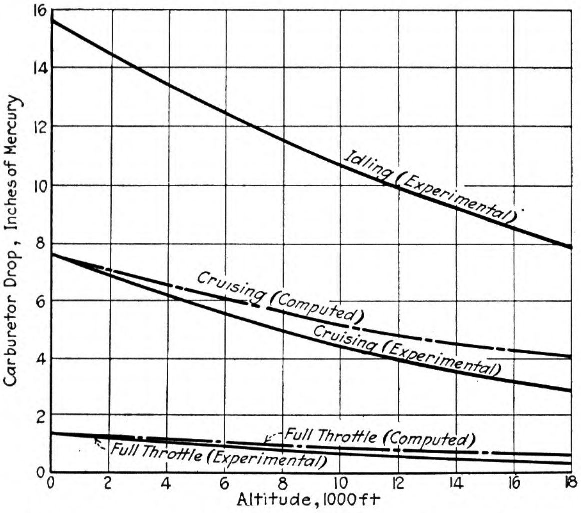

FIG. 16 CARBURETOR DROP VS. ALTITUDE AT VARIOUS THROTTLE POSITIONS

In the engine carburetor there is always a certain pressure drop through the choke and throttle assembly. A very desirable simplification would result if a satisfactory vacuum supply could be derived from this carburetor pressure drop.

In this discussion care has been taken to specifically consider pressure drop through the carburetor only. It is obvious that Diesel engines and engines using fuel injection with no air throttle are not available as sources of vacuum for instrument drive.

Fig. 16 indicates the results of a flight test made for the purpose of determining the variation of carburetor drop with throttle setting and altitude. Evidently the available vacuum is too low at full throttle and much too high with closed throttle for satisfactory instrument operation. Under cruising conditions the pressure difference is somewhat higher than the normal value for the gyros.

The data outlined indicate that a connection to the intake system just above the throttle will serve as an excellent source of vacuum under cruising conditions. However, the high pressure-drop existing at closed throttle makes it imperative that some sort of pressure regulating valve be included in the system as a protection for the instruments. Such an installation is inexpensive and reliable but has the serious disadvantage of becoming inoperative as the engine reaches its maximum output. This feature would eliminate the scheme from consideration for airplanes which must make long flights at full throttle. However, under conditions which require full throttle operation for short periods only, the momentum of the gyro wheels will keep the instruments in operation during the low-vacuum intervals.

CONCLUSION

There remain to be considered briefly the relative merits of the three sources of suction for gyro-instrument operation.

In point of satisfactory operation over the entire range of flight conditions, a suitable displacement pump is undoubtedly superior to either the venturi or the carburetor drop arrangements. It seems reasonable, therefore, to expect that the final solution of the instrument drive problem will be some form of displacement pump.

From the standpoint of installation, the venturi, the propeller-driven pump, and the manifold vacuum-control valve present about equal advantages. The engine-driven pump may be difficult to install properly on an engine not specially fitted for the purpose.

Considering the matter of efficiency, the venturi is undoubtedly the least desirable of the three vacuum sources.

In the case of a manifold connection the useful work obtained in driving the gyroscope rotors does not reduce the output from the aircraft engine. Consequently the overall efficiency may be considered as infinitely great.

No data on the power requirements of engine-driven pumps were available so that no numerical estimate of efficiency for this system is given here. It seems certain, however, that the power absorbed by a displacement pump will be negligible compared to the output of the modern airplane engine.

ACKNOWLEDGMENTS

In conclusion the writers wish to express their appreciation of the many courtesies extended by the staff of the Department of Aeronautical Engineering at the Massachusetts Institute of Technology.

A number of the experimental results are published through courtesy of the Sperry Gyroscope Company. In particular, the writers wish to extend their thanks to Messrs. E. A. Sperry, Jr., and P. R. Bassett of that company, both of whom have shown helpful interest in the present work.