USE OF SECONDARY FUELS IN THE CEMENT MANUFACTURING: A CASE STUDY

C. A. TSILIYANNIS[1*], I. L. FOTINOPOULOU[1], M. GEORGIOPOULOU[2] AND G. LYBERATOS[2]

[1]ANION Environmental Ltd, Em. Lykoudi 26, 11141, Athens, Greece
[2]National Technical University of Athens, Athens, Greece
Presenting Author: Dr. Martha Georgiopoulou, Email: mgeorgiop@yahoo.gr
Corresponding Author: Dr. C. Tsiliyannis, Email: anion@otenet.gr, Phone: +30 210 2285650

ABSTRACT

As one of the most energy intensive consumers, the cement industry has long pioneered substitution of fossil fuels by alternative fuels (AFs). Municipal, agricultural, commercial, industrial wastes, biowastes and industrial sludges, animal and wood processing wastes, cutting oils and spent solvents, as well as end-of-life consumer products such as tires and auto shredded residues, are the main sources of AFs. Based on a stoichiometric balance of AF combustion, the present study assesses the use of more than 20 distinct AFs classified according to Eurocodes. The operational efficiency and the emission rates in an actual dry process clinker plant are analyzed. It is shown that the type of AF significantly affects the individual kiln/precalciner/preheater species flowrates and the overall flue gas flow rates. Based on the kiln flue gas rates, overall off-gas flow rates from the main air-pollution control system (APCS), i.e. the kiln/ raw mill APCS, are determined under compound operation, taking lime dissociation, raw mill air and exhaust blower draft into account. Off-gas rates impinge on the mean residence time in the APCS and associated removal efficiency. Non-biogenic carbon dioxide emissions are also affected due to varying renewable constituents in various AFs. Varying off-gas flow rates affect emission rates of conventional and trace hazardous compounds. Emission rates are determined assuming that the plant operates at the compliance limit. The latter is often the case for most actual plants for at least one pollutant; in the present case NOx emissions are assumed to be the limiting pollutant emissions. The limit of these emissions for cement plants using AFs has been restricted by enacted legislation to 500 from the current 800 mg/Nm^3, effective on 01.03.2017.

key words: Alternative fuels; cement manufacturing; resource recovery; clinker process.

INTRODUCTION

Cement plants are large industrial facilities located nearby appropriate quarries and easy transportation crossroads (fig. 1) Cement is made from clinker, the product of high temperature sintering of soil materials (raw meal), mainly lime (fig. 2) which is calcined to alkaline oxides. Acting as a paradigm of industrial symbiosis fostering dematerialization, cement plants utilize high volumes of byproducts and wastes from several other industries, both organic and inorganic partly substituting virgin raw materials in the raw meal (by about 10% in the domestic industry [1]. Substitute inorganic materials include quarry fines, lignite and coal ash, concrete returns, demolition wastes, blast furnace slag, foundry sand, red mud from aluminium production, ore rejects, mineral tailings and residues from steel manufacturing.

Substitute organic materials or water-oil mixtures are used as alternative fuels (AFs). They mainly include waste or biomass derived combustible materials [1-15]: wastepaper, cellulosic agricultural residues, agricultural plastic waste from greenhouse horticultures, wood processing wastes, textile industry wastes, wastes from plastics manufacturing, wood, plastic and paper packaging, end-of-life tires, refuse derived fuel, animal byproduct waste, automotive plastic waste, biological and manufacturing sludges, cutting oil emulsions, cable plastic waste, demolition waste, refinery sludges, spent solvents, waste oils, etc. (some Eurocodes given in Table 1).

Enacted legislation [16 – 19], sets strict limits for AF utilization, expressed as standardized emitted concentrations. Led by the Netherlands (82%), overall thermal substitution by AFs in the EU is at 38.7% [4].

Cement kilns reach high temperatures [3] (clinker exits at about 2000^{o}C) surpassed only by plasma gasification. Kiln residence times exceed 12-15 s at temperatures above 120°C and 5-6 sec at temperatures above 1800°C [1]. As intuitively understood, thermal substitution of fossil fuels modifies the volume and composition of flue gases and final offgases, emitted at the main exhaust chimney, after cleaning in the main air pollution control system (APCS) (fig. 2), namely the kiln-soil mill APCS which cleans the kiln flue gases under direct operation (fig.3), or jointly the kiln and soil mill flue gases under compound operation (fig.3). Other emission points and APCS present in cement plants are primarily de-dusting systems (fig. 3). Such modifications affect emissions and emission rates. In addition, varying ooxygen and moisture off gas contents affect the standardization factor (dry, 10% oxygen, STP), via which final emissions (off gas concentrations) are assessed and compared to the standard maximum off gas concentration limit. The emission rates of release to the environment are the primary environmental concern. The present work will endeavor to assess the impact of AF utilization on off gas volumes and emission rates in an actual cement plant producing 1.500.000 tons of clinker per year. Section 1 presents the plant characteristics and the candidate AFs, section 2 describes the assessment method and section 3 presents the results and discussion.

1. The Cement Plant

A 1.500.000 tpa clinker, dry-process cement plant, featuring two parallel kiln / precalaciner / cyclone preheater lines is analyzed. The plant is located in Drepanon, Achaia, Greece (fig. 1). It is currently utilizing fossil fuels (70%, Pet Coke 30% coal) in order to meet the total fuel energy demand of 4.600 TJ/a, resulting in a specific energy consumption of ε =3.550 kJ/kg clinker. Use of alternative fuels (AFs) for 30% thermal Pet Coke substitution is investigated in this work, leading to a fuel mixture of Pet Coke 40%, Coal 40% and AF 30%.

The legal framework includes Directives 2010/75/EC on integrated pollution control, 2000/76/EC on waste incineration, and Ministerial Decisions 22912/117/2004 (B759) adjusting to Dir. 2000/76/EC, 36060/1155/E.103, Appendix VI, part 4, par. 2 emission limits for cement plants co-incinerating wastes) (GG/B/1450/14.06.2013 modifying MD 22912/117/2005, MD 56366/4351, OGG/B/3339/12.12.2014 and Law 4042/2012 (A’/24) on Solid recovered fuel and refuse derived fuel specifications and EN 15359:2011 «Solid Recovered Fuels- Specifications and Classes»).

The plant operates mostly under compound operation, i.e. the soil mill is active when the kiln is operated. The dominant fraction (θ), fig. 2, of kiln/ precalciner /preheater flue gases pass through the soil mill to heat up the raw meal and subsequently they are jointly cleaned together with the raw mill air in the main APCS. The raw mill air is proportional to the raw meal mass (α_{sm} x raw meal). The rest of the flue gases (fraction 1- θ) pass through the fuel mill in order to create an inert atmosphere. Under direct operation the raw mill is off and the kiln is using stored raw meal. Energy is saved by the two main heat integration couplings, (a) heating up of raw meal by the flue gases in the 4-stage cyclone preheater and (b) heating up of combustion air in the clinker cooler. There are several emission points in the plant (fig. 3), yet the most important one is the kiln-raw mill point in which advanced APCS including SNCR NOx removal and hybrid electrostatic filter / bag filter have been installed.

The Alternative fuels investigated

Acting as high temperature long-residence-time alkaline scrubbers, cement kilns have been shown capable of efficient co-processing various waste derived AFs. Several AFs are investigated herein (Table 1) for thermal substitution of pet coke, each one as a separate case.

2. METHOD

The method is schematically depicted in fig. 4. Individual combustion flue gas flow rates are determined, given the “as received” ultimate analysis of alternative fuels and fuel feed rates. The flow rate of CO_2 from lime dissociation is determined from the clinker production level (1.500.000 tpa). The latter is used to determine the raw meal needed, which in turn is used to determine the raw mill air (fraction of raw meal), which is jointly cleaned with the kiln flue gases in the main APCS (figs 2, 3).

2.1 Kiln Stoichiometry and Mass Balance

The operation of the rotary kilns operation at high temperatures (above 1.450 ^{o}C) is described by the reactions below.

A. Fuel combustion stoichiometry

$$C_xH_yO_zCl_wS_vN_u + (1+E)\,(x + \varphi + v - 0{,}5\,z)\,O_2 + (1+E)\,79/21\,(x + \varphi + v - 0{,}5\,z)N_2 \rightarrow$$
$$x\,CO_2 + 2\varphi\,H_2O + (x + \varphi + v - 0{,}5\,z)\;E\,O_2 + w\,HCl + v\,SO_2 +$$
$$(0{,}5\,u + (1+E)\,79/21\,(x + \varphi + v - 0{,}5\,z))\,N_2 \qquad (1)$$

where

$C_xH_yO_zCl_wS_vN_u$ is the empirical formula of the fuel and

$$\varphi = 1/4\,(y - w) \text{ if } y > w \qquad (2)$$

$$\varphi = 0 \text{ if } y \leq w \qquad (3)$$

Fig. 5a gives the individual combustion species flue gas flow rates, i.e. without including the CO_2 generated by lime dissociation and Table 3 gives the overall (m_{fg}) combustion flue gas flow rates.

B. Lime dissociation

$CaCO_3 \rightarrow CaO + CO_2$ (4)

The following equations are valid [20]

$m_{CO2,lime,0} = \eta\ MW_{CO2}\ (m_{clinker} - \text{fuel ash})_0$ (5)

$V_{CO2,lime,o} = \eta\ 22.400\ (m_{clinker} - \text{fuel ash})_0$ (6)

Raw meal required = $m_{CO2,lime}\ (1+ \eta\ MW_{CO2}) / \eta\ MW_{CO2}$ (7)

where

$\eta = \zeta /56 * (1- MW_{CO2}\ \zeta/56)-1$ (8)

ζ= %w CaO in $CaCO_3$ (9)

From the fuel analysis the fuel ash is found to be, fuel ash_0 = 8.660 tn/y (~8.000 tn/y from coal) which is three orders of magnitude less than the clinker production level in equations 5 and 6. Using the parameter values in Table 2, the mass flow rate of CO_2 from lime dissociation in the base line scenario (fossil fuels, subscript 0) is found to be $V_{CO2,lime,0}$ =86.743 kg/h and the volumetric flow rate equal to $m_{CO2,lime,0}$ =44 160 Nm^3/h. The raw meal required is found to be, raw meal_0 = 256.744 kg/h.

2.2 Determination of off gas flow rates (main APCS, kiln-soil mill)

Based on mild assumptions, overall off gas flow rates (kiln-soil mill), $\mathbf{V_{k,sm}}$, are given by eq. (11) (see Appendix)

$$\mathbf{V_{k,sm}} = V_{k,sm,0} + V_{k,sm,0}\ \mathbf{\{}(1+\psi)\theta\ V_{fg}\ MW_{fg} - (1+\psi)\theta\ V_{fg,0}\ MW_{fg,0}\mathbf{\}}\ / \\ \mathbf{\{}\theta\ V_{fg,0}\ MW_{fg,0} + \theta\ V_{CO2,lime,0}\ MW_{CO2} + \upsilon\ \alpha_{sm}\ m_{CO2,lime,0}\ (1+\eta\ MWCO_2) / \eta\ MWCO_2 + \\ \upsilon\ \theta\ \psi\ (m_{fg,0} + m_{CO2,lime,0})\ \mathbf{\}} \quad (11)$$

where ψ = the mass fraction of induced air draft from main exhaust blower with respect to overall kiln flue gases
MW = molecular weight
V_{fg} = flue gas volumetric flow rate.

All variables in eq. (11) are known either from base line operation data (subscript $_0$) or from the combustion balance under AF utilization. Use of equation (11) gives the off gas volumes, $V_{k,sm}$. Numerical values are given in Table 3.

To determine actual emission rates we proceed as follows. Denoting by x_l denoted the standardized emission limit for any pollutant, the actual pollutant emission rates are given by:

$$r_i = x_{i,l} \; / \; SF \tag{12}$$

where *SF* is the standardization factor,

$$SF = \frac{21-10}{21-\%[O_2]_{k,sm}} \frac{100}{100-\%[H_2O]_{k,sm}} \frac{T}{T_s} \frac{P_s}{P} \tag{13}$$

and where the off gas water and oxygen %vol concentrations $[O_2]_{k,sm}$ and $[H_2O]_{k,sm}$ are found from the respective off gas content %v (taking into account the induced air draft from the exhaust blower, as well as the soil mill air) and from the overall off gas volumetric flowrate, $V_{k,sm}$

$$V_{k,sm\ H2O} = 100\ (V_{H2Ofg} + V_{pseudo\ air\ moisture} + V_{soil\ mill\ air\ moisture})\ /\ V_{k,sm} \tag{14}$$

$$V_{k,sm\ O2} = 100\ (V_{O2fg} + V_{pseudo\ air\ O2} + V_{soil\ mill\ O2})\ /\ V_{k,sm} \tag{15}$$

The volumetric flowrate of the fluegas water and oxygen, V_{H2Ofg} and V_{O2fg} respectively, are found from the combustion balance. Air moisture is found from the H_2O molar fraction=0.0141 at 65% humidity in air. Temperature and pressure are at normal conditions ($T=T_s$, $P = P_s$).

3. RESULTS AND DISCUSSION

Table 3 and fig. 5 show the combustion flue gas volumetric flow rates, as well as the overall off gas volumetric flow rates under compound operation for baseline case (fossil fuels) and various AF utilization scenaria. It is seen that both the flue gas and the off gas flow rates vary under AF utilization: flue gas flow rates from 176.000 to 234.000 Nm^3/h, while off gas volumes vary from 551.000 to 617.000 Nm^3/h, a change of about 12% with respect to baseline. As a result of the increased offgas rates through the APCS and the continuous emissions' monitoring system (CEMS) for most AFs, the residence time decreases, resulting in a lower removal efficiency. Thus the control system must be revamped to meet the new needs, especially if some of the limits are stricter under AF utilization (e.g. NOx, starting 01.03.2017). Assuming that such a necessary action will take place, emitted concentrations will not exceed the standardized limit and thus equations 12-15 will be valid. Consequently, maximum actually emission rates may be determined. For instance, for NOx (fig. 6), several AFs feature lower emission rate than the base line, under a maximum limit of 800 mg/Nm^3 and all the more so, under the new anticipated stricter limit of 500 mg/Nm^3, (fig. 7) which applies for AF utilization.

The SO_2 emission rates (fig. 8) are lower for all AFs, as intuitively expected due to the substitution of pet coke which features a larger S content than the AFs. In contrast, TSP emission rates (fig. 9) are anticipated to be higher, since the enacted legislation [16] allows higher emitted concentrations under AF utilization (30 mg/Nm^3 versus 10 mg/Nm^3). The AFs under the Eurocodes 13 05 06/07 (oily waters from oil/water separators) and 19 02 03 / 04 (premixed wastes) feature lower off gas volumes and the lowest emission rates for the pollutants investigated. In regard to greenhouse emissions, the overall CO_2 emissions (fig. 10) rise for most AFs due to higher fuel consumption and higher volumes of combustion-generated CO_2. Nevertheless, the biogenic AF CO_2 has to be subtracted from this total figure in order to determine the net CO_2 contribution and to compare with the baseline greenhouse emissions (CO_{2eq}) for determination of tradeable CO_2 reduction rights. The overall net CO_2 emissions are reduced up to 16% (figs 10, 11).

It is concluded that (a) all AFs substituting for petcoke lead to lower SO_2 emissions (b) the lower NOx emission limit for AF utilization results in lower NOx emission rates by more than 50% and that (c) AFs resulting in low off gas volumes may bring along significantly lower actual pollutant discharge rates to the environment.

ACKNOWLEDGEMENT

The authors are grateful for conducting the AF assessment study for TITAN SA. They have benefited from discussions with A. Katsiamboulas, Environment, Qualityand Sustainable Development Senior Manager and N. Papageorgiou, Environmental Engineer at Drepanon Cement Plant.

REFERENCES

[1.] Katsiamboulas, A., Contribution of cement industry to circular economy, www.wtert.gr, 15.01.2016

[2.] CEMBUREAU (1999). Environmental Benefits of Using Alternative Fuels in Cement Production. Brussels, The European Cement Association: 25.

[3.] GTZ and Holcim, Guidelines on Co-Processing Waste Materials in Cement Production. The GTZ-Holcim Public Private Parternship, GTZ and Holcim Group Support Ltd.: 135, 2006..

[4.] Cement Sustainability Initiative. Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process, World Business Council for Sustainable Development: 38, 2005

[5.] Genon, G., Brizio, E. "Perspectives and limits for cement kilns as a destination for RDF." Waste Man. 28, 2008, 2375 – 2385, 2008

[6.] Mokrzycki, E. and A. Uliasz- Bochenczyk. "Alternative fuels for the cement industry." Applied Energy 74(1-2): 95-100, 2003.

[7.] Murray, A., L. Price, Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector, ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY, June 2008

[8.] Bech, C. "GCHI-a leader in waste derived fuel management." Cement Industry Technical Conference, 2006. Conference Record. IEEE: 11, 2006.

[9.] CEN/TC 343/WG 2 N081 Draft 5, Solid Recovered Fuels – Specifications and Classes

[10.] Kolovos, K., G., S. Tsivilis, G. Kakali, The Use of Secondary Raw Materials and Fuels in the Cement Industry 2006, Tech. Chron. Sci. J. TCG, V, No 1-2, 7 – 17

[11.] European Commission- Directorate General of Environment, refuse derived fuel, current practice and perspectives (B4-3040/2000/306517/MAR/E3) Final report, July 2003 EC

[12.] Fytili, D., Zabaniotou, A. "Utilization of sewage sludge in EU application of old and new methods - a review." Renewable and Sustainable Energy Reviews 12(1): 116-140, 2006.

[13.] Zabaniotou, A., Theofilou C., Green energy at cement kiln in Cyprus – Use of sewage sludge as a conventional fuel substitute, Renewable and Sustainable Energy Reviews 12 (2008) 531-541

[14.] Giannopoulos, D., D.I. Kolaitis, A. Togkalidou, G. Skevis, M.A. Founti, Quantification of emissions from the co-incineration of cutting, oil emulsions in cement plants – Part II: Trace species, Fuel 86, 2491–2501, 2007

[15.] D.Giannopoulos, D.I.Kolaitis, A.Togkalidou, G.Skevis, M.A.Founti. Qualification of emissions from the co-incineration of cutting oil emulsions in cement plants –Part I: NOx ,CO and VOC . Fuel 86 (2007) 1144-1152, 2007

[16.] Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste, OJ L 332, 28.12.2000, p. 91–111

[17.] Directive 2001/81/EC, on maximum emission limits for atmospheric pollutants

[18.] Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control

[19.] Waste Eurocodes, Decision 2000/532/EC

[20.] Tsiliyannis, C. A. Alternative Fuels in Cement Manufacturing: Modeling for Process Optimization under Direct and Compound Operation, Fuel, 99, 20-39, 2012.

APPENDIX. Proof of eq. 11

Use of conventional fossil fuels (baseline): $(1+\psi)\,\theta\, m_{fg,o} + m_{others,o} = m_{k,sm,o}$ (A1)

Use alternative fuels: $(1+\psi)\,\theta\, m_{fg} + m_{others} = m_{k,sm}$ (A2)

where (fig. 2): $m_{others} = m_{soil\ mill\ air} + m_{CO2,lime}$.

Then

$$(1+\psi)\theta(m_{fg} - m_{fg,o}) + m_{others} - m_{others,o} = m_{k,sm} - m_{k,sm,o} \quad \text{(A3)}$$

Assumption 1. Clinker level is assumed approximately constant (an assumption introducing about 10% deviation for up to 30% thermal substitution of fossil fuels by AFs [20]). Assumption 1 implies that raw meal is nearly constant and therefore the CO_2 from lime dissociation is nearly constant. Since the soil mill air is proportional to raw meal it also remains at about the same level. It follows that:

$$m_{others} \approx m_{others,o} \quad \text{(A4)}$$

for, $m_{others} = m_{soil\ mill\ air} + m_{CO2,lime}$ and $m_{soil\ mill\ air} \approx m_{soil\ mill\ air,0}$, $m_{CO2,lime} \approx m_{CO2,lime,0}$.

Then eq. A3 becomes:

$$(1+\psi)\theta\,(V_{fg}\,MW_{fg} - V_{fg,\,0}\,MW_{fg,\,0}) = \mathbf{V_{k,sm}}\,MW_{k,sm} - V_{k,sm,\,0}\,MW_{k,sm,\,0} \quad \text{(A5)}$$

which, if $MW_{k,sm,0}$ and $MW_{k,sm}$ were known, could be solved for $\mathbf{V_{k,sm}}$, since $V_{fg,\,0}$, V_{fg} MW_{fg} , $MW_{fg,\,0}$ are known (they were determined from kiln stoichiometry, Table 3) and $V_{k,sm,\,0}$ is known from baseline operation using fossil fuels ($V_{k,sm,\,0}$ = 578.000Nm^3/h).

The baseline offgas molecular weight, $MW_{k,sm,\,0}$, can be determined as follows:

Offgas molecular weight under fossil fuels

With υ denoting the molar volume (υ =22.4 lt under STP), from the offgas mass balance it follows that:

$$MW_{k,sm,\,0} = \{\theta V_{fg,o}\,MW_{fg,o} + \theta V_{CO2,lime,0}\,MW_{CO2} + V_{soil\ mill\ air,\,0}\,MW_{air} + V_{pseudo\ air,\,0}\,MW_{air}\} / V_{k,sm,o} \quad \text{(A6)}$$

But

$$V_{soil\ mill\ air,\,0} = \upsilon\, m_{soil\ mill\ air,\,0} / MW_{air} = \upsilon\, \alpha_{sm}\,(\text{raw meal}_0) / MW_{air} \quad \text{(A7)}$$

$$V_{pseudo\ air,\,0} = \upsilon \text{ fraction of kiln fluegas}/ MW_{air} = \upsilon\, \theta\, (\psi\, m_{fg,\,0} + \psi\, m_{CO2,lime,\,0}) / MW_{air} \quad \text{(A8)}$$

where $(\text{raw meal}_0) = m_{CO2,lime,0}\,(1+ \eta\, MWCO_2) / \eta\, MWCO_2$

Substitution of equations A7 and A8 in eq. A6 gives

$$MW_{k,sm,o} =$$
$$\{\theta\, V_{fg,o}\,MW_{fg,o} + \theta\, V_{CO2,lime,o}\,MW_{CO2} + \upsilon\, \alpha_{sm}\,(\text{raw meal}_0) + \upsilon\, \theta\, \psi\, (m_{fg,\,0} + m_{CO2,lime,\,0})\} / V_{k,sm,o} \quad \text{(A9)}$$

From eq. A5 it follows that

$$\mathbf{V}_{\mathbf{k,sm}} = \{ (1+\psi)\theta V_{fg} \, MW_{fg} - (1+\psi)\theta V_{fg,o} \, MW_{fg,o} + V_{k,sm,o} \, MW_{k,sm,o} \} / MW_{k,sm} \qquad \text{(A10)}$$

But since the molecular weight of kiln flue gases is nearly constant (Table 3), use of assumption 1 implies **that** $MW_{k,sm} \approx MW_{k,sm,\,0}$ and then eq. A10 gives

$$\mathbf{V}_{\mathbf{k,sm}} = V_{k,sm,o} + \{ (1+\psi)\theta V_{fg} \, MW_{fg} - (1+\psi)\theta V_{fg,o} \, MW_{fg,o} \} / MW_{k,sm,0} \qquad \text{(A11)}$$

Substitution of eq. A9 in eq. A11 gives eq. (11):

$$\mathbf{V}_{\mathbf{k,sm}} = V_{k,sm,\,0} + V_{k,sm,\,0} \, \boldsymbol{\{}(1+\psi)\theta \, V_{fg} \, MW_{fg} - (1+\psi)\theta \, V_{fg,\,0} \, MW_{fg,0} \boldsymbol{\}} \, / \\ \boldsymbol{\{}\theta \, V_{fg,\,0} \, MW_{fg,\,0} + \theta \, V_{CO2,lime,\,0} \, MW_{CO2} + \upsilon \, \alpha_{sm} \, m_{CO2,lime,0} \, (1+ \eta \, MWCO_2) / \eta \, MWCO_2 + \\ \upsilon \, \theta \, \psi \, (m_{fg,\,0} + m_{CO2,lime,\,0}) \boldsymbol{\}} \qquad (11)$$

Table 1- Alternative fuels investigated in the Case Study (Decision 2000/532/EC)

	CODE	**DESCRIPTION CODE (EUROPEAN LIST OF WASTE)**
1	02 01 03	Plant tissue waste
2	02 01 04	waste plastics (except packaging)
3	03 01 05	sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03 01 04
4	04 02 21	wastes from unprocessed textile fibres
5	04 02 22	wastes from processed textile fibres
6	12 01 05	plastics particles
7	13 05 07 *	oily water from oil/water separators
8	13 05 08 *	mixtures of wastes from grit chambers and oil/water separators
9	15 01 01	paper and cardboard packaging
10	15 01 02	plastic packaging
11	15 01 03	wooden packaging
12	16 01 03	end-of-life tyres
13	16 01 19	plastic
14	17 02 01	wood
15	19 08 05	sludges from treatment of urban waste water
16	19 12 01	paper and cardboard
17	19 12 04	plastic and rubber
18	19 12 07	wood other than that mentioned in 19 12 06
19	19 12 08	textiles
20	19 12 12	other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11
21	19 12 11*	other wastes (including mixtures of materials) from mechanical treatment of waste containing dangerous substances
22	19 02 03 / 19 02 04*	premixed waste composed only of wastes marked as hazardous* or not
23	19 08 11*	sludges containing dangerous substances from biological treatment of industrial waste water
24	19 08 12	sludges from biological treatment of industrial waste water other than those mentioned in 19 08 11
25	19 12 10	combustible waste (refuse derived fuel)

- Classified as hazardous

Table 2 - Case Study Plant Data (baseline)

ζ	η **(kmol/kg)**	θ	**E**	ε **(kJ/kg clinker)**	ψ	α_{sm}	h	MW_{air}	MW_{CO2}
0.43	0.0116	0.85	20%	3550	0.15	1.66	0.0141	28.91	44

Table 3 - Fluegas and Offgas characteristics

	CODE	**Combustion fluegas flowrate (without $CO_{2\,lime}$), V_{fg} (Nm^3/h)**	**Offgas flowrate, V_{ksm} (Nm^3/h)**	**m_{fg} (tpa)**	**Molecular weight, MW_{fg} (gr/mole)**
	Baseline, (Subscription)	195 379	578 087	8 802	30.00
1	02 01 03	234.210	617 110	9 064	29.98
2	02 01 04	210.968	591 547	9 267	29.95
3	03 01 05	219.271	602 212	9 226	29.97
4	04 02 21	212.472	593 674	8 900	29.99
5	04 02 22	212.472	593 674	8 900	29.99
6	12 01 05	190.445	571 156	9 297	29.94
7	13 05 07 *	176.185	558 615	8 816	29.99
8	13 05 08 *	176.185	558 615	8 816	29.99
9	15 01 01	205.491	586 814	8 844	29.99
10	15 01 02	222.002	601 607	9 030	29.96
11	15 01 03	217.945	599 225	9 044	29.97
12	16 01 03	205.550	576 712	9 200	29.97
13	16 01 19	200.157	581 115	8 950	29.98
14	17 02 01	217.945	599 225	9 044	29.97
15	19 08 05	207.242	588 328	8 903	29.99
16	19 12 01	205.491	586 814	8 844	29.99
17	19 12 04	213.224	593 686	8 852	29.99
18	19 12 07	217.945	599 225	9 044	29.97
19	19 12 08	212.472	593 674	8 900	29.99
20	19 12 12	207.209	588 802	9 075	29.97
21	19 12 11*	208.587	592 267	8 843	29.99
22	19 02 03 / 19 02 04*	169.618	551 616	8 816	29.99
23	19 08 11*	202.531	584 481	8 884	29.99
24	19 08 12	202.531	584 481	8 884	29.99
25	19 12 10	208.587	588 802	8 843	29.99

FIGURE CAPTIONS

Fig. 1. Cement plant investigated

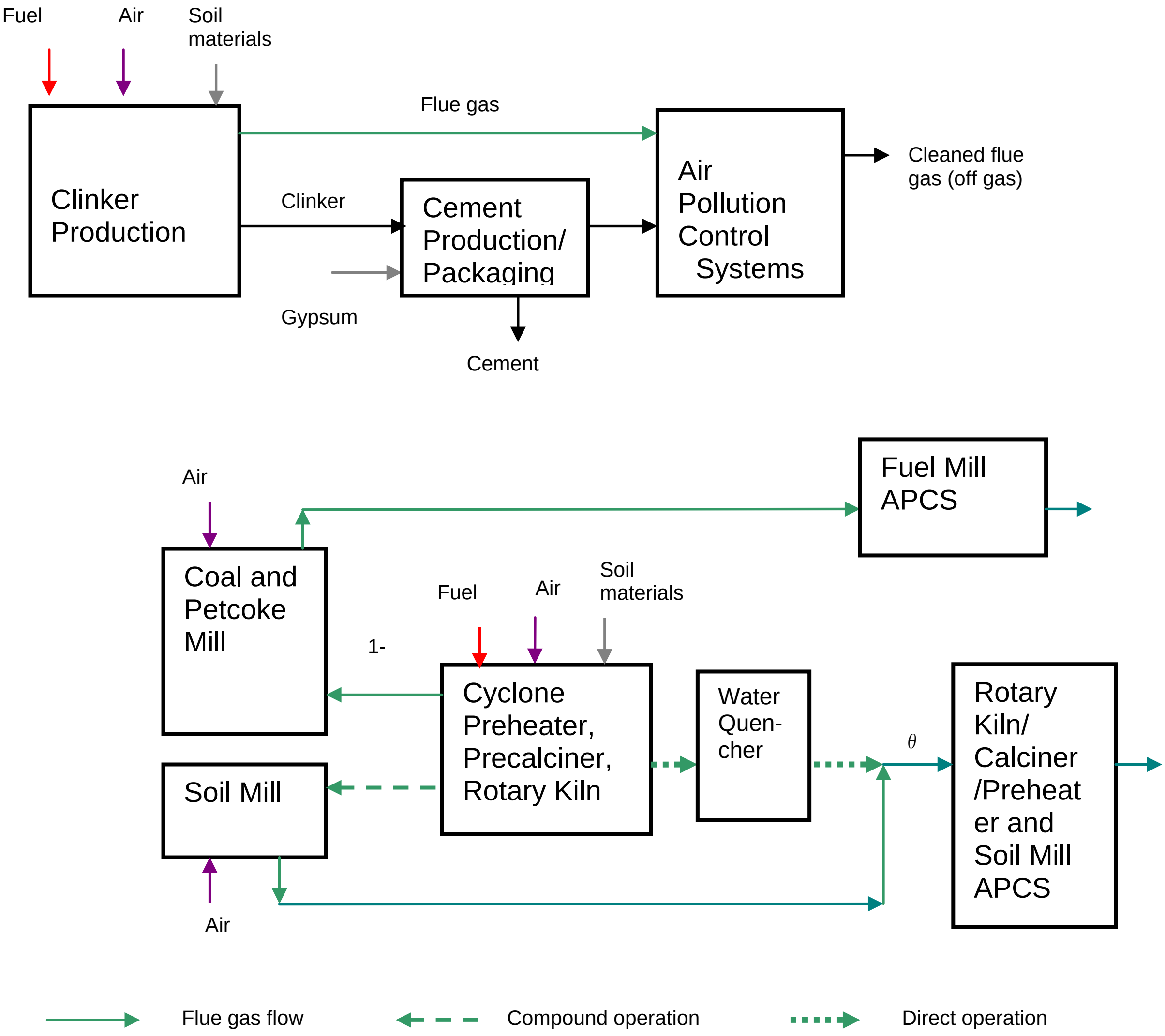

Fig. 2. Cement plant flow diagram

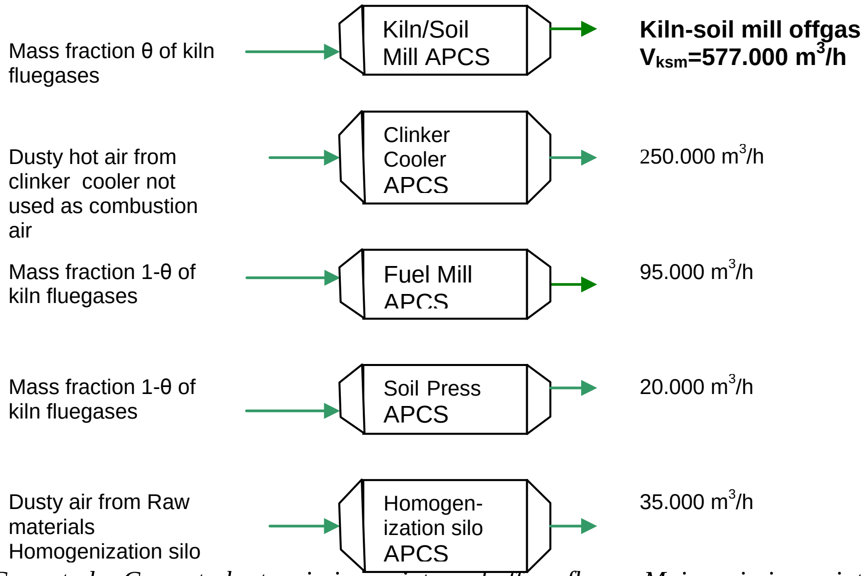

Fig. 3. *Case study: Cement plant emission points and offgas flows. Main emission point is the kiln –soil mill APCS (2 stacks with a total of 578000 Nm^3/h offgas flowrate)*

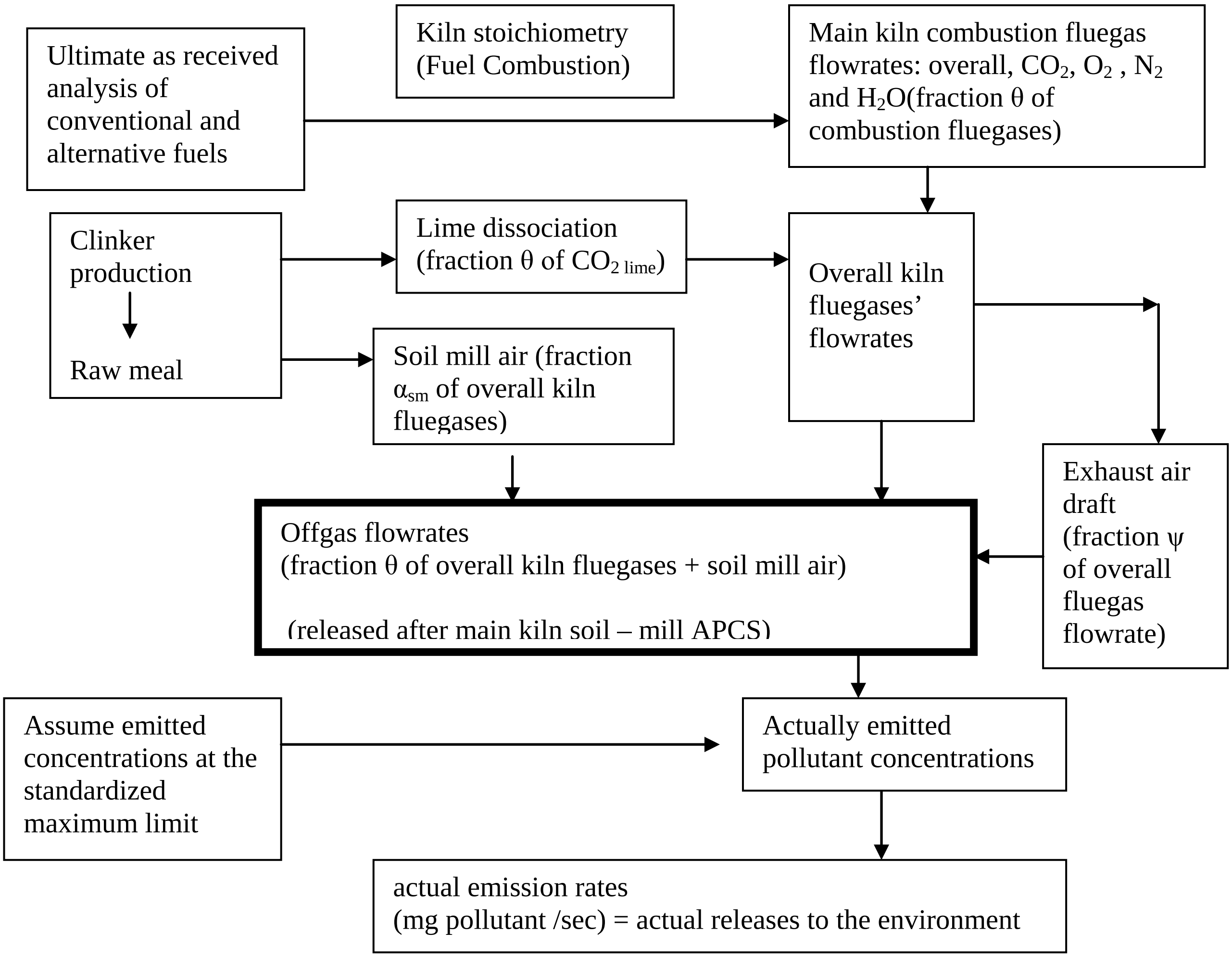

Fig. 4. Schematic description of the method used to asses AF utilization and emissions.

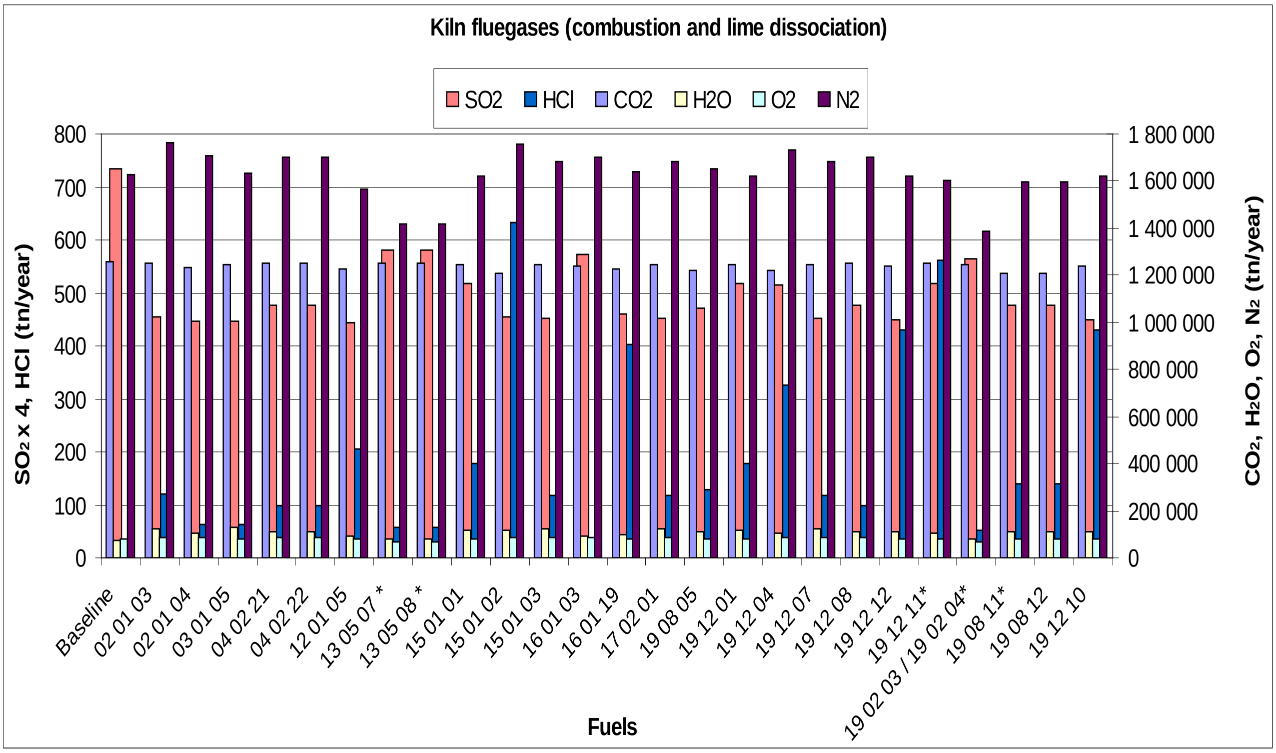

Fig. 5a. Kiln flue gas species’’ flowrates under AF utilization (30% thermal petcoke substitution).

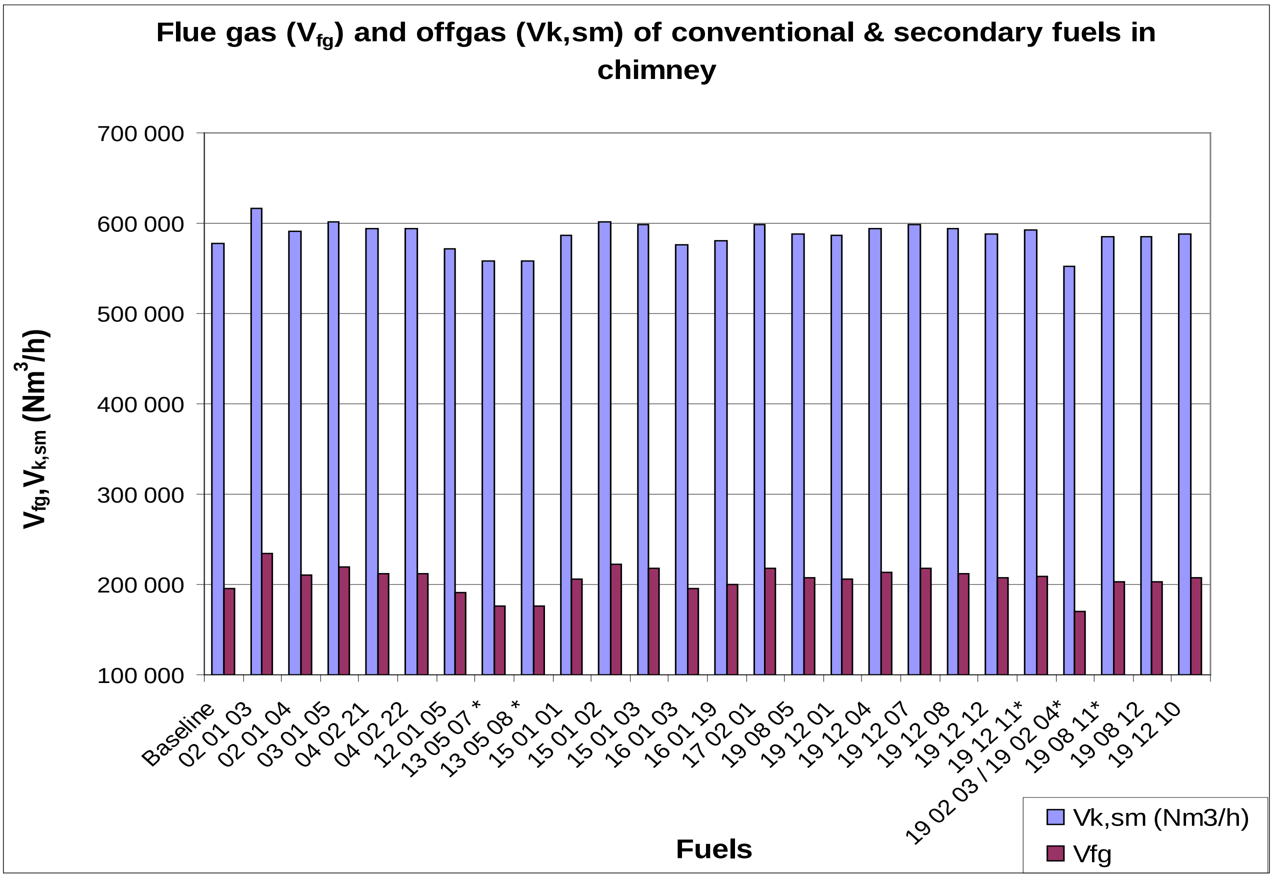

Fig. 5b. Flue gas (V_{fg}) and offgas (V_{ksm}) under AF utilization (30% thermal petcoke substitution).

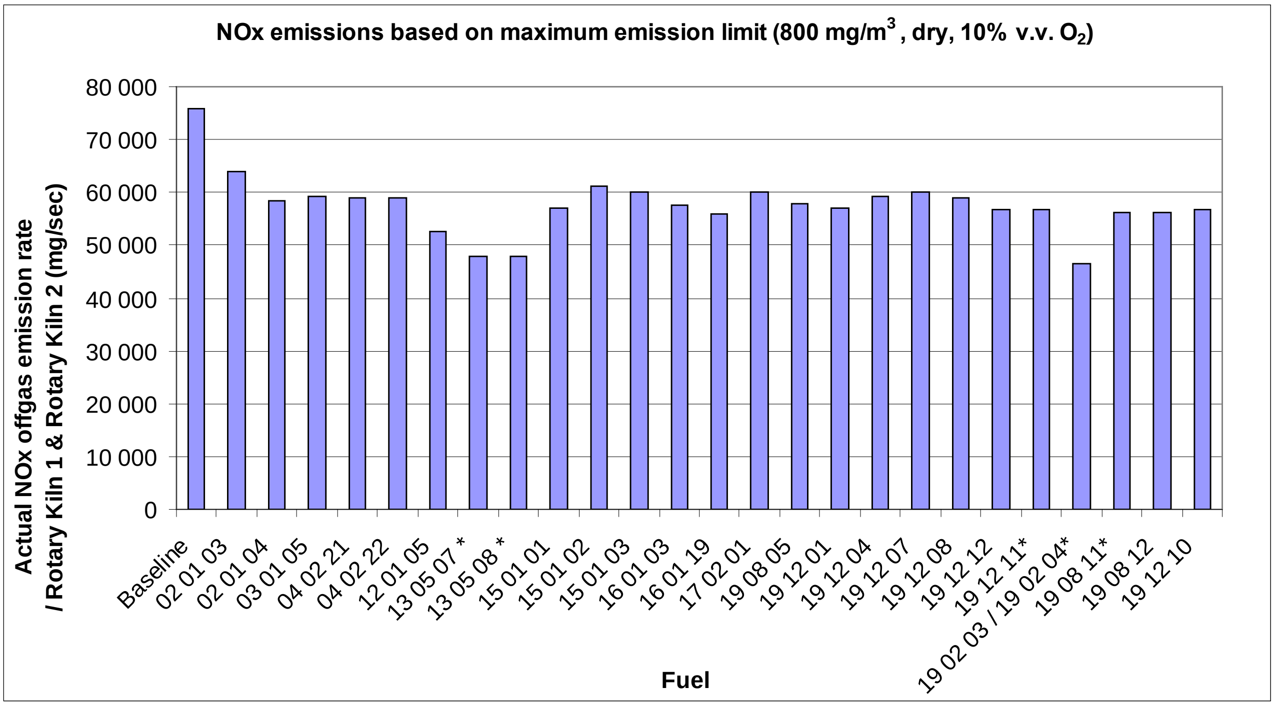

Fig. 6. NOx emissions based on maximum emission limit (800 mg/m^3, dry, 10%v.v. O_2) under conventional fuel or AF utilization (30% thermal petcoke substitution)

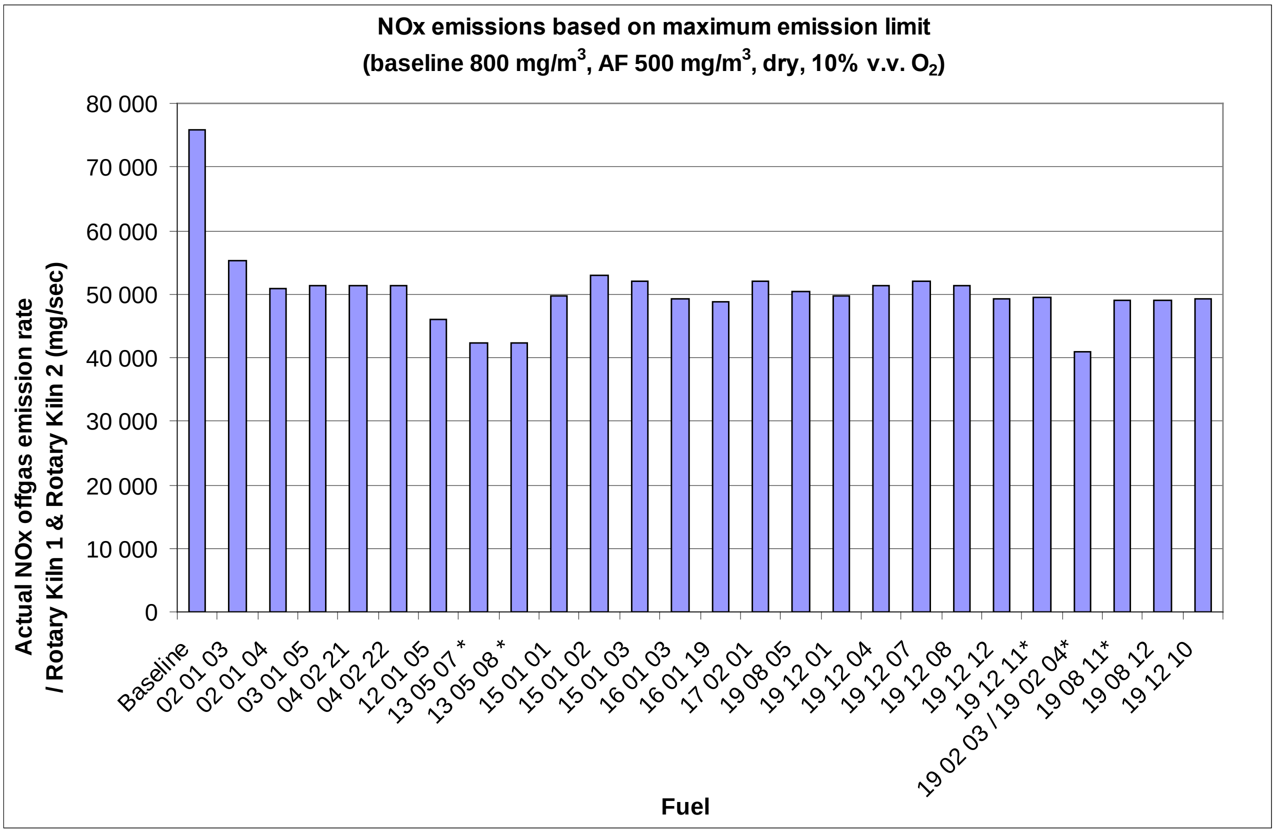

Fig. 7. NOx emissions based on maximum emission limit (800 mg/m^3 under conventional fuel, 500 mg/m^3, dry, 10%v.v. O_2 under AF utilization) (AF: 30% thermal petcoke substitution)

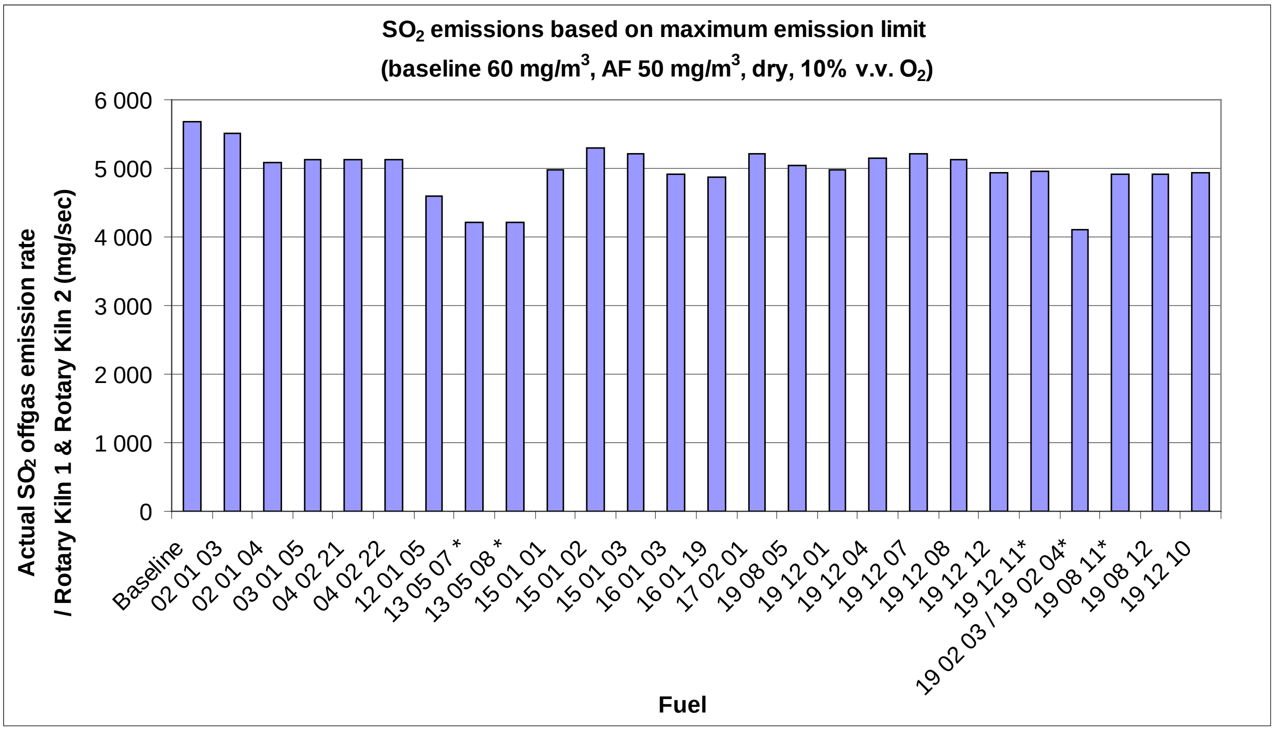

Fig. 8. SO_2 emissions based on maximum emission limit (60 mg/m^3 under conventional fuel, 50 mg/m^3 under AF utilization, dry, 10%v.v. O_2) (AF: 30% thermal petcoke substitution)

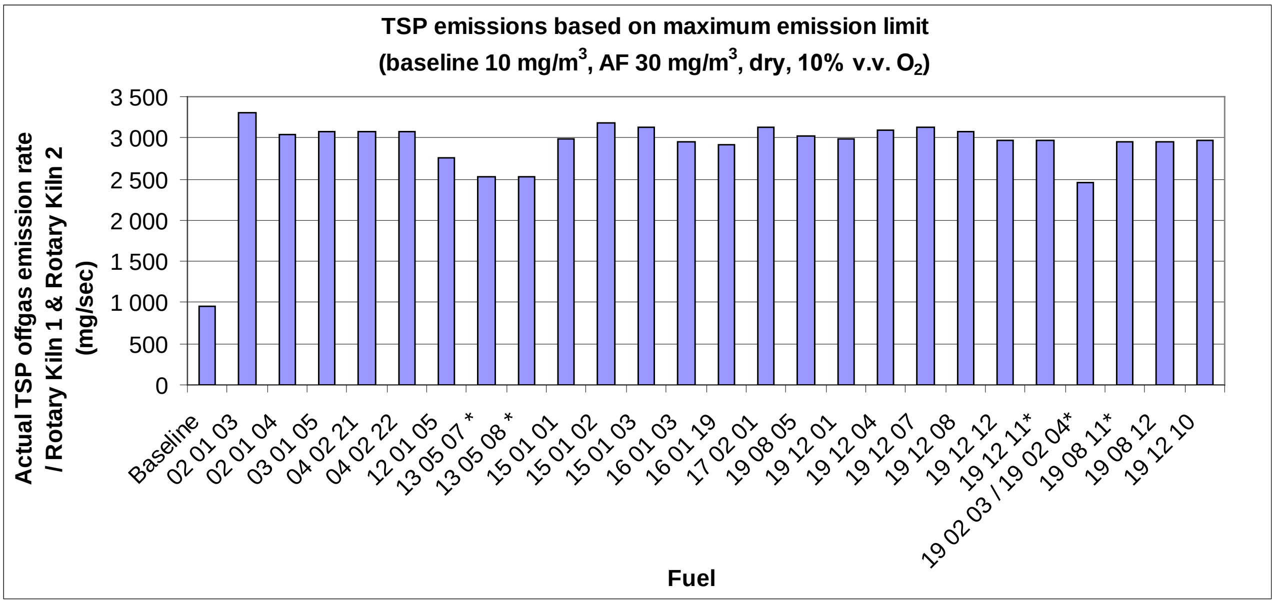

Fig. 9. TSP emissions based on maximum emission limit (10 mg/m^3 under conventional fuel, 30 mg/m^3 under AF utilization, dry, 10%v.v. O_2 (AF: 30% thermal petcoke substitution)

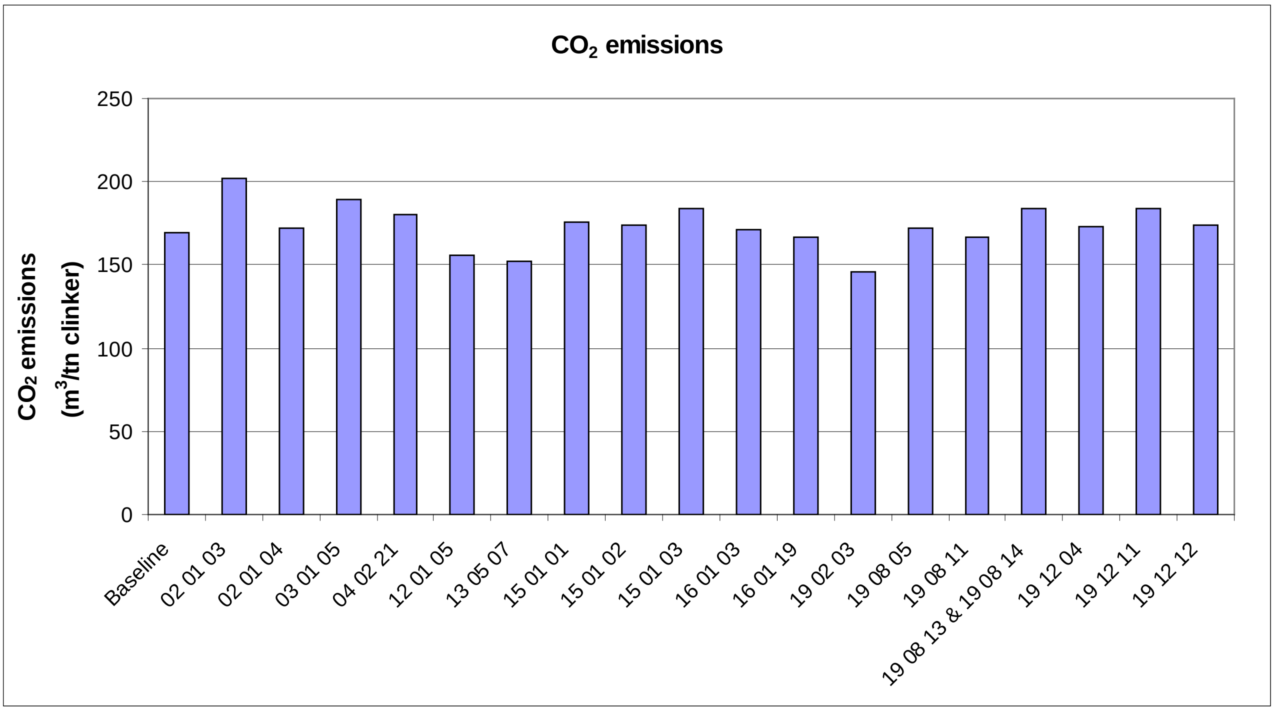

Fig. 10. CO_2 emissions under AF utilization (30% thermal petcoke substitution)

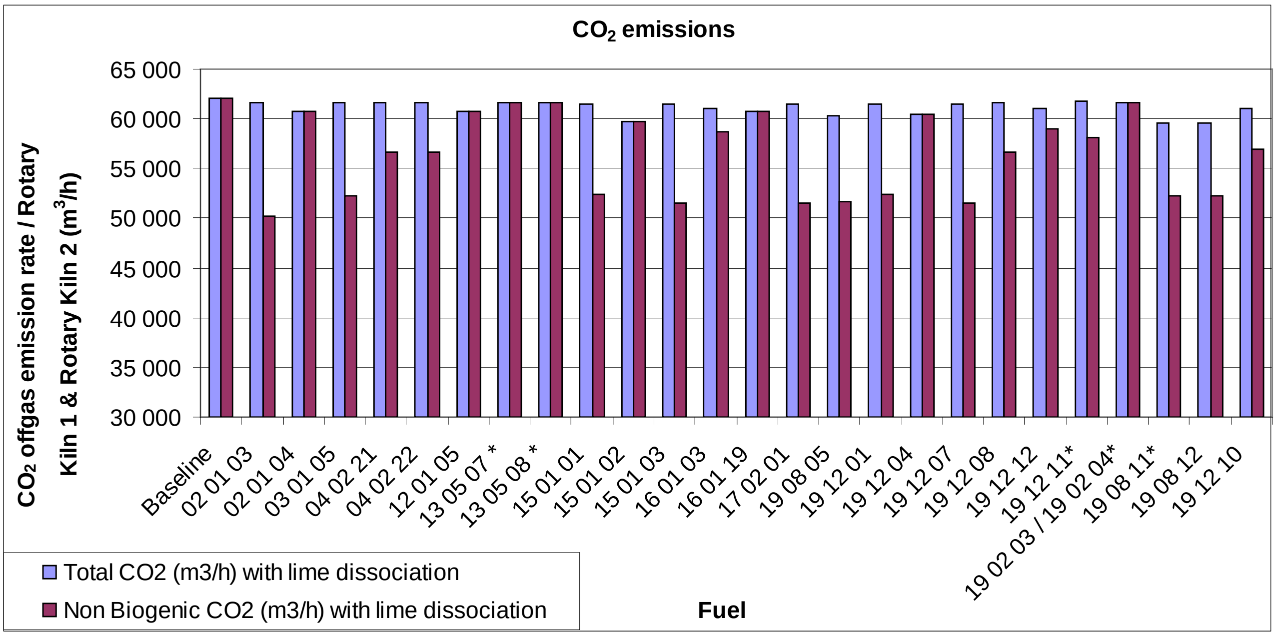

Fig. 11. Total (with lime dissociation) and non biogenic CO_2 emissions rate under AF utilization (30% thermal petcoke substitution)