

DEW POINT OF THE FLUE GAS OF BOILERS CO-FIRING BIOMASS WITH COAL

Szymon Ciukaj*, Marek Pronobis

Silesian University of Technology (SUT), Institute of Power Engineering and Turbomachinery,
Konarskiego 20, 44-101 Gliwice, Poland

The paper deals with the impact of co-firing biomass with coal in boilers on the dew point of the flue gas. Co-firing of biomass may have twofold implications on corrosion and fouling, which are the processes that determine the lowest acceptable flue gas outlet temperature and as a result, boiler efficiency. Both phenomena may be reduced by co-firing of usually low sulphur biomasses or enhanced due to increased moisture content of biomass leading to increased water dew point. The present study concerns the problem of low-temperature corrosion in utility boilers. The paper gives (in the form of diagrams and equations) a relationship between water dew point and moisture content of fuel mixture when co-firing coal and various biomasses. The regression analysis shows that despite significant differences in the characteristics of coals and these of additional fuels, which are planned for co-firing in large-scale power boilers, the water dew point can be described by a function given with the accuracy, which shall be satisfactory for engineering purposes. The discussion of the properties of biofuels indicates that the acid dew point surplus over the water dew point ($\Delta t_r = t_r - t_{wr}$) is not likely to exceed 10 K when co-firing biomass. The concluding remarks give recommendations for the appropriate operation of boilers in order to reduce risks associated with biomass co-combustion.

Keywords: acid-dew point, low-temperature corrosion, biomass, co-firing

1. INTRODUCTION

The main factor limiting the reduction of flue gas exit temperature in power boilers is the necessity of preventing dew condensation on “cold end” elements (air heaters, electrostatic precipitators and connecting ducts). Particularly endangered are the rotary air heaters (RAH) where the liquid phase emerging on the surfaces of heating elements results in severe fouling and corrosion. Both phenomena are associated with condensation of vapours from the flue gas. When firing sulphur-containing fuels, sulphur partly oxidises to form SO_3 , which after having reacted with water vapour present in the flue gas forms vapours of sulphuric acid. When cooled, the mixture of H_2SO_4 and H_2O condensates. The dew point temperature and composition of liquid mixture are determined by the partial pressures of water and sulphuric acid vapours in the flue gas. By lowering the fraction of H_2SO_4 , the dew point drops and reaches, by zero concentration of the acid, the water dew point t_{wr} .

Particular emphasis on combustion of renewable fuels for CO_2 emission reduction and simultaneous demand for thermal utilisation of wastes guarantee that co-firing of such fuels is now and will be in the future unavoidable in the ration of large power boilers. The share of energy to be generated from renewable sources is in Poland established in Decree of the Minister of Economy (2012) which adapt Poland’s national law according to respective EU Directives (2001) and (2003).

*Corresponding author, e-mail: szymon.ciukaj@polsl.pl

The co-firing of biomass with coal in boilers may have twofold implications on low-temperature corrosion and fouling processes. Both phenomena may be reduced by co-firing of usually low sulphur biomasses or enhanced due to increased moisture content of biomass and increased water dew point.

Most biomass fuels, which are now burnt for power generation, are characterised by much lower sulphur content than those found in coal. This leads to an indisputable positive effect on SO_x emissions. Nevertheless, a similar positive effect may not be directly associated with corrosion and fouling hazards.

The EU Decree (2003) in its Article 4(3) requests a gradual increase of biomass share originating from energy crops and agricultural residues. Thus, the unavoidable broadening of biomass variety beyond the most used wood, whose co-firing characteristics are relatively advantageous in terms of low *S* and *Cl* contents and high ash fusion temperatures, is expected.

The lowest acceptable flue gas outlet temperature $t_{fg_out}^{min}$ has to be set on the level avoiding condensation. By increasing dew point the $t_{fg_out}^{min}$ has to be also increased to prevent condensation what, in consequence, decreases boiler efficiency.

It has to be mentioned that the necessary elevation of $t_{fg_out}^{min}$ exceeds by more than two times the increase of t_r . A respective example is presented in Fig. 1, which has been calculated according to (Pronobis, 2002), assuming that the last heating surface is a RAH with air inlet temperature 20 °C.

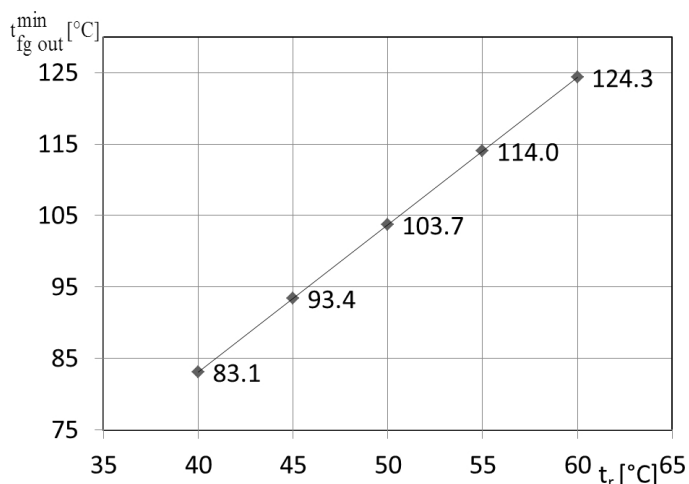


Fig. 1. Lowest acceptable flue gas outlet temperature as a function of the dew point

2. EXPERIMENTAL

2.1. Direct measurement technique

Although direct estimation of the dew point may be carried out by means of various methods (Derichs et al., 1991), the conductivity method is usually used for boiler flue gases. The method is based upon detection of rapid conductivity rise between two electrodes when condensation occurs. In parallel, the temperature of the surface being exposed to condensation is measured. The probes are made out of glass or ceramics in which electrodes and thermocouples are embedded. When measurement takes place, a controlled drop of probe temperature is induced by a cooling agent (compressed air) until conductivity steeply rises.

It is likely that new biomasses such as DDGS, cereal straw, variety of grass, meat and bone meal and sewage sludge are to be used for power generation. The following considerations concerning co-firing are based on 2 coals highly diverse in terms of moisture content and calorific value in combination with 7 biomasses with strongly different properties - Table 1. The data for coals A and B, BCT, WC and RG are obtained from analyses carried out at Wrocław University of Technology.

2.2. Properties of coal and biomass for the corrosion studies

When a relatively low calorific value biomass replaces coal, significant amounts of moisture or sometimes sulphur, are introduced into the furnace. An estimation of this phenomenon in terms of moisture and sulphur fed with biomass (when biomass displaces coal by energy input) is calculated according to the following equation (for sulphur):

$$S_{equiv} = (Q_{iC}^r / Q_{iBio}^r) / (S_{Bio}^r / S_C^r) \left[\frac{\text{kg S from biomass}}{\text{kg S from coal}} \right] \quad (1)$$

Calculation results are grouped in Table 2 and values exceeding 1 are typed in bold. Those values indicate co-firing cases when lower-than-coal calorific value biomass contributes to increased streams of moisture and sulphur being fed to the furnace. It means, that the emission in mg/m^3_n or ppm will also increase - see values of S_{equiv} in the last row of Table 2.

The results show that biomass co-firing may either decrease sulphur stream fed to the furnace, which is the case for majority of vegetable biomasses, or increase it when co-firing sewage sludge, rape or DDGS.

It should be noted that when co-firing raw sewage sludge and other wet biomasses, a multiplied water stream fed into the furnace will result in a significantly increased water dew point.

Table 1. Properties of coals and additional fuels

	Unit	Coal		Additional fuels						
		A	B	BCT	WW (Wandrasz et al., 2006)	DSS (Wandrasz et al., 2000)	WC	RG	DDGS (IChPC, 2007)	WSS (Nowaczyk, 2007)
	kJ/kg	17878	21034	6295	14460	10900	9706	17502	18569	1000
W_i^r	%	19.4	9.70	52.42	20.00	10.34	45.65	5.25	6.90	77.50
S^r	%	0.70	0.66	0.11	0.10	1.83	0.177	0.678	0.72	0.29

Table 2. Properties of additional fuels calculated as energy equivalent of coal (eq. 1)

	Additional fuels													
	BCT		WW		DSS		WC		RG		DDGS		WSS	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Q_{iC}^r / Q_{iBio}^r	2.84	3.34	1.23	1.45	1.64	1.93	1.84	2.16	1.02	1.20	0.96	1.13	17.87	21.03
W_{equiv}	7.67	18.1	1.26	3.0	0.87	2.06	4.32	10.16	0.27	0.64	0.34	0.80	71.38	167.9
S_{equiv}	0.44	0.55	0.17	0.22	4.28	5.35	0.46	0.57	0.98	1.23	0.98	1.23	7.40	9.24

For pure coal combustion and co-firing with biomass (biomass percentages $Z_D = 2.0; 5.0; 10, 20$ and 50% on an energy base), the mass percent, Y_D , proximate and elemental analysis as well as concentration of H_2O in the flue gas was calculated based on properties of fuels shown in Table 1. For

WSS the 50% share was omitted, because fuel of such a composition cannot be combusted autothermally. Additionally, for the sewage sludge share $Z_D = 1.0\%$ was investigated due to the fact that according to EU Directive (2000) this is an upper limit allowed for co-firing. Below the limit the same emission standards are to be kept as for basic fuel e.g. coal.

2.3. Calculation of water dew point

In order to estimate the influence of co-firing fuels listed in Table 1 on the water dew point level of the flue gas, calculations were carried out and the results are presented in Figs. 2 and 3. A water vapour saturation temperature for a given partial pressure was calculated from Antoine equation (Irvine and Lilley, 1980). It was assumed that flue gas composition corresponds to that, which is typically observed for boiler outlet, e.g. $O_2 = 4.0\%$.

The results shown in the figures indicate that when changing coal properties, the variations in dew point t_{wr} are limited to 4 K. An addition of biomass practically always increases the dew point. Usually, when realistic biomass amounts are co-fired, the dew point increase does not exceed 8 K. Only when co-firing wet sewage sludge, t_{wr} is shifted much more, when it is accompanied by lower sulphuric acid concentrations being the result of its dilution in a huge flue gas stream. There are biomasses (e.g. DDGS) which practically do not increase t_{wr} , and where sulphur content in the fuel in comparison to that in coal does not decrease.

Based on the data presented in Figs. 2 and 3 a dependence $t_{wr} = f(W_{t\Sigma}^r)$ was elaborated and shown in Fig. 4. The calculations were carried out using the polynomial regression model with assumed confidence level 95 %. The diagram depicts that despite significant differences in the characteristics of coal and these of additional fuels, the water dew point can be described by a function given with the accuracy, which shall be satisfactory for engineering purposes.

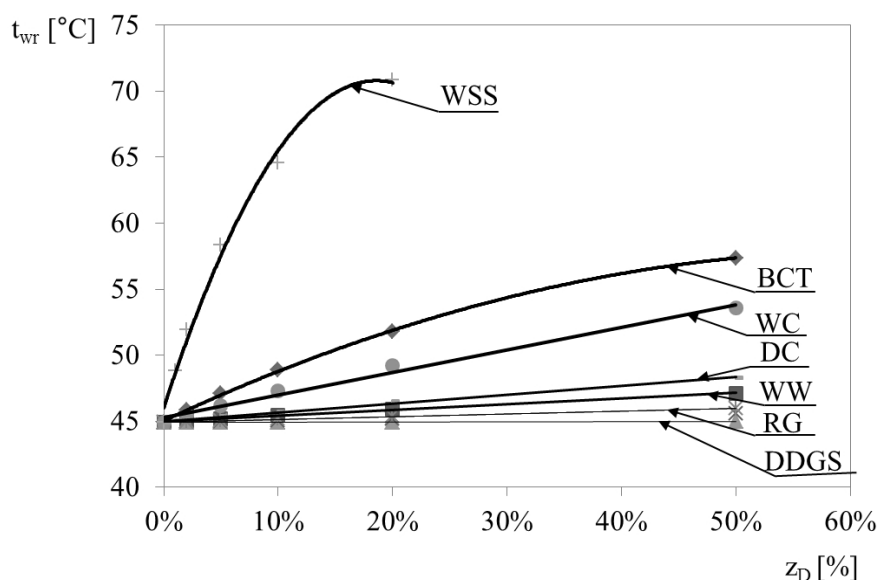


Fig. 2. Calculated water dew points while co-firing biomasses with coal A

It can be seen that a better fitting is obtained for higher than for lower moisture content. It is clear that the total moisture content in the flue gas directly determines the level of the dew point temperature. However, the amount of moisture is not only dependent on water content in the fuel but also on the amount of hydrogen in the fuel and moisture in the air led to the combustion. For the accurate water dew point determination the total moisture content in the flue gas should be measured. In case of utility

boilers, calculations based on the moisture content in the fuel give a satisfactory accuracy of determining the water dew point.

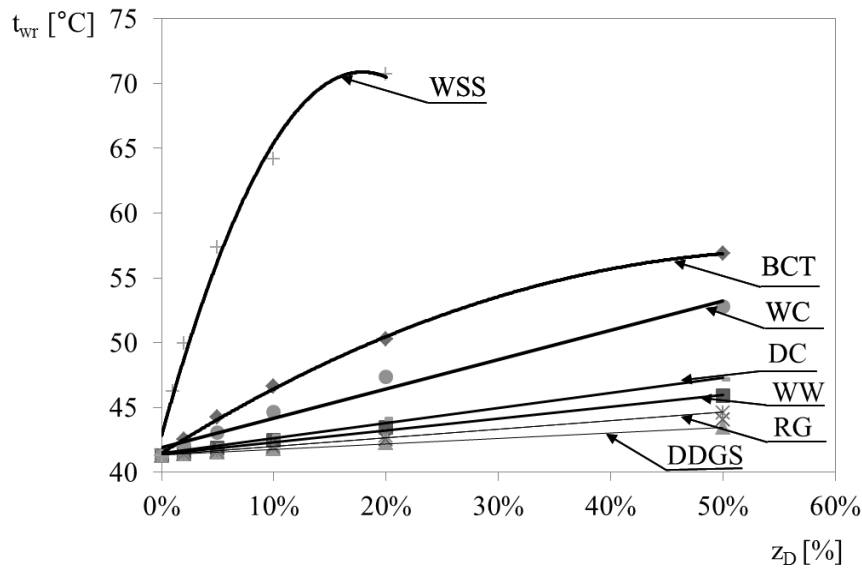


Fig. 3. Calculated water dew points while co-firing biomasses with coal B

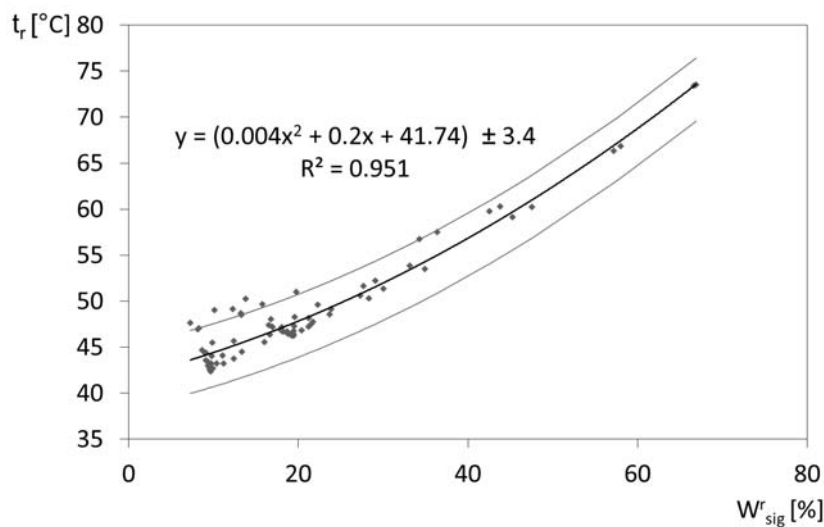


Fig. 4. A dependence of water dew point versus moisture content of fuel mixture when co-firing coal and biomass (the lines depict borders of confidence intervals)

2.4. Acid dew point

For estimation of an acid dew point for co-firing, the investigations reported in (Pronobis, 2002) were used. The results of these investigations are shown in Fig. 5, which depicts the differences between the measured acid dew point and the calculated water dew point $\Delta t_r = t_r - t_{wr}$ in relation to sulphur content in coal.

Fig. 5 shows that the measured temperatures of acid dew points at the boiler outlet (downstream air heater) were only slightly higher than those calculated for water dew points. The difference between t_r and t_{wr} do not exceed 10 K. Chemical analyses of the fly ashes proved that for all the cases the alkali compounds were present in the quantities sufficient for neutralisation of sulphuric acid in the flue gas.

The sulphates present in the ash (0.5-2.2 %) might be the products of this neutralisation. It was even more evident when analysing the ratio of free CaO to H₂SO₄, which was an order higher than the stoichiometric one.

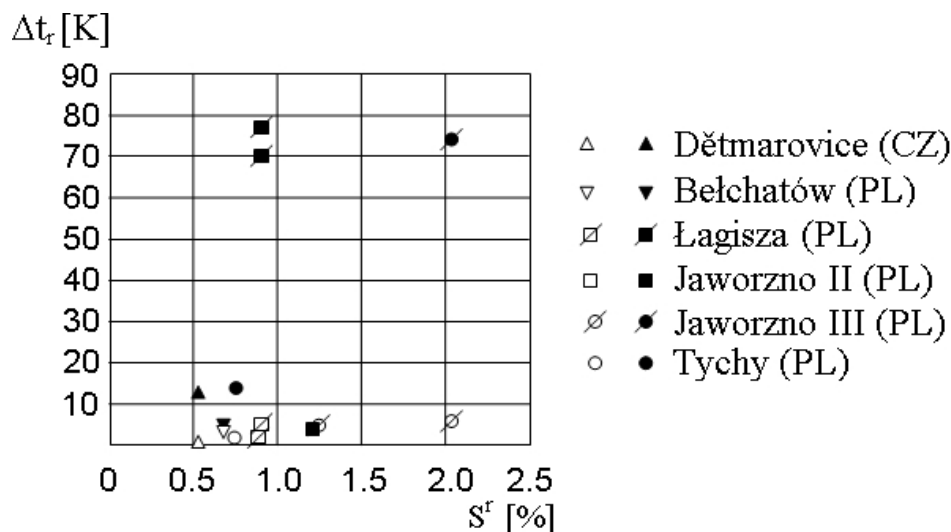


Fig. 5. The difference between acid and water dew points in the flue gas of boilers in various Polish and Czech power plants; dark marks denote measurements taken upstream air heater

The investigations carried out upstream the RAH point out that t_r in that region may be significantly higher than downstream air heater. This proves that conditions in RAH promote self-desulphurisation of the flue gas. Nevertheless, upstream RAH the acid dew point was often only slightly higher than the water dew point.

The phenomenon observed proves that in modern pulverised-fuel, low-emission boilers, the risk of corrosion of flue gas ducts is greatly reduced. Consequently, a low level of acid dew point allows for lower temperatures of the flue gases to be used at boiler outlet.

3. DISCUSSION

As presented earlier, co-firing of some sorts of biomasses contributes to increased streams of sulphur being fed to the furnace. It does not mean that the sulphur percentage in the fuel mix must also increase. As an example the WSS can be pointed out. Its co-firing increases the sulphur stream many times, decreasing simultaneously S^r_{Σ} – Figs. 2 and 3. Even in cases when an increase of S^r_{Σ} is observed (DSS, DDGS), the resulting values of sulphur content do not exceed in severe degree the S^r values for Polish coals.

Wet woody biomasses, although they increase t_{wr} when co-fired, do not contribute to significant differences between acid and water dew points due to their low sulphur content. In such circumstances, the acid dew point may even be lower than that noted for coal. Additionally, the wood ash consists mainly of CaO (Pronobis, 2002) improving the flue gas desulphurisation.

The only problematic fuels are from this point of view DSS and WSS. The sulphur contents in other biomasses listed in Table 1 do not differ significantly from those noted for Polish coals. Therefore, it is justified to assume that the acid dew point surplus over the water dew point is not likely to exceed 10 K when co-firing biomass.

4. CONCLUDING REMARKS

- A significantly higher water dew point is noted for co-firing of wet biomass with coal. This can be a particularly problematic issue for boilers not equipped with steam air heaters. Therefore, it is recommended that before a decision is taken on co-firing of wet and high-sulphur biomasses, an appropriate installation preventing a temperature drop at the air heater inlet is built.
- It is recommended to avoid high moisture content coals when co-firing biomass.
- An additional threat shall be associated with the presence of substances catalysing formation of SO_3 . They can be fed into a boiler when heavy oils are used for start-up or flame support. These oils contain V_2O_5 , which then deposits on heating surfaces and contributes to the increase of difference between water and acid dew points.
- The above presented considerations may lead to the conclusion that biomass co-firing can either limit low-temperature corrosion due to usually low sulphur content of biomasses, or increase it (due to an increase in water dew point level when wet biomass is used, or due to increased sulphur streams fed into boiler with high sulphur biomasses). Therefore, for estimation of actual corrosion risk it is mandatory to carry out dew point measurements for given operating conditions.
- From last row of Table 2 it can be seen that the values of S_{equiv} are in most cases lower than 1 - only the co-firing of DSS and WSS leads to increased SO_2 emissions.

SYMBOLS

A^r	ash content, %
Q_i^r	lower heating value, kJ/kg
S_{equiv}	equivalent sulphur content (Equation 1)
$t_{fg_out}^{min}$	lowest acceptable flue gas outlet temperature, °C
t_r	acid dew point of the flue gas, °C
t_{wr}	water dew point of the flue gas, °C
W_t^r	moisture content, %
W_{equiv}	equivalent moisture of biomass (Equation 1)
$[H_2O]$	concentration of H_2O in the flue gas, %
YD	biomass co-firing percentage (mass base), %
ZD	biomass co-firing percentage (energy base), %

Abbreviations

<i>BCT</i>	biomass from coniferous trees
<i>DDGS</i>	dried distillers grains with solubles
<i>DSS</i>	dry sewage sludge
<i>RAH</i>	rotary air heater
<i>RG</i>	rape grains
<i>WC</i>	wood chips
<i>WSS</i>	wet sewage sludge
<i>WW</i>	waste wood

Subscripts

<i>C</i>	coal
<i>Bio</i>	biomass

Superscripts

r as-received state

Greek symbols

Σ mixed fuel

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