DRAFT

The Effect of Superheat on Cylinder Condensation

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Introduction

Perhaps I should start by stating how much effect cylinder condensation has on the performance of small steam engines. I have found in my experiments that an unsuperheated engine consumes two or three times as much steam as would be expected from the dimensions of the cylinders and the engine speed. Condensation can be reduced by superheating the steam, and the steam consumption will then be halved with little or no effect on power output. That is fine, but we don't know just how much superheat to apply, and how this depends upon things like steam pressure, engine speed and cut-off.

Neither is it generally known just how the condensation process operates. For example, a 5″ gauge engine can consume something like 25 - 30 lb. of steam per hour, which is equivalent to a heat supply of about 10 kW. If half of the steam is condensed, we have to explain where around 5kW of heat disappears! Certainly it cannot be lost by convection and radiation from the outside of the cylinders, even if they are unlagged . As an illustration of why this is impossible, a 2″ dia. × 6″ long cylinder would need to be at about 800°C to get rid of this amount of heat.

In fact a plausible answer to this conundrum has been around for more than a century. The idea is that during admission (TDC to cut-off) steam is condensed and forms a film on the cooler walls of the cylinder and the latent heat of condensation heats up the cylinder wall: as expansion proceeds after cut-off the steam temperature falls to a point when it is cooler than the cylinder wall, whereupon condensation will cease. For the rest of the expansion and for the exhaust stroke, the heat deposited in the cylinder is extracted and used to evaporate the water film left on the surface. Some of this evaporation can contribute a little work by raising the steam pressure during expansion, but by far the greater part is a hindrance and may increase backpressure during the exhaust stroke.

Further study shows that this process of heat conduction into and out of the cylinder only affects a thin layer beneath the surface - something like a millimetre (0.040″) or two, so that its effect is not felt in the bulk of the cylinder material. The nature of this transient conduction process will be illustrated below, when the experimental results are outlined. Much depends upon the temperature of the bulk of the cylinder, for if this is above the inlet steam temperature condensation will be eliminated. However, when using unsuperheated steam the bulk cylinder temperature lies somewhere between the inlet steam temperature and the exhaust steam temperature, and condensation occurs. So the answer to the above conundrum is that the latent heat of the condensing steam is temporarily side tracked into the cylinder wall, and returned too late to be of any use!
So we are left with much the same work output and a considerable increase in steam consumption; hence a drastically reduced efficiency.

When these ideas were first introduced they caused great controversy. Unambiguous experimental support was difficult to obtain with the techniques then available, and indeed the controversy was never fully resolved before the introduction of superheat partially removed the problem. It is also fair to state that many supporters of superheat believed its merit was in improved thermodynamic cycle efficiency rather than reduced condensation; they did the right thing for the wrong reason, which is regarded in some circles as worse than doing the wrong thing for the right reason!

Improvement in instrumentation and the help of computers, rather than greater insight, is all that I can claim for what follows.

An Experimental Approach

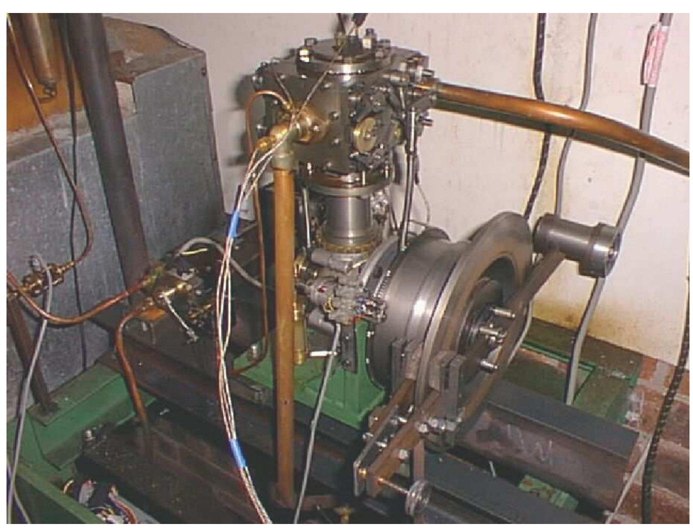
It was realised in the late 1800s that measurements of the temperature fluctuation at the surface of the cylinder wall would greatly help in understanding the process. Callendar and Nicolson in a paper dated 1897 (Ref.1) reported measurements of temperature in the cylinder cover at an engine speed of 100 rpm. They used thermocouples in holes drilled from the outside to within 0.01″ of the inner surface, and the output of these was measured on a galvanometer that was connected via a contact-maker at various positions of the piston in its stroke. It was a remarkable achievement, but the number of readings that could be taken in one revolution was limited. Since the aim is to determine the temperature of the surface exposed to steam, some method had to be devised to extrapolate from temperatures measured at points below the surface. This involved using a standard theoretical solution for transient conduction; this is not strictly correct, but is probably a reasonably good approximation.

Using a computer and modern instruments it is possible to overcome the limitations faced by Callendar and Nicolson. Firstly it is possible to measure the surface temperature directly using a very fine thermocouple welded to the inner surface of the cylinder cover. Secondly the signal from the thermocouple can be read very quickly using a computer; in fact, I have been able to take measurements every 2 degrees of rotation on an engine running at 1000 rpm - this means reading and storing 3000 measurements per second.

For small engines running at high speed the temperature gradient near the surface of the cylinder is steep, and it is essential to measure the temperature ***at the surface***. The technique of using a small thermocouple bead and attaching this to the surface is not satisfactory because of the difficulty of ensuring that the whole of the bead is at cylinder surface temperature: there is also the possibility that the presence of the bead may affect heat transfer at just the point where temperature is to be measured. However, a technique I have used to measure the surface temperature of nuclear reactor fuel elements seemed appropriate. This is to spot weld the thermocouple wires to the surface a small distance (a few mm) apart, using fine thermocouple wires (~ 0.15 mm dia.). The intervening material does not affect the thermocouple output, and the fine wires lying close to the surface cause minimal interference to the surface temperature.

Given the surface temperature variation around one cycle it is then possible to deduce the heat flow into and out of the cylinder surface. This is possible because the temperature wave travels only a short distance into the cylinder wall, so the wall may be regarded as that mathematically simple object, the ‘semi-infinite solid’. In other words the behaviour is the same as it would be if the cylinder wall were infinitely thick, because only a thin layer at the surface is affected. Such information is crucial to an understanding of the condensation process, and may enable us to discover just how much superheat is required to prevent condensation.

Figure 1



The Apparatus

The engine used was a single cylinder vertical with a 50mm bore and 32mm stroke. It has separate Corliss type inlet and exhaust valves, the inlet valves being trip operated so that cut-off can be regulated without affecting exhaust and compression events, Fig.1. The supporting equipment is very much as described in an earlier paper (Ref.2) : thus the bulk of the measurements, for example steam flow rate, temperatures, speed, brake load and indicator diagram are handled by a computer. In these experiments measurements were also made of the surface temperature of a stainless steel plug (Fig.2) inserted in the top cover. These temperatures were recorded every 2 degrees of rotation for one revolution. The voltage generated by the thermocouple was amplified and fed into an analogue-to-digital converter, and thence into the computer memory.

The computer programme controlling the experiment recorded the following data:

Engine speed
Indicator diagram (i.e cylinder pressure every 2° of rotation, for 1 rev.)
Cover surface temperature (every 2° of rotation , for 1 rev.)
Steam flow rate
Steam inlet temperature

At the conclusion of a test the programme then automatically computed the following:

Mean Effective Pressure
Indicated Efficiency
Steam Ratio (Ratio of steam actually used to that calculated from cylinder dimensions and speed
Superheat
Saturation temperature of steam for each point on indicator diagram

Experimental Data.

The tests were at nominally constant speed and constant steam chest pressure. The superheat was gradually increased over a period of about 2 hours, during which time 40 sets of data were obtained. The brake (a motor car disc brake with home made pads!) , together with the boiler gas supply was used to control speed and steam pressure. In all the tests cylinder oil was fed into the steam pipe leading to the steam chest. (There appears to be a slight reduction in condensation when oil is supplied in the case of unsuperheated steam; the oil supply was of course always maintained when using superheated steam). A test using air rather than steam (Test No.40) is also included, since it has a bearing on cylinder and valve leakage

Let us look firstly at the records of temperature and pressure for one revolution of the engine. These contain all the information needed to show how much condensation is occurring . Two sets of data, one using unsuperheated steam (Test No.8) and the other superheated steam (Test No.21) are presented.

TEST No. 8 (Unsuperheated)

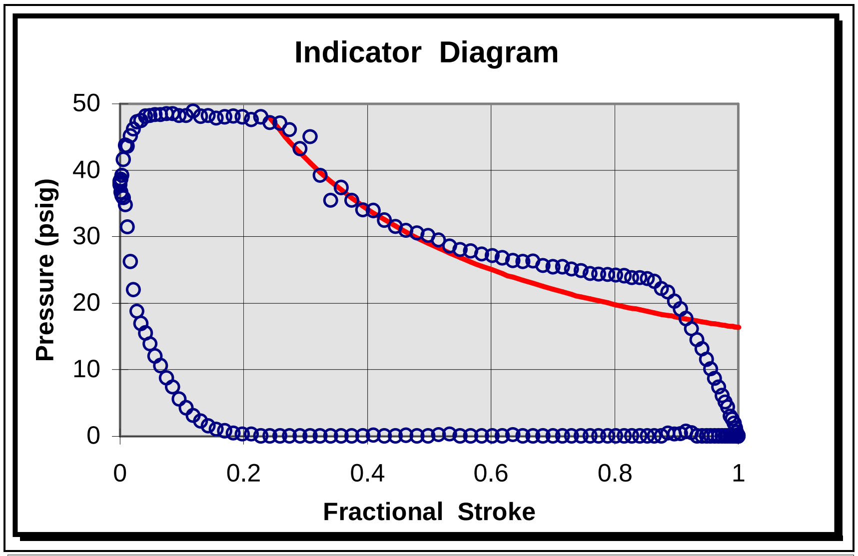


Figure 2

Points:- cylinder pressure
Continuous line:- PV=const

Speed 544 rpm
Indicated Efficiency 3.08 %
Steam Ratio 2.62

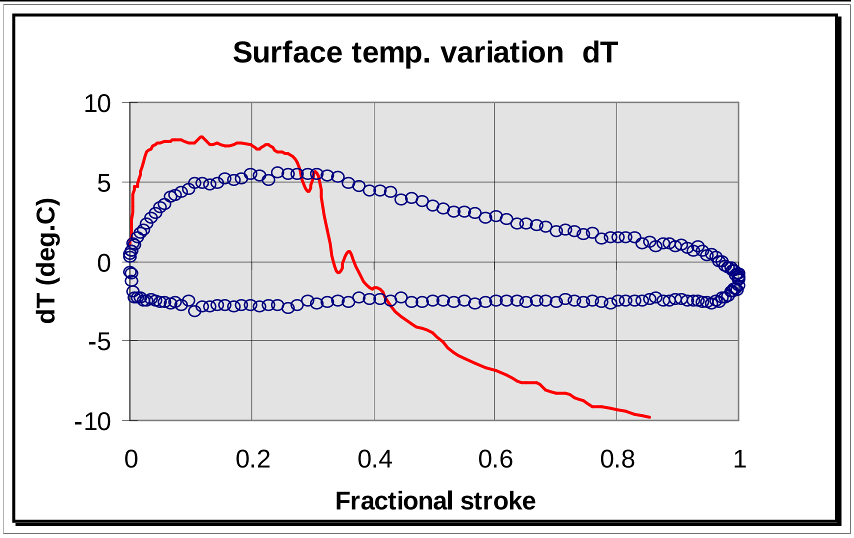


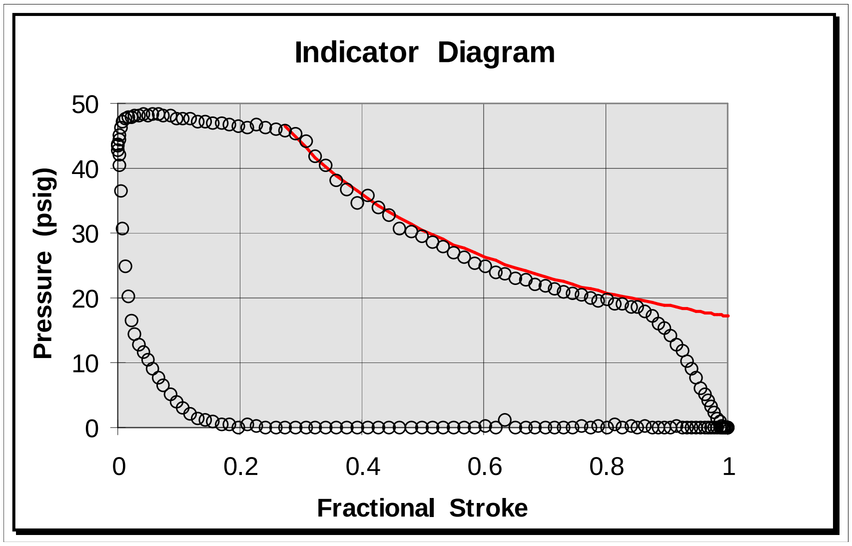
Figure 3

Points:- Surface temperature

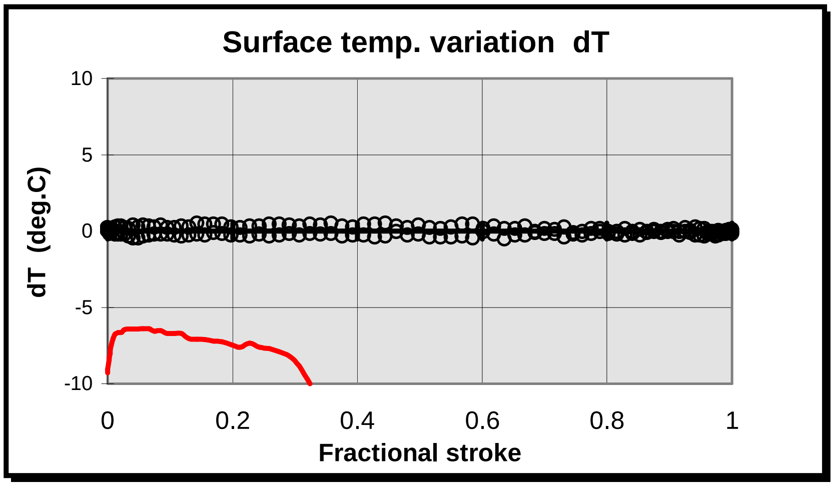
Continuous line:-
(saturation temp. -
mean surface temp.)

The surface temperature loop in Fig.3 is the measured surface temperature minus the mean of all the set of surface temperatures. The temperature variation (7 or 8 °C) may not seem very large but, as will be demonstrated later, it represents a considerable heat input to and extraction from the cylinder cover as a result of condensation and evaporation. Such condensation occurs when the saturation temperature of the steam exceeds the surface temperature of the cover . The difference between the saturation temperature and the *mean* surface temperature is shown as a continuous red line. (The *saturation temperature* of the steam is merely the boiling point of water corresponding to steam at a given pressure. The computer is programmed to calculate the saturation temperature at each of the pressures recorded on the indicator diagram, Fig.2) Not surprisingly this loop bears a resemblance to the indicator diagram.. Notice that the surface temperature rises during the period when the saturation temperature exceeds the surface temperature, and then declines . This indicates that the heat of condensation is passing into the cover during admission, and that shortly after cut-off this heat is removed and used in evaporating the condensate left on the surface. This evaporation process continues throughout the exhaust stroke.

The continuous line superimposed on the indicator diagram, Fig.2, represents a hyperbolic expansion (Pressure × volume = constant), which is a good approximation for the expansion of saturated steam. Notice that the measured pressures rise above this line as expansion proceeds. This is due to the evaporation of the water layer described above. The effect is to increase the area of the indicator diagram slightly, and therefore the work output. Thus we reach the surprising conclusion that condensation may slightly increase power, but at the expense of a much reduced efficiency. Consequently it would be difficult to detect condensation except by measuring the steam consumption, the power output being little affected.



The evil effects of condensation are reflected in the low Indicated Efficiency of around 3 %, and the Steam Ratio indicates that 2.62 times as much steam was admitted than could be accounted for from the known dimensions of the cylinder, cut-off, speed, and the density of the inlet steam.



<u>TEST No. 21 (Superheated)</u>

Figure 4

Continuous line:- PV=const expansion

Continuous line:- Sat. temp - Mean surface temp.

Speed 555 rpm
Superheat 73.1 °C
IndicatedEfficiency5.25%
Steam Ratio 1.74

Figure 5

Points:- Surface temperature

Continuous line:-
(saturation temp. -

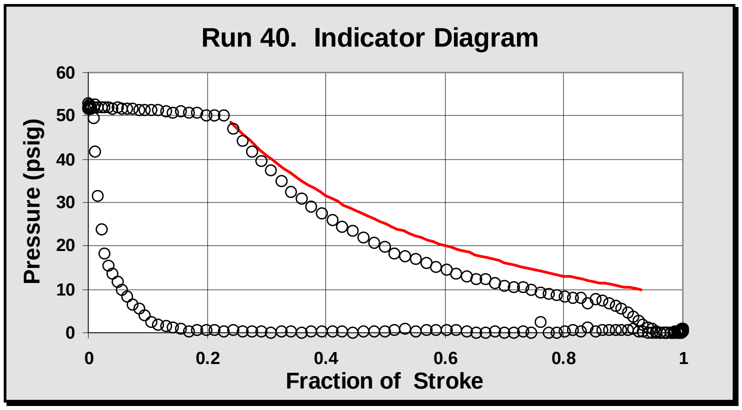
mean surface temp.)

In this test the surface temperature is always above the saturation temperature of the steam; consequently no condensation can occur, and this is indicated by the virtually constant surface temperature. Notice also the change in shape of the indicator diagram; the pressure now falls slightly below the 'PV=const' line. Most striking, however, are the values of the Indicated efficiency and the steam ratio.

It must be emphasised that the above temperature measurements refer only to the cylinder cover, whereas the condensation process will also occur on the cylindrical surface of the cylinder. The cover is probably more important, area for area, and its temperature fluctuation seems to be a reliable indicator of condensation. In the case of the test engine the Corliss type exhaust valve , well cooled by exhaust steam but also exposed to inlet steam, may well make a significant additional contribution

TEST No. 40 (Air)

Figure 6 (Air, 237 rpm)



It is instructive to test the engine using air as the working fluid at conditions fairly similar to the steam tests. The indicator diagram from such a test is shown in Fig.4. In this case the expansion falls well below the 'pv = const' line; the greater part of it is close to a ' $pv^{1.4}$ = const' line, as would be expected for adiabatic expansion of air. This result is quite useful in that it confirms that leakage past the piston is not significant. Another quite interesting aspect of Fig.4 is the contrast in shape of the diagram when compared with the steam indicator diagrams. The start of the diagram following admission is much 'sharper', as is that following cut-off. I think that in the case of steam when both liquid and vapour may be present together with a heat source/sink in the form of the cylinder surface, the mixture is much more 'compressible' and does not adjust as quickly to changing conditions. There is certainly a noticeable difference in the running of the engine - steam gives smoother running!

Analysis of Results

Whilst the width of the temperature loop and the Steam Ratio are both good indicators of cylinder condensation, it is possible to extract more direct evidence concerning the heat flow into and out of the cylinder by analysing the surface temperature fluctuations. As mentioned above, these fluctuations do not penetrate more than a millimetre or two into the cylinder wall, and in these circumstances it is possible to calculate the changing temperature profiles in the cylinder wall. I will not go into the details here; sufficient to say that they have been calculated using the Crank-Nicholson finite difference method. My computer programme accepts a disc containing the experimental measurements and applies the surface temperature fluctuations to a semi-infinite solid; the resulting temperature profiles corresponding to the data of Figs 3 and 5 are shown in Figures 7and 8. Whilst the profiles are calculated for each 2 degrees of rotation, I have shown profiles only for every 20 degrees in Figs 7 and 8 to improve the clarity of the figures. The drastic reduction in both amplitude and penetration as a consequence of superheat are clearly evident

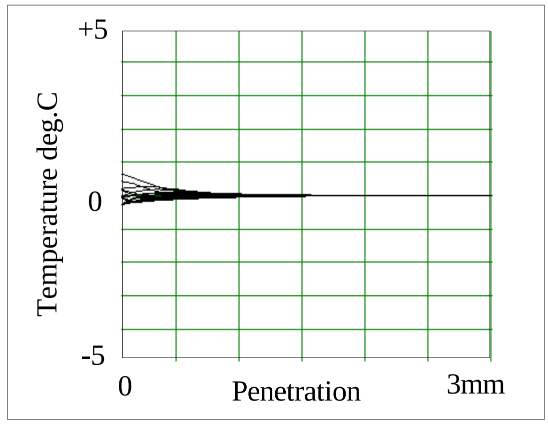
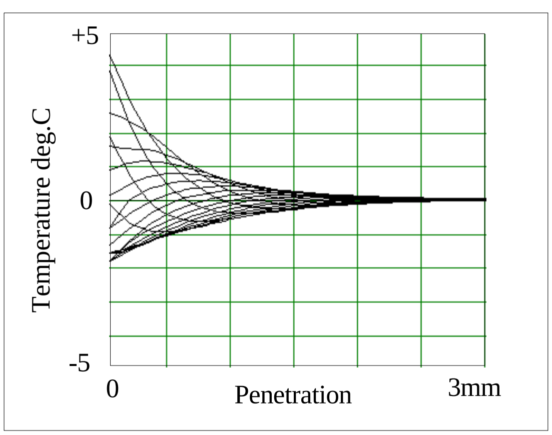


Figure 7 **Figure** 8

The programme that calculates the shape of the above temperature profiles (Figs 7 & 8) also determines the rate of flow of heat into or out of the cylinder corresponding to each profile. If all the profiles that give a heat input are added together, we get the amount of latent heat that is deposited in the cylinder cover during the period when condensation is taking place. This is in reasonable agreement with the amount of condensation indicated by the measured Steam Ratio. (Exact agreement would not be expected because condensation takes place also on the cylinder bore as well as the cover)

Discussion

The experiments have shown very clearly the cyclical nature of condensation and evaporation that occurs in an unsuperheated steam engine, and the effectiveness of superheat as a remedy. However, there remains an important factor that is still to be elucidated - the relationship between the temperature of the cylinder and the superheat. Consider firstly unsuperheated steam. Condensation to and evaporation from a water layer are available as a heat transfer mechanism and the fluctuations in the inner surface temperature of the



cylinder must lie between the saturation temperature of the inlet steam and that of the exhaust steam. The heat transfer rates under these conditions are potentially very high, and the cylinder temperature is tightly bound between these two temperatures. Because the heat flow into the cylinder must be nearly balanced by the heat flow out it is tempting to imagine that at some point when condensation is balanced by evaporation the cylinder will be dry; however, there is no reason why this should be so, and a water layer, albeit of varying thickness, may be present for the whole cycle. If superheat is applied condensation is still possible during admission provided the surface temperature of the water layer is below the ***saturation*** temperature of the steam. Presumably less will be condensed because of the higher enthalpy of the condensing steam , and consequently the layer may be thinner. The crucial question is then to determine how much superheat will cause the water layer to disappear. In the above experiments it appears that around 100°C is required, but at the present the problem is too complex to analyse in detail.

It is interesting to speculate what happens after the cylinder has completely dried out, when the cylinder temperature will then be less tightly coupled to the steam temperature by relatively low convective heat transfer coefficients. The cylinder surface temperature will at all points around the cycle be above the saturation temperature of the steam, and it seems possible that a reduction in superheat may not cause the system to revert to one in which condensation occurs; in other words, there may be some hysteresis in the process. In fact, such hysteresis was observed in the above experiments, and it appeared that reversion did not occur until the superheat was reduced to around half the value at which it initially prevented condensation. More data are necessary before the matter can be taken further.

Other factors affecting condensation, in addition to superheat, were engine speed and pressure. Data obtained so far are insufficient to define these accurately, but it became clear that even with unsuperheated steam condensation had less effect as speed and pressure increased. Some of these factors were investigated in the tests reported in Ref.2.

It was found that even when superheat has removed the surface temperature fluctuation, a sudden increase in steam pressure could cause reversion to condensation; possibly a decrease in speed could also have the same effect. This has interesting implications for driving technique with small locomotives. Driving on the regulator at fixed cut-off clearly involves pressure variation, and might be expected to increase condensation and reduce efficiency. It may well be that the alternative, i.e. using cut-off rather than regulator, improves efficiency more by reducing condensation than by improving thermodynamic efficiency. It would therefore be interesting to fit a locomotive with a surface thermocouple to see what happens with various driving techniques. My friend Tom Jones has in fact devised an portable instrument that continuously displays the magnitude of the surface temperature loop when attached to a surface thermocouple. This works well on the test engine, and we hope to test it on the track before long.

References

1. "On the Law of Condensation of Steam deduced from Measurements of Temperature-Cycles of the Walls and Steam in the Cylinder of a Steam-Engine". H.L.Callendar and J.T.Nicolson, 1897. Min.Proc.Inst. C.E. vol.CXXXL, 1897.
2. "Measuring Steam Engine Performance". W.B.Hall, Journal of SMEE, vol.9 No.3, 1998