Constructing models for a Pebble Heater and Drying Wood

Internship report

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Preface

This is the report of my internship at Clean Fuels b.v., located in Oldenzaal. Goal of the internship was to construct numerical models for a heat exchanger and the drying of wood. Though these models seems to differ among each other, both models use approximately the same equations. Therefore both reports are bundled into this one.

I would like to thank Roland Siemons and Loek Baaijens for their help and support during the internship. The internship was very interesting and I personally learned a lot about engineering in the 'real' world.

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Part 1: Pebble Heater

1. Introduction

In a process to make char coal out of biomass a lot of heat is generated. In order to save energy heat is regenerated by a heat exchanger. Since this carbonisation process is a batch process the purpose of the heat exchanger is not only exchanging heat but also storing it. The type of heat exchanger chosen for this process is a pebble heater. Figure 1 shows a schematic pebble heater. gas flows over a bed of pebbles and exchanges heat with it by convection. If hot gas flows over a cold bed heat is stored in the bed, making a part of the energy of the hot gas available for later use in the process, the drying of a new batch of wood. ‘re using’ the heat is done simply by letting a cold gas flow over the, now hot, pebble bed and into the process.

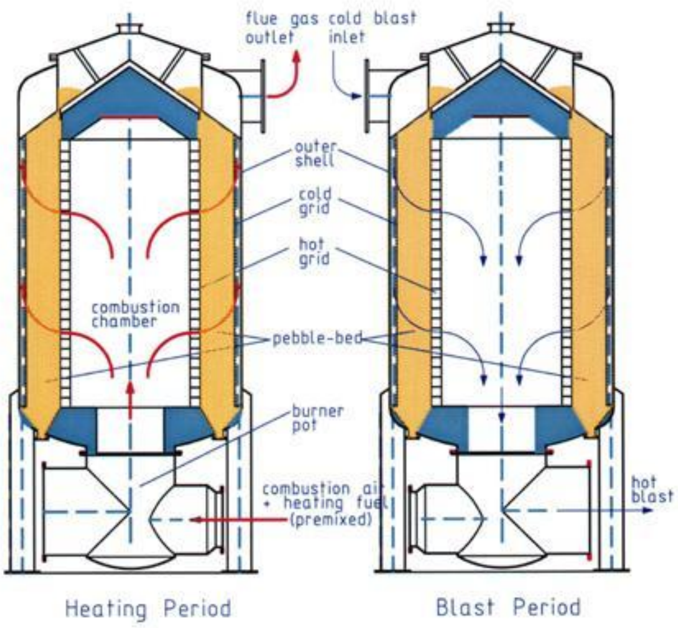


Figure 1

To predict the performance of the pebble heater a numerical model is made. This part of the report discusses the model and the predicted performance of the pebble heater based on the model. All modelling was done in Maxima, an open source calculation program functioning like Matlab.

2. General assumptions

Because modelling the real behaviour is impossible within the allotted time frame some assumptions are made. The assumptions listed here are made for every model in the Pebble Heater section.

1. No heat transfer by radiation.
2. No heat transfer by conduction in pebbles.
3. No heat transfer by conduction in gas.
4. No thermal capacity in gas.
5. Gas is pure air.
6. Models are 1D.

Models are made in 1D since there are very little variations expected in other directions than the gas flow direction.

Since local temperature differences are usually very small the effects of radiation are also very small. Therefore radiation is neglected.

The pebbles are small compared to the entire bed so one can expect that the conduction inside a pebble is very small and therefore negligible. In the first two models the conduction of heat inside the pebbles is neglected. In the third model the pebble conduction in modelled to determine the temperature inside the pebble.

Since conduction in a gas is usually very low conduction in the gas phase is neglected. The same counts for the thermal capacity of the gas. These assumptions are quite standard [1] so no checks have been made.

The gas flowing over the pebble bed is assumed to be pure air. In reality this gas will also consist of steam and organic process gases. It is hard to determine the real composition of this gas since data of the process is not yet available.

3. List of symbols

Table 1 shows all symbols used in the report of the pebble heater. The second column shows the meaning and unit of a symbol. These symbols are also used in the programmed code.

Symbol	Quantity (unit)
k_g	Conductivity gas (W/mK)
k_s	Conductivity pebble (W/mK)
e	Bed porosity (-)
c_f	Heat capacity gas (J/kgK)
$\dot{m}_f$	Mass flow gas (kg/s)
c_s	Heat capacity solid (J/kgK)
h_t	Heat transfer coefficient (W/m^{2}K)
T_s	Surface temperature bed (C)
T_b	Temperature inside pebble (C)

T_g	Temperature gas (C)
T_{omg}	Gas temperature hot (C)
h	Spatial stepsize bed (m)
dt	Timestep (s)
r	Spatial stepsize in pebble (m)
d_o	Outer diameter pebble heater (m)
d_i	Inner diameter pebble heater (m)
V	Volume of all pebbles (m^3)
a_s	Surface area of all pebbles (m^2)
V_p	Volume of 1 pebble (m^3)
A_p	Surface area of 1 pebble (m^2)
Nu	Nusselt number (-)
Re	Reynolds number (-)
Pr	Prandtl number (-)
Bi	Biot number (-)
l_c	Characteristic length (m)
τ	Dimensionless time (-)
α	(m^2/s)
nu	Kinematic viscosity (m^2/s)
rho_s	Density of pebbles (kg/m^3)
rho_g	Density of gas (kg/m^3)
d_{pebble}	Diameter of pebble (m)
T_0	Initial temperature bed cold (C)
a_s	Surface area per volume (m^2/m^3)

Table 1

4. Model

This chapter handles the modelling of the pebble heater as described in the introduction. First the heat transfer mechanics used in the modelling are described, than the three models in order of increasing complexity.

Heat transfer mechanisms

In general there three heat transfer mechanisms: conduction, convection and radiation. In the models built for the pebble heater convection and conduction are used..

As mentioned before heat transfer in the pebble heater happens by convection and conduction. Heat transfer between gas and pebble bed happens by forced convection, 0.1. Heat transfer between two pebbles takes place by conduction. Inside the pebbles there is also conduction. These 3 mechanisms characterise the pebble heater and are shown below.

Forced convection between gas and bed

$$Q = h_t * a_s * (T_g - T_s) \tag{0.1}$$

Conduction between 2 pebbles

$$Q = \mathrm{k_s} * \frac{\mathrm{dT_s}}{\mathrm{dx}} \tag{0.2}$$

Conduction inside a pebble

$$Q = \mathrm{k_s} * \frac{\mathrm{dT_b}}{\mathrm{dr}} \tag{0.3}$$

5. 1 phase model

As a first a 1 temperature model is constructed, the 1 phase model. This model assumes perfect heat transfer between the gas and the bed of pebbles. Perfect heat transfer means the pebble bed and gas have the same temperature. The 1 phase model is derived from the 2 phase model by Vortmeyer and Schaefer [1]. This model has 1 governing equation 0.4.

$$(1-e) * \rho_s * c_s * \frac{dT}{dt} = k_s * \frac{d^2T}{dx^2} - \dot{m}_f * c_f * \frac{dT}{dx} \tag{0.4}$$

To solve this equation 1 initial condition and two boundary conditions are required. Vortmeyer and Schaefer [1] used the following conditions to solve the equation numerically.

At t=0 the pebble bed has one uniform temperature.

$$T(t=0) = T_0 \tag{0.5}$$

At x=0 the enthalpy change of gas stream is equal to the thermal energy conducted in the pebble bed.

$$\dot{m}_f * c_f * \left(T_{omg} - T\right) = -\frac{k_{ax} dT}{dx} \tag{0.6}$$

At x=L.

$$\frac{dT}{dx} = 0 \tag{0.7}$$

This is a simple model and thus easy to work with. To determine whether it has any use some more complicated models are built. Table shows the data used in this model.

$\dot{m}_f$	0.045 kg/s	c_f	1200 J/kg	T_{omg}	1000 C
ρ_s	1400 kg/m^3	k_s	27 W/mK	T_0	40 C
c_s	800 J/kg	e	0.45		

Table 2

Figure x shows the temperature distribution in the pebble heater after 1 hour. Since the temperature is dependent on both x and t two plots are made. The left plot shows the temperature profile at a certain time. The x-axis shows the spatial coordinate, ranging from 1 to 51. Where 1 corresponds to x=0 and 51 to x=L. The right plot shows the temperature through on a fixed point, at the entrance and at the exit.

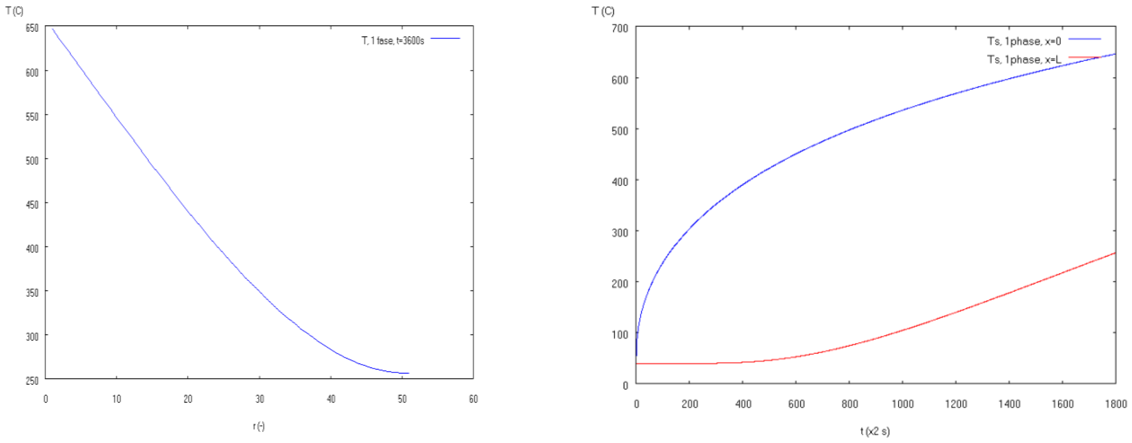


Figure 2

6. 2 phase model

The 2 phase model was also constructed by Vortmeyer and Schaefer [1]. It determines a temperature for the gas and a temperature for the pebbles. Where the 1 phase model assumes perfect heat transfer between gas and solid, here the heat transfer is characterised by the heat transfer coefficient h_t. At first h_t is taken as a constant value (h_t=15 W/m^{2}K). The 2 phase model is characterised by 2 PDE's, which are the energy balances for the solid pebbles and for the gas.

The energy balance of the pebble bed. The change of temperature in time is caused by forced convection between gas and pebbles and conduction between pebbles.

$$(1-\mathrm{e}) * \mathrm{rho_s} * \mathrm{c_s} * \frac{\mathrm{dT_s}}{\mathrm{dt}} = \mathrm{h_t} * \mathrm{a_s} * (\mathrm{T_g} - \mathrm{T_s}) + \mathrm{k_s} * \frac{\mathrm{d^2\,T_s}}{\mathrm{dx^2}} \qquad \mathbf{0.8}$$

The energy balance of the gas flowing through the bed. The change of temperature in space is caused by forced convection between gas and pebbles.

$$\mathrm{m_f} * \mathrm{c_g} * \frac{\mathrm{dT_g}}{\mathrm{dx}} + \mathrm{h_t} * \mathrm{a_s} * (\mathrm{T_g} - \mathrm{T_s}) = 0 \qquad \mathbf{0.9}$$

Vortmeyer and Schaefer [1] used the following initial and boundary conditions to solve the PDE's.
At t=0 the pebble bed has one uniform temperature.

$$T_s(t=0) = T_0 \qquad \mathbf{0.10}$$

At x=0 the change of enthalpy of the gas stream is equal to the thermal energy transferred between the incoming gas and the pebble bed at the entrance.

$$\mathrm{m_f} * \mathrm{c_f}(\mathrm{T_{omg}} - \mathrm{T_g}) = (1-\mathrm{e}) * \mathrm{h_t} * (\mathrm{T_{omg}} - \mathrm{T_s}) \qquad \mathbf{0.11}$$

At x=0 the thermal energy transferred between the incoming gas and the pebble bed is equal to the conduction in the pebble bed at x=0.

$$-k_s * \frac{dT_s}{dx} = (1-e) * h_t * (T_{omg} - T_s) \tag{0.12}$$

x=L has the boundary equations as x=0. However the outgoing gas temperature is unknown. To solve this the 2 boundary conditions can be combined to one equation.

$$(1-e) * h_t * (T_s - T_g + (\frac{k_s}{\dot{m}_f * c_g}) * \frac{dT_s}{dx}) + k_s * \frac{dT_s}{dx} = 0 \tag{0.13}$$

Table 3 shows the data used in the 2 phase model. The specific surface area, a_s, takes the bed porosity into account so the bed conductivity is equal to the pebble conductivity.

$\dot{m}_f$	0.045 kg/s	a_s	284.7 m^2/m^{-3}	T_{omg}	1000 C
ρ_s	1400 kg/m^3	k_s	27 W/mK	T_0	40 C
c_s	800 J/kg	e	0.45	h_t	15 W/m^2K
c_f	1200 J/kg				

Table 3

Figure 3 shows the temperature distribution of the pebble bed and the gas after 1 hour.

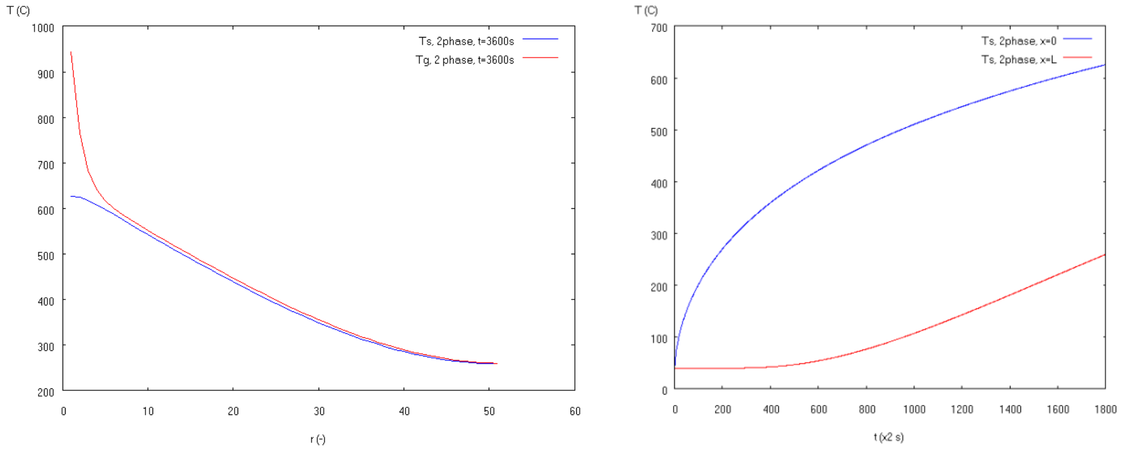


Figure 3

When looking at the plots of the 1 and 2 fase models they look quite similar. Figure 4 shows both models in one graph. Biggest difference is near the entrance of the heater. This is to be expected since the 1 phase model assumes perfect heat transfer and the 2 phase model needs some time to transfer heat from gas to solid. With time this ‘entrance’ region becomes smaller since the temperature difference between gas and pebbles at the entrance decreases with time.

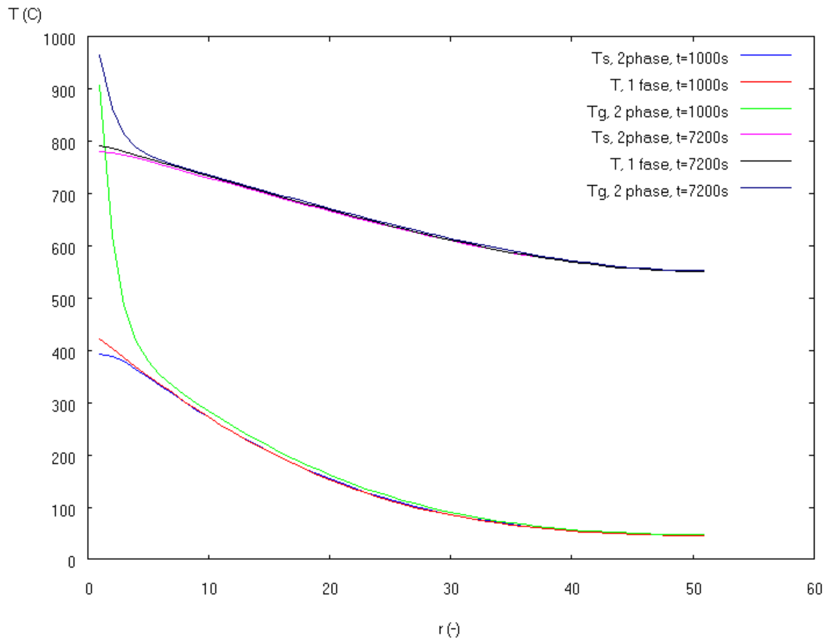


Figure 4

The heat transfer coefficient was taken as a constant in Figure 4. To get a more realistic model a relation for h is derived in Appendix A: relation for heat transfer coefficient. This relation adds some realism in the part of the reactor where the temperature between pebble and gas in big, near the entrance. Figure 5 shows the 2 phase model with a fixed heat transfer coefficient and with a variable coefficient. Differences are only noticeable in the entrance region of the reactor.

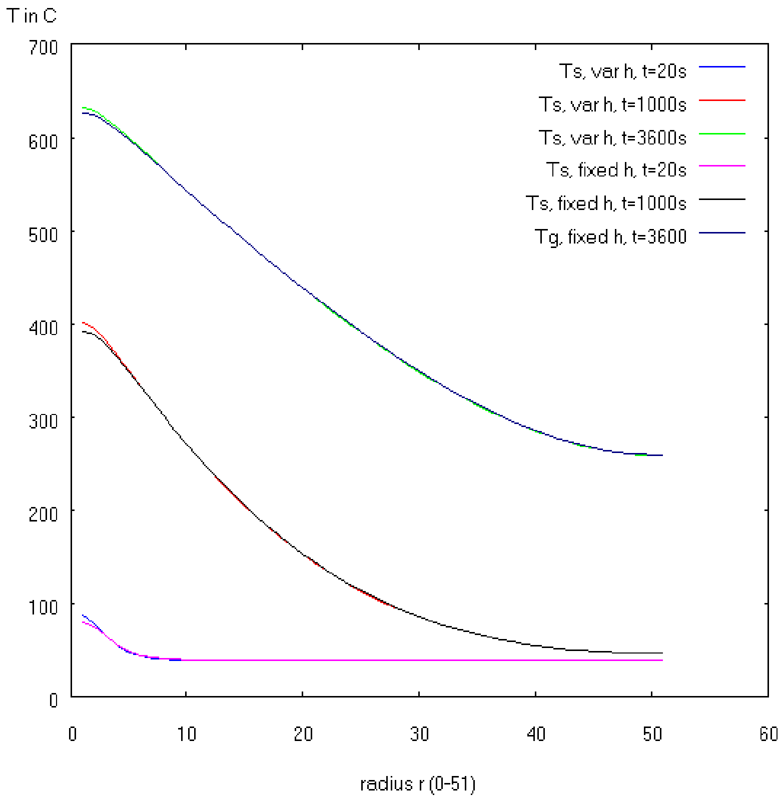


Figure 5

7. Expansion of the 2 phase model

The models of Vortmeyer and Schaefer assume a uniform temperature throughout 1 pebble. This basically means pebbles are very small or that conduction within a pebble is infinitely fast. To see what effects pebble size has on the performance of the pebble heater a third model is created. Pebbles are not negligible and have their own temperature profile inside them. This means there are now 3 temperatures; the temperature of the gas (T_g), the surface temperature of the pebbles (T_s) and the temperature inside the pebbles (T_b).

To describe the temperature profile inside the pebbles the one-term approximation is used. This method is described extensively in the book Heat and Mass transfer [2]. Pebbles are spherical so the general formula for spherical geometry is used. With this formula the temperature of point in the pebble can be calculated dependent on its radial position (r) and time (t).

$$\theta_{sph} = \frac{T(r,t) - T_\infty}{T_i - T_\infty} = A_1 * e^{-\lambda_1^2 * \tau} * \frac{\sin\left(\lambda_1 * \frac{r}{r_0}\right)}{\lambda_1 * \frac{r}{r_0}} \qquad \textbf{0.14}$$

Where A_1 and λ_1 are values dependent on the Biot number. The formula's for $A_1$and λ_1 are fitted from the data of Heat and Mass transfer [2] tab 4-2 since only discrete data was available. The fitted formula's for $A_1$and λ_1 are given by equation 0.15 and 0.16.

$$A_1 = -0.03Bi^2 + 0.3Bi + 1 \tag{0.15}$$

$$\lambda_1 = -3.9Bi^4 + 9.6Bi^3 - 8.8Bi^2 + 4.5Bi + 0.16 \tag{0.16}$$

The most interesting part of the pebble is the centre of which the temperature is calculated by a simpler formula, since sin(0)=0.

$$\theta_{\mathrm{sph}} = \frac{T(r,t) - T_\infty}{T_i - T_\infty} = A_1 * e^{-\lambda_1^2 * \tau} \tag{0.17}$$

To apply this method the dimensionless time, τ, has to be larger than 0.2, equation shows this is the case for a time step of 2.

$$\tau = \frac{(\alpha * dt)}{(d_{\mathrm{pebble}})^2} = \frac{2.41 * 10^{-5} * 2}{(1.25 * 10^{-2})^2} = 0.3 > 0.2 \tag{0.18}$$

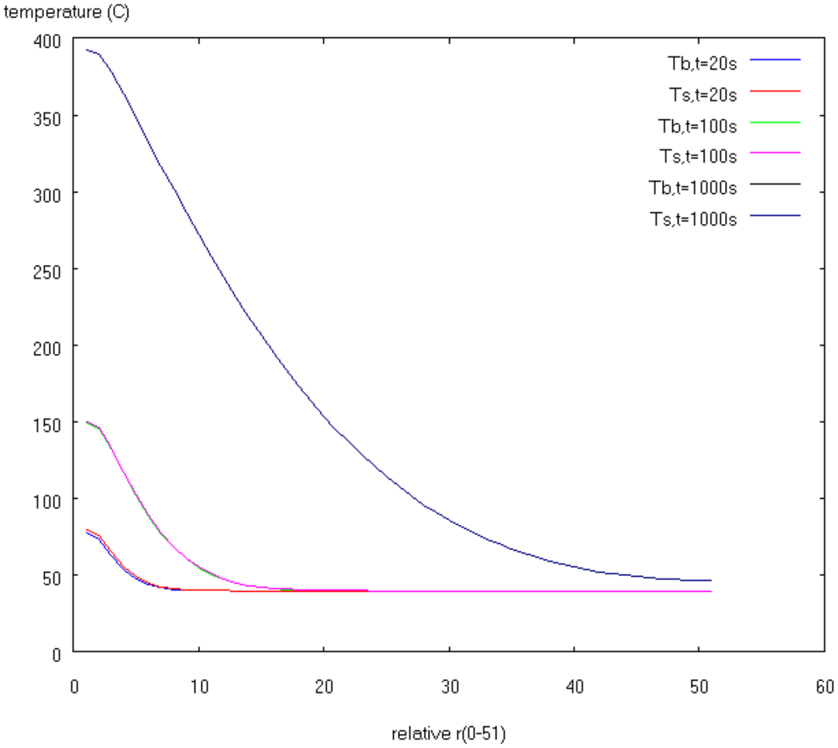


Figure 6

Figure 6 shows some temperature profiles of the pebbles (T_s) and the pebble centers (T_b). In the first period of heating the surface of the pebble at the entrance is a bit hotter than their centers. With time, when the surface temperature does not increase very fast anymore, T_b catches up with T_s. After 1 hour the difference between the 2 is negligible.

8. 3 phase model

The models of Vortmeyer and Schaefer [1] assume a uniform temperature throughout 1 pebble. This basically means pebbles are very small. To see what effects pebble size has on the performance of the pebble heater a third model was created. Pebbles are not negligible and have their own temperature profile inside them. This means there are now 3 temperatures; the temperature of the gas, the surface temperature of the pebbles and the temperature inside the pebbles. This yields a system of three PDE's.
The equation for the gas energy balance is the same as in the 2 phase model.

$$\mathrm{m_f * c_g * \frac{dT_g}{dx} + h_t * a_s * (T_g - T_s) = 0} \tag{0.19}$$

The equation for the energy balance of a pebble becomes equation 0.20. In addition to the situation of the 2 phase model some energy now moves into the pebble by conduction.

$$\mathrm{(1 - e) * \rho_s * c_s * \frac{dT_s}{dt} = h_t * a_s * \left(T_g - T_s\right) + k_s * \frac{d^2\, T_s}{dx^2}} + k_s \frac{\partial T_b}{\partial r} \tag{0.20}$$

The third equation is the energy balance inside a pebble. This is the heat equation. T_b is dependent on x,t and its position in the pebble r.

$$\mathrm{rho_s * c_s * \frac{dT_s}{dt}} = k_s \frac{\partial^2 T_b}{\partial r^2} \tag{0.21}$$

To find the temperature profiles the initial and boundary conditions of the 2 phase model have been applied. The 3 phase model also uses the relation determine in Appendix B: Data fits for the heat transfer coefficient.

To solve equation 0.21 the one term approximation is used. The one term approximation is valid only for τ>0.2, this is the case in the entire pebble heater, as is shown by equation 0.18.

Table 4 shows the data used in the 3 phase model.

$\dot{m}_f$	0.045 kg/s	a_s	284.7 m^2/m^{-3}	T_{omg}	1000 C
ρ_s	1400 kg/m^3	k_s	27 W/mK	T_0	40 C
c_s	800 J/kg	e	0.45		
c_f	1200 J/kg				

Table 4

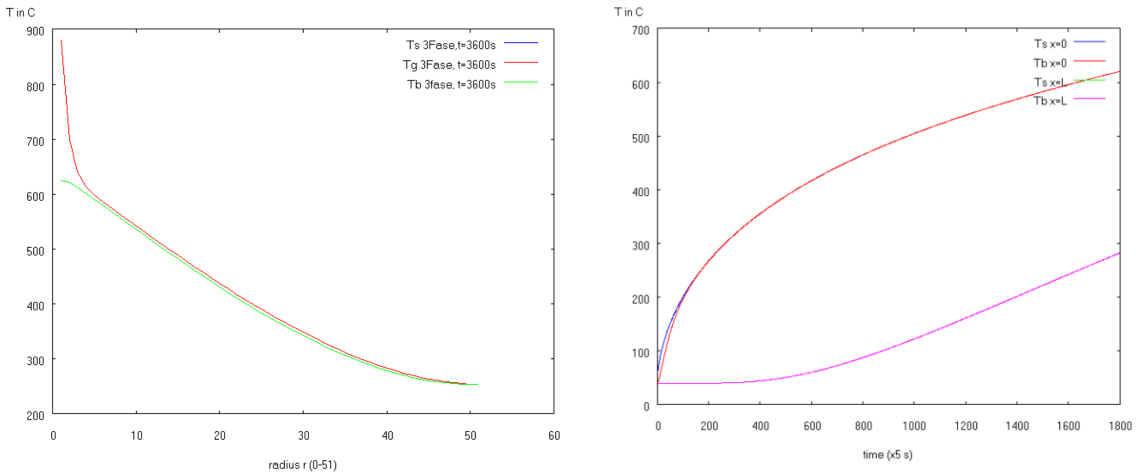


Figure 7

Figure 7 shows the temperature profile in the pebble heater as modeled by the 3 phase model. The graph looks similar to the 2 phase model with variable h_t. Figure 8 shows these two models in one graph (left) and the absolute difference in temperature on several locations (right). The maximum difference in temperature between the models is 8 C which is quite small on scale of 1000 C.

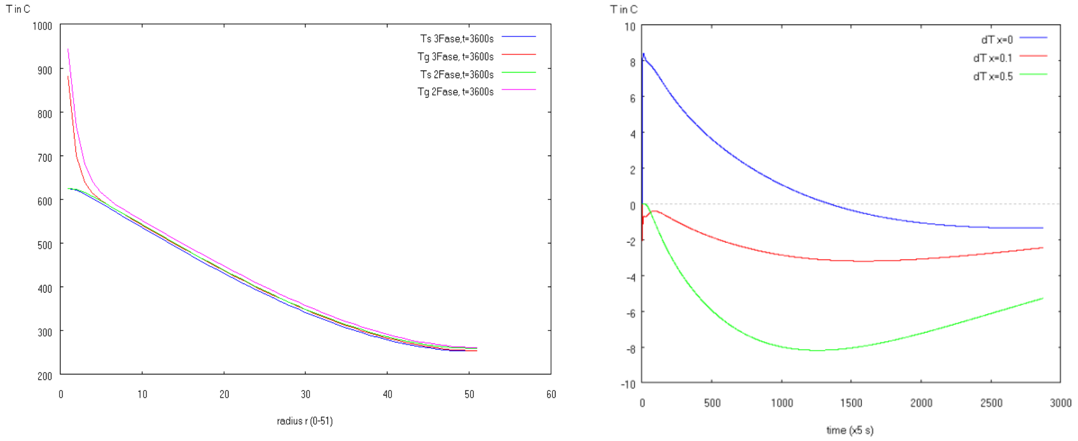


Figure 8

9. Conclusions and remarks

To predict the performance of a Pebble heater 3 models have been constructed. The first model assumed perfect heat transfer between air and pebble bed, air and pebbles are always at the same temperature.

The second model introduced the heat transfer coefficient to characterize the heat transfer between air and bed. First this coefficient was taken to be constant, later this war refined by making the heat transfer coefficient dependent on the air temperature. The 1 phase model and 2 phase model showed difference at locations/times where the difference in air temperature and pebble temperature of the 2 phase model is large.

To determine whether large temperature gradients can be expected inside the pebbles a third model was constructed. This model added an equation to determine the temperature profile inside a pebble. This equation was approximately solved using the one-term approximation. A comparison in the third model the centre temperature of a pebble and its surface showed little difference between the two. For short times the centre of a pebble warms up slower than the surface. This means the conduction inside the pebble is slower than the conduction+convection on the outside of the pebble. Later, when the outside of the pebble does not heat up very fast any more, the temperature difference between centre and surface becomes negligible.

Comparing this third model with the 2 phase model showed very small differences between the two, which was expected since after a while the pebble centre temperature was approximately equal to its surface.

To simulate the behaviour of the pebble heater it is advised to use the 2 phase model with a variable heat transfer coefficient. It is expected to be more accurate than the 1 phase model and the fixed heat transfer coefficient. The 3 phase model takes a lot longer to run than the 2 phase model and the differences are small. When one is planning to use larger pebbles the 3 phase model is advised since it can deal with the ‘slow’ conduction inside the pebbles.

Part 2: Drying Wood

1. Introduction

An important parameter in the process of making charcoal is the moisture content of the wood. To better monitor the quality of the wood and to reuse the energy of the hot flue gases of the carbonization process the wood is dried by Clean Fuels itself. A batch of wood is placed in the reactor and dried by flowing drying gas over/through it.

Drying wood is a difficult process to model. A lot of models exist in literature, all of which are quite complicated. In this part of the report several simple models for drying wood are constructed. Practical experiments will have to show whether these models are usable.

There are two main reasons why the drying of wood is hard to model. The grains in wood cause it to be very anisotropic. This causes all kinds of properties to vary per direction, for example the diffusivity of water in wood. The geometry of the wood can influence the degree of anisotropy greatly. A big block of wood is very anisotropic, infinitely small pieces of wood are isotropic. Smaller pieces are be favorable in terms of isotropicness, however making small pieces costs more money and energy than bigger ones.
In the first part of report a pebble heater is modeled. To reuse some of the equations constructed there the wood pieces are assumed to be spheres with a diameter of 0.1 m.

Another difficult aspect of drying wood is the presence of different forms of water in wood. The first form of water is 'free' water. This is water present between the cells of a piece of wood. Removing this water is relatively easy and happens by a constant rate. In literature [3] the removal of free water is called the 'constant drying' phase of a wood drying process. The second form of water is 'bound' water. This water inside the cells of piece of wood. To get 'bound' water out of the cells it has to diffuse from inside the cells to the outside. Since the quantity of water inside a cell is not infinite the speed of drying is not constant, but decreases with time. This phase is called the 'falling drying rate' [3]. The third, hardest to remove, form of water is 'chemically bound' water. This form of water is part of the molecules of the wood and will be typically be removed in the carbonization phase of the process. The models constructed in this report all concern the 'constant drying rate' phase since it is very hard to construct a model for the 'falling drying rate' phase without experimental data.

In the process of making charcoal the wood is dried by leading hot gas over the wood. So the way of drying is forced convective drying. In the real process the kind of gas is dependent on the state of the process. Initially 100% drying gas is led over the wood. However, since the drying gas is reused, with time the gas will become more and more saturated with steam changing its properties.

To make the modeling possible within the allotted time frame some assumptions have been made. Assumptions made for every drying model are listed at General assumptions. Extra assumptions per model are listed in the specific section of that model. The models go from simple to more complex and are: ‘simple approximation’, ‘2fase constant drying approximation’ and ‘2fase wood and air’.

2. General assumptions

These are assumptions made for every model. An explanation for some of the non-trivial assumptions is given under the list.

1. The wood is isotropic.
2. The model is 1D.
3. Drying gas behaves like an ideal gas.
4. The drying gas led into the reactor is air.
5. No volumetric shrinkage of wood.
6. All water is ‘free’ water.
7. All water is divided perfectly uniform throughout the wood at t=0.
8. Drying rate (kg/s) is constant.
9. Evaporated water cannot condense ‘back’ onto the wood.
10. Wood consists of identical spheres.
11. There is no heat conduction between or in wood pieces.

The models are chosen to be 1D. This means that properties only vary in the direction of the gas flow. It can be expected that the greatest variation in properties is in this direction.
Evaporated water cannot condense ‘back’ onto the wood. The drying gas can be become saturated with water, if its temperature drops further in the domain water can condense ‘back’ onto the wood. This effect is neglected in order to keep the models simple.
There is no conduction between or in wooden spheres. Wood is a poor conductor of heat, conduction of heat is therefore left out of this model.

3. List of symbols

Table 5 shows a list of all symbols used in this second part of the report. These symbols are also used in the programmed code.

Symbol	Value (unit)
mwood	Mass of wood (kg)
mH2Ot	Total mass of water (kg)
mH2O	Mass of water per spatial step (kg)
mST	Mass of steam (kg)
mflow	Massflow of air (kg/s)
rho_wo	Density of wood (kg/m3)
rhog	Density of gas (kg/m3)
Tg	Gas temperature (C)
Ts	Wood temperature (C)
kg	Conductivity gas (W/m^{2}C)
ht	Heat transfer coefficient from gas to wood (W/m^{2}C)
cpa	Heat capacity of air (J/kg)

cpwo	Heat capacity of wood (J/kg)
cpst	Heat capacity of steam (J/kg)
cpH2O	Heat capacity of water (J/kg)
M	Massfraction water in wood, dry base (kg water/kg wood)
MC0	Initial moisture content in wood (-)
H	Massfraction steam in air, dry base (kg steam/ kg air)
A_sphere	Surface area 1 wooden sphere, (m^2)
V_sphere	volume 1 wooden sphere, (m^3)
D	Diameter bed (m)
A	Frontal area bed (m^2)
He	Bed height (m)
Vre	Reactor volume (m^3)
Vwo	Volume all spheres (m^3)
Awo	Surface area all spheres (m^2)
n	Number of spheres (-)
as	Surface area per volume (m^2/m^3)
T_omg	Initial gas temperature (C)
T0	Initial bed temperature (C)
hv	Heat of evaporation of water (J/kg)
time	Total time of simulation (s)
Pr	Prandtl nr (-)
Re	Reynolds nr (-)
Nu	Nusselt number (-)
mu	Dynamic viscocity (kg/ms)
vgas or vair	Speed of gas in bed (m/s)
e	Porosity of bed (-)
Ps1	Vapor pressure of water in wood (kPa)
Pv1	Vapour pressure of steam in air (kPa)
dt	Discrete timestep (s)
h	Discrete spatial step in bed (m)
nh	Nr of discrete spatial steps (-)
r	Spatial step inside sphere (m)

Table 5

4. Simple approximation

The simple approximation assumes all properties except moisture level and the wood temperature to be constant throughout space and time. There are 7 extra assumptions on top of the ones made under General assumptions. The goal of this model is to get an idea of the time required under ideal circumstances.

1. The drying gas has 1 constant temperature.
2. All other properties of the drying gas are also constant.
3. The wood has always 1 uniform temperature.

4. Until the wood reaches a temperature of 100 C no water evaporates.
5. All energy added to wood of 100 C is used for evaporating water.
6. Heat transfer coefficient is constant during heating of wood.
7. Heat transfer coefficient is constant during evaporation of water.

The model consists of two phases. In the first phase the wood+water is heated up to 100 C by means of forced convection, equation . In the second phase the water is evaporated, the wood has constant properties throughout this phase, equation .

$$\left(m_{wood} c_{p,wood} + m_{H2O} c_{p,H2O} MC_0\right)(T_1 - T_0) = h_{t1}\, a_s V_{wo}\left(T_{omg} - T_0\right) t_{phase1} \qquad \mathbf{0.1}$$

$$h_v m_{H2O} = h_{t2}\, a_s V_{wo}\left(T_{omg} - T_1\right) t_{phase2} \qquad \mathbf{0.2}$$

Using the values listed in table 1 the total time to evaporate all water out of the wood is given by equation.

m_{wood}	1383 kg	h_{t1}	15 W/m^{2}K	h_v	-2257 kJ/kg
$c_{p,wood}$	2000 J/kg	h_{t2}	25 W/m^{2}K	T_{omg}	150 C
m_{H2O}	484 kg	a_s	31.5 m^2/m^3	T_0	20 C
$c_{p,H2O}$	4180 J/kg	V_{wo}	2.66 m^3	T_1	100 C
MC_0	0.35	D_{bed}	1.8 m	L_{bed}	2 m

Table 6

$$t_{total} = t_{phase1} + t_{phase2} = 3168 + 10440 = 13608\, s \qquad \mathbf{0.3}$$

5. 2 phase constant drying approximation

In the Simple approximation model the wood is considered as a piece with constant properties throughout the spatial coordinate. In the 2 phase constant drying approximation

This is no longer the case. Since convection takes place the drying gas which enters the reactor has a higher temperature than the gas exiting the reactor. The spatial domain is split in n equal portions of uniform temperature.

The heat transfer coefficient h between drying gas and wood is given by the relation derived for the pebble heater. In this relation h depends only on T_g.

The additional assumptions are listed here.

1. Until the wood reaches a temperature of 100 C no water evaporates.
2. All energy added to wood of 100 C is used for evaporating water.
3. In a spatial step there is 1 uniform wood temperature and 1 uniform gas temperature.
4. Properties of the drying gas are only dependent on T_g.

Because it is assumed that the properties of the drying gas only depend on T_g the same fits as the ones constructed for the pebble heater are used.
If the temperature of the wood (T_s) is lower than 100 C the governing equations are:

$$\rho_{wo} * c_{p,wood} * \frac{\partial T_s}{\partial t} = h_t * a_s * (T_g - T_s) \tag{0.4}$$

$$\rho_g * v_{gas} * \frac{\partial T_g}{\partial x} = h_t * a_s * (T_g - T_s) \tag{0.5}$$

In order to solve these equations a boundary condition for T_g and an initial condition for T_s are required. The initial condition is simply that the wood is initially at room temperature.

$$T_s(x, 0) = T_0 \tag{0.6}$$

The boundary condition for T_g is the same as in the pebble heater model; the change of enthalpy of the gas stream is equal to the thermal energy transferred between the incoming gas and the pebble bed at the entrance.

$$\dot{\mathrm{m}}_{\mathrm{f}} * \mathrm{c}_{\mathrm{p,a}}(\mathrm{T}_{\mathrm{omg}} - \mathrm{T}_{\mathrm{g}}(0, \mathrm{t})) = (1 - \mathrm{e}) * \mathrm{h}_{\mathrm{t}} * (\mathrm{T}_{\mathrm{omg}} - \mathrm{T}_{\mathrm{s}}(0, \mathrm{t})) \tag{0.7}$$

Note that in this model T_g and T_s have both space (x) and time (t) as variables. When at a certain point T_s gets larger than 100 C all energy transferred from the drying gas is used evaporating gas. The governing equation becomes 0.8. the initial condition is simply MC0*mwood.

$$\frac{\partial m_{H2O}}{\partial t} = h_v * h * a_s * (T_g - T_1) \tag{0.8}$$

Table shows the values used in this model. Most are the same as in the Simple approximation.

m_{wood}	1383 kg	$c_{p,a}$	1100 J/kg	h_v	-2257 kJ/kg
$c_{p,wood}$	2000 J/kg	e	0.48	T_{omg}	150 C
m_{H2O}	484 kg	a_s	31.5 m^2/m^3	T_0	20 C
$c_{p,H2O}$	4180 J/kg	V_{wo}	2.66 m^3	T_1	100 C
MC_0	0.35	$\dot{m}_f$	1	D_{bed}	1.8 m
				L_{bed}	2 m

Shows the temperatures T_g and T_s throughout time at the entrance and exit of the reactor. Shows the moisture content of the first and last spatial step as well as the total amount of water in the wood.

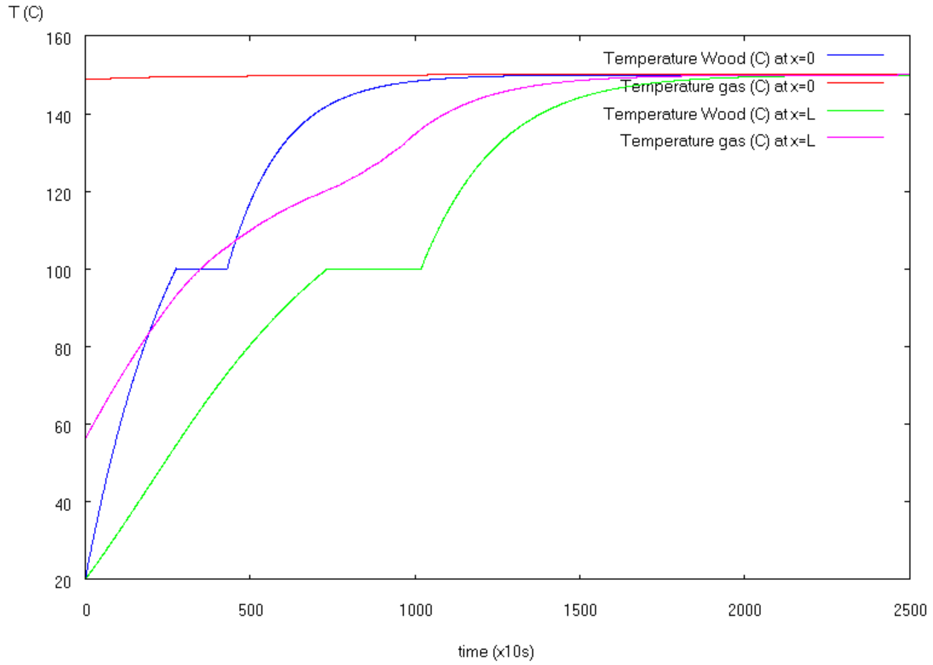


Figure 9

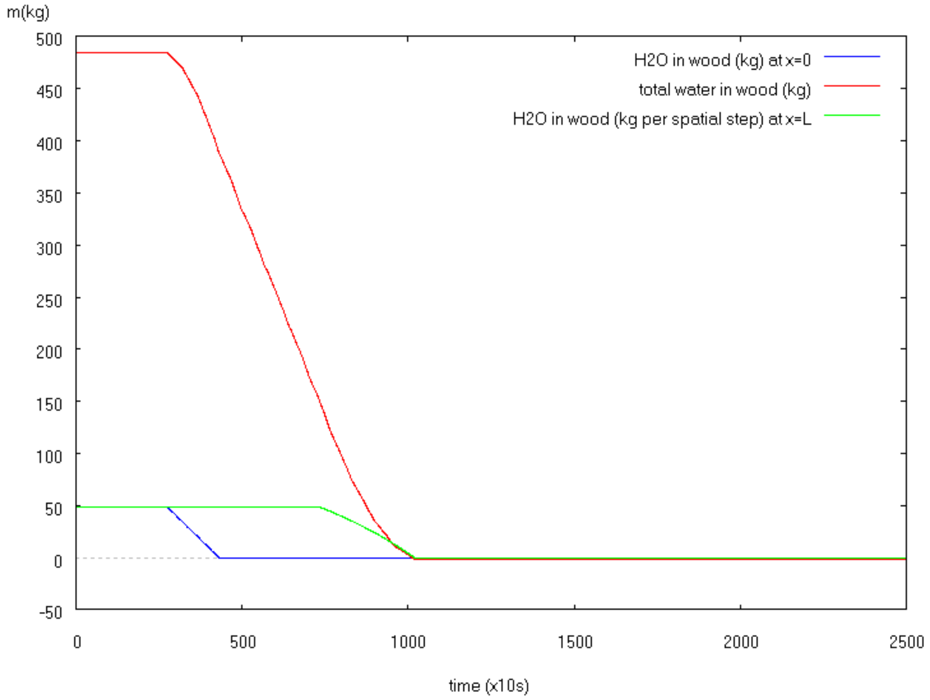


Figure 10

The ‘platforms’ in the graphs of the wood temperatures are the periods at which water is evaporated from the wood. From the figures it becomes clear that the wood is dry much earlier when placed at the entrance of the reactor. This is definitely something to keep in

mind since in reality the wood will not be dried completely and the moisture content has influence on the quality of the charcoal produced.
The drying gas is set to enter the reactor at 150 C. In order to dry the ‘furthest’ parts of the wood hot gas flows past the dry wood at the entrance of the reactor. At t= 5000s the wood at the entrance is dry but is still heated for about 5000s to dry all the wood. Being exposed to high temperatures for this long can cause chemical reactions to occur on the wood. This might be undesirable.
This model shows that the wood is completely dry after about 10000 s. To decrease the drying time one can increase the mass flow of drying air.

6. 2 phase Wood and Air

This is the third and final model constructed in this report. Please note that this model is complete in its current state and needs to be checked and supplemented thoroughly. In this section the assumptions, governing equations and some not-complete results for this model are discussed. In comparison with the former two models this model uses a different driving force for evaporation. The former models simply put that above 100 C all incoming energy was used to evaporate water. This model uses the pressure difference between the vapor pressure of the water in the wood and the vapor pressure in the drying gas. The 2 phase constant drying approximation stated that the properties of the drying gas only depended on its temperature and the drying gas was pure air. Now the moisture content of the drying gas is also important as it determines the water vapor pressure and the composition of the gas. Assumptions made for this model above the General assumptions are listed here.

1. Driving force for water evaporation is pressure difference between air and wood.
2. In a spatial step there is 1 uniform wood temperature and 1 uniform gas temperature.
3. Properties of the drying gas are only dependent on T_g.

Please keep in mind when looking into the graphs of this model (Figure 11, Figure 12 and Figure 13) that this model is still under construction.

Since the driving force for evaporation in this model is pressure difference it is important to determine the vapor pressure in the liquid water in the wood and the water vapor partial pressure in the air. For the vapor pressure of water a lot data exists. Data from a table [4] has been fitted using excel. This produced equa to calculate the vapor pressure of water dependent on its temperature. Liquid water can reach a maximum temperature of 100 C, under normal circumstances, wood however can reach temperatures above 100 C. In this model wood and liquid water are modeled having one temperature, T_s, in order to avoid impossible situations like liquid water of 140 C the temperature of the incoming drying gas, T_{omg}, is set to 100 C.

$$P_{s1} = (-2.5 * 10^{-12}\, T_s^6 + 3.5 * 10^{-9}\, T_s^5 + 2 * 10^{-7}\, T_s^4 + 3 * 10^{-5}\, T_s^3 + 1.4 * 10^{-3}\, T_s^2 + 4.5 * 10^{-2}\, T_s + 0.6089 \qquad \mathbf{0.9}$$

The partial pressure of water vapor is assumed to be dependent only on T_g. Because no good relation for the determination of the partial pressure of water vapor could be constructed the same relation as for liquid water is used.

$$P_{v1} = (-2.5 * 10^{-12}\,T_g^6 + 3.5 * 10^{-9}\,T_g^5 + 2 * 10^{-7}\,T_g^4 + 3 * 10^{-5}\,T_g^3 + 1.4 * 10^{-3}\,T_g^2 + 4.5 * 10^{-2}\,T_g + 0.6089 \tag{0.10}$$

Using the two pressures calculated above one can calculate the evaporation rate of water from wood to air using equation 0.11 in quantity per second. This formula is found in literature [5] where it was used to calculate evaporation of water from a pool at atmospheric. It is assumed the formula is applicable at the higher temperatures in the reactor.

$$\frac{\partial M}{\partial t} = \frac{(P_{v,wood} - P_s) * \left(0.089 + 0.0782 v_{gas}\right) * a_s}{h_v * rho_{wo}} \tag{0.11}$$

Besides the moisture content of the wood (M) there are 3 more unknowns in this model. T_s and T_g are, like in the models, also unknown. The fourth unknown is the moisture content in air (H) since this property is no longer constant. To find these 4 quantities 4 governing equations are required. The first one is equation 0.11 for determining the evaporation rate.

The second governing equation is found by setting up the energy balance for the drying air [6]. The energy at point x is given by the energy at point x-1 plus the energy added to the air by evaporating water minus the energy transferred to the wood by forced convection. In formula form the second governing equation is given by 0.12.

$$\rho_g v\left(c_{pa} + c_v H\right)\frac{\partial T_g}{\partial x} = \rho_{wo} c_v\left(T_g - T_s\right)\frac{\partial M}{\partial t} - h\, a_s(T_g - T_s) \tag{0.12}$$

This energy balance can also be constructed for the wood [6]. The energy content at point x at time t is given by the energy content at time t-1 plus the energy added by forced convection from the drying air minus the energy removed by evaporation of water. The energy balance of the wood is the third governing equation.

$$\rho_{wo}(c_s + c_{H2O} M)\frac{\partial T_s}{\partial t} = \rho_{wo} h_v \frac{\partial M}{\partial t} + h\, a_s(T_g - T_s) \tag{0.13}$$

The fourth governing equation is the mass conservation of water [4]. All liquid water evaporated from the wood is converted to steam in the drying air.

$$v\, \rho_g \frac{\partial H}{\partial x} = -\rho_{wo}\frac{\partial M}{\partial t} \tag{0.14}$$

In order to solve these 4 equations some initial and boundary conditions are required. These conditions are given by .

$$T_s(x,0) = T_0 \tag{0.15}$$

$$M(x,0) = MC0 \tag{0.16}$$

$$\dot{\mathrm{m}}_\mathrm{f} * \mathrm{c}_\mathrm{f}(\mathrm{T}_\mathrm{omg} - \mathrm{T}_\mathrm{g}(0,\mathrm{t})) = (1 - \mathrm{e}) * \mathrm{h}_\mathrm{t} * (\mathrm{T}_\mathrm{omg} - \mathrm{T}_\mathrm{s}(0,\mathrm{t})) \tag{0.17}$$

$$\mathrm{H}(0,\mathrm{t}) = 0 \tag{0.18}$$

Using the boundary and initial conditions the 4 governing equations are solved numerically using Maxima. The data used is listed in table .

m_{wood}	1383 kg	c_v	2200 J/kg	h_v	-2257 kJ/kg
$c_{p,wood}$	2000 J/kg	$c_{p,a}$	1100 J/kg	T_{omg}	100 C
m_{H2O}	484 kg	a_s	31.5 m^2/m^3	T_0	20 C
$c_{p,H2O}$	4180 J/kg	V_{wo}	2.66 m^3	D_{bed}	1.8 m
MC0	0.35	e	0.48	L_{bed}	2 m
ρ_{wo}	519 kg/m^3				

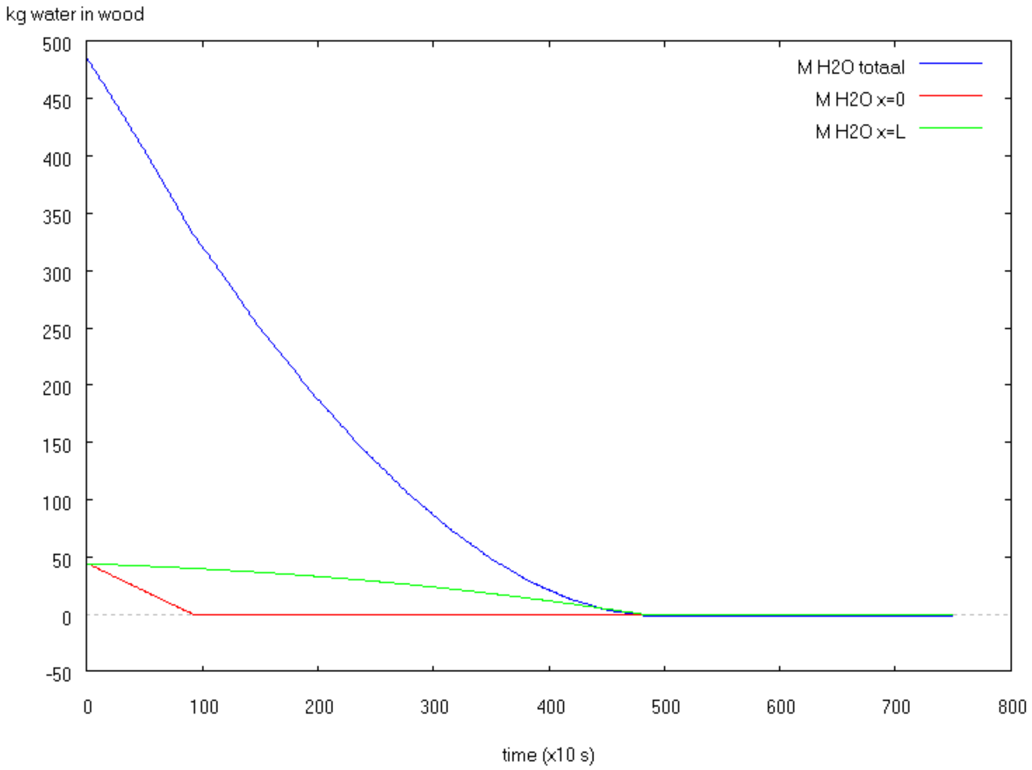


Figure 11

Figure 11 shows the mass of H_2O in the wood over time. This model shows that the wood is completely dry after 5000 s. The red and green line show the mass of H_2O in the wood at the entrance and end of the reactor respectively. The beginning is dry after 1000 s, the end takes about 5 times longer. Changing the amount of spatial will change the time required to dry the wood at the entrance, decreasing the spatial step size will decrease the time required for drying. Changing the spatial step size will not change the time required to dry the wood.

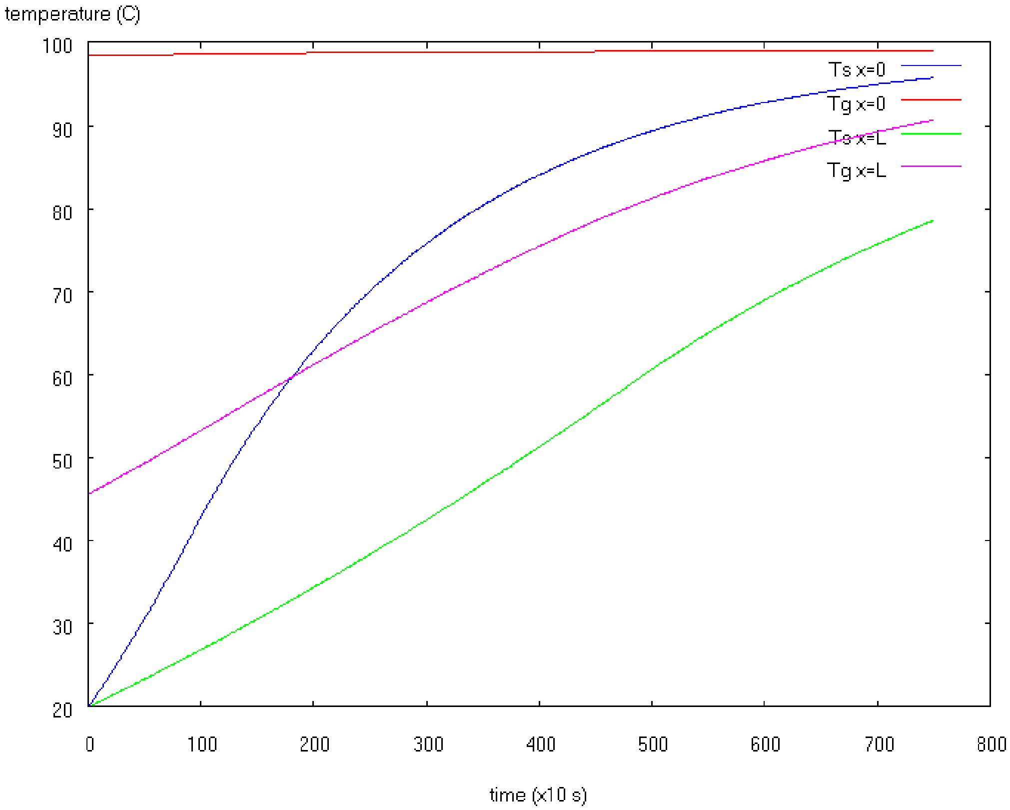


Figure 12

Figure 12 shows the temperatures of the wood and drying gas over time. The temperature of the wood 'crawls' slowly towards the graph of T_g. This takes long compared to the pebble heater because energy is consumed by the evaporation of water and wood has a high heat capacity $(\rho * c_p)$.

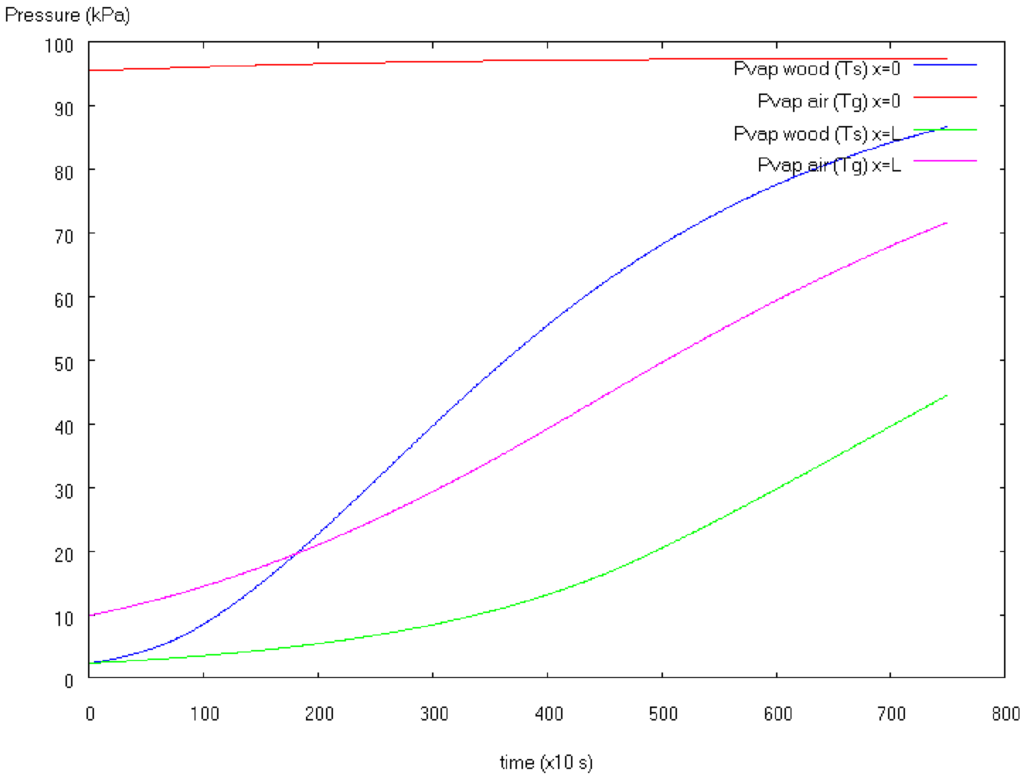


Figure 13

Figure 13 show the vapor pressure of H_2O in wood and in the drying air over time. The graphs are quite similar to the ones for the temperatures. At the entrance the vapor pressure of the vapor is high all the time because of the high value of T_g.

7. Conclusions and remarks

3 models have been constructed for the evaporation of water out of spheres of wood. The first two models, Simple approximation and 2 phase constant drying approximation, are based on the amount of energy required for heating the wood and converting water from its liquid to the vapor phase. The models are made only for evaporating the ‘free’ water from the wood

The third model is still ‘under’ construction. The relation used for the vapor pressure of the vapor is not right. It should depend on both temperature and the vapor content of the air. The relation used now is chosen merely to test if the model works in terms of solving the other equations, which it seems to do.

In order to improve the 2 phase Wood and Air model and get a more realistic model a better relation for the partial pressure of the vapor in air. This relation should at least depend on both temperature, T_g , and moisture content, H.

Another thing to improve is the temperature of the solid part of the model, liquid water and wood. Currently this 1 temperature, T_s. At the 100 C mark however wood should be able to get a higher temperature where the liquid water cannot.

Adding the second phase of the drying process, the ‘falling drying rate’, is another essential thing to improve the model. It will require an equation to simulate the diffusion of water from inside the wood cells to ‘free water’, between the cells. When water is ‘free’ water it can be evaporated as is modeled in the 2 phase Wood and Air model. Adding this diffusion component also allows for an estimation of the temperature profile inside the wooden spheres. When a diffusion model is present this can be done quite easily using the one-term approximation of the pebble heater.

The model as it is constructed now assumes the wood to be shaped like spheres. When in reality the wood is shaped like sticks in direction of the gas flow diffusion inside the wood will be play a much bigger role than in the sphere-shaped wood. The final model will have to somehow simulate the geometry and shape of the wood in the reactor in a realistic way, this also requires some model for anisotropy.

The anisotropy, diffusion inside wood and geometry of wood are hard to predict as there is much variation in these properties in real wood. So when all things suggested here are implemented in the drying model experiments will have to performed to get the real drying curve and improve the model to a realistic one.

Appendix

Appendix A: relation for heat transfer coefficient

The heat transfer coefficient h determines the heat transfer between the gas phase and the solid phase. Knowledge of this coefficient is especially important in the part of the pebble heater where the temperature difference between gas and solid phase is big. This temperature difference decreases with time, and so does the important of an accurate h. making some hand calculations the average h should be about 15 W/m2K, this value is assumed as the fixed h in the previous discussed 2fase model.
A more realistic h can be calculated by the correlation between the Nu, Re and Pr-numbers in a packed bed, determined by Whitaker [7]. This correlation uses the properties and velocity of the gas flowing past the bed to determine the heat transfer coefficient h_t.

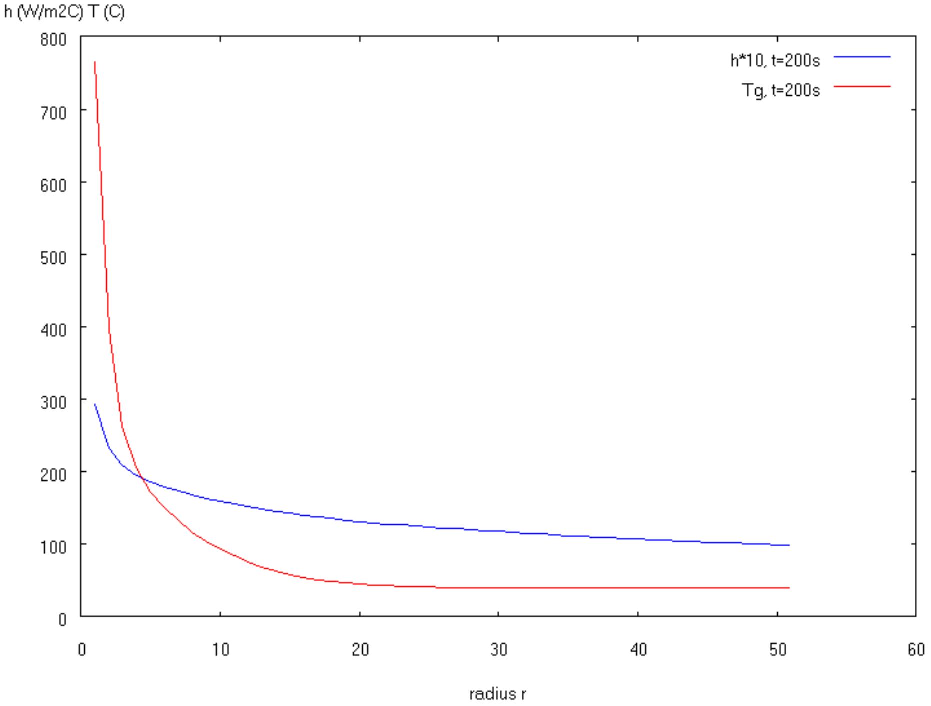
$$\mathrm{Nu} = \left(0.5 * \mathrm{Re}^{0.5} + 0.2 * \mathrm{Re}^{\frac{1}{3}}\right) * \mathrm{Pr}^{\frac{1}{3}} \tag{0.1}$$

Where

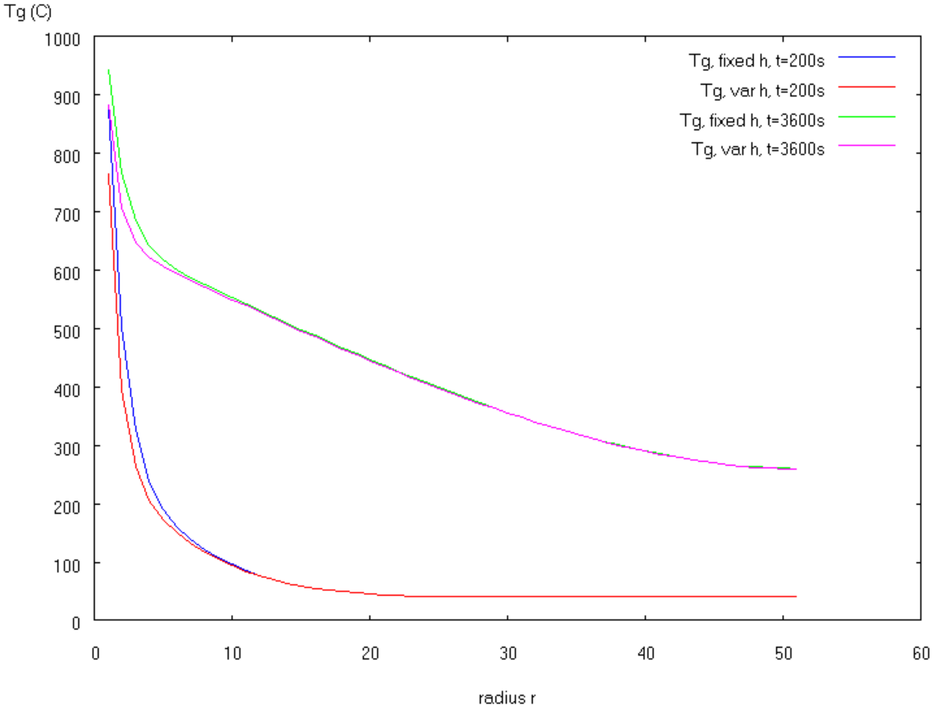
$$\mathrm{Nu} = \mathrm{h} * \frac{\mathrm{L_c}}{\mathrm{k_g}} \tag{0.2}$$

$$\mathrm{Re} = \mathrm{rho_g} * \mathrm{v_{gas}} * \frac{\mathrm{L_c}}{\mathrm{nu}} \tag{0.3}$$

Notice that for a gas cooled from 1000 to 40 C properties like ρ_g, nu and k_g change dramatically. In Appendix B: Data fits relations for these properties and the gas temperature are derived.
The variable h is heavily temperature dependent, as shown in Figuur 1. Figuur 2 shows several temperature distributions with both a various and a constant h. Figuur 2 shows that the influence of the heat transfer coefficient grows less with time, which is logical since with time the temperature difference between bed and air diminishes.



Figuur 1



Figuur 2

Appendix B: Data fits

During the heating/cooling of the pebble heater temperatures of the gas and pebbles vary from 40 to 1000 C. For the solid pebbles material properties are considered constant throughout the entire process. For the gas phase however properties like density and conductivity change a lot. Using data from the engineering toolbox [8] relations for the properties of air have been fitted using maxima. The heat capacity of the gas is considered constant since it varies little with temperature. In these fits the air temperature needs to be in degrees Celsius.

Relation for air density dependent on air temperature.

$$\rho_g(T_g) = \frac{101325}{(T_g + 273) * 287} \tag{0.4}$$

Relation for conductivity of air dependent on air temperature.

$$k_g(T_g) = 1.78 * 10^{-11} * T_g^3 - 2.84 * 10^{-8} * T_g^2 + 7.75 * 10^{-5} * T_g + 0.02 \tag{0.5}$$

Relation for the dynamic viscosity of air dependent on air temperature.

$$mu_g(T_g) = (-1.52 * 10\wedge - 5 * T_g^2 + 0.05 * T_g + 16.97) * 10\wedge - 6 \tag{0.6}$$

The fitted relations between the gas properties and the gas temperature are primarily used to determine the convective heat transfer coefficient h. The specific heat capacity, c_p, and Prandtl number, Pr, of air are considered to be constant since it changes little with temperature.

Appendix C: discretization and stability

In order to solve the various systems of PDE's listed in this report a numerical code was written. In this code the spatial coordinates and their derivatives are determined by a spatial discretization. Equation 0.7, 0.8 and 0.9 show the discretization for first and second derivatives, there are no higher derivatives in the code.

$$\frac{\partial T}{\partial x} = \frac{T(x+1) - T(x)}{h} \tag{0.7}$$

$$\frac{\partial T}{\partial x} = \frac{T(x) - T(x-1)}{h} \tag{0.8}$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T(x+1) - 2\,T(x) + T(x-1)}{h^2} \tag{0.9}$$

Where h is the spatial step size in the bed.
The system of PDE in time coordinates is solved by an euler forward scheme, shown by equation yy.

$$T(t+1) = T(t) + dt * \frac{\partial T(t)}{\partial t} \tag{0.10}$$

Where dt is the step size in time. Combining the discretizations with the Euler forward method allows the systems of PDE's to be solved.

Stability

The Euler forward method used to calculate the numerical solutions of the PDE's in time is simple to program method. Drawback of the method is its' instability. In order to make sure the system stays stable the stability criterion has to be met. Equation 0.11 gives the stability criterion.

$$\tau = \frac{\alpha * \mathrm{dt}}{\mathrm{h}^2} =< 0.5 \qquad \mathbf{0.11}$$

With α the thermal diffusivity of the pebbles $\alpha = \frac{k}{\rho * cp}$.

The time step and spatial step are chosen in such way that the Euler forward method is stable.

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