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SOME DESIGN ASPECTS OF RECOVERY BOILER FOR OIL SHALE RETORTING UNIT SHC-3000

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The oil shale retorting unit with solid heat carrier (SHC) is in operation at Estonian Power Plant for producing fuel oil. This unit needs a recovery boiler for utilizing the heat of exit gases from technological furnace. The problems of thermal operation and some design aspects of this boiler are discussed.

The mean oil productivity of the SHC unit from oil shale is 13%. From a simplified heat balance for the SHC unit it is known that by using the oil shale with calorific value of 8.8 MJ/kg for producing the oil with calorific value of 37 MJ/kg the unit gives to oil 55% of the energy from oil shale. The initial design characteristics of recovery boiler allows the capacity of 25 t/h of steam generating which utilizes 27% of oil shale energy. It means that the role of recovery boiler in the general heat balance of the SHC-unit is significant and the optimal operation of it is necessary.

The recovery boiler of SHC unit has to perform three functions: 1) to cool the gas from the technological furnace reactor up to 600°C (the normal temperature for oil shale dryer); 2) to utilize the enthalpy of gas for generating steam; 3) to burn out the combustibles in exit gas. The boiler operates as inversion furnace. Inlet gas temperature is about 800°C. Due to the not completely burned components in it, the gas has calorific value of about 0.8 MJ/m^3. The gas has a sufficient ash content (55 g/m_n^3) and it causes fouling of the boiler's heating surfaces. In design calculations the thermal and radiation properties of ash deposits must be taken into account.

It seems that in the initial design calculations of recovery boiler the intensive fouling of heating surfaces by ash deposits with low thermal conductivity was not taken into account. Due to the low temperature level in the SHC-process (not higher than 800°C) the sintering and slagging of ash in fouling process are not so intensive as in conventional oil shale boilers. Friable ash deposits have low density and it makes possible their thermal conductivity values to be on the level of 0.2-0.25 W/(m·K).

In Figure 1 the location of recovery boiler in the entire technological flow is shown. The boiler consists of radiation chamber covered by water-wall tubes, vaporization platens and in initial variant in the exit chamber the steam superheater was located.

Due to low thermal efficiency of radiation chamber (lower than predicted in design), the steam generating was significantly lower and for superheater the flow rate of inner media (steam) was insufficient. It was the reason why the tubes of superheater were destroyed and it was dismounted. After this action the boiler was not able to cool gas to the required temperature and the boiler was running without air supply, i.e. without burnout of combustibles. Sometimes for reaching the required exit temperature the gas was cooled by sprinkling water into gas before the dryer.

It is clear that the operating of the recovery boiler in that way is not effective and some measures must be taken for enhancement the thermal efficiency of the SHC unit.

In D. Lipatov's diploma paper (Thermal Engineering Department of Tallinn Technical University), the variant of boiler with feed-water economizer located in the exit chamber was calculated. Now with new design the boiler will generate saturated steam of capacity of 25 t/h with pressure of 2.5 MPa. The steam of those parameters is more suitable for steam customers. On the other hand, the heat transfer conditions for the economizer are better due to the higher temperature difference.

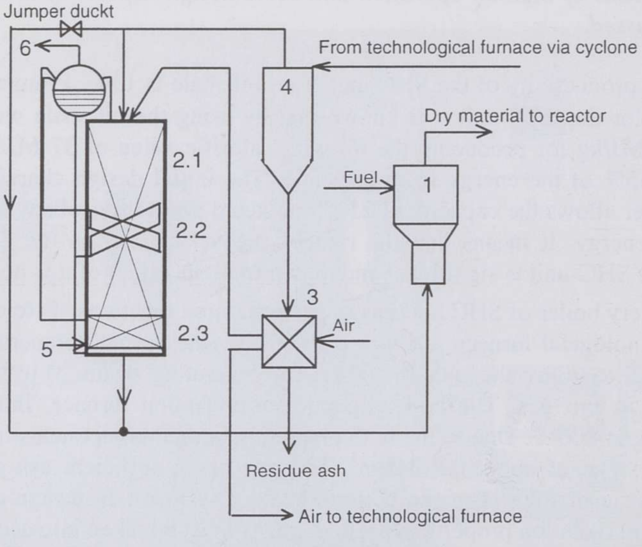

Figure 1. Flow diagram of recovery boiler supplies by flue gas and water. 1 - dryer; 2 - recovery boiler with: 2.1 - radiation chamber; 2.2 - vaporizator screen-tube bank; 2.3 - economizer; 3 - air heater; 4 - third cyclone; 5 feeding water; 6 - saturated steam exit

For the design calculations and successful control on the operating of the boiler the properties of ash deposits on heating surfaces must be known. The heating surfaces' fouling intensity depends on the fly ash concentration in gas from technological boiler, the fractional composition of particles and on the "thermal history" of the ash. Fouling conditions also depend on gas velocity (Re number), temperatures of gas and heating surfaces. It is known [1] that the cyclones of SHC are able to remove from gas up to 95% of ash particles and the content of CaO in fly ash decreases with increasing of Al_2O_2 and SiO_2 content in fly ash. The char content also increases when rubber waste is used in addition to oil shale as raw material for retorting.

There are two ways to estimate the thermal properties of ash deposits. It is difficult to follow all the details of forming the deposit sample with "natural" structure during laboratory investigations. It is not a problem however with unsintered deposits which are certain to appear in the recovery boiler. The second way is to analyze the results of some tests on the boiler by calculation of the deposit thermal resistance using the data of gas temperature distribution at the established gas flow rate and content. The precision of this method depends on the accuracy of initial measuring and on the maintaining of steady state conditions during the experiment.

In Figure 2 are presented the results of gas temperature distribution measurements before (2 tests) and after (3 tests) the cleaning of heating surfaces. Feed-water economizer design curve of temperature distribution is also presented. The tests, performed by the SHC-unit staff have different gas flow rate and air supply. The burnout of combustibles depends on the air supply. For estimating of the real burnout rate some data from Table 1 were used. The burnout rate is estimated through the calorific values of exit and entering gas combustibles content. For tests, where gas combustibles content was unknown, the burnout rate was evaluated on the basis of its dependence on air supply.

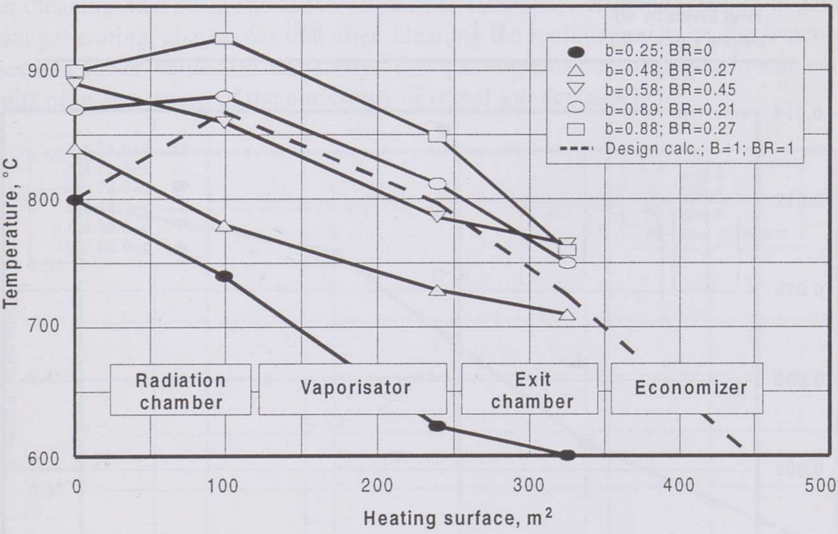

Figure 2. The flue gas temperature distribution along the recovery boiler in experiments with empty exit chamber and according to the calculations for design of the economizer; $b=B/B_0$; BR - burnout rate; B - actual gas low rate; B_0 - nominal gas flow rate.

As shown in Table 1, the heat losses by unburned gases are sufficient up to a half of the nominal thermal capacity of the boiler. The same situation is also indicated in Figure 2, which shows us that the required temperature level will be obtained by using feed-water economizer at nominal gas flow and by completing burnout of combustibles.

In Figure 3 is presented the dependence of thermal resistance of radiation chamber deposits on the burnout rate at the measured at tests gas temperature distribution.

As shown in Figure 3, some differences in the thermal resistance before and after cleaning of heating surfaces are presented. The main component in the decreasing of the thermal efficiency here is the low thermal conductivity of mainly unsintered ash deposits.

Table 1. **Combustible Components in Gas of SHC Recovery Boiler**

Component, parameter	Content and calorific values of combustibles in the precipitator and entering gas		
	Test 2	Test 3	Entering gas
H_2, %	1.2	0.9	1
CO, %	3.2	2.6	1.2
CH_4, %	0.45	0.5	1.5
Calorific value, MJ/m^3	0.70	0.60	0.80
Burnout rate	0.13	0.24	
Air supply/stoichiometric air	0.22	0.42	
Heat losses by unburned gases, MW	11.2	9.9	

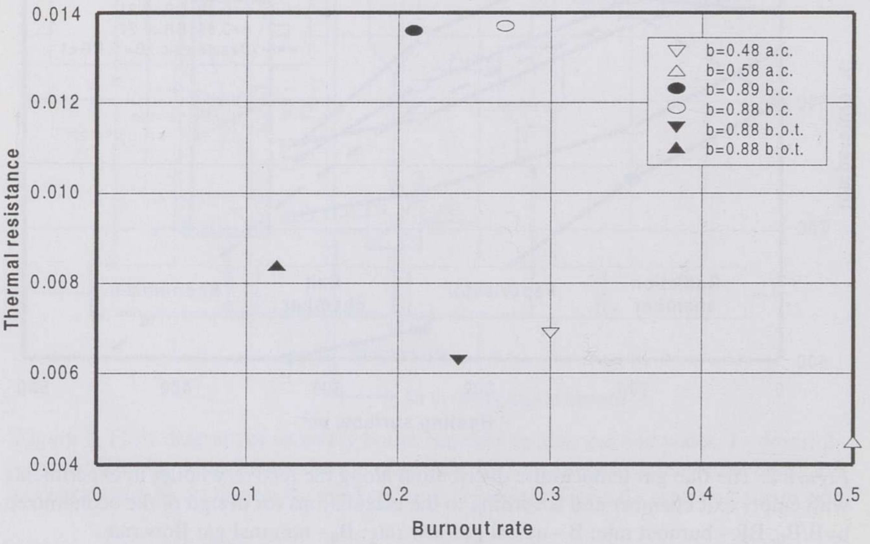

Figure 3. The estimation of thermal resistance (m^2·K/W) of radiation chamber from the test results at different considered burnout rate.

a.c. - after cleaning and b.c. - before the cleaning of heating surfaces; b.o.t. - burnout test; $b=B/B_0$ - gas flow rate

It is interesting to connect the data on thermal resistance with the physical thermal efficiency (Equation (1), A. Blokh [2]) and used for analysis of the thermal operation of oil shale boiler in [3] as the ratio of absorbed (resultant q_{res}) and incident (q_i) heat fluxes:

$$\psi = \frac{q_{res}}{q_i} = \varepsilon_f \cdot \varepsilon_w \frac{1-\left(\frac{T_w}{T_f}\right)^4}{\varepsilon_f + \varepsilon_w\left(1-\varepsilon_f\right)\left(\frac{T_w}{T_f}\right)^4} \qquad (1)$$

The thermal efficiency can be estimated by two independent ways. The first one accords to the equation (1) and depends on the emissivity (ε_w) and thermal resistance (outer surface temperature T_w depends on the thermal resistance) of the deposits. The second way is the estimation of the ratio of heat absorbed by steam and incident heat flux. In Figure 4 the thermal efficiencies for the radiation chamber as they were calculated from data of tests before cleaning (test 1 and 2) and after the cleaning (test 3 and 4) are shown. Thermal efficiencies calculated from gas side are given at three values of emissivity of deposits. The decreasing of thermal efficiency for radiation chamber after the cleaning caused probably by the significantly lower thermal capacity of the boiler (before cleaning the gas flow rate was 88% of nominal and after cleaning 48-58%). The curve of thermal efficiency, estimated using the data on steam generating, also shows that after cleaning the initial deposits on the water-wall tubes had lower values of emissivity. This phenomenon corresponds to our earlier results of investigation of the emissivity of initial ash deposits [7].

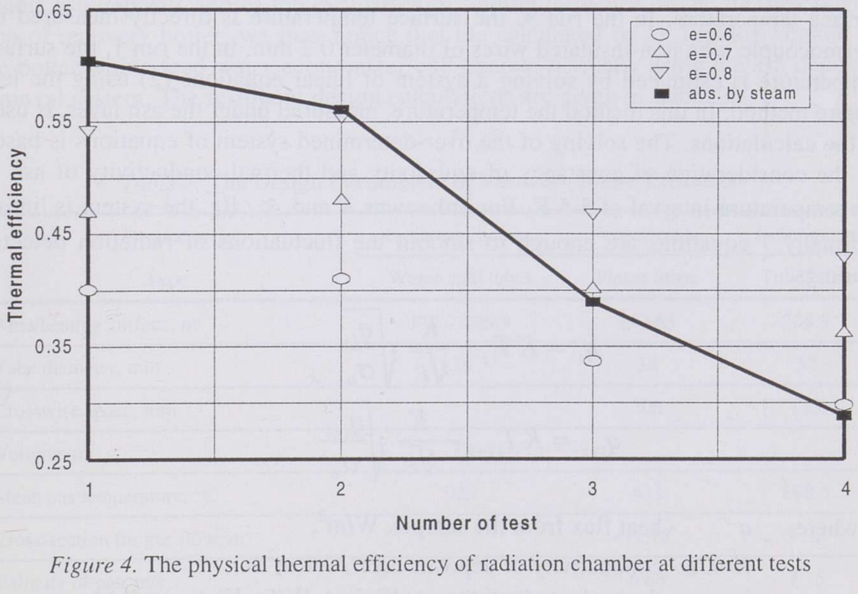

Figure 4. The physical thermal efficiency of radiation chamber at different tests

Some laboratory tests were performed using a simple radiation method for simultaneous determination of the normal total emissivity and thermal conductivity of unsintered (friable) oil shale ash from the electric precipitator of the Estonian Power Plant. In Figure 5 the results of measuring of the emissivity and thermal conductivity with the different methods of data treatment are presented.

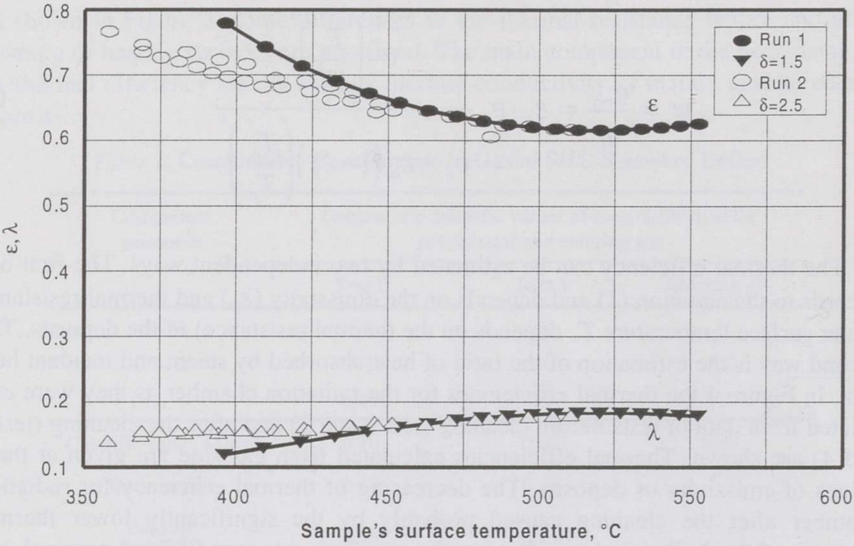

Figure 5. Some results of laboratory investigation of the emissivity ε and the thermal conductivity coefficient λ (W/(m·K)) of oil shale ash

In the radiometric method the horizontally located free deposit layer with thickness of 1.5-2.5 mm is heated from the underside and the heat flux from the upper surface is measured by detector. The main problem here is the estimation of the surface temperature. In the run 3, the surface temperature is directly measured by thermocouple with non-insulated wires of diameter 0.2 mm. In the run 1, the surface temperature is estimated by solving a system of linear equations (2) using the less square method. In this method the temperature, measured under the ash layer, is used in the calculations. The solving of the over-determined system of equations is based on the consideration of constancy of emissivity and thermal conductivity of ash in the temperature interval of 3-5 K. For unknowns K and $K / \sqrt[4]{\varepsilon}$ the system is linear. Normally 7 equations are enough to smooth the fluctuations of radiation detector readings.

$$\begin{aligned} q_i &= K\,T_{1,i} - \frac{K}{\sqrt[4]{\varepsilon}} \sqrt[4]{\frac{q_i}{\sigma_0}} \\ q_{i+1} &= K\,T_{1,i+1} - \frac{K}{\sqrt[4]{\varepsilon}} \sqrt[4]{\frac{q_{i+1}}{\sigma_0}} \end{aligned} \qquad (2)$$

where q - heat flux from the sample, W/m^2;

$K=\lambda/\delta$ - conductivity of deposits layer, W/(m^2·K);

λ - thermal conductivity coefficient, W/(m·K);

δ - thickness of ash layer, m;

T_1 - temperature, measured below the ash layer, K;

ε - normal total emissivity of the sample;

σ_0 - the Stefan-Boltzmann constant, W/(m^4·K);

i - ordering number of the equation.

As shown in Figure 5, those two methods give in practice the same results. The emissivity data are in good accordance with our previous results [3], the thermal conductivity coefficient is very low. It shows that the friable layer of oil shale ash is a good thermal insulation which decreases the thermal efficiency of heating surfaces covered by ash deposits. The received values of thermal conductivity are the same as for inertially impacted particles (by E. Raask [4]).

The heating surfaces fouling by fly ash is controlled by several processes including adhesion, thermophores, inertial forces from the flue gas velocity, etc. Some self-cleaning effects may appear when the velocity of flue gas exceeds a certain value. This value may be calculated, accordingly to our investigations of oil shale ash with a particle size of 30-40 μm at the cold model [5], from equation (3).

$$G = \exp\left(5{,}42 - 0.00072\,\mathrm{Re}\right),\ \mathrm{g/(m^2{\cdot}s)} \qquad (3)$$

The Re number in equation (3) is estimated by flue gas velocity, viscosity and tube diameter. The calculations by the equation (3) give, for the conditions of economizer of this recovery boiler, the gas velocity values of 20 m/s when the full self-cleaning will take place (Re>10000). This gas velocity is too high and some different ways of cleaning must be looked for. One way for it is usage of sonic cleaning [5, 6] which is able to remove unsintered deposits if the intensity of the sonic field is more than 130 dB.

Taking into account the results of this investigation of the properties of oil shale friable ash deposits and of the evaluation of fouling influence on the thermal operation of recovery boiler, we may notice that the calculated by D. Lipatov version of the boiler with a feed-water economizer will operate normally using the ash deposits removal system. The results of design calculations are given in Table 2.

Table 2. **The Design Parameters of Recovery Boiler Elements**

Parameter	Radiation chamber	Vaporizator	Economizer
Type	Water-wall tubes	Platen tubes	Tube bank
Area/heating surface, m^2	116.72/99.9	112.65	208.9
Tube diameter, mm	38	38	32
Crosswise space, mm		300	135
Volume, m^3	79		
Mean gas temperature, °C	925	833	698.5
Cross-section for gas flow, m^2		12.18	9.98
Velocity of gas, m/s		6.63	7.15
Thermal resistance of deposits, m^2·K/W	0.005	0.0146	0.0056
Aerodynamic resistance, Pa	0.45	0.96	8.36

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REFERENCES

1. *Elenurm A. et. al.* Sulphur compounds in the solid residues of oil shale processing by solid heat carrier // Oil Shale. 1988. Vol. 5, No. 3. P. 285-296 [in Russian].
2. *Blokh A. G.* Heat Transfer in Steam Boiler Furnaces. - Hemisphere Publ. Corp., 1988, 283 P.
3. *Tiikma T.* Thermal operation of oil shale boiler furnaces // Oil Shale. 1994. Vol. 11, No. 4. P. 325-329.
4. *Raask E.* Mineral Impurities 9n Coal Combustion. - Hemisphere Publ. Corp., 1985.
5. *Käär H., Tiikma T.* Soot removal from staggered surfaces by sound waves // Transactions of Tallinn Technical University. 1987, No. 656. P. 69-73 [in Russian].
6. *Jõgeva J., Käär H., Tiikma T.* Industrial testing of sound cleaning on economizer of boiler TP-67 from external friable deposits // Transactions of Tallinn Technical University. 1989, No. 692. P. 29-35 [in Russian].
7. *Tiikma T., Mic'evic' Z.* The study of thermophysical properties of boiler furnace deposits. Recent Advances in Heat Transfer // Proceedings of the First Baltic Heat Transfer Conference, Göteborg, Sweden, August 26-28, 1991, Amsterdam, 1992. P. 453-466.

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