Heat transfer to a single plastic resin particle – Experimental investigations by flames and laser pulses

M. Lackner[1], *M. Schwarzott*[1], *G. Liedl*[2], *C. Feilmayr*[3], *S. Schuster*[3], *F. Winter*[*, 4]

[1]ProcessEng Engineering GmbH, Jörgerstrasse 56-58, 1170 Vienna, Austria
[2]Vienna University of Technology, Institute for Forming- and High Power Laser Technology,
Franz Grill Straße 1/345A, 1030 Vienna, Austria
[3]Voestalpine Stahl GmbH, VOEST-ALPINE-Strasse 3, Postfach 3, A-4031 Linz, Austria
[4]Vienna University of Technology, CD Laboratory for Chemical Engineering at High Temperatures,
Getreidemarkt 9/166, 1060 Vienna, Austria

Abstract

Heat transfer is of crucial importance to understand the conversion kinetics and the behavior during combustion of fuels such as plastics particles. In this work, the heat transfer onto single plastic resin particles (5x7 mm) by flames and a pulsed laser was studied by recording time resolved series of images with a high speed CCD (charge coupled device) camera. Images in the visible spectrum were recorded with a time resolution between 1 ms and 25 ms for a total duration of up to 60 s. A pulsed Nd:YAG laser was used in this study. For comparison, also a McKenna flat flame burner and a Bunsen burner operating on fuel-rich to fuel-lean CH_4/air mixtures were used. The plastic resin particles were drilled and mounted horizontally on a thin wire. In the middle of the particle under investigation, a thermocouple was placed. For the experiments with the laser, the particle was suspended in room air (illuminated area 2 mm², pulse duration 10 ms, pulse energy 5-30 J, laser wavelength 1064 nm). For the experiments in the flames, the particle was placed in different areas of the flame in a temperature range between 670 and 1470 K. A laser pulse energy of 5 J was found necessary to ignite the particles. At pulse energies of 30 J strong ablation was noticed. The mass loss was 0.6 mg (at 5 J) to 3.1 mg (at 30 J). The ablated material did not burn completely, but left a cloud of soot behind. In the laser experiments, only a small temperature rise of approx. 10 K was measured inside the particle. The laser-induced flame could not be sustained, it extinguished again after 5-20 s. The mass loss was determined after 10 consecutive laser shots. The plastic particles suspended in the flames took considerably longer to react. Only after approx. 10 s of heat transfer, a flame could be seen. The full process was studied. The effects of particle swelling, volatilization and char combustion were studied in the flames. (Fast) combustion of gaseous material, stemming from ablation and volatilization, could be discerned from (slow) combustion of the solid particle. The composition of the plastic resin particles was found to have a strong influence on the heat transfer.

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[*] Corresponding author: franz.winter@tuwien.ac.at

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Introduction

The overall thermodynamic properties of plastic resin particles can be determined by several analytical methods like thermo gravimetric analysis (TGA) or differential scanning calorimetry (DSC). However, in order to gain a deeper insight into the conversion kinetics of the material and its behavior during combustion, knowledge about the heat transfer is necessary. In this area, only little data can be found. Therefore, the authors carried out a preliminary experimental study to describe the phenomenological behavior of single plastic resin particles under the influence of a pulsed laser beam and a flame, thereby exposing the particles to two different regimes of heat transfer.

Experimental

In this work, the heat transfer onto single plastic resin particles by flames and a pulsed laser was studied by recording time resolved series of images with a high speed CCD (charge coupled device) camera. Images in the visible spectrum were recorded with a time resolution of 1 ms with time steps between 1 ms and 25 ms for a total duration of up to 60 s. The plastic resin particles were of cylindrical shape and approx. 5 mm in diameter and 7 mm in length. They were composed heterogeneously of pressed material, containing various plastic resins like PVC, PP, PE and PUR. A pulsed Nd:YAG laser was used in this study. For comparison, also a McKenna flat flame burner and a Bunsen burner operating on fuel-rich to fuel-lean CH_4/air mixtures were used. The plastic resin particles were drilled and mounted horizontally on a thin wire. In the middle of the particle under investigation, a thermocouple was placed. For the experiments with the laser, the particle was suspended in room air (illuminated area 2 mm², pulse duration 10 ms, pulse energy 5-30 J, laser wavelength 1064 nm). For the experiments in the flames, the particle was placed in different areas of the flame in a temperature range between 670 and 1470 K. Fig. 1 and 2 show the experimental setup. In Fig. 1, the setup of the laser experiments can be seen.

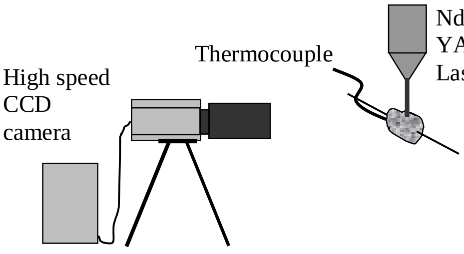

Fig. 1: Scheme of the experimental set up for heat transfer onto plastic resins by laser pulses

The setup for the experiments in the flames was similar, see Fig. 2 below.

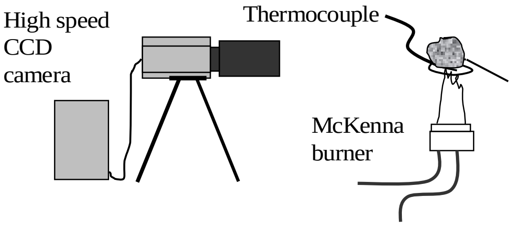

Fig. 2: Scheme of experimental set up for heat transfer onto plastic resins in flames.

2.1 Heat transfer studied with the Nd:YAG laser

In Figs. 3-5, typical sequences are shown. Each sequence was conducted with a new pellet.

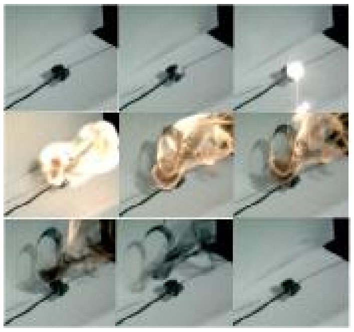

Fig. 3: Heat transfer onto a single plastic resin particle from a low energy laser shot (5 J). Recording times of photos (from top to bottom): 0ms, 1ms, 2ms, 24ms, 33ms, 39ms, 48ms, 66ms, 447ms.

In Fig. 3, a single laser shot of comparatively low energy (5 J) is depicted. The camera looked on top of the particles. The laser pulse can be spotted in the 2nd image of Fig. 3. One can see that material is evaporated, which then burns in the gas phase and left behind a cloud of soot. In contrast, Fig. 4 shows a laser shot of higher energy (30 J), recorded in a front view.

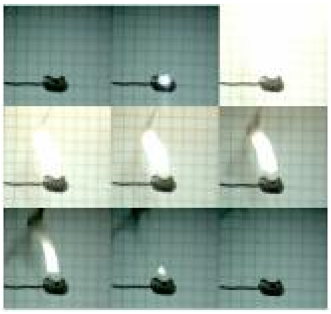

Fig. 4: Heat transfer onto a single plastic resin particle from a high energy laser shot (30 J). Recording times of photos (from top to bottom): 0ms, 1ms, 38ms, 41ms, 44ms, 50ms, 62ms, 77ms, 89ms.

Note that the reaction is much faster in the case of the highly energetic pulse (89 ms as opposed to 447 ms in Fig. 3). Again, the laser pulse can be spotted in the 2nd image of Fig. 4. One can see that the pellet starts burning on the surface, but that the flame extinguishes again rapidly. Compare this behaviour to the lower energetic laser pulse interaction in Fig. 3 where evaporated material burns in the gas phase. The burning behaviour was found to be dependent on the composition of the pellets, which was heterogeneous. As stated above, the pellets consisted of pressed plastics material. For the investigations, pellets were chosen that had a uniform appearance (no protruding fibrous or foam-like components, no visible metal contamination parts).

2.2 Heat transfer studied in flames

In order to study the heat transfer in a less energetic setup, the authors repeated their study with suspended plastics particles in flames. To this end, a McKenna flat flame burner and a Bunsen burner operating on fuel-rich to fuel-lean CH_4/air mixtures were used (compare Fig. 2). The flame of the Bunsen burner (20 mm diameter) was found to be too unstable for the duration of the measurement. The McKenna burner (65 mm diameter, stabilized by an air shroud) was found to burn smoothly at temperatures between 670-1470 K. In Fig. 5, an experiment in a stoichiometric CH_4/air flame (9.5 cm from the burner surface) is depicted. This is where the highest temperature (1470 K) could be achieved.

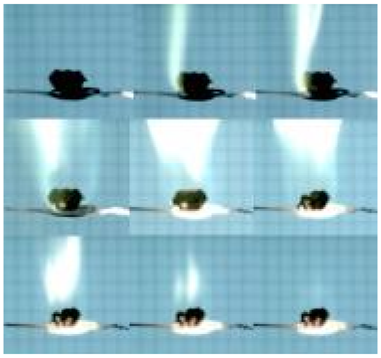

Fig. 5: Heat transfer onto a single plastic resin particle in a CH_4/air flame (9.5 cm from the surface, 1470K). Covered time span: 0-14 s Recording times of photos (from top to bottom): 0ms, 250ms, 450ms, 1300ms, 3800ms, 8675ms, 13200ms, 13650ms, 14025ms.

Compared to the experiments in Fig. 3-4, the images in Fig. 5 show that the heat transfer in the flame is considerably slower than in the case of the laser pulse. The images span a time of 14 seconds, compared to less than 100 ms and 500 ms in the case of the 30 and 5 J laser pulse, respectively.

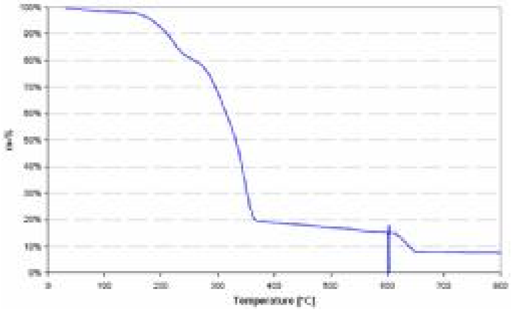

Fig. 6: TGA of a plastics resin particle as used in this study (heating rate: 20K/min, at 873K (600°C): switch from N_2 to air).

In Fig. 6, the characterization of the plastic resin particles by Thermo Gravimetric Analysis (TGA) is shown.

Fig. 7 below depicts the pellets from Fig. 4 after 10 laser shots with 30 J pulse energy.

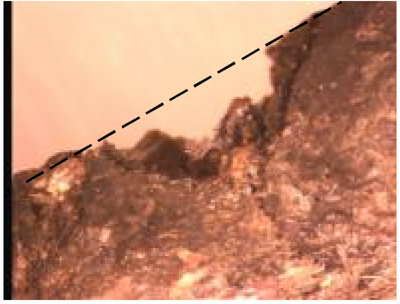

Fig. 7: Image of a plastic pellet after 10 laser shots, see the"crater". Size (enlarged) = 7.76 x 5.90 mm

It can be seen from Fig. 7 that only limited melting has occurred, that is at the edge and in the groove of the "crater" (as opposed to the plastics particles in the flame experiments).

Results and Discussion

The experiments in the flames differ strongly from those with the laser. In the former experiments, the full combustion could be studied with the distinct phases of volumetric expansion, gasification and combustion as described in [1]. The experiments were aborted when only ash was left. In the case of the laser experiments, where the heating process was much more abrupt, the fast energy deposition led to material evaporation that burnt in the gas phase and/or a flame at the location of interaction, that extinguished again before it could ignite the entire particle (compare Fig. 3-5). Fig. 8-10 show results from the laser-based and flame-based studies. In Fig. 8, the "history" of the pellet from Fig. 3 is shown. 14 consecutive laser shots were applied to the particle. The time between these shots was > 60 s. The laser energy of these shots was increased from 5 J (1st shot) to 30 J (14th shot). Each of them had a pulse duration of 10 ms.

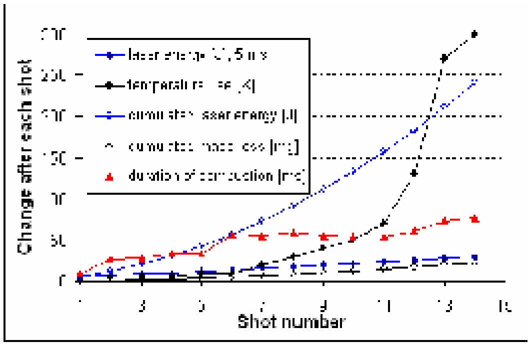

Fig. 8: Changes after 14 laser shots with ascending laser pulse energy.

It can be seen from Fig. 8 that with increasing laser energy, the combustion duration increases. The temperature in the middle of the pellet was recorded using a type K thermocouple. Fig. 8 also shows the maximum temperature rise. Only after shot 5 had enough material been ablated to allow a temperature increase in the core of the pellet. The cumulated mass loss is also shown. At the beginning of the experiment, the particle weight was 0.2 g. A 30 J pulse typically caused a mass loss of 3.1 mg, whereas a 5 J pulse only removed 0.6 mg of material. Fig. 9 shows the temperature trace of the particle after the 1st laser shot (compare Fig. 3 and Fig. 8).

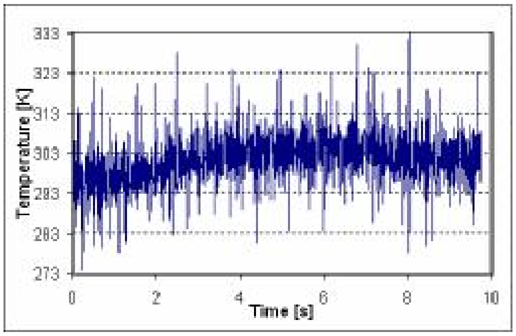

Fig. 9: Temperature trace of the plastic resin at a laser shot with 5 J.

Compare to Fig. 9 the temperature trace of a similar pellet in a flame (Fig. 10): Fig. 10 shows the temperature measured inside the particle from Fig. 4. One can see from Fig. 10 that there is a steady temperature increase from approx. 300 K to 1400 K in the core of the pellet within 4 s. The temperature stayed at that level until the pellet was completely burnt.

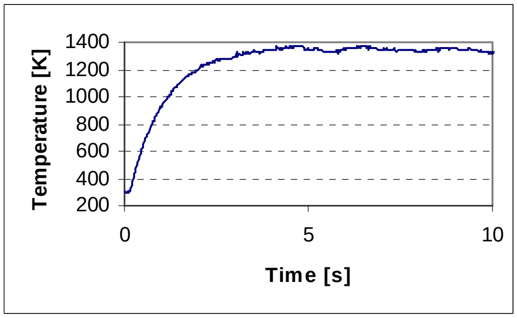

Fig. 10: Temperature trace of a plastic particle in a CH_4/air flame.

In [1], a phenomenological study comparable to this one was conducted on spherical plastics particles of polyethyleneterephalate (PET) and polyethylene (PE). In that work, a propane/air flame was used. With a CCD camera and Schlieren images, intense internal bubbling, multiple micro explosions, micro jets and micro diffusion flames could be observed. [2] used a CO_2 laser in a similar experiment. The interaction of a pulsed laser with matter has been widely investigated and used for material processing purposes [3]. Models have been developed for the interaction of a laser with a metal target [3], [4] incorporating the effects of heating, melting and evaporation. In [5], the interaction of pulsed laser light at an interface (liquid/solid) and the resulting temperature jump has been investigated. In [6], a 3 dimensional model is discussed. The time scales involved in these processes are discussed in [7]. The governing mechanism is absorption, which in turn depends on the surface reflectivity of the substrate. The absorption of the laser light is achieved through interaction of the photons with bound and free electrons in the material [8]. Because of plastics molecular structure, the thermal properties, that is thermal conductivity, thermal diffusivity and specific heat, are temperature-dependent [9], which makes modeling difficult. In [10], an attempt was made to model the heat transfer from a CO_2 laser onto carbonaceous particles (model char). In [11], the heat transfer from a CO_2 laser onto real-world carbonaceous particles (coal) was studied. In that work, an experimental approach was followed. The pyrolysis of plastics in contact with liquid steel is discussed in [12]. Pyrolysis of plastics waste is investigated in [13]-[16]. The literature also holds information on the pyrolysis of polyethylene (PE) [17], polypropylene (PP) [18] and polyvinylchloride (PVC) [19]. In the authors' work, a laser pulse energy of 5 J was found necessary to ignite the particles. At pulse energies of 30 J strong ablation was noticed. The ablated material did not burn completely, but left a cloud of soot behind. In the laser experiments, only a small temperature rise of approx. 10 K was measured inside the particle in the first shot; After several consecutive shots, the temperature rise was up to 300 K as the thermocouple came closer to the surface (see Fig,. 8). The laser-induced flame could not be sustained, it extinguished again after 5-20 s. The mass loss was determined after 10 to 14 consecutive laser shots. The plastic particles suspended in the flames took considerably longer to react. Only after approx. 10 s of heat transfer, a flame could be seen. The full combustion was studied. The effects of particle swelling, volatilization and char combustion were studied in the flames. (Fast) combustion of gaseous material, stemming from ablation and volatilization, could be discerned from (slow) combustion of the solid particle. The composition of the plastic resin particles was found to have a strong influence on the heat transfer. In the flame experiments, it was found that a minimum temperature of approx. 1400K is necessary for fast heat transfer onto the pellets. This observation is in agreement with [1] where conditions of 1270 K and 10% oxygen for a propane/air flame (equivalence ratio Φ=0.8) are reported. The key finding of the experimental study presented here are (Table 1):

Heat transfer from the Nd:YAG laser	Heat transfer in the burner
No fragmentation Limited melt phase No swelling Only reaction at the surface, volatile components are released and burn No significant temperature rise in the core of the pellet (non-isothermal) at 1st shot	Pellets do not react fast A melt phase can be seen Swelling and complete burning

Table 1: Key findings – a comparison.

Conclusions

In this study, the heat transfer onto plastics resin particles from a pulsed laser and a flame was investigated experimentally. The aim was to describe, in a phenomenological way, the particles' behavior until ignition. The observations between laser and flame differ significantly in the following ways: In the laser experiments, the flame could not be sustained, no extended melt phase was observed. There was no significant temperature rise in the core of the pellets. The pellet composition was found to have the strongest influence on heat transfer characteristics. The mass loss was 0.6 mg to 3.1 mg per shot for 5 and 30 J pulse energy, respectively. The laser-induced flames could not be sustained. In the flames, particle swelling and complete combustion occurred. There was a steady temperature rise up to 1400 K in the core of the pellet within 4 s.

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