STEAM NOTES FOR RICHARD.

Ok Rich,

You have made some good observations and also noted some degree of improvement when you changed certain things.

What is, perhaps, not so clear though is the WHY?

Lets look at these a bit more closely: -

Note… what follows is a VERY, VERY simplified over view of the subject which hopefully will be sufficient for the purpose of this discussion.

To explain it all in every detail would require the use of a lot of PHYSICS and MATHS etc and is beyond the scope of a simple post such as this.

Ok then here goes… Rich, put simply, all of your problems can be summed up in one-word 'HEAT'… or more specifically the LACK of it or the LOSS of it or BOTH, with the possible exception of the CARRY OVER OF WATER in the STEAM, but even here HEAT has a part to play but for a slightly different reason.

What do I mean by this?

It takes a specific amount (quantity) of HEAT to convert a specific MASS (volume) of water into a specific VOLUME of DRY SATURATED steam at a specific PRESSURE from an initial start TEMPERATURE.

This amount of HEAT is known as 'THE TOTAL HEAT OF FORMATION'

Some of this TOTAL HEAT OF FORMATION is required in order to raise the TEMPERATURE of the WATER to the EVAPORATION TEMPERATURE (boiling point) of water at the required PRESSURE.

NOTE… For those of you that may not be aware… the BOILING TEMPERATURE of WATER is not a CONSTANT, it varies with PRESSURE.

At NORMAL ATMOSPHERIC PRESSURE of 14.7 pounds per square inch absolute (usually written as 14.7psi or 14.7psia.) it is 212deg F.

Most standard steam PRESSURE GAUGES are made to read ZERO at NORMAL ATMOSPHERIC PRESSURE and in order to distinguish between the two the GAUGE PRESSURE is usually written as 0psig or 0psi gauge.

For PRESSURES above NORMAL ATMOSPHERIC PRESSURE the BOILING TEMPERATURE OF WATER is HIGHER… and for PRESSURES

below NORMAL ATMOSPHERIC PRESSURE the BOILING TEMPERATURE OF WATER is LOWER.
The remainder of the TOTAL HEAT OF FORMATION is required to change the water from liquid form into DRY SATURATED STEAM (VAPOUR) at the same PRESSURE and TEMPERATURE.

This portion of the TOTAL HEAT OF FORMATION is known as: -

‘THE LATENT HEAT OF EVAPORATION’.

HANDS up all of you who thought water instantly turned into steam at it’s boiling temperature?

WRONG… Sorry.

A smaller MASS (volume) of water beginning at the same START TEMPERATURE will require LESS TOTAL HEAT added to perform the conversion, but the TOTAL volume of STEAM it could produce would be reduced in the same proportion.

Rich, this partially explains one of the improvements you noted by lowering the water level, but it’s not the whole story, there are more subtle reasons involved as well but these are more of a DYNAMIC nature.

Ok, this is where it gets a little more complicated to explain what is going on, at least in simple terms…

Suppose we have a BOILER equipped with some sort of burner (HEAT SOURCE) and a STEAM STOP VALVE and a SAFETY VALVE set at the desired working PRESSURE.

Let us also say that we have a small steam engine connected to the boiler (via the STOP VALVE) for the purpose of running the engine.

Does this sound familiar Rich?

Now then, there are 2 possible modes of operation in this configuration… namely STATIC and DYNAMIC.

The STATIC mode is when NO STEAM is being drawn from the BOILER to run the engine. (STOP VALVE IS CLOSED).

The DYNAMIC mode is when STEAM is being drawn out of the BOILER and the engine is RUNNING. (STOP VALVE IS OPEN).

The STATIC mode would be the case when we were first raising STEAM from cold, or during period when the engine was not running.

IMPORTANT NOTE… For the purpose of the next section of this discussion, let us assume that the BURNER can extract ALL of the potential HEAT contained in the CHOSEN FUEL (it's CALORIFIC VALUE) and that the BOILER can absorb ALL of the HEAT produced by the BURNER for the purpose of STEAM production.

Neither of these statements is, in reality, actually true but lets ignore that for the moment.

Ok, first thing is to put some WATER into the boiler and some FUEL into the BURNER.
We now light the burner and sit back to wait for the WATER to heat up and produce STEAM.

When this process is started, the pressure acting upon the WATER inside the boiler and on the FREE SPACE above the WATER will be the same as the pressure outside the boiler… namely…'NORMAL ATMOSPHERIC PRESSURE'.
If we left the FILLER CAP off and lit the BURNER, the HEAT produced/released from the burning of the FUEL would pass through the boilers outer shell and into the WATER causing it's TEMPERATURE to increase. This would continue until the TEMPERATURE of the WATER reached the NORMAL ATMOSPHERIC BOILING TEMPERATURE of WATER… 212deg F.

OK so far… If we continue to add HEAT then some of the WATER inside the BOILER will change from a LIQUID STATE into a VAPOUR STATE (i.e. DRY SATURATED STEAM), however it's TEMPERATURE will not increase BUT it's SPECIFIC VOLUME will.
In other words, it will take up more space/volume than did the water from which it was produced.

This produced DRY SATURATED STEAM will rapidly fill the FREE SPACE above the water, displacing the AIR that originally filled the space via the open FILLER opening.

Now then, the FREE SPACE above the water inside the boiler can only hold a certain VOLUME of DRY SATURATED STEAM, (at any given pressure), so if we keep HEATING the WATER, the EXCESS DRY SATURATED STEAM produced will exit the BOILER via the open FILLER and escape into the atmosphere at NORMAL ATMOSPHERIC PRESSURE.

NOTE…
The increase in SPECIFIC VOLUME when water changes from its LIQUID STATE into its VAPOUR STATE is massive.

1lb of water (454ml) at a temperature of 212deg F at normal atmospheric pressure will occupy a volume of approx. 28 cu in.
If this same volume of WATER were all converted into DRY SATURATED STEAM, at normal atmospheric pressure, it would occupy approx. 26. 8 cu ft (=46,310 cu in)

This is an increase in volume of approx 1654.

It is this increase in volume (EXPANSION) that we make use of in our engines and it is HEAT energy, which allows us to do so.

Returning then to our boiler…

Now STEAM at atmospheric pressure is of a limited practical use, for sure it could cook some vegetables or some such, but it won't drive an engine.
This is because it cannot be conveyed under its own pressure along a steam pipe to the point of use.

For this to be possible we need a PRESSURE difference.

OK, lets fit the FILLER CAP… we now have a sealed container.

So now as we continue to add more heat the generated DRY SATURATED STEAM cannot escape, therefore, the PRESSURE and the TEMPERATURE of the WATER and the STEAM within the BOILER increases until the SAFETY VALVE opens.

NOTE… I repeat… this is a very simplistic description of the exact process, but it will serve for now.

How long this whole task takes, after lighting the burner, will be dependant upon 4 main things: - namely, the MASS (volume) of WATER, the STARTING TEMPERATURE of the WATER, the AMOUNT of HEAT available from the FUEL being BURNT and the PRESSURE required.

Eventually, after an amount of time has passed we reach the point where the PRESSURE is raised to the desired level, typically this would be either when the SAFETY VALVE opened or the PRESSURE GAUGE (if fitted) read the correct PRESSURE, and we are now ready to run the engine.

As soon as we open the STOP VALVE and begin taking DRY SATURATED STEAM from the BOILER we enter the DYNAMIC mode of operation.

NOTE… from now on I will use the word STEAM to mean DRY SATURATED STEAM… unless context dictates otherwise.

Now then, when STEAM is taken from the BOILER it also takes with it some of the HEAT used to create it. This lost HEAT now has to be put back into the BOILER In order for it to produce more STEAM and maintain the PRESSURE.
All things being equal, the burner would supply the heat required; and everything would be ok.

Sadly, this is very rarely the case since we have, so far, OMMITED one very important factor… namely the RATE of EVAPORATION required.

This will be determined by the STEAM requirements of the LOAD we wish to use/power/drive, in this case the ENGINE, and the RATE required is the product of the TOTAL SWEPT VOLUME of the engine cylinder/s multiplied by the desired running speed in RPM.

In other words, due to the RPM part of the above calculation, we now have a finite TIMESCALE involved. (Time ‘T’)

If the amount of STEAM required by the engine (and hence loss of HEAT from the BOILER) in time ‘T’ is more than the BURNER can replace in the same time; then THE RATE OF EVAPORATION of the BOILER/BURNER combination is too low and we WILL get a pressure drop.
In addition, the quality of the STEAM being drawn off will probably (more than likely) be lower in as much as it will be WETTER. (It would no longer be DRY SATURATED STEAM…but WET STEAM).

Rich, from my observation of your video, this is clearly the case with your current set-up. The PRESSURE can easily be seen to drop rapidly (on your PRESSURE GAUGE) when you start the engine.

Ok then, what can be done?

There are really only 2 options: -

Namely, increase the rate of HEAT DELIVERY from the burner (either by using a larger burner, capable of producing the required HEAT in the TIME required or switch to a higher CALORIFIC value FUEL, or possibly BOTH).

Or

Reduce the LOAD placed on the BOILER by running the engine at a much-reduced speed that will allow the burner to replace the HEAT at a slower RATE.

On the face of it, the second option looks more promising, however, it may not be in keeping with the purpose of the engines use… possibly Ok for a show model, but not so if the engine is, say, driving a boats propeller.
In this later case, the only real option is the first one.

So… we increase the output from the burner by some means…

Changing the FUEL to one with a higher CALORIFIC value is one option, BUT… even this may not be enough.

Any given BURNER can only BURN so much FUEL of a specific type in a given TIME… and the HEAT output is proportional to the amount of FUEL BURNT in that TIME and the CALORIFIC VALUE of that FUEL.

If the BURNER cannot BURN sufficient of the HIGHER CALORIFIC FUEL in the TIME required then it would not solve the problem.
It may well produce a small amount more HEAT than with a lower CALORIFIC FUEL, which will improve the situation a little, but it wont help much in the overall scheme of things.

The only remaining option is to use a LARGER BURNER, possibly in conjunction with the HIGHER CALORIFIC FUEL.

OK so far?

BUT… Yeh! There is always a BUT…

Lets say we have fitted a bigger burner which is just capable of BURNING sufficient FUEL in a TIME conducive with providing the necessary HEAT to keep up with the EVAPORATION RATE required by the LOAD (ENGINE)… i.e. the DYNAMIC mode… This would, in this case, be the MAXIMUM AVAILABLE FIRING RATE for the BOILER… So, what happens when we CLOSE the STOP VALVE, therefore stopping the ENGINE and we return to the STATIC mode?

Since we now have NO LOAD the required EVAPORATION RATE is LOWER and we now have TOO MUCH HEAT being supplied to the BOILER.

This is going to result in too much STEAM being generated and, in order to keep this in check, the SAFETY VALVE will lift at the NORMAL OPERATING PRESSURE, or maybe just a little higher, but certainly well within the MAXIMUM SAFE OPERATING PRESSURE of the BOILER DESIGN, and the surplus STEAM will vent off into the atmosphere… or can it?

Certainly the SAFETY VALVE will/should LIFT at its SET PRESSURE (if it does not then change it for one that does) and some STEAM will escape through it, BUT is it enough to keep the PRESSURE within acceptable limits?

UK Boiler TEST REGULATION state that the THROUGHPUT of a SAFETY VALVE when lifted shall be high enough to be capable of venting sufficient of the EXCESSIVE STEAM being produced, whilst the MAXIMUM AVAILABLE FIRING is being applied to the BOILER, such that the PRESSURE does not rise by more than 10% above the NORMAL WORKING PRESSURE. (Or the lifting pressure providing the permitted 10% rise does not exceed the MAXIMUM SAFE WORKING PRESSURE of the BOILER DESIGN)

If it can do this, then you will be OK… if it can't do this then you will need an alternative valve, set for the same OPERATING PRESSURE, but having a higher throughput. (This could be a bigger valve, or one with a larger bore).

Ok, Do you remember the assumptions I made at the beginning of this section?
Namely… that the BURNER can extract ALL of the potential HEAT contained in the CHOSEN FUEL (it's CALORIFIC VALUE) and that the BOILER can absorb ALL of the HEAT produced by the BURNER for the purpose of STEAM production.

Since neither of these statements is, in reality, actually true… what do they mean? And what happens when we take the actual reality of these into account?

Taking the BURNER first… the CALORIFIC VALUE of a FUEL is the amount of HEAT a given mass of the FUEL can produce if it is PERFECTLY burned. Since NO burner can actually PERFECTLY burn the FUEL there will be losses. How much largely depends upon the design efficiency of the burner. The NET result is that more FUEL will need to be burnt to provide the necessary HEAT output.

Moving on to the BOILER…

No boiler can absorb and/or transmit all of the HEAT produced by the BURNER into the WATER. There will always be losses.
Some HEAT will escape up the funnel or via other openings in the boiler housing. Yet more HEAT will be lost from the boiler, mainly by way of conduction/convection into the surrounding atmosphere; which is in contact

with the outer surfaces. (Lagging can help to some degree, but there will always be some loss).
Losses by means of RADIATION would be confined to those areas directly surrounding the FIREBOX, where the temperature difference is much higher.

If the BOILER is poorly designed, with too little HEATED SURFACE AREA, then a lot more of the HEAT produced will pass into the atmosphere having done NO WORK.
There are also more subtle things such a BOUNDARY LAYER EFFECT or MATERIAL of construction to take in to account with the NET RESULT being… even the BEST designed FULL SIZE BOILER can only make full use of, AT BEST, 80% of the available HEAT.

Most would fall well below this at around 65% to 75%.

Model BOILERS are even worse… and a figure of 50% to 60% would be about right for the best of them.

So… at best burning a bit more fuel in a given time can be of some benefit, if however, the boiler design meant the extra HEAT could not be used, there would be no advantage in doing so.

Go figure…

Before I move on to look at what happens when STEAM is taken out of the BOILER I would like to explain about the term DRY SATURATED STEAM since I am sure it will be confusing some of you… How can something be DRY and at the same time be SATURATED?

If we take a vessel, such as our boiler, fitted with a SAFETY VALVE, a PRESSURE GAUGE and a FILLER CAP. If it could also be fitted with a THERMOMETER then this would be useful for observation purposes.

If the vessel was partly filled with water and heated gently until all the air above the water was expelled through the filler and replaced by STEAM.
We now fit the FILLER CAP and continue heating for a time and then turn the burner off. (This should be done before the safety valve opens)

We should now leave the vessel to stand, undisturbed, for a short while to allow it to settle down to a STEADY STATE.

We should now be able to observe a certain PRESSURE and a certain TEMPERATURE (if thermometer is fitted).
The PRESSURE is said to be that corresponding to the TEMPERATURE, and the STEAM in the space above the WATER is said to be DRY AND SATURATED.

DRY because our STEADY STATE means that any particles projected out of the water into the space above are balanced by steam particles diving back into the water.

SATURATED because the SPACE when in contact with WATER can only contain a fixed amount of VAPOUR. The introduction of more VAPOUR would lead to the EXCESS being condensed back into WATER.
The removal of VAPOUR would result in more evaporation until equilibrium was restored.

The association of the word SATURATED with WETNESS is so deep rooted in everyday usage that the term DRY AND SATURATED appear at first to be a contradiction.

Now then… in an ACTIVE boiler system, such a STEADY STATE condition will rarely occur, since we would generally be applying HEAT at some level throughout the period of time the system was being used.
As a result, the WATER surface would be much more turbulent than in the STEADY STATE, thus more water droplets would be projected above the surface into the space above… due to this, the steam contained in the space would be a little wetter than the ideal…. Typically about 2% - 5% water content.

How far these droplets project into the space above the water will be dependant on the firing rate/evaporation rate, so the location of the STEAM TAKE OFF should be as far from the water surface as is practical. Typically this would be at the highest point on the boiler barrel.

If you have a steam take off point that is too close to the water surface, then a lot of these water droplets will be entrained in the drawn off steam.

Lowering the water surface in the boiler, thus leaving more space above it, then fewer droplets are liable to being carried out of the boiler.

Having said this, some caution must be taken to ensure that the reduced water level does not expose the boiler to other potentially dangerous situations.

E.G. taking the water level below the top of the firebox, or internal flue (in a horizontal boiler).

So… The level chosen for initially filling the boiler must not only allow for the initial expansion of the water as it is heated, it must also still leave sufficient room to contain the steam produced, whilst minimising the carry over of entrained water droplets.

Rich, this is the DYNAMIC element I was referring to earlier, when relating to your reduction in water level.

Can a steam dome help? YES… In general terms a steam dome will help with this, since it can permit a higher water level to be maintained whilst, at the same time, moving the take off point further away from the water.
Ok I think that covers enough of the steam generation/boiler side of things for now.

So lets take a look at what happens when our generated steam is taken out of the boiler to power the LOAD (ENGINE).

As stated above, when a quantity of STEAM leaves the boiler it carries with it some of the HEAT used in its FORMATION.
The TEMPERATURE of the STEAM is that which corresponds to the PRESSURE within the BOILER at the moment it leaves.

The PRESSURE of the STEAM at the input side of the engine is higher than the pressure on the exhaust side of the engine and it is this DIFFERENCE in PRESSURES that permits the STEAM to move through the engine and PRODUCE WORK.

It is the HEAT contained in the STEAM which keeps it at a given PRESSURE and if it looses any of it then the STEAM first becomes WETTER and then if the HEAT loss continues it looses some PRESSURE. This will continue until the PRESSURE falls to NORMAL ATMOSPHERIC PRESSURE ** and most of the HEAT is used up, at which point the STEAM condenses back into WATER.
This will happen at 0psi gauge and 212deg F and at this point the only HEAT remaining, from the TOTAL HEAT OF FORMATION originally INPUT, will be that amount which was required to raise the TEMPERATURE of the WATER from it's starting TEMPERATURE of 50deg F to the NORMAL ATMOSPHERIC BOILING POINT of 212deg F.

Ideally, this should not be allowed to occur until the steam has left the system into the surrounding atmosphere.

If it losses its HEAT and PRESSURE before it reaches this point then the resultant condensate (WATER) will tend to block some of the path.

The path between BOILER and ATMOSPHERE has many obstacles for the STEAM to overcome, most of which are capable of removing HEAT it carries on the journey.

NOTE**… For the purpose of this explanation I am assuming NORMAL ATMOSPHERIC PRESSURE and TEMPERATURE to be the external working environment and that the ENGINE is also EXHAUSTING into the same… SOME do make use of a partial VACCUUM to extract a little more WORK from the STEAM.

OK then, the first thing the STEAM meets is the PIPEWORK between the boiler and the engine STEAM CHEST (ignoring such things as lubricators for the moment).
This pipe is the first opportunity the HEAT carried in the STEAM has to escape, since the pipe is surrounded by air, at the normal atmospheric temperature (which is generally much lower). It should, therefore, be kept as short and direct as possible and be thickly lagged to minimise such loss.

On reaching the STEAM CHEST the STEAM is admitted to the engine CYLINDER by way of the STEAM PORTS, these ports are controlled by a valve, which is SYNCHRONISED with the position of the PISTON inside the CYLINDER and it would normally OPEN when the PISTON was at the END of its STROKE.
On entering the CYLINDER the STEAM PRESSURE applied to the face of the PISTON causes it to move back along the bore towards the opposite end of the CYLINDER.
By means of mechanical linkage, the piston is connected to the CRANKSHAFT of the engine, which now begins to turn.

On some types of engines the STEAM CONTROL valve remains open until the PISTON reaches the end of its STROKE at the opposite end of the CYLINDER, and the STEAM is applied to the piston at FULL PRESSURE for the whole time. Such engines are known as NON-EXPANSION engines (typically oscillating engines).

On another type of engine the STEAM CONTROL valve closes off the STEAM PORT after the PISTON has moved a certain distance along its STROKE, thus preventing any more HIGH PRESSURE STEAM from entering the CYLINDER, and the STEAM already admitted into the CYLINDER is allowed to EXPAND within the CYLINDER thus pushing the PISTON for the remainder of the STROKE. In doing so, the STEAM gives up some of its HEAT and, as a consequence, its PRESSURE reduces. The STEAM, in this case, will also become WETTER.

Such engines are known as EXPANSION engines (typically SLIDE VALVE or PISTON VALVE engines… but there are others).

Once the PISTON reaches the end of its STROKE the original STEAM INLET PORT is closed (if not already so) and the EXHAUST PORT is opened ready for the RETURN STROKE of the PISTON.
If the engine is of the DOUBLE ACTING type (one where fresh steam is used to push the piston back again) then the STEAM port at the opposite end of the cylinder is also opened and fresh STEAM is allowed to push on the other side of the PISTON forcing it back along the CYLINDER to the start position.
Whilst on this return stroke the STEAM previously admitted on the first stroke

would be expelled through the open EXHAUST PORT into the atmosphere taking with it any remaining HEAT; which would now be wasted. (In some cases this would be via another device, such as a feed water heat exchanger in order to extract as much of the NOW waste heat as possible).

On a SINGLE ACTING engine (one which only uses fresh steam to push the piston a single direction) then the force/energy required for the return stroke has to be provided from a different source, usually inertia from a heavy flywheel.

All very straight forward really, and not terribly complicated BUT… there's that word again!!…

STEAM CHESTS, STEAM CONTROL VALVES, CYLINDERS and PISTONS are generally relatively large lumps of METAL when compared to the volume of STEAM required for a single STROKE.
If all this mass of metal is at a TEMPERATURE that is LOWER than that of the STEAM (and it will be when we first try starting the engine) then it will very quickly remove the HEAT from the STEAM causing it to loose PRESSURE and CONDENSE back into WATER whilst inside the CYLINDER.

NOT exactly the plan!!

There will always be some loss of HEAT ENERGY in a steam engine (or any other combustion engine for that matter, be it INTERNAL or EXTERNAL combustion), simply due to the normal laws of THERMODYNAMICS, but, by careful design, a lot can be done to improve matters by e.g. keeping the MASS of the engine components down to the minimum required for strength and stiffness (minimum metal).

Lagging of areas such as the outside of STEAM CYLINDERS can also be of huge benefit by keeping the HEAT where it should be… in the STEAM.
Such steps will help reduce these LOSSES and will also allow the engine to get up to correct working temperature more quickly.

Ok then, I think you can see that the biggest issue with a steam plant is HEAT LOSS. If any loss occurs in the wrong place, e.g. too early in the cycle, then it is entirely possible that the cycle cannot be completed before the steam condenses back into water.

Where additional items, such as displacement lubricators, are introduced/required then their effect on the STEAM HEAT CONTENT must be carefully considered.
Too much HEAT loss in such an item will result in COOLER/WETTER/LOWER PRESSURE steam entering the engine on the INLET side, as a result, the EXHAUST side of the engine could be nothing more than WATER, or very close to it, which in turn can lead to problems in any following equipment, such as OIL TRAPS, as has previously been discussed in a earlier post.

To sum up then: -

Lowering the initial water level in the boiler will be beneficial in reducing the amount of water carried over with the steam.
Alternatively, a STEAM DOME could be fitted to raise the take off point further above the water surface.

Smaller initial water content will need less TOTAL HEAT to convert it to DRY SATURATED STEAM but will result in a shorter total running time unless an additional means of adding water, during operation, can be arranged.

The EVAPORATION RATE required from the BOILER at any given time will determine the HEAT OUTPUT rate required from the burner.

The EVAPORATION RATE required from the BOILER will not be a CONSTANT.
It will vary according to the MODE of operation and will, ultimately, be determined by the requirements of the LOAD.

STATIC mode will require a lower EVAPORATION RATE and lower HEAT OUTPUT from the burner, since NO STEAM is being drawn from the BOILER.

DYNAMIC mode will require a much higher EVAPORATION RATE and will therefore require much more HEAT OUTPUT from the burner.

The STEAM THROUGHPUT of a boiler SAFETY VALVE should be high enough to permit the escape of excess steam from the boiler, whilst it is being HEATED at MAXIMUM FIRING RATE, such that the pressure in the boiler does not rise more than 10% above NORMAL OPERATING PRESSURE.

STEAM PRESSURE will affect STEAM TEMPERATURE.

STEAM at a HIGHER pressure will have a HIGHER initial temperature and so can lose more HEAT, once released from the BOILER, before it condenses back into WATER at ATMOSPHERIC pressure.

MINIMISE HEAT LOSS in any STEAM PIPEWORK by keeping the length of such pipes as short as possible and by lagging the pipes to insulate them from the surrounding atmosphere.

MINIMISE HEAT LOSS in the engine components by keeping their metal MASS to the minimum required for strength and stiffness.

Where possible, lag the outside of STEAM CYLINDERS.

Items such as DISPLACEMENT LUBRICATORS (on the INLET SIDE of an engine) and OIL TRAPS (on the EXHAUST side of an engine) should be designed and mounted in such a way as to minimise unwanted HEAT LOSS whilst at the same time meeting their specific operational requirements.