Oil Shale, Vol. 14, No. 3 Special
pp. 218-224

ISSN 0208-189X

ON THE FOULING OF HEAT TRANSFER SURFACES OF CFB OIL SHALE BOILER

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Supposed fouling of heat transfer surfaces was one of the main questions needing clarification along interpretation of the results of Estonian oil shale test burning in circulated fluidized bed (CFB) test devices [1]. Knowing of the operation conditions of heat transfer surfaces is urgently needed for designing new oil shale fired CFB boilers. The detailed research of this problem was impossible because of construction of test devices and short duration of the tests. Nevertheless, the new test data enable to prognose, with sufficient probability, the operation conditions of heat transfer surfaces in CFB boilers, keeping in view their fouling.

The long-term experience showed that the intensive fouling of heat transfer surfaces by ash deposits is one of the main problems in the boilers with pulverized firing (PF) of oil shale at the Estonian power plants [2, 3]. Formation of the hard bound ash deposits takes place at all heat transfer surfaces of boiler starting from the combustor and finishing with economizer. The fouling worsens significantly the heat reception conditions of heat transfer surfaces and demands the frequent and quite intensive cleaning. Finally, fouling decreases the boiler efficiency and increases the operation costs.

The recognizing of fouling conditions of heat transfer surfaces needs long-term tests because the formation of ash deposits needs a long time. This conclusion is proved by the long-term experience of oil shale boilers as well as by earlier researches. With help of short-term tests, only quite preliminary data may be obtained. Unfortunately, only short-term tests (maximal duration of test regime was a little more than one week) were carried out during above mentioned test burning [1]. Besides that, both test devices, used for research works, were not foreseen to carry out the special fouling tests. Therefore, the installation of all needed tube-samples into the combustor and gas passes of these devices was impossible. The carried out tests, because of above mentioned circumstances, were not representative keeping in view the fouling problems of heat transfer surfaces. On the basis of the obtained results only quite preliminary prognoses about supposed fouling of the heat transfer surfaces in CFB oil shale boilers can be done. Nevertheless, these conclusions show that the circumstances of the fouling in the PF and CFB oil shale boilers are very different.

Let start from the combustor. As it was mentioned above, in oil shale PF boiler an intensive fouling of the combustors takes place. Here, from one hand, the reaction of CaO, present in oil shale ash deposited on heat transfer surfaces, with SO_2 arising along burning is the reason of fouling. As a result, the forming of so-called sulfate-bound deposits takes place. On the other hand, the "sticking" on the heat transfer surfaces of the softened at high temperature ash particles takes place, leading also to the formation of bound ash deposits. Conditions in the CFB boiler are very different. In the circulating ash the softened ash particles are lacking because of low temperatures (~850 C) in the combustor. Among components of fuel mineral part only $CaCO_3$ and $MgCO_3$ are decomposed in these conditions. As a result, the formation of free CaO and MgO in ash takes place. Although CaO plays a very great role at formation of sulphate deposits, the intensive formation of these in given case obviously will not take place. Formation of sulphate deposits does not take place despite the fact that binding of CaO into other ash minerals due to low temperatures is slow and temperature 850°C is excellently suitable for sulphur binding.

It may be supposed that one reason of reactions mentioned above is the real decreasing of the formation of bound ash deposits in CFB boiler, due to SO_2 binding by great amounts of fine ash particles of high specific surface. As earlier research in Tallinn Technical University on deposits formation has shown, the ash particles binding with formation of hard deposits takes place only in the case when the sulphation goes on the heat transfer surface. Ash particles sulphated previously in gas flow do not form bound deposits. Thus, it may be noted that the intensive SO_2 binding by the circulating ash decreases both the concentration of SO_2 in the gas flow and sulphation of ash particles deposited on heat transfer surfaces.

A certain effect owns here the great amount of the circulating ash, abrasive action of what to ash particles, deposited on the tubes, does not enable a sufficiently long staying of these particles on the heat transfer surfaces. So it may be supposed previously that intensive formation of hard bound ash deposits in the CFB boiler does not take place or it goes very slowly. This supposition has been confirmed also by the first test results. During the tests, the walls of both tested combustors were clean. Along test burning of oil shale at test boiler of Ahlstrom also additional research with cross-flow tube-samples placed into combustor for imitation of heat transfer surface was carried out. Duration of these single tests was up to a week (about 100 hours) at varying operation regime of the test device. At the end of tests the very thin layer of bound deposits in confusion with metal oxides was observed on the front side of the test-tubes. At the same time the back side of the sample was covered by the loose ash. The chemical analysis of deposits showed that these were the sulphated ones with SO_3 content up to 40%. Therefore, the possibility of sulphated deposit formation on the heat transfer surfaces, placed in fluidized bed, obviously cannot be excluded at all. Obviously this process occurs quite slowly.

The fouling of the recycling cyclone, placed after the combustor, at current tests was not observed. Obviously the low burning temperature comparing with the softening temperature of oil shale ash [2, 3] was one reason of that, due to what sticking of ash particles on the cyclone walls did not take place. Also, the cleaning effect of the considerably coarse circulating ash as well as a small content of SO_2 in flue gas flowed into the cyclone, due to the high SO_2 binding rate in the combustor, decreased the possibility of the formation of sulphated deposits.

From the viewpoint of fouling, the object of interest was the fluidized bed heat exchanger (FBHE; LLB Lurgi) for cooling the ash returned from the cyclone into the combustor. Fouling of placed there heat transfer surface was not observed at the carried out tests. The reasons for that were obviously the low tube surface temperature in FBHE, coarse ash, small gas velocities and lack of SO_2. Flue gas does not flow into the cooler because the fluidized bed was generated by the secondary air feed under the FBHE. So the secondary air was preheated in FBHE.

On the basis of above mentioned facts it may be guessed that in the case of CFB oil shale boilers the problems, arising with heat transfer surfaces fouling in the combustor and recycling cyclone, are not so acute as in the case of PF burning. Nevertheless, the placing of cross-flow heat transfer surfaces into the circulating fluidized bed is not recommended before getting additional data about the long-term fouling.

A serious question can arise accompanying fouling of the convective heat transfer surfaces of the CFB oil shale boilers. As research of ashes from CFB test devices showed, the intensive pulverizing of ash particles in the combustion process takes place [4]. Fineness of the fly ash, leaving recycling cyclone, may be compared with that of ash from the electrostatic precipitators. Up to 30% of fly ash consists particles of sub-micron size. Taking into account the great amount of ash that is leaving cyclone (50-60% at test devices) and tendency of finest ash fractions to deposition onto heat transfer surfaces by the molecular and diffusion forces, the intensive fouling of these surfaces by the loose deposits may be waited. At the same time it is very probable that due to the binding of practically all sulfur in combustor the formed ash deposits are unbound and easy removable. All the more, the gas flow does not consist the coarse ash particles, wearing and thickening influence of which is a presumption for arising of the bound deposits [2, 3]. So, it may be supposed that formation of hard, bound ash deposits onto heat transfer surfaces placed in the convective gas pass of the CFB oil shale boiler, like in the case of PF, generally will not take place.

Research of fly ash deposits collected at tests proved this supposition. At test boiler of Ahlstrom, the tube blade, imitating heat transfer surface, was placed in the gas pass after the cyclone. At test device of LLB Lurgi, the deposit sample was gathered by the tube-sample placed in the gas pass. As research of the deposit samples showed, in both cases the fly ash deposits were very fine-grained but unbound. By that, the circumstance that the sides of tube-samples, normally wearied maximally, were covered by the deposits speaks about low wearing influence of the gas flow to the deposit (see Fig. 1).

The chemical analysis of the deposit-samples showed the noticeably higher chlorine content in these deposits compared with the fly ash. An increase in the chlorine content was observed at both test-devices. At the same time any formation of the chlorine-rich, bound deposit layer onto tube metal, as it takes place at oil shale PF boilers at condensing of KCl vapors onto heat transfer surfaces, does not took place. Obviously the temperature in CFB furnace is not sufficiently high for evaporating of the potassium from the fuel minerals. Therefore the concentration of KCl vapors occurring in flue gas is not sufficient for forming condensed deposits. Reaction of the gaseous HCl, formed in the combustion process, with the ash deposited onto heat transfer surfaces (firstly with minerals containing CaO and K_2O) plays the main role in accumulation of chlorine-compounds into the deposits, as result of above mentioned. Also the increased chlorine content in ash samples from the bag-house filter of test device and the content of both, KCl and $CaCl_2$, in deposit samples confirm that conclusion. It means that the ash layer onto filter has enough time to react with flue gas components. Such chlorine content in deposits is not sufficient for binding them on basis of chlorides. (A separate question from the viewpoint of heat transfer surfaces operation conditions is the corrosive activity of the chloride-containing deposits.) The content of sulphates in deposits was more or less at the same level as in fly ash. The latter confirms, as it was mentioned above, SO_2 binding mainly in the combustor. Therefore, the influence of SO_2 on ash particles binding and chlorine displacing from deposits obviously is not sufficient for arising of hard deposits. The deposit arisen on heat transfer surfaces will be a soft loose deposit.

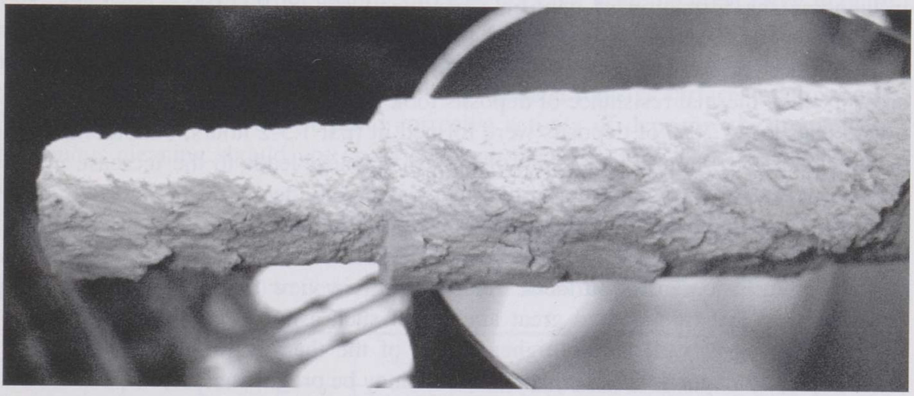

Figure 1. Fly ash deposit on the non-cooled two-part sample deposited at gas temperature ~550°C in the gas pass of CFB test device of LLB Lurgi Lentjes Babcock

Such soft ash deposit, as generally known, has a quite high thermal resistance and can significantly worse the heat transfer conditions of the heating surface. Therefore, the influence of such deposits should be taken into account at designing heat transfer surfaces. Special researches of the thermal resistance of fine-grain ash deposits were not carried out. Results of the earlier research enable, to some extent, to estimate the influence of deposits on the operation of heat transfer surfaces. For example, the thermal resistance of loose deposits of fly ash in different conditions has been referred in [5, 6]. According to these works, the empirical formulas were elaborated for calculation of conventional thermal resistance for deposits (ε), when on tubes of heat transfer surface the formation of purely loose fly ash deposits takes place.

Using of heat transfer surfaces designed as in-line tube bank is suitable in case of the intensive formation of loose deposits, as it probably may be waited in oil shale CFB boilers. The formula for calculation of thermal resistance of deposits given below takes the above mentioned facts into consideration. The calculation formula for the seeming thermal resistance of stabilized deposits (thermal resistance increase of which has been stopped) in case of in-line tube bank is following [5, 6]:

$$\varepsilon = 0.034\left(1 - 1.71\lg\frac{R_{30}}{33.7}\right)\left(1 + 3.31\lg\frac{d}{38}\right)10^{-0.08w},\ (\mathrm{m^2 \cdot K})/\mathrm{W},$$

where:

R_{30} - 30 μm sieve residue, %; d - outer diameter of tube, mm; w - gas velocity, m/s.

It should be noted here that the formula was compiled considering ashes with R_{30}~3-60% got at PF burning. These ashes were significantly coarser than the ash from the CFB device [4]. Therefore it is possible that thermal resistance of the very fine deposits of fly ash, growing onto convective heat transfer surfaces of CFB boilers, is somewhat bigger than the calculated one.

This assumption was based on the results of investigations of different factors influencing the formation of deposits, mentioned above. So, for example, it was cleared that the maximal value of the thermal resistance does not depend on the ash concentration in the gas flow but the fouling speed depends. By that, the main growth of the thermal resistance of deposits took place in a quite short time. At mentioned tests up to 70% of deposits were formed in first 1.5-2 hours, but stabilization of them took 9-10 hours. Increasing of the ash fineness leads to the increase in the thermal resistance but increasing of the flue gas velocity decreases the latter. In case of in-line tube banks the interline pitch and gas flow direction do not essentially influence the thermal resistance. The high fly ash fineness favors deposition of ash particles onto heat transfer surfaces. Keeping now in view the high fineness of fly ash from the CFB furnace and great amount of such ash, the high intensity of the deposit growing as well as the higher values of the thermal resistance comparing with the fly ash deposits in PF oil shale boilers may be prognosticated.

To show the influence of the gas flow speed and ash fineness on the thermal resistance, Figure 2 gives the calculated values of the thermal resistance at 5-11 m/s gas velocity and fly ash fineness R_{30}=20-60%. In calculations the tube diameter of Ø38 mm was used.

It can be seen that the change of the gas velocity from 5 m/s to 11 m/s (more than 2 times) leads to the change of the thermal resistance about 3 times in case of the finest ash (R_{30}=20%).

The very intensive fouling of the convective heat transfer surfaces by loose ash deposits is a main problem in CFB oil shale boilers, where fly ash contains much more very fine fractions than in case of PF oil shale boilers, as it may be supposed on basis of above mentioned. In addition to that it may be supposed that the cleaning, used in case of PF oil shale boilers to guarantee normal operation of the heat transfer surfaces, is not sufficient.

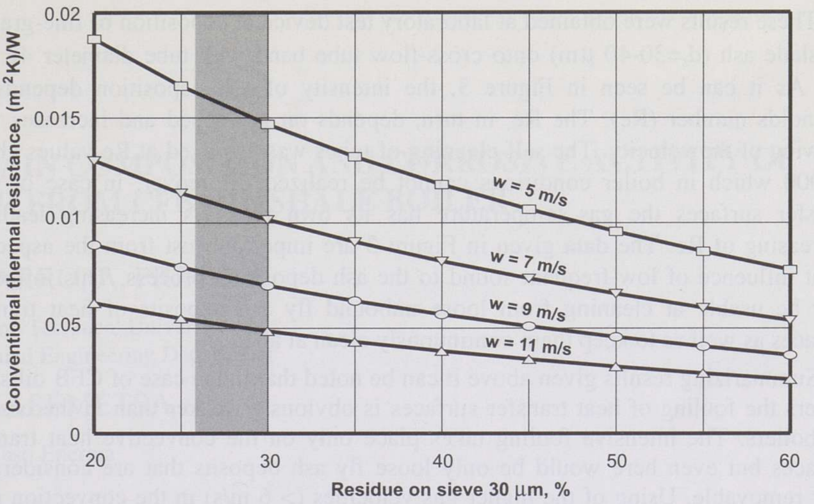

Figure 2. The conventional thermal resistance versus residue on sieve 30 µm, in case of loose fly ash deposits on in-line tube banks

At choice of cleaning methods it should be accounted that removing of such loose, unbound deposits from heating surfaces does not need the great force impulse or thermal chock that take place in the case of steam or water shoot-blowers. The needed cleaning may be significantly weaker as, for example, at the vibration. The cleaning should be frequent and should keep the heat transfer surfaces continuously clean. In connection to the possible corrosive activity of deposits, the frequent or continuous cleaning should not crush any way the oxide film on the heat transfer surface.

The infra-sound cleaning which may be used in case of the loose deposits is one of such methods but it should be tested in the demo-boiler. Influence of the low-frequent sound (up to 50 Hz) to deposit formation is shown on the Figure 3.

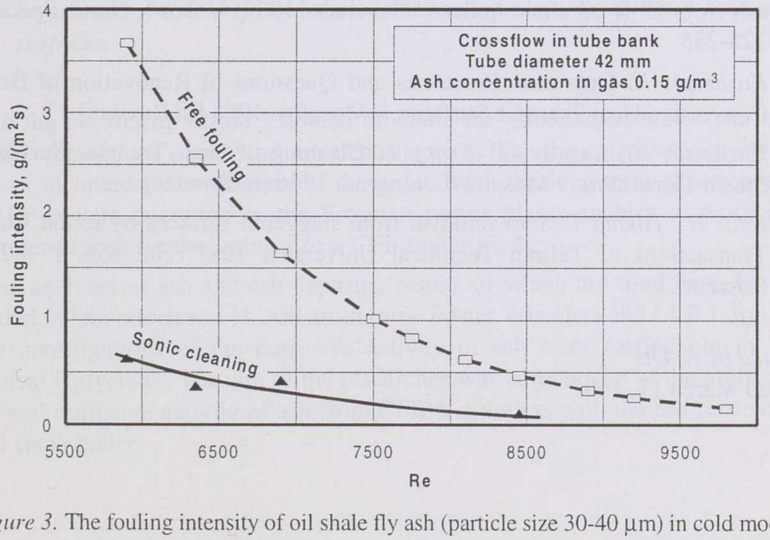

Figure 3. The fouling intensity of oil shale fly ash (particle size 30-40 µm) in cold model

These results were obtained at laboratory test device at deposition of fine-grained oil shale ash (d_s=30-40 μm) onto cross-flow tube band with tube diameter 42 mm [7]. As it can be seen in Figure 3, the intensity of ash deposition depends on Reynolds number (Re). The Re, in turn, depends on gas speed and increases with growing of the velocity. The self-cleaning of tubes was achieved at Re values above 10,000 which in boiler conditions cannot be realized. Moreover, in case of heat transfer surfaces the gas temperature has its own role. Its increasing leads to decreasing of Re. The data given in Figure 3 are important just from the aspect of great influence of low-frequent sound to the ash deposition process. This influence may be usable at cleaning from loose unbound fly ash deposits of heat transfer surfaces as well as to keep them continuously clean at all.

Summarizing results given above it can be noted that in the case of CFB oil shale boilers the fouling of heat transfer surfaces is obviously weaker than in the case of PF boilers. The intensive fouling takes place only on the convective heat transfer surfaces but even here would be only loose fly ash deposits that are considerably easy removable. Using of the higher gas velocities (> 6 m/s) in the convection pass may be recommended to decrease fouling. For cleaning of heat transfer surfaces the weaker cleaning methods should be used (vibration, ultra-sound). The cleaning devices should be able to operate continuously or at short intervals.

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Presented by A. Ots
Received March 17, 1997