The Electric Variometer

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Summary

The performance of existing variometers is first considered in relation to the size and shape of typical thermals, the performance of a modern glider, and the reaction time of the pilot. The need for an electric instrument is shown.

Two basically different ways of using thermistor beads to measure speed and direction of airflow from a flask are considered, with equations and practical curves relating output to airflow. Some practical arrangements for getting the required sensitivity are shown. It is then shown how to calculate lag in the airflow through the variometer, and in the heat flow from the beads, and other lags.

Simple arrangements for checking the performance of a variometer on a test bench and in a car are described in detail. The performance of different static and total-energy systems is compared in theory and practice, and the full specification of the Crossfell variometer* is given.

Reference

[1] «The Convection of Heat from Cylinders in a Stream». L. V. King, Phil. Trans. Roy. Soc. A 214, pp. 373–432, May 1914

Introduction

It is of critical importance to a pilot soaring in a glider to have a rate-of-climb meter which is both sensitive and rapid. This instrument is called a variometer because it acts by detecting the rate of variation of static pressure in the glider. A new type of variometer has been developed using an electrical sensing element and a small transistor amplifier which drives a milliammeter. Before considering its design, the performance of existing instruments can be compared with the conditions the glider is likely to meet and the reactions of the pilot, in order to establish the ideal specification for a variometer.

A glider flying at 27 m/sec (50 knots) passes right through the centre of a thermal of diameter 150 m (480′) in 5.5 secs. On its first pass, it is likely only to go through the outside fringe of the lifting area; not only is the air here not moving up so fast, but the glider is in it for a much shorter time. Such small thermals are perhaps the hardest form of "lift" for a pilot to use, so it is reasonable to tailor a variometer to make this as easy as possible.

The first thing to consider is the speed with which the pilot can react with his hands to information read from a moving needle. This situation is similar to the driver of a car approaching an unexpected corner at night. Our experiments with glider pilots suggest that reaction is improved as the lag (or "time constant") of the indicator is reduced towards ½ sec, but that with smaller lag the eye is unable to interpret the movement of the needle and the pilot gets confused. Therefore a variometer of time constant between 1 and ½ sec is needed. Reaction is also improved as the indicator movements are made larger; so that it is useful to be able to change the sensitivity for different flight conditions in order to get easily visible movement all the time.

* Available from Crossfell variometers, 1 Lyndale Avenue, London, N. W. 2. England

Mechanical variometers have been considerably developed in the last few years. A good modern specimen may have a full scale sensitivity of 5 m/sec with a lag of about 3 sec. It is then necessary to have a second variometer on the instrument panel to give readings under exceptional lift—inside cloud, etc. An electric variometer can be switched to give either 3 or 9 m/sec sensitivity, with a lag of between 0.5 and 0.9 sec (or much less if required). Under some conditions of rough lift more lag is an improvement: a switch can be fitted to increase the damping at will to 3 secs or more.

A simple further development is to make the variometer present its information as a changing audible note. It seems likely that a pilot could respond via his ears to an instrument with even less lag, thus picking up lift even more quickly.

The electric variometer

The difference in performance between a mechanical and an electric variometer is shown graphically in Fig. 1. This shows first of all a possible curve (a), of vertical airspeed against horizontal distance for the thermal mentioned before, of 150 m diameter. To make calculation easy, this has been simplified into the crude steps of (b). A glider falling at a constant speed through the air in which it flies, and having negligible inertia, would have a true vertical speed of (c). Then a good mechanical vario would indicate (e) and an electric vario (d). A pilot who would act at time E with the first vario will act at time D with the second; thus giving himself and his machine much longer to enter a suitable steep turn.

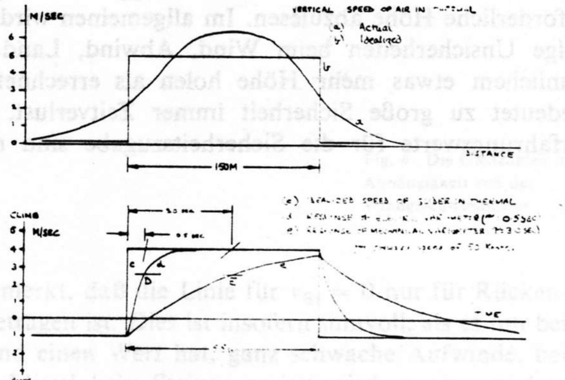

Fig. 1

There are various ways of detecting change in static pressure electrically. The "Crossfell" variometer, like ordinary ones, measures the small air flow in and out of a flask as it is raised and lowered in the atmosphere. This air flow is quite hard to detect, since a rate of climb of 0.5 m/sec produces a flow of only 0.026 cc/sec at ground level from a ½ litre flask. The air is made to flow over small beads warmed by an electric current. These beads are made of a semi-conductor material similar to that in a transistor, and their resistance changes very rapidly with temperature (about 5% per deg. C). These "Thermistor" beads are used in a Wheatstone bridge circuit, so that the small airflow, cooling the beads, produces an unbalance current. This is amplified about 10 times by transistors, and is then used to deflect a milliammeter which can be scaled directly in rate-of-climb units.

The design problem is not unlike that of a sensitive anemometer, although it is more difficult since direction as well as speed of the airflow must be indicated, to distinguish between rise and fall. This means that more than one thermistor bead must be placed in the airflow, and the difference of temperature (or resistance) between two beads measured.

Basically, there are two ways of producing such a differential change in resistance:

(a) The air flows at the same speed over each bead, but is warmer when it flows over one than when it flows over the other.

(b) The air flows at the same temperature over each bead, but is made to flow faster over one bead than the other.

With care, it is possible to make the difference in air temperature, or in air speed, between the two beads, proportional to the rate of volume flow through the instrument. In this way the current from the thermistor bridge can be made proportional to rate of climb (i.e. a straight-line scale for the variometer) over a fairly wide range.

Shape of scale for a hot-bead variometer

The ideal scale for a variometer would probably be a linear one from zero to 3 m/sec, either rise or sink, becoming logarithmic for larger speeds—although indication of large rates of sink is of little or no value to a soaring pilot. In this way, changes in sink when entering weak lift would show up well, yet it would still be possible to centre on a source of quite strong lift without changing the range. Such a scale is illustrated in Fig. 2.

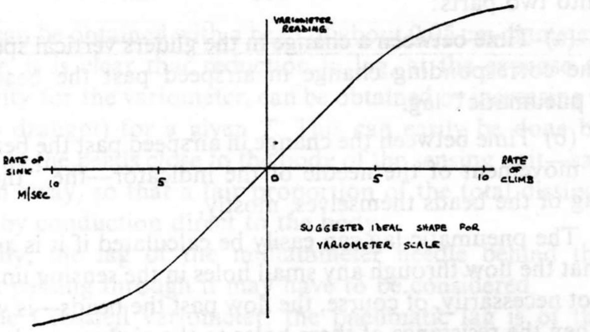

Fig. 2

Scientific prediction of a curve like this from a knowledge of the beads and their temperature is a particularly difficult problem. This is because the pattern of heat flow from the beads cannot be calculated for any but extremely simple, accurately known, patterns of air flow around them. In practice, the air flow patterns themselves have to be made so complicated that even they cannot be calculated in terms of volume flow through the instrument. Nevertheless, it is worth considering two highly simplified models, which indicate the correct trends, at least.

First, the dissipation of a small, isolated, round bead in still air due to conduction only is

$$W = 4 \cdot \pi \cdot k \cdot a \cdot T$$

where $k =$ thermal conductivity of air,
$a =$ radius of bead,
$T =$ excess temperature of bead,

providing convection currents are ignored. So for a bead of diameter 0.066 cm (a typical figure) and an excess temperature of 100 deg. C

$$W = 4 \times 3.14 \times 0.237 \times 0.033 \times 100 = 10 \text{ milliwatts}$$

This shows that even for the smallest beads available, care must be taken to see that the hot beads do not warm up the bulk of air in the flask appreciably. The excess temperature must be kept above 100 °C if possible, to minimise the effect of changes in air temperature on the scaling of the instrument. In general, the smaller the beads, the easier it is to make a satisfactory instrument, though when you have finished it, you are likely to be too cross-eyed ever to fly a glider straight again!

Second, it is possible to calculate the heat loss from a long wire being cooled by a transverse air flow. This was done in a classic investigation by L. V. King in 1914—Ref. 1—who, for a streamline flow, obtained and verified the law

$$W = (k + 2\sqrt{k \cdot s \cdot p \cdot a \sqrt{V}}) \times T \text{ per unit length of wire}$$

where $V =$ velocity of airflow
$k =$ thermal conductivity of air
$s =$ specific heat of air
$p =$ density of air

$$= (0.237 + 1.66\sqrt{aV}) \times T \quad \text{milliwatts/cm in c.g.s. units}$$

provided $V \cdot a > 0.0093$ cm/sec

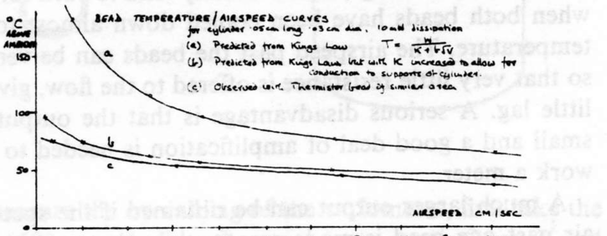

Fig. 3

Absolute values of dissipation calculated from this relation for a short cylinder roughly the same size as the bead above indicate that $W = 10$ milliwatts for 430 °C excess temperature and an airspeed of 1 cm/sec. Thus the absolute values can only be taken as correct to an order of magnitude. Nevertheless, if W is assumed constant—this is nearly true since the electrical power supplied to the bead can be made to vary little with its temperature—and King's law is used to deduce the relation between T and V, a curve is obtained (see Fig. 3) whose shape agrees well with that found in practice. From this, the resistance/airspeed curve can be deduced for a given Thermistor bead.

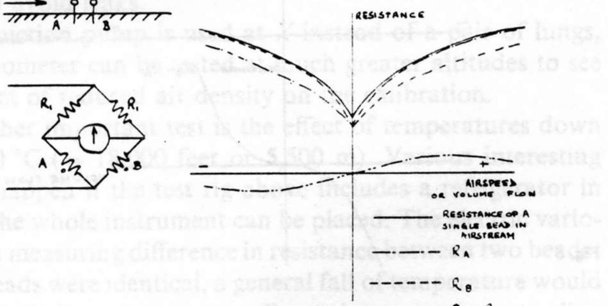

Fig. 4

When two beads are used in a bridge circuit, the output curve is obtained by subtracting the resistance/airspeed curve of one bead from that of the other, if the airspeed past the two beads is different. This approach is used in considering practical arrangements of beads below.

Fig. 4 shows a variometer "sensing unit" based on principle (a) above. The airflow from the flask passes at the same speed over each bead. If the beads were very far apart, the resistance/airspeed (R/V) curve for either is line A. If now the beads are put close together, the second bead is surrounded by air which is slightly warmer because of the heat picked up by the flow from the first bead. The R/V curves for the two beads are now different, as in line B: in effect, some of the heat lost by the first bead has been transferred to the second. The output current, proportional to $Ra - Rb$ if R is large, is line C. In this type of sensing unit, it is easy to make the airspeed V closely proportional to rate of climb, so that line C also represents the calibration curve of the variometer, i.e. output current/rate of climb.

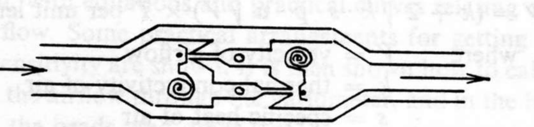

Fig. 5

This arrangement is attractive because it gives a nearly linear relation for small rates of climb; moreover, this becomes logarithmic for rather larger speeds since the output must stop increasing (and eventually tend toward zero again) when both beads have been cooled down almost to the air temperature. The airspeed past the beads can be very small, so that very little resistance is offered to the flow, giving very little lag. A serious disadvantage is that the output is very small and a good deal of amplification is needed to make it work a meter.

A much larger output can be obtained if the speed of the air past one bead is made greater than that past the other. The simplest way to visualise doing this is to use valves which divert air flowing one way through the sensing unit through a different channel to air flowing the other way—Fig. 5. However, such a device would involve highly delicate moving parts, and throws away most of the advantages of an electric instrument.

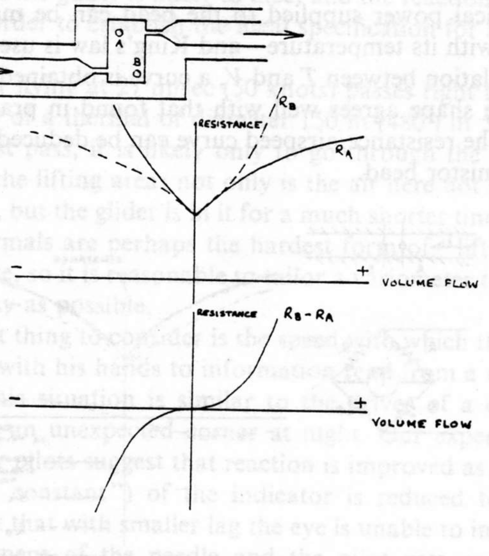

Fig. 6

A better way of obtaining a difference in speed is to use jets (Fig. 6). The disadvantage of this method is that there must inevitably be a range of very small airflows for which the flow is purely viscous, in which case the jet cannot form and the airspeed past each bead is the same, giving no output at all. It is only when the airflow rises sufficiently to make the momentum (inertia forces) of the air emerging from one of the fine holes large compared with the viscous forces—i.e. Reynold's No. greater than 1—that a jet develops around one bead only, cooling it very much more than the other. This means that if small rates of climb are to be measured at all, either a large flask or very small holes must be used.

For example, for a rate of climb of 0.5 m/sec and a ½ litre flask the flow rate is 0.026 cc/sec, as mentioned before. For a Reynold's No. of 10, the required hole diameter d is given by

$$10 = \frac{4 \times 0.026 \times d}{\pi d^2 \times 0.14}$$

where 0.14 is the kinematic viscosity of air, so that

$$d = 0.025 \text{ cm}$$

A hole of this size is accelerating the airflow to 50 cm/sec; so it can be seen that once a jet has been formed, the airspeed is fast enough to cool a bead placed in it quite drastically, and very large outputs can be developed before the temperature of the bead finally falls to that of the air.

The disadvantages of this arrangement are that the fine holes can easily become partly blocked, that they can introduce quite a serious constriction between the flask and the atmosphere, with corresponding lag and, perhaps most serious, that the output curve—Fig. 6—is never linear and has a shape opposite to what is wanted, for the smaller airflows in particular: As can be seen, the sensing unit becomes more sensitive rather than less sensitive as the rate of climb increases.

Prediction of Lag in a hot-bead variometer

The lag in response of an electric variometer can be divided into two parts:

(a) Time between a change in the gliders vertical speed and the corresponding change in airspeed past the beads—the "pneumatic"-lag.

(b) Time between the change in airspeed past the beads and a movement of the needle of the indicator—the "thermal" lag of the beads themselves, mostly.

The pneumatic lag can easily be calculated if it is assumed that the flow through any small holes in the sensing unit—but not necessarily, of course, the flow past the beads—is viscous. Then the resistance of these holes to the airflow can be calculated from

$$r = \frac{8\,\mu\,L}{\pi\,a^4}$$

where r is the resistance of a constriction of length L and radius a, and μ ist the viscosity of air. For a flask of capacity C and a constant resistance r, the lag will be a simple time constant t given by

$$t_1 = \frac{r\,C}{P} \text{ secs}$$

where P is atmospheric pressure (see Appendix).

For example, considering the 0.025 cm diameter hole mentioned above, drilled through a 1 mm thick plate, with a ½ litre flask,

$$t_1 = \frac{8\,\mu\,C\,L}{\pi\,P\,a^4} = 0.95 \text{ secs}$$

This shows that the particular design of jet-type sensing unit considered above would be useless because of its large pneumatic lag; the remedy would be to use a flask of, say, double the size, keeping Reynold's No. for the jet the same by doubling the jet-hole diameter. Then the lag would be reduced by a factor of 8.

The thermal lag, or time taken for the temperature of the beads to follow a change in airspeed through the unit, can also be calculated (see Appendix) in terms of the excess temperature of a bead, its heat capacity, and the characteristics of the electrical heat supply to the bead. This lag is not a simple decay; in other words the "time constant" alters with the temperature of the bead. For small changes about a mean temperature T the time constant is t_2, where

$$t_2 = \frac{D\,T}{S} \text{ secs}$$

for a constant electrical input power S to a bead of heat capacity D and mean excess temperature T, or

$$t_2 = \frac{D\,T}{I^2\,R_0} \text{ secs}$$

for a constant input current I to a bead whose resistance at air temperature is R_0. An arrangement giving roughly constant input power to the beads would be that of Fig. 4 if the upper resistances in the bridge are made equal to the bead resistances with no draught through the sensing unit.

Since T falls with increasing airflow, this relation shows that the electric variometer recovers more rapidly from large deflections (from 10 to 1 m/sec, say) than from small ones (1 to 0.1 m/sec)—all time constants quoted elsewhere are for small deflections about zero sink, i.e. the slowest possible. It also shows that to achieve a thermal time constant of about 0.2 secs with, for example, a heating power of 10 mw and excess bead temperature of 100 °C, the heat capacity of the bead D should be only

$$D = 0.2 \times \frac{10 \times 10^{-3}}{4.2} \times \frac{1}{100} = 5 \times 10^{-6} \text{ calories/deg. C}$$

which can be obtained with a bead of about 0.05 cm diameter. Further, it is clear that reduction in lag, at the expense of sensitivity for the variometer, can be obtained by increasing S (for no draught) for a given T. This can easily be done by mounting the beads close to the body of the sensing unit—say 0.05 cm away, so that a fair proportion of the total dissipation is by conduction direct to the body.

Finally, the lag of the milliammeter needle behind the current passing through it may have to be considered.

In the Crossfell variometer, the pneumatic lag is of the order of 0.2 secs, and the thermal and mechanical lag 0.4 secs, although in early experiments both these were halved to see if any advantage resulted. The damping switch which can be fitted for use in rough lift operates a large condenser which increases the overall lag from about 0.6 secs to 2.0 secs.

It is often supposed that an appreciable lenght of rubber tubing between bottle and instrument introduces extra lag. This is not so. Applying the formula for pneumatic resistance of a tube once more, it is found that 0.5 cm diameter tubing only adds lag at the rate of 0.016 secs per metre run, for a ½ litre flask.

Some simple tests for measuring variometer performance

Variometers are often checked by the tedious method of timing a descent of, say, 100 m in the glider. It is easy to build a very simple altitude chamber which does the job much more quickly and accurately—see Fig. 7. A 5 gallon (20 litre) drum is sucked out via the tap X until the altimeter B reads about 500 m, or your lungs burst. Sucking is better than blowing, since it keeps cool dry air in the drum and the instruments instead of warm hot breath. The tap X is then shut. The altimeter will fall steadily for a few seconds as the air in the drum goes on expanding due to heat flowing in through its walls, but then comes to rest. The tap Y is then opened until the altitude is changing fast enough to give a certain reading on the variometer. The altitude is noted and the stopwatch started. The tap is opened progressively to keep the variometer deflection steady until the altitude has fallen by 100 m, when the stopwatch is read. In this way, any point on the scale of the variometer can be calibrated as accurately as the altimeter and stopwatch allow.

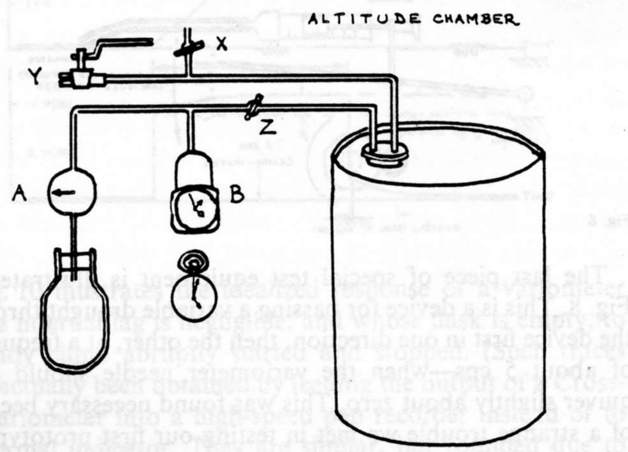

Fig. 7

To measure the overall lag of the variometer, first take the drum to 500 m and allow the pressure to settle. Open Y and adjust the leak to give a deflection of 2.7 on the instrument. Quickly shut Y and see how long the variometer takes to fall to 1.0. This time, in seconds, is the time constant of the instrument over the range of deflections checked. With an electric variometer the drop from 2.7 to 1 may be too rapid to measure easily; in this case it is better to time it from 2.7 to 0.37 and divide this time by 2.

The pneumatic lag can be eliminated by repeating the process, but shutting the tap Z. This leaves the thermal and mechanical lags only.

Note that this test rig is different from an actual flight in that pressure corresponding to the whole altitude is applied between the inside and the outside of the variometer. This means that the sealing of instrument and bottle must be very good to avoid leaks.

If a suction pump is used at X instead of a pair of lungs, the variometer can be tested at much greater altitudes to see the effect of reduced air density on the calibration.

Another important test is the effect of temperatures down to —20 °C (= 18,000 feet or 5,500 m). Various interesting things happen if the test rig above includes a refrigerator in which the whole instrument can be placed. The electric variometer is measuring difference in resistance between two beads: if the beads were identical, a general fall of temperature would increase their resistance equally and no spurious reading would result. But the beads can never be made quite identical, so that there is always a small drift of the zero point of the variometer at extreme temperatures. The drift between 15 °C and —20 °C averages less than 0.1 m/sec in the Crossfell variometers being produced; lower drifts still can be obtained by complicated electronic feedback arrangements.

The second temperature-effect is that the bead temperature generally does not fall so much as the air temperature, since it is difficult to keep the electrical power fed to the beads precisely the same as their resistance varies. Application of King's Law shows that if this power varies by, say 10% over a certain temperature range, the calibration of the variometer will also change by roughly the same percentage. This means that as air temperature falls with increasing height, the variometer will tend to become more sensitive; however, this gain in sensitivity is partly offset by the fall in air density with altitude so that the overall effect is not too serious.

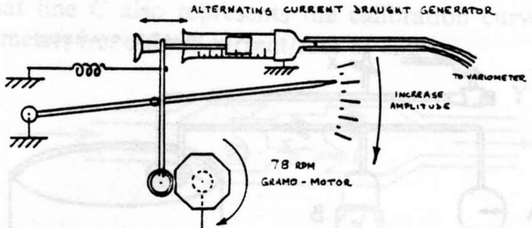

Fig. 8

The last piece of special test equipment is illustrated in Fig. 8. This is a device for passing a variable draught through the device first in one direction, then the other, at a frequency of about 5 cps—when the variometer needle should only quiver slightly about zero. This was found necessary because of a strange trouble we met in testing our first prototype in the air. It behaved excellently on the ground and in lifts, but as soon as it was flown on a Total Energy venturi it always showed 3 m/sec climb—even after the strictest attention to sealing the instrument. Some hopeful circles in the glider merely produced a sharp fall on the altimeter; the variometer was useless. The trouble turned out to be the presence of fluctuating draughts, due to the turbulent output of the venturi. These fluctuating draughts through the variometer were found to be many times the steady flow corresponding to 3 m/sec full scale deflection; they affected the instrument in much the same way as a really drastic fall in air temperature by cooling both beads a great deal. Later designs were made quite insensitive to this treatment. However it is most important to try the effect of a fluctuating airflow on any electric variometer expected to work from a Total Energy venturi.

Total Energy compensation

There are two total energy systems which have been widely used with electric variometers: the venturi, whose suction is differentiated by the capacity of the flask to give a flow proportional to rate of change of glider airspeed, and the rubber (or metal bellows) diaphragm whose stiffness differentiates pitot pressure to produce a similar flow. In the first system the pressures due to changing height and changing airspeed are subtracted, and their difference drives the "total energy" flow through the variometer. In the second, flows proportional to changing height and airspeed are subtracted and the difference flow passed direct through the variometer to the static head (see Fig. 9).

The venturi system is tending to be replaced by the diaphragm system for several reasons. These include the inelegance of a protruding venturi compared with a pot pitot and static vents which have to be there anyway, its liability to ice up, and the turbulent output of a venturi. This serves to give the mechanical piston type of variometer a really good automatic shaking which saves the pilot the need to do it himself; but an electric variometer, although it can be made not to give spurious readings under these conditions, will nevertheless respond to the slower fluctuations faithfully, to the possible confusion of the pilot.

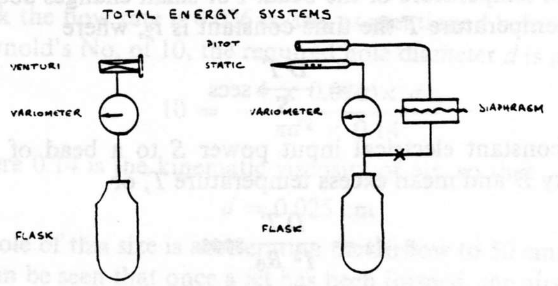

Fig. 9

On the other hand, it is easy to show that while the compensation of the venturi is exact in spite of increasing altitude, the compensation of the diaphragm is not, since the compliance of the diaphragm

$$\frac{dV}{dp} \text{ should ideally } = \frac{C}{P}$$

where P is the atmospheric pressure at the height of the glider, and C is the capacity of the flask. Thus a diaphragm which is correct on the ground under-compensates by half at 18,000 feet (5,500 m) while the venturi (if not iced-up) will be compensating correctly. Stiffening of the rubber diaphragm due to low temperatures may further reduce the compensation. It is an interesting advantage of the diaphragm system that a constriction at the point X can be used to damp slightly the response of the Total Energy compensation without damping the up/down response of the variometer.

Complete checks of a total energy system at ground level can be made by fixing pitot and static, or venturi heads to a suitable streamline point on a motor car and connecting them to the variometer. The driver gets the car up to, say 75 km/h and sets a hand throttle to a fixed opening. He then studies the behaviour of his variometer minutely on a road with plenty of small hills, hoping no-one is coming the other way. The variometer reading should be steady in spite of the rise and fall of the road and the compensation adjusted until it is.

Future developments in variometer design

As far as the calibration of an electric variometer goes, there is still room for improvement in accuracy of calibration over varying air temperatures and densities. If this was improved. and a damping switch giving a lag of 2 or 3 seconds was fitted as standard to electric variometers to smooth out most of the unsteadiness of lift in thermals when accurate readings are being taken, there seems no reason why a best-speed-to-fly calculator ring of the type due to Mac Cready should not be built into the milliammeter dial, with markings to suit the polar curve of various gliders. It may also prove possible to make an electrical Total Energy attachment which measures the difference between pitot and static pressure electrically. and differentiates it with a condenser, although this system would have only a small advantage over the diaphragm method.

For competition flying it may well be found an advantage to make the variometer audible rather than visible, thus reducing the possibility of collision in thermals overpopulated with pilots concerned too much with a dial on their instrument panel, as well as possibly reducing the reaction-time of a pilot entering weak lift.

Acknowledgement

Calculations of pneumatic lag, total energy compensation, and some other matters in this paper were done by my colleague P. J. Bulman. It was his idea in 1958 to start designing a new electric variometer, which eventually became the Crossfell.

Appendix

1. Pneumatic lag

Assume an isothermal expansion of air in the flask. Then if p, v are the pressure and volume of a certain mass of air,

$$p \times v = \text{constant}$$

Therefore $$dv = \frac{v \times dp}{p}$$

Now let p = excess pressure in flask above an atmospheric pressure P. Then volume of air expelled in time dt from flask of capacity C, by a change in pressure dp is:

$$\frac{C \times dp}{P} \text{ cc}$$

The volume flow through the variometer, of pneumatic resistance r, is:

$$\frac{p}{r} \text{ cc/sec}$$

So

$$\frac{C}{P}\frac{dp}{dt} - \frac{p}{r} = 0 \text{ for small changes in pressure c.f. } P$$

Therefore $$p = \text{const.} \times e^{-\frac{P}{rC}t}$$

i.e. a time constant $$t_1 = \frac{rC}{P} \text{ secs}$$

2. Thermal lag

Assume King's Law:

Heat loss from cylinder $= (k + b\sqrt{V})\,T$

Then for a constant electrical input power S to cylinder, the rate of change of stored heat must equal rate of heat supplied, less the rate of heat lost:

$$D\frac{dt}{dT}\; S + (k + b\sqrt{V})\,T = 0$$

Therefore

$$T = \text{const.} \times e^{-\frac{(k + b\sqrt{V})}{D}t} + \frac{S}{k + b\sqrt{V}}$$

i.e. a time constant

$$t_2 = \frac{D}{(k + b\sqrt{V})} \text{ secs}$$

for small changes in air velocity about a mean value V. But after a long time,

$$(k + b\sqrt{V})\,T = S$$

so the time constant can be rewritten in terms of the mean temperature T

$$t = \frac{D\,T}{S}$$

The capacity flask

The flask must of course be a Thermos type to avoid spurious response to changing external temperature. Some disagreement exists, however, as to whether it is worthwhile loosely filling the flask with wire wool, in order to ensure that expansion (or compression) of air in the flask takes place at constant temperature.

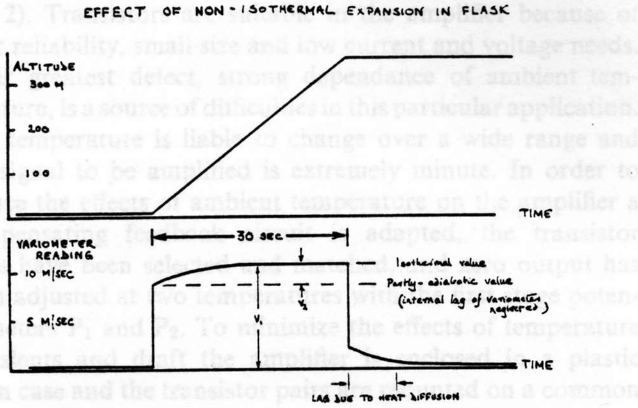

Fig. 10

Fig. 10 illustrates the idealized response of a variometer whose internal lag is negligible, and whose flask is empty, to a steady climb abruptly started and stopped. (Such traces have actually been obtained by feeding the output of a Crossfell variometer into a high-speed pen recorder instead of to its normal indicator. They are similar, but rounded due to the internal lag.) The variometer reading rises rapidly to a large fraction of its final value, and then rises more slowly towards its correct value as the air in the flask settles to some steady temperature rather below that of the inner wall of the flask. When the climb stops the air in the flask does not abruptly stop expanding, but warms up in the course of a few seconds until it again reaches the wall temperature. Since the heat capacity of the glass wall is much greater than that of the air inside, it can be assumed that the wall temperature is the same throughout the process.

Theoretically, the residual indication v_2 should be less than

$$\frac{\gamma - 1}{\gamma} \times v_1$$

where γ = ratio of specific heats giving v_1 less than 2/7 v_1, for air.

Its decay depends on how quickly heat diffuses inward from the cylindrical inner wall of the flask to warm the body of air inside. We have been unable to solve the general diffusion equation for this geometry, but a rough estimate based on diffusion from a flat surface suggests a diffusion lag of several seconds. This will be the duration of the spurious "*UP*" reading after a sudden climb—e.g. a winch launch.

From measurements with a Crossfell and recording milliammeter while simulating a winch launch to 300 m in 20 secs, it was found that v_2 is about 2 m/sec decaying with a 5.6 sec time constant. After 10 secs the residual reading with an empty flask is 0.5 m/sec, compared with 0.15 m/sec for a similar flask lightly filled with wire wool.

Such a reduction of residual reading is probably only just noticeable in normal use, since even in a winch launch the rate of climb does not fall abruptly to zero, but tails off gradually over the last 5–10 secs. Wire wool in the flask can lead to the danger of small metal bits emerging and getting lodged in the variometer; and on balance is thought hardly worthwhile.

(Swiss Aero-Review 1961/6)