# Propulsion of a boat by means of a pop-pop engine

Contribution to the knowledge of the pop-pop engine.

**Warning:** This document was written in its original version in February 2005. Some complements and corrections have been made but it has not been completely updated. See the documents written later.

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**0. Forewords**

With no special interest at that time I had seen pop-pop engines for decades. In January 2005 one of my children brought back to me from India the toy whose picture is given on the front page. I really enjoyed this toy… from the scientific point of view. Curiosity, availability (just retired), adapted scholarship and industrial experience about thermal engines do the rest.

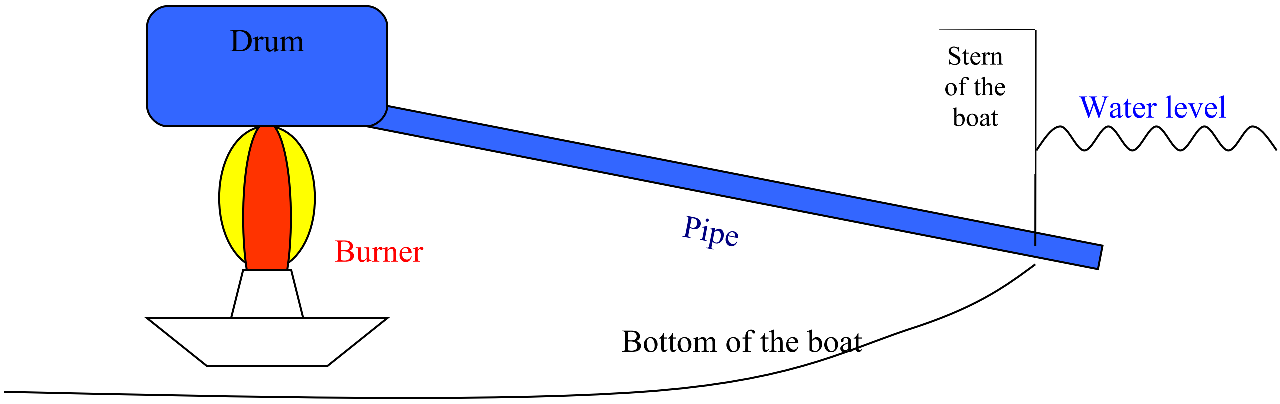
Looking at tens of Web sites (in French and English) related to pop-pop engines shows that most of them have mostly a mercantile content or purpose. One can see mainly small toy boats built abroad, notably in India and sold in Europe 10 to 50 times more than locally. A few sites of enthusiastic amateurs are more interesting. Finally, a limited number of sites show a scientific aspect. Unfortunately the given explanations (Helmoltz resonator, Stirling engine, Rankine or other Carnot cycle…) have only a remote connection with our subject, or are incomplete. At least these sites do exist, and joining forces…

Though the quantification of the phenomenon of physics that makes the pop-pop engine works is difficult, its description is nevertheless easy (cf. §6). However none of the examined sites explain why at a given time of the cycle a vacuum is created in the boiler. Two basic scientific notions are generally missing: kinetic energy and overheated steam. In addition, many other details are not mentioned. We are going to try to fill this lack with explanations understandable by anyone.

Despite the fact that the efficiency of a pop-pop engine is very very bad, knowing the problems of water quality and water treatment in a water-steam cycle it is unrealistic to foresee building a big pop-pop engine for an industrial application because the water that it uses is the one on which the boat is sailing. Nevertheless the topic – even for toys manufacturing – is interesting. Therefore, for those who are willing to go deep in it we will supply a calculation method and the formulas that apply to relevant phenomena of physics and thermodynamics. There is much to do!

Some recommended sites:
www.eclecticspace.net
www.sciencetoymaker.org/boat/index.htm (the best)
www.chez.com/llegoff/poppop (has a picture of the same Indian boat as mine)
www.galepp.com/boat/popboat.htm (idem)
http://ourworld.compuserve.com/homepage/jp_perroud/poppop.htm
http://membres.lycos.fr/moudge
A last site interesting for the history and an eccentric point of view, but which is disgusting for its mercantile aspect: www.pop-pop.fr . But, whatever, if INPI (French office which registers the brand names) accepted in 95 to register “bateau à moteur pop-pop” (pop-pop engine boat) for the exclusive usage of a privileged company, it is mostly INPI that is to be blamed because this group of words was known and used for decades. It is as if today a car seller would register “car with a diesel engine” as a brand name to try to dominate the market. This present document has no commercial issue, nevertheless, to avoid any misunderstanding this said registered group of words will not be reused.

**1. Architecture of a pop-pop engine.**




**2. Description.**

Though there are many kinds, the pop-pop engine is a model of simplicity. There is not any moving part. The most common ones use two parallel pipes to ease the filling, but to understand how it works, only one suffices. (This will be demonstrated.) This pipe which sends water towards the boat stern (pulsated waterjet effect) is supplied by a steam drum. This one is a drum in name only. It doesn't have the usual shape of a boiler steam drum because at the same time it is used as a drum and as a heating place, and must have a large internal surface to ease the steaming. And, in order to generate a pop-pop sound the drum includes a deformable metallic diaphragm. The heat needed for steaming comes generally from a candle or a very small pan filled with alcohol.

According to one of the examined Web sites there is a model improved by using of a condenser. The condenser is a simple absorbent tissue damped with cold water and set on the pipe near the drum. At the same time the tissue is supposed to be a bilge pump thanks to capillarity. Some people dare to say that!

**3. Where does the "pop-pop" sound come from?**

Let's now say a few words about this in order not to come back on this matter. The well known sound is due to the deformation of a small and thin metallic membrane (as the top of some preserve cans), sometimes convex, sometimes concave. This metallic membrane is an integral part of the drum and is distorted by the cyclic pressure variations inside the drum. The sound level increases with the suddenness of the change between concave and convex. To improve this, at rest the membrane could be concave with a slight strain. The sound is something that can be heard by spectators, but it is not needed for the good working of the engine. On the contrary! The variation of the steam drum volume due to the deformation of the membrane decreases the efficiency of the engine. But the efficiency of the pop-pop engine seems not to be a concern for anybody (except on one site*).

For additional info about the sound generator of the toy we have studied see annex 1.

Note*: Only one of the examined Web sites says something about efficiency. And what an efficiency! 60%! 60% of what? Knowing the works of so many smart scientists for decades to reach an efficiency of about 50% on a supercharged diesel engine, and far less on a turbine one must be dreaming. See §8.3.3.

## 4. Small reminders of mechanics and thermodynamics:

### 4.1. Thermal engine.

Can only work between two heat sources having different temperatures. There are many theoretical (simplified) cycles: Carnot, Rankine, Beau de Rochas, Sabathé, Stirling, Lenoir, Diesel… None of them corresponds to our application. But we always find 4 main steps:

1. Compression of a gas
2. Addition of heat
3. Expansion and production of mechanical energy
4. Cooling

### 4.2. Physical characteristics of the water:

At standard atmospheric pressure and at 100°C, the specific density of water is 958kg/m$^3$, the steam one is 0,59kg/m$^3$. Therefore, a drop of water changed into steam takes 1650 times its initial volume.

### 4.3. Kinetic energy:

Any moving object having a speed V (in m/s) and a mass m (in kg) is characterized by a kinetic energy E (in Joules) which is defined by $E = \frac{1}{2} m V^2$.

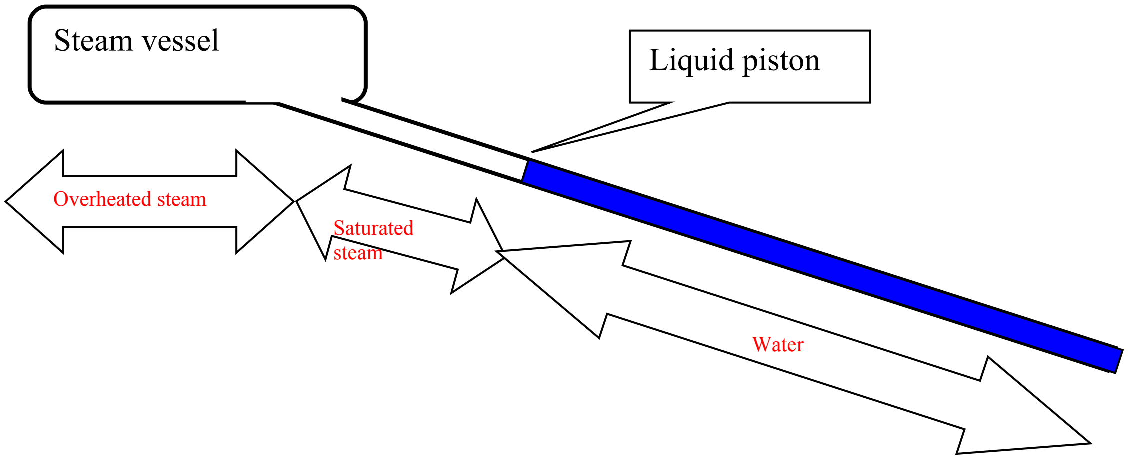
Any speed change of this mobile requires a transfer of energy between it and the outside. The term *object* is to be understood here in a broad sense. It is not necessarily a solid. For our application it will be a liquid: the water inside the pipe.

### 4.4. Saturated or overheated steam:

Everybody knows the improperly called saturated steam. It is the one we see just above the saucepan or at the pressure cooker output when the water boils. In fact it is visible because it is a mixture of steam (gas) and micro-droplets of water (liquid). It exists another kind of steam which is not so known, nor even easily guessed: it is the overheated or superheated steam. It is not visible. It is commonly used to supply steam turbines; for instance at 60 bars and 515°C, though the boiling temperature at that pressure is only (!) 275°C.

When a mass of steam is overheated its energy (it is called enthalpy) is increased, which doesn't mean that the pressure is changed. For instance, at standard atmospheric pressure and 100°C the enthalpy of the saturated steam is 2672 kJ/kg, but if at the same pressure the temperature is increased to 150°C, the volume is multiplied by 1.13 (ratio of the temperatures in °K) and the enthalpy becomes 2777 kJ/kg.

What must be understood to follow is that it is possible simultaneously to increase the temperature and decrease the overheated steam pressure. That could be obtained by heating a container of variable volume, for instance a cylinder provided with a piston. During the heating process, the temperature and the enthalpy can increase though the pressure can decrease because the piston is moved. In a pop-pop engine there is no metallic piston, but the free surface of the water inside the pipe moves and acts as a piston.



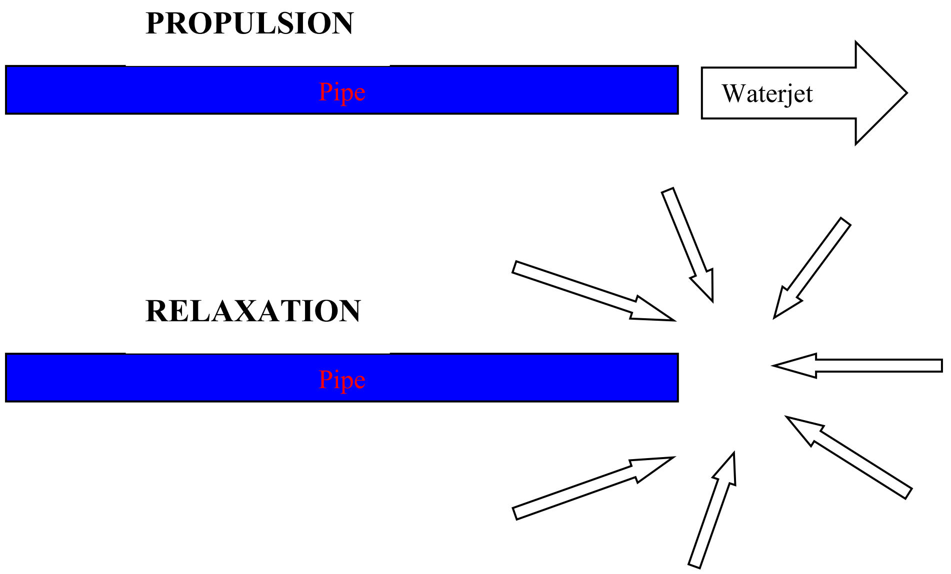

**5. How does the pop-pop engine propel the boat?**

The water located inside the pipe is alternately pushed and pulled (sucked) by the drum. We will see later why. From that point, 3 asymmetrical phenomena contribute or could contribute to propel the boat.

1°) The hull of the boat has an asymmetrical profile which facilitates its forward move when submitted to alternate solicitations. Certainly this is not the most important factor. When we rock between ahead and astern on a dinghy with sharp bow and stern transom we succeed in making it move forward, but using the same energy to handle a scull oar gives a quite better effect.

2°) The alternate movement of the water inside the pipe is not symmetrical. Indeed, water can move faster towards the stern than forward because the effective depression inside the drum cannot exceed the steam limit (0,023 barA at sea level with standard atmospheric pressure). There, once more, one can doubt the effect of this asymmetry except in one case described in §11.

3°) The water flow at the extremity of the pipe is not reversible. In the propulsion phase the water is pushed astern (propulsion by pulsed waterjet). In the relaxing phase the water comes from any direction. This is something which is well described on many Web sites.



A comparison can be done with a two stroke engine which is characterized by a period of propulsion during the expansion of the gasses, and a period of braking – not so much – during the compression phase.

To eliminate any a priori a test has been performed on our Indian toy by fitting two elbows at the outlet of the pipes in order to aim the jets sideways. Result: phenomena 1 and 2 have no effect. The boat was no longer sailing in spite of a good working of the engine.

For those who would be interested, we have written a small specific document to explain the "working principle of a pulsed waterjet".

**6. Running (simplified) of the pop-pop engine:**

The chronological break down is as follows:

- Initial situation: drum and pipe full of water.
- Firing of the burner.
- Vaporization of the water inside the drum.
- The steam pushes the water into the pipe.
- The water snake located in the pipe is in progress.
- The drum contains only a remaining of steam that is being overheated.
- The water snake – due to its inertia – continues to move and creates a partial vacuum in the drum. The vacuum is improved by the fact the steam moving in the pipe cools down and condenses. This slows the liquid piston, and then reverses the movement.
- The water reaches the drum and is transformed quasi-instantaneously into steam when touching the metal. ….

And this, until the flames extinguishes. Then the drum cools down, the steam condenses and we come back to the initial situation with drum and pipe full of water.

This qualitative description illustrates perfectly how the pop-pop engine works but nothing is quantified, and if it is easy to justify the permanent conditions it is more difficult to explain why or how it starts. How can we succeed in reaching during the first seconds a speed of water sufficient enough to create a vacuum in the drum? The answer is not obvious. Indeed, as soon as boiling begins steam pushes water (at approximately 100°C). As the steam gets further in the pipe it cools down, on one hand by contact with the pipe, and on the other hand by conduction and mixing with the one met further down in the pipe. This cooling involves condensing of the steam located close to the separation surface. This pulls up the water… We will try to give a more detailed explanation in chapter 12.

Our Indian pop-pop engine seems to find its cruise frequency after between 2 and 3 seconds, but the amplitude of the vibrations increases during the 2 or 3 following seconds.

About the amplitude of the water movements inside the pipe, intuitively one can think that the exhaust of the steam is to be avoided, but the best result should correspond to the renewing of practically all the water at each cycle. Therefore, there is a good compromise to find between the heating power and the sizes of this propulsion plant.

**7. Factors influencing the performances:**

Temperature and power of the hot source
Temperature (and power) of the cold source
Areas and thermal exchange coefficients
Shape of the drum
Diaphragm softness
Position and shape of the drum-pipe junction
Thermal inertia of the drum
Thermal inertia of the pipe
Length of the pipe
Diameter of the pipe
Diameter and profile of the nozzle (the orifice)

It can be added that for the adaptation to the propulsion of a boat some other factors play a role:

Hull profile
Displacement (mass)
Position of the center of gravity
Inclination of the pipe
How deep in the water is the nozzle
Height of the drum from the water

Theoretically we also should take into account the hydrodynamic pressure due to the boat speed, but this one is very small and consequently negligible.

**8. Analysis of what exists:**

What was learned form the tests – up to now non destructive – performed on a toy:

**8.1 Measurements:**

- Boat mass: 30g (including the engine, but empty)
- Drum mass: about 4g
- Thickness of the heated part: 0,4mm (including soft metal)
- Material: steel (tin-plate) except for the membrane which is made of brass.
- Internal diameter of the 2 pipes: 3.3mm
- Length of each pipe: 86mm
- Total volume (drum + pipes): about 2.2cm$^3$

**8.2. Experiments:**

- The frequency of the cycle is quasi independent of the heating power; above a certain minimum. Some tests were performed with power ratio approx from 1 to 10.
- The delivered mechanical power increases with the heating power. This is visible on vibrations and amplitude of the generated waves. It is clearly felt when the boat is held in place by a hand.
- The toy speed (from 0.2m/s ahead to 0.2m/s astern; forced by hand) has practically no influence on the frequency.
- The geometrical height of the drum from the water level (between 2 and 6cm by lifting the bow of the boat) doesn't influence significantly the frequency and doesn't disturb the pop-pop generation.
- Plugging one of the pipes involves a decreasing of the frequency. As soon as it is unplugged it works as previously.
- Lengthening of the pipes by 50% doesn't change significantly the frequency.

- Even after a long period of running the pipes are cold where the fingers can touch them.

- The "cruise" frequency is 7 to 8 Hz.

- At very low power (when the candle goes out but while the wick is still red) the engine is still generating a pop-pop but you must be very close to it to ear it because the membrane is no longer moving as before.

- The heating power that we used (F) was about 28W. (The heat source is a small birthday candle, the power of which was evaluated by heating a well known water quantity and measuring the temperature increase versus time. Pictures of the test and file of the measures are available.)

- The "cruising speed" V is approx 0.15m/s (0.54km/h)

- Towing the boat at that speed requires a pulling force of approx 2mN (2 milliNewtons). It is minute. So minute that it is the measure on which the uncertainty was the worst one. We performed many additional tests with better measuring tools to improve it's knowledge.

**8.3. Deductions:**

8.3.1. Frequency.

It seems not influenced by most of the parameters. It is something as for a pendulum the amplitude of which can be changed easily, but the frequency of which is constant so long as neither the moving mass nor rope length is changed.

8.3.2. Liquid piston stroke.

Because of the propulsion principle, the boat being sailing at the speed V, the output of the waterjet needs to be at least once par cycle faster than V.. $v_{max}>V$

Let's suppose the flow perfectly sinusoidal. Every point of the liquid snake moves by $d = aSIN\omega t = aSIN 2\pi Ft$ F being the frequency of the cycle. Derivation of this equation gives the speed of the water inside the pipe. $v = 2\pi FaCOS 2\pi Ft$

$v_{max}=2\pi Fa>V$. With F=8Hz and V=0.15m/s we get $a>3,2.10^{-3}$m a>3,2mm

a being the half amplitude of the displacement, the total stroke is more than 6.4mm.

8.3.3. Efficiency:

These last three data allow to compute the global efficiency which is the ratio between the released mechanical power (drag force multiplied by speed) and the supplied heating power which is the one of the candle: $r = \frac{T \times V}{F}$ For this application $r = \frac{0.002 \times 0.15}{28} = 0.0011\%$. It's pathetic! As the measures were not performed as laboratory ones, the relative uncertainty on some of them is big; but they are only three. Assuming we were very bad or very unlucky so that on the three of them we made an error in the same way, and from single to double (it is nevertheless enormous to do that), the efficiency would become 0.0088%. We can accept that during the "endurance" test the flame of the candle was not as big as it could have been, and if we accept a worse condition 10 times less, the best result could only reach 0.088%. It is to be compared to the 35% of a classic propulsion (50% for the engine and 70% for the propeller). This is still very very bad and justifies that there has been no industrial application of the pop-pop engine.

Comparison of a propulsion by pop-pop engine with a mechanical propulsion (spring+propeller) on toys of the same size.

1°) Spring. To wind up the spring requires about 10 turns of the key with a torque of 200mNm (0.2Nm). Corresponding energy: 0.2*2*p*10=12.6Joules. It is minute. This engine propels the boat for approx 12.6 seconds (to simplify). Therefore, the power is 1W. Taking into account the mechanical efficiency and the one of the propeller the delivered power is smaller. Let's say 0.5W.

2°) Candle. Though it is not obvious, the power and the energy delivered by a candle are relatively big. A small birthday candle (mass: 1 gram) delivers approx 35W as heat, and it takes 10 minutes to burn. Corresponding energy: 21kJ. With 2 grams burnt in 5 minutes (data from Professor Le Bot) it means 42kJ and 140W.

3°) Efficiency. The efficiency of such a small toy is likely about 10 times less than the one of a big ship; i.e. approx 3.5%. Professor Le Bot measured similar thrusts with mechanical propulsion (1W $3.10^{-2}$N) and pop-pop propulsion (140W $1.8.10^{-2}$N). It means a ratio of 233 in favor of the mechanical propulsion. Dividing 3.5% by 233 gives 0.015% and it can be checked that it is lower than 0.088% calculated before by excess. This consolidates our measures and computations.

Note: specific experiments ran in 2006 with an electric heating source allowed to improve the knowledge of the efficiency and to improve the efficiency in some circumstances. However, it remains very bad. See the document entitled "Efficiency of a pop-pop engine".

### 8.3.4. Pipe temperature:

The efficiency being what it is, nearly all (more than 99%) is heat; that is to say increase of the water temperature and of the surrounding air. At this step some data are missing. Let's assume that the amplitude of the water oscillation in the pipes is 40mm (the only certitude is that 6.4<<a<86). The volume of water renewed at each cycle is $V = \frac{\pi D^2}{4} \times 40 \times 2 = 0.68 cm3$. At 7 to 8 Hz this corresponds to an average flow of 5 $cm^3/s$. This water comes from the surroundings in which the boat sails, for instance at 20°C it increases by $\Delta \theta = \frac{F}{Q \times c} = \frac{28}{5 \times 10^{-3} \times 4185} = 1.3^\circ C$ and becomes 21.3°C. In fact, due to the partial renewing of the water, and due to permanent agitation, the temperature is very likely progressively higher when approaching the drum, and this is in accordance with the fact the pipes seem cold when we touch them where they are accessible. This is based on a plausible but not verified hypothesis. If we use a pessimistic one corresponding to a stroke of 10mm instead of 40 (ratio 4), the temperature becomes 25.3°C. It's still cold for the fingers. We will come back on that further in this report.

### 8.3.5. Pressures.

In operation, the effective pressure in the drum fluctuates at 8Hz between a minimum lower than -20mmWG and a maximum higher than 66+40=106mmWG.

Note: Mini and maxi pressures were measured with some other engines. They show that the absolute value of the low pressure is always lower than the one of the high pressure.

8.3.6. Massic power.

When in operation the total weight of the engine (drum + pipes + water) is approximately 8 grams (excluding fuel). This engine delivers a mechanical power of 0.3mW (2mNx0.15m/s). Hence, the mass power is 37.5W/ton.

Let's compare with a pleasure boat. For 37.5kW (51HP) the total weight of engine+reduction gear+shaft+propeller is approximately 250kg. Therefore, the mass power of our pop-pop engine is about 500 times weaker than the one of a classic propulsion plant. It is pathetic.

To be honest we must say that industrial life learned us that extrapolations bring sometimes amazing results. The scaling factor between the toy and the pleasure boat is so big that the truth could be better, but the probability to equal classic propulsion is very low. And we let you imagine how much fuel would have to be carried.

**9. Laws of physics/Mathematical models:**

Remarks:

1°) The best efficiency of a propulsion by waterjet corresponds to an outlet water speed which is very close to the double of the one of the boat; this water being thrown in the air (horizontally). But this principle cannot apply here because the pipe must imperatively be in the water in order not to suck air.

Note 1: In the first release of this document we wrote what follows in italic: *To convince you that it is less efficient you could make a little experiment. Set yourself in the garden with the watering hose and a bucket of water. To hold the hose nozzle you need to exert a certain force in the direction were the water goes. (You counter the propulsive force of a waterjet.) Now, put it inside the water of the bucket, and you will notice that the effort to maintain the hose nozzle is far less.* This is subjective and wrong. In the air the jet noise is louder but the thrust is roughly the same. We did a specific experiment to measure this.

Note 2: Mathematically one demonstrate that the best efficiency of an aircraft jet corresponds to an outlet speed of the gasses which is very close to the one of the aircraft. For a boat the problem differs because the water which is sucked is not steady. The comparative demonstration is available upon request.

2°) The pop-pop engine is disconcertingly simple, but to calculate such a motor requires computing tools which did not exist when it was invented. We face a periodical phenomenon in biphasic environment (water and steam) which is very complex. To analyze it you could simply (soft euphemism) write the equations at time "t" to determine the values of the parameters at time "t+Δt", and do it again for "t+2Δt"… It's a stupid job that a PC is able to do very well and fast insofar as all the algorithms and initial conditions are given to it.

3°) Thanks to relatively high frequency of the pulsations generated by the pop-pop engine (generally several hertz, sometimes several tens of hertz) some parameters can be considered as constant; which ease a little bit the problem. We will note "Hn" the simplifying hypotheses which seem sensible to use.

It remains to write the equations that apply to any subsystem, and to make them interact. We will not go up to the resolution of the problem because there is an infinite number of possibilities depending on the materials used, the geometry of the parts, the power of the heat source… Our purpose is just to show that a modeling is possible, and hence it could be possible to optimize a pop-pop engine, for instance by adapting the heat power and/or the length of the pipes to the water temperature.

## 9.1. Drum

It receives a calorific flow (a power) that can be considered as constant. Also by convection and radiation it loses a power that can be considered as constant. The resulting power F is used to heat the drum and the water in it or to overheat the remaining steam. (For connoisseurs, look at Mollier's diagram.)

H1: the heat power F is constant.

The cycle analysis will be quite longer than the real cycle! To simplify, we will split it in three phases:

- Filling of the drum. Water goes from pipe to drum.
- Water exhaust from the drum. It goes to the pipe.
- Steam overheating. There is no liquid in the drum.

### 9.1.1. Filling of the drum.

The heating power is transmitted to the drum and to what is inside.

$$F = Q_t \rho .c(\theta_t - T_1) + M\Sigma \frac{d\theta_t}{dt} + m_t c \frac{d\theta_t}{dt} + dm_t \alpha$$

In this formula,

the first term corresponds to the temperature increase of the water entering the drum,

the second corresponds to the temperature variation of the metal of the drum,

the third to the temperature rise of the water inside the drum,

the fourth and last term to the steaming of part of the water.

The notations are the following ones:

$Q_t$ = flow as volume of water entering the drum at time t.

$\rho$ = specific gravity of the water. (It varies a little with the temperature, but we will use $\rho$ = 1000 kg/m$^3$)

c = heat coefficient for water. (It varies only a very few with the temperature. We will use c= 4185 J/kg°C)

$\theta_t$ = temperature of the water inside the drum at time t.

$T_1$ = temperature of the water entering the drum. (If the engine is sized properly practically all the water is renewed at each cycle. It can be considered that T1 is the temperature of the water on which the boat is sailing. For instance: 15°C.)

M = Metallic mass of the drum

$\Sigma$ = Mass heat of the metal. (It varies a little with the temperature, but we will use 460 J/kg°C for steel and 400 J/kg°C for copper.)

$m_t$ = mass of water as liquid in the drum at time t

$P_t$ = pressure in the drum at time t. (To limit the risks of errors, use everywhere in the calculations the absolute pressure.)

$\alpha$ = vaporization heat of water at temperature $\theta_t$.

In addition, during this drum filling phase, the content is biphasic and pressure and temperature are linked by the saturation curve (Mollier's diagram). This allows to calculate $P_{(t+\Delta t)}$ and $\theta_{(t+\Delta t)}$ from $P_t$. and $\theta_t$. Therefore, we can track the evolution of the pressure in the drum at each computing step.

### 9.1.2. Water exhaust from the drum.

As the drum contains simultaneously water and steam, it will be assumed that this latter is saturated. The formula is similar to the previous one, but the term corresponding to the water that was entering no longer exists. $F = M\Sigma \frac{d\theta_t}{dt} + m_t c \frac{d\theta_t}{dt} + dm_t \alpha$ .

In addition, there is an equation for the mass variation. During the time interval Δt some of the water goes from the drum to the pipe. But this $\Delta m = m_t - m_{(t+\Delta t)}$ will only be known at the occasion of the whole computation including interacts between drum and pipe.

During the phase of water exhaust from the drum, we can calculate $P_{(t+\Delta t)}$ and $\theta_{(t+\Delta t)}$ from $P_t$. and $\theta_t$.

9.1.3. Steam overheating.

In this phase there is no more liquid water in the drum. Due to the fact the pop-pop engine works at relatively low pressures the steam mass (taking into account its specific heat coefficient) is minute and negligible compared to the one of the drum itself.
H2. In this phase the steam mass can be neglected.
Therefore, the formula becomes $F = M\Sigma \frac{d\theta_t}{dt}$. The temperature rise is linear. The thermal energy stored during this phase will be restored later when the water comes back

9.2. Pipe

It contains a quantity of water and a quantity of steam that are changing. Due to a relatively good heat transfer coefficient of water and bad steam one, it can be checked experimentally that the pipe remains cold when the engine is "shaking". As a confirmation, some pop-pop engines were built, using plastic straws as pipes. Consequently, it can be assumed that there is no heat transfer through the pipe above where it is in contact with the surrounding water; but there is condensation of some steam by contact with the water film which is created along the inner wall of the pipe when the water goes down.

The vacuum being created on one hand by the condensation and on the other hand by the displacement of water upon inertia effect, one must find a good compromise between the kinetic energy ($E = \frac{1}{2} m V^2$) and the friction losses ($R=kV^2$) that is to say between diameter and length of the pipe. It is obvious that any hitch (sudden bend, diameter change, ringed flexible hose…) is to be avoided. For a given kinetic energy, the friction losses are minimized by:

- Use of only one pipe instead of 2 or more.
- Circular section of the pipe
- Pipe without a hitch between drum and nozzle
- Good surface roughness inside the pipe.

Note: It is amazing to see that some of these basic precautions were not taken into account on many pop-pop boats.

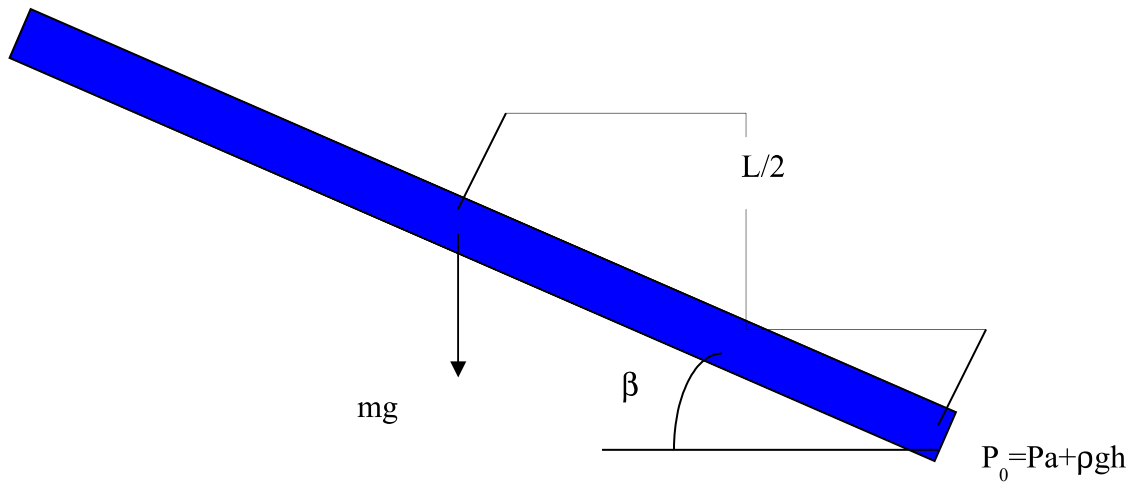
The specific gravity and the viscosity of the water are quite different from those of the steam.
H3: The friction losses of the steam inside the pipe can be neglected compared with the ones of the water.

Inside the pipe there is a water snake of mass *m* that is submitted upstream to the absolute pressure of the drum, and downstream to the atmospheric pressure increased by the draught of the nozzle, and by the pressure drop because this snake is moving and there are friction losses against the pipe internal wall. In addition to all that we have to take into account the fact the pipe is more or less inclined.

Notations:

- $S$ = area of the pipe cross section
- $L_t$= length of the water snake at time t
- $m_t$ = its mass at time t
- h = geometrical height between nozzle and water surface
- $\beta$ = inclination angle of the pipe
- $V_t$ = velocity of the snake center of gravity
- $\chi_t$ = acceleration of this center of gravity
- $Q_t$ = flow as volume through a cross section of the pipe

P= drum pressure



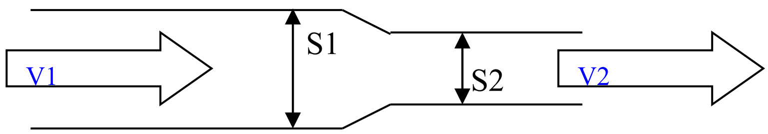

$V_t=1/2\ Q_t/S$

$(P-P_0)S+m_t.g.\sin\beta=m_t\chi_t$

$m_{(t+\Delta t)}= m_t-Q_t\rho.\Delta t$ (Let chose a convention for the sign and stick to it!)

## 9.3. Nozzle

It is the more or less narrow end piece fitted to the pipe. Its purpose is to increase the speed of the water coming out.

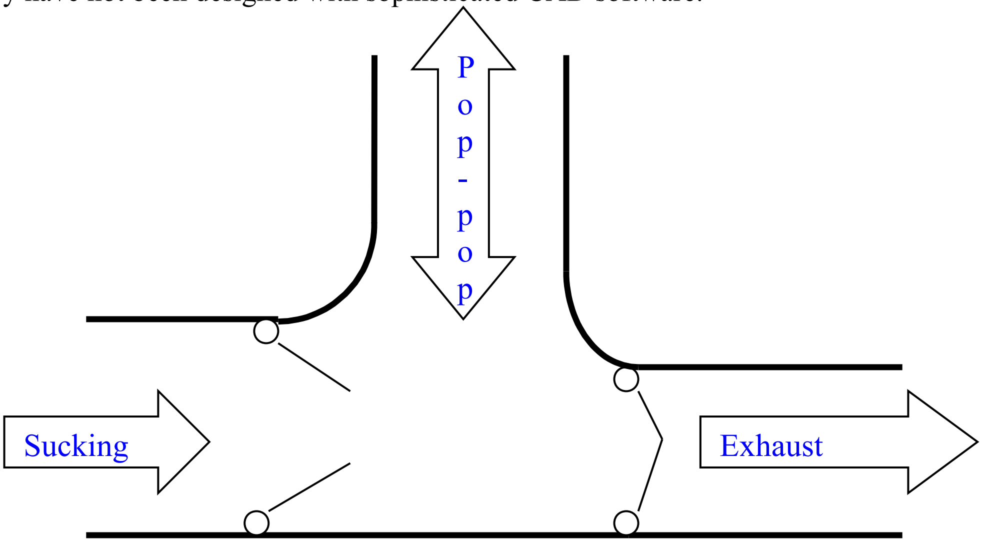



The application of Bernoulli theorem allows to write: $\frac{P1}{\varpi}+\frac{V1^2}{2g}=\frac{P2}{\varpi}+\frac{V2^2}{2g}$

And, the liquid being considered incompressible we get: $V1\times S1=V2\times S2$

Should the pulsation be not so frequent, one could imagine an improvement consisting to put in parallel a nozzle and a bigger orifice provided with a check valve (non return valve), and even to add also a check valve on the nozzle in order to push water astern and to suck on the fore. This deserves to be tested for example with check valves of the “duck beak” type which can work at rather high frequencies. See the following scheme. Thus, the relaxation phase would be propulsive as well and the efficiency could be quite improved. The pop-pop engine would be the prime mover of a reciprocating pump (without piston except a liquid one) used to propel the boat.

Note: The drawings are not as good as we would have expected, but by easiness and to give everybody an easy access they have not been designed with sophisticated CAD software.




Note: For those who would be interested to do such an experiment, for the manufacturing a piece of thin plastic hose with a soft ironing on one end can do a cheap check valve with a very small inertia.

Let’s come back to what exists! In practice it is very seldom that there is a nozzle because a reduction of the cross section means an increase of the friction losses and consequently:

- A decrease of the kinetic energy created by the vacuum
- An increase of the relaxation time; hence of the cycle period.

H4: For the first calculations, it will be considered that it is the end of the pipe itself which is the nozzle. (No cross section change).

9.4. Boat

It sails at a speed that can be considered as constant because of the ratio between its relatively big mass (ex: several tens of grams) and the mean value of the mass of water in movement in the pop-pop engine (ex: an average of 1,4 grams).

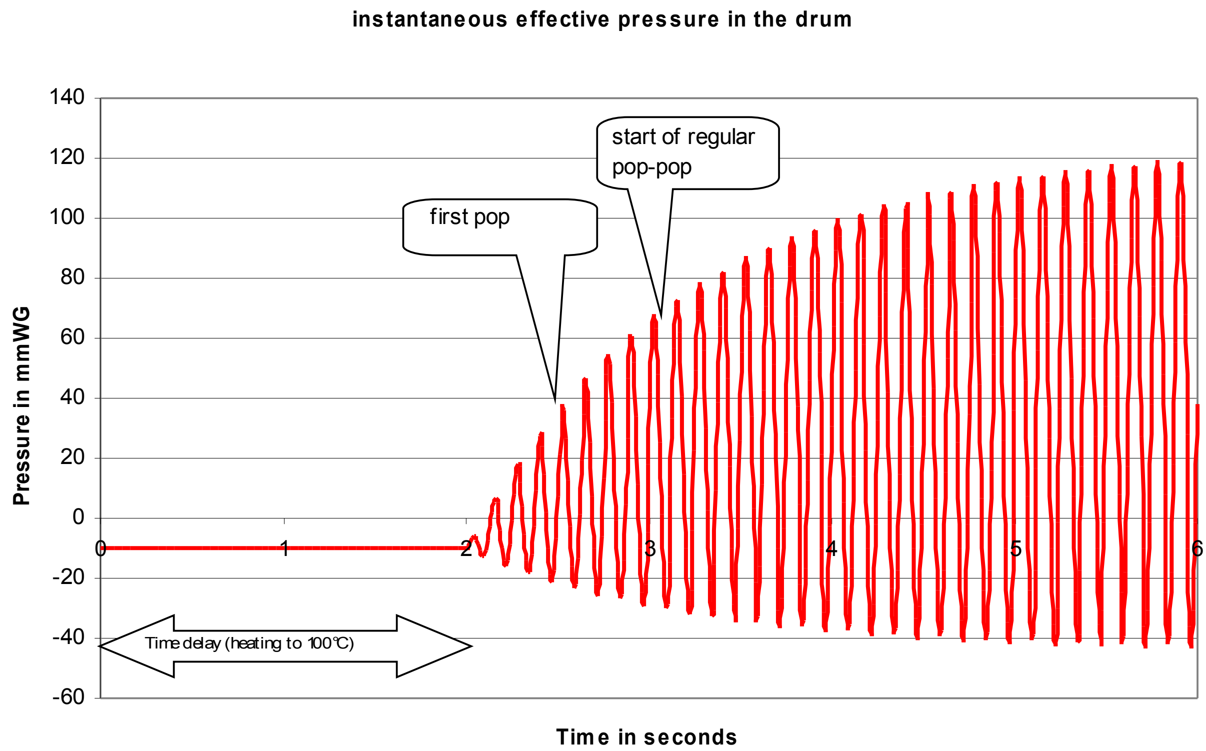
When the boat is stopped (bollard pull test) there is no noticeable change of the cycle frequency.

H5: The speed of the boat is constant and too slow to influence the performances of the pop-pop engine.

To validate all these simplified hypotheses, an existing pop-pop engine is to be modelized and the final results of the computations are to be compared with the real measures.

## 10. Probable response (due to lack of measuring tools)

According to all what has been seen or heard, the response of a pop-pop engine should be similar to what follows.




At t=0 the fire is lit
At t=2 the drum reaches 100°C
At t=2.6 the first pop can be heard. Then there is one pop per cycle
At t=3.4 the pop-pop becomes regular (2 pops per cycle).
At t=5 the engine delivers practically its full power.
Times and pressures are given for indication only. They can vary with many parameters.

## 11. Additional measurements and results.

Five pop-pop engines (2 small ones and 3 bigger ones) each one using a single pipe have been first built and tested with different materials, several diameters, and several lengths for this pipe. Pictures and file of the measures are available. At each new test only one parameter was changed. Engines n°1 and 2 had many similar characteristics (mass, volume, heating surface). Engines n°2, 3 and 4 had big drums (24.6cc) as the goal was to get low frequencies for better looking at the hunting. Then other engines have been built. The knowledge from all this is what follows:

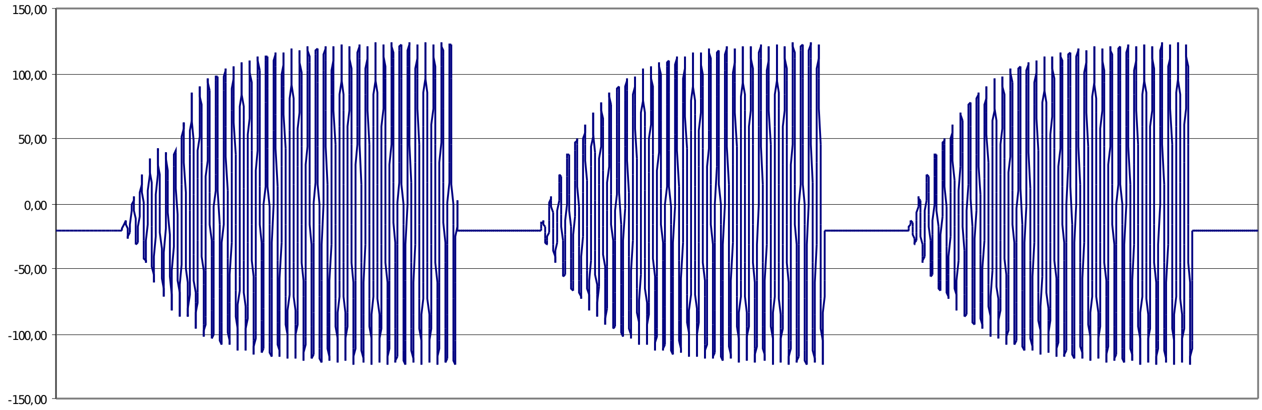
- It is confirmed that one pipe only suffices. (However it is more difficult to fill.)
- The height of the drum from the water level is not a major criterion. It changes slightly the boiling pressure and temperature inside the drum, but there is no visible change of the rest (within the limits of the pipe length). Successful tests were done in 2005 with the drum up to 30 centimeters above the water level surface, and down to 15

centimeters. Since that time we exceeded 2 meters above and 10 meters below (thanks to a pressurized tank).

- A good thermal conduction between the drum and the pipe degrades the performances. This is due on one hand to the fact that the overheating is more difficult and on the other hand to the fact that the boiling is not so sudden. To interpose a short isolating connection improves things.
- The drum must be located more or less at the top of the engine, and an inclination of the pipe is needed in the area where is located the interface.
- The length of the pipe has little influence on the frequency of the hunting.
- With a short pipe the hunting is difficult to get and not regular, sometimes impossible to get.
- The frequency increases with the heating power, but not much.
- The amplitude of the reciprocating movement of the water in the pipe increases with the heating power.
- For a given volume, starting and maintaining the hunting is easier and the amplitudes are bigger when a drum with a large vaporization area is used.
- The frequency seems related only to the volume of the drum and the diameter of the pipe in its part where there is steam in it. The formula <u>could be</u> something as $F = \alpha \sqrt{\frac{n}{V}} \times \left[Log(1.5 * \phi^{2} + 1\right]$ in which V represents the volume of the drum in cc and $\phi$ the diameter in mm, and *n* the number of pipes. According to our first estimates, the coefficient $\alpha$ could be 5.3. Additional tests with laboratory means would be necessary to define $\alpha$ more accurately or to find a more relevant formula. In the coil engines (with the pipe itself coiled in the middle and heated at that place) it is difficult to say where the drum ends and where the pipe begins to apply the formula. What is for sure is that the volume which is used as drum is small and that the resulting frequency is high. Most of these fabrications are made of copper; which has the inconvenient of a good thermal conduction between the hot part and the cold one. One of the fabrications (cf. www.eclecticspace.net ) was made of glass. For what concerns the thermal conduction it is rather bad ($\lambda$=1W/m°K while for copper it is $\lambda$=390W/m°K), but to look at what happens it is excellent. It is noted a very long time to start, and then a high frequency (25Hz) due to a small volume of what works as a drum.
- When the pipe is made of thermally isolating material (plastic) and is narrow, the water temperature increases regularly from the nozzle to the drum.
- When a nozzle is fitted where the pipe is connected to the drum, the length and the diameter of the pipe have no influence insofar as the pipe diameter is larger than the one of the nozzle. The frequency is then only a function of the drum and of the length and diameter of the nozzle. The alternate movement of the separation surface between water and steam expressed as volume (diameter of the pipe multiplied by the stroke of the liquid piston) seems only linked to the heating power.
- Air inside the drum increases the performances (frequency and amplitude).
- At cruising speed the free surface of the water inside the pipe is more or less distant from the drum. The water never enters the drum on its liquid state. It is the interface between saturated steam (more or less titrated) and overheated steam which goes in and out of the drum. There are only micro droplets. If there was one drop (0.05cc) of water, when vaporizing it would occupy approx 82cc and would through out all the water from the drum and from the pipe.
- When the heating power is removed the engine continues to run (for 15 to 30 seconds for our first two prototypes) due to the thermal inertia of the drum. The separation

surface between water and steam comes closer to the drum. If some water is poured on the drum it boils. It is a proof that the temperature is more than 100°C. And, when the temperature comes down to approx 100°C it can be seen and heard that the water climbs up suddenly through the pipe into the drum. It is a proof that the drum was filled with overheated steam. If the drum is naturally cooled down, it takes a longer time, but the result is the same. When one drop of water enters into the drum it is because the temperature is less than 100°C and the whole steam collapse. There is a water hammer effect which propels the boat.

- A minimum heating power is required to start the hunting. Below this, there is a static equilibrium with the free surface of the water very close to the drum.
- For the same heating power we noticed a ratio of about 12 between the momentum of the first engine (diameter 6, stroke 25, frequency 4) and the one of the second engine (diameter 3, stroke 10, frequency 3.3). Consequently, the surface of the pipe cross section is to be chosen as large as possible… but it seems that there are practical limits for the ration S/V (section of the pipe/volume of gas; this volume being bigger than the drum one when the interface is located inside the pipe). These limits are approximately such that to build an engine which can work we need $\frac{1}{2000} < \frac{S}{V} < \frac{1}{100}$ with S in $mm^2$ and V in $mm^3$.
- Some tests were performed with the addition of a condenser. No improvement was seen. When an engine works well (rather high frequency and long stroke), the water in the pipe is so shaken that its temperature is progressively higher when approaching the drum, but still cold enough not to vaporize inside the pipe.
- A series of tests at bollard pull conditions has been carried out to determine the thrust developed by several pop-pop engines, any of them supplied by a small candle. Our Indian toy (2 pipes of diameter 3.3) is in the top four. We have got similar or slightly better thrust with engines using only one pipe of:
  - Diameter 6 with a nozzle of diameter 5.2. (Transient test. Not confirmed).
  - Diameter 5.2 with a nozzle of diameter 4.4.
  - Diameter 4.2 without nozzle.
- Several web sites refer to a burning out phenomenon which could be due to some air ingress. Don't confuse air and overheated steam! Some of our tests lasted several tens of minutes without encountering this problem. But, if you wait for a time long enough, you can observe that in addition to the well known HF hunting (4 Hz for our first engine, 3.3 for the second) there is sometimes a LF one (period 25 seconds for our first engine, 220 seconds for the second one) which is far from symmetric. If in these conditions the pipe is big there is periodically a violent waterjet, and then the water comes back slowly to the drum. If the pipe is not big there is a steam blast, and then the water comes back slowly to the drum, and suddenly fills it (when it is cooled by the first drops of water). Graphically the result (pressure in the drum versus time) looks like what follows. The dead zones correspond to the time needed to increase the temperature of the water which filled the drum from cold to 100°C.




Concerning the presence of air, some “accidental” tests or very long ones (several hours) were enlightening.

1°) With some air the frequency and the amplitude are higher.

2°) Air is removed automatically in case of burning out.

Why? We have no certitudes, but strong presumptions based on the fact that we saw very clearly, on some occasions when the engine refused to start hunting (shaking), that the gas (air and steam) was pushing down the whole water column and bubbles were finally escaping (at 10 to 15cm below the water surface) and going up to the surface. If it had been steam it would have collapse. After having though it through, air has an atomic mass of approx 29 though the steam one is approx 18. So, air is heavier than steam and accumulates at the bottom when there is no hunting. It could be the same when the engine is hunting. Whatever it is, the presence of air (accumulated or mixed with steam) modifies the heat transfer between steam and water film.

**12. Detailed description of the running of the pop-pop engine.**

To look at the phenomenon 3 different types of “transparent” engines have been built. Those of Jeff (who believes that everything is to be seen in the drum) use a drum with a transparent plastic top cover. Loïc made one with a glass coil to see everything. The engines of Jean-Yves (who believes that everything is to be seen inside the pipe) use a transparent plastic pipe. Each of those who had prejudices (antagonist) has got confirmation that he was right. Why? Because the engines could not be compared. The performance depends on the materials, on the heating power, and on the geometry of the engine.

Jeff’s engines use a drum with a thin lower wall which is not very good heat transferring, and an isolating top cover, and pipes made of copper. The heat source is located at the place where the flame touches the drum. The cold source climbs up to the top of the pipes. Result: when Jeff looks at the drum he sees everything in it. The steam bubble rises just above the flame and its size varies at the same frequency as the pop-pop.

Jean-Yves’ engines have a massive drum made of copper and a pipe made of isolating material. The whole drum is submitted to the heat source while the cold source is far down in the pipe. Result: the (oscillating) steam/water interface is located inside the pipe. During some of our tests with small diameter pipe the position of the interface was measured to be down to 20cm from the drum.

Loïc’s engine is isolated everywhere. The interface is created somewhere between the heated place and the cold source. And the hunting exists around this mean position.

Since that time, Joao Cordero, Christophe, Loïc, Guus and Jean-Yves built engines made of glass, and every experiment completes or confirms the other ones.

In spite of the visible differences, in any of these engines the process is nevertheless the same. As soon as boiling starts, steam pushes water. At one end of the steam pocket there is overheating and volume increase, while at the other end the steam is cooled down by contact with the surrounding material and with the free surface of the water. This cooling down involves steam desuperheating with volume reduction, and condensation of the steam located close to the water surface. And there, depending on the circumstances and on the engines, one can observe very different phenomena versus time. Hunting could be either immediate, or it could occur after a long "hesitation" delay (sometimes more than 30 seconds). This latter case is the result of a quasi equilibrium between the volume increase created by the overheating of the steam located close to the heat source, and the volume decrease involved by the desuperheating and the condensation on the cold side, because in this slow – even very slow – process, the kinetic energy is negligible.

When the steam/water interface reverses its way, it goes quickly towards the heat source. There the inertia plays a non negligible role. The volume of the steam pocket decreases, while the heat source increases its energy. The pressure has got two reasons to increase. This pressure increase slows the water column progress, and reverses it. The steam that goes away from the heat source cools down… The reciprocating movement is fed until the heat source disappears.

**Note 1**: by feeding Jeff's engine with a power bigger than usual we succeeded to make it work as ours with a "dry" drum. Though it didn't last long (because the plastic cover melted) this confirms if it had been needed that the same laws of mechanics and thermodynamics apply. The mean volume of the steam pocket depends (among others) on the heating power.

**Note 2**: on our engines the temperature of the thick copper drum is usually between 110 and 130°C. The steam/water interface never goes into the drum. The heat is exchanged by conduction, convection and radiation between various steam layers. This thermal exchange is helped by the reciprocating movement of the steam molecules. To simplify, let's say that it is the invisible interface between saturated (and titrated) steam and overheated one which moves at the drum inlet. Except in case of incident, the water in its fully liquid state never enters into the drum.
A very high overheating is possible. Guus ran non-destroying tests of coil engines with temperature between 700 to 800°C. We confirmed with same test on one of our coil engines.

## 13. Why does the boat vibrate?

It is evident that the pulsated waterjet contributes to make the boat vibrates, but over all there is a resonance or pendulum effect.

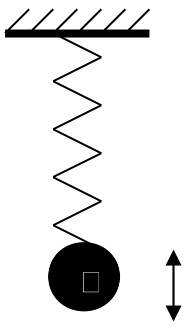
### 13.1. Helmholtz resonator?

Some ones have searched an analogy between pop-pop engine and Helmholtz resonator. This latter is only made of a tank (volume V) prolonged by a pipe of section S and length L. The natural frequency of such a resonator is given by the formulae

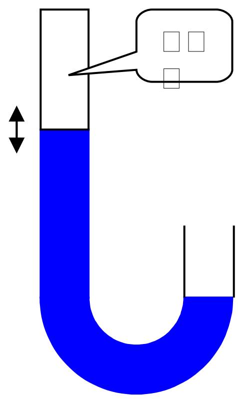
$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$ ; $c$ being the velocity of sound in the gas filling the tank. The more classic Helmholtz resonator is the bottle which is more or less empty in which air is blown transversally. It emits a musical sound which depends on the volume of air inside the bottle. In our application, the tank is the steam drum, the pipe is the pipe and the gas is the steam. According to most of our experiments it is true that the frequency evolves with $\sqrt{\frac{S}{V}}$ . But the remaining is not so obvious. What $c$ and what L are to be used? At low pressure and relatively low temperature (that is our case) the steam can be considered as a perfect gas, and c can be calculated by Laplace's formula: $c = \sqrt{\frac{\gamma .R.T}{Mmol}}$ where $\gamma = \frac{Cp}{Cv} = 1.32$ R=constant of the perfect gasses=8314J/kmol°C and T=temperature in °K. It is between 373 and 400°K depending upon overheating of the drum. Mmol is the molar mass of the water. It is the sum of the molar mass of its constituents: $H_20$=15.9994+2x1.0079=18.0152. That gives $c \simeq 485$m/s.
Many tests were carried out with a drum (of 3.2cc) provided with a nozzle (of diameter 3 and length 11) prolonged by a more or less big and more or less long pipe. The frequency was always the same: approx 4.7Hz; and yet, the strict application of Helmholtz formula gives f=1290Hz. The difference is enormous! The pop-pop engine is definitely not a Helmholtz resonator; or if it is, this is invisible because it is high frequency and minute amplitude.

Since that time we did some measurements and wrote a small report on that matter. See "Pop-pop engine and Helmholtz resonator".

**13.2. Simple resonator.**



In mechanics, the simplest resonator needs a fixed point where is suspended a mass M through a spring of stiffness k. When the equilibrium is destroyed, this resonator vibrates at the frequency $f = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$ . In practice the movement is damped due to the friction with the surrounding air.



In hydrodynamics, the same thing can be done by replacing the spring by a gas and the solid mass by a liquid one. The most available gas a

**13.3. Two-mass resonator.**

The fixed point of the previous resonators is a sort of infinite mass. When no fixed point is available we have a two mass resonator.

From the mechanical point of view a pop-pop engine can be considered as two masses linked by a spring. One of the masses (M1) is the boat (30g in our example) and the other one is the mean water mass (M2) inside the pipe (approx 1.5g). The spring is the steam.

In such a system, when M1 moves of a distance d1 toward left side, M2 moves right by $d2 = d1\frac{M1}{M2}$. Therefore, the amplitude of the vibrations of the water inside the pipe is quite more important than the (visible) one of the boat. In our example the ratio is about 20. This allows to "see" what happens inside the pipe. For that, one easy way is to fit at the end of the pipe an elbow oriented downward (or, better, 2 elbows oriented sideways if the engine has two pipes). Thus, the waterjet no longer propels the boat. By observing (with a movie camera because of the relatively high frequency) the boat vibrations we can calculate the amplitude of the water movements inside the pipe.

The apparent stiffness of the spring made of steam can be calculated because the frequency is known (8Hz in our example) thanks to the formula of such a pendulum: $f = \frac{1}{2\pi}\sqrt{\frac{k(M1+M2)}{M1.M2}}$ For our example, this gives a stiffness of approx 2,5N/m.

Remarks:

- Such an approach could allow to compare pop-pop engines, or to evaluate the performances of an engine depending on adjustments.
- Air mixed with steam can, depending on the volume, lead to a frequency decrease or increase. Measurements done later showed that it was mainly the water snake length which was influencing the frequency.
- At the first glance, the pop-pop engine looks like an ideal resonator because there is no damping. But in fact it is much more complicated than a simple resonator because there is a power supply from the heat source.
- Knowing the mean pressure (1 atmosphere – mean ρgh of the free surface of the water inside the pipe), the stiffness, the surface of the cross section of the pipe, and the stroke (2d) one can calculate the lowest pressure ("piston" at bottom dead center) and the highest one ("piston" at top dead center). $P_{\max} = P_{atm} + \rho gh + \frac{kd}{S}$ and $P_{\min} = P_{atm} + \rho gh - \frac{kd}{S}$. For our toy, this gives $P_{max}<103.10^3$Pa et $P_{min}>97.10^3$Pa ; that is to say peak to peak variations of less than 6000Pa=60mbar, or about 600mmCE.

**13.4. Change over from one to the other one.**

A stationary pop-pop engine is a one mass resonator. But if the engine is light and if you fit it onboard a very light hull it becomes a two mass resonator. This same engine could work easily in one case and not in the other one. Hereafter is a message from Slater that I received on 12/10/2007. *"Jean-Yves: I could not get the simple foam boats to work.*

*The engines seemed to be perfect but they would not start. Finally, I found I could make them start by holding onto them firmly. Then it became clear the boats would work if I weighted the foam with nails."*

**1.3.5. Can we use the energy of a resonator?**

The answer is no, but let's look why!

Let's examine the example of a grand-father clock. The pendulum is heavy and its swings much. To keep going its movement it suffices to bring back up one weight once a week. The corresponding energy is weak because it is used only to compensate the friction losses. One could wish to use the big movements of the heavy pendulum…, but it is not possible because the average of this energy is nil. Taking off a few (one fourth of the stroke) would suffice to stop everything. The whole available energy is the potential energy between high and low location of the pendulum. E=Mgh. This energy is weak because h is very short.

**14. What kind of flow in the pipe?**

To know it, Reynolds number $\Re_e = \frac{VD}{\nu}$ is to be calculated.

In this formula V is in m/s, D in m and ν is the kinetic viscosity in $m^2/s$.

- If **Re**<1000 the flow is laminar. Poiseuille's law applies. The pressure losses are proportional to the flow and viscosity, and inversely proportional to the power 4 of the diameter. The inner roughness has no influence. The linear losses coefficient (per meter of pipe) is given by $\lambda = \frac{64}{\Re e}$
- If 1000<**Re**<2500 the flow is undetermined. Often not stable between laminar and turbulent.
- If **Re**>2500 the flow is turbulent. The pressure drop is approximately proportional to the square of the flow, to the power 0.25 of the viscosity and inversely proportional to the power 5 of the diameter. If the inner of the pipe is smooth, the linear losses coefficient is approx $\lambda = \frac{0{,}316}{\Re e^{0{,}25}}$

For water, the kinetic viscosity in $m^2/s$ ($1m^2/s=10^6$ centiStokes) is about $1.10^{-6}$ at 20°C, $0.66.10^{-6}$ at 40°C, $0.48.10^{-6}$ at 60°C, $0.37.10^{-6}$ at 80°C and $0.30.10^{-6}$ at 100°C. For our examples, with a water temperature just above 20°C we will use $\nu=0.9.10^{-6}$.

For our toy, with a 40mm amplitude, the maximum velocity inside the pipe is 1m/s. Corresponding Reynolds number is **Re**=3667 ; hence higher than 2500. But, as the movement is sinusoidal **Re** oscillates between 0 and 3667.

For the prototype n°1 with a 6mm pipe diameter we have noted an amplitude of 50mm and a frequency of 4Hz ; this gives a maximum velocity of 0.625m/s. Corresponding Reynolds number is **Re**=4166; hence higher than 2500. But, as the movement is sinusoidal **Re** oscillates between 0 and 4166.

These two examples lead to Reynolds numbers that are very close. Therefore, to optimize a pop-pop engine, care will have to be taken as for a turbulent flow; i.e. the roughness of the inside of the pipe will have to be as low as possible.

For the prototype n°2 with a 3mm pipe diameter we have noted an amplitude of 20mm and a frequency of 3.3Hz ; this gives a maximum velocity of 0.1m/s. Corresponding Reynolds number is **Re**=700; hence lower than 1000. Theoretically the flow is laminar, but with the alternative movement up to which level? In practice, when in its upper half the pipe is hot where there is water inside, the flow is probably laminar. And when the pipe is cold it is turbulent.

**15. The ideal pop-pop engine?**

The question mark is intentional. At the origin (when we wrote the first release of this document) we had some a priori. Now we have got some certainties but there are some shadowed areas. How could be the ideal pop-pop engine from the efficiency point of view?

Only one pipe (in order to minimize the friction losses). In fact it is rather easy to fill with a syringe and a thin flexible hose.

Smooth inner surface of the pipe.

Drum made of thick copper. (Excellent thermal conductivity: 390W/m°K)

No diaphragm.

Pipe made of stainless steel. (Thermal conductivity far less than the one of copper: 15W/m°K)

Thermal shield between fire place and pipe

Pipe having a slight and long counter-slope (so that the dissolved gasses in water evacuate mostly out of the drum… though we have never met this problem. )

Small volume V of the drum (to get high pressure variations. )

Thick wall and wide area of the lower part of the drum (100 times S) to ease instantaneous steam flashing.

Surface of the pipe cross section so that $S \approx \frac{V}{100}$ with S in $mm^2$ and V in $mm^3$.

Shape of the nozzle: See "Shaping a nozzle for a pop-pop engine"

Relationship between pipe length and cross section size?

And last, the ideal application would use two identical engines side by side, working in opposite phases to cancel the boat vibrations. It's a dream. On a so simple engine there is nothing that could allow doing such a control; furthermore, it would be against nature because the longitudinal movements of the boat involved by one of the engine can only help the phasing of the other one. However, on a single engine we have demonstrated that it could be interesting to turn half of the tubes towards the bow and to add a 180° bend at the end. Hence, the hull vibrations are far less.

P.S : If we except some corrections, practically all this was written in February 2005 before contacting amateurs and/or specialists of pop-pop engines. There are still things to clarify, and some discrepancies subsist between the points of view of some passionate people.

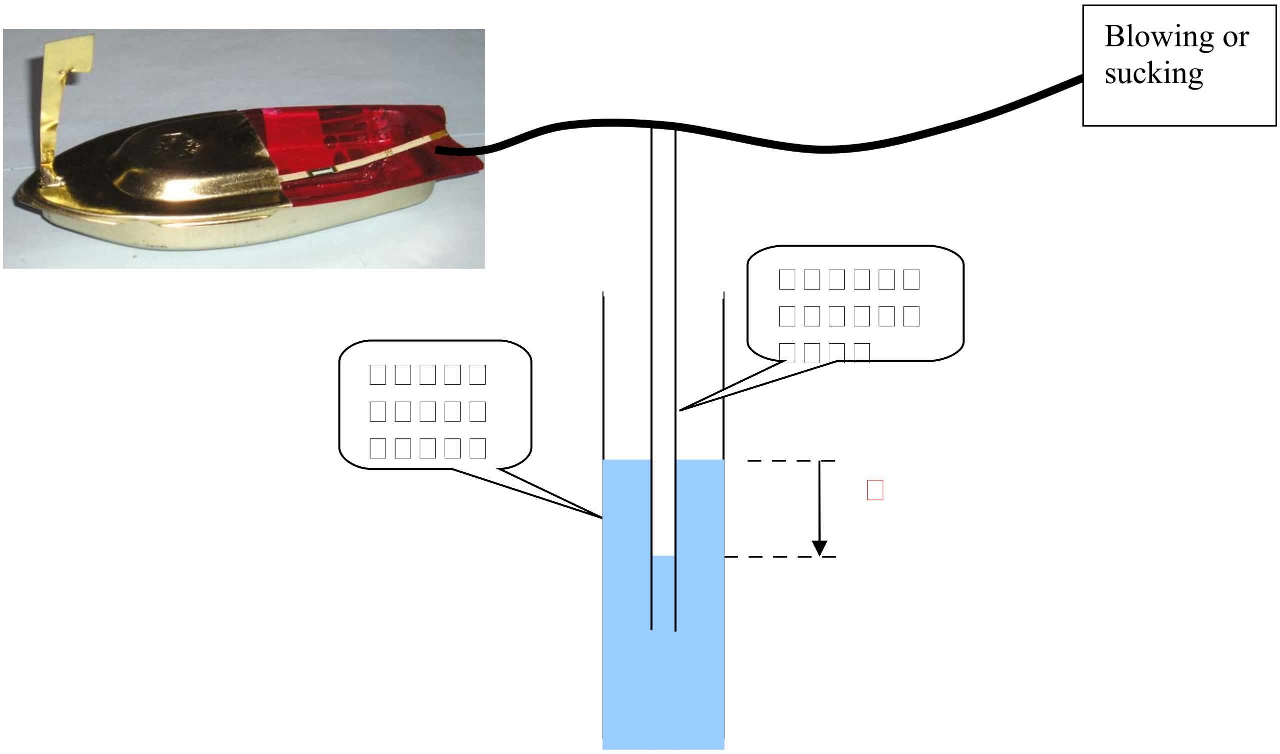
- Though many tests demonstrate that a diaphragm decreases the efficiency there are still some people who think it is needed. We are in favor of the diaphragm for the fun and for its contribution to ease the vibration of the engine.
- Some think that some air in the drum is useful.
- There are "dry" drums (most of ours) and drums with always some water in.
- Some engines refuse to start or don't run more than some seconds, and we don't understand why.
- Sometimes it has been noted big discrepancies in the performances though the tests conditions were a priori similar.

Approximately 5 years and 200 files later…the topic is not closed.

Annex 1

## Sound generator characteristics.

To evaluate the pressures used to deform the membrane the following arrangement was used, using compressed air… from the mouth of the operator.




Results:

- Slow pressure increase. For h=66mm the membrane becomes suddenly convex and emit a pop. For higher pressures nothing.
- Slow release of the pressure. For h=36 the membrane emits another pop, weaker, and comes back to its original shape nearly flat.
- Slow vacuum increase. For h=-20 the membrane becomes concave and emits again a pop. With better vacuum nothing happens.
- Slow release of the vacuum and slow pressure increase. The membrane modifies slightly its shape, but without sound. It remains slightly concave, and then suddenly becomes convex for h=66mm.

Therefore, there is a sort of classical hysteresis in one way, and two in the other way. This is very likely not made on purpose. It is a consequence of the hand made work with slight strains at rest due to soft metal welding.

When the drum is submitted quickly alternately to pressure and vacuum, one can hear the typical pop-pop sound, that is to say one clear pop in each way.