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Determining of the Suitable Burning Method for Wheat Straw and Sunflower Stalks

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Abstract: In this study, it was aimed to determine the suitable burning technique and grate type of wheat and sunflower stalks. Wheat and sunflower stalks were burnt in three different forms. In the first form, wheat straw was burnt in bale slices, sunflower stalks as it was removed from the field; in the second form, both stalks were burnt after being chopped without being compressed; and in the third one after being chopped and compressed in polyethylene bags. Three different grates with circle, oblong and mixed (circle+oblong) holed were used in the boiler. Fuels were burnt in the grates in three different forms, i.e., by front natural draft, bottom natural draft and bottom fan blowing. In the study, the highest boiler efficiency for the 1. forms of wheat and sunflower stalks were found as 25.7 and 25.1% in front burning with circle holed grate. The highest boiler efficiency in the 2. form trials were obtained under front burning conditions with circle holed grate, being 35.8 and 30.5% in wheat straw and sunflower stalks, respectively. The highest efficiency in the 3. form trials were obtained in the burning type bottom fan blowing and mixed holed grate with bottom fan blowing and circle holed grate in sunflower stalk with 30.9%. Low O_2 values were obtained for front and bottom burning conditions in all three grates for the I. forms of fuels, in the chimney gas measurements of wheat and sunflower stalks.

Key words: Agricultural biomass energy, agricultural residues, solid fuel boiler, emission

INTRODUCTION

Biomass is among the alternative energy resources. Different biomass materials may be grown under very different climatic conditions in the world. Biomass is a strategic energy resource contributing to environmental protection and convertible to the other energies. Therefore, biomass is of great importance with respect to energy for developed countries, as well as for developing countries[1]. 15% of the world energy consumption and 43% of the energy consumption in developing countries are supplied from biomass[2].

Turkey is a country which does not have sufficient energy resources and which imports 2.5 times of its energy consumption. Furthermore, Turkey has a considerably high level of renewable energy resources that can be utilised to satisfy a part of total energy demand in the country[3]. Especially biomass energy is widely used, although new and renewable energy resources do not take an important part in the energy balance of Turkey. Total energy supplied from the classical biomass in Turkey is about 350 PJ[2].

The stalk quantities and the net energy values that could be obtained from them, assuming the low heat value of the stalk as 15,000 kJ kg^{-1}, boiler efficiency as 65% and collecting value of stalk from the field as 60% are given in Table 1[5-9].

As can be seen in Table 1, nearly 46.28 Mt of stalk was produced in our country by the year 2002 (DIE, 2003), depending on the calculation based on stalk/product ratios changing with the crop species. When the collectible of stalk from the field was assumed as 60%, stalk quantity is nearly 27.76 Mt. Its energy value is 416.5 PJ. Here, it was accepted that all of the stalk was used in energy production. The energy that can be obtained from stalk is equivalent to 36% of total oil energy consumption and nearly 14% of total primary energy consumption in Turkey.

It was reported that the agricultural residues and firewood could be directly converted into energy by burning in the specially designed solid fuel furnaces, as well as they could be used in briquette manufacturing or via pyrolysis after being subjected to a pre-treatment[10]. It was also reported that the firewood

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and stalk are two important biomass energy resources used in heat production and that the timber wood and high density straw bales are being burnt with bottom draft, as large volume burning systems[11]. It was stated by Piechocki[12] that nearly 30 Mt of stalk was annually produced in Poland, equivalent to 15 Mt of coal. The cultivation of Miscanthus sinensis C4 an energy plant was realised in the Izmir province of Turkey. Information was given related to the dry matter content, production value, thermal value, ash quantity, cellulose content and storage requirements of the crop[13].

The suitable burning technique for burning the wheat straw and sunflower stalks was determined in this study.

MATERIALS AND METHODS

This research was realised in winter months in the years 1999-2000 and 2000-2001. In the study, the atelier of Agricultural Machinery Department, Faculty of Agriculture, Uludag University was selected as the area to be heated. The atelier was heated with the heat taken from the boiler. The floor area of the atelier was 72 m^2 and the volume was 388 m^3. Totally 138 radiator parts were used in the atelier.

In the research, half cylindrical type, steel, solid fuel boiler with 6 m^2 heating surface, hot water-heating and smoke tube was utilised. The boiler heating power was 150 MJ h^{-1} (for coal), water volume of boiler 250 L (all installation including the boiler: 580 L), furnace volume 0.1 m^3. Boiler dimensions (width, height, length) were 820, 106 and 1275 mm, respectively. Smoke box canal dimension was 250×250 mm, chimney pipe inner diameter was 300 and length 6000 mm. Boiler testing and operating pressures were 500 kPa and 300 kPa, respectively.

Three types of grates, being circle, oblong and mixed (circle + oblong) holed were used in the boiler (Fig. 1). The grates were flat grate type and made from cast iron material. The dimensions of the grate in the boiler were 510x600 mm, onto which 6 oblong holed grates and 5 circle and mixed holed grates each were placed.

The operating pressure of the water circulation pump used in the boiler was 10 bar. Maximum inlet pressures in the draft inlet were 0.2 and 0.8 bar at 95 and 110°C, respectively. The temperature range allowed for the pump was between 20 and 110°C. The pump was connected to the return line of the system.

Two pieces of glass thermometer with protection and liquid expansion within the measurement ranges of -10 and +130°C were utilised in the boiler water temperature measurements. One of the thermometers were connected onto the boiler for hot water measurement, whereas the other one was connected to the return line of boiler water for use in the measurement of returning water temperature.

A hydrometer was mounted onto the boiler for monitoring the water level connected to the returning water line of the boiler in order to measure the water flow rate in the boiler. The counter had a sensitivity of 1/1000 m^3 and was resistant to 90°C temperature. The counter parallel connected to the returning line and might be by passed except flow measurement.

Chimney gas analysis device was used in the measurement of chimney gas emissions. One pitot tube connected to a differential pressure gauge was utilised in the measurement of chimney gas speed.

A digital anemometer operating within the measurement sensitivity ranges of 2.6 and 26 sec was used in the measurements of burning air inlet speed and chimney gas speed. Thermometers with liquid expansion were used in the temperature measurements of the outer ambient and atelier and rooms which were heated.

A fan with a flow rate of 2,030 m^3 sec^{-1}, draft inlet diameter of 230 mm, rotation number of 1,380 rpm and a power of 0.25 kW was used in the burning experiments carried out with supplementary air.

Digital monophase electricity counter was used in the measurement of electrical energy consumed by the circulation pump and digital triphase electricity counter was used for measuring the electrical energy consumed by the fan used in the air burning trials.

Wheat straws and sunflower stalks which were used as fuel were burnt in three different forms, being the 1, 2 and 3 forms. In the 1. form, wheat straws were burnt as bale slices, sunflower stalks as it was harvested from the field; in the 2. form both materials were burnt as being chopped without compression; in the 3. form, they were burnt after being compressed in polyethylene bags being 0.5 kg in each bag, following the compressing.

Three different types of grates being circle, oblong and mixed (circle + oblong) holed were used in the boiler. The fuels were burnt in the grates in three different ways, i.e., with front and bottom natural draft and bottom fan blowing.

Used heat power (Q_N), is the part of the heat obtained via burning of the fuel in the furnace that passes to the heating fluid in hot water boilers. The value of this heat is determined with the following equation[14].

$$Q_N = W_1 \cdot c_w (t_h - t_c) \qquad [kJ\ h^{-1}] \qquad (1)$$

Here; W_1, is the quantity of hot water produced in an hour (kg h^{-1}) (which was found as 1,110 kg h^{-1} through measurement); c_w, is the specific heat of outlet water (kJ/kg°C) (was taken as 4.187 kJ/kg°C); t_h, is the hot water

Table 1: Net energy quantities that could be obtained from the stalks of some field crops in Turkey, according to the statistics of the year 2002

Crop species	Production quantity (x1000 t)	Straw/ grain ratio	Straw quantity (x1000 t)	Collectible 60%		Total energy value(*) (PJ)	Net energy value (boiler effic. 65%) (PJ)	Oil equivalent of total energy (**) (Million barrel)
				Total straw quantity (x1000 t)	Straw yield (t ha^{-1})			
Wheat	19,000	1.5	28,500	17,100	1.29	256.5	166.7	42.12
Barley	7,500	1.45	10,875	6,525	1.79	97.9	63.6	16.07
Corn	2,200	1.0	2,200	1,320	2.40	19.8	12.9	3.25
Cotton	922	2.0	1,844	1,106	1.60	16.6	10.8	2.72
Sunflower	650	2.8	1,820	1,092	2.14	16.4	10.7	2.69
Oats	265	2.0	530	318	2.12	4.8	3.1	0.78
Rye	220	1.5	330	198	1.41	3.0	1.9	0.49
Rice	216	0.78	182	101	2.86	1.5	1.0	0.25
Total			46,281	27,760		416.5	270.7	68.37

(*) Lower heating value for 14% moisture content of straw is taken 15,000 kJ kg^{-1}, (**) Energy equivalent an American barrel oil : 6.09 x 10^{6} kJ

Table 2: Chemical composition and heating values of wheat straw and sunflower stalk fuels

	Analytical method	Wheat straw	Sunflower stalks
Heating value	ASTM D 2015/E 711		
Moisture	ASTM E 871	12.8	10.5
Proximate analysis (wt.%)			
Ash	ASTM D 1102 (600°C)	6.2	7.6
Volatile matter	ASTM E 872/E897	73.8	68.0
Fixed carbon	by difference	20.0	24.4
Ultimate analysis (wt.%)			
Carbon	ASTM E 777	44.8	48.2
Hydrogen	ASTM E 777	5.4	5.7
Oxygen	by difference	40.6	38.3
Nitrogen	ASTM E 778	0.6	1.1
Sulphur	ASTM 775	0.2	0.1
Ash	ASTM D 1102 (600°C)	6.2	7.6
HHV (MJ kg^{-1})		17.879	18.647
LHV (MJ kg^{-1})		16.238	17.190

outlet temperature (°C) and t_c, is the cold water inlet temperature (°C).

The quantity of heat given to the boiler with fuel in an hour in order to get the desired used heat power forms the burning heat power (Q_B) of the boiler. Its value is calculated with the equation:[14]

$$Q_B = B \cdot LHV \qquad [kJ\ h^{-1}] \qquad (2)$$

Here; B, is the quantity of fuel sent to the boiler in an hour (kg h^{-1}) and LHV, is the lower heating value (kJ kg^{-1}) of the fuel. Lower heating values of wheat straw and sunflower stalks were taken as 16,238 and 17,192 kJ kg^{-1}, respectively[15].

The analytical methods of chemical components of wheat and sunflower stalks fuels used in trials and proximate and ultimate results are given in Table 2[15].

Boiler efficiency is the ratio of used heat power of the boiler to the burning heat power. Its value is determined by the equation below:[14]

$$\eta_B = \frac{Q_N}{Q_B}.100 \qquad [\%] \qquad (3)$$

Boiler efficiency and chimney gas emissions were determined for each burning method. Measurements of CO (carbon monoxide) SO_2 (sulphur dioxide), NO_x (nitrogen dioxide) were realised using gas analyser. Only CO emissions were given in the research results since this was important compared with other emissions.

Gas analyser directly measures the gas emission values of fuel types such as coal, fuel-oil, natural gas etc. The apparatus gives the data according to the calculation method programmed at the reference O_2 level given for these fuels in the Regulations for Protection from Air Pollution (RPAP) by the Ministry of Environmental Affairs[16]. Since the wheat straw and sunflower stalks in the study are involved in the solid fuel category, the coal option was taken as basis for measurement. O_2 reference for coal was 7%. Reference of the apparatus for wheat straw and sunflower stalks were taken as 13%, according to the article given in Appendix 7 guidelines as RPAP as "the volumetric oxygen quantity in chimney gas in the facilities burning wood and wood residues is taken as 13%.

The conversion of the concentrations calculated based on 13% O_2 to standard conditions (273°K and

1 atmosphere pressure) was realised according to the following equations:[14,15]

$$CO_N = \frac{4}{7}.CO.\frac{273+T_{CG}}{273} \quad (mg\ Nm^{-3}) \quad (4)$$

$$SO_{2N} = \frac{4}{7}.SO_2.\frac{273+T_{CG}}{273} \quad (mg\ Nm^{-3}) \quad (5)$$

$$NO_{xN} = \frac{4}{7}.NO_8.\frac{273+T_{CG}}{273} \quad (mg\ Nm^{-3}) \quad (6)$$

Here; CO_N, SO_{2N} and $NO_{x\,N}$ are the concentrations of carbonmonoxide, sulphurdioxide and nitrogendioxide pollutants, respectively under standard conditions according to 13% O_2 (mg Nm^{-3}); T_{CG} is the measured temperature of the chimney gas (°C); CO, SO_2 and NO_x are the concentrations of carbonmonoxide, sulphudioxide and nitrgendioxide pollutants, respectively, read from the apparatus according to 7% O_2 (mg m^{-3}); 273 is the absolute temperature (°K) under standard conditions (0°C and 1 atmosphere pressure).

Mass flow rates of converted concentrations of pollutants based on the chimney gas flow rate under standard conditions, depending on the measurement values taken from the apparatus:[14,15]

$$L_{CO} = \frac{0.9828.V_{CG}.A_C}{273+T_{CG}}.CO_N \quad (kg\ h^{-1}) \quad (7)$$

$$L_{SO_2} = \frac{0.9828.V_{CG}.A_C}{273+T_{CG}}.SO_{2N} \quad (kg\ h^{-1}) \quad (8)$$

$$L_{NO_X} = \frac{0.9828.V_{CG}.A_C}{273+T_{CG}}.NO_{XN} \quad (kg\ h^{-1}) \quad (9)$$

Here; L_{CO}, L_{SO2} and L_{NOx} are the mass flow rates of CO, SO_2 and NO_x pollutants, respectively (kg h^{-1}); V_{CG}, chimney gas speed (m s^{-1}), A_C is the internal cross section are of the chimney (m^2). The internal cross section area of the chimney used in the study was 0.07 m^2.

RESULTS AND DISCUSSION

When the data in the Table 3 and 4 are examined, the close relationship between boiler water temperature and fuel feeding speed can be noted. Increase in fuel feeding rate leaded to an increase in boiler water temperature. However, especially chopping 2. forms of fuels plug the grate holes, since the air inlet holes cross section (approx. 0.016 m^2) of round-holed grate are small sized (Fig. 1a). For this reason, burning air entrance during the burning of 2. form fuels was in sufficient and as a result, burning

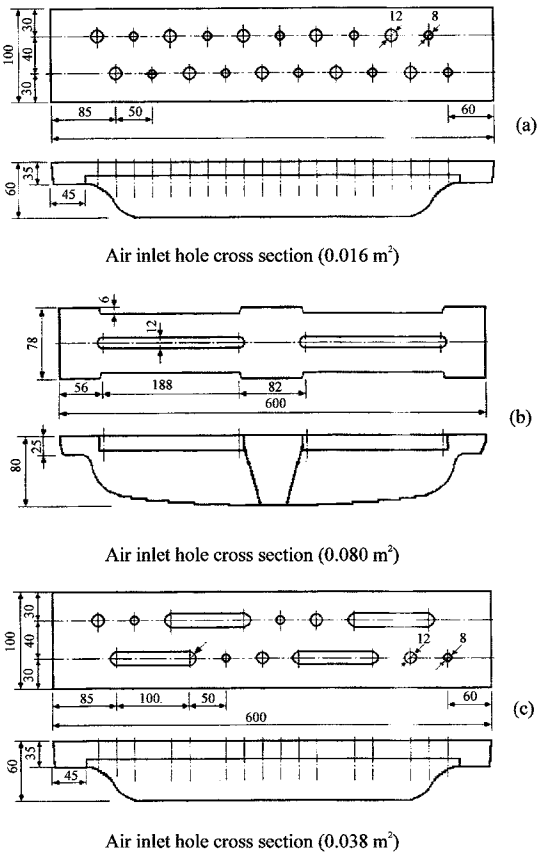

Fig. 1: Types and dimensions of the grates in the furnace (a) circle holed grate; (b) oblong holed grate; (c) mixed (circle + oblong) holed grate

process was retarded. Boiler heating power and boiler productivity values were calculated based on the values of fuel feeding rate and the differences between the temperatures of boiler entrance and return water given in Table 3 and 4 and showed in Fig. 2 and 3.

The highest CO quantity resulting from the measurements an wheat straw realised in CHG was determined in FB condition of the 2. form with 19893.0 mg Nm^{-3}, while the lowest CO quantity was found in BB condition of the 2. form with 6213.8 mg Nm^{-3}, as can be seen in Table 5. Front burning was not applied in mixed holed grate, since CO value for FB burning condition of 2. form in OHG was found high. Reduction in CO emissions during the bottom burning of wheat straw and involvement of O_2 entering the burning chamber in the burning process indicated that complete combustion took place.

CO emission was raised in FB condition either with round or with oblong holed grate in the burning experiments of sunflower stalk using the 2. form of stalk,

Table 3: Mean results related to the burning experiment with wheat straw with three different grates

	CHG						
Parameters	1. form FB	1. form BB	1. form *BB	2. form FB	2. form BB	2. form *BB	3. form *BB
Experimental number	3 exp.	2 exp.	2 exp.	1 exp.	2 exp.	2 exp.	2 exp.
Bulk density of fuel (kg m^{-3})	110.0	119.5	121.0	50.0	49.5	50.0	108.0
Moisture content of fuel (%)	10.7	11.2	11.1	9.8	12.0	13.4	10.3
Total fuel consumption (kg)	43.5	24.3	41.5	30.0	17.8	29.5	25.5
Ash (%)	7.7	7.5	8.5	8.0	9.3	9.5	--
Fuel feeding rate (kg h^{-1})	12.2	9.4	12.5	5.6	4.3	5.4	8.5
$t_{h\ max}$ (°C)	78.7	59.0	76.0	50.0	39.5	51.8	62.0
$t_{c\ max}$ (°C)	68.8	51.5	68.5	44.0	34.5	47.0	54.3
$Ät_{average}$ (°C)	8.4	6.2	7.0	4.8	4.7	5.1	7.3

Table 3: Continued

	OHG						MHG					
Parameters	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form BB	1. form BB	1. form *BB	2. form BB	2. form *BB	3. form BB	3. form *BB
Experimental number	2 exp.	3 exp.	1 exp.	2 exp.	1 exp	1 exp	4 exp.	3 exp.	2 exp.	3 exp.	1 exp.	1 exp.
Bulk density of fuel (kg m^{-3})	124.5	119.7	51.0	48.5	48.0	107.0	123.5	108.3	53.0	51.7	104.0	85.0
Moisture content of fuel (%)	13.5	11.4	16.3	9.7	9.2	10.4	10.4	13.5	12.8	13.5	11.6	9.4
Total fuel consumption (kg)	53.8	53.5	31.5	23.5	19.5	16.5	35.0	30.8	19.5	33.7	24.0	28.0
Ash (%)	8.1	8.3	11.4	9.1	--	--	8.7	8.7	--	7.1	--	5.7
Fuel feeding rate (kg h^{-1})	15.9	15.5	8.1	11.5	14.3	12.8	13.4	19.0	11.9	14.3	12.6	14.8
$t_{h\ max}$ (°C)	87.0	75.5	64.0	62.0	71.0	66.0	70.0	66.3	60.8	67.0	58.5	91.0
$t_{c\ max}$ (°C)	77.0	65.5	55.5	53.0	60.0	57.0	58.4	56.0	51.3	57.7	49.5	77.5
$Ät_{average}$ (°C)	9.4	9.4	7.6	7.9	9.2	9.8	8.4	8.7	7.3	8.2	7.5	10.2

CHG (Circle Holed Grate), OHG (Oblong Holed Grate), MHG (Mixed (Circle+Oblong) Holed Grate); FB (Front Burning), BB (Natural Draft Burning), *BB (Fan Blowing Burning)

Table 4: Mean results related to the burning experiment with sunflower stalks with three different grates

	CHG					
Parameters	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form *BB
Experimental number	3 exp.	1 exp.	1 exp.	1 exp.	1 exp.	1 exp.
Bulk density of fuel (kg m^{-3})	66.0	68.0	90.0	87.0	95.0	125.0
Moisture content of fuel (%)	14.6	14.5	10.4	10.3	14.7	11.8
Total fuel consumption (kg)	21.8	21.5	14.5	28.0	36.5	21.0
Ash (%)	13.3	12.1	11.7	14.2	17.5	13.3
Fuel feeding rate (kg h^{-1})	13.3	10.5	6.2	5.2	8.8	7.0
$t_{h\ max}$ (°C)	68.3	51.5	40.5	45.0	53.0	48.0
$t_{c\ max}$ (°C)	58.3	43.0	33.5	41.5	45.0	41.0
$Ät_{average}$ (°C)	8.7	6.6	6.2	5.2	7.3	6.3

Table 4: Continued

	OHG							MHG				
Parameters	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form BB	3. form *BB	1. form BB	2. form BB	2. form *BB	3. form BB	3. form *BB
Experimental number	3 exp.	3 exp.	1 exp.	2 exp.	1 exp.	1 exp.	1 exp.	2 exp.	1 exp.	2 exp.	1 exp.	1 exp.
Bulk density of fuel (kg m^{-3})	69.7	72.0	110.0	90.5	105.0	121.0	115.0	65.5	92.0	89.5	105.0	117.0
Moisture content of fuel (%)	15.4	16.2	9.7	16.4	12.5	11.4	10.2	13.5	13.4	11.0	11.8	9.8
Total fuel consumption (kg)	28.2	35.3	18.0	45.0	24.5	24.0	38.0	26.5	19.0	37.3	24.0	27.6
Ash (%)	14.5	14.5	--	18.6	--	13.8	--	16.0	15.4	13.1	13.3	--
Fuel feeding rate (kg h^{-1})	13.9	11.1	10.0	11.4	12.7	10.5	13.2	15.5	10.1	14.0	12.0	12.7
$t_{h\ max}$ (°C)	63.3	70.0	57.0	61.0	65.5	55.0	84.5	63.3	50.5	75.5	66.5	71.0
$t_{c\ max}$ (°C)	56.3	61.7	50.0	50.8	57.0	47.0	78.0	54.5	43.0	65.3	53.5	63.0
$Ät_{average}$ (°C)	8.1	7.1	6.8	8.2	8.3	6.8	8.5	8.0	7.7	8.5	10.8	9.1

as can be seen in Table 7. Failure in mixing of the oxygen with fuel leaded to incomplete burning and increased CO emission in wheat straw, as well as in sunflower stalk. CO emission values in the experiments of mixed holed grate with bottom natural draft and bottom secondary air reinforcement gave better results compared with the other two grates.

The comparative results of concentration values and mass flow rates of CO, SO_2 and NO_x gases under standard conditions calculated based on 13% O_2 for wheat straw

Table 5: Mean results related to the chimney gas measurement in wheat straw with three different grates

	CHG						
Parameter	1. form FB	1. form BB	1. form *BB	2. form FB	2. form BB	2. form *BB	3. form *BB
T_{CG} (°C)	122.9	86.3	117.3	72.1	72.6	81.4	77.4
V_{CG} (m s^{-1})	2.9	1.4	1.9	2.0	1.6	1.9	1.8
$Q_{N\,CG}$* (Nm^3 h^{-1})	498.1	268.1	340.8	403.7	318.5	375.3	359.9
O_2 (%)	15.8	13.4	13.7	19.0	12.2	12.8	13.6
CO_2 (%)	4.5	6.7	6.4	1.8	7.7	7.2	6.5
λ **(13% O_2)	1.55	1.06	1.10	3.95	0.91	0.97	1.08
CO (mg m^{-3})	8202.7	14440.3	12334.0	27453.5	8590.7	10806.0	8849.7
CO_N (mg Nm^{-3})	6797.9	10860.1	10075.5	19893.0	6213.8	8016.8	6491.3
SO_2 (mg m^{-3})	0	13.0	32.7	0	0	0	0
$SO_{2\,N}$ (mg Nm^{-3})	0	9.8	26.7	0	0	0	0
NO_x (mg m^{-3})	202.7	201.0	353.7	338.0	132.7	151.7	214.3
$NO_{x\,N}$ (mg Nm^{-3})	168.0	151.2	288.9	244.1	96.0	112.5	157.2

Table 5: Continued

	OHG						MHG					
Parameter	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form BB	1. form BB	1. form *BB	2. form BB	2. form *BB	3. form BB	3. form *BB
T_{CG} (°C)	138.8	134.9	82.3	145.6	131.3	140.0	142.8	156.8	137.2	166.5	149.6	135.4
V_{CG} (m s^{-1})	3.3	2.9	2.6	2.9	3.4	3.1	2.9	3.1	2.9	3.3	2.5	2.7
$Q_{N\,CG}$* (Nm^3 h^{-1})	543.0	497.5	498.6	468.4	578.5	508.1	471.5	488.2	486.4	516.6	398.9	454.9
O_2 (%)	17.0	15.3	18.7	13.6	15.4	15.0	15.4	12.9	16.7	13.2	14.0	13.8
CO_2 (%)	3.6	5.1	1.9	6.6	5.0	5.3	4.9	7.2	3.8	6.8	6.2	6.1
λ **(13% O_2)	1.98	1.39	3.48	1.07	1.42	1.33	1.43	0.98	1.84	1.03	1.13	1.10
CO (mg m^{-3})	3625.5	5168.5	19016.3	1961.0	7479.0	3336.0	4157.0	3991.5	4116.5	3192.0	3477.0	2494.0
CO_N (mg Nm^{-3})	3124.6	4412.8	14141.3	1718.2	6329.2	2883.5	3618.0	3590.9	3534.0	2936.4	3075.3	2131.7
SO_2 (mg m^{-3})	58.0	15.5	12.5	0	0	0	0	0	0	0	0	0
$SO_{2\,N}$ (mg Nm^{-3})	50.0	13.2	9.3	0	0	0	0	0	0	0	0	0
No_x (mg m^{-3})	505.5	336.0	372.8	230.0	202.5	312.5	388.0	232.5	284.0	427.0	286.5	271.0
$NO_{x\,N}$ (mg Nm^{-3})	435.7	285.9	277.2	201.5	171.4	270.1	337.7	209.2	243.8	392.8	253.4	231.6

* $Q_{N\,CG}$: Chimney gas flow to the standard conditions, ** λ : Excess air coefficient to the %13 O_2.

Table 6: Comparison of the gas and mass flow rate values related to wheat straw measured using three different grates with the limit values in the guidelines given in appendix 7 (for gases) and appendix 2 (for mass flow rates) by RPAP

		CHG						
Parameters	Limit value of regulation	1. form Ö.Y.	1. form A.Y.	1. form *A.Y.	2. form Ö.Y.	2. form A.Y.	2. form *A.Y.	3. form *A.Y.
CO_N	250 mg Nm^{-3}	6797.9	10860.1	10075.5	19893.0	6213.8	8016.8	6491.3
L_{CO}	1000 kg h^{-1}	3.386	2.911	3.434	8.032	1.979	3.008	2.335
$SO_{2\,N}$	2000 mg Nm^{-3}	0	9.8	26.7	0	0	0	0
L_{SO2}	60 kg h^{-1}	0	0.003	0.008	0	0	0	0
$NO_{x\,N}$	(*)mg Nm^{-3}	168.0	151.2	288.9	244.1	96.0	112.5	157.2
L_{NOx}	40 kg h^{-1}	0.084	0.041	0.098	0.099	0.031	0.042	0.057

Table 6: Continued

		OHG						MHG					
Parameters	Limit value of regulation	1. form Ö.Y.	1. form A.Y.	2. form Ö.Y.	2. form A.Y.	2. form *A.Y.	3. form A.Y.	1. form A.Y.	1. form *A.Y.	2. form A.Y.	2. form *A.Y.	3. form A.Y.	3.form *A.Y.
CO_N	250 mg Nm^{-3}	3124.6	4412.8	14141.3	1718.2	6329.2	2883.5	3618.0	3590.9	3534.0	2936.4	3075.3	2131.7
L_{CO}	1000 kg h^{-1}	1.697	2.196	7.051	0.805	3.662	1.465	1.706	1.753	1.719	1.517	1.227	0.970
$SO_{2\,N}$	2000 mg Nm^{-3}	50.0	13.2	9.3	0	0	0	0	0	0	0	0	0
L_{SO2}	60 kg h^{-1}	0	0.027	0.006	0.006	0	0	0	0	0	0	0	0
$NO_{x\,N}$	(*)mg Nm^{-3}	435.7	285.9	277.2	201.5	171.4	270.1	388.0	232.5	284.0	427.0	286.5	271.0
L_{NOx}	40 kg h^{-1}	0.237	0.143	0.138	0.094	0.099	0.137	0.159	0.102	0.119	0.203	0.101	0.105

(*) : It has not been given limit value for NO_x emissions at boilers under the 50 MW heating power

and sunflower stalks shown in Table 5 and 7 with the limit values given in the guidelines of RPAP[16] are given in Table 6 and 8, depending on the grate type. When the Table 6 and 8 are examined, CO emissions of wheat straw and sunflower stalks under all burning conditions in the three types of grates are observed to be much above the limit value given in the guidelines. However, when the mass flow rates of CO gases were

Table 7: Mean results related to the chimney gas measurement in sunflower stalks with three different grates

	CHG					
Parameters	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form *BB
T_{CG} (°C)	148.0	77.2	72.8	89.8	96.4	94.4
V_{CG} (m s^{-1})	3.4	1.7	2.6	1.5	2.0	1.9
$Q_{N\,CG}$ (Nm^3 h^{-1})	555.6	327.4	512.3	290.8	366.2	362.1
O_2 (%)	16.7	13.6	18.0	11.8	12.1	11.7
CO_2 (%)	3.8	6.6	2.7	8.1	7.8	8.1
λ (13% O_2)	1.84	1.08	2.64	0.87	0.90	0.86
CO (mg m^{-3})	5743.0	12440.3	17598.3	13923.0	9797.0	7185.3
CO_N (mg Nm^{-3})	5060.8	9119.0	12738.7	10572.1	7575.8	5525.2
SO_2 (mg m^{-3})	0	29.3	165.5	0	0	0
SO_{2N} (mg Nm^{-3})	0	21.5	119.8	0	0	0
NO_x (mg m^{-3})	502.5	291.3	433.3	220.0	142.7	179.3
NO_{xN} (mg Nm^{-3})	442.8	213.6	313.6	167.1	110.3	137.9

Table 7: Continued

	OHG							MHG				
Parameter	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form BB	3. form *BB	1. form BB	2. form BB	2. form *BB	3. form BB	3. form *BB
T_{CG} (°C)	133.9	152.2	88.5	135.9	176.8	149.7	142.8	149.1	116.0	121.8	130.2	167.5
V_{CG} (m s^{-1})	3.9	3.5	2.4	2.8	3.1	3.2	3.7	3.2	2.8	3.1	2.9	3.2
$Q_{N\,CG}$ (Nm^3 h^{-1})	650.9	558.2	460.5	471.1	474.2	520.9	612.2	521.6	486.4	531.5	486.3	499.8
O_2 (%)	16.5	13.7	18.3	13.0	14.1	13.8	13.9	13.0	13.1	14.3	13.9	14.4
CO_2 (%)	3.9	6.4	2.4	7.1	6.0	6.4	6.2	7.0	7.0	5.9	6.3	5.9
λ (13% O_2)	1.76	1.10	2.99	0.99	1.16	1.11	1.13	1.00	1.01	1.19	1.12	1.20
CO (mg m^{-3})	5366.0	3319.0	14403.3	2063.0	1727.5	3223.5	3923.5	3208.5	2679.5	3533.5	2022.0	4581.0
CO_N (mg Nm^{-3})	4570.2	2953.9	10808.8	1765.5	1626.3	2851.7	3414.7	2834.8	2181.5	2920.0	1706.3	4223.8
SO_2 (mg m^{-3})	0	17.5	0	27.5	0	0	0	0	0	22.5	4.0	0
SO_{2N} (mg Nm^{-3})	0	15.6	0	23.5	0	0	0	0	0	18.6	3.4	0
No_x (mg m^{-3})	406.5	305.0	263.3	226.5	429.0	312.0	383.5	215.0	144.0	208.5	292.5	331.0
NO_{xN} (mg Nm^{-3})	346.2	271.5	197.6	193.8	403.9	276.0	333.8	190.0	117.2	172.3	246.8	305.2

Table 8: Comparison of the gas and mass flow rate values related to sunflower stalks measured using three different grates with the limit values in the guidelines given in appendix 7 (for gases) and appendix 2 (for mass flow rates) by RPAP

		CHG					
Parameters	Limit value of regulation	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form *BB
CO_N	250 mg Nm^{-3}	5060.8	9119.0	12738.7	10572.1	7575.8	5525.2
L_{CO}	1000 kg h^{-1}	2.812	2.986	6.525	3.074	2.775	1.909
SO_{2N}	2000 mg Nm^{-3}	0	21.5	119.8	0	0	0
L_{SO2}	60 kg h^{-1}	0	0.007	0.057	0	0	0
NO_{xN}	(*) mg Nm^{-3}	442.8	213.6	313.6	167.1	110.3	137.9
L_{NOx}	40 kg h^{-1}	0.246	0.070	0.161	0.049	0.040	0.050

Table 8: Continued

		OHG							MHG				
Parameters	Limit value of regulation	1. form FB	1. form BB	2. form FB	2. form BB	2. form *BB	3. form BB	3. form *BB	1. form BB	2. form BB	2. form *BB	3. form BB	3.h form *BB
CO_N	250 mg Nm^{-3}	4570.2	2953.9	10808.8	1765.5	1626.3	2851.7	3414.7	2834.8	2181.5	2920.0	1706.3	4223.8
L_{CO}	1000 kg h^{-1}	2.975	1.649	4.978	0.832	0.771	1.485	2.090	1.478	1.061	1.552	0.830	2.111
SO_{2N}	2000 mg Nm^{-3}	0	15.6	0	23.5	0	0	0	0	0	18.6	3.4	0
L_{SO2}	60 kg h^{-1}	0	0.009	0	0.012	0	0	0	0	0	0.010	0.001	0
NO_{xN}	(*) mg Nm^{-3}	346.2	271.5	197.6	193.8	403.9	276.0	333.8	190.0	117.2	172.3	246.8	305.2
L_{NOx}	40 kg h^{-1}	0.225	0.152	0.091	0.091	0.192	0.144	0.204	0.099	0.057	0.092	0.120	0.153

(*) : It has not been given limit value for NO_x emissions at boilers under the 50 MW heating power

calculated, it was determined that the results were much above the values in the guidelines, being at insignificant quantities. This area and low chimney gas flow rate of the boiler used in the study. When the SO_2 quantities in the tables were examined, no SO_2 gas was detected in general, other than a few SO_2 measurements which might be considered as low. Since the SO_2 concentration values measured were much below the limit value given in the guidelines, the mass flow rates calculated were also insignificant. No_x concentration values measured in

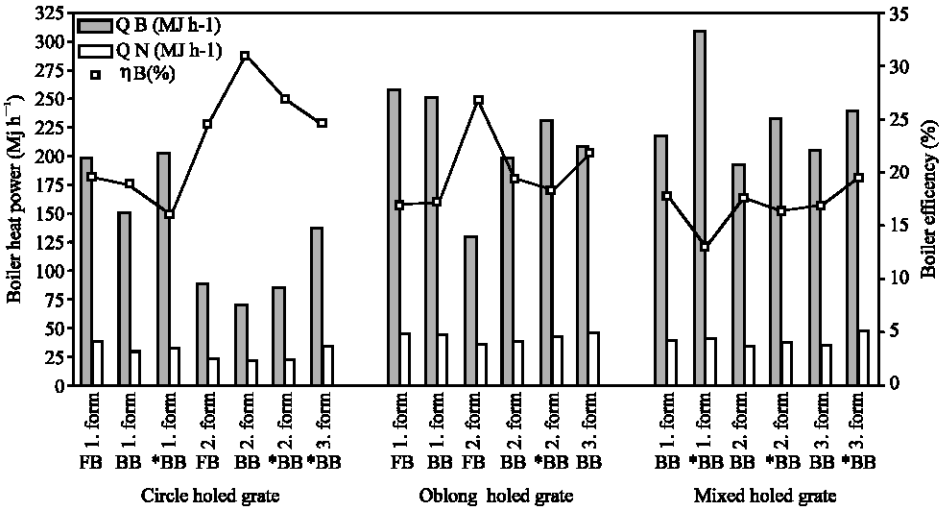

Fig. 2: Boiler used and combustion heat power of wheat straw in three different grates and boiler efficiency values

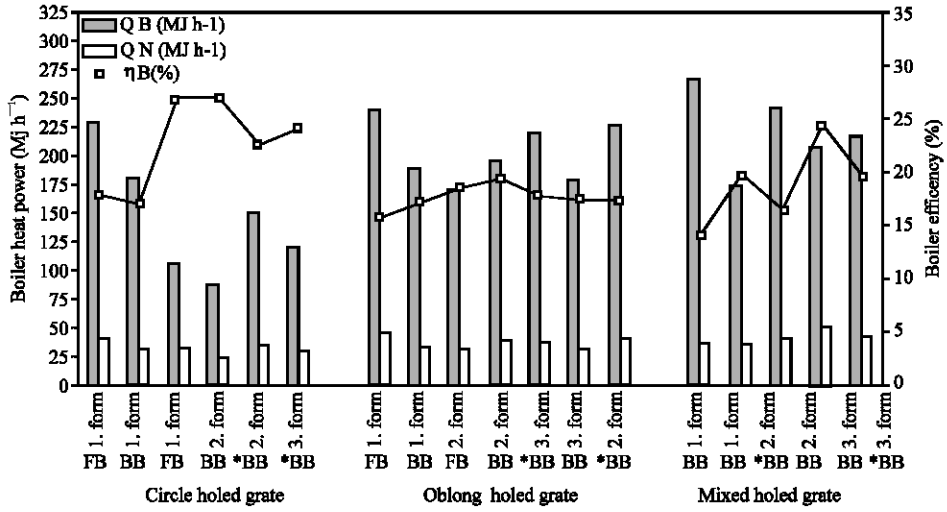

Fig. 3: Boiler used and combustion heat power of sunflower stalks in three different grates and boiler efficiency values

chimney gas were found as 96.0 mg Nm^{-3} (min) and 442.8 mg Nm^{-3} (max.). No limit value was given in the guidelines for NO_x concentration; however, the results obtained in the experiments were determined to be insignificant when compared with the mass flow rate value of NO_x.

The values of boiler used heat power (Q_N), boiler burning heat power (Q_B) and boiler combustion efficiency (η_B) obtained in the case of burning of wheat straw in three different grate types, three different burning methods and three different forms are given in Fig. 2.

The values of boiler used power, boiler combustion heat power and boiler combustion efficiency obtained in the case of burning of sunflower stalks in three different grate types, by three different burning methods and three different forms are given in Fig. 3.

The following results were obtained in the burning experiments with wheat and sunflower stalks under the burning conditions consisting of three different forms, three grate types and three different burning conditions FB, BB and *BB.

- Boiler water temperatures reached the highest values in the experiments made with the 1. forms of wheat straw and sunflower stalks. The fact that the particle dimensions of stalks in this form were greater and the air space in the stalks was in higher rates increased the boiler water temperature due to the easier generation of burning air into the fuel and owing to the improved burning quality.
- The highest boiler efficiencies were found in the FB conditions of CHG with the values of 25.7 and 25.1%

in the 1. form burning experiments with wheat straw and sunflower stalks, respectively. The boiler used heat values corresponding to these efficiencies were 51.1 and 57.3 MJ h^{-1}, respectively. The highest boiler burning powers in this form of fuels were obtained under BB and *BB conditions in MHG with 308.5 and 266.4 MJ h^{-1}, respectively. However, the fact that the boiler used heat powers under these conditions were not high, reduced the boiler efficiencies to the levels of 16.8 and 17.0%, respectively.

- The highest boiler efficiencies in the 2. forms of fuels were reached under FB conditions of CHG and these efficiencies were found as 35.8 and 30.5% for wheat straw and sunflower stalks, respectively. Boiler used heat power for these efficiencies was 32.5 MJ h^{-1}.
- The highest boiler efficiencies in the 2. form trials of wheat straw and sunflower stalks were found as 32.9 and 30.9% for *BB condition of MHG and *BB condition of CHG, respectively.
- CO emission under FB and BB conditions was low with the three types of grates in the chimney gas measurements of wheat straw and sunflower stalks in the 1. form, except BB and *BB conditions of CHG.
- As to the 2. and 3. forms of fuels, CO quantity was found high despite high excess air coefficient under FB conditions in CHG and OHG. This indicates the discharge of excess air entering the combustion chamber without being used in combustion. The high coefficient of excess air increased the emission of CO_2, instead of reducing it. Therefore, extremely high excess air ratios should be avoided in the burning of stalks. In general, no SO_2 was detected in the emission measurement, except few numbers of SO_2 emission which could be considered as low, since the sulphur contents of fuels were very low. In all measurements, SO_2 gases in chimney gas were found very lower than the limit value envisaged by the regulations (2000 mg Nm^{-3}), while CO gases were very higher than the limit values (250 mg Nm^{-3}). NO_x quantities were determined between the minimum and maximum values of 96.0 and 442.8 mg Nm^{-3}, respectively, in all measurements. No limit value was given for NO_x concentration in RPAP. A good mixture of fuel with burning air may lower the CO value to the suitable conditions.
- Although CO gas concentrations in the chimney gas measurements were found high, the mass flow rates of gases were found very lower than the limit value (1000 kg h^{-1}) given in RPAP, thus in insignificant quantities. The reason for this was the low chimney gas flow rates of the heating system used in the study.
- The highest efficiency in the burning of wheat straw was reached in FB conditions of CHG in the 2. form with 35.8%. The highest efficiency in the burning of sunflower stalk was reached in *BB of CHG in the 3. form with 30.9%. It is possible to say that these burning types are the most suitable burning methods in the evaluation made with respect to yield.

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