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THERMAL ENGINEERING DEPARTMENT OF TALLINN TECHNICAL UNIVERSITY

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The paper provides a survey of the history of the Thermal Engineering Department of Tallinn Technical University, training of engineers and research. Research in the field of the oil shale power engineering at Thermal Engineering Department comprises the whole complex. This research has significantly influenced the development and standard of the oil shale power engineering in Estonia. The results of research have been published in comprehensive scientific monographs and lots of writings.

In Estonia training experts in the field of thermal engineering and research has been consistent since the last quarter of the previous century until now. Despite the fact that thermal engineering is one of the oldest classical engineering fields, its essence has been constantly renewed and its impact among technical sciences has been continuously increasing.

Besides of university level education the Thermal Engineering Department (TED) of Tallinn Technical University (TTU) has provided research and development works in the field of oil shale utilization in power plants.

ON THE HISTORY OF THERMAL ENGINEERING DEPARTMENT

In Estonia the systematic training of thermal engineers started in 1880 as teaching steam mechanics and steam power equipment began at Tallinn Railway Technical School (TRTS). The graduates were awarded a lower level technician's trade. The first teachers at TRTS were diploma engineers, graduates of higher technical educational establishments in Russia Johannes Russvurm, Arthur Stürmer, Vladislav Hendel etc. The TRTS was at that time well equipped with high quality Physics and Engineering classrooms. One of the workshops, the power station for educational purpose included a working steam boiler, a steam engine, an internal combustion engine and a dynamo. TRTS worked until 1918. The number of TRTS graduates was approximately 800, most of them were specialized in the field of the steam power engineering.

The next and also higher step in training experts in thermal engineering was provision of higher technical education at Tallinn Polytechnic (TP, opened on September 17, 1918). TP was the predecessor of Tallinn Technical University and the same date is considered to be also the year of birth of Tallinn Technical University. Thermal Power Study and Research Laboratory was established at TP in 1920.

The supervisors of Thermal Power Laboratory and research in Thermal Engineering at Tallinn Polytechnic's workshop were Prof. Friedrich Dreyer (1879-1934), Prof. Evald Maltenek (1887-1938), Dip. Eng. Eduard Avik and Dip. Eng. Villem Reinok.

From 1923 until 1936 at least 32 engineers in Mechanical Engineering graduated from TP in the field of the Thermal Engineering according to the subjects of final thesis. It was approximately 2/3 of the engineers graduated in Mechanical Engineering.

In the beginning of the 20-ies, the research in the oil shale engineering started at TP. The properties of Estonian oil shale and appropriate constructions of the combustors and boilers for utilization of the oil shale were mainly researched. During the same period the research and utilization of the oil shale ash as a material with binding properties became a new issue on the agenda.

Research in the fuel properties, determination of the thermal power device capacity and specific fuel consumption, the properties of boiler alloys and several measurements in the field of Thermal Engineering took place at TP's Thermal Power Laboratory and in Thermal Engineering Office at the State Testing Center. It is interesting to note that as a result of the measurements in Thermal Engineering Office at State Testing Center the estimation was given to internal combustion engines imported to Estonia.

Research on the usability of shale oil as a tractor fuel and tests with the oil shale petrol were carried out. Usage of the mixture of oil shale petrol and alcohol as an engine fuel was researched. A lot of tests were carried out to apply timber gas generators for internal combustion engines.

At the establishment of Tallinn Technical Institute in 1936 also the professorship of Power Engines and Thermal Economics was opened and Thermal Power Laboratory was subordinated to it. Professors Evald Maltenek and Jaan Ivand (1896-1964) and Diploma Engineers Anton Tammert, Eduard Avik, Lembit Lätt, Johannes Taimsalu and Endel Türna provided education in the field of Thermal Engineering. Role of Professor Evald Maltenek in teaching thermal engineering courses, in creation of engineering terminology and initiating oil shale applied research should be stressed.

Later, in 1940 a Power Engineering Department and in 1947 a Thermal Engineering Department were founded on the basis of the professorship in Power Engines and Thermal Economics. Prof. Jaan Ivand was the head of the both departments until 1958. Professor Ilmar Öpik was the head of Thermal Engineering Department until 1968 and since then Prof. Arvo Ots has taken the responsibility. In 1960 the Thermal Engineering Research Laboratory was established and its main task was to research problems concerning oil shale utilization. Later the subjects of research broadened, including also problems concerning utilization of brown coals and heat transfer.

In 1992 Department and Thermal Engineering Laboratory were reorganized into Thermal Engineering Department, which included the following three chairs: Chair of Thermal Engineering (Prof. Harri Käär; 1944-1997), Chair of Heat Engineering (Prof. Toomas Tiikma) and Chair of Thermal Power Equipment (Prof. Arvo Ots).

TRAINING OF EXPERTS

From 1940 until 1944 engineers of mechanics with bias on the thermal engineering were educated in the Faculty of Mechanics at Tallinn Technical University. Specialized knowledge was gathered mainly during practical training and compilation of the final thesis.

From 1945 until 1990 education was provided on the basis of thermal engineering curriculum, which enabled also a narrower specialization. These programmes were generally valid in the USSR Application of the study programmes to the Estonian circumstances was done in lectures and practical training. Education was provided in the system of terms with duration of 5 years (10 terms).

From 1945 until 1974 graduation took place in accordance with the speciality of Thermal Power Equipment for power plants. This speciality was all-Union and the graduates were employed also outside of Estonia.

Besides the above mentioned speciality, a speciality of Heat Engineering was established in the Power Engineering Faculty at TTU in 1960 and it was more orientated to meeting the needs of the Estonian Republic. More attention was paid to industrial furnaces, industrial thermal engineering devices and district heating systems. From 1960 until 1974 both specialities existed side by side. Studies were both in Estonian and in Russian.

From 1974 until 1984 experts in Thermal Engineering were educated only in the specialty of Heat Engineering, but subjects concerning the interests of thermal power plants were included in the curricula.

Since 1984 there was more freedom in the arrangement of the education and compilation of the curricula was not so tightly tied with the all-Union requirements. A curriculum, which maximally took into consideration the Estonian specificity in the field of thermal engineering, was worked out. The curriculum was confirmed on the republican level and it was valid until the re-establishment of the Estonian independence.

In 1991 there was a transition from term system to subject system and accordingly the new principles were established: narrower specialization via optional subjects and modules, evaluation of results by Credits. Diploma engineer should obtain 180 Credits. Two main lines of specialization remained like before – Thermal Power Plants and Heat Engineering.

From 1992 until 1994 valid curricula broadened the possibilities of choice as subjects were gathered into modules and sub-modules to provide students with the needed narrower preparation.

On January 17, 1995 the Council of Tallinn Technical University passed the resolution to accept the new study scheme: Bachelor's degree, Master's degree, Doctor's degree and since 1995 admittance the system has come into effect.

Bachelor's degree requires 160 Credits and there is a larger impact of the general theoretical subjects, specialized profound knowledge should be obtained in the Master studies (80 Credits). In Bachelor studies there are subjects concerning knowledge in the field of Energy Engineering (80 Credits). The capacity of directional subjects in the Thermal Engineering provide approximately 55 Credits. Nominal duration of the studies is 4 years (8 terms).

The capacity of the Master's degree studies is 80 Credits, of which 35 Credits are dedicated to the final thesis. Nominal duration of the studies is 2 years (4 terms).

There are two main directions in the doctorate at Thermal Engineering Department: Thermal Power Equipment and Thermal Physics. Doctorate's capacity is 160 Credits, of which 120 Credits are dedicated to doctor's thesis. Nominal duration of the doctorate is 4 years (8 terms).

From 1940 until 1996 Tallinn Technical University has awarded 1058 engineer's diplomas in Thermal Engineering.

RESEARCH IN THE FIELD OF OIL SHALE

Thermal Engineering Department has researched a broad scale of subjects. Research has concerned the properties of the oil shale as an energy-producing fuel, its grinding and pulverizing, burning, formation of air polluting components, conversion processes in the mineral matter by burning, fouling of the boilers radiative and convective heat transfer surfaces with ash deposits, heat transfer in the boilers furnaces and convective gas passes, high temperature corrosion and corrosive-erosive wear of the boiler heat transfer surfaces tubes, cleaning of the steam boiler heat transfer surfaces from ash deposits, influence of the cleaning on the thermal fatigue of metal, lifetime of oil shale power plant components, wet cleaning of flue gas from sulphur dioxide, dry ash removal possibilities at power plants and some other issues.

The results of research on oil shale as fuel for power production have been published in the generalized mode in three comprehensive monographs: "Influence of the Oil Shale Mineral Matter on the Steam Boiler Work" by Ilmar Öpik, 1961, Tallinn; "Processes in the Steam Boilers by Burning Oil Shale and Kansk-Achinsk Coals" by Arvo Ots, 1977, Moscow; "Corrosion and Wear of the Boiler Heat Transfer Surfaces" by Arvo Ots, 1987, Moscow. Besides of them, the several collections of scientific works have been published, including 42 Thermal Engineering Proceedings series of Tallinn Technical University publications and articles in several scientific magazines as well as proceedings of scientific conferences, seminars, workshops, et al.

Next I will give a short survey of the oil shale research and its essence at Thermal Engineering Department.

Estonian Oil Shale as the source of the following research is a fuel with moderate moisture (9-12%), high ash (40-50% in dry mass) and high mineral carbonate dioxide (18-22 % in dry mass) content. The net lower heating value of the oil shale is between 7.5-9 MJ/kg. Due to the geological structure of the Estonian oil shale deposits its dry matter consists of the following three components: organic, sand-clay and carbonate. Such division of oil shale has been the source of many researches.

The composition of the listed constituents is constant, but mass proportion in the fuel as received may change on a large scale.

Due to a small C/H ratio in the organic matter (approximately 8) the volatile matter content in the oil shale organic part is very high – up to 85-90% . Sulphur content in the oil shale dry matter is in the range 1.5-1.6% and Ca/S molar ratio is within the limits of 8-10.

Composition and Properties of Oil Shale. The task is to determine the composition and heating value of the oil shale proceeding from the following data received in the approximate analysis: moisture, laboratory ash content determined at certain conditions and the mineral carbon dioxide quantity.

Mathematical statements for determination of the dry oil shale composition depending on the laboratory ash and mineral carbon dioxide content have been received on the basis of the theoretical and experimental research of the laboratory incineration process in the broad changing area of the parameters characterizing the oil shale. The heat effects taking place by burning of the oil shale and the processes in the calorimetric bomb have been theoretically and experimentally investigated. On the basis of these results the mathematical formulas have been derived for the determination of the oil shale heating value.

The correlation for the oil shale composition prognosis, based on the comprehensive statistical data (depending on the experimentally determined heating value), was established.

Grain Composition of Oil Shale and Oil Shale Ash. Oil Shale Grinding. These researches deal with the mass distribution of the pulverized (crushed, ground) oil shale or the oil shale ash particles formed by burning. Unlike many other fuels the product as a multi-component system obtained at the oil shale crushing and grinding does not subordinate to the widely used Rosin-Rammler exponent law. The logarithmic-Gaussian distribution with three parameters suits considerably better for description of the oil shale grain composition. This rule was first used for expression of the granular composition of the oil shale ash and later also for the oil shale. The generalized results have been obtained from the research in both oil shale as well as oil shale ash separate components' mass distribution depending on the particles size.

The detailed research has been done on processes in oil shale grinding devices, especially in the hammer mills. Research on the separation process of the pulverized oil shale and separator's importance in grinding device have a special place. These research results were the source of the grinding equipment design improvement for oil shale power plants.

The matrix method has been developed for the grain composition description of the refined product received from the multi-component source material with certain grain composition. The method is based on the presumption that each fraction refines independently from the other ones and that the grain composition of the milled product is received by the summarizing of the compositions of separate fractions. This method has been applied on the grinding process description in the centrifugal bounding mill designed and erected in TED.

One of the characteristics of the Estonian oil shale is the increase of CaO amount at the simultaneous decrease in SiO_2 in the ash with the increase in ash content in dry mass of the fuel. The SiO_2/CaO ratio is decreasing with growing of ash particles size. These oil shale and oil shale ash separation characteristics determine the mass ratio correlation between different components separated from the oil shale ash, e. g. along steam boiler gas passes, along ash precipitators, etc.

Combustion Characteristics of Pulverized Oil Shale. The main objective of experimental research has been the determination of the main combustion characteristics of pulverized oil shale flame, research on the pulverized oil shale combustion dynamics, and the formation and stabilization of the flame in the nearby area of the burner.

Using the burner dynamic method for experimental research of the stabilized open flame of pulverized oil shale has provided with data concerning the normal propagation velocity of the flame, the length of the flame visible part and the specific volume heat release load depending on the initial parameters like fuel/air ratio, burner diameter, air and dust mixture velocity and temperature at outlet from burner, the fineness of the pulverized oil shale etc. On the basis of these results it is possible to evaluate the parameters of the visible part of the pulverized oil shale flame depending on the above mentioned initial parameters.

The burning time of the volatile matter, separated at devolatilization of the pulverized oil shale depending on the temperature and air/fuel ratio, was investigated by using an isothermal low capacity burning chamber with direct flow and external heating. On the basis of the data the combustion kinetic constants of the volatile matter were determined.

The dynamics of the pulverized oil shale combustion has been investigated at several experimental devices with thermal capacity 10 kW, 20 kW, 2 MW and in power plant boilers. As a result the burning rate of the pulverized oil shale, the flame temperature, the composition of the flue gas and the flue gas circulation rate, depending on time or coordinate length at different factors, have been obtained. The flue gas components and the temperature fields in the nearby area of the burner has been also explicitly researched. On the basis of the research the irregularity coefficients of the flue gas components in the nearby area of burner and the flue gas circulation number, as the factors determining the flame stability, have been established.

Kinetic-Diffusion Combustion Characteristics of Oil Shale Char. The char (coke) received at the thermal decomposition of the oil shale organic matter, due to the high mineral impurities content, is a porous material with a small amount of combustible constituent. The oil shale char particles do not change its volume during combustion process, i.e. the volume calculated on the basis of the particle external size does not change during combustion.

Based on the above given combustion postulate the internal oxygen diffusion coefficient of oil shale char, depending on the combustible constituent density in particle and temperature (constant volume combustion in the high temperature region), has been determined.

The experimental research showed that differently from the combustion of the pure carbon (electrode char) the inner active surface of oil shale char decreases continuously during the combustion process. The latter result was the basis for the experimental determination of the combustion kinetic constants of the oil shale char (combustion in the low temperature region).

Proceeding from these experimentally determined kinetic-diffusion constants the general differential equation describing the combustion of the oil shale char has been solved numerically. Also mathematical formulas for determination of the combustion kinetic-mass transfer factors have been derived.

Mathematical Modeling of Polyfractional Pulverized Oil Shale Combustion. The mathematical equations describing the combustion process of the pulverized oil shale were developed proceeding from the logarithmic-Gaussian law of the polyfractional size-mass distribution and established combustion kinetic-mass transfer factors. The pulverized fuel combustion was reduced to the combustion of the particle with the largest conventional diameter in the polyfractional system. The combustion of such particle has been determined by the change of oxygen concentration along flame. Proceeding from that mathematical formulas were derived for calculation of the burning rate of the polyfractional pulverized oil shale depending on the time and others initial parameters. The described methodology enables to determine analytically the influence of many parameters on the burning time of the pulverized oil shale (e.g. temperature, oxygen concentration, grinding fineness, etc.).

Behaviour of Oil Shale Mineral Matter at Burning. Combustion of fuel does not deal with only combustion (oxidation) of the fuel organic components, but also simultaneous phenomena in the mineral matter. These processes determine quite a lot the properties of ash formed at the burning of fuel.

Research in oil shale mineral matter behaviour have mainly been the following.

The oil shale ash melting characteristics (t_A, t_B, t_C) depending on the calcium oxide content in the ash have been determined. Also the relative amounts of the separate melting state phases in ash depending on temperature were determined. These results have been the basis for the exploration of the mechanism of steam boiler heat transfer surfaces fouling in the flue gas high temperature region.

The volatilization of the oil shale ash components heated in separate ambient atmospheres has been profoundly researched. It is declared that the potassium (one of the chief components of the oil shale mineral part) compounds are the main volatile components from the oil shale ash up to 1600°C. Thereby the volability of potassium compounds depends greatly on the gas environment composition and it is more intensive in the reducing atmosphere.

Besides the above mentioned research, also the dynamics of the change of calcium oxide, alkali metals and sulphur forms along the pulverized oil shale flame (depending on time) was investigated. In the pulverized oil shale flame the behaviour dynamics of alkali metals and sulphur compounds depends on the oxygen concentration in the flue gas. It is noteworthy to state that the oxidation of sulphide sulphur is much slower than that at combustion of the organic carbon.

Fouling of Heat Transfer Surfaces of Pulverized Oil Shale Boilers. This field of research deals with the formation of ash deposits on the combustor water wall tubes. The formation mechanism of such type ash deposits on heat transfer surface of oil shale boiler depends on flue gas temperature in furnace (flame radiation intensity on furnace wall is the indicator of temperature level in combustor). Iron, calcium oxide and alkali metal compounds are the main components determining the fouling character of the water wall tubes. The water wall tubes fouling intensity and the fouling mechanism depend on the flame radiation intensity. With the flame radiation intensity decrease the impact of iron compounds on the fouling process decreases and the impact of calcium oxide and alkali metals increases at the same time.

The furnace aerodynamic scheme (design, size, location of burners), fuel burning regime (mainly the air/fuel ratio) and especially the cleaning technology of heat transfer surfaces from ash deposits and cleaning regimes are also factors determining the fouling intensity of the radiative heat transfer surfaces.

The ash deposits formed on the furnace water wall tubes have typically a three-layer structure: a lower iron-rich layer binding metal and ash deposits; a middle hard, slowly growing unremovable in cleaning cycles deposits layer and an upper porous quickly growing layer. The chemical composition of the last layer is quite near the fly ash composition.

Heat Transfer in Combustor. The heat transfer in different types of the PF oil shale boilers combustors has been experimentally researched. The main objectives of research have been the fouling of combustor radiative heat transfer surfaces and the influence of thermal boundary layer in the area near water wall tubes on the heat transfer in combustor.

Heat transfer is a non-stationary process due to change in time of thermal resistance of the ash deposit layers formed on furnace water wall tubes. The non-stationarity of heat transfer is caused first, by the continuous increase in thickness of the hard deposit layer, and secondly, by increase in the porous deposit layers thermal resistance during the period between the cleaning cycles. The non-stationarity of heat transfer can be seen as a result of temporal change of the flue gas temperature after the combustor at the constant value of factors characterizing boiler operation (e.g. the boiler load, air regime etc.). Proceeding from these results the thermal resistance of the deposits on water wall tubes and the furnace fouling factors have been established.

The experimental investigation on distribution of the flame radiant heat flux density along the depth of the combustor, perpendicular to the wall has been carried out in the PF oil shale boilers. It was established that the radiant heat flux density in combustor increases at increase of the distance from wall tubes. To characterize the ratio of the radiant heat flux intensity on the combustor wall to the heat flux intensity on the distance of thermal boundary layer the non-isothermality rate was used. The thermal boundary layer located at the wall of a combustor adds conventional resistance to the heat flux from flame onto heat transfer surface. The latter is added to the thermal resistance of the ash deposits on the wall tubes. Proceeding from the conventional thermal resistance conception of the thermal boundary layer it is possible to estimate the radiative heat transfer intensity in combustor. The conventional thermal resistance of the thermal boundary layer is determined by the convective mass transfer intensity in combustion chamber and it is influenced by factors as burners location and design, combustor heat load, etc.

Fouling of Boiler Convective Heat Transfer Surfaces. The fouling of the boiler convective heat transfer surfaces has been theoretically and experimentally researched and a mathematical model has been worked out accordingly. The observed model combines the influence of physical and chemical factors on the fouling process. According to these results the ash particles washing the front side of the heat transfer surface tubes can be observed as consisting of the chemically neutral and active particles. The active particles are mostly calcium oxide or ash particles containing it. The following three phenomena occur simultaneously: the deposition of ash particles on the tube surface, the binding of the active ash particles onto surface (mainly calcium oxide as a result of sulphation) and the wear effect of ash particles with kinetic energy on the deposit layer. As a result of these processes a deposit layer with unlimited increase is formed on the tubes and its growth intensity depending on the flue gas velocity is a complicated function. Quite soft and loosely bound friable deposits are formed on the heat transfer surfaces up to the first critical flue gas velocity. The friable deposits growth intensity depending on the flue gas velocity has a maximum. The strength of such type deposits is approximately proportional to the kinetic energy of ash particles. The friable deposit is a mixture of the neutral and chemically active ash particles. If flue gas velocity exceeds the first critical (up to the second critical velocity) very hard deposits from only active ash particles will be formed. Exceeding the second critical velocity there is no possibility for deposits formation. The above described convective heat transfer surfaces fouling mechanism is in accordance with the different experimental results.

Oil shale ash sulphation in gas ambient containing sulphur dioxide has been profoundly researched to explain the formation mechanism of the hard ash deposits.

Alkali metals and chlorine compounds have also influence on the fouling of the oil shale boiler convective heat transfer surfaces.

Heat Transfer on Convective Heat Transfer Surfaces. The bound ash deposits on convective heat transfer surfaces have a layer structure and an unlimited growth. The cleaning of heat transfer surfaces is used to decrease the growth intensity of the ash deposit layers. The permanent growth of deposit layers and their cyclic influence by cleaning to the heat transfer through the heat transfer surface tubes is a non-stationary process. Proceeding from that the thermal resistance of ash deposits on convective heat transfer surfaces depending on time and on the fouling determining parameters (flue gas temperature and velocity, cleaning technology and regimes of the heat transfer surface tubes, etc.) have been obtained.

Thermophysical Properties of Ash Deposits. Heat absorption of the steam boiler heat transfer surfaces is determined by the thermal resistance of the ash deposits as well as by the radiation properties of the deposits surface.

In TED a determination method for ash deposits thermal resistance, spectral and integral emissivity (absorptivity) were worked out. Several devices for getting ash deposit samples and heat flux measuring in operating boilers have been made. The research results showed that in certain conditions a thin deposits layer with very low integral emissivity may be formed on the furnace wall tubes. The initial ash deposits are very good spectral radiators and their emissivity depends on their composition, in general on the calcium/iron ratio. Its impact on the radiative heat transfer is more decisive than the thermal resistance of this thin deposits layer. The ash deposit emissivity changes in time being a complicated function.

High Temperature Corrosion of Boiler Alloys. The problem of high temperature corrosion of boiler alloys is connected with the lifetime of the boiler heat transfer surfaces tubes, especially with superheater and reheater tubes.

The corrosion of metal, starting from the clean surface, is divided into two following regions – the initial and the main region. Proceeding from that and kinetic-diffusion nature of the metal high temperature corrosion and profound experimental research at TED an analytic calculation method for determination of the metals corrosion intensity in the initial and the main regions (in case of constant and changing temperature) has been worked out. Mathematical formulas for calculation of corrosion intensity of the metals have been made as a result of numerous long-term tests in laboratory as well as in real conditions of operating oil shale boilers.

Chlorine containing compounds deposited on the metal surface are the factors accelerating the boiler alloys corrosion at burning oil shale. Potassium chlorine, condensed from flue gas onto the tubes surface, is the main component in ash deposits accelerating corrosion. If in due time potassium chlorine (condensed onto surface) converts into potassium sulphate of less corrosion activity, the ash deposits' corrosive effect on metal will decrease.

Corrosive-Erosive Wear of Boiler Heat Transfer Surfaces. The nature of the corrosive-erosive wear of the boiler heat transfer surfaces lays in the periodic (partial or total) destruction of the protective oxide layer on the metal surface during the heat transfer surface cleaning cycles. This action is a factor accelerating corrosion. The problem of metal corrosive-erosive wear is foremost connected with the lifetime of oil shale boiler superheater and reheater tubes. Proceeding from this scheme a mathematical model of corrosive-erosive wear of the heat transfer surfaces metal has been compiled. This method enables to calculate analytically the metal lifetime depending on the type of alloy, corrosive activity of ash deposits, metal temperature, frequency of cleaning cycles, etc.

The model of heat transfer surfaces metal corrosive-erosive wear was worked out. Dependence of the heat transfer surface metal wear intensity on the cleaning force influencing oxide film on the surface in the cleaning cycle was the basis of the model. The latter is a physical quantity causing deposit removal from the heat transfer surface. Depending on the influence of the cleaning force the destruction of the oxide layer covering metal surface and decreasing the oxide layer diffusion resistance as the corrosion accelerating factor, would occur. In the case of a small cleaning force (up to the first critical cleaning force) the oxide layer on the tubes does not break down and there is no corrosion acceleration. On increasing the cleaning force up to the second critical value the erosive destruction of the oxide layer and the decrease in its diffusion resistance take place. As a result the corrosion is accelerated. At the second critical cleaning force the oxide layer is totally destroyed and by exceeding this value in addition to oxide layer also a part of the pure metal will be removed from the tube surface. According to this mechanism wear of alloys is called corrosive-erosive wear.

The metal corrosion does not become more intensive not only as a result of destruction of the oxide layer in the cleaning cycles, but also due to the higher chlorine content in the deposits formed onto clean surface (initial deposits). It means that the corrosive activity of the initial ash deposits is higher compared to the "older" ones due to the less chlorine content. Also this phenomenon has been taken into consideration in the given corrosive-erosive model of wear.

On the basis of this corrosive-erosive wear model of the metal the mathematical method for calculating of the wear and the lifetime of the heat transfer surface tubes were established.

Cleaning of Steam Boiler Heat Transfer Surfaces from Ash Deposits. TED has worked out a cleaning technology of the heat transfer surfaces from ash deposits (the OTI system), relying on the steam boiler heat transfer surfaces fouling mechanism and corrosive-erosive nature. The main element of this cleaning system is a long distance lance (blower), operating on water and having a head with water nozzles of special design. The system can be used for cleaning of furnace wall tubes as well as superheaters and economizers. The constructive parameters of this system and operation regimes should be selected according to the heat transfer surface type and size.

A combined superheater cleaning system has been worked out on the basis of OTI system. The system nature proceeds from the layer structure of ash deposits on the heating surface. The cleaning methods with weak cleaning force and a short period (e.g. vibration cleaning) are used for the removal of upper deposit layers. It restricts (but does not prevent) deposit growth and does not destroy the protective oxide layer on a tube surface, i.e. the acceleration of metal corrosive-erosive wear does not occur in cleaning cycles. The water lancing with strong cleaning force and long cleaning period is used to remove the hard lower deposit layer (formed when using weak cleaning force). As a result of it the heat absorption from heat transfer surfaces reaches the level of previous water cleaning cycle. During such kind of water cleaning cycle the destruction of oxide layers on heat transfer surfaces tubes takes place, but only after long periods, which do not accelerate metal wear significantly.

Influence of Water-Jet Cleaning on Heating Surface Tubes. This problem is connected with the water-jet cleaning of boiler heat transfer surfaces tubes. The boiler heat transfer surface tubes contact with water-jet in operation and cause a rapid temperature drop in the outside surface layer of the tube. In certain conditions the thermal stresses caused by rapid temperature drop may exceed metal yield limit and cause thermal fatigue cracks on the tube surface. To estimate non-stationary temperature fields and calculate thermo-stresses in tube wall, in case of water-jet cleaning, the methodologies of experimental research and analytical data processing have been worked out at TED. The initial conditions of forming such thermo-cracks and their development dynamics have been thoroughly researched. These results have been the basis of getting criteria for water-jet cleaning of boiler heat transfer surfaces' tubes. Also the change of mechanical and structural properties of boiler heating surface tubes' material has been researched.

Metal Lifetime at Power Plants. This problem is connected with metal lifetime in Baltic (building period 1959-1971) and Estonian (1969-1973) oil shale power plants. The remaining life assessment of power plant units became to be very important subject, because almost 50% of Baltic Power Plant units have exceeded the design life for major number of high temperature components. At the Estonian Power Plant the design life of the first unit will be achieved in 2005-2006.

To achieve further safe operation of power plant units, the Technical Diagnostic System was worked out and put into practice in TED. The System is based on the three most important documents and data: a standard for testing metal condition of power plant components under inside pressure; the data of operational history (temperature, pressure, vs. operational time, number of start-shutdown cycles); the data of components behaviour under creep and cyclic fatigue conditions.

The final assessment of a metal condition is accepted on the basis of the structure damage analysis. For this purpose it is possible to use a method of replica or micro-samples which have been cut out from the most stressed places of steam pipe elbows or headers. The particular arrangement of places for taking of replicas or metal test samples is determined by special accounts under the program "Elbow" created in TED. The analysis of microstructure damage is carried out by comparison of the given portrait with a scale of a damage made manually or with application of the computer programs.

The factory-manufacturer nominates a design life to all large-sized elements of power plant (steam boiler, turbine, steam pipelines etc.) that guarantee the duration of safe operation of the equipment in hours, under condition of operation with steam parameters which does not exceed design values. The design life of basic elements of the power plant equipment makes 150,000-300,000 hours. The computer assessments of residual life and results of testing of metal condition allow to assume that at the present time the residual life of the equipment elements of Baltic Power Plant is 40-45% and of Estonian Power Plant 75-80%. Such high level of a residual life is kept due to the lowered temperature of live steam, in spite of the fact that some equipment has reached the guaranteed design life. The low steam temperatures are due to specific properties of fly ash at PF of Estonian oil shale, that causes an intensive fouling of superheaters and appropriate fall of live steam temperature approximately 20°C below designed value.

Formation of Air Polluting Components at Burning Oil Shale. In these researches attention is paid to sulphur dioxide binding with ash in oil shale boilers. The influence of parameters (oxygen concentration, grinding fineness of the fuel, temperature, etc.), that determine the sulphur dioxide binding rate with the oil shale ash in the burning process has been elucidated as a result of research on laboratory equipment as well as in the boilers at power plants. Reduction possibilities of sulphur dioxide emission have been explained by technological methods. Also several principal schemes for cleaning oil shale flue gas from sulphur dioxide have been created.

Nitrogen oxide concentration in oil shale flue gas is modest due to low nitrogen content in the oil shale organic part. The formation of nitrogen oxides in the oil shale combustion process depending on such parameters as organic nitrogen content in oil shale, oxygen concentration in flue gas, flue gas temperature, etc. has been researched. The relation between the formation of nitrogen and sulphur oxides should be stressed.

Formation and content of the polycyclic aromatic hydrocarbons (PAH), especially benz(a)pyrene (B(a)P) in the oil shale combustion products and ash, was established.

Granular and chemical composition of the oil shale fly ash leaving the electrostatic precipitators have been profoundly researched.

Oil Shale Combustion in Atmospheric Circulating Fluidized Bed Boiler. This subject is connected with new oil shale combustion technologies – atmospheric circulating fluidized bed (CFB) boilers. As realized combustion tests showed in case of the Estonian oil shale, the CFB technology gives high burning efficiency. Big amounts of circulating ash unify combustor temperature fields and enable to control it in suitable limits, using, e.g., the fluidized bed heat exchanger (FBHE) in ash circulating contour.

The optimal bed temperature, 800-900°C, and high ash concentration in flue gas favour the sulphur capture. As realized tests showed, SO_2 was nearly completely bound during combustion. NO_x formation was limited due to low bed temperatures.

Such burning conditions at CFB induce remarkable peculiarities at behaviour of oil shale mineral matter compared to traditional PF technology. These should be taken into consideration when designing new oil shale boilers.

In case of the Estonian oil shale possibility to place the high temperature heating surfaces (superheaters) into FBHE gives a new potential to avoid the traditional troubles in operation of PF oil shale boilers – the fouling and corrosion of high temperature superheaters. Using of FBHE, besides possibilities to regulate the boiler load and to preserve the boiler operation stability enables to increase the permissible steam temperature and power plant efficiency.

Oil Shale Pressurized Combustion. This subject is connected with the solid fuel combustion high technology.

On the pressurized combustion conditions due to the high carbon dioxide pressure in flue gas carbonates in oil shale do not decompose in full rate as it takes place in the atmospheric combustion. Consequently, the emission of carbon dioxide is much lower compared to PF or AFBC technologies. For the same reason heating value of oil shale also increases.

A test device for the research of fuel burning in pressurized conditions has been designed and completed at TED. The experiments showed that during the oil shale pressurized combustion in gas environment that contained carbon dioxide with pressure exceeding the calcium carbonate dissociation equilibrium pressure, the carbonates did not dissociate directly but CO_2 would be freed in the chemical reactions between $CaCO_3$, sulphur and sandy-clay part of the oil shale. The experiments also showed a very high sulphur binding effect with ash when burning the oil shale in PFBC conditions.

Design of Boiler Heat Transfer Surfaces and Boiler Conception. A conception of the oil shale boiler construction has been worked out proceeding from the oil shale properties and processes in its combustion. This conception includes the design and arrangement of the heat transfer surfaces such as radiative surfaces in furnace, superheater and reheater section, platen and tube bank economizer, air preheater, etc., their geometrical and thermal parameters, location, as well as fouling with ash deposits, wear and cleaning conditions.

Research and Development Works in TED are not connected only with the Estonian oil shale. TED has done also comprehensive research concerning the utilizing of the calcium-rich brown coals in power plants (mainly of the Kansk-Achinsk basin and the German brown coals).

Recently the problems concerning the utilization of peat and wood as local fuels in the hot water boilers have been in the center of attention. TED has worked out and tested a fully automatic universal boiler device for the burning of the sod peat, wood chips and wood wastes. Also a hot water boiler for burning liquid fuel, gas, firewood and peat has been worked out.

Besides the R&D works to interlace with utilization of the fuels TED has realized research in the heat transfer field. The main subjects are the radiant heat transfer theory, the thermo-physical properties of materials, convective heat transfer in tube banks and roughness of plates, etc.

RESEARCH FELLOWS AND DIPLOMA ENGINEERS OF TED

The following Research Fellows and Diploma Engineers of TED have played a significant role in the research and problem solving in the field of oil shale engineering.

Raaja Aluvee (chemical composition of ash and ash deposits), **Hendrik Arro** (oil shale properties, behaviour of mineral matter, fouling and corrosion, gas cleaning), **Paul Anson** (1915-1986) (metal behaviour in cleaning cycles), **Svetlana Betmanova** (patent inquire), **Tatjana Bojarinova** (corrosion of metals), **Aleksander Hlebnikov** (oil shale pressurized combustion), **Karl Ingermann** (metal corrosion and wear), **August Ingerma** (cleaning of heat transfer surfaces), **Dimitri Jegorov** (oil shale char combustion, environmental protection), **Ülo Kask** (boilers preserve), **Voldemar Keerov** (combustion of shale oil, fouling), **Ivan Klevtsov** (heat transfer, metal lifetime), **Ants Koni** (1929-1986, volatiles combustion), **Rein Kruus** (heat transfer, fouling), **Arvo Kull** (steam-jet distribution in high temperature gas ambient), **Harri Käär** (1944-1997, ash deposits thermophysical properties, heat transfer surfaces cleaning), **Indrek Külaots** (oil shale pressurized combustion), **Jaan Laid** (metal corrosion and wear, boiler design), **Jüri Loosaar** (ash and ash deposits physical properties, environmental protection), **Heli Lootus** (heat transfer, metal corrosion), **Aime Mahlapuu** (1932-1994, oil shale properties, chemical composition of ash and ash deposits), **Vladimir Martšenkov** (heat transfer), **Ilmar Mikk** (1925-1989, heat transfer, granular composition of fly ash, fouling, thermophysical properties of ash deposits), **Ülo Must** (1926-1987, design of heat transfer surfaces, heat transfer), **Oskar Mäeküla** (oil shale properties, metal behaviour), **Maris Nuutre** (chemical composition of ash and ash deposits), **Agu Ots** (fouling, heat transfer), **Arvo Ots** (oil shale properties, burning, mineral matter behaviour; fouling, corrosion, wear and cleaning, heat transfer, environment protection, boiler design, pressurized combustion), **Aadu Paist** (fluidized bed technology, metal corrosion), **Teet Parve** (fouling, environment protection), **Villu Pella** (metal behaviour, corrosion and wear), **Tõnu Pihu** (oil shale grinding, pressurized combustion), **Arvi Poobus** (heat transfer, metal behaviour), **Arvi Prikk** (oil shale grinding, corrosion, ash removal, fluidized bed technology), **Kaido Rajur** (oil shale grinding), **Endel Ratnik** (1929-1968, fouling, deposits physical properties), **Velda Ratnik** (chemical composition of ash and ash deposits), **Rein Randmann** (heat transfer, wear, ash composition), **Hillar Rooraid** (fouling, boiler design), **Nikolai Rozanov** (1917-1986, oil shale granular composition), **Rein Rootamm** (oil shale grinding, ash properties), **Gustav Saar** (1920-1972, oil shale properties, heating value), **Karl Saar** (environment protection), **Vello Selg** (heat transfer), **Andres Siirde** (cleaning and wear, heat transfer, fluidized bed technology), **Uve Soodla** (metal behaviour), **Tõnu Suurkuusk** (heat transfer, fouling dynamics, wear), **Hans Taal** (mineral matter behaviour), **Harri Tallermo** (fouling, cleaning and wear, metal lifetime), **Toomas Tiikma** (heat transfer, thermophysical properties of ash deposits), **Raivo Touart** (metal corrosion and behaviour), **Elvi Tomann** (1935-1995, metals corrosion), **Voldemar Truumägi** (1909-1993, boiler design), **Villu Vares** (metal behaviour, energy economy), **Ants Veski** (heat transfer, boiler design), **Illar Viilmann** (thermophysical properties of ash deposits), **Leo Õispuu** (oil shale grinding and granular composition, environment protection), **Ilmar Öpik** (oil shale grinding, mineral matter behaviour, fouling, corrosion and wear, heat transfer, boiler design).

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