Mitigation of Climate Change by Reducing Carbon Dioxide Emissions in Cement Industry

Hrvoje Mikulčić*,[a], Xuebin Wang[b], Milan Vujanović[a], Houzhang Tan[b], Neven Duić[a]

[a]Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb Croatia
[b]MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, China
 hrvoje.mikulcic@fsb.hr

The cement industry is an energy intensive industry, and one of the largest carbon emitting industrial sectors. It is emitting 5 % of global anthropogenic carbon dioxide emissions, with especially high growth in Asia. While the energy efficiency of cement production has been increased significantly, the emissions can be further reduced by replacing conventional fossil fuels with alternative ones, mostly of waste origin. Due to the lower heating value of waste derived fuels than of the standardly used coal, the use of such fuels is possible where there is no need for very high process temperatures, e.g. in cement calciners where the desirable operating temperature is around 950 °C. Using waste derived fuels in cement calciners does not only reduce combustion related CO_2 emissions in cement production by 10-30 %, depending on the amount of used waste derived fuels and the biogenic fraction in the used waste derived fuel, but is also an environmentally beneficial alternative to waste landfill disposal. However, incineration of high share of waste derived fuels in cement calciners still faces significant challenges. A possibility for the ex-ante control and investigation of the incineration process are Computational Fluid Dynamics - CFD simulations. Early comprehensive information, parametric studies and initial conclusions that can be gained from CFD simulations are very important in handling modern combustion units. The purpose of this paper is to present the benefit of using waste derived fuels in the cement industry, and to give some preliminary results on waste incineration numerical modelling.

1. Introduction

Coal as the most available fossil fuel worldwide, is the most used solid fuel for electricity production worldwide (Wang et al., 2014a). In some countries the use of coal for heat and power generation is even more pronounced. Coal accounts for approximately 70 % of the primary energy consumption in China, with coal-fired power plants producing 97 % of China's thermal power capacity (Wang et al., 2014b). The utilization of coal has however over the past decade started to face arising environmental challenges, mainly because coal-fired plants are the biggest contributor to CO_2 emissions. Consequently, extensive efforts have been devoted to develop cleaner and more efficient technologies for the utilization of coal. Partial substitution of coal by alternative fuels like waste derived fuels and biomass has attracted worldwide attention, mainly because biomass and the biogenic fraction of waste derived fuels are considered CO_2-neutral (Mikulčić et al., 2014). Therefore in the European Union already 1.3 billion t of biomass was exploited in 2010, and in China, it is planned that 50 Mt of biomass pellets will be used annually by 2020 (Niu et al., 2010). Depletion of fossil fuels, rising of their prices and the Kyoto Protocol, are more and more directing plant operators towards renewable energy. In that sense, the displacing of fossil fuels with renewable fuels is gaining on importance in all industrial sectors (Ariyaratne et al. 2014).

The present cement production is facing two main problems. The first one is the production of large amount of greenhouse gases, around 5 % of world's anthropogenic CO_2 emissions, and second one is the high fuel prices, mainly coal. The cement producers are therefore under increasing pressure to reduce their fossil fuel consumption and associated greenhouse gases emissions. Due to the huge amount of

concrete used throughout the world as construction material, especially in the developing countries, researchers are searching for ways to reduce the cost of cement production and CO_2 emissions related to cement production (Amin et al., 2014). There are several measures, which applied to the cement manufacturing processes can reduce its environmental impact and improve its competitiveness. However, it was found that partial substitution of coal by alternative fuels like waste derived fuels and biomass may play a major role in the reduction of CO_2 emissions (Mikulčić et al., 2013). At the European Union level, there is a great potential for the use of solid waste derived fuels in the cement industry. As waste disposal at landfills is the last option in the waste management strategy, energy recovery of waste derived fuels, commonly known as solid recovered fuels – SRF, in the cement industry has a high potential (Usón et al., 2013). Municipal solid waste - MSW is generated in large amounts worldwide and has a significant environment impact, as for example atmospheric emissions and effluents from landfills (Talebi and Van Goethem, 2014). This MSW generation burdens the local communities for collection, handling and disposal, and due to this reason waste management has become a significant problem (Ng et al., 2013). Traditional landfill method is also facing the problem of land shortage. Therefore, waste to energy (WtE) methods, including incineration, pyrolysis and gasification are drawing more and more attentions (Zhou et al., 2015). Energy recovery of SRF in cement combustion units has one major advantage compared to regular combustion of SRF in incinerators. Due to the need for high combustion temperatures during the cement production and supply of fresh air within the cement calciner and rotary kiln, a complete combustion of the waste is ensured. Furthermore, any ash that is produced as a by-product of the combustion process falls to the floor of the rotary kiln, reacts with the raw material and exits the rotary kiln as clinker, so there is no liquid or solid residue to contend with. As a result, the process is clean and favourable for the environment (Najjar and Waite, 2014). This is not the case when the alternative fuels are combusted in incinerators or co-combusted in utility boilers. The ash from such applications needs to be disposed of in a different way, meaning that there is still a solid residue to contend with (Wang et al., 2011).

Due to the lower heating value of waste derived fuels than of the standardly used coal, the use of such fuels is possible where there is no need for very high process temperatures, e.g. in cement calciners where the desirable operating temperature is around 950 °C, whereas in the rotary kiln the operating temperature is around 1450 °C. Incineration of high share of SRF in cement calciners still faces significant challenges, mainly because it is well known that the use of alternative fuels in existing pulverized burners alters the flame shape, the temperature profile inside the furnace, and the burnout of the fuels used. A possibility for the ex-ante control and investigation of the incineration process are CFD simulations. CFD simulations have shown to be a powerful tool during the development and optimisation of chemical engineering processes and involved apparatuses. (Miltner et al., 2014). They can show some important flow characteristics and mixing phenomena, which cannot be experimentally investigated, and because of that CFD together with experiments and theory, has become an integral component of combustion research.

The aim of this paper is to present the benefit of using waste derived fuels in the cement industry, and to give some preliminary results on waste incineration numerical modelling. The cement calciner combusting coal and plastic is simulated, to better understand the influence of fuel substitution on the flow, on the mixing of raw material and fuel particles and on the flame shape. By using a commercial finite volume based CFD code AVL FIRE®, a three dimensional geometry of a cement calciner is simulated. The code is used to simulate the turbulent flow field, species concentrations and reactions, heat and mass transfer, and the interaction of raw material and fuels with the gas phase. Mathematical model taking into account the major effects of raw material thermal decomposition and fuel combustion are applied.

Previous study results (Mikulčić et al., 2012a), where only coal was used as fuel in the cement calciner, and the results obtained by simulating the same cement calciner with partly substituted fossil fuel, are compared. The temperature field in the near burner region and the distribution of gaseous species are analysed, finally particle trajectories of limestone and fuel are discussed. The results gained by this study can be used for improving the understanding of incineration process of plastic fuels in cement calciners.

2. Numerical models

In order to correctly numerically study the thermal decomposition of limestone particles, combustion of fuel particles, and gas emissions from a cement calciner, relevant thermo-chemical reactions occurring inside the cement calciner has to be treated, e.g. the raw material thermal decomposition and the combustion of coal and plastic. In this study, and in the most engineering applications today, the Eulerian-Lagrangian method for solving the multi-phase flow phenomena is used. The motion and transport of the particles, through the cement calciner, are tracked through the flow field using a Lagrangian formulation, while the

gas phase is described by solving conservation equations using an Eulerian formulation. The coupling between the solid and the gaseous phases is taken into account by introducing appropriate source terms for interfacial mass, chemical species, momentum and energy exchange. The developed mathematical models for the raw material thermal decomposition and the combustion of coal and plastic are treated in the Lagrangian spray module, where thermo-chemical reactions occur inside a particle as well as between the particle and the gas phase. The chemical reactions inside the gas phase are treated via an ODE solver providing additional sink and source terms for the species and enthalpy transport equations in the gas phase. The developed models, as well as a particle radiation model, were integrated into the CFD code AVL FIRE®, in order to simulate the calcination and combustion process properly (FIRE Manual, 2014).

2.1 Raw material thermal decomposition
Raw material used in the cement production is mainly composed of limestone. Prior to the cement calciner limestone is dried and preheated in the cyclones. In the cement calciner limestone is decomposed by heating to lime and carbon dioxide according to the following endothermic reaction:

$$CaCO_3(s) \xrightarrow{+178\,kJ/mol} CaO(s) + CO_2(g). \tag{1}$$

The developed model of the limestone thermal decomposition takes into account the effects that have an influence on the chemical reaction rate, like decomposition pressure and temperature, and on the physical reaction rate, like diffusion and limestone pore efficiency. The used model of the limestone thermal decomposition was extensively tested in our previous study (Mikulčić et al., 2012b).

2.2 Pulverized coal combustion
Pulverized coal is the most commonly used solid fuel in cement industry, and therefore has been extensively studied. The model of pulverized coal combustion used in this study has four stages. The coal particle first undergoes the drying process see Eq(2), after which the pyrolytic decomposition of coal particle starts. During this stage an important loss of weight occurs, because of the release of volatile matter, the quantity and composition of which depend on the coal ingredients, its particle size and temperature - see Eq.(3). After the pyrolysis is finished only char and ash is left in the solid particle. The char is oxidized to CO_2 parallel to the pyrolysis - see Eq(4), and afterwards only ash if left. The treated chemical reactions are:

$$wet\ Coal(s) \xrightarrow{H_2O\ evaporation} dry\ Coal(s), \tag{2}$$

$$dry\ Coal(s) \xrightarrow{pyrolysis} Volatile(g) + Char(s), \tag{3}$$

$$Char(s) + O_2(g) \longrightarrow CO_2(g), \tag{4}$$

$$Volatile(g) + O_2(g) \longrightarrow H_2O(g) + CO_2(g). \tag{5}$$

The heterogeneous reactions Eq(2), Eq(3) and Eq(4) cause mass transfer sources and sinks to the gas phase and particles. The homogeneous reactions - see Eq(5) - of volatile oxidation are treated within the gaseous phase reactions module of the CFD code used. Considered volatile species in this model are CO, CH_4, H_2, C_6H_6. For the oxidation of volatile species, a detailed chemistry approach is used for each of the homogeneous reaction.

2.3 Plastic combustion
To model the combustion of waste derived fuels like SRF is a challenging task, due to its inhomogeneous composition. SRF is a mixture of biogenic and plastic fractions, where each fraction undergoes a different combustion process. Biogenic fraction tends to have similar combustion behaviour as coal, whereas plastic fraction has simpler, but completely different combustion behaviour. To give some preliminary results on waste incineration in the cement calciner, only plastic fraction is modelled in this study. An assumption is made that polypropylene is the representative of the solid plastic fraction, since for polypropylene well known and established chemical reaction rates can be found in literature (Westbrook and Dryer, 1981).

There are no heterogeneous reactions during the polypropylene combustion. When polypropylene is heated-up, it thermally decomposes and evaporates to the gas phase Eq(6). Right then when there is vapour polypropylene, it starts to oxidize - see Eq(7) and Eq(8).

$$C_3H_6(s) \xrightarrow{\textit{thermal decomposition}} C_3H_6(g). \tag{6}$$

$$C_3H_6(g) + 3O_2(g) \longrightarrow 3CO(g) + 3H_2O(g). \tag{7}$$

$$CO(g) + 0.5O_2(g) \longrightarrow CO_2(g). \tag{8}$$
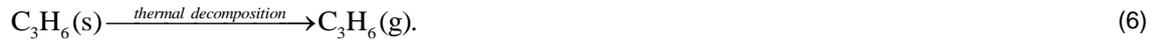
The thermal decomposition of polypropylene Eq(6) causes a mass transfer sources to the gas phase and a sink to the particle. The homogeneous reactions Eq(7) and Eq(8) of vapour polypropylene and carbon monoxide oxidation are, also like volatiles form the coal combustion model, treated within the gaseous phase reactions module of the CFD code used.

3. Computational details

A full scale three dimensional geometry of a cement calciner is used for the simulation. Its geometry and boundary conditions used for the simulation only the coal combustion case can be found in literature (Mikulčić 2012a). The modelled calciner consists of two parts, where one part is used for combusting fuels and the other is used to enhance the limestone thermal decomposition. The calciner is 24 m high in total. The computational domain consists of 47,000 cells, which were employed to discretize the computational domain. Turbulence was modelled by the standard k-ε model. A transient simulation was performed with a time-step of 10^{-4} s. The pressure velocity coupling of the momentum and continuity equations was obtained using the SIMPLE algorithm. The Central difference discretisation scheme was used for momentum, continuity and enthalpy balances, and the Upwind differencing scheme was used for turbulence and scalar transport equations. The P-1 radiation model was employed to model the radiative heat transfer, since it takes into account the particle radiation effects.

4. Results and discussion

Figure 1 shows the temperature field and the CO_2 mole fraction inside the calculated cement calciner for two cases. For combusting only coal, on the left hand side of the figure, and co-firing coal and plastic on the right side of the figure. Comparing the temperature fields of the two cases, it can be seen that co-firing of coal and plastic increases the temperature in the near burner region. This is due to the increased amount of combustible volatile hydrocarbons that are produced by the polypropylene thermal decomposition. As for the CO_2 mole fractions, it can be observed that co-firing also effects where most of the CO_2 is generated. Due to the lower temperature in the near burner region in the case where only coal is used for heat generation, CO_2 has the highest concentration in the lower part of the connecting cylinder, since limestone particles need more time to decompose. As opposed to that, in the co-firing case the temperature in the near burner region is higher, limestone particles react more quickly, realising the CO_2 during its decomposition and therefore CO_2 has the highest concentration in the middle part of the connecting cylinder.
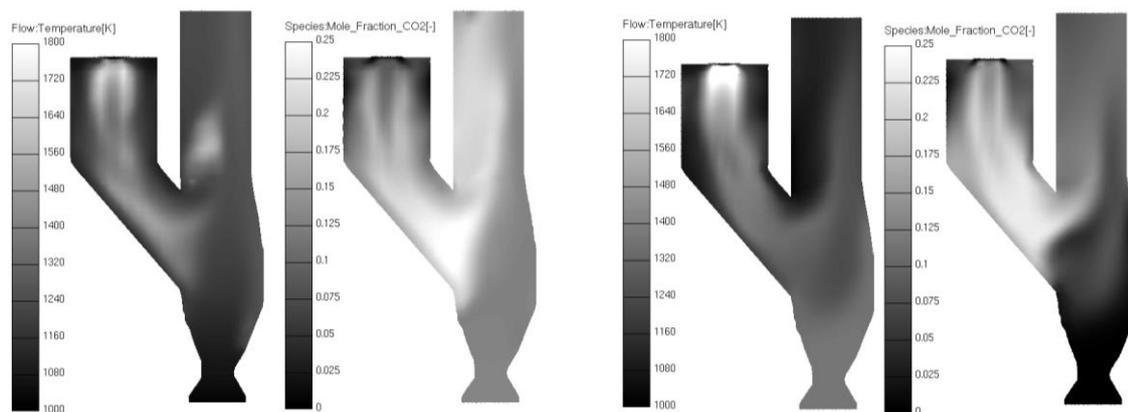
Figure 1: Temperature field and CO_2 mole fraction: Only coal(left); Co-firing coal and plastic(right).

Figure 2 shows the CO mole fraction and the velocity field inside the calculated cement calciner for two cases. Again on the left hand side of the figure is the case where only coal is combusted, and on the right side of the figure is the co-firing of coal and plastic case. It can be seen that in the co-firing case CO concentration has the highest concentration in the near burner region, whereas in the coal case still significant concentration of CO is observed in the connecting cylinder. This CO concentration difference is related to the temperature difference between two cases. In the first case where only coal is combusted, temperature in the near burner region is lower, and char particles need more time to fully burnout, and therefore CO is generated in the connecting cylinder. As for the velocity fields, it can be observed that previously described co-firing effects also have an impact on the flow.
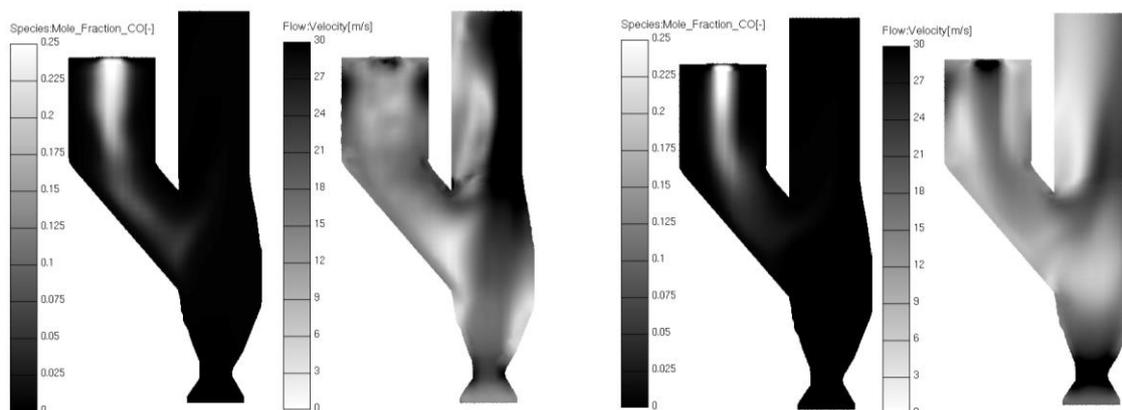
Figure 2: CO mole fraction and Velocity field: Only coal(left); Co-firing coal and plastic(right).

The simulation results showed that the use of alternative fuels in existing cement calciner changes its working conditions. Therefore an in-depth understanding of the process properties under a wide range of conditions is required, in order to start using alternative fuels in existing pulverized burners. Geometric and inlet condition parameter variation can give different operating scenarios that can be explored and used as a support for decision making.

5. Conclusion

Partial substitution of coal by alternative fuels like SRF and biomass has attracted attention in all industrial sectors. The present cement production is facing the problem of increased fuel prices, and the need for lowering its environmental impact. Therefore, cement producers are under pressure to reduce their fossil fuel consumption and to reduce their CO_2 emissions. To satisfy the need for cement and the increased governmental and public environmental awareness, cement producers are including alternative fuels, especially waste derived fuels like SRF, in their production process. The use of such fuel is beneficial in several ways. First benefit is that waste disposal at landfills is lowered, and therefore the greenhouse gas emissions and effluents from landfills are lowered. Second benefit is that by using SRF as a substitute fuel for coal in existing cement plants cement producers can lower greenhouse gas emissions. Third and probably the biggest advantage of using SRF in cement industry is that ash from combustion is incorporated in the clinker, so there is no residue to contend with. Co-firing coal and SRF of high share in cement combustion units still faces significant challenges, mainly because SRF changes the flame shape, the temperature profile, and the burnout of the fuels. Precisely because of this reason it is expected that CFD simulations may be a useful tool for the investigation of the SRF and coal co-firing process. The aim of this paper is to demonstrate that CFD can be used for the analysis and investigation of the co-firing process inside the cement calciner. The paper gives some preliminary results on coal and plastic co-firing numerical modelling. The results gained by this study can be used for improving the understanding of incineration process of plastic fuels in cement calciners. By improving the understanding of incineration process also the operating process can be improved, and thus a cement production with lower environmental impact can be achieved. Further research in this field will include the development of a simple SRF combustion model and the investigation of coal fuel substitution rate.

Acknowledgements

References

Amin N.U., Alam S., Gul S., 2014, Synthesis of alkali activated cement from local clay and its characterization, Chemical Engineering Transactions, 39, 1555-1560 DOI:10.3303/CET1439260

Ariyaratne W.K.H., Melaaen M.C., Tokheim L.-A., 2014, Determination of biomass fraction for partly renewable solid fuels, Energy 70, 465-472.

FIRE_v2014_Manuals, 2014, Graz, Austria

Mikulčić H., von Berg E., Vujanović M., Priesching P., Tatschl R., Duić N., 2012a, CFD analysis of a cement calciner for a cleaner cement production, Chemical Engineering Transactions, 29, 1513-1518, DOI: 10.3303/CET1229253

Mikulčić H., von Berg E., Vujanović M., Priesching P., Perković L., Tatschl R., Duić N., 2012b, Numerical modelling of calcination reaction mechanism for cement production, Chem. Eng. Sci. 69, 607-615.

Mikulčić H., Vujanović M., Markovska N., Filkoski R., Ban M., Duić N., 2013, CO_2 emission reduction in the cement industry, Chemical Engineering Transactions, 35, 703-708, DOI:10.3303/CET1335117

Mikulčić, H., von Berg E., Vujanović M., Duić N., 2014, Numerical study of co-firing pulverized coal and biomass inside a cement calciner, Waste Manag. Res. 32, 661–669.

Miltner M., Jordan C., Harasek M., 2014, On the applicability of RANS-turbulence models in CFD simulations for the description of turbulent free jets during biomass combustion, Chemical Engineering Transactions, 39, 913-918 DOI:10.3303/CET1439153

Najjar Y.S.H., Waite D., 2014, Energy conservation and waste utilization in the cement industry serve the green technology and environment, Int. J. Sustain. Eng. DOI:10.1080/19397038.2014.991775

Ng W.P.Q., Varbanov P.S., Klemeš J.J., Hegyhati M., Bertok B., Heckl I., Lam H.L., 2013, Waste to energy for small cities: economics versus carbon footprint, Chemical Engineering Transactions, 35, 889-894 DOI:10.3303/CET1335148

Niu Y., Tan H., Ma L., Pourkashanian M., Liu Z., Liu Y., Wang X., Liu H., Xu T., 2010, Slagging Characteristics on the Superheaters of a 12 MW Biomass-Fired Boiler, Energy Fuels 24, 5222–5227.

Talebi G., Van Goethem M., 2014, Synthesis gas from waste plasma gasification for fueling lime kiln, Chemical Engineering Transactions, 37, 619-624 DOI: 10.3303/CET1437104

Usón A.A., López-Sabirón A.M., Ferreira G., Sastresa E.L., 2013, Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options, Renew. Sustain. Energy Rev. 23, 242–260.

Wang G., Silva R.B., Azevedo J.L.T., Martins-Dias S., Costa M., 2014a, Evaluation of the combustion behaviour and ash characteristics of biomass waste derived fuels, pine and coal in a drop tube furnace, Fuel 117, 809–824.

Wang X., Tan H., Niu Y., Pourkashanian M., Ma L., Chen E., Liu Y., Liu Z., Xu T., 2011, Experimental investigation on biomass co-firing in a 300 MW pulverized coal-fired utility furnace in China, Proc. 33th Int. Symposium on Combust., The Combustion Institute, 2725–2733.

Wang X., Tan H., Yan W., Wei X., Niu Y., Hui S., Xu T., 2014b, Determining the optimum coal concentration in a general tangential-fired furnace with rich-lean burners: From a bench-scale to a pilot-scale study, Appl. Therm. Eng. 73, 371-379

Westbrook C.K., Dryer F.L., 1981, Simplified reaction mechanisms for the oxidation of hydrocarbon fuels in flames, Comb. Sci. Techn. 27, 31-43.

Zhou H., Long Y.Q., Meng A.H., Li Q.H., Zhang Y.G., 2015, Classification of municipal solid waste components for thermal conversion in waste-to-energy research, Fuel 145, 151–157.