Hydraulic test bench for pop-pop engines

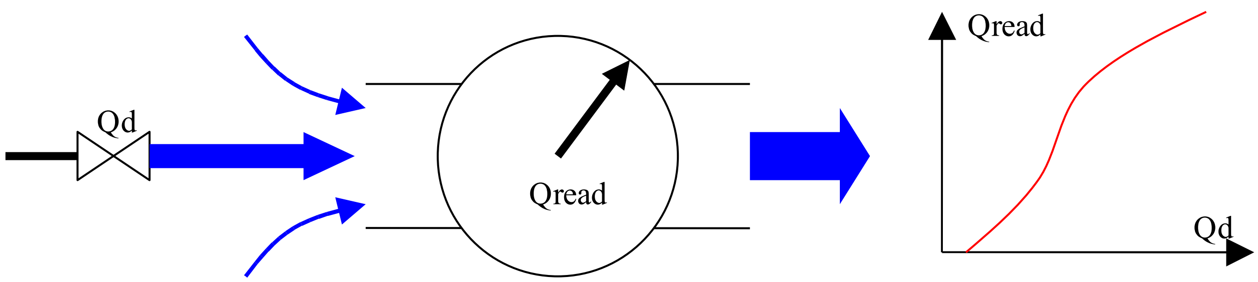
By Jean-Yves

Ultimate goal: to be able to measure and optimize the hydraulic pop-pop engine performances.

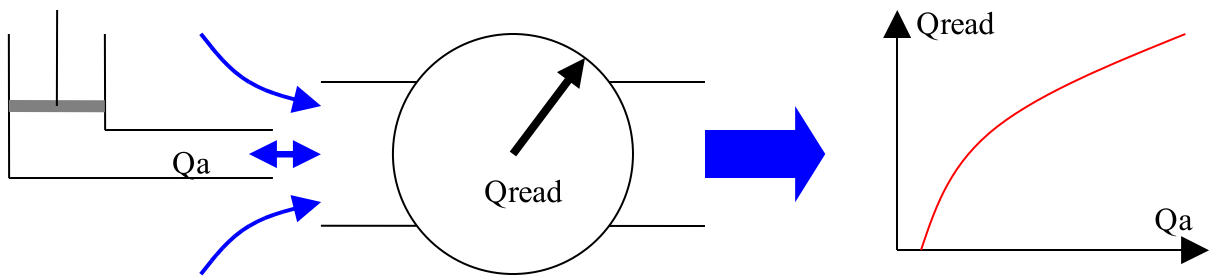
To do that, we had to build and calibrate a test bench. As previously several thrust measuring devices had given us insufficiently reliable results, another way has been searched: the one of the "effective flow" measurement of the pulsed waterjet. What we call "effective flow" here is the direct flow Qc which gives the same global result as an alternative flow Qa. (A comparison can be done with DC and AC in electricity).
In hydraulics, it could be something that is known from specialists, but we found no publication on this matter. Therefore, we decided to take ourselves by the hand and to use available means. The recovery of a water flow meter when remodeling an apartment was the starting point of this test bench.

1°) Measuring principle.

1.1. Calibration with direct flow

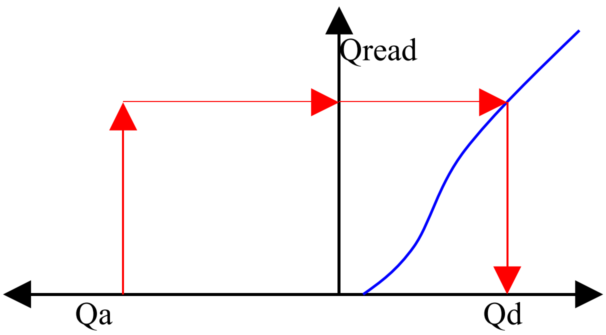


Calibration with alternative flow



1.2. Compilation

Knowing both the value of a direct flow *Qd* and the one of an alternative flow *Qa* which generate any read value Qread, we can define the relation between Qa and Qd.



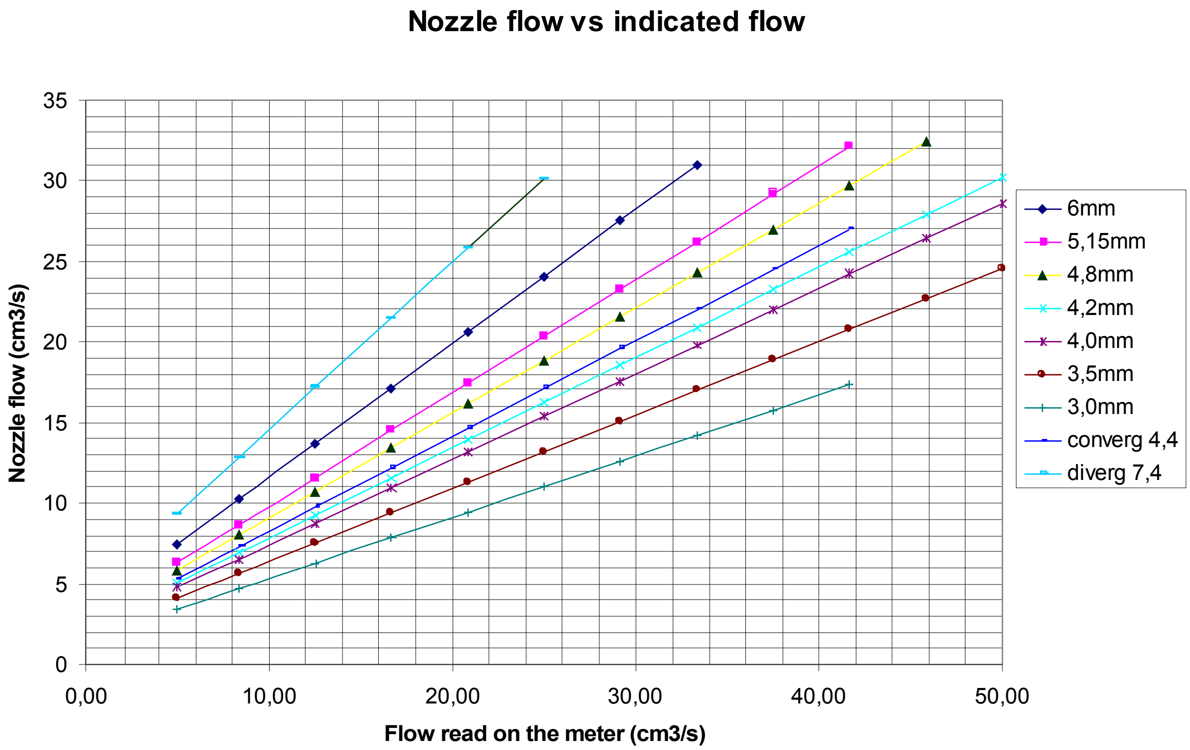
1.4. Test of a pop-pop engine.

This is not yet the purpose of this document. Later, the alternative flow Qa will be the one of a pop-pop engine.

2°) Calibration with permanent flow.

To supply the nozzle representing the outlet of a pop-pop engine (see annex 2), a (5 liter) graduated water tower was built, located approximately 1.5m above the flow meter. Between this water tower and the nozzle, a throttling valve and a stop valve were fitted. For each test, the water tower was filled, the throttling valve set at a defined number of turns, then the stop valve was opened, and after stabilization of the flow, the chronometer was set on between two graduations of the water reservoir, and the indicated water flow was read on the meter.

The result, as a graph is the following one:



And it can be summed up by a single mathematical formula:

Qd=(0,15xD – 0,07)Qread **+ 4**

With Qd = flow through the nozzle in cm^3/s.
Qread= flow seen by the flow meter in cm^3/s.
D = diameter of the nozzle in mm.

Note 1: The last term 4 represents the flow under which the meter doesn't turn.
Note 2: The formula is given for information only, because the coefficients are specific to this test bench.

Note 3: The curves are voluntarily limited to the values plotted on this graph because above they become non-linear.

Some reverse flow tests were done with some nozzles. (It means that instead to being delivered, the water was sucked by the nozzle). In spite of sometimes big flows (more than 40 cm^3/s), the meter (intrinsically absolutely reversible) never turned. We could see that the water was mainly sucked laterally. The free surface just above the nozzle was hollow…down to suck air during some extreme tests (through the 4 holes of diameter 9. (See pictures and drawing).

3°) Calibration with alternative flow.

After two doubtful attempts with diaphragm pumps, the calibration was done by means of a reciprocating piston pump. It has a well known stroke volume, and it is driven by a crank and a long connecting rod in order to get a practically sinusoidal movement. As built, the system allowed to testing 4 different piston strokes, hence 4 stroke volumes.

For each test we were able to record:

Frequency (F)

Flow meter indication (Qread)

and we knew the **stroke volume** and the **nozzle diameter**.

11 nozzles were tested at variable frequencies with a 3.6cm^3 stroke volume. 5 of them – deemed to be the most representatives – were tested with 4 different stroke volumes. And each time approximately 10 records were done. All the records are coherent.

As for the calibration with a direct flow, for each series we got dots that are aligned, taking into account the inaccuracy of the measurements.

When analyzing the data, it has been seen that the special nozzles (convergent, divergent, thick pipe) were rather less performing than the others. They are not displayed on the final graph because it would be useless to adapt such nozzles when doing the basic design of a pop-pop engine. On the other hand, below FxV=5cm3 the dots have not been taken in consideration because they are going away from the linear zone.

The result as a graph is the following one:

The whole graph can be represented by the following approximate mathematical formulae:

FxV=0,095xDxQread + 0,5xD-1

With F= Frequency in Hz

V= stroke volume in cm^3.

Qread= flow seen by the flow meter in cm^3/s.

D = diameter of the nozzle in mm.

The formulas which give Q and FV versus nozzle diameter have not the same structure and we are a little bit sorry of that. But we don't want to "manipulate" the data. The formulas are the simple ones which are close to what we measured.

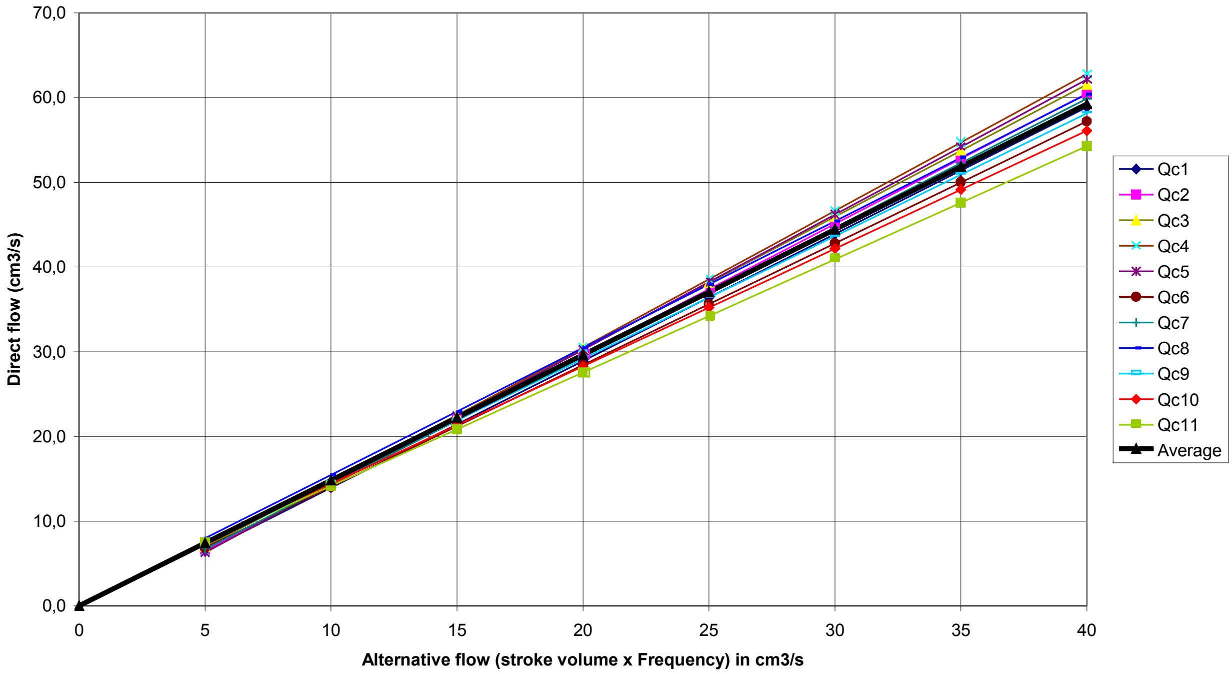
Thanks to this calibration, now we have got a measuring tool which will allow later to test pop-pop engines. The indication "Qread" of the flow meter and the diameter of the nozzle will allow us to know the product "Stroke volume x Frequency". And measuring the frequency will lead to the knowledge of the cylinder stroke.

4°) Comparison

We came back to the individual curves, and to each value Qa we associated the value Qd giving the same indication Qread on the flow meter.

The dots of abscissa Qa and ordinate Qd were then displayed on a graph.

Direct flow which would give the same result as a reciprocating one (for various nozzles).



It was obvious a priori, but we can see on this graph, that (taking into account the inaccuracy) the curves are crossing the zero. As nothing was measured below 0.8Hz, we added the dot of abscissa zero and ordinate zero, and the average was calculated.

For the whole batch of 11 nozzles that were tested, **Qd=1,48**x**Qa** with less than 10% error.

5**) Conclusions :**

1°) If we define the flow of a pulsed waterjet by the product *Stroke volume x Frequency*, its effectiveness is higher than the one of a permanent waterjet. The ratio between them is approximately 1.5 whatever the nozzle diameter.

2°) The many measurements done show that **this coefficient tends to increase with the nozzle diameter. The extreme records are 1.56 with a diverging nozzle of 7.4mm diameter, and 1.35 with a cylindrical nozzle of diameter 3mm**. The difference is too narrow and the uncertainty too big to define reasonably a law.

3°) It was not the purpose of the tests, but we saw what follows. For a given flow, the efficiency of a direct flow waterjet depends only on the inner diameter of the nozzle. However, an alternative waterjet is more powerful when the nozzle is thin and free (to ease the relaxation).

4°) Now we have a tool to test pop-pop engines. The indication on the flow meter will allow us to know the product "Stroke volume x Frequency". Then, for diaphragm engines it will be easy to know the frequency and hence to deduce the stroke volume. For coil or spiral engines, or for drum ones without diaphragm, a (easy) way to measure the frequency remains to be found to do the same. Thanks in advance for your suggestions.

Note: All the measures allowing to reaching this conclusion have not been done with certified tools. Nevertheless, the same tools were used for all of them and a few tests were repeated later and gave the same results.

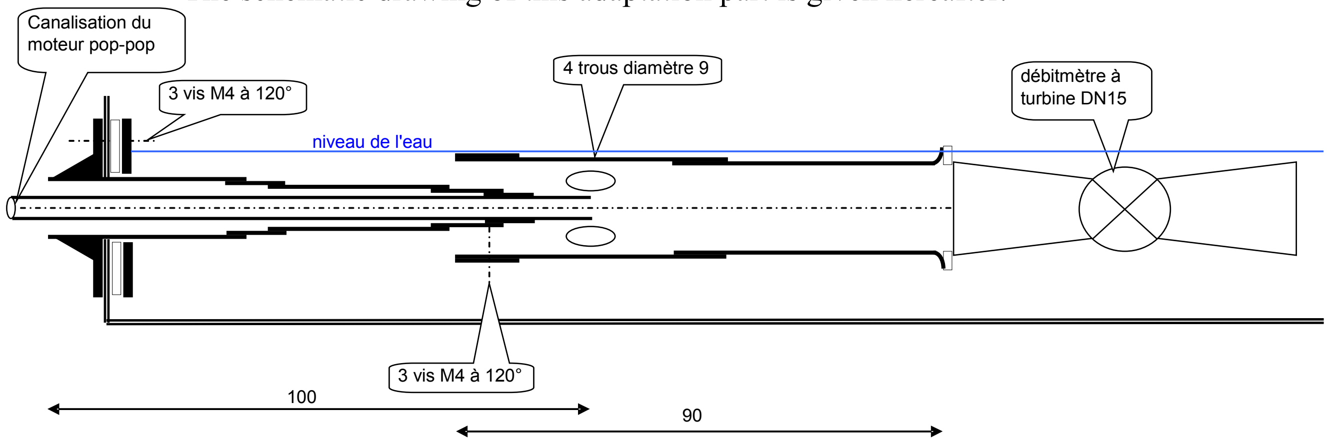
The test bench will be kept as it is for some weeks in order to be used to answer eventual proposals for additional tests.

Annex1

Design of the test bench.

The heart of the test bench is the flow meter, but it is not sufficient. After some hesitations, we built at the flow meter inlet an adaptation part designed to receive the nozzle jet. As this part was finally designed, it has been checked that a bad centering or a misalignment of the nozzle has little impact on the result.

The schematic drawing of this adaptation part is given hereafter.



It is the part which is 90mm long. The part which is on the left will be mainly used later with pop-pop engines. The immersed part of the pipe is very short, and the pipe is close to horizontal as it is generally in pop-pop boats.

The scale of this sketch is correct. Starting from the left, the size of the copper pipes that are brazed inside each other is 14x1, 12x1, 10x1, 8x1, 6x1 et 5x0.4 for the brass pipe representing the pop-pop engine one (in this case).

For the adaptation piece: 24x1, 22x1 and 20x1. The 24x1 ring is just there to double the thickness where holes are thread for M4 screws.

Measuring assembly out of water.

Thus, roughly, the flow meter sees the positive quantity of motion of the water, and doesn't see something during the relaxation phase.

Annex 2

Influence of shape and size of the nozzle.

We have tested 11 different nozzles in order to build a map of the performances versus shapes and sizes. In fact, as one can see further on a graph, the shape has practically no influence. Only the cross section of the outlet orifice has one (insofar as the converging or diverging angles are not exceeding usual values in hydraulic).

1°) Size of the nozzles:

Item	internal diameter	external diameter	Shape of the outlet end
#1	6	8	Strait cut
#2	6	8	Internal groove at 45°
#3	6	8	External groove at 45°
#4	6/4,4	8/6,4	Converging from 6 to 4,4 low conicity
#5	6/7,4	8/9,1	Diverging from 6 to 7,4 low conicity
#6	5,15	6	Strait cut
#7	4,8	8	Strait cut (thick pipe)
#8	4,2	5	Strait cut
#9	4	4,4	Strait cut (thin pipe)
#10	3,5	4	Strait cut (thin pipe)
#11	3	4	Strait cut

Calibration with direct flow.

Upstream, the nozzle to be tested was fitted on a removable housing provided with a quick change over device.

The (white) tank is horizontal and full, overflowing all along both sides. (No recirculation)

Annex 3.

Generation of a pulsed waterjet.

Main pieces of equipment used for the pulsed waterjet generation:

Reciprocating pump

Crank and connecting rod

Drilling machine provided with speed control.

Complementary pieces of equipment:

Shaft and bearings (from an old milling machine) because the roller bearings of the drilling machine are not sized to sustain radial forces.

Cardan transmission joint (to compensate possible misalignment)

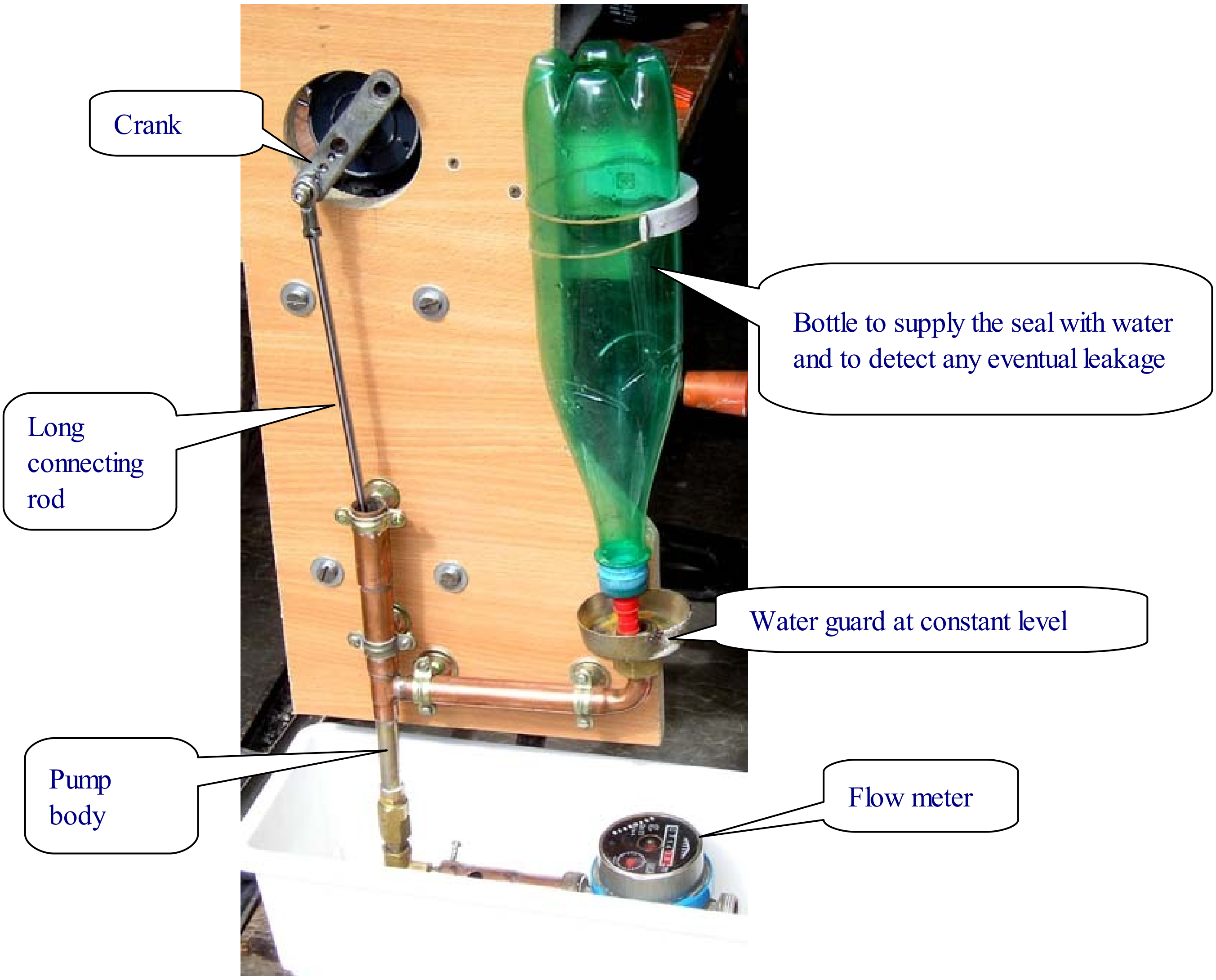
Tachometric measuring device.

Taking into account the problems encountered during the first tests with diaphragm pumps, on one hand a piston pump was designed with a water seal to avoid air ingress; and on the other hand, a new frame for the test bench was made of steel for better stiffness.

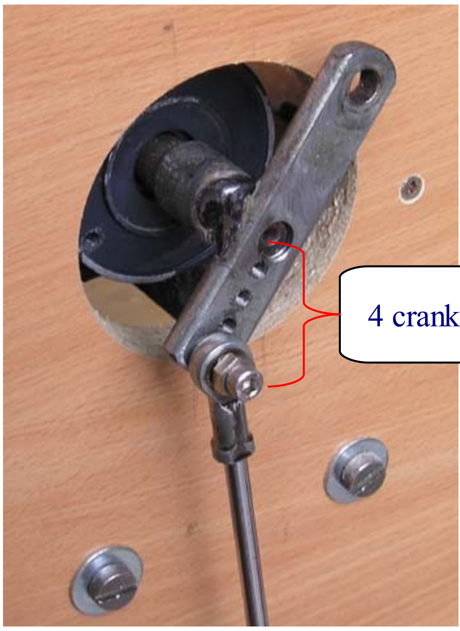
Principle:

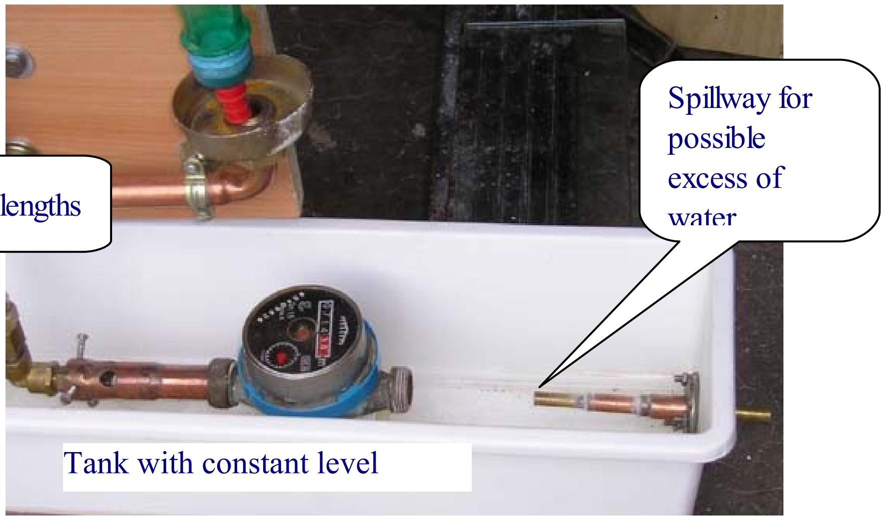
For those who are interested I can send the file “plan de pompe”. (in French for the moment).

Realization:

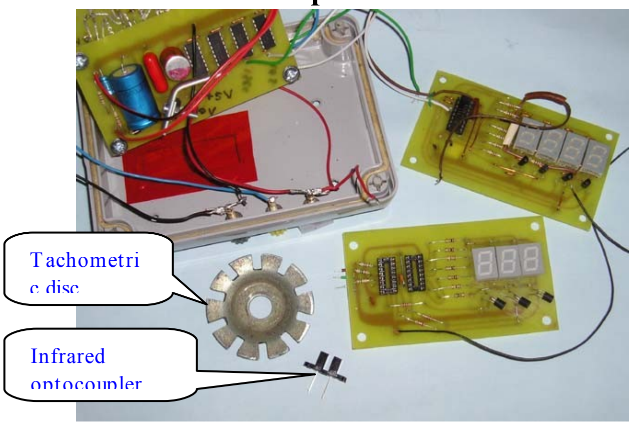


Some detailed views





A few additional pictures

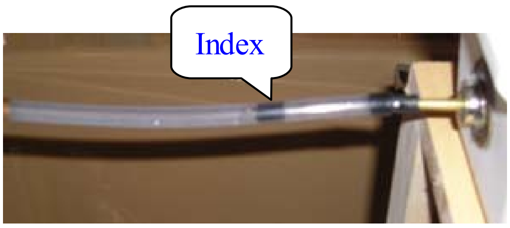


The first tachometry
Much energy spent for poor results

The final one (Faraday cage from a canned beans supplier)

The electronic corner

Cam (made of Lucite) and its lubrication (wick from an oil lamp soaked with oil)



Stroke volume measurement

Cardan joint (Facom make)

Annex 4.
Problems met with the first pump.

The pump was the fuel pump of a car. A diaphragm type one. It was sealed. We didn't know how it was inside.

The analysis of the first results showed a decreasing of the apparent stroke volume when the frequency increased. Hence, we measured this evolution with two different methods.
1°) During the test by means of an index (small plastic cylinder of density 1) located inside the transparent pipe connecting the pump to the nozzle.
2°) During a specific test by installing after the engine pipe, a vertical column in which the free surface was observed.
Amazing result: after a plateau at constant stroke volume for low frequencies, the volume evolutes of hyperbolic manner versus frequency. Later, by doing a destructive autopsy of the pump, we discovered that this was due (by voluntary design) to some air that couldn't escape.