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Animal-fat investigation and combustion test

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Abstract The department was commissioned to investigate the possibilities for animal-fat combustion in industrial steam generators operating originally on fuel–oil or natural gas. There are two main reasons for operating generators on animal fat as a fuel: On one hand, this material is considered as hazardous waste, thus an important goal is its environmentally benign elimination or disposal. On the other hand, fat is an excellent energy source and can be used as combustion fuel. This way fossil fuel usage can be saved while environmental regulations can also be met. The usage of animal fat as a fuel for furnaces required classification according to fuel classification rules, and comparison with the properties of fuel oil. In addition, its pollutant content was determined and the effects on the combustion process and emission were investigated. Finally the savings in fossil fuel energy consumption and related CO_2 emission achieved were determined. The first stage involved the determination of the composition of animal fat. Subsequently other properties such as viscosity and flash point variation were investigated. These data were compared to the properties of fuel oil. The theoretical investigations of animal-fat classification were promising. Initially one steam generator, originally designed for fuel oil combustion, was modified and fitted with a parallel animal fat fuel supply system. The results of the test were encouraging, although there were some problems with power regulation and later with fuel supply. A rotary cup type burner was then fitted to the boiler. Using this system, all the requirements including environmental regulations were met.

Keywords Animal fat analysis · Features and combustion · Fuel–oil replacement

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Animal waste treatment in Hungary

Table 1 shows the stages of processing of animal carcasses. This process has significant heat demands for sterilization in the form of saturated steam. The output of this process is solid ‘meat flour’ and fat.

Animal fat can be merchandized, although sales of this product are steadily decreasing. It can instead be burnt in a steam generator, supplying the steam for the process itself. Meat meal can also be merchandized, depending on the source, or can be burnt, e.g. in solid fuel power stations or in cement kilns. Animal carcasses can also be used for biogas fermentation. However, not all parts of the animal are suitable for biogas fermentation, e.g. feather, hair, blood or bone are unsuitable. Furthermore even after fermentation more than 90% of the carcass remains as waste material. In some cases, it can be used as fertilizer. In contrast, the system discussed in this article processes the total mass of the carcass and produces no other output than solid meat flour and fat.

Properties of fat

Animal fat has been used as fuel since the Stone Age. It was used for example in oil lamps for lighting, beside plant oil and whale oil. Animal fat is a kind of biomass produced by animals. The application of these types of fuels is

Table 1 Flow chart of applied animal carcass processing technology

<table>
<tr><td colspan="4">Raw material input
↓</td></tr>
<tr><td colspan="4">Grinding (50 mm)
↓</td></tr>
<tr><td colspan="4">Sterilization with steam
(min.133 ºC, 2 bar, min. 20 min)
↓</td></tr>
<tr><td colspan="4">Homogenization, vent condensation,
inner storage → waste water treatment
↓</td></tr>
<tr><td colspan="4">Drying
↓</td></tr>
<tr><td colspan="4">Pressing and fat extraction
↓</td></tr>
<tr><td>↑</td><td colspan="2">↓
Fat
↓</td><td>↓
solid part
(cake of press)</td></tr>
<tr><td rowspan="2">↑</td><td colspan="2" rowspan="2">↓
Decantation
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rough breakage</td></tr>
<tr><td>↓
Milling</td></tr>
<tr><td>↑</td><td>↓
Solid part</td><td>↓
Fat</td><td>↓
Screening</td></tr>
<tr><td>↑</td><td colspan="2">↓
Separation</td><td>↓
Meat meal (tankage)</td></tr>
<tr><td>↑</td><td>↓
Sludge</td><td>↓
Fat</td><td rowspan="2">↓
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Meat meal tanks
↓</td></tr>
<tr><td>↑</td><td>Back to
extraction
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Fat tanks
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</table>

advantageous from the viewpoint of the CO_2 balance of the earth. Animal fat is not a stable material in the long term. Upon storage, it undergoes a change, becoming rancid. There are three ways of rancidification: hydrolytic, oxidative and microbial. The oxidative rancidification has no effect on the surrounding materials, but the fatty acid carbon chain will be broken releasing aldehydes and ketones. Rancidification can be prevented with the application of antioxidants. There are several synthetic antioxidants, for instance butyl-hydroxide-anisole (BHA), butyl-hydroxide-toluol (BHT), ethoxy-methyl-quinoline (EMQ) and propyl-gallate (PG). Another process which occurs during the perishing of fats is hydrolysis. During storage, the quantity of free fatty acids increases continuously, so the age of fat can be computed from its acid number. If the peroxide number is also known, the condition of the fat can be established. Table 2 shows the classification of fat according to peroxide number and acid number [1, 2].

Animal fat contains mainly open chain fatty acids with carbon numbers from 2 to 26. The largest number of open chain fatty acids in animal fat has carbon atomic numbers from 16 to 18. Fatty acids in animal fat can be either

Table 2 Classification of fat

Classification	Peroxide number	Acid number
Fresh	0–15	0–35
Slightly perished	16–25	36–45
Perished	26–40	46–55
Strongly perished	41–50	56–60
Become rancid	51–60	61–70
Rancid	Over 60	Over 70

saturated or unsaturated. The ratio of saturated and unsaturated fatty acids has an effect on the physical and biochemical properties of animal fats. For example, increasing the ratio of saturated fatty acids increases the melting point temperature of fat. Increasing the carbon atomic number of fatty acids has a similar effect on the melting point. The fatty acid content of different types of animals is characteristically different. Table 3 summarizes the average composition of fats of different animals. One can conclude that in beef tallow saturated fatty acids (mainly palmitic acid and stearic acid) can be found in a large proportion (~53–54%). The unsaturated part of the fatty acids in beef tallow can be contributed to oleic acid. In fat from poultry, however, the portion of saturated fatty acids is generally not more than 32–33%. Compared to beef tallow, fat from poultry contains more oleic acid (45%) and linoleic acid (22–23%). The composition of pig fat is in between beef fat and poultry fat. Saturated fatty acid part is in the region of 43–44%. It contains more oleic acid (~50%), but less linoleic acid (~11%) compared to poultry fat. Bone grease largely corresponds to pig fat. The fatty acid composition of animal fat depends also on the parts of the body it originates from. For example, interstitial tissue under the skin contains much more unsaturated fatty acid than that found around the abdominal cavity or kidney. Fatty acid composition is also affected by the ambient temperature in the animal's habitat. Colder weather conditions correlate with an increase in the proportion of unsaturated fatty acid in the interstitial tissue under the skin. The fodder content of feeding animals also affects fatty acid composition [1, 6].

Technology of ATEV did not give any possibility to separate different animal fats. That is why only average mixture was investigated hereafter.

For preliminary calculations, the ultimate analysis of two different animal fat samples was performed. Table 4 contains the results of these tests and it contains other parameters important from a combustion viewpoint. For comparison, standard light and heavy fuel oil properties are also shown. Figure 1 shows the density variation and Fig. 2 shows the viscosity variation of animal fat with temperature.

Table 3 Composition of different animal fat [1, 6]

Fatty acids	Formula	Beef-fat/% m m^{-1}	Lard (Pig fat)/% m m^{-1}	Poultry fat/% m m^{-1}	Boiling temp./°C
Saturated fatty acids					
Lauric acid	$C_{12}H_{24}O_2$	0.1–3.4	0.1–0.5	0.1–0.5	299
Myristic acid	$C_{14}H_{28}O_2$	2–6	1–4	0.9–3	309
Palmitic acid	$C_{16}H_{32}O_2$	20–33	21–32	15–27	352
Stearic acid	$C_{18}H_{36}O_2$	2.7–34.8	8–21	4–14	355
Monounsaturated fatty acids					
Myristolein acid	$C_{14}H_{26}O_2$	0.5–5.4	0.1–0.5	≤0.5	114
Palmitolein acid	$C_{16}H_{30}O_2$	0.7–13.4	1–4	1–8	162
Oleic acid	$C_{18}H_{34}O_2$	26.3–53.0	39–60	35–55	334
Multiple unsaturated fatty acids					
Linol acid	$C_{18}H_{32}O_2$	1.2–19.7	0–22	10–35	229
Linolenic acid	$C_{18}H_{30}O_2$	0.1–7.9	0.5–2.5	1–6	231
Melting point/°C		40–50	27–46	25–40	

Table 4 Comparison of animal fat with fuel oil

	Fuel oil EL	Fuel oil S	Fuel oil SA	Animal fat
Composition/% m m^{-1}				water free
Carbon (C)	86.3	85.2	86.6	76.85
Hydrogen (H)	13.4	11.1	11.0	12.51
Sulphur (S)	0.3	2.3	1.0	0.1
Oxygen (O)	–	1.0	1.0	10.19
Nitrogen (N)	–	0.3	0.3	0.35
water (W)	–	0.1	0.1	–
Density at 15 °C/kg dm^{-3}	0.84	0.95	0.96	0.916
Solidification temp./°C	−6	50	50	28
Flash point/°C	70	120	120	202
Air requirement/m^3 kg^{-1}	11.22	10.65	10.79	9.81
Flue-gas volume (dry)/m^3 kg^{-1}	10.46	10.04	10.16	9.09
Fluegas volume (wet)/m^3 kg^{-1}	11.86	11.17	11.33	10.48
Water content in flue gas/kg kg^{-1}	1.20	0.97	1.00	1.12
CO_{2max}/% V V^{-1}	15.31	16.00	16.02	15.71
CO_2 emission/kg kWh^{-1}	0.27	0.28	0.28	0 (0.26)
Lower heating value/MJ kg^{-1}	42.82	40.38	40.94	39.3
Higher heating value/MJ kg^{-1}	45.76	42.76	43.38	42.1

Each test result shows that characteristic values for animal fat are in between the corresponding values belonging to light and heavy fuel oil. Animal fat is renewable, a kind of biomass, that is why CO_2 emission can be considered as zero. But actually combustion of fat produces that amount of CO_2 that is given in the bracket [3–5, 8].

Thermal gravimetric analysis of animal fat samples was also performed. The TGA measurements were performed by a computerized Perkin-Elmer TGS-2 thermobalance equipment. It was first carried out in an argon atmosphere, and then in an oxidative atmosphere. The temperature variation was 10 °C min^{-1} in both cases (Fig. 3).

From the diagrams, it can be concluded that the temperature at which there is a 50% mass reduction is 370 °C in a neutral atmosphere and 270 °C in an oxidative atmosphere. The behaviour is quite different in the presence of oxygen compared to the oxygen free atmosphere. The combustion chamber boundary conditions also make a considerable difference. Evaporation depends not only on temperature, droplet size and viscosity, but also on the oxygen content of

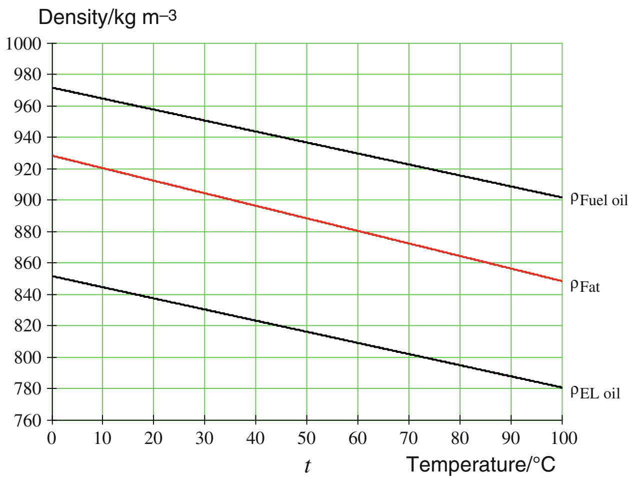


Fig. 1 Variation of animal-fat density with temperature

the surrounding air and flue-gas mixture. When there are large droplets more time is required for evaporation and for hydrocarbon and soot reaction with oxygen. Results comply with kinetic analyses of biomass [7].

Suitable combustion system for animal-fat firing

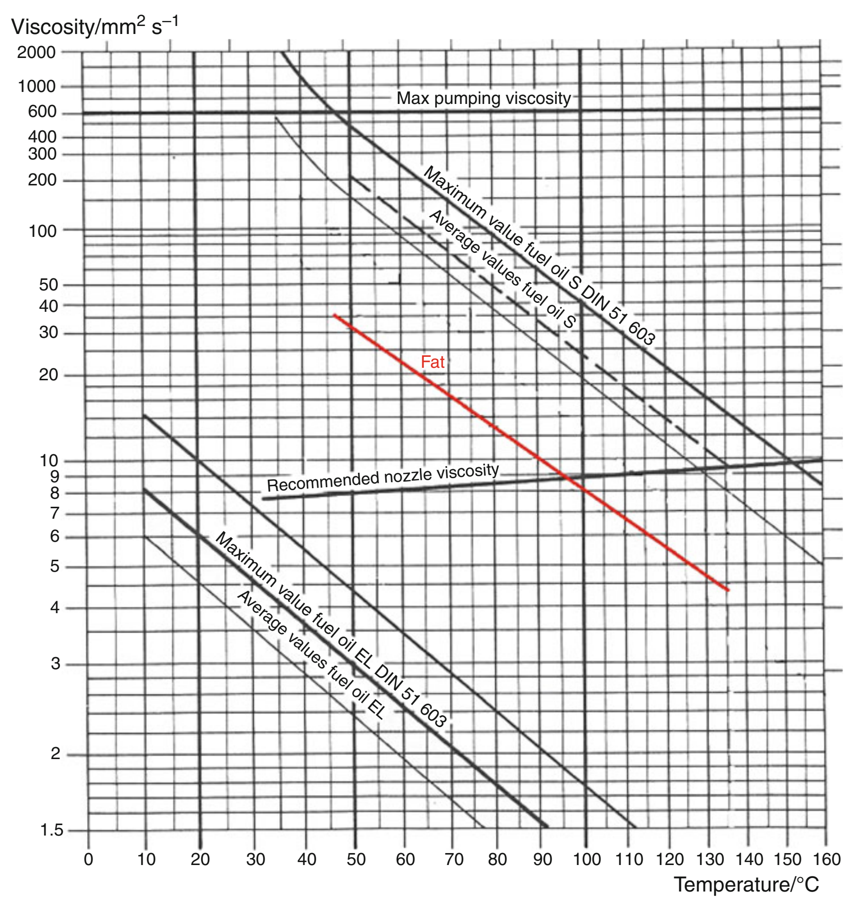
The combustion system and applied steam generator have to match the conditions determined by the optimum parameters for animal-fat firing. The main aims are complete combustion and high boiler efficiency. The most important conditions can be summarized as follows:

- The combustion chamber has to have enough space for the flame of animal-fat firing. It has to provide ample retention time for the combustion process.
- The combustion chamber, return chambers and smoke tubes should be easily cleanable.

The combustion process is chiefly affected by the following factors:

- The combustion process needs a high enough temperature in the combustion chamber for the oxidation process, but it should not be too high, in order to avoid high level of thermal NO_x formation.
- An adequate oxygen supply level is needed for the combustion process. Increasing the excess air factor (generally up to $\lambda \approx 1.8$) augments and quickens the

Fig. 2 Variation of animal-fat viscosity with temperature



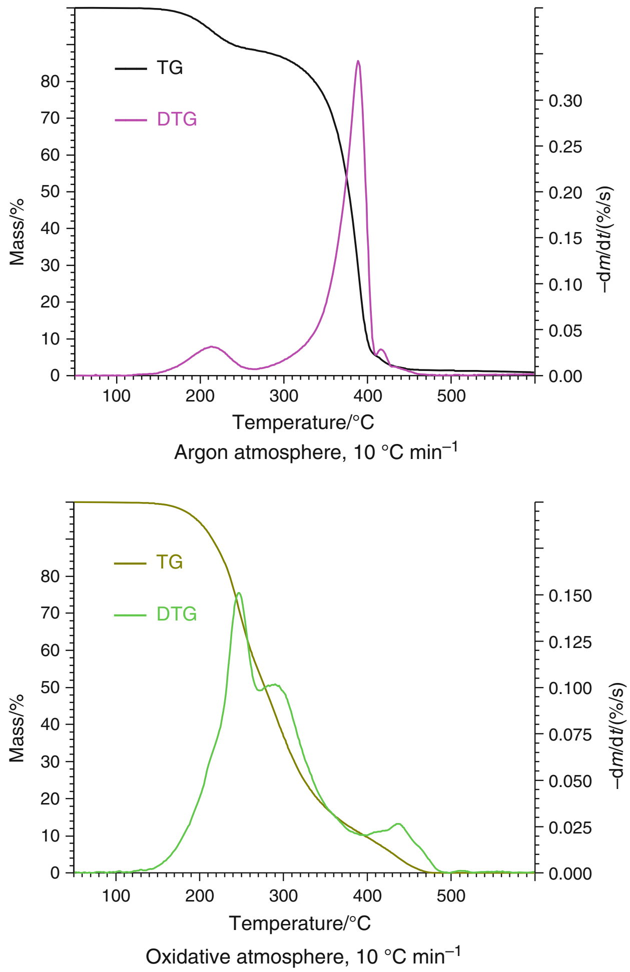


Fig. 3 Results of thermal gravimetric analysis of animal-fat samples

combustion process. However, increasing the excess air factor decreases the boiler efficiency. According to the test results, animal fat firing requires somewhat larger excess air compared to fuel oil combustion.

- For complete combustion, there must be an appropriate mixture of fuel vapour and air. This can be achieved by sufficiently strong violent turbulence. That is generated by the burner. A sufficiently long retention time is necessary for complete chemical reactions, i.e. complete combustion. The combustion chamber must also be large enough to ensure this.

Combustion chamber load is an important parameter for the comparison of different firing systems. In the case of natural gas and light fuel oil combustion, the load can be up to 2 MW/m^3. In the case of heavy fuel oil with low NO_x, it is recommended to maintain a value of around 1 MW/m^3. The combustion behaviour of animal fat is in between that of light and heavy fuel oil. There are components in animal fat, however (proteins, bone particulates), for which the combustion process requires more time. Therefore, it is suggested that animal fat be treated in a similar way to heavy fuel oil, so the combustion chamber load shall not exceed a value of 1 MW/m^3. The combustion chamber in general has to be larger (10–20%), than the flame size. A smaller combustion chamber causes burn out problems, meanwhile in much larger combustion chambers the turbulence flow might be too low.

Smoke tubes

Turbulizator inserts are applied in the smoke tubes of several boilers. These inserts have to be removed from the smoke tubes, because animal fat can contain solid particulates, and thus the inserts would pose a continuous risk of becoming blocked up. This would in turn increase the hydraulic resistance. Removing these inserts generally slightly increases the flue-gas outlet temperature and decreases the efficiency of the parallel boiler. It is advised to slightly reduce the boiler load in order to keep boiler efficiency at an acceptable level.

Pre-test operation

A 2 weeks long pre-test of animal-fat combustion was performed on a steam generator originally designed for use with heavy fuel oil. This boiler was fitted originally with an oil pressure atomization firing system. Animal fat was supplied through the fuel line. Test operations showed that spray formation of animal fat was satisfactory at a pre-heating temperature of 60–95 °C. This pre-test proved that animal fat can be burnt and used for steam generation; however, there were several problems that needed to be tackled. The quality of the animal fat fluctuated during this pre-test. Water and solid particulate content of the fuel sometimes reached an unacceptable level. Protein content in animal fat caused the filters to become blocked up as well as causing higher NO_x emission, since it increased the Nitrogen content of the fuel. During the test, a significant quantity of inorganic solid dust deposit was accumulated in the combustion and return chamber. The fuel supply gear pump wore out and the lubrication condition of animal fat was not satisfactory. Heat exchanger surfaces also became very dirty. The outlet flue-gas temperature increased from 232 to 341 °C. Flue-gas analysis showed that NO_x formation depends on fuel quality, on the excess air factor and even on the dirtiness of the combustion chamber. Figure 4 shows the deposit in the combustion chamber and Fig. 5 depicts the blocked-up filters.

A sample was taken from the deposit in the fire chamber and was tested with EDAX ZAF quantification method. It

Fig. 4 Deposit in fire chamber after the combustion of 2000 t animal fat

Fig. 5 Blocking-up of the filter

shows the components of a living organism (bone, blood, fat, meat) (Table 5).

Final installations and operation

Final installation was performed at two sites of a Hungarian animal carcass disposal company. The basic infrastructure at these sites needed for animal fat supply is present, since animal fat is one of the products at these sites. Storage and transportation is therefore resolved and only a supply pipeline system needed to be installed in between the storage tanks and the boiler house. The supply lines were fitted with parallel steam heating lines. Some modification

Table 5 Results of EDAX ZAF quantification test

	% w w^{-1}
O	30.2
Na	12.0
Mg	1.8
Al	1.0
Si	1.9
P	11.8
S	1.2
K	11.0
Ca	20.9
Fe	8.2

was needed to the animal carcass processing technology in order to keep animal-fat quality at a constant and acceptably clean level. A fuel tank was installed in the boiler house to store animal fat. It was fitted with steam heating, in order to maintain pumping temperature. From the tank, the fat was streamed to a centrifugal pump with a heating case. This pump is controlled by a frequency controller in order to keep fat pressure constant. Filters are installed in two places at the entrance of the fat tank, and in front of the fat pump. Each filter is of a rotating type with automatic rotation mechanism, and with a filter mesh of 500 and 250 μm. Each filter is installed in a pair, with one in operation and the other one in reserve. In case of an increasing pressure drop at the filter, a pressure sensor switches automatically to the reserve filter. The filters are heated with self regulating electrical heating. The fat is heated to the evaporation temperature in a heat exchanger (heated also by steam) before entering the burner. Pre-test operation showed that spray formation of animal fat was satisfactory at a pre-heating temperature of 60–95 °C. However, animal fat always contains a varying quantity of water. Vaporization of this water should be avoided, because steam can cause pressure and flow fluctuation in the supply line. For this reason the pressure in the supply line always has to be significantly greater than the saturation pressure of water belonging to the maximal temperature. For animal fat combustion, the existing burners were replaced with a new rotary cup type firing equipment, which is much more convenient than the original a pressure atomization system, since it is less sensitive to impurities in fuels. These types of burners had actually been design even for these type 'problematic' fuels. The burners can be operated with the fuels originally used, i.e. heavy fuel oil at one site and natural gas at the other. Some boilers are fitted with the economizer made from finned tubes. In case of animal fat firing, flue gas is streamed so as to bypass this in order to avoid the blocking-up of its surface. This causes the outlet flue-gas temperature to increase and boiler efficiency to

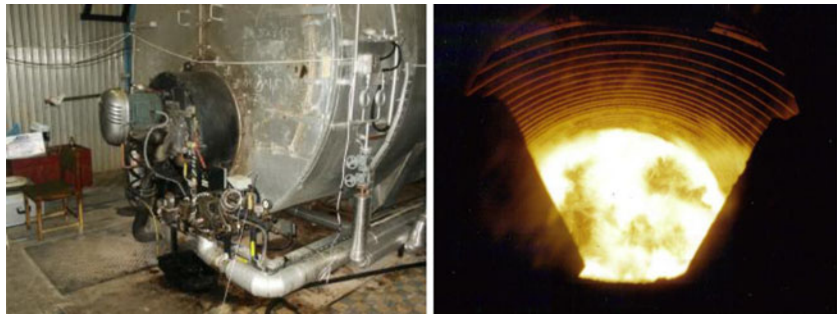


Fig. 6 Installed burner for animal fat firing and picture of flame

Table 6 Test operation with fuel oil S firing

Load factor	Minimum	30%	70%	100%
Oil consumption/dm^3 h^{-1}	88	235	336	455
Oil consumption/kg h^{-1}	82.4	220.0	314.5	425.9
Oil temperature/°C	92.2	95.4	95.7	94.1
Oil pressure/bar	3.1	3.0	3.8	3.3
Air temp. before air preheater/°C	33.2	33.9	29.9	31.4
Air temp. after air preheater/°C	91.2	81.4	74.4	73.4
Flue-gas outlet temperature/°C	169	201	246	303
Flue-gas composition				
O_2/% V V^{-1}	7.1	5.9	3.4	4.0
CO/ppm	20	29	37	36
NO_x/ppm	246	255	313	279
Soot number/B	2	3	2–3	2
Firing power/kW	938	2506	3582	4851
Excess air factor	1.49	1.38	1.19	1.23
Boiler efficiency/%	82.14	87.61	87.85	85.71
Useful power/kW	770	2196	3147	4158
Steam capacity/t h^{-1}	1.16	3.31	4.74	6.26
Nominal load/%	16.79	47.88	68.61	90.65
Combustion chamber load/kW m^{-3}	187.6	501.2	716.4	970.2
Heating surface load/kW m^{-2}	4.40	12.55	17.98	23.76

Table 7 Test operation with animal fat firing

Load factor	Minimum	30%	70%	100%
Fat consumption/dm^3 h^{-1}	90	210	366	503
Fat consumption/kg h^{-1}	76.8	179.1	312.2	429.1
Fat temperature/°C	96	96	94	95
Fat pressure/bar	2.5	2.5	2.5	2.5
Air temp. before air preheater/°C	32.1	31.8	31.9	28.5
Air temp. after air preheater/°C	–	–	–	66.1
Flue-gas outlet temperature/°C	172	178	193	238.1
Flue-gas composition				
O_2/% V V^{-1}	10.2	4.9	6.8	7.4
CO/ppm	2	2	2	1
NO_x/ppm	–	–	–	124
Soot number/B	0–1	0–1	0–1	0–1
Firing power/kW	830	1935	3373	4636
Excess air factor	1.93	1.30	1.47	1.54
Boiler efficiency/%	78.63	88.04	88.31	85.82
Useful power/kW	652	1704	2979	3979
Steam capacity/t h^{-1}	0.97	2.53	4.42	5.91
Nominal load/%	13.83	36.15	63.20	84.42
Combustion chamber load/kW m^{-3}	166.0	387.0	674.6	927.2
Heating surface load/kW m^{-2}	3.73	9.74	17.02	22.73

decrease compared with the original operation. Figure 6 illustrates one example of the installation of a rotary cup burner for animal fat firing as well as a picture of its flame.

Adjustment of burners

Burners were adjusted for both animal fat and the original fuel (fuel oil or natural gas) firing. The adjustment was successful in each case; however, it is worth mentioning that the fire-proof burner port was installed in each case next to the new burner, greatly helping the stabilization of the flame.

With animal fat firing, the capacity of steam generators was reduced to 85–90% of nominal power, in order to ensure complete combustion and to avoid overloading some parts of the boiler wall.

Pollutant emission

After the burner adjustments, the pollutant emissions were also tested. Unburnt components (e.g. CO and soot) were at a minimum level. The main aim of the adjustment was to reduce the NO_x emission. Burner adjustment can only reduce thermal NO_x formation, while fuel NO_x (formation originating from the N content of the fuel) cannot be affected. This fact also highlights the importance of preliminary filtering of the fuel. The results of the test operation can be seen in Tables 6 and 7. Table 6 summarizes the results of fuel oil operation for comparison, while Table 7 shows the results of animal-fat firing. It is worth noting that a much lower level of NO_x emission was attained with animal fat firing than that with fuel oil firing. Rotary cup burner results lower NO_x emission comparing with pre-test operation, since it produces quite another swirls and flame shape, so reaction was not so concentrated. It is also worth mentioning that NO_x emissions can be reduced further by re-circulating the flue gas. This solution reduces the average fire chamber temperature even in cases where there was a small excess air. This solution can also help reducing thermal NO_x emission for the case of fuel oil firing. Flue-gas recirculation is applicable. 20% flue-gas recirculation result up to 50% reduction in thermal NO_x. For this to be achieved, an injector must be installed.

Results of test operation

At these two sites of the company, large amounts of animal fat were fired in recent years. Animal fat can be merchandised only to a limited extent and its selling price is generally lower than the price of fuel oil or natural gas. In the future, this gap is expected to increase. Therefore, the combustion of animal fat is becoming more and more economically viable. Moreover, it is considered a renewable energy resource, thus it can help reducing CO_2 emissions by the savings in fossil fuel usage.

Conclusions

Firing animal fat is not as easy as it appears at first glance. Meeting all the requirements of firing and pollutant emission requires several special measures and actions. However, the difficulties experienced can be overcome and this dangerous waste material can be utilized in a way, that a certain amount of thermal energy can be generated so some fossil fuel can be saved and CO_2 emissions reduced.

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