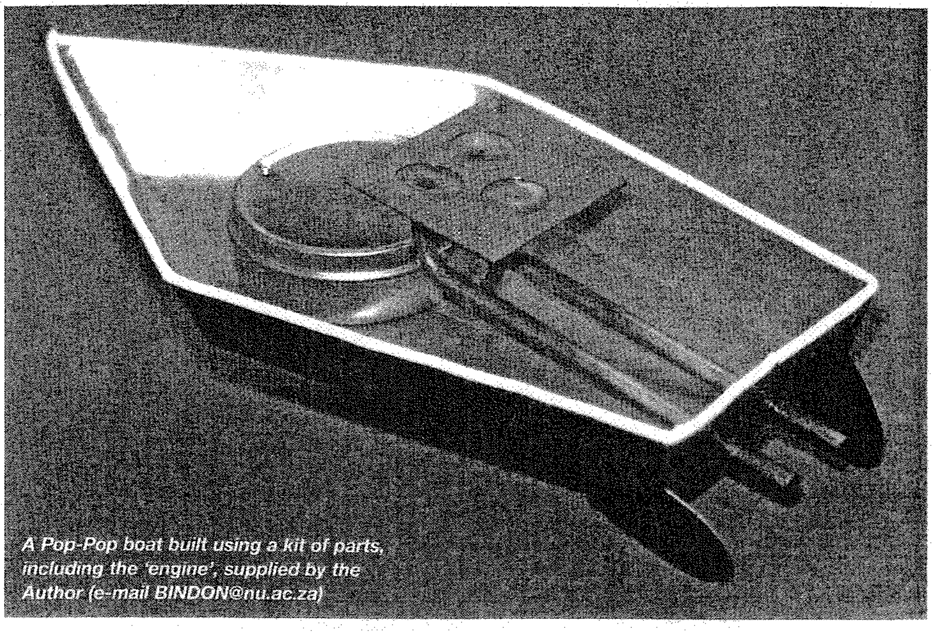


A Pop-Pop boat built using a kit of parts, including the 'engine', supplied by the Author (e-mail BINDON@nu.ac.za)

THE SECRET WORKINGS OF A TRANSPARENT POP-POP ENGINE

Jeff Bindon

in South Africa reveals some intriguing aspects of Pop-Pop engine operation and explains how to make a transparent engine with a throb that announces its dynamic internal processes.

The water pulse (Pop-Pop, Putt-Putt or Toc-Toc) engine is an exciting and fascinating device. Even when not made from flexible transparent material, you will be kept watching and wondering for hours at its lively antics. Up to now, the explosive internal operating 'life' cycle could only be heard. Now the enhanced throbbing becomes something you can feel and see. Everyone with an interest in things mechanical cannot but appreciate the sheer audacity of such action achieved without moving parts.

Although they have been made for toy boats for over a century (**Ref. 1**), only some aspects of the way they work have been suggested at various times. What follows summarises the ideas and findings of others and presents some new observations and conclusions from simple experiments with transparent engines.

The upper flexible metal plate of an essentially flat boiler was replaced with a piece of overhead projector (OHP) film to permit observation of what was happening inside. The processes in one of the two copper pipes were also observed by replacing it with a silicone rubber tube. A modern video camera system was used to film the action inside the boiler in slow motion. Finally, because OHP film can work up to 250deg. C and is so readily available, some ideas are given for making a transparent engine (**fig 1**).

From 1916 to 1926, McHugh made some very important contributions in two patents (**Ref. 2**). In the second one, he seems to have clearly and correctly understood the way the oscillatory momentum of the water columns causes the pressure fluctuations in the boiler and how steam condensation onto the walls of the cold tube causes the drop in pressure necessary for pulsation to be initiated and maintained.

There have been previous reports of experiments with transparent engines. A rigid transparent upper plate was fitted by Crane (**Ref. 3**) in place of a flexible metal membrane. He concluded from the experiment that the flexibility of the membrane was not essential, a finding that has not been confirmed by the present study. From seeing that the boiler contained only 25% liquid he incorrectly concluded that the remainder was full of *"superheated steam."* He proposed that the water columns are propelled by the steam formed, that the pressure drove the membrane outwards and that the water was sucked back by steam condensing. However, this does not take place *"primarily on cold boiler surfaces"* as stated.

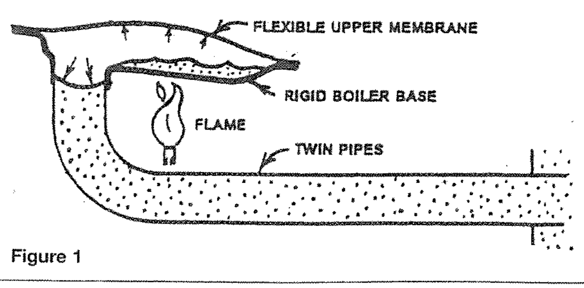
Payne *et al* (**Ref. 4**) gives a good review of previous work and reports the findings from two single tube water pulse jets, one electrically heated and one oil heated. They were considerably larger than the normal Pop-Pop engine. Inclined glass tubes of 25mm diameter and 3100mm long were heated at their upper ends. All their experiments included some air in the hot end and they appreciated that it played an important role in bouncing back the column of water. Pressure fluctuations were measured and although their scale is uncertain, a variation of up to 2 atmospheres may have been reported.

It is often asked if two tubes are essential and many, for example **Ref. 5**, and in the present work, when one tube is blocked by hand, pulsing continues but at a reduced rate. Twin tubes certainly make filling the boiler easier but no-one had made an engine with a single tube that has either the same cross-sectional area or the same internal surface area.

A number of exceptionally well designed engines and boats are available in the streets of India. They have pressed tin 'motor-boat' hulls and a particularly lively 'chinky' noise. Anyone travelling there simply must purchase one although they sometimes filter onto the European street markets. Reference 5 specialises in a range of exquisite hand made hulls powered by a superb deep throated sounding engine that won all the competition categories in **Ref. 6**.

Experiments with transparent engines

In the present experiments, the first surprising observation was the magnitude of the peak pressure inside the boiler. Although this was not quantified, the upper membrane, being more flexible than metal, was stretched rigid, was distinctly 'hard' to the touch, and could only barely be pressed down onto the lower metal plate. Since the boiler is completely open to the atmosphere via the two pipes, such a pressure can only arise dynamically from the inertia of the water columns. This confirms McHugh's ideas and perhaps the measurements of Crane. Rapid water column motion is crucial in understanding how the engine works. It bears more resemblance to a piston engine with compression and expansion than simply to the idea of steam evaporating, pushing and sucking. Pressure reduction may play a key role in the rapid periodic evaporation of steam that must take place. Conversely, there may also be re-condensation when the pressure rises.



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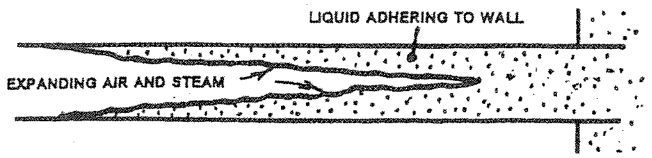

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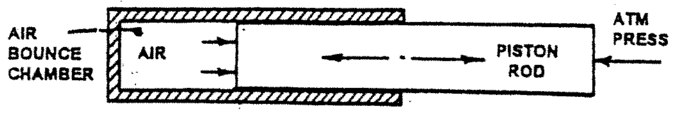

© Figure 3

The second finding confirms the 'bounce' role played by air inside the boiler. Without fully understanding the reasons, many Pop-Pop engine designers have found by experience that a better performance results if the tubes are pointed upwards when filling the boiler. See for example Ref 5. This means that the (temporary) upper half of the boiler cavity forms an air lock and only a limited amount of water is allowed to enter. Observations show that when the boiler is filled in this manner, an air bubble fills approximately half the boiler and the pulsing is vigorous and regular with a relatively small amount of liquid being crisply snapped around. In contrast, when all air is purged, pulsing is sluggish and irregular. The cavity is full of water and steam which churns and sloshes with a spongy gurgling sound. This does not continue indefinitely. As will be shown later, dissolved air from the water soon forms a bubble.

It is believed that air stores energy which allows the water columns to oscillate vigorously to effectively form twin 'pistons'. A further possibility is that the air controls the amount of liquid trying to flood back into the boiler.

A third observation through a semi-transparent silicone rubber tube confirmed that the water columns do indeed oscillate back and forth in the tubes over roughly two thirds of the total length. At the far extremity of the 'stroke', the 'meniscus' could not be seen and the liquid steam/air interface may be ragged and well mixed. Since the retreating liquid would tend to stick to the tube wall while the centre is pushed downstream by the expanding air and steam, the water column is likely to bear more resemblance to a pipe full of syrup than to the clean meniscus we see when we use a drinking straw (**fig 2**).

A touch test showed that the first half of the tubes were hot while the last half were only lukewarm. A surprising result was that when observations were attempted with both tubes made of silicone rubber, the engine would not work at all and gave no hint of even incipient pulsation.

The next observation relates to the control of the air bubble size in the boiler. It has been the painful experience of many an engine designer to have the boiler burn out after puttering happily for anything from a few minutes to as long as an hour depending on the design. A burnout is always preceded by a weakening and then cessation of pulsing. The tubes become hot over almost their whole length. An alert operator can prevent damage by blowing the flame out when this happens.

A view via the transparent upper membrane revealed that cessation of pulsing and subsequent burnout were due to a completely dry boiler. Just prior to this, as the pulse rate first begins to weaken, there was no longer any free liquid being disturbed and sloshed around by the upper membrane. Dry patches could be seen on the heated surface. The patch fluctuated in size in sync. with the pulse of the engine and grew until all wetness vanished and pulsing stopped.

When a still intact engine was allowed to cool to condense the steam, it could clearly be seen that the bubble of air was much larger than at the start. Since the boiler is sealed, the additional air must be coming out of solution from the water. As will be mentioned later, a Pop-Pop engine is a heat engine and discharges its waste heat by expelling warm water at each pulse. Cold water must therefore be entering the tubes and when it eventually reaches the boiler, the dissolved air will be released.

Since there is a steady release of air into the boiler it seemed logical to hypothesise that a successful engine that operates indefinitely is one that steadily discharges air. This was confirmed by placing an inverted beaker of water above the two pulse tubes to trap and observe any discharged air. This was seen to take place every few minutes and was as a spurt of two or three tiny bubbles. Additional confirmations came from obtaining the same result for an engine from a completely different source and to deliberately start each one without an air bubble. After a few minutes of sluggish pulsing, the rate gradually increased. When the transparent engine was stopped, the normal complement of air was found in the boiler.

It is suggested that this crucial discharge of excess air takes place when the ragged 'meniscus' of the water column extends beyond the end of the tubes. It is likely that all remaining steam has been condensed into the water which is coldest near the exit.

The resulting tiny bubbles may oscillate for many strokes and be thoroughly scrubbed before finally being discharged. Thus the term meniscus must not be taken literally. It may be a small bubbly zone near the centre of the tube surrounded by slower moving fluid 'stuck' to the surface of the tubes. This zone will oscillate back and forth and will gradually be pushed closer and closer to the outlet as the air volume inside the boiler increases. The length of the tubes and the pulse strength should affect the discharge of air. While a larger flame does not enhance the pulse strength, a very small flame was found to produce a weak pulse that did not result in a discharge of air.

Further observations were made that are interesting without revealing or confirming aspects of engine operation. These are also not to be taken as universal because they depend on engine design and shape. Very small incipient pulsations could often be seen the moment steam bubbles begin to form. As the liquid reaches its boiling point and even the smallest of bubbles emerge, both the flabby transparent membrane and the air bubble begin to flutter. It appears that even when a small volume of steam expands and enters the cold tube, it will immediately condense to reverse the expansion and set up the fundamental unstable mechanism that drives the oscillations. This small incipient flutter will not be noticed with an opaque metal membrane.

An experimental engine with a flat lower boiler surface except for distinct cavities around the pipes and in the centre, did not exhibit this 'flutter'. The boiler simply filled with steam without any pulsations and then boiled dry. It would appear that if the upper membrane touches the lower plate, the surface tension of the resulting thin film of water prevents it from pulsing.

Pulsations are also unreliable with a freshly installed taut OHP membrane. When they do occur, they are sometimes not strong enough to discharge any air. However, after a 24 hour soak in water, the polyester appears to absorb moisture and become flabby. Pulsations are then regularly initiated and strong enough to deliver the air to the ends of the tubes. A similar result has been reported by Ref 5 and stronger pulsations result when the shim brass membrane of a new engine is manually deformed inwards. It is thus concluded that the upper membrane needs to be flexible.

A modern video camera and editing facility enabled the processes through a 40 x 40mm transparent membrane to be seen in slow motion. However, the clamp plate holding down the membrane had only a 25mm dia. viewing hole centred at the front of the boiler over the pipes. No surprising observations were made except to find that the engine has a double pulse, one as the membrane bulges fully outwards and the other at the end of its inward stroke. The two sounds are distinctly different, the loudest being at the end of the implosion. A more appropriate name for the device could be the 'Pip-Pop' engine!

There was no sign of any 'boiling' taking place and in the visible zone, steam does not form as bubbles on the heated surface. There is very little liquid in the boiler and there is a gaseous central region with a meniscus of liquid all around its edges where surface tension seems to keep liquid in contact with both surfaces. The surrounding meniscus expands and contracts as the membrane goes up and down. In the central region, the little liquid there is moves rapidly. Although this region is largely hidden underneath the clamp plate, bubbles of steam appear to emerge from the back of the boiler where the liquid layer is thin. This happens periodically on explosive downwards strokes of the membrane.

An unexpected result was that no liquid was seen to emerge from the pipes. This was because some engines showed a droplet or two of liquid being spewed back on a somewhat irregular basis. These were seen momentarily as they hit the membrane and the engine misses a beat or two as the new liquid is heated. On other engines, this periodic spew back of liquid was much more than a drop and water rushes in with a distinct gurgling choke. The boiler becomes flooded and pulsing can stop for a few seconds. Such engines operate with a continuous gurgling sound that can be heard against the regular pulsing.

A summary of pop-pop engine operation

For those unfamiliar with the kinetics of a water column and the way air and steam behaves, two preliminary explanations are presented.

'Air bounce' and column momentum

Consider some air trapped in a cylinder in which there is a heavy, well fitting piston rod (**fig 3**).

If the rod is pushed hard against the air, the air volume will decrease and the pressure will rise above that of the atmosphere. When the rod is released, air pressure will accelerate the rod. The air volume increases and the pressure decreases.

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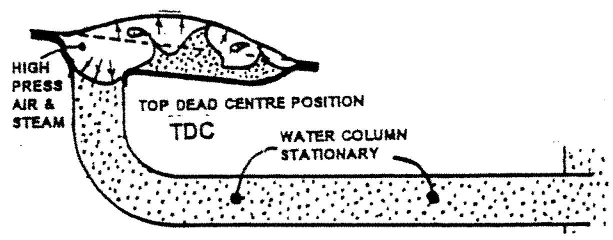

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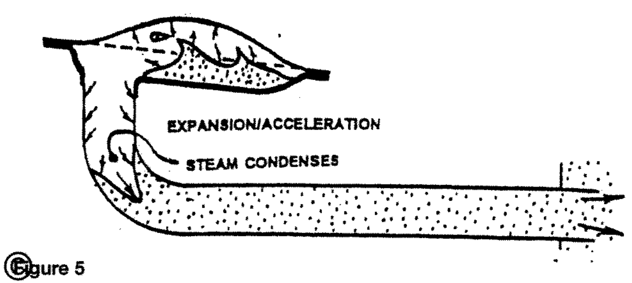


© Figure 5

When the pressure falls below that of the atmosphere, which is trying to push the rod back again, the rod will begin to slow down. However, it has momentum and so before it finally stops, the air pressure will have fallen well below atmospheric. The outside air will then accelerate the rod back into the tube and it will only begin to slow down when the air pressure again rises above atmospheric.

Due to momentum, the pressure continues to rise until the rod finally stops. Thus the air acts like a spring or 'bounce volume' and the rod will oscillate in and out until friction eventually stops it. This principle applies to the boat engine because there are moving columns of water in the tubes that have mass and which will bounce back and forth just like metal rods.

Evaporation and condensation

When water at its boiling point is heated it turns into steam at the same temperature. Because vapour has a much larger volume (about 1700 times at atmospheric pressure) it 'pushes' outwards and any restriction of this expansion will tend to increase the pressure. If steam encounters a surface colder than the boiling point, it will begin to condense back into water and the volume and pressure will tend to decrease.

The boiling point of water depends on its pressure. If the pressure of water at 100deg. C and 1 atmosphere is suddenly lowered to say 0.7 atmospheres, the new boiling point will be 90deg. C. The liquid will tend to stay at 100deg. C and will be much hotter than its boiling point. Steam will rapidly 'flash' off until the temperature falls because the energy or latent heat to do this comes from the sensible heat of the liquid. If the pressure is forced back up to 1 atmosphere, the liquid will tend to remain at 90deg. C while the steam temperature will increase due to its compression. It will therefore condense rapidly into the relatively cold liquid until the temperature rises back to 100deg. Celsius.

A 'boiler', consisting of two closely spaced metal plates, is filled with *air and water*. Two metal pipes full of water lead from the bottom of the boiler to the back of the boat below the water-line. The bottom plate is heated by a flame. The upper plate is thin and flexible to produce a change of volume and a sound pulse as it is stretched taught. Some craftsman are able to induce a vigorous over centre 'oil can' snap action that adds considerably to the noise produced.

Two processes are thought to be crucial. The first is that which fundamentally causes the oscillations. As flame driven steam forms, it pushes outwards and displaces water down the tubes. Since this zone is relatively cold and wet, steam immediately condenses and draws the water column back. Those familiar with hot air engine operation may see similarities.

The second relates to the rapid motion of the water columns which become fast moving 'pistons' able to generate pressures well above and well below the atmospheric. Since the pipes are open to shallow water and hence to the atmosphere, it is only the inertia of the liquid in the tubes that can do this. The presence of an air bubble allows energy to be stored during the compression process and return it during the expansion process.

Because of the surprising dynamism that the transparent and more flexible membrane has revealed, it is proposed that the engine actually resembles a piston engine with certain 'strokes' of compression, expansion, etc. Such an approach certainly helps to develop a logical description of the processes. An engine cycle needs to start at a readily identifiable point from which more complex processes can be developed. The point chosen is when the water columns have come to rest at 'top dead centre' (TDC), somewhere near where the tubes join the boiler. The air and steam are fully compressed and the upper membrane is extended with the pressure at its highest and well above that of the atmosphere, **fig 4**.

Since the pressure at the open end of the tubes is atmospheric, the higher pressure in the boiler will now accelerate the water columns down the tubes allowing the volume of air and steam to expand. This is the *'expansion/acceleration stroke'*. The flame will evaporate steam from the liquid but the wet tube surface left exposed by the retreating water columns is relatively cold. Thus steam will start to condense and the air to cool. The combined expansion and condensation process will attempt to decrease the pressure and counteract the effect of the evaporating steam, **fig 5**.

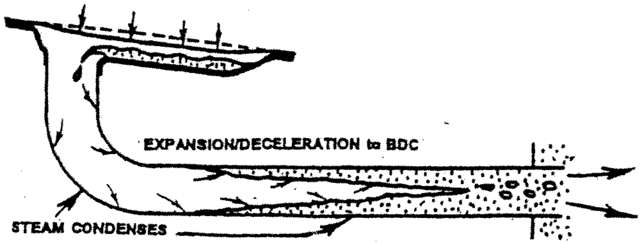
As the water columns retreats, not only is more cold wet surface exposed, but fluid becomes increasingly colder and remains 'stuck' to the walls. Air and steam are increasingly forced to move down the centre of the tubes and become more intimately mixed with the cold water. Thus despite the evaporating steam, condensation and cooling soon dominate and the pressure will decrease. When it falls below atmospheric the upper membrane will be slammed downwards and the water columns will begin to slow down.

A sudden decrease in pressure may lead to a pulse of steam emerging from the boiling water in the boiler.

The higher pressure at the end of the tubes will now begin to slow the water columns to form an *'expansion/deceleration stroke'* until the water stops at BDC. The stream of expanding steam and air will become increasingly narrower and the surrounding water colder, and both these factors will ensure that most of the steam will condense to leave only tiny bubbles of air (**fig 6**). Atmospheric pressure will now push the water columns back into the tubes to form a *'compression/acceleration stroke'*. Cooling surfaces are covered, condensation stops, steam continues to form and the pressure begins to rise. When it exceeds atmospheric, the columns begin to slow down, the upper membrane is slammed outwards and the *'compression/deceleration stroke'* starts. The momentum of the columns is such that the pressure rises well above atmospheric. This sudden high pressure may cause steam to actually condense back into the water. Small amounts of liquid may flood back into the boiler to replace that which was evaporated. This may be regular or sporadic. The cycle is now ready to repeat itself (**fig 7**).

As mentioned below, a Pop-Pop engine is a heat engine and discharges its waste heat by expelling pulses of warm water. Cold water therefore enters the tubes to replace the water discharged. Air is less soluble in hot water than in cold (this can be seen in a kettle just before it begins to boil) and when the cold water works its way towards the hot end of the tubes and even enters the boiler, the dissolved air will be released. The steady release of air into the boiler will gradually cause the columns to push further and further down the tubes until a tiny amount is discharged with a pulse of water.

The distance steam and air will push down the tubes depends on the pulse strength which can depend on the flame size. Thus the overall length of the tubes, the flame and the vigour of pulsing could be important factors in the discharge of air.



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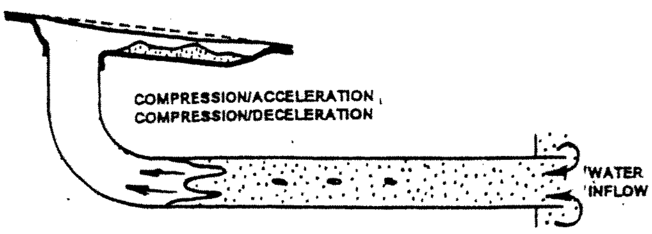

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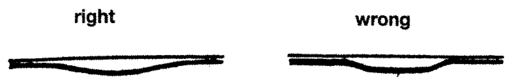

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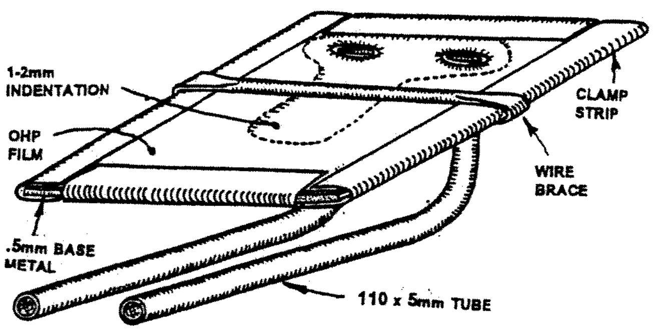

© Figure 9

Pop-Pop engines and the Second Law of Thermodynamics

The Pop-Pop engine is a form of heat engine. It is driven by heat and it produces mechanical work. According to the Second Law of Thermodynamics, the difference between the heat supplied and the work produced must be rejected as waste heat. The work produced is in the form of the kinetic energy of the water ejected from the tubes. There is no way for a significant amount of heat to be rejected other than via these water jets which must be warmer than the water sucked in.

At the hot end of the columns, it is thought that steam condenses into the face (meniscus) of the water and into the film of water in contact with the tubes. As the columns move backwards and forwards, the hot water at one end mixes gradually to warm the cold end which is the part that leaves the engine. A finger test will show that the first half of the tubes are hot to the touch while the last section is only lukewarm.

Making a transparent engine

It is not easy to design a Pop-Pop engine that starts reliably and pulses regularly and indefinitely. This is not surprising since the working processes are complex and hidden from view and there is probably still much to learn. On occasion it has been found that when the design of a well performing engine was copied or changed slightly, the new engine would not work at all or at best, it functioned poorly. Design has been intuitive with generous proportions of luck and persistent trial and error. The handful of engine manufacturers should receive great respect and the ownership of a lively boat highly treasured.

Even with the insights gained, the ideas below are presented with trepidation because no guarantee can be provided that they will work. However, it is hoped that many will be lucky and persistent enough to make a transparent engine and experience the sight, sound and feel of your own creation.

The suggested engine has a 40 x 40mm lower boiler plate of 0.5mm thick copper, brass or stainless steel. It should be slightly indented with a ball pein hammer to a depth of from 1 to 2mm roughly over the shape indicated. Allow the metal to slope down to the indentation and do not attempt to form a perfect 'dish' (**fig 8**).

Two holes should be pierced, not drilled, 10mm from the edge at a 15mm pitch. The deformed metal can then provide support and strength for the tubes to be soldered in. First drill a 2mm hole and then drive through the sharpened shank of a drill bit matching the size of the copper tube chosen. This should be between 4.8mm (${}^{3}/_{16}$in.) and 5 millimetres. Two 110mm long copper tubes should be bent around a former and then soldered in. Silver-soldering is not necessary (**fig 9**).

Cut a 40 x 40mm square of OHP film and lightly sandpaper a 5mm wide strip around the edges. Apply a generous layer of contact adhesive to the roughened areas and also around the edges of the boiler base plate. Allow the glue to dry thoroughly and then press the film down onto the boiler. Prepare four 12mm wide clamp strips made of thin tin plate. Bend them in half along the centre line. Squeeze them around the four sides of the boiler first by hand and then tightly with a pair of pliers or a vice. Fill the boiler with water by trickling water down one tube until it emerges from the other. Allow to soak for at least 12 hours before use.

Mount the engine into the hull of your choice using Prestick (double sided adhesive tape). The enjoyment of the boat will be enhanced by finding a readily available pond. A round plastic tray with the boat tethered with a strip of OHP film is ideal. Light a small stub of a candle or a night light and place it at the centre of the boiler. Alternatively a *vertical* meths wick can be made using the thinnest possible string inside a matching brass tube.

The engine should soon begin to pulse. Unlike shim brass, OHP film is more flexible and the natural pulse rate of the engine will be slow. This can be speeded up by fitting one or more thin (0.9mm) wire braces with flattened ends across the top of the window. This appears to limit the outward bulge. Experiment with the number, shape and position of the braces and you may be lucky enough to find a combination that is rapid and pleasingly noisy. Alternatively, if you are able, make a single full size tin clamp plate with a matrix of holes for viewing. A 3 x 3 pattern of 8mm holes works well, as do three 14mm holes.

Watch your new engine carefully until you are sure that it not only pulses but is an indefinite pulser. Blow the flame out if the boiler simply fills up with steam without pulsing or if pulsing stops after some time because of too much air. There are no certain cures for these problems. If pulsing does not start, the base plate may be too flat near the edges. To promote the discharge of air, try shortening the tubes or adjust the wire braces to enhance the pulse strength.

If these measures do not work, try making another engine. You are as likely to succeed if you change something as you are if you try and make it identical. But once you try, you automatically join the small club of designers finding out by intuition and experiment which parameters and materials work consistently.

It is hoped that the insights provided here could help designers make engines that not only work but also perform better. Knowing some of what is happening has increased the author's enjoyment and wonder of these lively little devices that pulse briskly for as long as they are fed fuel and are given cold water into which to dump their waste heat.

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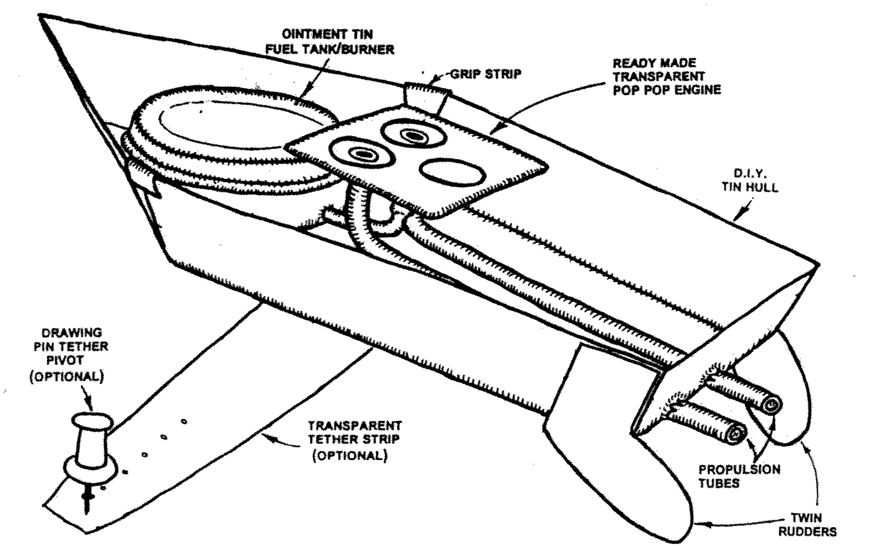

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