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Experiments and modeling of single plastic particle conversion in suspension

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ABSTRACT

Conversion of single high density polyethylene (PE) particles has been studied by experiments and modeling. The experiments were carried out in a single particle combustor for five different shapes and masses of particles at temperature conditions of 900 and 1100°C. Each experiment was recorded using a camera. For selected experiments, the center and surface temperatures of the particles were measured using a thermocouple and an IR camera, respectively. During each experiment, the polyethylene particles went through melting, deformation, and decomposition. After the start of decomposition, the surface temperature became almost constant within the range of 480–550°C. The total conversion times of polyethylene particles were mainly influenced by the reactor temperature and particle mass, and the effect of particle shape was less significant. A non–isothermal 1D model was established and validated against the experiments as well as literature data. Furthermore, a simplified isothermal model appropriate for CFD applications was developed, in order to model the combustion of plastic particles in cement calciners. By comparing predictions with the isothermal and the non–isothermal models under typical calciner conditions, it is shown that the accuracy in prediction of the total conversion times of thermoplastic particles is within ± 30%, for particles lighter than 1000 *mg*.

1. Introduction

The cement calciner is a part of a cement plant where the thermal decomposition of calcium carbonate into calcium oxide takes place. As this reaction is highly endothermic, around 55–65% of the fuel used in the cement plant is consumed in the calciner [1]. In recent years, there have been progressive attempts in the reduction of fuel cost and CO_2 emission in the cement calciner by substituting fossil fuels with alternative fuels, especially Refuse Derived Fuel (RDF).

As RDF particles are generally larger than the conventional fossil fuel particles, one of the main challenges of substituting fossil fuels with RDFs in the calciner is the fuel burnout. The unburnt fuel particles exiting the calciner will be carried out along with the calcined raw meal to the lowest cyclone and may cause melt–induced buildups [2]. Additionally, the substitution of fossil fuels with RDF may change the operational conditions inside the cement calciner, e.g. temperature distribution, emissions.

RDF is a highly heterogeneous fuel consisting of different materials such as plastics, paper, wood, textile. Around 10 to 30% of RDF in Europe is composed of plastics [3,4] with the main constituents being polyethylene (PE) and polypropylene (PP) [5]. Both PE and PP are thermoplastics, meaning that they undergo a reversible deformation at elevated temperatures until the temperature reaches the minimum decomposition temperature [6]. For thermoplastic polymers, a well–defined temperature region of melting exists because of their high degree of crystallinity [6]. After the melting process, the thermal decomposition of non–charring thermoplastics happens in the liquid phase by breakage of the large polymer molecules into smaller molecules and gaseous species. For PE and PP, the main decomposition mechanism is random–chain scission, i.e. the breakage of large polymer molecules at random locations of the polymer chain [6].

The suspension conversion of small size plastic particles, i.e. smaller than 1 *mm* in diameter, is investigated in a drop–tube furnace [7,8]. The heating rate of these particles may reach up to 10,000 *K/s* and for PE particles of 70–250 *μm*, the conversion time is in the range of 9–75 *ms*. For larger sized plastic particles, i.e. in the range of 1–10 *mm*, which are more relevant for typical RDF plastics used in the cement calciners, the conversion time is significantly higher. This makes the drop–tube experiments less applicable for combustion of RDF–sized plastic particles.

In calciners, the gas temperature is typically in the range of 850–1200°C [9], and the recommended size limit for RDF particles to be converted in suspension inside the calciner is 50–80 *mm* [10].

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Nomenclature

C_p	Particle specific heat
d_p	Particle diameter
G	Radiation intensity
K_m	Melting reaction rate
K_d	Decomposition reaction rate
m_L	Particle liquid mass
m_p	Particle overall mass
m_S	Particle solid mass
Nu_p	Particle Nusselt number
Pr_g	Gas Prandtl number
r	Position in spherical coordinates
Re_p	Particle Reynolds number, $\frac{\rho_g d_p U_{slip}}{\mu_g}$
T	Temperature
T_g	Gas temperature
T_p	Particle overall temperature
U_{slip}	Slip velocity between the gas and the particle

Greek symbols

α	Absorption coefficient
Δh_m	Heat of melting
Δh_d	Heat of decomposition
ϵ_p	Particle total emissivity
κ_g	Gas thermal conductivity
κ_p	particle thermal conductivity
μ_g	Gas viscosity
ρ_g	Gas density
ρ_p	Particle density
σ	Stefan–Boltzmann coefficient
ϕ	Wadell's degree of sphericity

Subscripts

L	Liquid phase
S	Solid phase
V	Vapor phase

Experimental studies of conversion of large plastic particles in suspension are rare. Yang et al. [11] studied the combustion of individual spherical polymethylmethacrylate (PMMA), PP, and polystyrene (PS) particles with a size range of 2.0–6.4 *mm* in low gravity conditions. Two heated coils were used to ignite particles in an oxygen–rich atmosphere. During the combustion of particles, different dynamic events were observed including bubbling, sputtering, break–up, and soot–shell formation. Two distinct periods during the conversion were reported: an initial period with a constant diameter followed by a shrinking period. They proposed a D^2 law to model the average rate of particle mass change. Bluhm-Drenhaus et al. [12] investigated pyrolysis of PE particles in a single particle reactor at a temperature range of 900–1100°C and inert atmosphere. They measured the temporal evolution of the temperature inside the particle using a thermocouple until the time when the particle is dropped on the reactor wall after melting. They reported the conversion times of PE particles of the same mass (466 *mg*) with different shapes, concluding that both reactor temperature and particle shape are important factors affecting the conversion time.

There are also a number of studies dealing with the combustion of plastic pellets in fluidized beds [13,14]. In general, in fluidized beds, a plastic particle sinks inside the bed immediately after melting and quantification of the conversion time becomes complex. Also, the combustion behavior of plastic particles in a fluidized bed would be different from that of a suspended particle in the cement calciners.

Besides experimental work, there are a number of studies focusing on the modeling of large plastic particle conversion. The existing 1D models for conversion of non–charring plastics are generally based on Cartesian coordinates. These studies are mainly preliminary and usually applicable for purposes other than suspension combustion of particles, e.g. fire–safety issues (for example, see [15-22]). However, for suspension conversion of non–spherical plastic particles, the shape of particles in suspension will change to close–to–spherical bodies after melting [23]. Therefore, it is reasonable to use the spherical coordinate system for modeling particle conversion. To the authors' knowledge, there is no 1D model in the spherical coordinates to predict the conversion of non–charring plastics in suspension. Bluhm-Drenhaus et al. [12] proposed a simplified model that is applicable for CFD calculations. However, the model is limited by the assumption of constant heat transfer coefficient to the particle during the whole decomposition process.

The literature survey above reveals that there is a lack of comprehensive experimental data as well as an extensively validated model regarding the conversion of large thermoplastic particles in suspension. In the present study, conversion experiments of high density

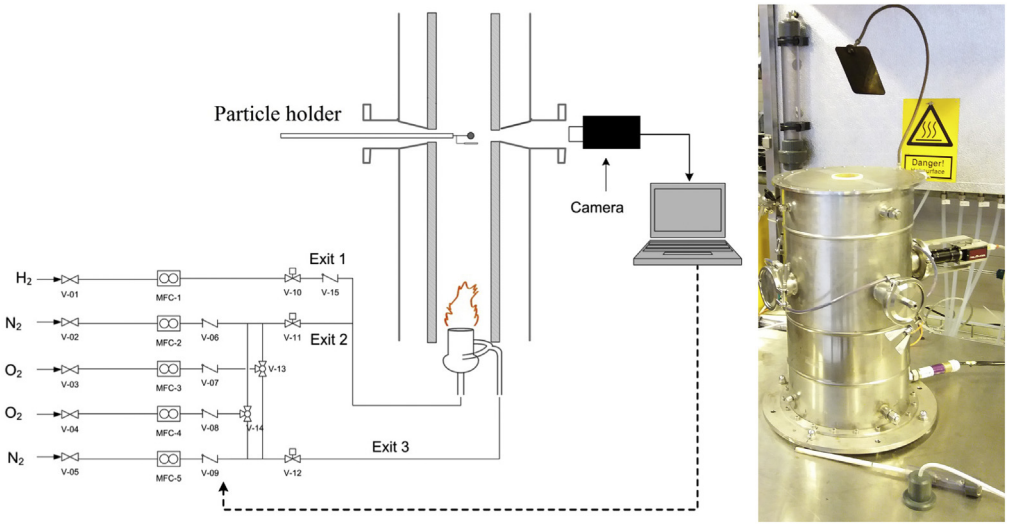

Fig. 1. A schematic configuration [41] (right) as well as a picture (left) of the SPC setup.