Assignment 1

COMPUTATION OF POLLUTANT EMISSION FROM FOSSIL FUEL FIRED ELECTRIC UTILITIES BOILERS

Computation of flue gas emission from stationary combustion sources

The main components of the flue gas produced due to fossil fuel burning in power plant boilers are computed via the following technique. Under burning a combination of various fuels, the calculations of fuel consumption and pollutant emissions are separately made for every fuel based on the fuel fraction in the burned mixture, the results summed.

– **Natural fuel rate/consumption under nominal loading of all the power plant boilers, kg/s**:

$$B = n\frac{41.868}{3.6Q_{LHV}} \cdot \left(b_E \cdot N_E^U + b_H \cdot Q_H^U\right), \tag{1.1}$$

или

$$B = \frac{41.868}{3.6Q_L^w} \cdot \left(b_E \cdot N_E^{PP} + b_H \cdot Q_H^{PP}\right), \tag{1.2}$$

where n – number of generating units;

41.868, MJ/kg – net calorific value (NCV) or lower heating value (LHV) of oil equivalent; according to Dulong’s formula, LHV=HHV-50.6**H**%-5.85**M**%-0.191**O**%) [kcal/kg] or GCV-0.212**H**%-0.0245**M**%-0.0008**O**%) [kJ/kg], where M is for Moisture, H is for Hydrogen, O is for Oxygen (As Received).

Q_{LHV}, MJ/kg –LHV (NCV) of the fuel burnt;

b_E, ktoe/kWh – specific fuel oil equivalent consumption for electricity output;

b_H, ktoe/Gcal – specific fuel oil equivalent consumption for heat output;

N_E^U, MW – nominal unit electricity output;

Q_H^U, Gcal – nominal unit heat output;

N_E^U, MW – nominal power plant electricity output;

Q_H^U, Gcal – nominal power plant heat output.

In case the plant burns mixture of fuels, the natural fuel consumption is calculated for each fuel (fuel$_i$)

$$B_i = \frac{Fuel_i\,content\%}{100} \cdot n \cdot \frac{41.868}{3.6Q_{LHVfuel_i}} \cdot \left(b_E \cdot N_E^U + b_H \cdot Q_H^U\right), \tag{1.1a}$$

– **Total fly ash and noncombustible volatiles emission with flue gas (from solid fuel burning boilers), g/s:**

$$M_{\mathrm{A}} = 10 \cdot B \cdot \left(A^{ar} + q_4\right) \cdot \alpha_{EF} \cdot \left(1 - \eta_{FAC}\right), \tag{1.3}$$

where A^{ar}, % - as-received fuel ash;

q_4, % - carbon loss (table 1.1);

α_{EF} – entrainment factor (table 1.1);

η_{FAC} – fly ash collector efficiency, 0.96…0.999 – for electrostatic precipitators;

0.92…0.96 – for wet scrubbers; 0.82…0.9 – for inertial fly ash collectors (multi-cyclones).

– **Total soot emission (from fuel oil burning boilers), g/s**:

$$M_{\mathrm{C}} = 0.01 \cdot B \cdot q_4 \cdot \frac{Q_{LHV}}{32.68} \cdot \left(1 - \nu_{OAC}\right), \tag{1.3'}$$

where ν_{OAC} – fuel oil ash fraction captured by fly ash collectors, $\nu_3 = 0.4$;
32.68, MJ/kg – carbon calorific value.

Table 1.1 – Values of q_4 and α_{EF}

Fuel and furnace type	q_4, %	α_{EF}
coal combustion in dry bottom furnaces	2	0.95
coal combustion in slag-tap furnaces	1.5	0.7
double-shaft furnaces	1.0	0.6
horizontal cyclone furnaces	0.5	0.15
lignite combustion in dry bottom furnaces	0.5	0.9
lignite combustion in slag-tap furnaces	0.4	0.6
fuel oil combustion	0.02	0.06

– **Total sulfur dioxide (SOx) emission with flue gas g/s**:

$$M_{\mathrm{SO_2}} = 20 \cdot S^{ar} \cdot B \cdot \left(1 - \eta'_{\mathrm{SO_2}}\right) \cdot \left(1 - \eta''_{\mathrm{SO_2}}\right) \cdot \left(1 - \eta_{\mathrm{SO_2}}\right), \tag{1.4}$$

где S^{ar}, % - as-received fuel sulfur;

η_{SO2} – flue gas desulfurization efficiency (η_{SO2}=0,8…0,86 – for state-of-the-art desulfurization systems);

$\eta'_{\mathrm{SO_2}}$ – volatile sulfur fraction bonded by fly ash in the boiler (table 1.2);

$\eta''_{\mathrm{SO_2}}$ – sulfur dioxide fraction captured in wet scrubbers along with fly ash; it is determined as function of specific sulfur content in as-received fuel, S_s=S^{ar}[%]/Q_{LHV} , in fig. 1.1.

Table 1.2 – Indicative values of $\eta'_{\mathrm{SO_2}}$

Fuel	$\eta'_{\mathrm{SO_2}}$
Peat	0.15
Inferior shales	0.5
Ukrainian coal from Volyn coal field	
• for dry-bottom furnaces	0.5
• for slag-tap furnaces	0.2
Ukrainian coal from Donetsk coal field	
• for dry-bottom furnaces	0.2
• for slag-tap furnaces	0.05
Coals from other coal field	0.1
Fuel oil	0.02
Gas	0.0

Sulfur dioxide fraction captured in dry cyclone ash collectors and electrostatic precipitators is accepted equal to zero.

– **Total nitrogen oxide (NOx) emission with flue gas, g/s**:

$$M_{\mathrm{NO}x} = 0.034 \cdot \beta_1 \cdot K \cdot B \cdot Q_{LHV} \cdot (1 - 10\beta_2) \cdot (1 - \eta_{\mathrm{NO}x}), \quad (1.5)$$

where η_{NOx} – nitrogen oxides inhibition system efficiency, accepted equal to $\eta_{\mathrm{NOx}} = 0.4$ – for solid fuel combustion, and $\eta_{\mathrm{NOx}} = 0.8$ – for fuel oil and natural gas combustion;

β_1 – correction factor (table 1.3);

β_2 – fuel-type factor, $\beta_2 = 0.01$ – for solid fuel combustion, and $\beta_2 = 0.02$ – for fuel oil and natural gas combustion;

K – parameter allowing for boiler evaporative efficiency (for steam boilers) or thermal capacity (for hot water boilers), it is calculated as:

- for steam boilers with steam rate $D_{SG} > 70$ t/h

$$K = \frac{12 \cdot D_{SG}}{200 + D_{SG}},$$

where $D_{\text{ПГ}}$, t/h – steam generator capacity;

- for steam boilers with steam rate $D_{SG} < 70$ t/h

$$K = \frac{3.5 \cdot D_{SG}}{70},$$

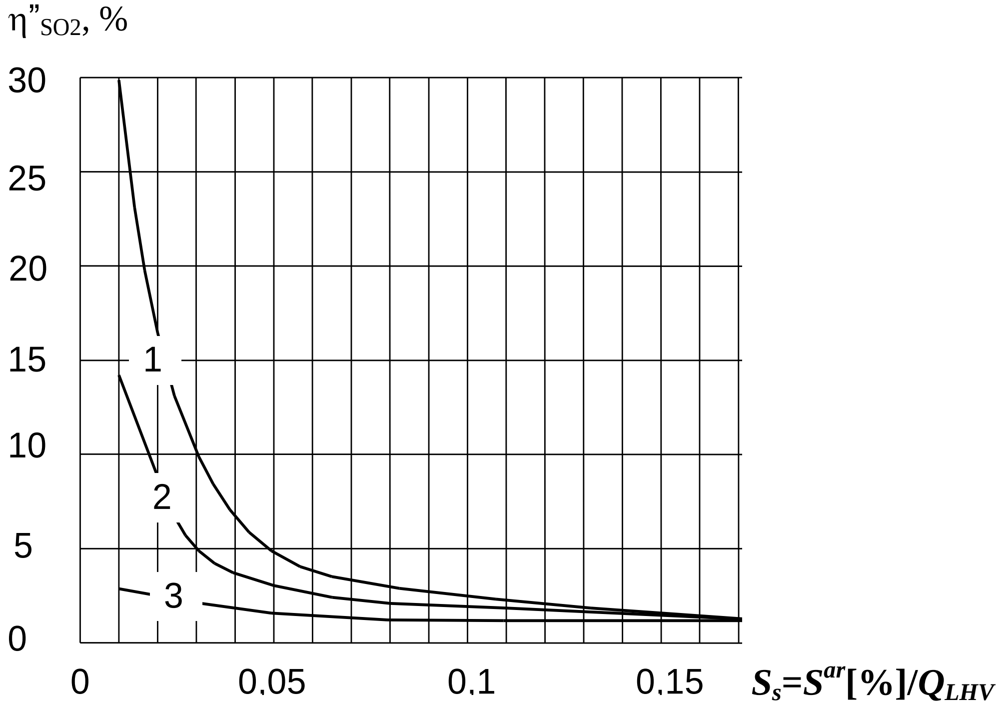
- for steam boilers with steam rate $D_{SG} < 30$ t/h

$$K = 0.01 \cdot \sqrt{D_{SG}} + 0.1,$$

- for hot water boilers

$$K = \frac{2.5 \cdot Q_{WB}}{20 + Q_{WB}},$$

where Q_{WB}, GJ/H – the boiler thermal capacity.



1 – alkaline hardness is 10 mg-eq/dm^3; 2 – 5 mg-eq/dm^3; 3 – 0 mg-eq/dm^3

Figure 1.1 – Efficiency of sulfur dioxide collection in wet scrubbers versus specific sulfur content in as-received fuel and alkalinity of the spray water

Table 1.3 – Correction factor β_1

Fuel	β_1	
Natural gas Fuel oil	0.85 0.8	
Solid fuel	dry-bottom furnaces	slag-tap furnaces
Lignite Char coal	0.6 1.0	0.8 1.4

– **Total carbon monoxide emission with flue gas, g/s**:

$$M_{\text{CO}} = C_{\text{CO}} \cdot B \cdot \left(1 - \frac{q_4}{100}\right), \tag{1.6}$$

where C_{CO}, kg/t (kg/(1000 m^3)) – carbon monoxide ratio under burning of solid, liquid, or gaseous fuel:

$$C_{\text{CO}} = 0.01 \cdot q_3 \frac{R \cdot Q_{LHV} \cdot \gamma_{\text{CO}}}{Q_{\text{CO}} \cdot 10^{-3}}, \tag{1.7}$$

where q_3, %, –heat loss due to chemically incomplete combustion (table 1.4);

R – coefficient allowing for chemically incomplete combustion heat loss fraction due to carbon oxide presence in the flue gas (table 1.4);

γ_{CO}, kg/m^3 – specific gravity of carbon oxide under standard conditions, 1.25 kg/m^3;

Q_{CO}, MJ/m^3 – carbon oxide calorific value, 12.65 MJ/m^3.

Table 1.4 – Indicative values of q_3 and R

Fuel	q_3, %	R
Anthracite	0.5 -1.0	1.0
Char coals	0.5 -1.0	1.0
Lignites	0.5 -1.0	1.0
Peat	0.5	1.0
Fuel oil	0.15	0.65
Natural gas	0.15	0.5

– **Total vanadium oxide emission for liquid fuels (calculated as V_2O_5), g/s**:

$$M_{V_2O_5} = 0.001 \cdot G_{V_2O_5} \cdot B \cdot (1 - \eta_\alpha) \cdot \left(1 - \frac{\eta_{V_2O_5}}{100}\right), \tag{1.8}$$

where G_{V2O5}, g/t – vanadium oxide content in 1 t of fuel oil;

η_α - vanadium oxide settlement on the boiler heating surface (table. 1.5);

$\eta_{V_2O_5}$, %– flue gas fuel oil ash cleaning efficiency in ash collectors.

Vanadium oxide content in 1 t of fuel oil is assessed with the following approximate formula, g/t:

$$G_{V2O5} = 2222 \cdot A^{ar}, \tag{1.9}$$

where 2222 – empirical coefficient;

A^{ar}, % - fuel oil ash (as-received).

In the as-received sulfur content in the fuel oil exceeds 0.4%, S>0.4%,

$$G_{V2O5}=95.4 \cdot S^{ar}-31.6 \quad (1.10)$$

Efficiency of flue gas cleaning from fuel oil ash (calculated as vanadium oxide) in special multi-cyclone collectors is calculated via empirical formula, %

$$\eta_{V_2O_5}=0.076 \cdot (\eta_{FAC})^{1.85}-2.32 \cdot \eta_{FAC}, \quad (1.11)$$

where 0.076 and 2.32 - empirical coefficients;

1.85 - empirical index;

η_{FAC}, % - overall collection efficiency for particles resulted from fuel oil burning in thermal plant boilers, $65\% < \eta_{FAC} < 85\%$.

For fuel oil cofiring with coal

$$\eta_{V_2O_5}=k \cdot \eta_{FAC}, \quad (1.12)$$

where *k* is equal to 0.6 – for electrostatic precipitator, 0.5 – for wet scrubbers, 0.3 – for multi-cyclones).

Table 1.5 – η_α values

Fuel	Value
For boilers with reheat superheaters (heating surface cleaning in shut-down state)	0.07
For boilers without reheat superheaters (heating surface cleaning in shut-down state)	0.05
For other boilers	0

Carbon dioxide M_{CO2} and water vapour M_{HO2} emissions with flue gas under solid and liquid fuel firing, kg/s:

$$M_{CO_2}=3.67 \cdot \frac{\%C^{ar}}{100} \cdot B \cdot \left(1-\frac{q_3}{100}\right) \cdot \left(1-\frac{q_4}{100}\right),$$

$$M_{H_2O}=\left(9 \cdot \frac{\%H^{ar}}{100}+\frac{\%W^{ar}}{100}\right) \cdot B \cdot \left(1-\frac{q_3}{100}\right) \cdot \left(1-\frac{q_4}{100}\right),$$

where 3.67, kgCO_2/kg of fuel – carbon dioxide volume under complete firing of 1 kg of carbon;

C^{ar}, % – as-received fuel carbon;

q_3, % – heat loss due to chemically incomplete combustion (table 1.4);

q_4, % – carbon loss (table 1.1);

9, kgH_2O/kg of fuel – water vapour volume under complete firing of 1 kg of hydrogen;

H^{ar}, % – as-received fuel hydrogen;

W^{ar} – as-received fuel moisture.

Carbon dioxide M_{CO2} and water vapour M_{HO2} emissions with flue gas under gaseous fuel firing, kg/s:

$$M_{CO_2} = B_M \cdot \left(2.75 \cdot \frac{\%CH_4}{100} + 2.93 \cdot \frac{\%C_2H_6}{100} + 3 \cdot \frac{\%C_3H_8}{100} + 3.03 \cdot \frac{\%C_4H_{10}}{100} + \frac{\%CO_2}{100} \right) \cdot \left(1 - \frac{q_3}{100}\right) \cdot \left(1 - \frac{q_4}{100}\right),$$

$$M_{H_2O} = B_M \cdot \left(2.25 \cdot \frac{\%CH_4}{100} + 1.8 \cdot \frac{\%C_2H_6}{100} + 1.64 \cdot \frac{\%C_3H_8}{100} + 1.55 \cdot \frac{\%C_4H_{10}}{100} \right) \cdot \left(1 - \frac{q_3}{100}\right) \cdot \left(1 - \frac{q_4}{100}\right)$$

where B_M - natural gaseous fuel consumption, kg/s;
or

$$M_{CO_2} = 1.964 \cdot B_V \cdot \left(\frac{\%CO}{100} + \Sigma\left(m \cdot \frac{\%C_mH_n}{100} \right) + \frac{\%CO_2}{100} \right) \cdot \left(1 - \frac{q_3}{100}\right) \cdot \left(1 - \frac{q_4}{100}\right)$$

where 1.964 - carbon dioxide specific gravity, kg/m^3 of gas;

CO, C_mH_n, CO_2 – correspondingly, gaseous fuel carbon oxide, carbon dioxide, and hydrocarbons, %;

B_V - natural gaseous fuel consumption, м^3/s;

m, *n* – number of carbon and hydrogen atoms in the hydrocarbons, correspondingly.

Table 1.6 – Components of various hard coals (as received)

Component$^{a.r.}$, %	**Coal 1 (Indonesian)**	**Coal 2 (SAR)**	**Coal 3 (Chinese)**	**Coal 4 (Ukrainian K)**
Moisture	9.43	1.6	7.0	5.0
Mineral matter	13.99	14.3	12.0	18.0
Carbon	58.96	70.1	66.4	67.0
Hydrogen	4.16	4.0	4.5	3.7
Sulfur	0.56	0.44	0.6	2.8
Nitrogen	1.02	1.5	0.8	1.1
Oxygen	11.88	8.06	8.7	2.4
LHVMJ/kg	23.02	23.65	25.95	26.37

Table 1.7 – Components of fuel oils (as received)

Component$^{a.r.}$, %	**Fuel oil 1**	**Fuel oil 2**
Moisture	3	6
Mineral matter	0.3	0.6
Carbon	85.1	79.5
Hydrogen	10.4	10.3
Sulfur	0.5	1.8
Nitrogen	0.5	1.5
Oxygen	0.2	0.3
LHV, MJ/kg	38.93	36.84

Table 1.8 – Chemical Composition of Natural Gas from various pipelines

Component$^{a.r.}$, %	**Chemical Formula**	**NG 1 (Nigerian)**	**NG 2 (Nigerian)**	**NG 3 (Ukrainian)**	**NG 4 (Russian)**	**NG 5 (Libyan)**
Methane	CH_4	95.0	92.69	93.5	96.96	86.482
Ethane	C_2H_6	3.2	3.43	4.0	1.37	10.392
Propane	C_3H_8	0.2	0.71	1.0	0.45	0.496
Butane	C_4H_{10}	0.05	0.47	1.0	0.18	0.014
Hydrogen sulfide	H_2S		-	-	-	
Nitrogen	N_2	1.05	2.18	0.4	0.86	0.593
Carbon dioxide	CO_2	0.5	0.52	0.1	0.18	2.023
Specific gravity		0.58	0.59	0.61	0.63	0.77
GHV, MJ/m^3		38.0	37.8	38.21	37.01	34.17

Assignment 1.

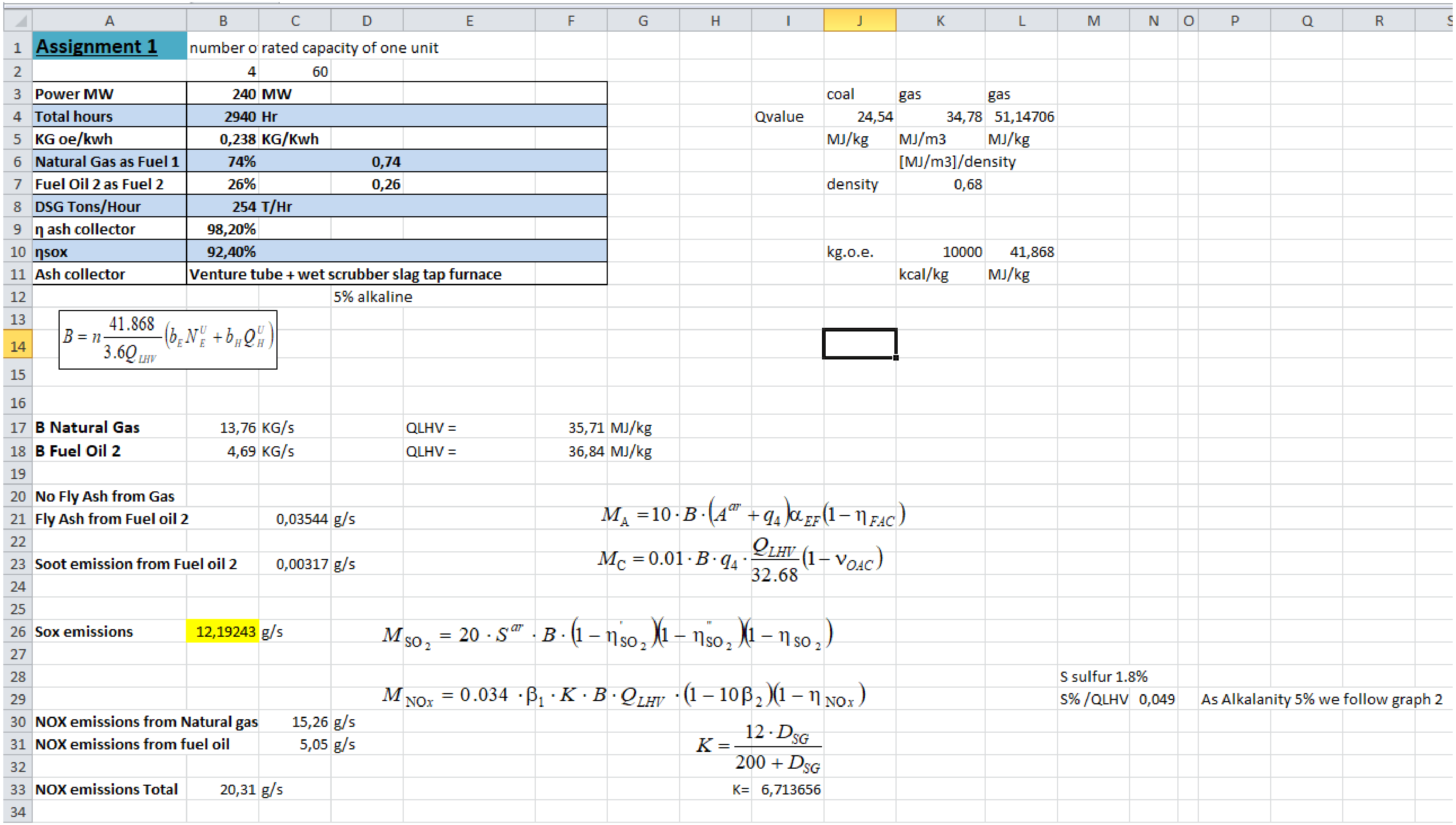
Assess the pollutant emission from the given fossil fuel fired at a thermal power plant according to the variant.

The initial data for the computations are given at table 1.9. The calculations must be made in MS Excel.

Table 1.9 – Initial data for pollutant emissions assessment

№	***N*rated, MW**	**T_0, hrs**	**b_e, t.o.e./kWh**	**Fuel1**	**Fuel2**	**Fuel3**	**D_{SG}. t/hrs/per unit**	**η_{FAC}**	**η_{SOx}**	**ω_{FG}. m/s**	**Flue gas collector/furnace type**
1.	2x150	2520	0.246	84% coal1	10% fuel oil 1	6% NG1	547	0. 985	0. 91	26	Cyclone+Ventury tube (alkaline hardness 10%) / slag-tap furnace
2.	4x100	3060	0.257	30% coal2	63% coal3	7% NG2	419	0. 989	0. 92	28	Ventury tube (alkaline hardness 5%)
3.	3x250	2390	0.254	35% coal1	55% coal4	10% NG3	749	0. 988	0. 84	27	ESP / dry bottom furnace
4.	6x60	2940	0.259	25% coal 3	70% coal4	5% fuel oil 1	254	0. 975	0. 87	25	Scrubber+Ventury tube (alkaline hardness 5%) / slag-tap furnace
5.	2x300	1970	0.251	90% coal 3	3% fuel oil 1	7% NG4	924	0. 982	0. 82	29	ESP / dry bottom furnace
6.	3x125	2520	0.258	78% coal1	12% fuel oil2	10% NG2	516	0. 979	0. 88	26	Ventury tube (alkaline hardness 10%) / slag-tap furnace
7.	2x120	3164	0.252	45% coal1	50% coal3	5% NG5	485	0. 987	0. 86	27	Scrubber+Ventury tube (alkaline hardness 10%) / slag-tap furnace
8.	4x60	2691	0.249	52% coal2	37% coal 3	11% fuel oil1	215	0. 978	0. 81	25	Cyclone+Ventury tube (alkaline hardness 5%) / dry bottom furnace
9.	6x180	2160	0.241	35% coal3	60% coal1	5% NG2	689	0. 989	0. 85	28	ESP / dry bottom furnace
10.	4x180	2448	0.253	85% coal3	8% fuel oil2	7% NG4	745	0. 987	0. 84	29	ESP / dry bottom furnace

Example of calculating pollutant emissions in MS Excel



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	**Assignment 1**	number o	rated capacity of one unit															
2		4	60															
3	**Power MW**	**240**	**MW**							coal	gas	gas						
4	**Total hours**	**2940**	**Hr**						Qvalue	24,54	34,78	51,14706						
5	**KG oe/kwh**	**0,238**	**KG/Kwh**							MJ/kg	MJ/m3	MJ/kg						
6	**Natural Gas as Fuel 1**	**74%**		**0,74**							[MJ/m3]/density							
7	**Fuel Oil 2 as Fuel 2**	**26%**		**0,26**						density	0,68							
8	**DSG Tons/Hour**	**254**	**T/Hr**															
9	**η ash collector**	**98,20%**																
10	**ηsox**	**92,40%**								kg.o.e.	10000	41,868						
11	**Ash collector**	**Venture tube + wet scrubber slag tap furnace**									kcal/kg	MJ/kg						
12				5% alkaline														
13																		
14																		
15																		
16																		
17	**B Natural Gas**	13,76	KG/s		QLHV =	35,71	MJ/kg											
18	**B Fuel Oil 2**	4,69	KG/s		QLHV =	36,84	MJ/kg											
19																		
20	**No Fly Ash from Gas**																	
21	**Fly Ash from Fuel oil 2**		0,03544	g/s														
22																		
23	**Soot emission from Fuel oil 2**		0,00317	g/s														
24																		
25																		
26	**Sox emissions**	12,19243	g/s															
27																		
28													S sulfur 1.8%					
29													S% /QLHV	0,049		As Alkalanity 5% we follow graph 2		
30	**NOX emissions from Natural gas**		15,26	g/s														
31	**NOX emissions from fuel oil**		5,05	g/s														
32																		
33	**NOX emissions Total**	20,31	g/s						K=	6,713656								
34																		

$$B = n\frac{41.868}{3.6Q_{LHV}}\left(b_E N_E^U + b_H Q_H^U\right)$$

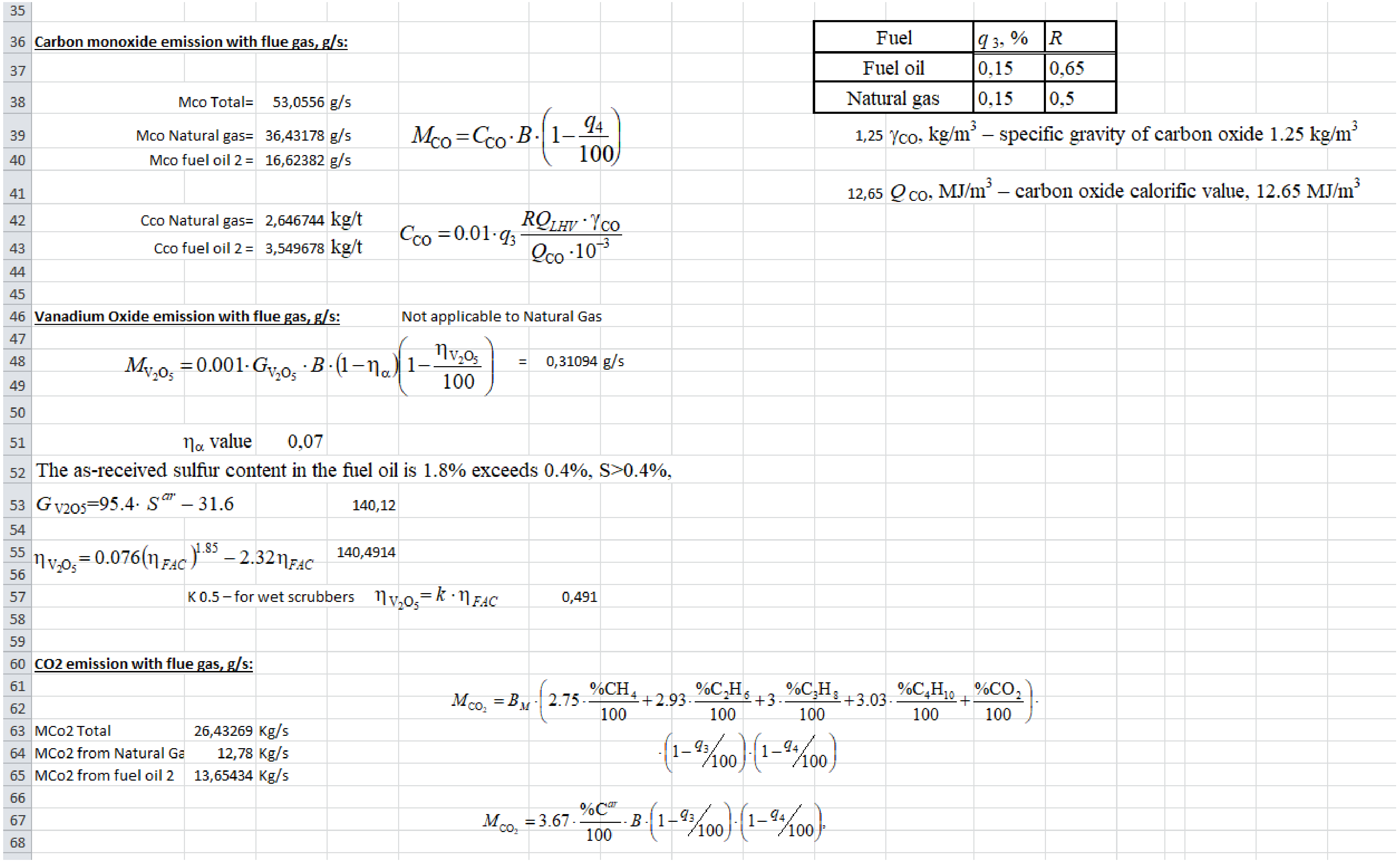
$$M_A = 10 \cdot B \cdot \left(A^{ar} + q_4\right)\alpha_{EF}\left(1 - \eta_{FAC}\right)$$

$$M_C = 0.01 \cdot B \cdot q_4 \cdot \frac{Q_{LHV}}{32.68}\left(1 - \nu_{OAC}\right)$$

$$M_{SO_2} = 20 \cdot S^{ar} \cdot B \cdot \left(1 - \eta'_{SO_2}\right)\left(1 - \eta''_{SO_2}\right)\left(1 - \eta_{SO_2}\right)$$

$$M_{NOx} = 0.034 \cdot \beta_1 \cdot K \cdot B \cdot Q_{LHV} \cdot \left(1 - 10\beta_2\right)\left(1 - \eta_{NOx}\right)$$

$$K = \frac{12 \cdot D_{SG}}{200 + D_{SG}}$$



Carbon monoxide emission with flue gas, g/s:

Fuel	q_3, %	R
Fuel oil	0,15	0,65
Natural gas	0,15	0,5

Mco Total= 53,0556 g/s

Mco Natural gas= 36,43178 g/s

Mco fuel oil 2 = 16,62382 g/s

$$M_{CO} = C_{CO} \cdot B \cdot \left(1 - \frac{q_4}{100}\right)$$

1,25 γ_{CO}, kg/m^3 – specific gravity of carbon oxide 1.25 kg/m^3

12,65 Q_{CO}, MJ/m^3 – carbon oxide calorific value, 12.65 MJ/m^3

Cco Natural gas= 2,646744 kg/t

Cco fuel oil 2 = 3,549678 kg/t

$$C_{CO} = 0.01 \cdot q_3 \frac{RQ_{LHV} \cdot \gamma_{CO}}{Q_{CO} \cdot 10^{-3}}$$

Vanadium Oxide emission with flue gas, g/s: Not applicable to Natural Gas

$$M_{V_2O_5} = 0.001 \cdot G_{V_2O_5} \cdot B \cdot (1 - \eta_\alpha)\left(1 - \frac{\eta_{V_2O_5}}{100}\right) = 0,31094 \text{ g/s}$$

η_α value 0,07

The as-received sulfur content in the fuel oil is 1.8% exceeds 0.4%, S>0.4%,

$G_{V2O5} = 95.4 \cdot S^{ar} - 31.6$ 140,12

$\eta_{V_2O_5} = 0.076(\eta_{FAC})^{1.85} - 2.32\eta_{FAC}$ 140,4914

K 0.5 – for wet scrubbers $\eta_{V_2O_5} = k \cdot \eta_{FAC}$ 0,491

CO2 emission with flue gas, g/s:

MCo2 Total 26,43269 Kg/s

MCo2 from Natural Ga 12,78 Kg/s

MCo2 from fuel oil 2 13,65434 Kg/s

$$M_{CO_2} = B_M \cdot \left(2.75 \cdot \frac{\%CH_4}{100} + 2.93 \cdot \frac{\%C_2H_6}{100} + 3 \cdot \frac{\%C_3H_8}{100} + 3.03 \cdot \frac{\%C_4H_{10}}{100} + \frac{\%CO_2}{100}\right) \cdot \left(1 - {}^{q_3}\!/_{100}\right) \cdot \left(1 - {}^{q_4}\!/_{100}\right)$$

$$M_{CO_2} = 3.67 \cdot \frac{\%C^{ar}}{100} \cdot B \cdot \left(1 - {}^{q_3}\!/_{100}\right) \cdot \left(1 - {}^{q_4}\!/_{100}\right)$$

Assignment 2
COMPUTATION OF CHIMNEY HEIGHT

On leaving the chimney, the flue gas changes its structure and concentration during its movement and propagation in the atmosphere due to turbulent diffusion, atmospheric air dilution, etc. Pollutants react with other air components and change in space and time their quantitative and qualitative composition.

Atmospheric dispersion is one of the ways to reach established permissible levels of air quality in the ground-level layer in area with emissions source. The dispersion efficiency is function of

– the chimney height;

– flue plume height above the chimney mouth that depends on the flue gas velocity ω_0, m/s;

– horizontal wind velocity that decreases the vertical velocity action and the rise effect;

–others.

Minimal chimney height H, m, at which maximum concentration of every pollutant must be below one-time maximum permissible concentration (MPC) for this pollutant (table 2.1) is computed separately for particulate matter (fly ash) and gaseous emissions, the bigger height chosen.

- for fly ash and noncombustible volatiles emission

$$H_{\mathrm{A}} = M \sqrt[2]{\frac{M_{\mathrm{A}}}{MPC_{\mathrm{A}} - C_{\mathrm{A}}^{bg}}}\,; \tag{2.1}$$

- for sulfur dioxide (SOx) and nitrogen oxide (NOx) emissions

$$H_{SOx} = M \sqrt[2]{\frac{M_{SO_2}}{MPC_{SO_2} - C_{SO_2}^{bg}} + \frac{M_{NOx}}{MPC_{NOx} - C_{NOx}^{bg}}}\,. \tag{2.2}$$

Here C_{A}^{bg}, C_{SO2}^{bg}, C_{NOx}^{bg} – background concentrations for urban thermal plants which are assessed to equal 10% – 15% of daily-average MPC of the corresponding pollutants (table 2.1);

MPC_{A}, MPC_{SO2}, MPC_{NOx} – one-time maximum permissible concentrations of those pollutants, in milligram per cubic meter of air.

Parameter M ia calculated as

$$M = \sqrt[2]{A \cdot F \cdot m \cdot n \cdot \sqrt[3]{\frac{z}{V\left(t_g - t_a\right)}}}\,, \tag{2.3}$$

where z – number of shafts in the chimney (nowadays thermal power plants are often built with multi-shaft chimneys, one shaft for every 500 through 800 MW);

A , $s^{2/3}$*mg*grad$^{1/3}$/g – atmospheric thermal stratification factor that specifies conditions of vertical and horizontal dissipation of hazardous emissions in the atmosphere. The value of this factor is determined for unfavorable meteorological conditions under which the hazardous emission concentrations reach their maximum. For subtropical zones $A = 240$.

Table 2.1 – Maximum permissible concentrations of atmospheric pollutants

Atmospheric pollutant	Ukrainian $MPC_{one-time}$, mg/m^3	Ukrainian $MPC_{daily-average}$, mg/m^3	US-EPA MPC, mg/m^3	Relative harmfulness
Carbon monoxide	5	3	10	1
Particulate matter, fly-ash	0.5	0.15	0.035	20
Nitrogen oxide	0.4	0.06		50
Sulfur dioxide	0.5	0.05	0.365	60
Soot	0.15	0.05		60
Nitrogen dioxide	0.085	0.04	0.1	75
Vanadic pentoxide V_2O_5	-	0.0003		30000
Benzapyrene $C_{20}H_{12}$	-	0.000001		3000000

F – coefficient that allows for the rate of hazardous emission sedimentation and depends on the emission matter:

- for gaseous emissions and aerosols $F = 1$;
- for fly ash and noncombustible volatiles F depends on the fly ash collector efficiency:

$$\text{if } \eta_{FAC} \geq 90\%,\ F = 2;$$
$$\text{if } 75\% \leq \eta_{FAC} \leq 90\%,\ F = 2.5;$$
$$\text{if } \eta_{FAC} \leq 75\%,\ F = 3.0;$$

m and *n* – coefficients that take into account the flue gas exit velocity from the chimney mouth ω_0, m/s, and depend on parameters f and V_m:

$$f = 1000 \frac{\omega_0^2 \cdot D}{H^2 \cdot \Delta T},$$

$$V_m = 0.65 \cdot \sqrt[3]{\frac{V \cdot \Delta T}{H}},$$

$$m = \frac{1}{0.67 + 0.1 \cdot \sqrt[2]{f} + 0.34 \cdot \sqrt[3]{f}} \text{ for } f < 100;$$

$$m = \frac{1.47}{\sqrt[3]{f}} \text{ for } f \geq 100;$$

$$n = 1 \text{ for } V_m \geq 2;$$

$$n = 0.532 V_m^2 - 2.13 V_m + 3.13 \text{ for } 0.5 \leq V_m \leq 2;$$

$$n = 4.4 V_m \text{ for } V_m \leq 0.5;$$

for typical flue gas velocities of 20 …30 m/s, *m* and *n* are chosen equal to 0.9 and 1, respectively;

D – chimney mouth diameter;

$\Delta T = t_g - t_a$,

t_g, °C, – flue gas temperature on leaving the chimney mouth, under firing solid fuels t_g equal 120…130 °C, under firing fuel oil and gas t_g equal 135…140 °C;

t_a, °C, – ambient temperature at 13-00 in the hottest month;

V, m^3/s – actual gas volumetric flow rate under rated loading capacity of all the steam generators:

$$V = k_{\mathrm{CHF}} \cdot B \cdot \left[V_G^0 + \left(\alpha_{\mathrm{EAF}} - 1\right) \cdot V^0\right] \cdot \frac{t_g + 273}{273}, \tag{2.4}$$

where k_{CHF} – fossil boiler critical heat flux (CHF) ratio, equal to 1.05;

α_{EAF} – excess air factor in the flue gases before the chimney, accepted equal to 1.55 for solid fuels and 1.40 for fuel oil and gas;

V_{G}^0, m^3/kg (m^3/m^3) – theoretical flue gas volume;

V^0, m^3/kg (m^3/m^3) – theoretical air volume required for burning the fuel.

<u>Theoretical air volume</u> V^0 is calculated with the following expressions:

- for coal and fuel oil, m^3/kg (of coal, oil):

$$V^0_{\mathrm{coal,oil}} = \frac{1}{30} \cdot [2.67 \cdot (\%\mathrm{C}^{\mathrm{ar}} + 0.375 \cdot \%\mathrm{S}^{\mathrm{ar}}) + 8 \cdot \%\mathrm{H}^{\mathrm{ar}} - \%\mathrm{O}^{\mathrm{ar}}] \tag{2.5}$$

- for natural gas, m^3/m^3 (of gas):

$$\begin{aligned} V^0_{\mathrm{NG}} &= \frac{100}{21} \cdot V^0_{\mathrm{O2}}, \\ V^0_{\mathrm{O2}} &= [0.01 \cdot (2 \cdot \%\mathrm{CH}_4 + 3.5 \cdot \%\mathrm{C}_2\mathrm{H}_6 + 5 \cdot \%\mathrm{C}_3\mathrm{H}_8 + 6.5 \cdot \%\mathrm{C}_4\mathrm{H}_{10} + 8 \cdot \%\mathrm{C}_5\mathrm{H}_{12} + \\ &\quad + 0.5 \cdot \%\mathrm{CO} + 0.5 \cdot \%\mathrm{H}_2 - \%\mathrm{O}_2)] \end{aligned} \tag{2.6}$$

<u>Theoretical flue gas volume</u> V_{G}^0 is calculated with the expressions:

- for coal and fuel oil, m^3/kg (of coal, oil):

$$\begin{aligned} V^0_{\mathrm{G\,coal,oil}} &= 1.87 \cdot \frac{\%\mathrm{C}^{\mathrm{ar}} + 0.375 \cdot \%\mathrm{S}^{\mathrm{ar}}}{100} + V^0_{\mathrm{N2}}, \\ V^0_{\mathrm{N2}} &= 0.79 \cdot V^0 + 0.8 \cdot \frac{\%\mathrm{N}^{\mathrm{ar}}}{100} \end{aligned} \tag{2.7}$$

- for natural gas, m^3/m^3 (of gas):

$$
\begin{aligned}
&V^0_{\text{G NG}} = V_{\text{CO2}} + V_{\text{SO2}} + V_{\text{N2}} + V_{\text{O2}},\\
&V_{\text{CO2}} = 0.01 \cdot (\%\text{CH}_4 + 2 \cdot \%\text{C}_2\text{H}_6 + 3 \cdot \%\text{C}_3\text{H}_8 + 4 \cdot \%\text{C}_4\text{H}_{10} + 5 \cdot \%\text{C}_5\text{H}_{12} +\\
&\qquad\qquad + \%\text{CO} + \%\text{CO}_2), \qquad (2.8)\\
&V_{\text{SO2}} = 0.01 \cdot \%\text{H}_2\text{S},\\
&V_{\text{N2}} = 3.76 \cdot V_{\text{O2}} + 0.01 \cdot \%\text{N}_2
\end{aligned}
$$

– Calculation of chimney mouth diameter, m:

$$D = 1.13 \cdot \sqrt[2]{\frac{V}{z \cdot \omega_0}}, \qquad (2.9)$$

where 1.13 – empirical coefficient;

ω_0, m/s – flue gas velocities at the chimney mouth.

– Selection of standard chimney height:

For the bigger value of the calculated chimney height and *D*, the size of the chimney is chosen upward among the standard chimney size line:

- *H*, m – 30, 60, 90, 120, 150, 180, 210, 250; 330
- *D*, m – 2.4; 3.0; 3.6; 4.2; 4.8; 5.4; 6.0; 6.6; 7.2; 7.8; 8.4; 9.6.

Assignment 2.

Calculate the height of the chimney for the pollutant emissions at the power plant according to your variant in Assignment 1.

Assignment 3
COMPUTATION OF MAXIMUM PERMISSIBLE EMISSIONS

On leaving the chimney, the flue gas is diluted with atmospheric air, which results in pollutants concentration decrease. The degree of the dispersion is proportional to the distance covered by the pollutant.

Flue gas pollutants are propagated along with the wind within an expansion angle of 10°–20°.

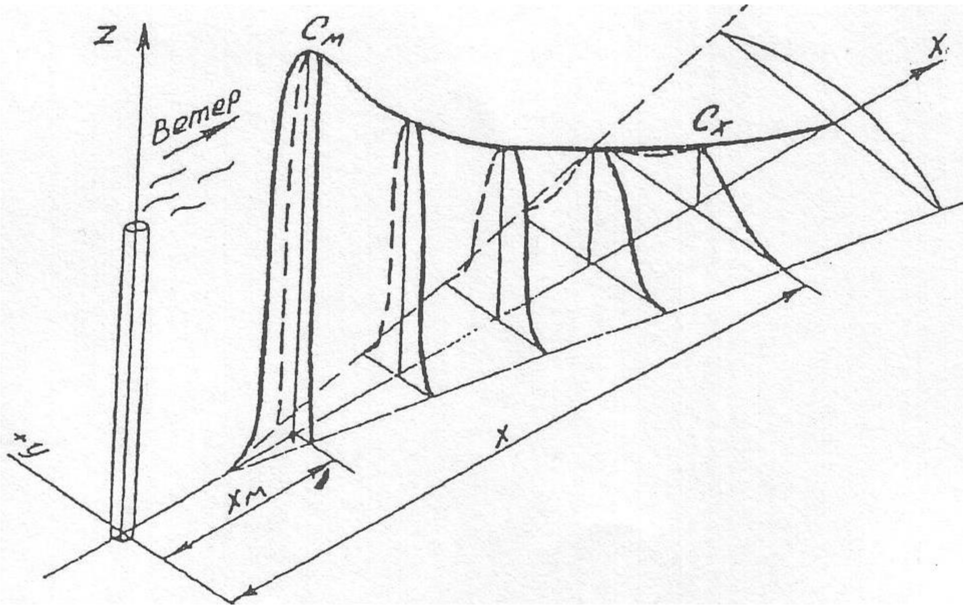


Figure 3.1 – Ground-level pollutant concentration change with the distance from the chimney

Distance from the emissions source x_m, m, at which the ground-level concentration C, mg/m^3, under unfavorable weather conditions reaches maximum value C_m is calcutated with the following expression:

$$x_m = \frac{5 - F}{4} \cdot d \cdot H\ , \tag{3.1}$$

where dimensionless coefficient d for $f < 100$ is found as

$$d = 2.48 \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ for } V_m \le 0.5;$$
$$d = 4.95 \cdot V_m \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ for } 0.5 \le V_m \le 2.0;$$
$$d = 7 \cdot \sqrt[2]{V_m} \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ for } V_m > 2.0;$$

The atmospheric pollutant concentration C, mg/m3, is distributed along the flue plume at different distances x, m, is calculated with formula

$$C = s_1 \cdot C_m \tag{3.2}$$

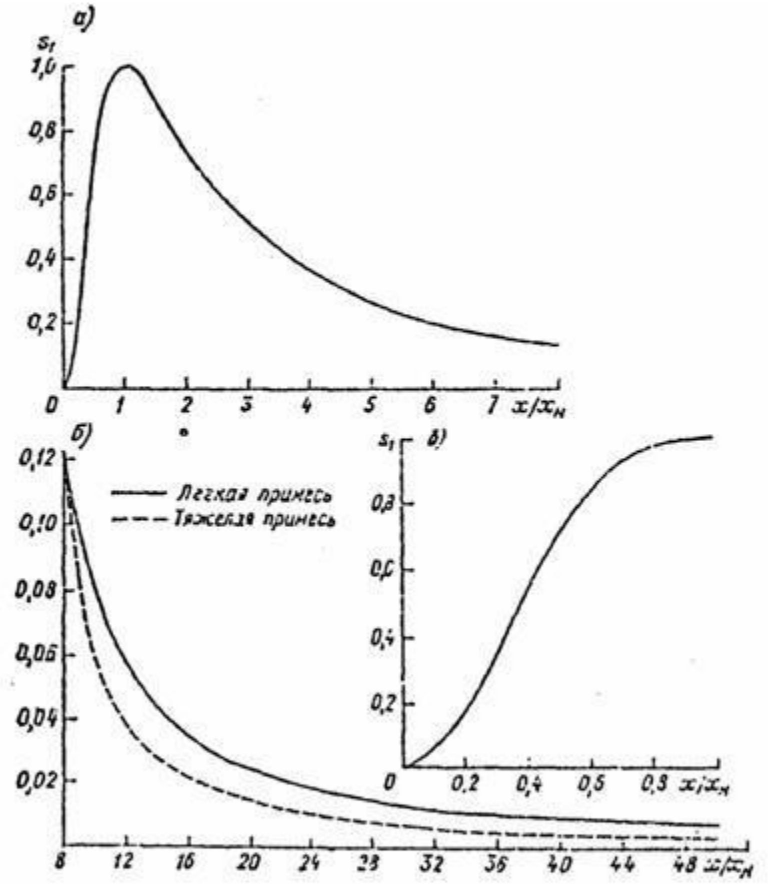


Figure 3.2 – s_1 versus x/x_m

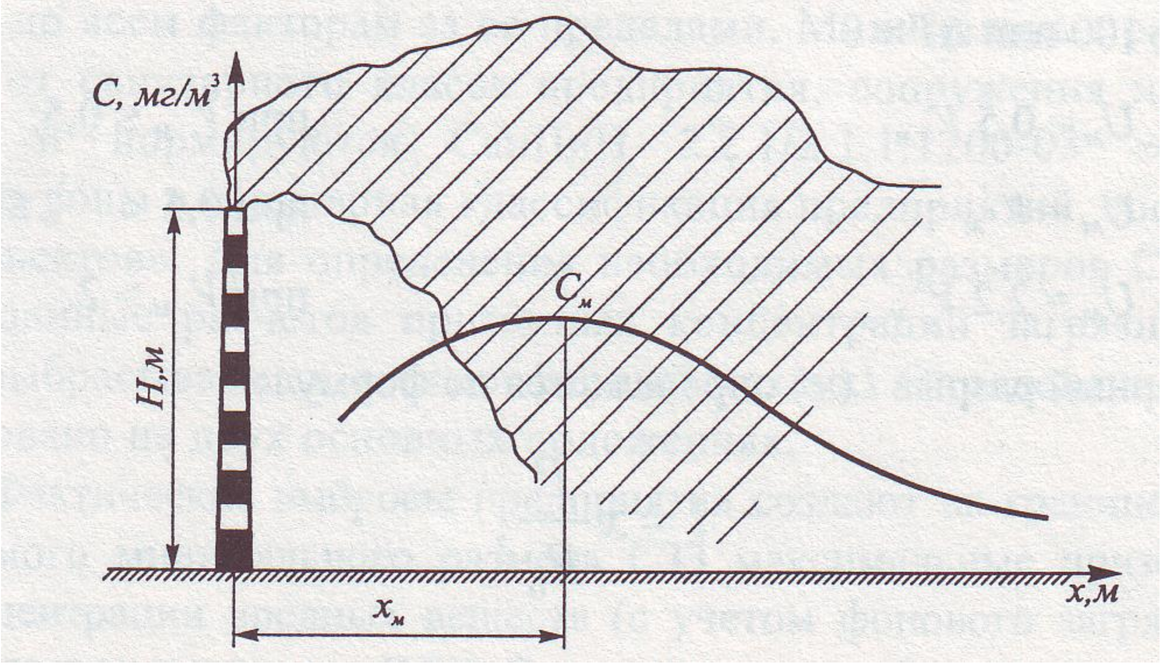


Figure 3.3 – Maximum pollutant concentration

Maximum ground-level concentrations for the main flue gas pollutants under unfavorable weather conditions are calculated with formulae:

– for fly ash

$$C_{\mathrm{A}m} = \frac{0{,}15c_{\mathrm{A}}}{H}\exp\left[\frac{-\left(x_m - 0{,}02H\right)^2}{0{,}05H + 4{,}5x_m}\right] \tag{3.3}$$

– for gaseous pollutants

$$C_{SO2m} = \frac{0{,}018c^{\Sigma}}{H}\exp\left[\frac{-\left(x_m - 0{,}025H\right)^2}{0{,}067H + 6x_m}\right] \tag{3.4}$$

$$c^{\Sigma} = c_{SO_2} + c_{NO_X}\,\frac{MPC_{SO_2}}{MPC_{NO_X}} = c_{SO_2} + 5.88\cdot c_{NO_X}$$

where x_m is in km;

c_i – i-pollutant concentration on leaving the chimney mouth, mg/m3:

$$c_i = \frac{M_i}{B\cdot V_G^0}\cdot 10^3$$

Maximum permissible emission (MPE) for every flue gas pollutant is specified as

$$MPE_i = \frac{\left(MPC_i - C_i^{bg}\right)\cdot H^2}{AF\,mn\eta}\sqrt[3]{V\left(t_g - t_a\right)} \tag{3.5}$$

BUFFER ZONE COMPUTATION

For every emission source, there is established a buffer zone where pollutant concentration may be increased. On the buffer zone boundary, the pollutant concentration must not exceed the pollutant background concentration. When determining the buffer zone, the wind velocity pattern must be taken into consideration.

Wind pattern (wind rose) is an N-point wind velocity diagram where frequency of wind directions (arrows, percent) and calmness (center, days) is shown (fig. 3.4). The arrow length depicts the percent direction frequency value.

The buffer zone inversely reflects the wind diagram

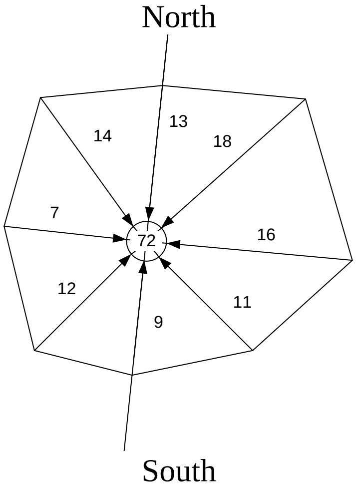


Figure 3.4 – Prevailing wind diagram

For $H > 10$ m, the buffer zone is a circle with inner and outer radii

$$R_{\text{int}}=2\cdot\varphi\cdot H; \qquad R_{\text{ext}}=20\cdot\varphi\cdot H, \tag{3.6}$$

where φ – dimensionless correction allowing for thermal rise of the emissions plume,

$$\varphi = 1+\frac{\Delta T}{75}.$$

With allowing for the wind diagram:

$$l_{bzi} = R_{ext}\frac{W_i}{W_0}, \tag{3.2}$$

where l_{bz} – the buffer zone size in *i*-direction;

W_i, % – the wind frequency in that direction;

W0, % – average value of the wind frequency equal to 12.5 % for eight-point wind pattern:

$$W_0 = \frac{100\%}{N}$$

Below is given an example of buffer zone calculation.

Table 3.1 presents the wind frequency in the 8-beam wind rose at the power plant site and calculated buffer zone sizes in the eight directions. Figure 3.5 presents the wind rose at a power plant site. Figure 3.6 presents the buffer zone calculated.

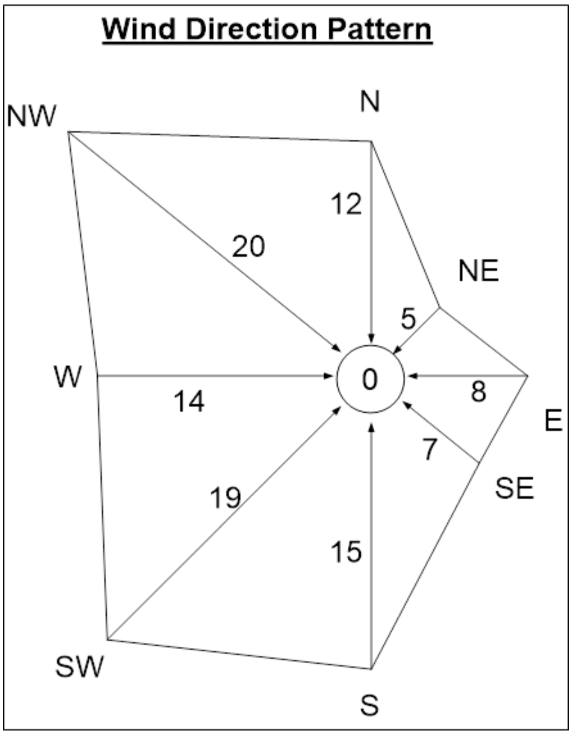


Figure 3.5 – Wind direction pattern given

Table 3.1 – The wind frequency and the buffer zone size

Point	N	NE	E	SE	S	SW	W	NW
W_i	15	19	14	20	12	5	8	7
W_0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
l_{bz}, м	1584	2006.4	1478.4	2112	1267.2	528	844.8	739.2

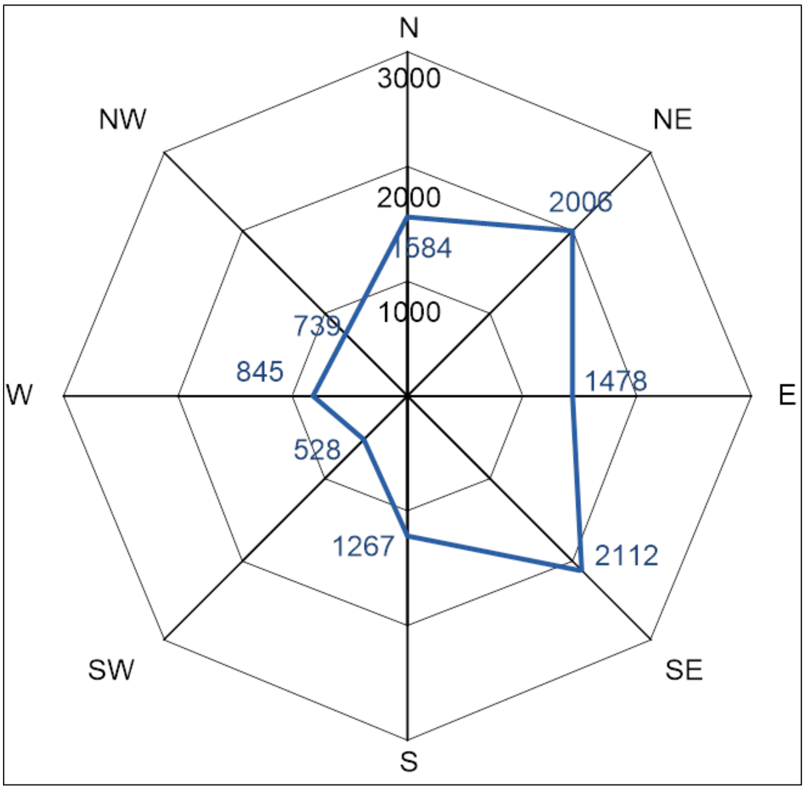


Figure 3.6 – Buffer zone pattern

Assignment 3

Determine the buffer zone to the power plant according to your variant in assignments 1 and 2.

The initial data for the calculations are given in table 3.1.

Table 3.1 – Wind frequency in the wind rose

№	Wind frequency in the wind rose, %
	N->NE->E->SE->S->SW->W->NW
1.	17>20>12>7>9>10>14>11
2.	9>13>11>16>14>12>15>10
3.	12>11>14>10>9>6>17>21
4.	8>7>15>19>14>20>12>5
5.	15>18>7>8>6>11>16>20
6.	7>14>11>18>15>9>12>14

7.	10>9>11>13>16>14>15>12
8.	9>14>11>16>15>10>12>13
9.	12>16>14>11>10>13>8>16
10.	21>17>12>11>14>9>6>10