A NEW INSTRUMENT FOR FUEL CONSUMPTION MEASUREMENT IN LIGHT AIRCRAFT AND MOTORGLIDERS

by Piero Morelli - Dipartimento di Ingegneria Aeronautica e Spaziale,
Patrizio Nuccio - Dipartimento di Energetica, Politecnico di Torino

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Summary

An original instrument for fuel consumption measurement in reciprocating internal combustion spark ignition engines for light aircraft and motorgliders has been developed and built. It is based on the detection of two parameters. the engine rotational speed and the manifold pressure. The aim of the instrument is to provide a "fuel consumption index" which can be utilized both in "Economy Air Race" competitions and during cruising flight. The instrument is not intended to replace the usual onboard fuel level gauge, but could be used to integrate the flight information with the instantaneous fuel consumption or even with the cruising range indications.

Some results of fuel consumption measurements, from both computer simulation and experimental tests, are first presented and then discussed. These were obtained with the instrument installed on the engine during bench tests. Some flight tests were then carried out with the instrument installed on a light aircraft in order to evaluate the instrument response under real operating conditions. The first results thus obtained encourage further development of the instrument.

1. Introduction

Over the last twenty-five years fuel cost has become an important item in the breakdown of aircraft direct operating costs. Because of the limited availability of oil, its increased cost and the polluting effects on the atmosphere, aircraft design is affected, today much more than in the past, by the requirement of low fuel consumption.

The aerodynamic improvement of the aircraft, the reduction of the operational empty weight, the improvement of engine performance and the introduction of active control techniques are the main ways of achieving this goal.

Stimulated by free market competition, civil aviation has, for many years, been developing in this direction. General and sport aviation, which includes business, touring, recreational aircraft and motorgliders [1, 2] seems to be less active.

A good deal of these aircraft are equipped with reciprocating internal combustion spark ignition engines, 4- and 2-stroke, with a power output in the range of 25 to 400 hp (18 to 300 kW)

These aircraft categories have here been taken into consideration, and their employment in sporting events has in particular been considered.

Indeed, sporting competition is in many cases able to orientate the technical development towards objectives of social value. Races have been promoted since the beginning of aviation: to increase the speed of a vehicle has always been a primary objective of man. This is particularly true for air vehicles which have produced a big jump in speed and a bigger one is announced for the future.

Speed, however, has a price, in terms of fuel burnt or, in more general terms, of wasted energy. With general and sport aviation, however, this aspect has so far received inadequate attention, whereas the promotion of high speed, but with low fuel consumption, is of obvious relevance. These requirements are in evident conflict [3, 4, 5,6].

Competitions with the aim of rewarding the speed/consumption ratio were proposed and organized in the past. The following can be mentioned:

- CAFE 400 in California (CAFE is an acronym for Competition for Aircraft Fuel Efficiency), annually reported upon by the American magazine *Sport Aviation*;
- the race at Fond-du-Lac (Oshkosh, USA);
- the French Icarè;
- the International Economy Air Race (IEAR), Torino, Italy, July, 1988 [3,4,5,6].

The latter (one edition only) was the first to involve international participation and also the first to admit motorgliders.

2. Fuel consumption measurement in the economy races

This is a delicate problem to be solved, and one which makes economy races a rare event.

In some of these competitions the measurement is made in a simple but approximate way. Before take-off: plane leveled and fuel tanks filled up; after landing: plane leveled again and tanks filled up again. The total consumption over a flight of several hours, measured in this way, is a consumption in volume, which is not easy to correct into a consumption in mass, because of the fuel thermal expansion. It is well known that petrol, a mixture of hydrocarbons, has not only a high thermal expansion coefficient but one also dependent on the origin of the crude oil and on the refining process.

In other competitions (CAFE 400, IEAR) the consumption is determined by weighing the aircraft (with the crew on board) just before take-off and after landing.

The economy race challenges the pilot's capability to exploit the air motions, i.e. winds and up-currents (the way sailplanes do). It may happen, therefore, that even after several flying hours the fuel consumption, in other words the difference in weight assumed to be the fuel consumption, results to be very low. This was the case several times during the IEAR, where motorgliders competed and soarable meteorological conditions occurred.

The scales, therefore must be able to yield reliable measurements of two slightly different weights. Practically, they must appreciate 100 grams in a range going up to 2000 kg, depending on the aircraft types admitted to the competition.

Such scales are not available on the market. For the IEAR these scales were specifically designed and built by ALENIA (then AERITALIA) and they fully met the requirements. The success of that competition, run under the auspices of the FAI (Federation ,Aeronautique Internationale), was largely due to those special scales (Figure 1).

The CAFE 400 too, thanks to generous sponsorships, could employ scales of the same kind.

These solutions are however expensive, require automatic data processing and therefore equipment and adequately trained personnel. Furthermore, the weighing must be carried out somewhere like a large hangar that is sheltered from the wind: even a very slight wind may produce up or down lift, thus unacceptably affecting the measurements.

This appears to be the main obstacle to the reiteration of this type of competition, which would otherwise be clearly promoted and also supported by FAI and its international specialized Commissions.

3. An instrument for energy output measurement

In order to obviate the drawbacks of the means so far used, the idea of an instrument installed on board of each competing aircraft could be pursued, which gives an output reading correlated to the fuel consumption over a known period of time.

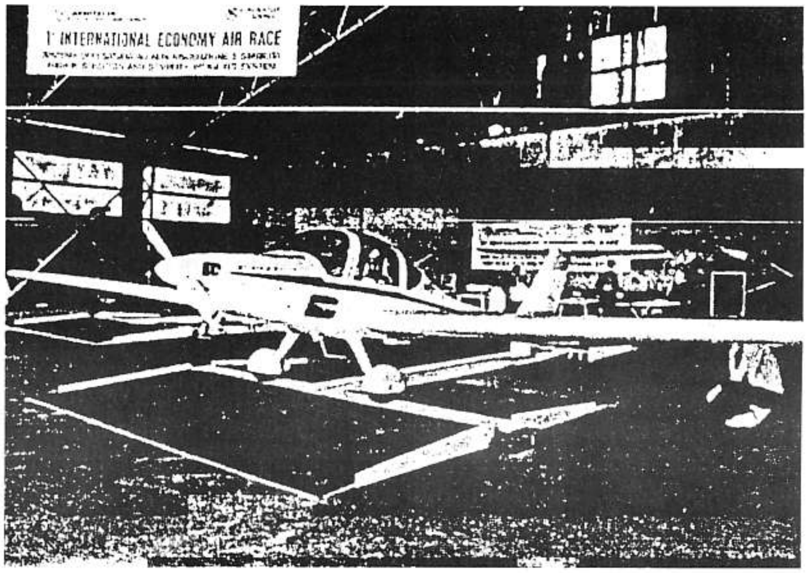

Figure 1. Weighing of a motorglider for fuel consumption determination during the "International Economy Air Race".

The idea of an onboard traditional flow meter, the indication of which would be integrated over time, is the first to come to one's mind, but again the problem to be solved is to convert volume into mass - not an easy task.

The instrument described here does not really measure fuel consumption, but a quantity correlated to it. Indeed, what is relevant for an economy race is not so much the absolute value of the fuel consumption as rather a quantity correlated to it, allowing one to compare the performance of different competitors along the same course. The proposed instrument should be able to provide such an indication with a reasonable approximation.

4. Implementation and limitations

If, after extensive testing, the instrument results to be adequate and, at the same time, reasonably cheap when produced in quantity, an economy race could be envisaged where all competing aircraft are equipped with it.

The performance evaluation would be quite easy, through the readings of the instrument digital display at the end of the flight. The expensive unwieldy scales would no longer be necessary.

The obvious objection to the basic concept, i.e., the direct correlation of fuel consumption per unit time with the product manifold pressure x engine rotational speed (the latter being, with a good approximation, the shaft power of the engine) is that both engine efficiency and propeller efficiency are not taken into account, or assumed to be the same for all competing aircraft. This is true!

Obviously this objection would not apply to a competition for one-design aircraft, all competing aircraft being equipped with the same engine and propeller. Such a competition would be a challenge to the pilot's ability to exploit the air motions in the available meteorological conditions, and would not be an incentive to improve the efficiency of the propulsion unit .

In other cases a more generous approximation should be accepted or corrective factors introduced into the score formulas.

It should furthermore be understood that fuel consumption alone cannot be the evaluation criterion in an economy competition. Otherwise, the optimum airspeeds, those minimizing the fuel consumption per unit distance flown (f), would be very low, in contrast to the main distinction of air transport, speed.

One could think of rewarding the ratio between the average speed along the course (V) and the consumption per unit distance flown (f), V/f. This would not be satisfactory either. Indeed, competitors who achieve the same V/f but at different speeds would obtain the same score, whereas it would make more sense to reward the fastest.

A solution is a score formula that rewards V^n/f, where $n>1$. The higher the value chosen for the exponent n, the more the speed is rewarded. CAFE 400's choice was n=1.25, IEAR adopted n=1.2. Special flight techniques can be used to improve V^n/f [8,9].

5. Theoretical background for fuel consumption determination

A correlation between the fuel consumption and two engine parameters which are very easy to detect, i.e. manifold pressure and the engine rotational speed, can be approximately established through the following considerations.

As is well known, the fuel mass-flow mb can be expressed as follows:

$$\dot{m}_b = \frac{\dot{m}_a}{\alpha} = \frac{\lambda_v \cdot \rho_a \cdot iV}{\alpha} \cdot \frac{n}{m} \tag{1}$$

where ma is the air mass-flow in the engine, α the air-fuel ratio, λ_v the volumetric efficiency, ρ_a the intake-air density, iV the total engine displacement ("V" is the cylinder displacement, "i" is the cylinder number), n the engine angular velocity, m a parameter which depends on whether the engine is a two (m = 1) or four stroke engine (m = 2).

As the most important parameter that can influence the volumetric efficiency is the in-cylinder pressure, the volumetric efficiency of a four stroke engine, results to be expressed by the following relationship, where the air throttling, during the intake and exhaust stroke, is constant (the heat exchange from the cylinder walls to the fluid, the back-flow into the intake manifold and the dynamic effects are not considered) [10]:

$$\lambda_v = \frac{p_i}{p_a} \cdot \left[1 - \frac{\frac{p_s}{p_i} - 1}{k \cdot (\rho - 1)} \right] \tag{2}$$

where ρ_a is the external air pressure, p_i and p_s the in-cylinder pressure during the intake exhaust stroke, k is equal to C_p/C_v (thermal capacity at constant pressure/ thermal capacity at constant volume), and ρ is the volumetric compression ratio. If the throttling during the exhaust stroke is also not considered and p_l can be considered equal to the manifold pressure p_c, the previous relationship becomes:

$$\lambda_v \propto p_c \tag{3}$$

and, if the previous m_b expression is now considered (assumed α = const.):

$$\dot{m}_b \propto \lambda_v \cdot \rho_a \cdot iV \cdot n \propto p_c \cdot \rho_a \cdot iV \cdot n \tag{4}$$

and for a given engine (i.e. at given i•V) and at ρ_a = constant[1]:

$$\dot{m}_b \propto p_c \,.\, n \tag{5}$$

As far as the correlation between λ_v and p_c is concerned, Figure 2 shows that there is a good linearity agreement between the volumetric efficiency vs. the manifold pressure for the propeller characteristic of a four stroke engine for angular velocities between 1200 and 3200 rpm

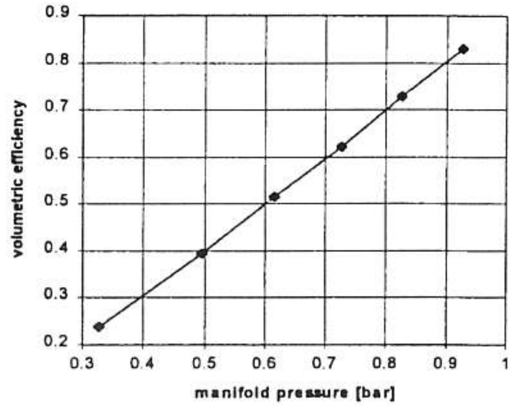

Figure 2. Volumetric efficiency (λ_v) vs. manifold pressure (p_c) for the propeller load in a four stroke s.i. engine. Angular velocity = 1200/3200 rpm.

[11].

The previous simplified relationship between λ_v and p_c therefore seems to be sufficiently approximated, at least for the conditions which are far from angular speeds where the back-flow into the intake manifold is possible, owing to the large closing delay of the intake valve.

This particular condition is however verified for the propeller load characteristic, where the engine is usually utilized for aeronautic propulsion. The α = const hypothesis can also be considered to be sufficiently reliable if the engine does not run at wide open throttle conditions, where the air-fuel ratio is normally rich, but instead at part-load conditions, that is, during cruising, when the air-fuel ratio is around the stoichiometric value. On the other hand, the engine runs at maximum power only for a few minutes, i.e. during take-off and the subsequent initial climb and, more or less, at part load during cruising.

The fuel consumption vs. the dimensionless product $p_c \bullet n$ for the propeller characteristic for a KFM 112 M aeronautical engine (the product $p_c \bullet n$ is divided by the maximum $p_c \bullet n$ value) is shown in Figure 3 as an example. The cruise condition is also indicated. In this case the cruise condition corresponds to 70% of the maximum power (62 HP at 3400 rpm) and at 2800 rpm. These experimental results have been obtained through bench tests on the KFM 112 M engine [12].

The same picture shows the possibility of identifying a straight line that permits one to correlate fuel consumption and the product $p_c \bullet n$ using a linear relationship. Outside the cruise point, where the straight line crosses, the maximum deviation results approximately to be 7% at wide open throttle ($p_c \bullet n / (p_c \bullet n)_{max} = 1$) and approximately 3% at part-throttle.

As far as the correlation between the fuel consumption and the total engine displacement is concerned, Figure 4 shows the maximum fuel consumption vs. total displacement iV for eight different aeronautical engines. The maximum fuel consumption (kg/h) and total displacement here show good agreement with a linear relationship whose slope is 7.4 kg/h/litre.

6. The proposed instrument for the fuel consumption measurement

The determination of the quantity of fuel in tanks and of he quantity of fuel consumption in aircraft that use alternative engines has already found adequate technical solutions; there are, in fact, specific indicators or instruments for this purpose. The aim of this instrument instead is that of providing a "fuel consumption index" which can be utilized both in "Economy Air Race" competitions and during cruising. Therefore, the instrument is not intended to replace the usual onboard fuel level-gauge, but could be used to integrate the flight information with the instantaneous fuel consumption or even with the cruising range indications. At the present re-

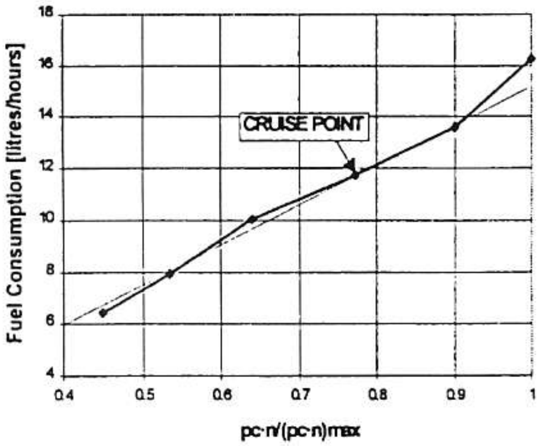

Figure 3. Fuel consumption vs. dimensionless product $p_c \bullet n$ for the KFM 112 M engine along the propeller load (the procuct $p_c \bullet n$ is divided by the maximum $p \bullet n$ value).

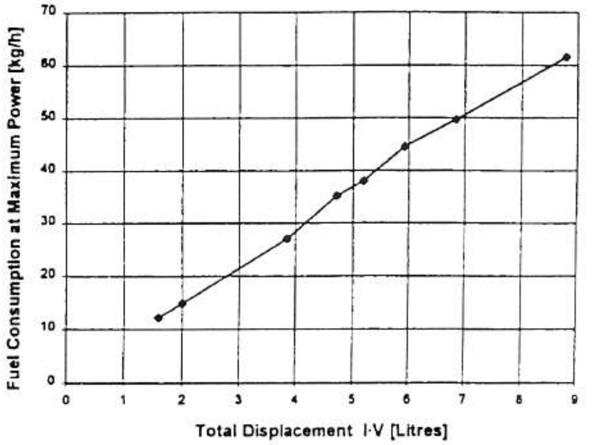

Figure 4. Fuel consumption (kg/h) at max. power for aeronautical reciprocating s.i. engines vs. total displacement iV.

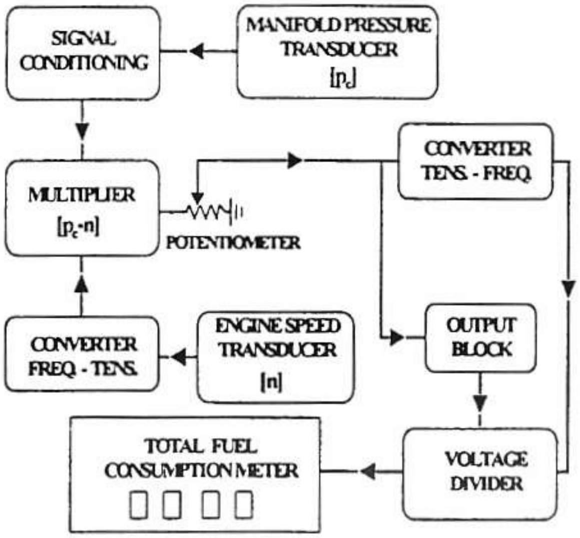

Figure 5. Block diagram of the proposed instrument.

search stage, the instrument has been built in a simple and cheap way and is able to carry out only the product between the signals of a pressure transducer for p_c and from an encoder for n, as shown in Figure 5, by means of a block diagram [13]. The influence of air conditions, i.e. pressure and temperature, has consequently not been considered at the moment and its working principle is therefore as follows.

The input signals come from the intake-manifold pressure and from the engine angular velocity. The p_c value is acquired from a pressure transducer, the voltage response of which is perfectly linear; at first this signal is increased by using a signal conditioning. The frequency signal from the angular velocity transducer (an optical encoder) is converted into a tension signal by a tension-frequency converter. These two signals can therefore be multiplied. The signal level can be changed by means of the potentiometer and then it is again turned into a frequency-signal.

Finally, after a divider stage, the signal comes to the instrument for the total fuel consumption metering; the stage for the output block intervals if the signal level results to be lower than the minimum value required for the divider stage; on the contrary, the error in the divider stage becomes unacceptable.

The instrument calibration is therefore as follows:

- choose the cruise conditions for a given airplane, that is, engine angular velocity and throttle lever position (the manifold pressure can be measured during the flight);
- send the signals from the angular velocity and pressure transducers which correspond to the cruise conditions into the instrument (the pressure manifold can be converted into a tension level through the pressure-transducer calibration-curve);
- find the potentiometer position that corresponds to the fuel consumption for cruising conditions.

The fuel consumption cruising conditions can be deduced from the engine calibration curves.

7. In-flight simulation of fuel-consumption measurement

Before checking the instrument under flight conditions, a theoretical verification was also carried out by means of a simulated application to two airplanes [14]. The first plane is a Robin ATL Club, powered by a KFM 112 M engine; the second is a CESSNA SKYHAWK, powered by an AVCO Lycoming O-320 engine (maximum power 160 HP at 2700 rpm).

Figures 6 and 7 show the fuel consumption (litres/h) for the two airplanes versus $p_c \bullet n/(p_c \bullet n)_{max}$ for cruising and also for three other different flight conditions. These figures also show the instrument calibration for the cruising conditions by means of the thin straight line which represents the instrument response. This first theoretical verification was therefore carried out by means of a simulation of a flight of three hours, for the airplanes with a

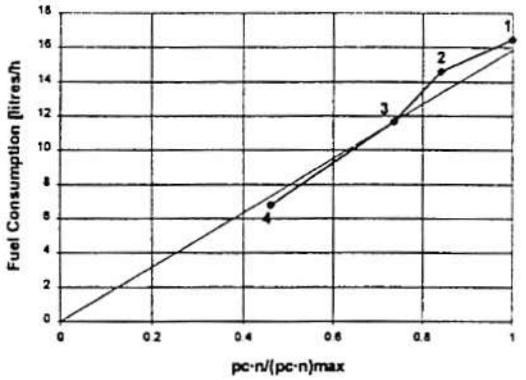

Figure 6. Fuel consumption (litres/h) for the ROBIN ATL Club powered by a KFM 112 M engine vs. $p_c \bullet n/(p_c \bullet n)$max; point 1: Take-off; point 2: climb; point 3: cruise; point 4: descent; thin line: instrument calibration.

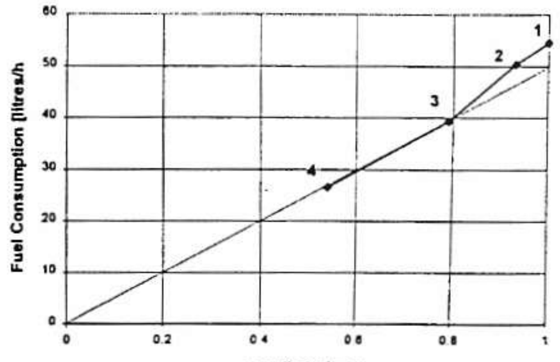

Figure 7. Fuel consumption (litres/h) for the CESSNA SKYHAWK powered by an AVCO Lycoming O-320 engine vs. $p_c \bullet n/(p_c \bullet n)$max; point 1: take-off; point 2: climb; point 3: cruise; point 4: descent; thin line: instrument calibration.

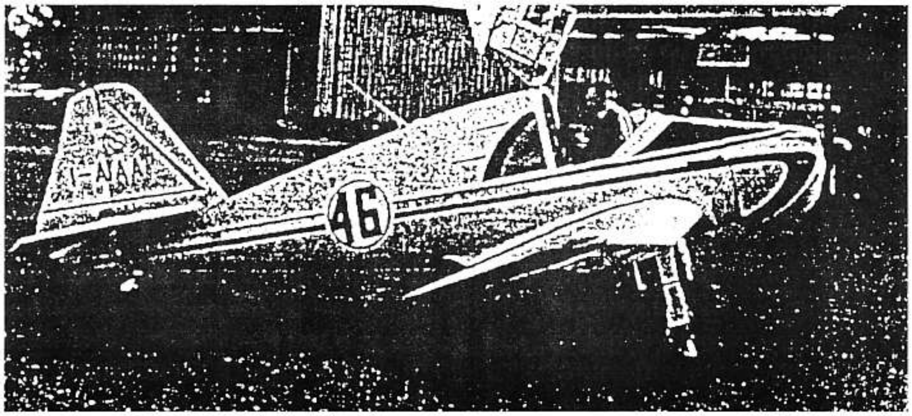

Figure 7. AVIA LM5 Aircraft: wing span 11 m; empty weight: 420 kg; cruising speed: 170km/h; cruising range: 850 km.

cruising time of approximately 86% of the total time and at 1000 m altitude. In both cases the difference between the simulated instrument indication and the evaluated fuel consumption, on the basis of the real running conditions of the engines (i.e. points 1,2 and 4 of Figures 5 and 6) was less than 1%. In this case the influence of the altitude on the fuel consumption was omitted. The differences increase to ~2.3% if, for example, a cruise altitude of 2000 m is chosen and the influence of altitude on the engine fuel consumption is also considered, whereas the instrument calibration is maintained at sea level.

After these computational determinations the instrument was installed on a light aircraft for the first experimental verifications.

8. In-flight fuel-consumption preliminary experimental tests

Flight tests were then carried out with the instrument installed on a light AVIA LM5 aircraft (see Figure 7) powered by a 90 HP Continental engine O-200 C90 (total displacement: iV = 201 cubic inches) in order to evaluate the instrument response in real operating conditions. The pressure transducer and the encoder were installed on the aircraft in order to calibrate the instrument for the Continental engine, that is, to first carry out a measurement of the manifold pressure during a cruise. Then two input signals equivalent to the output voltage of the pressure transducer and to the frequency of the encoder (2200 rpm) in cruise conditions, were introduced using a simple test rig.

Finally, it was possible to carry out the instrument calibration by means of the potentiometer (see the instrument block diagram in Figure 5) so that the instrument indication coincided with the effective fuel consumption in cruise conditions. Unfortunately, in the case of this particular engine (Continental O-200 C90) not all the calibration curves were available. The instrument calibration was therefore performed only by means of the propeller load performance (this is slightly different from real steady-flight conditions [12]) and by means of the manifold pressure which was measured in cruising conditions. The optical encoder installed on the AVIA LMS has been connected to the engine speed-indicator drive and an electronic tachometer was used in flight instead of mechanical ones. As aeronautical engines are normally provided by a pressure tap near the cylinder head for the engine power percentage indication, when the variable pitch propeller is adopted, the pressure connection between the pressure transducer and the intake manifold was very simple.

The results of the first flight tests carried out on the AVIA LMS are reported. In Figures 8 and 9, Figure 8 shows the measured fuel consumption during a first cruise of ~58 minutes for a distance of ~130 km; some experimental points which were taken during the flight are also indicated. The final instrument indication is of 17.45 litres, on the contrary the effective final fuel consumption results to be 18.5 litres, with a difference of -5.40%. In these first tests, the effective fuel consumption has been measured by means of the complete tank-refilling after the flight (the tank was completely full before the flight). This measurement therefore does not permit the conversion of volume into mass.

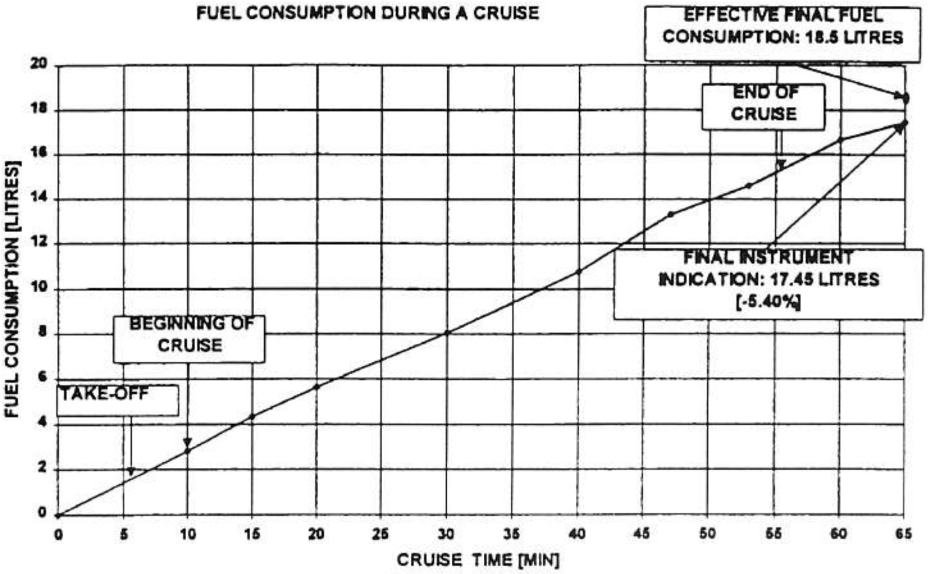

Figure 8. Measured fuel consumption during a cruise; flight time: ~58 minutes; cruise distance: ~ 130 km.

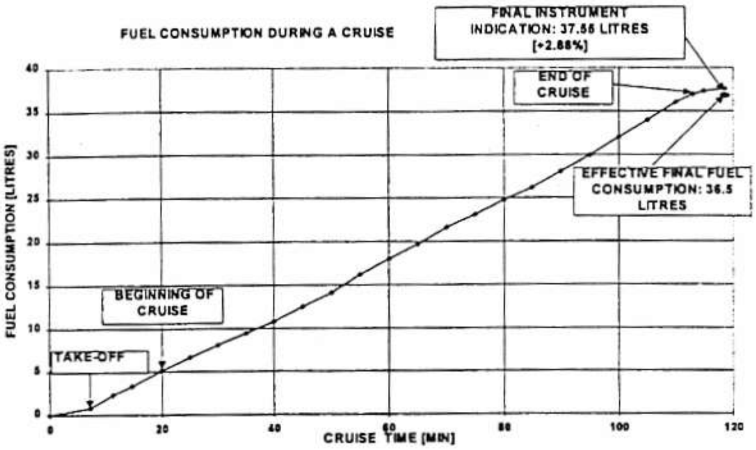

Figure 9. Measured fuel consumption during a cruise; flight time: ~109 minutes; cruise distance: ~290 km.

Conclusions

This first part of the research work can be considered satisfactorily concluded and the results would encourage further development of the instrument. In particular tests will be necessary by means of an engine whose calibration curves are available, especially as far as the specific fuel consumption is concerned (mass flow per unit of power) in all operating conditions (rotational engine speed and pressure manifold). Further tes=ts are therefore planned using of an aircraft whose engine calibration curves are all available, i.e. a Piper Cherokee powered by the AVCO Lycoming O-320 engine.

Nevertheless some improvements on this instrument for fuel consumption determination are necessary and will be carried out in a further research phase. At first the influence of air density variations with altitude could be considered in order to improve the instrument indication, because this quantity actually influences the engine performance. A second improvement concerns the possibility of using a different and more reliable technology for this instrument, such as digital technology.

Acknowledgments

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