Hydraulic simulator of pop-pop engine

By Jean-Yves

Following the measurements of Pmax and Pmin in a pop-pop engine (see documents "Pressure in a pop-pop" and "Diaphragm engine") we have modified the test bench in order to supply the nozzles with an alternative flow closer to the one delivered by a pop-pop engine. To do that, the kinematics of the reciprocating pump has been altered. And to get a thrust measure as accurate as possible we have adapted the thrust measuring device using a laser beam described in "Test bench for pop-pop engines", the final goal being to qualify the test bench.

Kinematics of the pump :

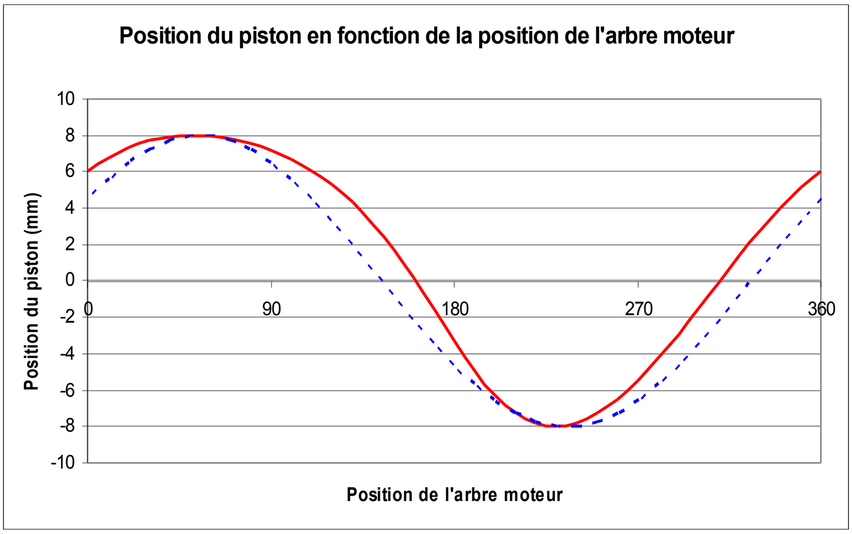
After studies of several possible kinematics (mathematical approaches reported in “The water snake movements”) we have selected a rather simple alternative allowing the reuse of the main components: the prime mover, the pump body and its piston. We only added a small connecting rod and a rocker arm articulated on a fixed axis. Some details are given in appendix.

X being the distance between the motor axis and the rocker arm one we have studied the function $\beta=f(\alpha)$ for different values of r, d, L et X and selected the following ratios: L/r=2,5 ; X/r=3 ; d/r=2.

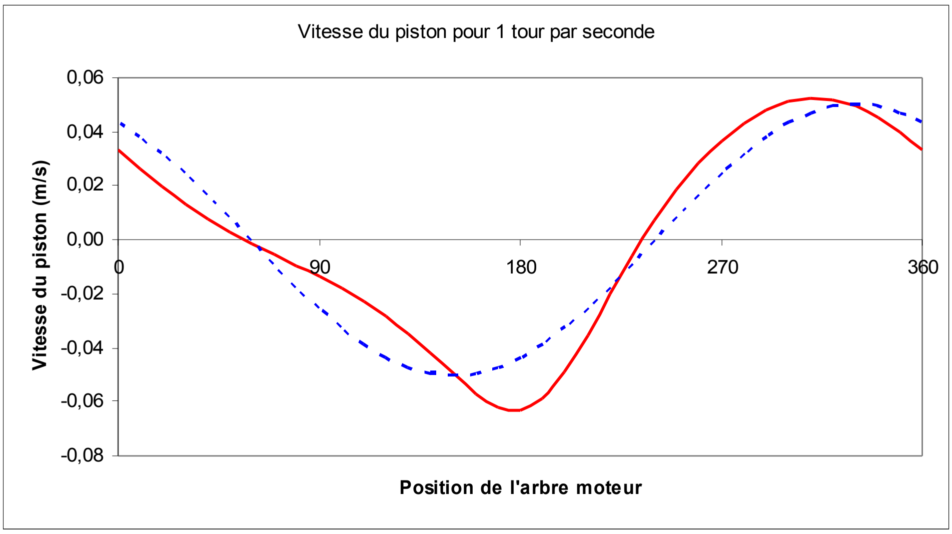
Consequently, the full angular movement of the oscillating arm will be 47.2°. To get a com-promise between inertia (to allow fast rotation) and relative plays, we have selected a radius r=16mm; which defines X=48, L=40 and d=32. And to get the piston stroke we are interested in (16mm in order to compare with the sinusoidal kinematics that is already known), we have used the oscillating arm as a rocker arm with a lever R such as 8=R.Sin(47.2/2); i.e. R=20mm. In the extreme positions, the horizontal projection of the small arm is 20.cos(47.2/2)=18mm. Between 18 and 20 we have selected 19 in order to make the system as linear as possible. (We have studied the function $\sin(\beta)$ between -23.6° and +23.6°. The non linearity doesn’t exceed 1.35%. However, as it was not very much complicated, we have taken into account $\sin(\beta)$ in the calculation, and we have adjusted the angular offset of the small lever of the rocker arm compared to the horizontal reference and we named it Gamma). For some photographs see at the end.

Graphical display :

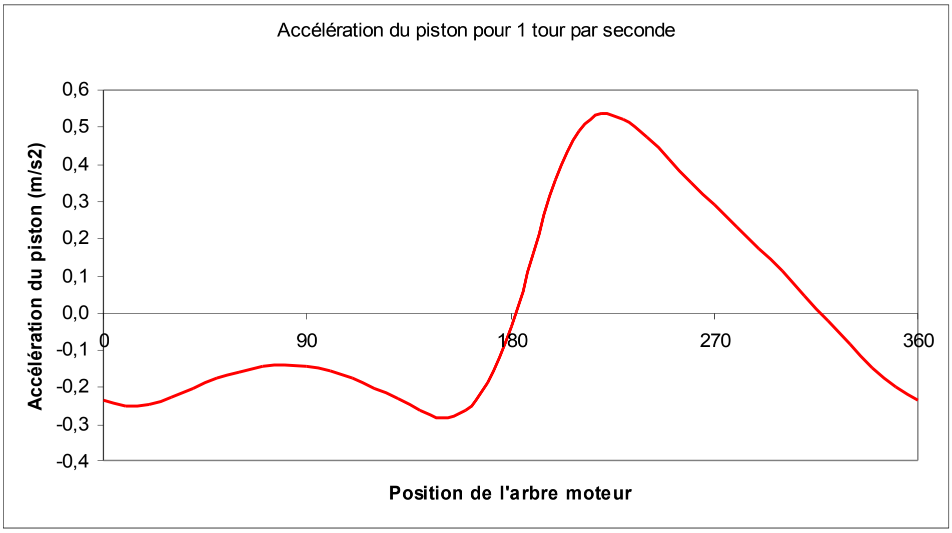
Position, velocity and acceleration of the piston versus motor crank angle, the speed of this motor being supposed to be constant.



One can see that the cycle is dissymmetric in x and in y. Hence, it is not very close to a sinusoid (represented in blue dashes).



Positive and negative areas are equal, but the momentums which evolve as V^2 are different.



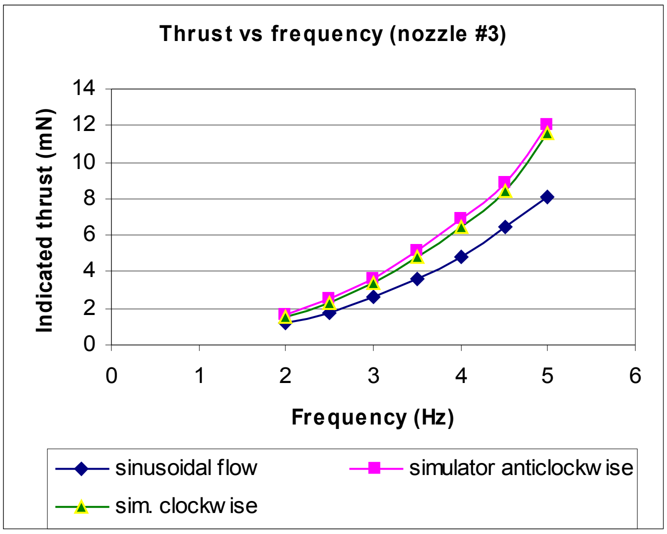
This graph shows that the absolute value of the max pressure is approximately twice the one of the min pressure (as during our measurements with a real pop-pop engine).

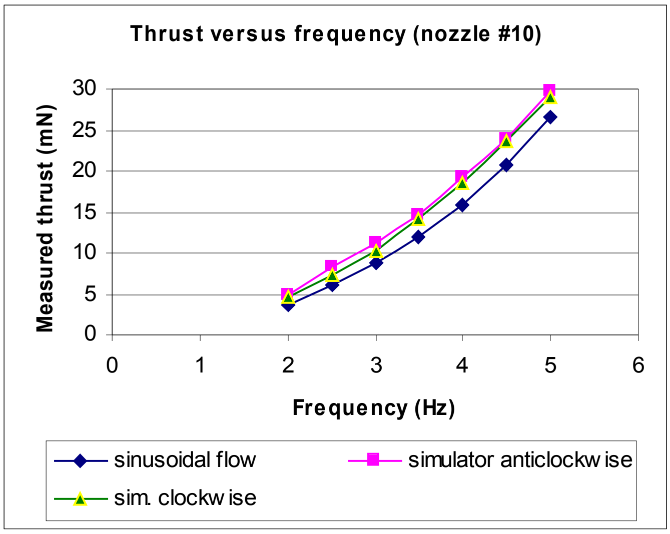
Test results :

In a first stage we have calibrated the test bench using a static load (hung to the calibration arm of the bench, see the *ad hoc* document) so as to get a deviation of one centimeter of the laser for exactly one 1 milliNewton. Then, we have tested two well known nozzles (#3 and #10). For any one three series of tests were run:

A series with sine flow
A series with the simulator running anticlockwise
A series with the simulator running clockwise

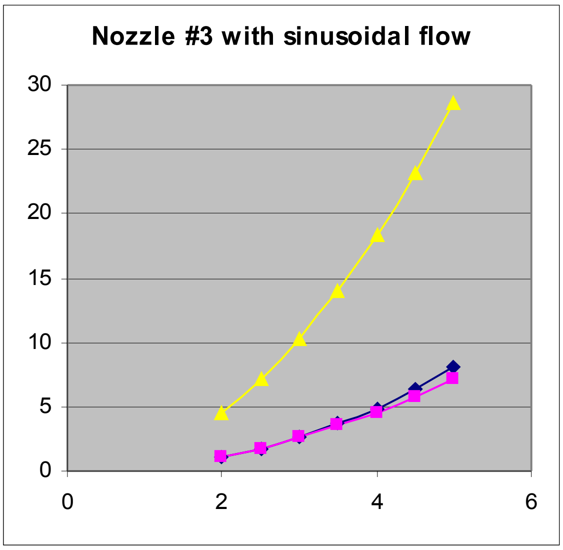
The graph results are the following ones:

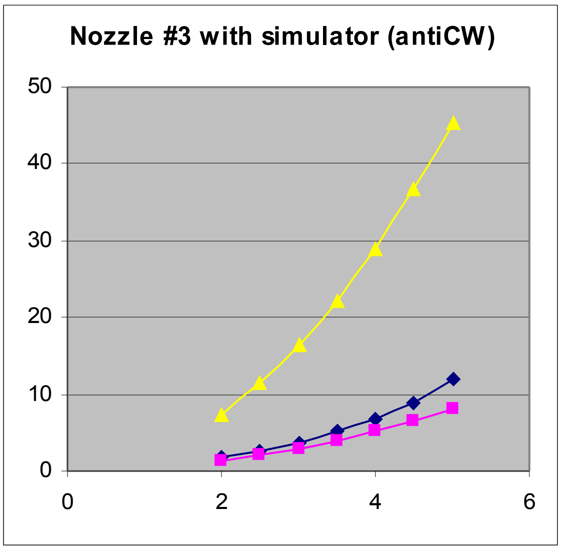




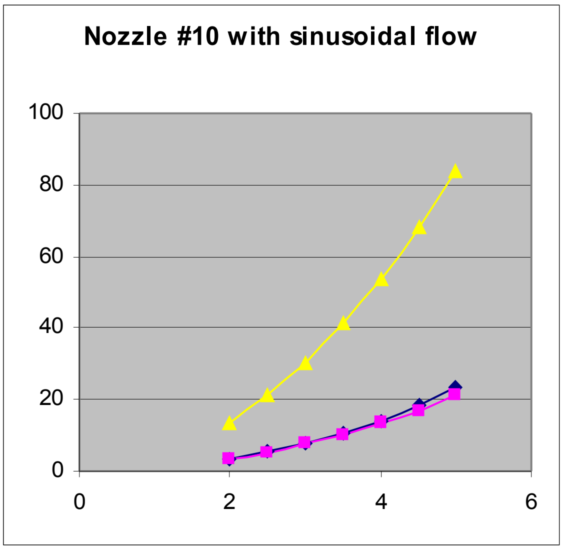
These records set as an evidence the fact that the pop-pop cycle is better than a sine cycle ; and this corresponds to our thoughts.

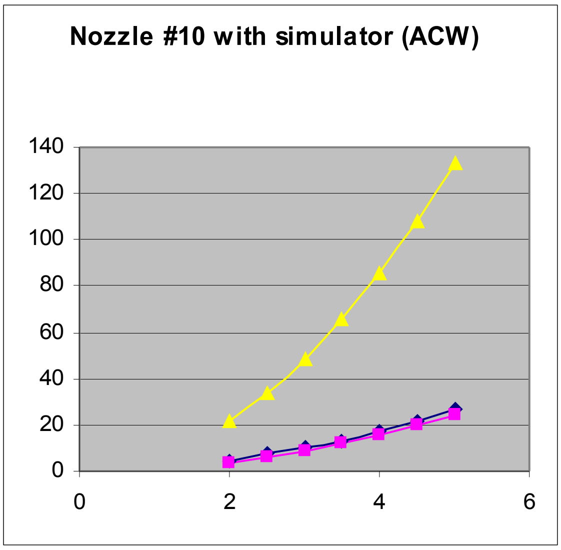
After these measurements (in order not to be influence by an early knowledge of what we should have recorded) we have calculated for the nozzle #3 what we should have theoretically measured. The method used for the calculations is explained in the appendix.



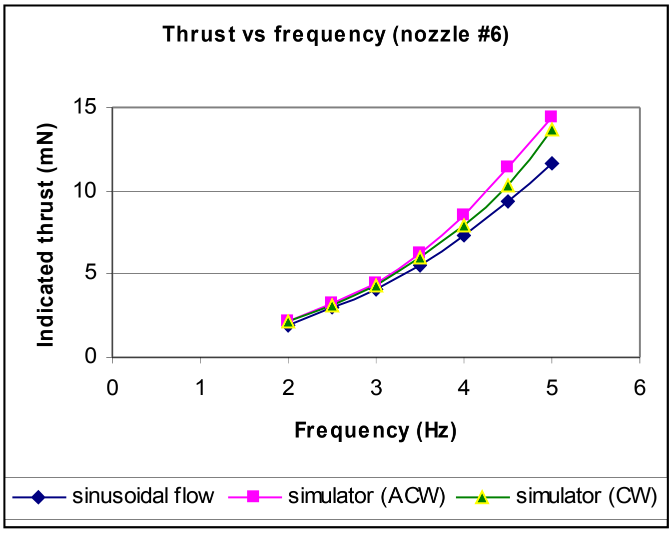


The blue curve shows the measured thrust. The magenta one shows the calculated mean value. Both curves should be identical. The yellow curve shows the pick value of the thrust. For the simulator, the graph displays what we got in the anticlockwise running. In the other way the curves are similar. They are not displayed to limit the size of this report. Then we did the same with the nozzle #10.



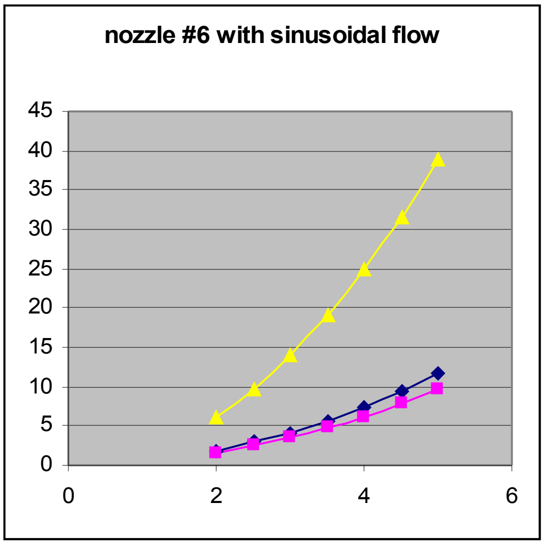


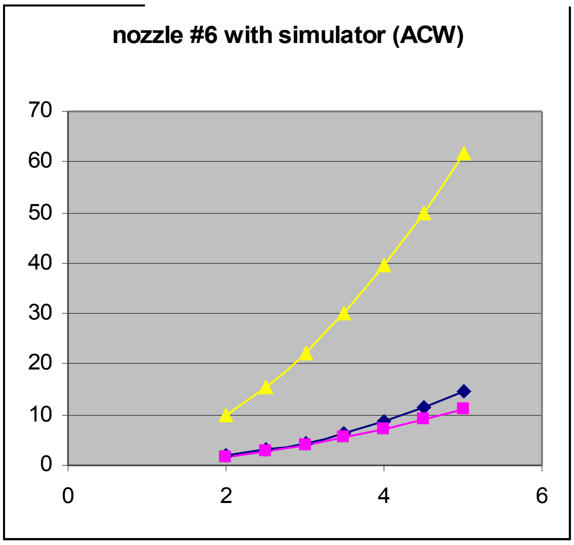
There, the curves are closer. We would have liked the same for the nozzle #3. Therefore, to look for a possible error or a particular law we have tested a third nozzle (#6).



The discrepancies between records done clockwise and anticlockwise are closer to what we expected.

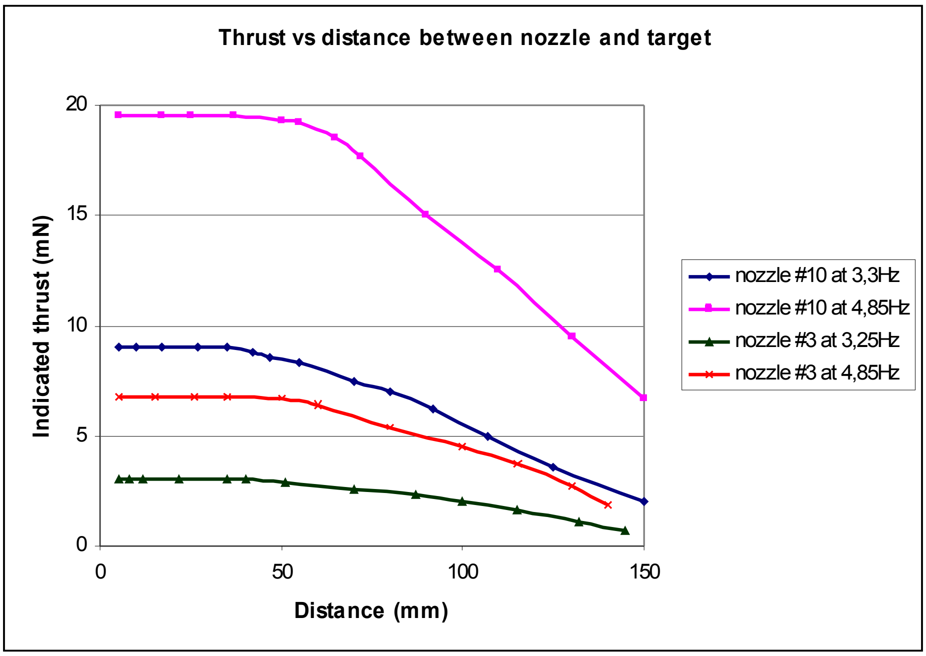
This could be due to the fact the test bench was dismantled and reassembled before these tests. The main axis of the rocker arm was more rigid, and a spring helped the movement of the rocker arm.





With the nozzle#6, like with the nozzle #3, we find again a measured thrust bigger than the theoretical mean value.

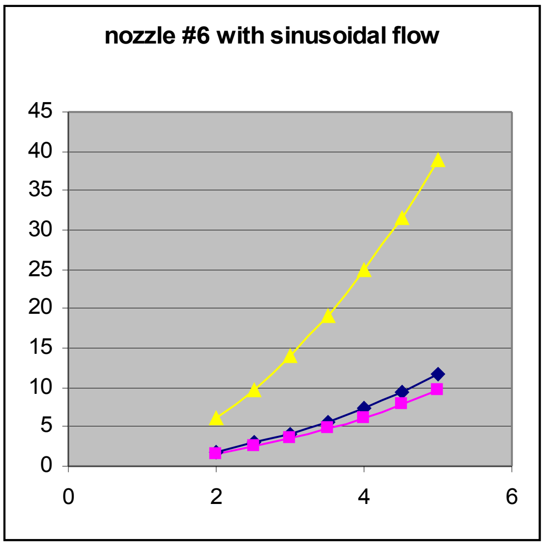
Before to examine why we observe this difference, we took the opportunity of the use of an accurate test bench to confirm a study previously done with more rustic means : the study of the influence of the distance between nozzle and target.



One can see that up to 40mm there is no decrease of the indicated thrust. As all our measurements were done with a distance between 10 and 15mm they are not erroneous because of the distance.

Why do we measure more than the theoretical thrust ?

Example of record:



In purple the theoretical mean thrust versus frequency.

In blue the measured thrust.

In yellow (for information) the maximal theoretical thrust; i.e. the pick value.

Thrust in mN and frequency in Hz.

The thrust measuring test bench indicates <u>always</u> (we ran approx hundred tests) a thrust that is bigger (by 10 to 40%) than the theoretical mean value. This could be caused by at least two phenomena:

<u>1°) Lack of filtration.</u> The thrust indication was fluctuating between 1 and 4 mN, depending on the nozzle. (2mN for our example). We always used the arithmetic mean value, but doing that we introduced a small error => The measuring pendulum is to be completed by a dash-pot.

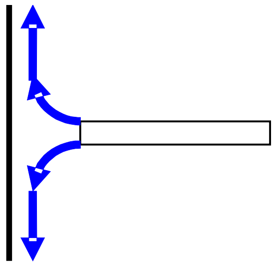
However, the lack of filtration cannot explain so big discrepancies between theory and practice.

<u>2°) Recirculation of the water in the tank</u>. This phenomenon was evoked in a previous report. Here, we set it as evident.

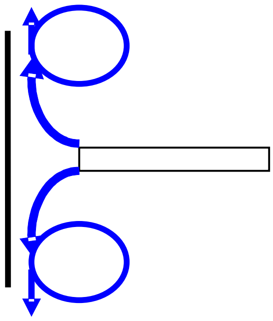
a) First we observed vortexes thanks to (unexpected) impurities into the water.
b) Then we built a micro mooring buoy.

This device is made of a small weight (2g), a piece of sewing thread and a small polyurethane foam float (diameter 8mm) adjustable along the thread thanks to a little pin. We placed this device in the tank at various places and we observed the inclination of the thread, and most of all the movements of the float. It was clearly visible that some water was re-circulated towards the target; therefore, the momentum was bigger than what it would have been in air.

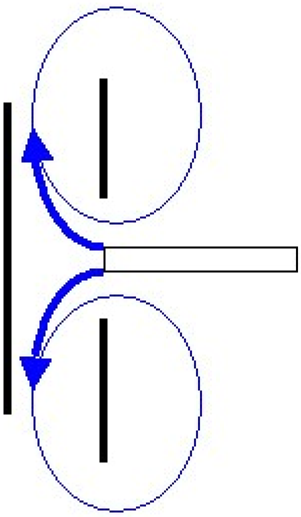
Dans l'air T=q.V



Dans l'eau T>q.V



c) Then we placed some screens (chicanes) at various places inside the tank (not on the direct jet flow) and we saw a decrease of the thrust indication. The *right* thrust was got with a screen arranged as shown on the following scheme.



Such a screen doesn't prevent vortexes, but they are large rand the water which comes again towards the target has lost most of its velocity.
Our screen had a hole in the middle of approximately 3.5 times the nozzle diameter.

Another alternative could be to decrease the target size, but in that case you must be sure that the jet is well oriented.

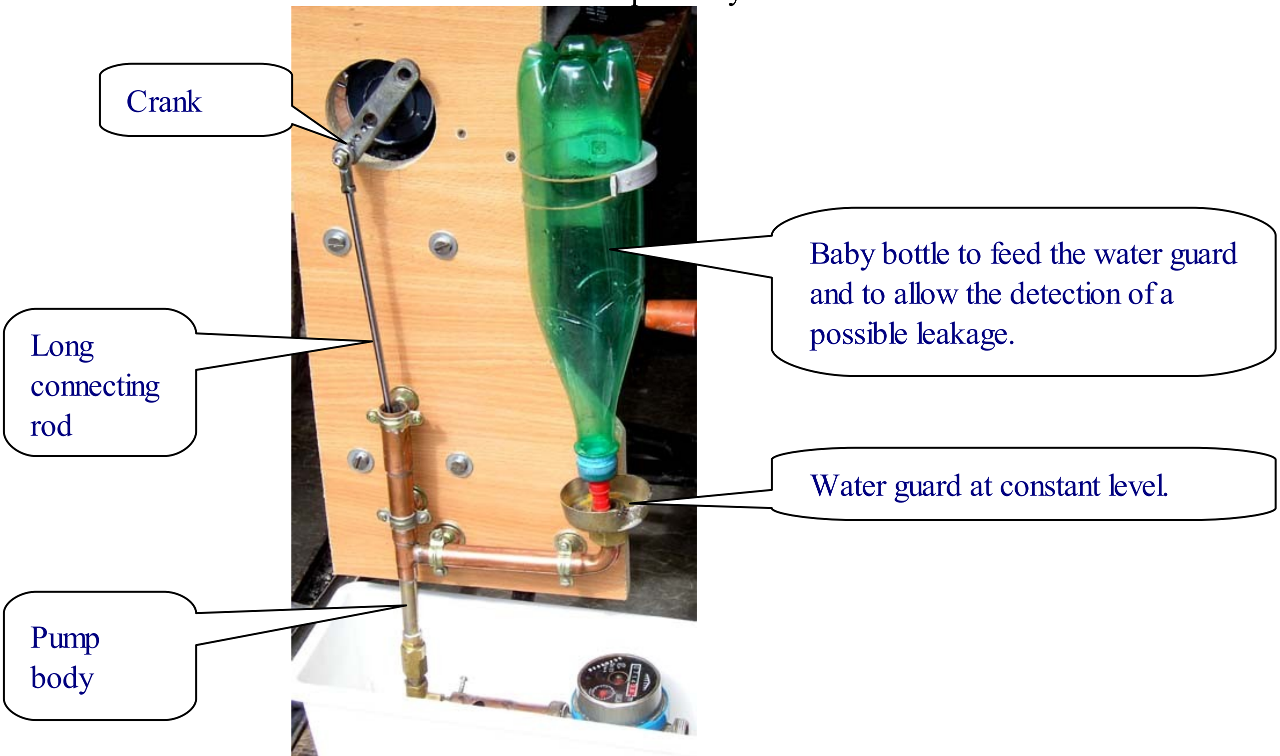
Conclusions (preliminary) :

- As expected, the recorded curves are parabolas (taking into account the accuracy of the measurements).
- The thrust difference measured with the simulator between the clockwise and the anticlockwise rotations is smaller than expected. It cannot be a measuring error because that is true for every record. The flexibility of the assembly could be the cause. The axis used for the rocker arm was not rigid enough. After dismantling and reassembly, for the test of nozzle #6 we have got results that are more in accordance with theoretical values.
- The relative accuracy is rather good with nozzle #10. It is not so good with nozzle #6 and worse wit nozzle #3. The absolute error is roughly the same; maybe because the recirculation velocity is mainly evolving with the flow instead of the jet velocity
- Due to the inertia of the water snake the cycle of a pop-pop engine is not so far from a sinusoid. A simple sinusoidal model could help to get estimates.

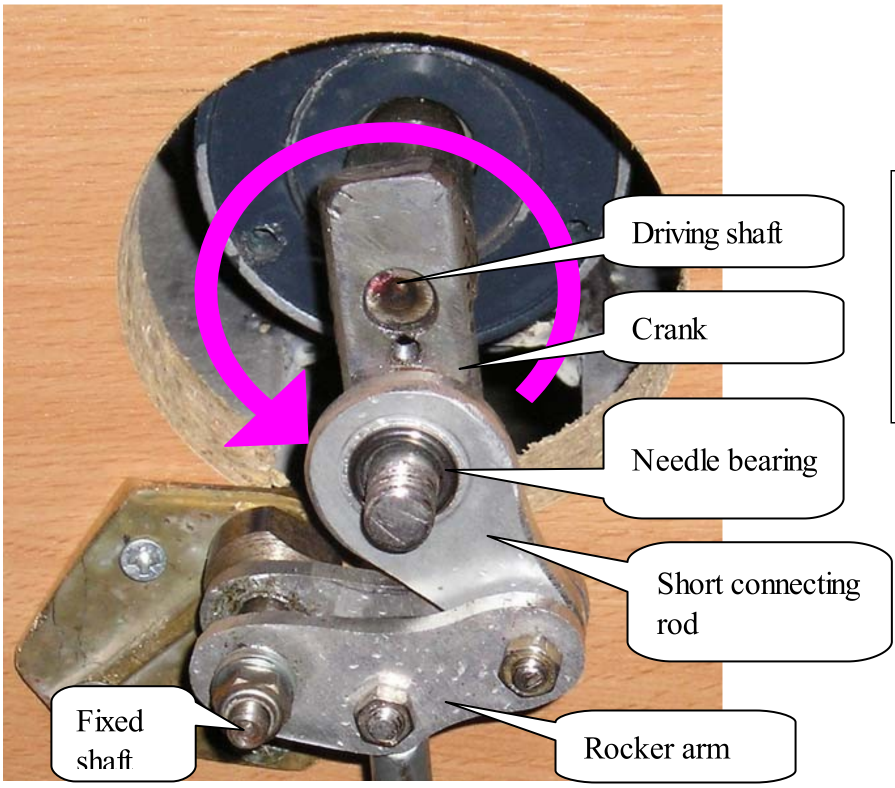
Appendix

Practical realization :

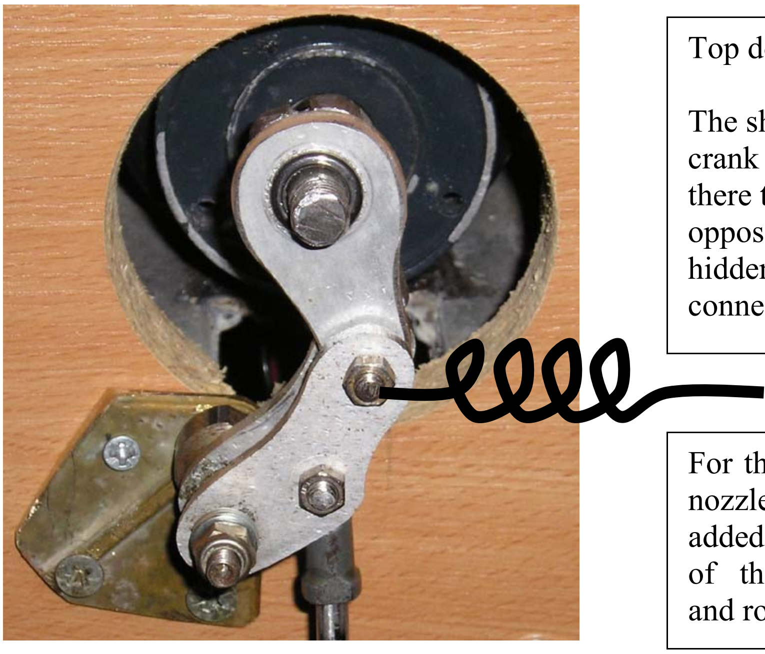
We have reused the bench described in the report "Hydraulic test bench" reminded hereafter



and we have modified the upper part.



Picture taken just before arrival at the BDC. Connecting rod and crank are nearly aligned.



Top dead centre.

The short rod and the crank are aligned, but there the crank is in the opposite direction (and hidden by the connecting rod).

For the tests of the third nozzle this spring was added to avoid buttress of the connecting rod and rocker arm.

Nozzle data (in the same order as the tests)**:**

Nozzle #3. Cylindrical. Internal diameter 6mm. Thickness 1, but end outlet grooved at 45°.
Nozzle #10. Internal diameter 3.5mm. Thickness 0.25mm.
Nozzle #6. Internal diameter 5.15mm. Thickness 0.42mm.

Thrust calculations :

At any time the thrust is T=q.V q being the mass flow and V the velocity of the water going out of the nozzle. On a whole cycle (rotation of 2π of the driving shaft) the mean thrust is given by integration of elementary thrusts <u>positive or negative</u> (but not both simultaneously).

$$T_{moy} = \frac{1}{2\pi}\int_0^{1/F} qV dt = \frac{\rho S}{2\pi}\int_0^{1/F} V^2 dt = \frac{\rho d^2}{8}\int_0^{1/F} V^2 dt$$

d being the nozzle diameter and ρ the specific gravity of water (1000kg/m^3).

<u>When the movement is sinusoidal,</u> the displacement of the piston (for our 16mm stroke) is: $8.10^{-3}\sin(2\pi Ft)$. The one of the water through the nozzle is $8.10^{-3}.(12.10^{-3}/d)^2\sin(2\pi Ft)$. Its speed is the derivate; i.e. $V=8.10^{-9}(12/d)^2 2\pi F\cos(2\pi Ft)=7,238.10^{-6}F/d^2\cos(2\pi Ft)$; which leads to

$$T_{moy} = \frac{1000d^2}{8}\int_0^{1/F}[7,238.10^{-6}\frac{F}{d^2}\cos(2\pi Ft)]dt = 6,55.10^{-9}(\frac{F}{d})^2\int_0^{1/F}\cos^2(2\pi Ft).dt$$

The integral of the positive part of cos^2 is 0,5π. Hence $T_{moy} = 10,3.10^{-9}(\frac{F}{d})^2$

Or, with more common units with d in millimeters and T en milliNewtons:

$$T_{moy} = 10,3(\frac{F}{d})^2$$

<u>When the movement is complex</u> (case of the simulator mechanism with connecting rod and rocker arm) we don't know easily how to write the equation and getting its derivate is worse. But, thanks to computer science it is easy to get the result by splitting the function in small time intervals. We

used that method to split the cycle (360°) into slices of 10° each. A better accuracy was not needed at this stage. At each calculation step we have determined V and replaced the integral $\int V^2 dt$ by the sum $\sum (V_{t+\Delta t} - V_t)^2 \Delta t$.