SOME LOOSE NOTES ON STEAM ENGINE CYLINDER TRIBOLOGY.

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1. Object.

The Author's paper on steam engine cylinder tribology (1) detailed the state of his knowledge about 1975. In the mean time, up to 1980, some additional information (extracted from the enormous volume available) has been incorporated toghether with further thoughts and reflexions. The object of the present notes is no more than to record such observations, leaving for a future exercise its analysis.

2 Comments on the Author's 1975 paper (1).

It is very good to read the own papers after a time, and find them all right! If the yardstick of past "good enough" locomotive engineering is taken, it is clear that, at least, many unsuspected problems have been attacked, starting with the collection of other people's experience. If the yardstick is I.C. engine technology, the enormous gap between the latters' knowledge and the paper is appalling. This means that, (i) contrary to what was assumed by the last golden steam days, a large room for progress lies ahead; (ii) the path for this progress is traced, (iii). it can be expected that with no more progress than that resulting from the better (offered) understanding of steam cylinder tribology, substantial improvements can be accounted for SGS (Second Generation Steam) locomotive technology. And (iv), advanced, future, Third Generation Steam Locomotive Technology, can be looked at with confidence.

The paper contains many assertions still remaining on the qualitative level, thereby waiting... ///

///... quantitative formulations and experimental checks. Perhaps the most pressing need is to be able to "see" (in the broadest sense of the word) inside the cylinder so as to judge what is the actual consist of the lubricating film. New measuring technologies are now available; but even crude experiences could be organized measuring wear in the various rubbing parts, direct looking through windows, etc.

Since the time the paper was written, two new enters on the locomotive picture require adequate consideration: (a) TGS (Third Generation Steam), for which triple expansion, 60 ate, 550 °C, steam conditions are proposed, and (b) condensing. Wear theory should be reworked incorporating recent knowledge in the field, while film thickness forecasting (hence leading to improved design) should increase the accuracy of many statements still being at the level of "steps in the right direction". However, it is strongly felt that no significant changes respect to what has been said can be expected. At least, this applies to the material analyzed during the 5 years following the issue of the paper.

While every effort is done to increase the hydrodynamic component of film support, more emphasis should be placed upon the knowledge of mixed lubrication phenomena. After all, WEAR OBTAINS IN SUCH RÉGIME, on which, unfortunately, knowledge becomes more and more uncertain at higher rubbing surface temperatures. In this connection, gear technology can make a considerable contribution.

The idea of poppet valves as a means of dispensing valve lubrication and getting better steam distribution ...///

///-- deserves new attention. Substituting large valves by a number of smaller ones, and simplifying the drive by the application of the WILLAMS's principle, coupled to the new knowledge on heat transfer, etc. now available, opens interesting possibilities reflecting upon lubrication, which is now to be confined only to the cylinder.

The Author has found that, unlike it happens in other fields of technology, his potential interlocutors are not current about what a steam locomotive is, nor about the lubrication world dealing with reciprocating engine tribology. It is a must that discussers study -as is the rule- the literature which makes an indissoluble body with the paper.

It is clear that the paper reflected the path to find out the true, and also the need to get a proper answer to questions which were matter of dispute in the past.

3. The new material.

3.1 The recent analysis (PORTA (2)) of test data carried out by HILLIGER about 1918 (3), is perhaps an important contribution to confirm and understand lubrication phenomena. The tests were carried out in a small locomobile engine with various combinations of superheated steam and oil qualities; they consisted in interrupting the oil feed, or feeding below the minimum rate, and registering the friction by means of a nearly continuous record of the mechanical efficiency. Very little could be said about what happens in such circumstances other than the usual vagaries. The analysis fully confirmed the thesis sustained by the present Author in his paper (1). It showed - now supported by test figures - the over-=///

///... whelming importance of evaporation as a main conditionant of lubricant consumption. The extremely low oil consumption of German locomotives can now be explained essentially because oil for the valves is injected "between the rings". The steep function of evaporation with temperatures has been experimentally confirmed, namely

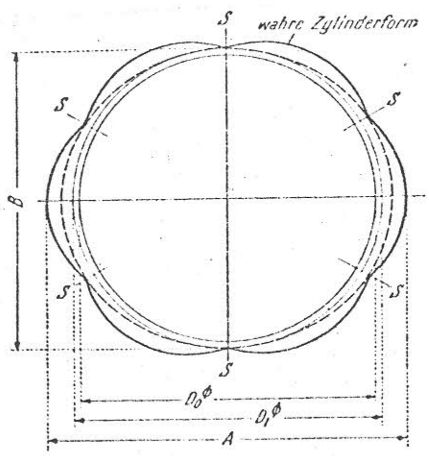
$$\left\{\begin{matrix}\text{evaporation} \\ \text{in kg } m^{-2} h^{-1}\end{matrix}\right\} \propto \left\{\begin{matrix}\text{rubbing surface} \\ \text{temperature in} \\ {}^{\circ}C\end{matrix}\right\}^{12} \cdot \left\{\begin{matrix}\text{normal oil boiling} \\ \text{point temp. in } {}^{\circ}C\end{matrix}\right\}^{-12}$$

The exponent 12 is a very strong one (see 3.8 .), leading to a lot of reflections and opening the door to many potential advantages. Upon restoration of lubrication after a no-oil period, friction conditions take an appreciable time to recover (say 10 minutes). This is interpreted in the sense that surface deterioration inherent to scuffing requires a new running in. No abundance of oil supply can change this, nor produce any benefit in reducing friction. The experiments showed that the effect of oil interruption are felt only after a variable "initial time" which depends on the potential of the system to accumulate an oil reserve. A high boiling point oil shows a considerable advantage in this respect. The tests proved that it is possible to run the engine on "saturated" cylinder oil if the supply was several fold increased so as to compensate for the largely augmented evaporation inherent to its low boiling point. This suggests that, in future advanced technology, the oil feed can be monitored after some rubbing surface temperature permanent monitoring.

3.2 The above reported experiencies strongly lead to think that, in current locomotive practice, a large proportion of cylinder wear was produced as a result of ...///

III.... many repeated circumstances in which no apparent harm was done, yet not showing as a significant damage in daily working. Essentially, this was due to minor but frequent interruptions in the lubrication, oxidations, abrasions, etc.

While it is possible to define a minimum ideal amount of oil feed, there still remains the question of insuring that such minimum oil feed becomes uniformly distributed over the rubbing surfaces. So far, very little is known concerning this uniformity, and it is clear that the efficiency of the system depends on sufficient oil reaching the most unfavourable spot. No-oil-uniformity shows in the form of oil streaks, which are familiar on the piston rod when oiling has been starving. It is clear that the minimum oil consumption is conditioned to the suppression of the last dry streak. Unfortunately, while the piston rod can be seen, the cylinder works hidden. The supply to large diesel engines is usually done in several points (say six), yet uneven wear is apparent ('ENGLISCH, Ref. (4), p.193) as shown in the figure below.



D_0 Ursprünglicher Zylinderdurchmesser
D_1 Form des allseitig gleichmäßig verschlissenen Zylinders
--- Ovalverschleiß unter Einfluß der Schiffsbewegung
A Gemessener Zylinderdurchmesser, längsschiffs
B Gemessener Zylinderdurchmesser, querschiffs
S Schmierstellen

Abb. 177. Wahre Gestalt verschlissener Zylinderbohrungen eines Zweitakt-Schiffsdieselmotors 760 ø, bei gesonderter Zuführung des Zylinderschmieröls (Druckschmierung) — Nach BAUER [121]

Until now, capillarity and transport by the steam has been relied upon, but their action is very uncertain and ill defined. In the case of pistons, steam transport can be facilitated if ring joints are distributed along the piston crown; in that case, leakage steam will perform a good oil distribution. It must be remembered that the scraping action of the rings will tend to concentrate the oil near the middle of the cylinder. If the outer rings are given a proper bevel shape, the hopes are that the space between the piston rings will become somewhat "flooded" with oil. The possibility of incorporating some oil pockets for reserve purposes should be considered.

3.3 Concerning the very low minimum oil consumption of German engines (the incredible figure of 0,6 to 0,7 g km^{-1} has been mentioned, (Ref.(12)), it should be noted that cylinder feed is far from being "solid" (see Ref (1)): most of the oil is blown to the steam space during the exhaust phase, thence stight to the exhaust, never reaching contact with the walls. Cylinder wall evaporation is very low because it depends on $(\text{wall temperature})^{12}$, very little oil feed would be required (≠). Were not because of the above impefection (which can be corrected, see (1)), the former figure could probably be reduced to some 0,3 g km^{-1}, hence making $\frac{1}{30}$th of the consumption of an equivalent American engine with oil-in-the-steam feed. This is an important concerning condensing engines.

(≠) Oil is also blown to the steam space by steam leaking through the end steam joint.

3.4 Locomotive cylinder wear can be classified in two categories: (a) normal wear obtaining in spite of the lubrication being as near as possible to the ideal, and (b) abnormal wear. Ref. (1) gives a long list concerning the various causes for the latter. It is important to bear constantly in mind that normal wear is irrevocably associated to boundary lubrication. Unfortunately, knowledge in this field leaves much to be desired; it is coupled to the complicated physicochemistry of surfaces; the influence of temperature of the oil film is less and less known the higher the temperature is (I.C. engine studies do not go beyond 200°C); it depends on the oiliness of the lubricant and its associated metal surface energy; and so on, all that making at present an unsatisfactory picture. Nevertheless, it must be clearly stated that by no means this unsatisfactory state puts a bound to achieve a satisfactory performance of the concerned engines: rather, it shows a promising future once these questions can be cleared up.

There are several important differences concerning normal wear in I.C. and steam engines:

(a) under the present state of I.C. engine technology, most of the life of I.C. engine piston rings goes in hydrodynamic lubrication, hence with zero adhesive wear. I.C. engine piston ring only touches (if at all) the liner only at the top dead end. This state of affairs obtains in spite of fluid temperatures reaching the 2000°C region, YET NOBODY SPEAKS ABOUT HIGH TEMPERATURE LUBRICATION FOR THEM;

(b) fluid pressures are immensely high: 100 ate compared to 20 ate;

(c) the fluid is oxidizing, corrosive, and the oil is ...///

///-- exposed to oxidizing conditions in the crankcase;
(d) the film operates at low temperatures (less than 200°C), in the range in which knowledge concerning oiliness, material properties, additives, etc. is fairly abundant;
(e) thermal stresses and distorsions are far lesser in the case of steam engines, etc.

The drastic Authors' proposal of cooling valve (if necessary cylinder) liners (5)(6)(7)(8)(9) results also in a drastic change in the scene because of the also not less drastic principle stating that what counts, in steam engine tribology, is RUBBING SURFACE TEMPERATURE and not steam temperature. Therefore, WE SHOULD NO LONGER SPEAK ABOUT HIGH TEMPERATURE LUBRICATION.

This results in consequences like these:
(i) very high steam temperatures (say 550°C) are compatible with current, good quality, cylinder oils;
(ii) better, more viscous, more unstable, oils with much higher molecular weight can be employed;
(iii) as explained, expected consumption will drop by a large factor;
(iv) the incorporation of additives can be envisaged as an extension of lower temperature field developments;
(v) better understanding of boundary lubrication and wear becomes easier;
(vi) higher ring-wall pressures, associated to higher steam pressures, become easier; etc.

This does not means that high temperature lubrication studies are to be disregarded, for they will illuminate the scene.

3.4. Concerning high temperature lubrication, the present Author put, in his paper (1) the emphasis on lubricant life (whichever the definition for life is!). This was important to understand the formation of (abrasive) coke and carbonaceous deposits, especially when the lubricant was subjected to the effect of high temperature steam. The latter obtained when the oil was injected in the steam (as it was the case of the latest American NATHAN system), and a sensible proportion of it was deposited in the steamchest, where it remained there for a considerable time. At the time that the oil is no longer in contact with high temperature surfaces, its residence time at critical places is reduced to a small fraction.

From FOWLE data (10), it can be deduced that lubricant life is roughly proportional to (temperature in °C)^{27}. This means that if a good cylinder oil can support, say 1 hour at 400°C (3 h at 425°C in the case of French Cg_4 in BANCELIN Test (11), if rubbing surface temperature is reduced just not below 350°C, the life is increased to $1h \cdot (400/300)^{27} = 2400\ h$, hence completely out of question.

3.5 Since oiliness (lubricity) properties are dominant concerning wear, there is much to commend the decision to stay to known cylinder oil brands, at least as a first safe step. Proper wear studies are to be carried out in which the various cast iron - oil combinations are to be evaluated in a steam atmosphere. This is something different from costumary testing.

Colloidal graphite can reduce wear by ...//

///... by 50 % as reported by ZWEZ (12), both in piston and valve ring. Therefore graphite is to be definitively incorporated to the lubrication creed.

3.6 Several not current items are to be explored:

(a) emulsions have been used as steam cylinder lubricants;

(b) "Voltolization" as a means to improve viscosity, viscosity index and oiliness;

(c) what advantages can be gained in converting the oil into a grease (which is now possible (US Patent 3,384,583, May 1968), (13), etc.

3.7 The use of bronze and cast iron rings should be thoroughly investigated. The chances are that metal transfer to bronze leads to a smoother surface, hence increasing the share of hydrodynamic support, thereby reducing wear. ENGLISCH (4) (p. 442, and foll.) speaks about bronze rings having a composition like 10 Sn, 15% Pb, rest Cu as used in high temperature steam engines. "The combination "of bronze-cast iron rings results in an extraordinary "increase in the life both for the rings and the "cylinder. The bronze ring produce a thin, very "adherent, bronze film over the cylinder surface; this "film has an extraordinary smoothness; and the cast "iron ring, as result of its better oil adhesion properties, "insure the lubrication of both parts". This match CHAPELON's statements, and can be interpreted as a transfer of bronze worn out particles into the liner surface, and from this back to the cast iron ring companion. Besides the above spoken better boundary lubrication properties, the surface, upon acquiring a lower roughness, leads to thinner oil films, hence increasing the hydraulic support. This should receive confirmation after applying RABINOWICZ's (15) ---///

III--- Theories for wear.

3.8 Whether the exponent is 12 or 8 it does not matter: what counts is that it is very high. It was established as a rough approximation only, requiring better refinement in oil data and evaporation theory.

3.9 DUPLEX bronze - cast iron ring combination for 141 R engines was

(a) Bronze segment (analysis of a sample):

Sn, 12,3% ; Pb, 5,5%; Ni, 0,9% ; P, 0,015%

Zn, 0,0% ; Cu, rest. Brinell 10/500/30, 85

Structure α solid solution, eutectic (α+δ) and lead.

(b) Cast iron segment (sample analysis):

C_{total}, 2,28% ; $C_{graphite}$, 2,00% ;

$C_{combined}$, 0,28% ; Si, 2,1% ; Mn, 0,79% ;

S, 0,08% ; P, 0,41% ; Ni, 1,26% ; Cr, 0,23%.

Brinell 10/3000/30 = 201

Conclusions.

The Author does not cease to stress the fact that new concepts in lubrication, new valve and piston designs embodying a large number of revised details, and the application of all known concurrent means to achieve the best results, etc., have completely changed the scene of steam engine cylinder tribology; which scene remained unchanged since 1925 in Germany, let alone 1914 in the USA. The cardinal point is that liner cooling did away with high temperature lubrication as something inexorably associated to very high steam temperatures.

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