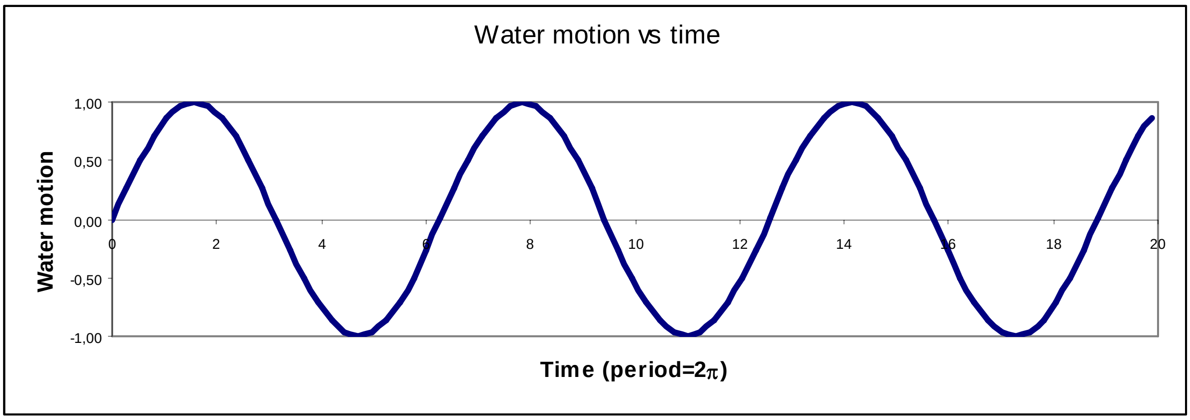
Pop-pop engine and electrical analogy

One can reasonably think that the water motion in the pipe of a pop-pop engine is sinusoidal. This assumption is justified –thanks to some experiments done with transparent pipes- by looking at the steam-water interface, and by looking at the motion of small particles in suspension in the water.

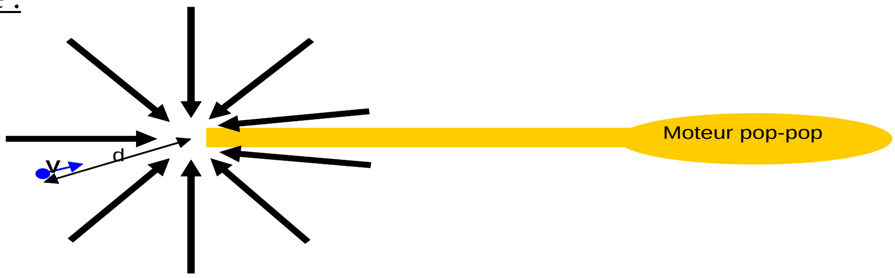


Professor Le Bot did some thrust measurements, and we did some flow ones at 1 or 2cm of the pipe end. Neither the thrust balance, nor the flow meter has seen the negative half of the wave. This can be justified by the following explanation.

<u>Propulsive phase :</u>

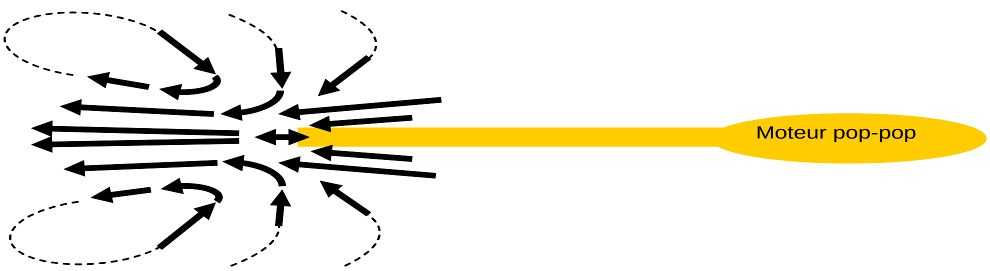
Outgoing water drives surrounding water in the same direction. Along the axis of the nozzle the speed is high.

<u>Relaxation phase :</u>



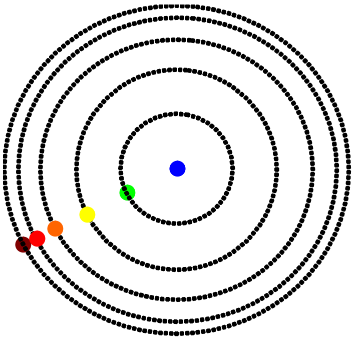
A low pressure is created. It draws from every direction the surrounding water. If we except the pipe itself, it can be considered that along each direction there are two opposite water motion which cancel each other out. Furthermore, the more the water is away from the sucking orifice, the slower is its speed.

<u>Superposition :</u>

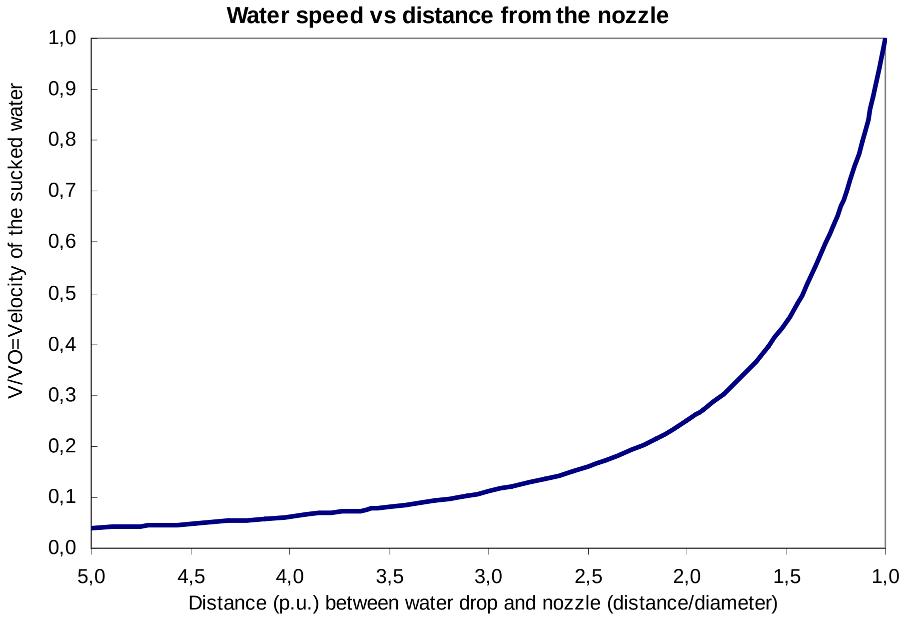


1°) Mathematical approach of the relaxation phase :

Water being incompressible, when a small amount is sucked by the pipe (a sphere of radius R, volume $4/3\Pi R^3$), it is replaced by water coming from the surrounding sphere of which the initial volume was double, itself replaced by water coming from the surrounding sphere of which the initial volume was triple, and so on.



Let's consider a water droplet (in color on the drawing). At each successive time interval it is located as shown in brown, then, red, orange, yellow, green and blue. At time "t" it is located at a distance "d" of the *black hole* which attracts it. To simplify, in the numerical application we will neglect the small volume of the pipe inside the sphere. The droplet is moving at velocity "V" which is the derivate of "d" versus time. We can display as a graph the speed which varies versus the distance of the droplet from the center of the low pressure.



This graph shows for instance that at a distance of 3 times the nozzle diameter, the speed is already divided by approximately 10.

2°) Visual approach :

We have looked at solid particles in suspension in the water.

When there is a permanent sucking flow, we can see them from all around going slowly towards the nozzle, then faster, and finally entering quickly into the nozzle; which confirms or justifies the mathematical approach.

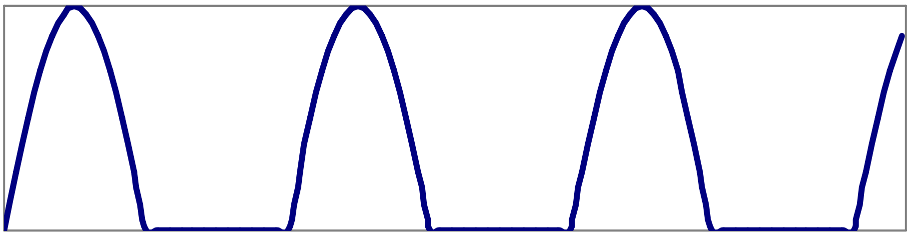
When it is a reciprocating motion, (case of a pop-pop engine) the particles away in a radial direction follow a sort of elliptic motion (as the two loops drawn on the superposition image). On several occasions we could observe this during more than a tenth of minutes. The particles that reach the nozzle are animated of a reciprocating motion. But as soon as they move a little away from the nozzle in its axis vicinity, they get an axial movement, (towards the left on the drawing) the amplitude and the speed of which depend on the distance.

Last, we have to say (though it will not be taken into account later) that due to the incompressibility of the water and due to its high density, and due to the fact the pop-pop boat nozzles are generally near below the water surface, the amplitude and speed are in fact slightly bigger near the surface, compared to side ones or to the ones below the nozzle. When there is a really low pressure (permanent or alternate) an indentation can easily be observed on the water surface just above the nozzle.

The purpose of all this was to show the important dissymmetry of the flow out of the pipe. In practice, during the relaxation phase neither flow, nor thrust can be measured if a bit away from the nozzle.

3°) Useful flow versus time :

Hence, the useful flow (useful for propulsion) versus time can be represented as follows.



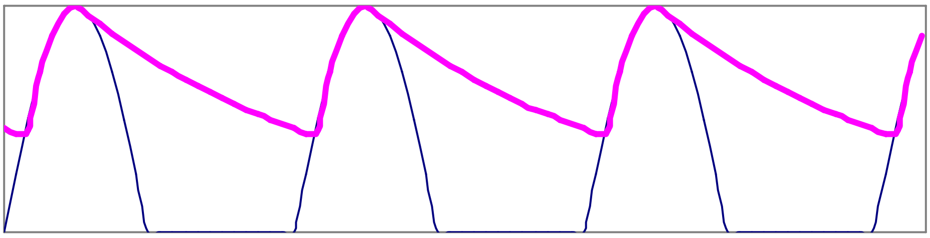
The maximum flow of a sinusoidal water jet is $Q_{\max} = \pi.Volume.Frequency$

Electrical analogy

In electricity, the above curve looks like the one delivered in AC after a half-wave rectifier (single diode). We will push further the electrical analogy. The mean velocity of the flow is $v_0 = \frac{C.F}{S}$ and the mean flow as volume is $Q_{moy} = \frac{\pi}{2} C.F$, but what are the effective values? They are the ones which would give the same thrust as a direct flow when observed during a long time (or an integer number of periods).

$$V_{eff} = \frac{\pi}{2} v_0 \qquad Q_{eff} = \frac{\pi^2}{4} S.v_0$$

But, in fact, the flow seen by the flow meter (or the thrust seen by the flap) looks like the voltage after a half-wave rectifier followed by a capacitance and a resistor. When the frequency is high the flow (or the voltage) is close to the peak one. When the frequency decreases, the flow decreases too.



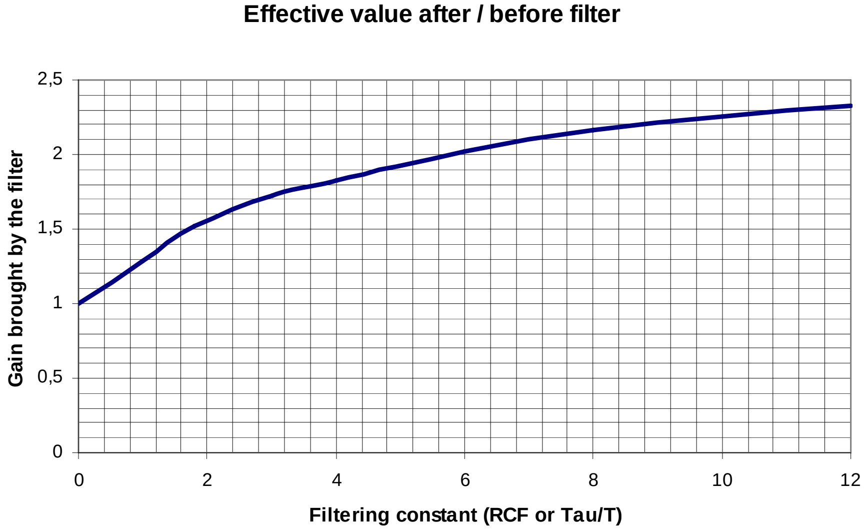
When starting a pop-pop engine, the flow and the thrust are zero. We will neglect this phase which doesn't last long. Then, if RCF (Time constant x Frequency) is infinite, the flow is equal to the pick one. And if RCF is zero, the flow is equal to the pick value divided by $2\sqrt{2}$. The truth is in between these two extreme values.

What could represent C and R?

The capacitance of the capacitor corresponds to the inertia of the water in motion. The capacitor accumulates energy ($E = \frac{1}{2}\int_0^t QV^2 dt$) when the speed of the water delivered by the nozzle increases, and restitutes this energy when the speed decreases. The resistor represents the mechanical losses involved by the water movements (fluid friction losses). This energy becomes calorific energy which dissipates in surrounding water. (Nothing is lost, nothing is created…)

If T is the pop-pop period, the effective flow can be defined by analogy with the formula used in electricity as $Q_{eff}^{\ 2} = \frac{1}{T}\int_0^T Q_{(t)}^{\ \ 2}\,dt$, $Q_{(t)}$ being the flow at time t.

When designing a filter in electronics, to do it easily, we use to replace the unloading exponential by its tangent at the origin. But our filter being a bad one (we will see this soon) the sine and exponential functions being well known, by means of a PC it is easy and more accurate to calculate Q_{eff}/Q_p versus RCF. And, as we know that $Q_p = \pi(Vol \times F)$, we can draw the curve Q_{eff}/(Vol x F) versus RCF.



Simultaneous measurements on a flap and on the hawser of a pop-pop boat have shown that the thrust indication given by the plate is overestimated. The excess of thrust varies according to the test means; mainly according to the tank size and the flap area. Let's take the example of an overestimate of 50%. Entering 1.5 on the left of the above graph allows to determining the coefficient RCF which is 1.8. This means that the practical flow versus time looks like the following curve.