

# Numerical Modelling of Plastic Pyrolysis in a Solar Cavity Receiver Reactor

Anna Viviane Reeves  
anna@annareeves.eu

Instituto Superior Técnico, Universidade de Lisboa, Portugal

December 2017

## Abstract

Finding more economical ways of utilising waste plastic is important to keep it from polluting our environment and for resource sustainability. Solar pyrolysis by direct absorption seems like a promising candidate as operational costs should be low. This thesis details the first ever published attempt to numerically model this process.

The literature on plastic pyrolysis was reviewed, and a simple cylindrical fixed bed reactor chosen, illuminated through a window via a parabolic dish. The catalyst was assumed to be placed after the thermal decomposition step, for better contact and to avoid poisoning, hence it was not part of the simulation. The three most common plastics were included, with an empirical model for their thermal decomposition and DSC data from the literature. Additives were randomly assigned with certain probabilities, comprising the most common pigments as well as a UV absorber and calcium carbonate filler. Two additional decomposition products were included, calcium oxide and copper.

The standard solar reference spectrum was used as input and the energy distributed via Monte Carlo ray tracing.

The results look promising and thus further research is recommended. Losses from escaping rays are only between 1% and 3.5% for normal feedstock. A practically feasible granule size of 3-5mm is small enough for the heat transfer from coloured to transparent plastic to be efficient enough. However, limitations on computing power mean that the simulated reactors are quite small, and additional phenomena might appear in realistically sized reactors.

**Keywords:** Solar Pyrolysis, Solar Reactors, Plastic Pyrolysis, utilisation of plastic waste

## 1. Introduction

The majority of plastic waste these days still goes to landfill or dump sites, even in most developed countries where efforts are being made to recycle or incinerate instead. However, this is problematic because plastic takes hundreds of years to degrade, and some of the toxic additives it contains may leach out and contaminate groundwater or be taken up by animals and enter the food chain. Also, an estimated eight million tonnes are thrown into the oceans each year [10], killing millions of marine animals that mistake it for food or get entangled in it.

All this happens despite the fact that waste plastic still has a high heating value, on average 32 MJ/kg [4] which is more than that of coal. But utilising this energy in an economical way has so far proven to be difficult. Recycling requires a lot of work and energy only to produce an inferior quality good, so recycling facilities in the EU are indirectly subsidised by consumers to make it possible [5]. Direct incineration creates a lot of pollutant gases, which need to

be removed at high energy expense, meaning that most waste incinerators have an overall energy efficiency of only around 15% [9] and make a big monetary loss despite selling electricity to the grid. Gasification plants are also costly to build and operate. Besides, plastic is anyway better suited for pyrolysis than for gasification due to its high volatile content. By simply heating it up to around 400 to 500°C in an inert atmosphere, the long polymer chains it consists of break apart into many small fragments. A lot of valuable oils and gases are created in such a process, which, after separation and refining, can be used as fuels and as feedstock for the petrochemical industry.

However, breaking apart so many atomic bonds requires a high energy input. Several companies who attempted to do this using an external energy source during the last century found that they were not being profitable enough due to low margins, and ended up closing down their facilities after some time. In more recent times though, several startup companies seem to have sprung up that burn the off-

gas produced in the process to generate the heat for it, and they seem to be able to make do that way. Whether they will continue to prosper and expand fast enough to solve the pressing problem of plastic pollution remains to be seen. In the meantime, it seems worthwhile to explore the possibility of improving on their approach by instead supplying the necessary input energy directly from solar energy via direct absorption. This could potentially keep operating costs as low as possible while also being as green as possible and maximizing profits. This is because the gas contains some valuable petrochemicals, which could replace those currently being custom produced from fossil fuels. Also, the remainder of the gas could be steam-reformed into pure hydrogen which could then be used for the necessary hydrogenation of the unstable oil, so it would no longer be required to purchase hydrogen from the market which is currently mostly being produced from fossil fuels.

Solar thermochemical reactors are currently being researched for various chemical processes, however it seems that nobody has investigated the possibility of applying them to plastic pyrolysis in any detail yet. This may be because plastic is not the ideal candidate material for such a process, having a low thermal conductivity and hardly absorbing any light within the solar spectrum. However, with over 300 million tonnes of plastic produced worldwide every year and growing, all possible conversion methods for it need to be explored regardless. And some simple estimates can confirm that at a particle size of 3-5mm, which is achievable with commercial granulators, large amounts of heat can be transferred between neighbours via conduction on timescales of seconds. Since around half of plastic contains pigments and most of these are inorganic, thus not decomposing before the plastic does, they might pass on enough energy to the transparent plastic if mixed in well. This thesis therefore details the first published attempt to numerically model this process, to get an idea of how big these difficulties really are.

## 2. Background

Due to operational difficulties caused by the stickiness and low thermal conductivity of plastic, only three types of reactors are generally considered to be suitable for plastic pyrolysis at all: Fixed beds, fluidised beds and spouted beds [7]. However, fluidised beds have issues with possible defluidisation if the reaction temperature drops below a certain threshold [8], hence they do not seem suitable for adaptation to solar input. Spouted beds are a variant of fluidised beds and seem like a good choice as they do not have defluidisation issues, however they would have been way too complex to model for a

master thesis. So a fixed bed non-stirred batch reactor was chosen instead, which also seems promising as it is much cheaper to produce and maintain. This type is not at all suitable for conventional industrial scale plastic pyrolysis, due to the inefficiency of the heat transfer and the fact that melted plastic has such a high viscosity that stirring it would be impractical. But with solar input this would not be an issue.

This reactor was taken to be a simple cylindrical cavity with a quartz window at the top and perfectly reflective mirrors on the inside. The window has a rugate filter reflecting radiation of wavelength  $2.5\mu\text{m}$  or more coming from the inside, but this has only a small effect on the simulation results since emission of thermal radiation by hot objects was neglected. A parabolic dish captures and focuses the sunlight towards a flat mirror that redirects it downwards onto the window of the reactor. The standard reference spectrum ASTM G173 was used for the incoming solar energy, which represents a location of average quality solar resource. Losses due to imperfections of the concentrating system were neglected.

The catalyst was assumed to be located in a separate chamber after the thermal decomposition step, which is standard practice among researchers these days as it leads to better contact area with the plastic and less chance of catalyst poisoning. Thus, the cracking step was not modelled here as there was no need to do so, and besides it would unnecessarily constrain the results to one choice of catalyst among many.

The feedstock material was modelled as a mixture of the three most commonly used plastics: LDPE, HDPE and PP. The relative fractions used are the ones of global non-recycled plastic waste [2]. PET was not considered at all because it is much better suited for recycling than for pyrolysis, and PVC would have to be dechlorinated first. PS would be very suitable, however the paper from which the degradation kinetics are taken does not include it. Future work could also focus on a feedstock consisting of electrical and electronic waste, which is mostly black with some white and should yield a lot of valuable styrene monomer. It would have to be debrominated first, but this should be doable [11].

Inert argon carrier gas was assumed to sweep through the reactor and fill the gaps, though it does not take any energy with it through convection nor does it participate in the heat transfer, because that would have necessitated using a very small time step for the whole simulation.

Though plastics typically contain many different additives [13], only two could be included due to time constraints, since finding all the necessary ma-

terial properties, especially the scattering spectrum, is a lot of work and in some cases impossible. Many of these would have to be determined through own measurements. So, only the two seemingly most important ones for solar absorption were chosen: The UV absorber UV351, for obvious reasons, and a calcium carbonate filler since fillers can make up quite a significant fraction of the total weight of a plastic and may have high scattering coefficients. The most common pigments were selected for the colours: Titanium dioxide for white, carbon black, hematite for red, goethite and lead chromate for yellow, a 50/50 mix of hematite and goethite for orange, phthalocyanine blue and green, and dioxazine violet. Data for the prevalence of pigments are hard to find, so half coloured and half clear plastic was assumed, and estimates of 14% titanium dioxide and 10% carbon black were made based on what little information could be found. In practice, the numbers might even be better though because recycling facilities prefer clear plastic, and their infrared sorting facilities cannot process black plastic. The only decomposition products included were calcium oxide and copper, due to time constraints. The organic pigments may also leave behind some carbon though, which is the same as carbon black pigment in this simulation.

There is a considerable scatter in the literature data on plastic pyrolysis kinetics, probably mainly because too many authors use non-isoconversional and/or first order reaction models. Therefore, a detailed empirical model derived using the advanced isoconversional method was selected from the literature [1], and the activation energy, pre-exponential coefficient and reaction model as functions of conversion for all three plastic types were taken from this paper. The model is based on a laboratory setting where the plastic is heated at a constant heating rate by supplying however much energy is needed for that to it. Since the plastic decomposition process is very complex, values obtained in such a way may not apply too well to a case where the input energy varies randomly and determines the future temperature. But due to the absence of research on more similar cases, there was nothing else that could be done than to use such a model. Two other papers were found from which the heat flow versus conversion could be calculated for HDPE and PP. Values for LDPE could not be found, so those of HDPE were used, although in reality the side chains do affect the kinetics, so performing own measurements is recommended for the future.

Direct bond breakage by absorption of UV photons was neglected, due to lack of data on it, though it seems possible. The influence of additives on the process had to be neglected too, although it can

be expected that this influence is not negligible, especially that of the antioxidants, flame retardants and light stabilisers which can catch free radicals. Photocatalysis by titanium dioxide should be negligible though, since there will be very little oxygen present to form free radicals with an electron that has crossed its bandgap. Change of reaction kinetics due to mixing of different types of plastic was justifiably neglected, since it has to be on a much smaller scale for the different types to diffuse into each other and thus affect each other's degradation via radical transfer. [3]

### 3. Implementation

A code was written from scratch in C++11 to simulate the full pyrolysis process of a batch of average plastic waste.

In reality, a granulator will produce granules of varying shapes and sizes, however these had to be approximated by cubes, all of the same size and stacked perfectly. To partially compensate for the unrealistically good heat transfer that this leads to, the granules are subdivided into pieces, also cubes and stacked perfectly in an imaginary three-dimensional lattice. The user can set a certain fixed probability that each lattice element will be a hole instead of plastic, which will be filled by the argon gas blowing through the reactor. The user can also set the amount of pieces that each granule is subdivided into, as well as all dimensions and other simulation constants in a separate header file.

Whenever a plastic piece has finished the plastic pyrolysis process and leaves behind some of its additives, they turn into a sheet object which goes to the surface in between that lattice volume and the one below it. The sheets are assumed to not take up any space in the main simulation, as that would have complicated the ray tracing too much, but they do know their own vertical thickness which is used in the heat transfer part and to calculate the absorption when a ray passes through it, or gets scattered inside it. Multiple sheets may stack up on top of each other at any of these interface positions, all without affecting the positions of the lattice elements above them. Sheets and plastic pieces together are called 'participating elements', since the argon gas does not absorb, scatter or take part in the heat transfer.

Since the reactor is cylindrical, there will be some space left over in between the participating lattice columns and the wall, which is assumed to contain argon. The area above the lattice but below the reactor ceiling is also assumed to contain argon.

The input energy is constant throughout and is calculated only from DNI and dish area, neglecting losses from the concentrating system. The window is assumed to be a diverging lens, so all rays are

treated as coming from the focal point and are assigned a random initial angle from the vertical with uniform probability in between zero and the maximum it can have so as to just hit the edge of the plastic surface. Each ray is randomly assigned a wavelength via the Monte Carlo method and then tracked until its remaining energy falls below a set threshold.

A ray loses energy to a participating element according to the standard exponential power law while traversing it. If the element scatters at the ray's wavelength, then the path length until the next scattering event is determined stochastically based on that element's scattering coefficient. If this projected event lies within the element, the ray gets scattered there, obtaining a random angle perpendicular to its original path and a deflection angle from its original direction which is drawn from a power law probability distribution based on the forward scattering ratios from the paper that provides all the coefficients [6]. It may be reflected via Fresnel reflection at boundaries between elements with differing refractive index, with probabilities given by the standard formula for fractions of reflected and transmitted light, and changes incidence angle according to Snell's law when entering a new element. If a ray happens to leave the lattice area, or is reflected before even entering it, it bounces off the walls and ceiling and may escape through the window at some point, in which case its energy is added to the variable that keeps track of the losses. The reactor walls were assumed to be adiabatic and perfect reflectors. Emission of thermal radiation by hot elements was neglected due to time constraints. The heat transfer via conduction is calculated with explicit time integration, which necessitates determining the minimum time step for it to remain stable and then applying it to all elements. This derivation neglects phase transitions. This time step is multiplied with the heat flow across each boundary obtained from Fourier's law to obtain the energy entering one element and leaving another. The temperature gradient is simply the difference in temperature between the two elements divided by the distance between their centres. Sheets only transfer heat vertically, not sideways. However, before the sheets appear and the time step becomes very small anyway, it is restricted by a maximum value that can be set by the user, so that not too much solar energy is distributed at once, as the two parts use the same timestep if possible. There is also a safeguard to prevent too little input energy from being distributed. If the timestep is so small that the incoming energy is below the minimum set in the file with the constants, then that energy accumulates in a separate variable until there is enough. The two energy contributions from solar and con-

duction are added together before being applied to each object to raise or lower its temperature accordingly, taking all possible phase transitions into account.

The code starts off by reading in the solar input spectrum and all the required material properties from Excel and csv files and creating an object of type "Material" for each material, with constant properties. It then goes through all participating granules and creates identical objects of type "Plastic" for each of its pieces, which contain pointers to the material objects of which they are made. Which type of plastic it is and which additives it contains at what concentration is determined stochastically, based on probabilities and a maximum and minimum additive content that can also be set in the Excel input files. The resulting overall properties are calculated by their own functions, mostly based on mass or volume fractions, except in the case of overall refractive index, for which the Newton formula is used. Though all pieces start off the same, they evolve as independent entities as time progresses, and may become separated even when the granule is still solid. After all plastic pieces are set, it calculates how much there is in total of each material in the reactor and outputs the results.

Each plastic piece and each sheet has wavelength dependent absorption and scattering coefficients, as well as forward scattering ratios, which are calculated from those of its constituent materials using their volume fractions. The values for pure plastic itself are always zero, as only the additives interact with light in this simulation. The refractive index may depend on wavelength too, if that dependence is known and supplied in a csv file, else the one given value is filled in for all wavelengths.

Then, it starts going forwards in time, one time step at a time, until there are no more plastic pieces left. At the end, it calculates how much in total of each material is left and the average temperature of each and outputs all that information.

The minimum time step for heat transfer is proportional to the mass of each element it is calculated for. Some sheets may at times have very low masses, leading to such a low timestep that the simulation would take too long. Therefore, safeguards had to be devised to prevent this from happening if possible. If two sheet objects on top of each other have only one material and it is the same, then they are merged together. If the thickness of a sheet object falls below one thousandth the value of the lattice constant, it is merged into the plastic or sheet object right underneath it, or above in case that is not possible.

Lattice elements can only move by jumping instantaneously from one allowed cubic volume to another. Mostly, they are just shifted downwards

to fill exposed argon bubbles or because a plastic piece underneath has finished decomposing. However, sometimes they may also move sideways to correct a too steep gradient. Real fluid flow would have been way too complicated to model. Sheets can only move downwards from one surface to another, always going to the top of a stack if one already exists there.

Phase transitions of all materials due to melting, evaporation or decomposition are taken into account, and they always occur at a fixed temperature, although in reality organic pigments may decompose gradually over a wide temperature range. The only exception is the plastic decomposition, which begins once the threshold of 340°C has been exceeded and continues as long as the temperature stays somewhere above it. A variable keeps track of the converted percentage, and the rate of change of this variable is calculated from the standard formula. A numerical integration in time with respect to both conversion and temperature is performed for this process. The temperature thus only goes up if there is more energy available than what the plastic consumes at that conversion in that available time. If the input is negative or less than the consumption, then the temperature drops. A higher temperature speeds up the reaction rate significantly as it affects the exponential in the Arrhenius law.

To check that no energy is lost due to coding errors, the code projects the estimated total that would be needed to evaporate everything in the beginning and compares it with the remainder at the end plus what came in minus losses. Indeed the two values have always been very close thus far.

## 4. Results

The sheet objects with low masses lead to very small timesteps as soon as they begin to appear, so this last part of the simulation takes up most of the computing time. In fact it takes so much time that only very small reactors could be simulated in any reasonable time. So, a scale factor was introduced which is multiplied with all the reactor dimensions, and the solar input energy scales along with the volume of the reactor. The granule size was kept constant as it determines the efficiency of the heat transfer which is an important aspect.

A reactor of 1m diameter, 1m height and filled with plastic up to 0.8m is assumed, illuminated through a 7cm window via a parabolic dish that collects sunlight with an area of 56.65m<sup>2</sup>. This window size should be sufficient to let through almost all of the collected light [12]. In the base case, these dimensions are adjusted with a scale factor of 0.025, so that most of the simulations could be run in a few hours.

With those dimensions and only one piece per granule, a total of 259 lattice elements take part in the simulation, of which 237 contain plastic pieces. The total plastic mass in the reactor is 6.6g, of which 7.4% is taken up by additives. More than 80% of that is calcium carbonate filler, followed by titanium dioxide, iron oxide red and carbon black. Actually, 10% of granules are supposed to contain carbon black and only 5% iron oxide red, however being a stochastic simulation with a low number of participating objects, it so happened that the percentage of iron oxide red mass slightly exceeds that of carbon black. The masses of blue, green and violet are very small in comparison because they are organic pigments and organic pigments have a much higher tinting strength than inorganic ones.

### 4.1. Base Case

The results of the base case simulation are shown in Figures 1 to 6.

Figure 1 shows the number of plastic pieces as function of time. The most strongly absorbing ones begin to disappear after 150min, and the rest follow over the course of the next hour. This is a good result, since it means that the heat transfer is efficient enough that none of the non light absorbing granules get left behind.

Figure 2 confirms the efficiency of the heat trans-

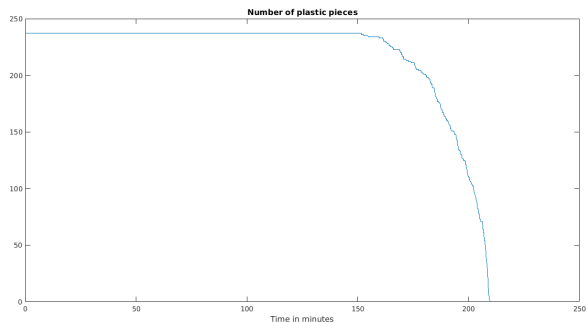


Figure 1: Time evolution of number of plastic pieces

fer. It can be seen here how the maximum and minimum temperatures stay fairly close together at all times. The slope of the curves decreases noticeably as the plastic pyrolysis reaction begins as this consumes a lot of energy.

Figure 3 shows the total number of sheet objects, whose creation correlates with the disappearance of plastic pieces. Figure 4 shows the maximum, average and minimum temperatures of the sheets. It can be seen here how they are constrained by the plastic temperature for most of the time, and only begin to rise significantly above them once enough plastic has disappeared for some of them to become separated. One sheet of carbon black manages to evaporate right at the end, but all others remain. This is good because it means all the additives can

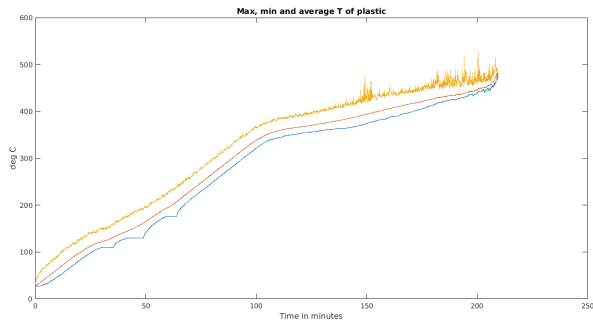


Figure 2: Time evolution of temperature of plastic pieces

potentially be recovered, not much energy is wasted evaporating them and if a layer of sheets forms at the surface, it should not be a problem since the solar energy they absorb is passed on to the plastic quickly enough.

In fact, a layer of sheets at the surface even de-

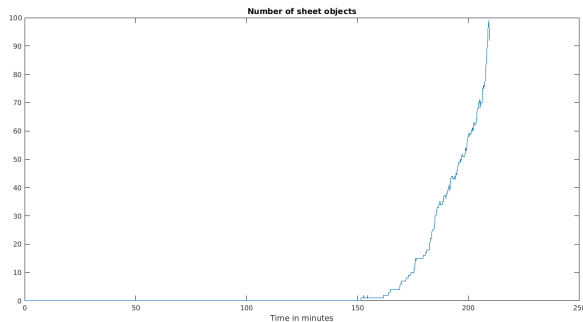


Figure 3: Time evolution of number of sheet objects

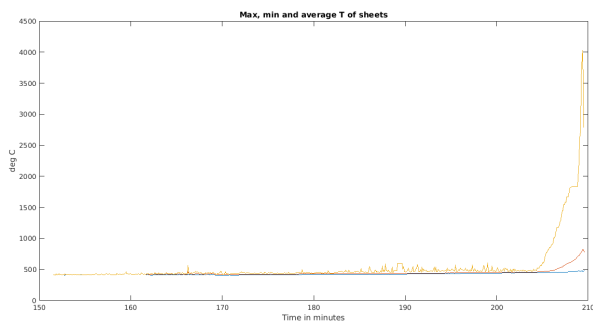


Figure 4: Time evolution of temperature of sheet objects

creases the overall losses, as can be seen from Figure 5, which shows the calculated cumulative fraction of energy that is lost by escaping through the window. It starts off around 4% and then drops to around 3.5% at the end. Since the base case by chance contains less carbon black than it should, it is higher than in some of the other cases, where it can be less than 1.5%. This is a very encouraging re-

sult, because one might think that with 48% of plastic that contains no pigment at all, 14% that contains highly scattering Titanium Dioxide and 10% that contains highly scattering calcium carbonate the losses might be high. But since only a small window is needed in a large reactor, the probability of hitting that window is low.

Finally, Figure 6 shows the time step at which

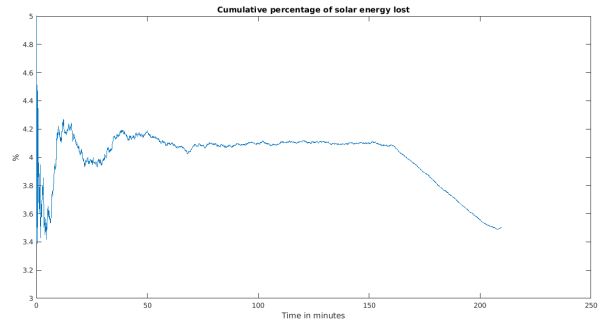


Figure 5: Time evolution of cumulative fraction of energy lost

the simulation is progressing. In the beginning, the heat transfer could be much faster but the amount of radiation per step has to be restricted, so it stays equal to that maximum. Here, it can be seen that all the safeguards that merge sheets to prevent the time step from becoming even lower due to very thin sheets are mostly working well. Without them, it would quickly go down to the order of  $10^{-8}$ s or even less, and the whole simulation would take forever. The later stages are of course slow even so and take up most of the simulation time, but this cannot be avoided.

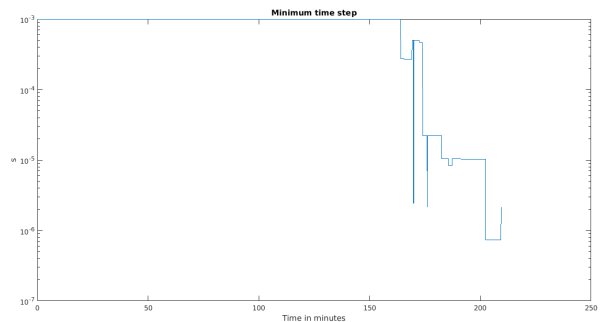


Figure 6: Time evolution of simulation time step

#### 4.2. Sensitivity Analyses

Several simulations with different input were run to test the robustness of the main conclusions. A brief overview is given here.

##### *Change of random number generator seed*

Since 237 is not a lot of granules given the fact that probabilities of containing certain pigments can be as low as 2%, another simulation was run in which

all parameters are identical to the base case and only the seed given to the random number generator was changed. This changed the initial composition of the plastic mass a lot, and probably also which ones happened to be located at the surface, as the losses are now only around 1.2%. The shape of all the curves changed noticeably too. The temperatures of the plastic pieces remain mostly the same of course, except for the fluctuation of the maximum towards the end which happens to be slightly different. The curve for number of plastic pieces is of the same qualitative shape, with just slight variations as would be expected from a stochastic simulation. The same goes for the number of sheet objects curve. Two sheets with carbon black manage to evaporate towards the end and another almost reaches the evaporation temperature. The time step drops lower right at the end, almost to  $10^{-7}$ , probably because the evaporating sheets can temporarily have a low mass.

Such a natural variability needs to be taken into account when comparing other results to the base case.

#### *Lower maximum time step*

The results might be a little more accurate if less energy per timestep was distributed, but making it so small that sudden big jumps in temperature could definitely be avoided would not be practical, as the simulation would then take very long. One simulation was run where the maximum timestep was lowered from 0.001s to 0.0001s, and the curves only change slightly. The fluctuation of the maximum temperature is anyway not too big in the base case, and it does not look like much less in this case. Thus, it did not seem worthwhile to run all the other analyses with such an accuracy as it takes a very long time.

#### *Less surface flow correction*

In the base case, the surface is checked every 10s for gradients and those larger than or equal to 5 lattice constants are corrected. Another simulation was run where this happens only every 60s, which might be more realistic actually. But the difference is small and within the natural stochastic variability, thus it is not possible to say if the overall results are more accurate or it is simply due to chance.

#### *Different scale factor*

The scale factor mainly affects the temperature stratification, which is probably almost nonexistent in small reactors of 0.02. At a size of 0.03 though, the maximum temperature is already noticeably further removed from the average and minimum than in the base case. In an industrial scale reactor, the surface would probably already be decomposing before the bottom has even melted. All other curves for those two cases vary considerably in

shape, but this is to be expected from a stochastic simulation, so no general conclusions can be drawn from that. Much larger simulations would have to be run to be able to see other general trends for varying scale factors.

#### *Change in pigmented fraction*

To address potential concerns that some batches might contain large amounts of transparent plastic and then solar pyrolysis might no longer work well, one simulation was run in which the fraction of pigmented plastic was reduced from 52% to 26%, by reducing each pigment's prevalence value by half. Even so, the results do not look too different. Losses go up to 7%, but the clear plastic still decomposes together with the coloured. Only two clear pieces becomes separated from the absorbing ones near the end, so their temperature goes down as they consume their own heat, but that heat is sufficient for them to finish by themselves. This probably would not happen in real life though, as their content would not remain confined to a cubic volume.

#### *Increase in scattering material*

Another concern might be that a batch containing a lot of white plastic would scatter so much light that the losses would become high. To address this concern, a simulation was run in which the fraction of calcium carbonate containing plastics was increased from 10% to 30%. The minimum temperature curve remains much closer to the average here than in the base case, which is probably due to the increase in thermal conductivity caused by the extra calcium carbonate. The losses go up to 5.3%, which is still manageable. No non-absorbing granules get left over and no sheet objects evaporate. Bigger simulations should be run though to more accurately determine the influence of light scattering.

#### *Increase in granule size*

Although granulators are available that can granulate plastic down to 3mm and this seems to be sufficient, it is nevertheless interesting to know how small the granules really need to be. To this end, four more simulations were run with a granule diameter of 4mm, 5mm, 7mm and 1cm, and the reactor dimensions scaled accordingly. As expected, this increases the thermal lag significantly, which causes more and more non-absorbing granules to get left over. Figures 7 to 10 show the time evolution of the plastic temperatures for these cases.

At 4mm, the thermal lag is already almost double as much as for 3mm, and one non-absorbing granule gets left over at the end for a little while, causing evaporation of sheet objects and higher losses. However, this probably would not happen in real life and the solar input could be turned off towards the end.

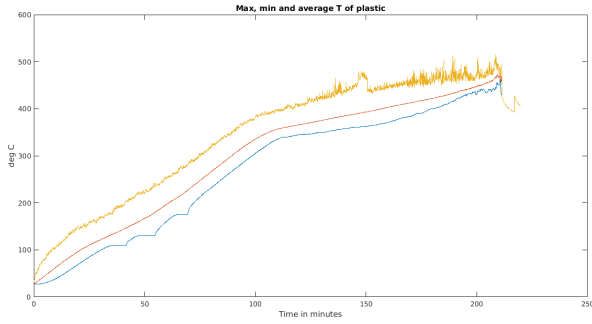


Figure 7: Time evolution of plastic temperatures for granule size of 4mm

At 5mm, the lag is even higher, over 100K at times,

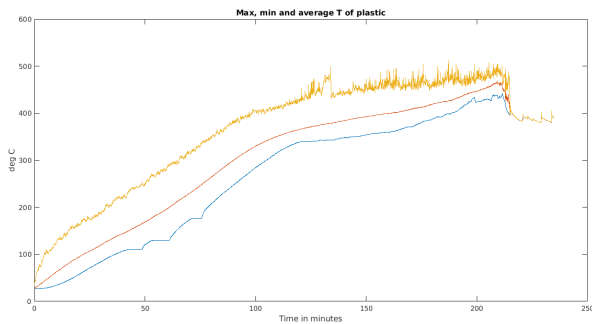


Figure 8: Time evolution of plastic temperatures for granule size of 5mm

and again one granule gets left over. Yet overall, the process still seems to work well enough, though a smaller size would be recommended if possible.

A larger size is not at all recommended though.

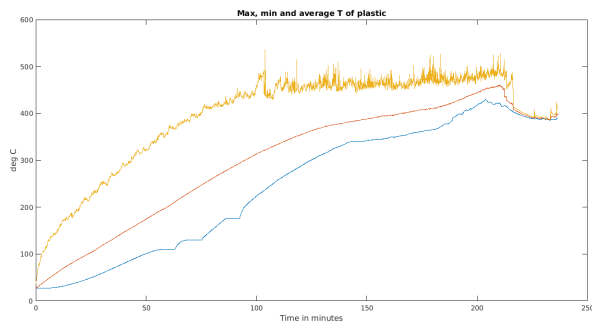


Figure 9: Time evolution of plastic temperatures for granule size of 7mm

At 7mm, the lag is already very high, and six non-absorbing granules get left over at the end. After 20 minutes of no more change in plastic piece number, the simulation stops because it has a safeguard to not continue forever in such a case, so it is not known if those granules would finish by themselves. Even if they would, no operator would want to wait for them to do so, and shredders can do better than

this.

Even less recommended is a size of 1cm, as the

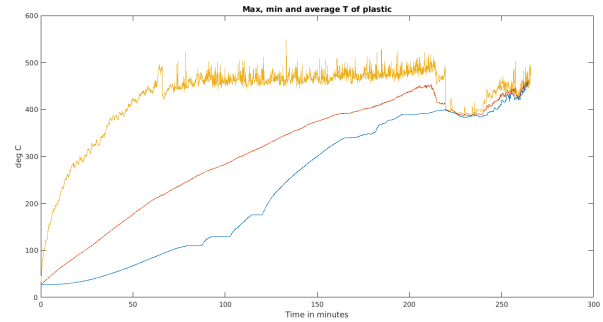


Figure 10: Time evolution of plastic temperatures for granule size of 10mm

thermal lag is quite extreme here, reaching 400K. The losses go up to almost 8%, and a lot of energy is also wasted evaporating almost all of the sheet objects. The simulation takes 56 minutes longer because quite a few non-absorbing granules get left over at the end, and they may not have had enough energy left to finish by themselves. The high temperatures that some of the sheet objects could reach might damage the reactor walls, so this size is totally out of the question.

## 5. Conclusions

Despite all the simplifications and assumptions that had to be made, it can be safely said based on these results that the potential problems due to low thermal conductivity of plastic and transparency of much of it can be easily overcome by simply shredding and mixing large amounts together. Realistically achievable granule sizes of 3-5mm should be sufficient, though 3mm is the recommended size. Due to the small window size, losses from escaping radiation are only around 1% to 3.5%, and only go up to around 7% even if the fraction of coloured plastic is low or white content is high. As the heat transfer is efficient enough, there does not seem to be any possible danger of a white surface layer forming from leftover additives, because the coloured additives do not get a chance to evaporate and thus remain among it.

Overall, the concept seems promising and more research should be done, not just to refine the simulation but also to experimentally obtain a lot of the material properties that had to be estimated. TGA experiments should be performed to determine the plastic pyrolysis kinetics under a given heat flow. A prototype should be built to see how the simulation compares with a real life situation, and to convince potential investors of the feasibility.



## Acknowledgements

The author would like to thank Professor Lemos and the research group on CSP at the CTTC in Terrassa for their advice on various issues, and the CTTC for providing fast computers to run the simulation on.

## References

- [1] P. Das and P. Tiwari. Thermal degradation kinetics of plastics and model selection. *Thermochimica Acta*, 654(March):191–202, 2017.
- [2] S. Dayana, A. Sharuddin, F. Abnisa, W. Mohd, A. Wan, and M. K. Aroua. Energy recovery from pyrolysis of plastic waste: Study on non-recycled plastics (NRP) data as the real measure of plastic waste. *Energy Conversion and Management*, 148:925–934, 2017.
- [3] T. Faravelli, G. Bozzano, M. Colombo, E. Ranzi, and M. Dente. Kinetic modeling of the thermal degradation of polyethylene and polystyrene mixtures. *Anal. Appl. Pyrolysis*, 70:761–777, 2003.
- [4] B. Gershman and I. Bratton. Gasification of Non-Recycled Plastics From Municipal Solid Waste in the United States. Technical Report September, The American Chemistry Council, 2013.
- [5] R. H. J. M. Gradus, P. H. L. Nillesen, E. Dijkgraaf, and R. J. V. Koppen. A Cost-effectiveness Analysis for Incineration or Recycling of Dutch Household Plastic Waste. *Ecological Economics*, 135:22–28, 2017.
- [6] R. Levinson, P. Berdahl, and H. Akbari. Solar spectral optical properties of pigments Part II: survey of common colorants. *Solar Energy Materials & Solar Cells*, 89:351–389, 2005.
- [7] G. Lopez, M. Artetxe, M. Amutio, J. Bilbao, and M. Olazar. Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. *Renewable and Sustainable Energy Reviews*, 73(October 2016):346–368, 2017.
- [8] M. L. Mastellone and U. Arena. Bed defluidisation during the fluidised bed pyrolysis of plastic waste mixtures. *Polymer Degradation and Stability*, 85(3 SPEC. ISS.):1051–1058, 2004.
- [9] J. Morris. Recycling versus incineration: an energy conservation analysis. *Hazardous Materials*, 47:277–293, 1996.
- [10] L. Parker. Eight Million Tons of Plastic Dumped in Ocean Every Year, 2015.
- [11] Y. Shen, R. Zhao, J. Wang, X. Chen, X. Ge, and M. Chen. Waste-to-energy: Dehalogenation of plastic-containing wastes. *Waste Management*, 49:287–303, 2016.
- [12] A. Steinfeld and M. Schubnell. Optimum aperture size and operating temperature of a solar cavity-receiver. *Solar Energy*, 50(1):19–25, 1993.
- [13] M. Tolinski. *Additives for Polyolefins, Getting the most out of Polypropylene, Polyethylene and TPO*. Elsevier, 2 edition, 2015.