Commissioning of an Flame Reactor for Research on Entrained-Flow Gasification

INTERNSHIP REPORT

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Commissioning of a flame reactor for research on entrained-flow gasification

Report of an internship at Luleå university of technology.

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1 abstract

The present report describes the commissioning of an entrained flow gasification reactor for research on wood gasification. Work is carried out at University of Luleå at the division of Energy Engineering. A review of entrained flow gasification of wood powder is presented. The design of the gasification reactor which did not work so far is described. Improvement have been made on the fuel feeding by means of pneumatic conveying. The stability and steadyness of massflow of wood particle is highly improved. Furthermore improvement on leakage control, ignition, safety in general and windowpanes for optical measurements are made. The reactor has been run with a flame inside for the first time. Results and finding from these testruns are discussed and further improvement are extracted for further improvements. In principle the reactor is working. However before scientific research can be done more improvement have to be made for safety reasons and more test runs have to be conducted to map out the reactors characteristics.

Keywords: gasification, entrained-flow, wood, biomass, combustion.

Contents

2 Introduction

With the growing awareness of climate change and global warming in the past decades the research onto more sustainable fuels is a big issue. One alternative to reduce the CO_2 emmision is the use of bio-based fuels instead of fossil fuels. Using bio-based fuels the balance between emitting and extracting CO_2 from the athmosphere can be equilibriated. The net amount of CO_2 will reduce and in ideal situations equal to zero. Examples of biomass feedstocks used for fuel production are algae, sugar cane, cattle manure and agricultural waste and wood. The latter is particular interesting for Sweden since the woodlogging is a major industry. Sweden stated a goal that in 2030 the country's vehicle fleet should be fossil fuel independent[4]. Since Sweden has a large industry in logging, the use of wood as a fuel stock can contribute to energy independency. This also holds for countries like Canada, Finland, Russia but also Southern American countries where they have a large wood industry as well.

Wood can be used as a fuel by direct combustion to produce heat or electricity, for example in grate fired wood burners. Another way of using wood as a fuel is to pyrolyse it to a combustible (pyrolysis)oil. This oil can be used in industry. The use of pyrolyse oil is already tested in industry. Stork Thermeq (Netherlands) and Dreizler (Germany) tested their combustion equipment with pyrolysis oil which gave succesfull results for commercial usage.

A third way of using wood as a fuel is by gasification. Wood can be gasified into a syngas which in the end can replace natural gas. Gasification technology is an already proofed technology which is used in commercial industry for coal applications. GE, Shell and Lurgi have the biggest share with together around 70 % of the total amount of syngas produced from coal worldwide. Mainly produced by entrained flow gasification or moving bed gasification. However for biomass the gasification technology is still in its development. There are commercial available biomass gasifiers but still on a small scale. Since there is not a specific biomass gasification technology which is better than the other, research focusses on several kind of biomass gasification technologies.

3 Gasification

Gasification is a thermal oxidation process where carbonaceous fuels, for example coal but also lignocellulosic materials, are converted into a synthetic fuel gas. These synthetic fuel gasses, often called syngas consist generally of N_2, CO, CO_2, CH_4 and H_2. In a gasification process the carbonaceous fuel particle is subjected to several chemical processes. First the solid fuel particle should be dried to reduce the moisture content. Fresh wood contains over 50 wt% of moisture. By a simple evaporation process in ambient air the moisture content can be reduced to levels around 20 wt%. The remaining moisture will evaporate during the gasification process. The next step in the gasification process is the devolatilization (or pyrolysis). The solid fuel particle is heated up to temperatures above 350 degrees celsius where volatilization of the solid fuel starts. Gasses are released to the surroundings and char is produced as a residue. The rate of devolatilization is dependent on the rate of heat applied and the solid particle size. At low rates of heat supply the devolatilization starts at lower temperatures and takes a slower reaction rate. Smaller particles will devolatilize faster since the particle surface to volume ratio is higher than with bigger particles.

After devolatilization the volatile gasses together with recirculated hot combustable gasses undergoe a combustion reaction in a sub-stochiometric condition. The volatile and reccirculated gasses react with oxygen to produce primarily carbon dioxide and carbon monoxide and water. This oxidation reaction are exothermic and the released heat will increase the temperature of the char particles. When the char particles are increasing in temperature they will undergoe a reaction with the surrounding gasses in absence of oxygen. This reaction is the gasification of the solid char particle. The main reactions which occur are:

$$C_{char} + CO_2 \rightarrow 2CO \tag{1}$$
$$C_{char} + H_2O \rightarrow H_2 + CO \tag{2}$$
$$C_{char} + 2H_2 \rightarrow CH_4 \tag{3}$$
$$C_{char} + O_2 \rightarrow CO_2 \tag{4}$$
$$C_{char} + \frac{1}{2}O_2 \rightarrow CO \tag{5}$$

Reaction 1 is the boudouard reaction. The second reaction 2 is the water gas reaction. The water is produced by the combustion of the volatile gasses and the water which is released from the biomass particle. The third reaction is called the methanation reaction. Methane is produced after hydrogen reacts with the carbon. The last two reaction 4 and 5 are oxidation reaction of the carbon with oxygen. Since most of the oxygen will be consumed to combust the volatile and recirculated gasses at the vicinity of the burner these reactions are unlikely to occur. After the gasification step, when all the char is gasified an ash particle remains. Depending on the temperature of the particle it is in solid state or melted. Most gasification technologies work in so called slagging mode where the ash leaves the reactor as a molten slag.

4 Gasification process technologies

For gasification processes several technologies have been developed. In general these broad scale of processes can be categorized in three groups of technologies: Moving-bed gasifiers, fluidized bed gasifiers and entrained-flow gasifiers. Moving-bed gasifiers and fluidized-bed gasifiers are already used for commercial biomass applications in contrast to entrained-flow gasifiers which is still in its development. The European Biomass Industry Assocation (EUBIA) did a review on manufacturers offering commercial biomass gasification plants. 77.5% of the design are fixed bed gasifiers, 20% of the design are fluidized bed systems. and 2.5% are of various other design. It is clear that the entrained flow gasification technology is still lacking.

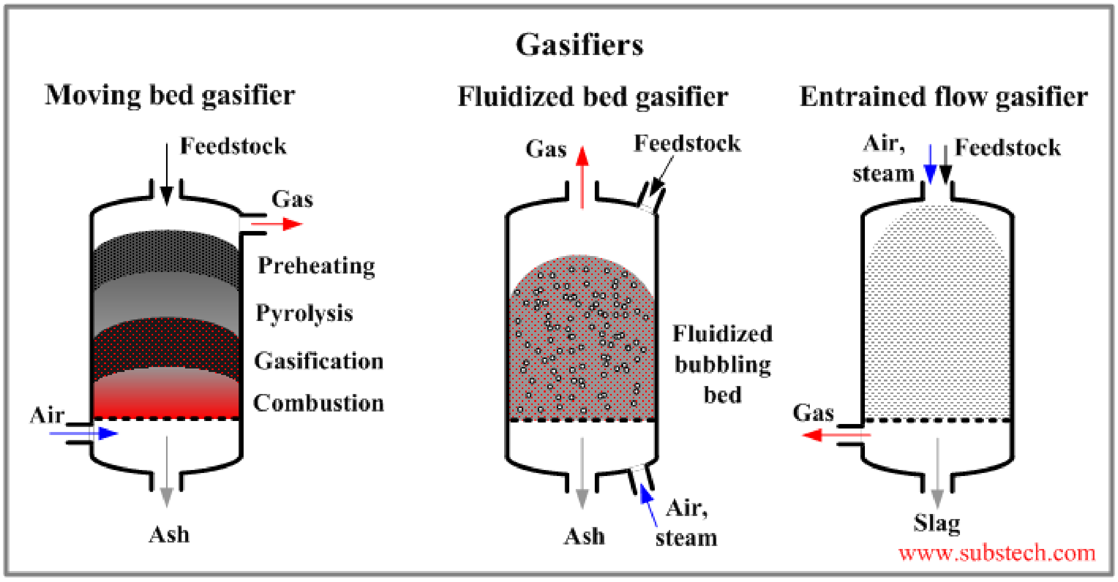


Figure 1: Three main technologies in gasification [5]

4.1 Moving bed gasification

In a moving bed gasifiers the feedstock moves in a countercurrent flow with the gasification agent air. Air flows from the bottom through the grate upwards while the feedstock falls down from the top under action of gravity. In the upper region of the gasifier the solid fuel particles are heated up by the hot gasses coming from below. The next region is the pyrolysis region where volatile gasses and chars are produced. The volatile gasses released flow upwards through providing the heat for the pyrolysis and drying zones. Downstream the pyrolisis region the gasification takes place. Here gasification of the char with the surrounding gasses occurs. Remaining char particles are oxidized with the gasifying agent in the bottom of the reactor, the combustion zone. Here the temperature is the highest. The syngas leaving the reactor is contamined with amounts of tars from the pyrolysis region.

4.2 Fluid bed gasification

The thermochemical reactons of gasification takes place in a fluidized bed which can be either in bubbling mode or circulating mode. The blast acts as the gasification agent as well as the fluidizing medium. Fluidized bed offer good mixing which promotes the heat and mass transfer and gives a homogenous temperature zone. however, a homogeneous temperature zone also results in unfully reacted fuel particles which will be removed with the ash. Therefore there is a limitation on the carbon conversion rate. Operation temperatures are between 800 - 1000 $^{\circ}C$. Temperatures should be below slagging temperature to prevent the ashes to get sticky and agglomerate.

4.3 Entrained flow gasification

Entrained flow gasifiers works with a co-current flow of oxidizer and solid feul particles. Residence times are small. Therefore high temperatures (1100-1500 $^{\circ}C$) and small fuel particles ($< 1mm$) are required to get a proper carbon conversion rates. Generally the oxidizing agent is pure oxygen in order to get the high temperatures. Thereby, oxygen is prefered above air since the latter contains N_2 which at high temperatures will form undesirable NO_x gasses. Entrained flow gasifiers operate at high temperature above the ash slagging temperature. Ash will leave the reactor as a molten slag. This high temperature ensures full conversion of chars and oils. This compared to the other gasification technology results in a very clean syngas.

4.3.1 Gasification steps in an Entrained Flow Process

A mix of solid fuel particles and an oxidizer is entering the reactor from the top producing a jet flame inside the reactor. The zone close to the burner is the region where drying and pyrolysis takes place. The volatile gasses released from pyrolysis and recirculated hot combustable gasses react with the oxidizer producing heat and consuming O_2. (Reaction 6) Further down gasification of the remaining char particles occur. The char particles, in absence of oxygen, react with the surrounding gasses, to form syngas. (Reactions 1,2,3,4,5). By the aerodynamics of the jet flame, part of the combustable gasses are recirculated. The rest is leaving the reactor as syngas. The remaining ash leaves the reactor as an molten substance. By (water)quenching it at the exit the temperature of the ash is decreased under the ash melt temperature to prevent the downstream piping section from getting clogged with the sticky molten slag.

$$\begin{gathered} CO + \frac{1}{2}O_2 \rightarrow CO_2 \\ H_2 + \frac{1}{2}O_2 \rightarrow H_2O \\ CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \\ CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \end{gathered} \tag{6}$$

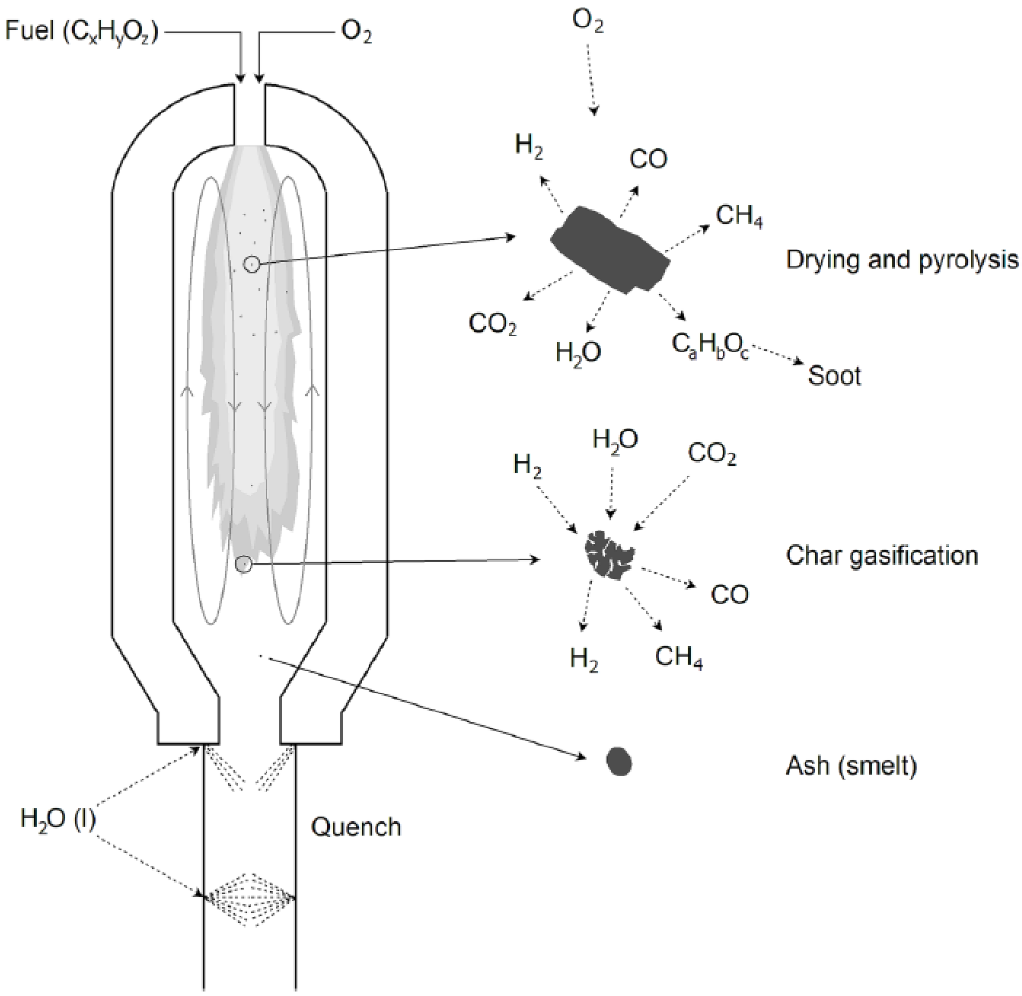
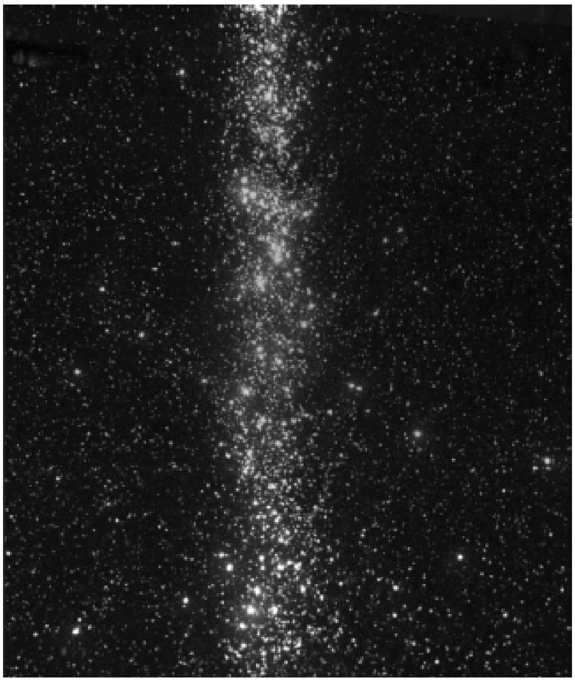


Figure 2: Entrained flow gasification process steps [9]

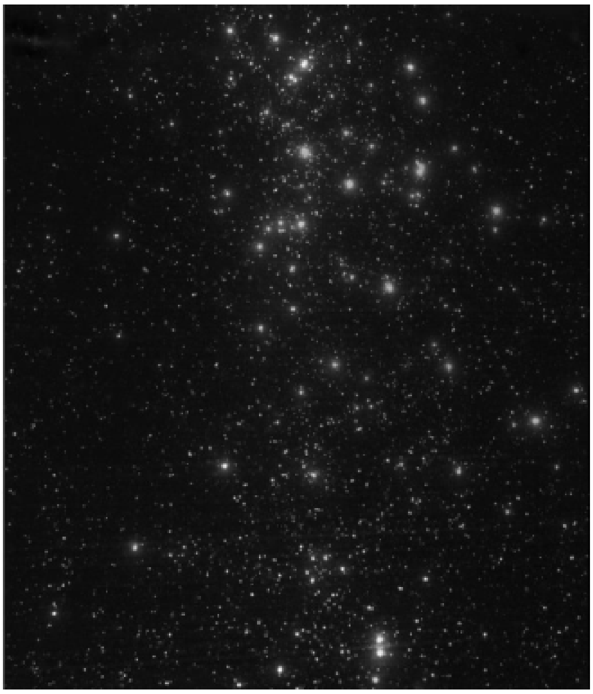
5 Objective

5.1 former research

The most relevant research done at the division is done by Dr. B. Göpteke [3]. In his work he investigated soot formation and flame stability in entrained flow gasification of biomass. The focus lies on the behaviour and dispersion of biomass particles in turbulent flow and the influence of dispersion on pollutant emission and flame stability. He tested two ways of improving the dispersion of biomass particles.
In a cold flow situation he investigated the particle dispersion in a swirl flow. Results are shown in figure 3 In the left figure particle dispersion in a non-swirl jetflow is shown. The particles are concentrated in the centerline. In the right figure particle dispersion in a high swirling jetflow is shown. The particles are much more distributed. The average interparticle distance is higher.



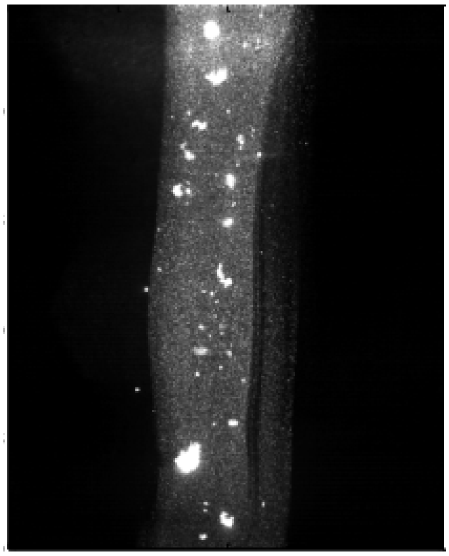
(a) Swirl number S=0



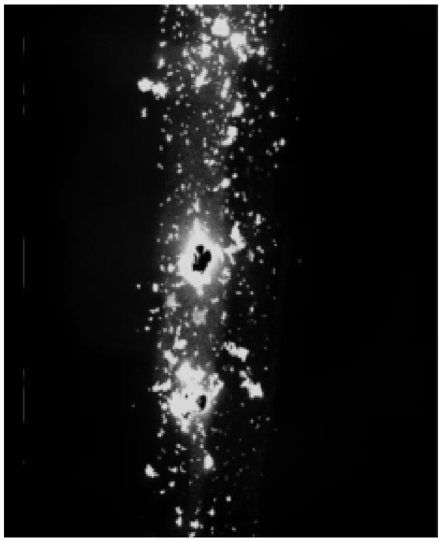
(b) Swirl number S=0.66

Figure 3: Instantaneous snapshot of particle air flow in non-swirl flow and swirl flow.[2]

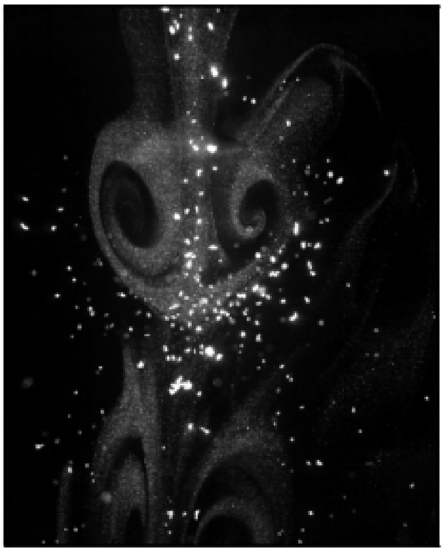
An other way of increasing particle dispersion is by active force flow. A synthetic jet actuator consisting of a 4 ohms loudspeaker produces pressure fluctuation in the central burner tube. At the burner rim this creates vortex rings. In figure 4 the effect on the particle distribution is visualized. Figure 4a and 4b shows the particle dispersion in unforced flow for two different mass load ratios. Instead of dispersion particles tend to agglomorate to each other. Figure 4c and 4d show the particle dispersion in forced flow for two different mass load ratios. The vortex ring can be recognized and it is clear that a better particles dispersion is achieved.



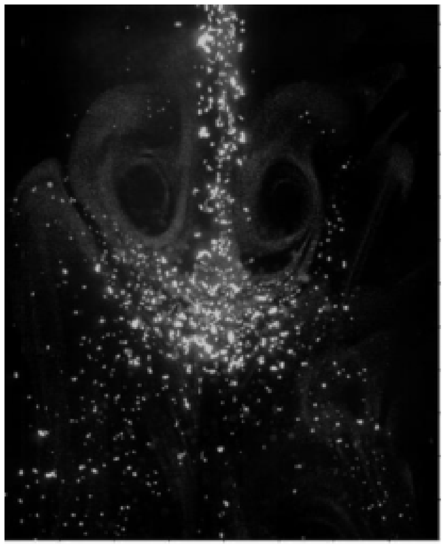
(a) Unforced laminair Flow. Mass load ratio 0.47



(b) Unforced laminair flow. Mass load ratio 2.67



(c) Forced initially laminair flow. Mass load ratio 0.47



(d) Forced initially laminair flow. Mass load ratio 2.67

Figure 4: Snapshot image of particle-air flow at distance 2-30mm from burner exit. For forced and unforced situations.[2]

For the case of the synthetic jet actuator hot flow test have been conducted to measure the influence of particle dispersion on soot formation. Particle are feeded into a flat flame burner under action of the synthetic jet actuator. With laser extinction method and a particle sampling system the soot formation is measured. Figure 5 show a decrease in soot formation with the use of a synthetic jet actuator.

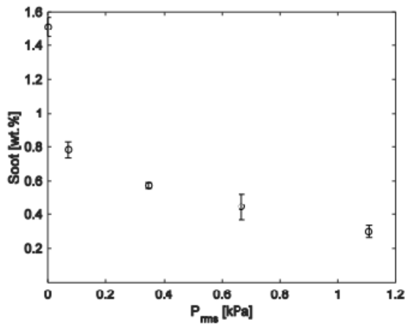


Figure 5: Soot mass% with respect to forcing amplitude P_{rms}.[2]

Other research which is still ongoing at the division is the use of alkali as an catalyst. Pre treating wood particles before combustion should result in cleaner combustion. This researchtopic is new and mainly conducted in the flat flame burner. I case results are promising the step to a larger experimental set up would be interesting.

5.2 Aim of building Flame reactor

In göktepe work a flat flame burner is used with acoustic jet actuator. The flat flame burner is designed to simulate a small part of a jet flame reaction sheet. The combustion reaction in a flat flame burner can be controlled precisely. In real large scale reactors, much more parameters have to be taken into account. Therefore the next step following from göpteke's work will be to investigate the soot formation in a set-up more realistic to large scale entrained-flow reactors. Furthermore, Göpteke did experiments on the effects of swirl on particle dispersion. Therefore he designed an 30 kW swirl burner. This experiment has in contrast to the acoustic jet experiment only been run in cold-flow. In order to execute a hot-flow experiment an combustion reactor is needed. In the scope of this a project has been started to build a 30kW flame reactor. Of course, the flame reactor will be used for all kind of flame research. Besides solid biomass fuels it the reactor can be adjusted to burn liquid fuels like Black liquor and pyrolysis oil if this is required in future research.

6 design of Flame Reactor

6.1 Design of reactor

The Flame reactor is designed for combustion reactions up to 30kW. The main body consist of a carbon steel vessel 814 mm in diameter and 1200 mm in length. On the inside the walls are isolated with a ceramic layer leaving an inner reaction zone of length 950 mm with a diameter of 400 mm. The ceramic isolation layer is build with a electric heater system consisting of 4 resistors. The reactor walls can be heated up till 800 $°C$ in 48 hours.
There are 4 openings in the wall equally dividid in azimuthal direction. Three of these openings are an 800x100 mm rectangular for visual inspection and measurements. On the fourth side there is a vertical row with 5 circular openings of 2-1/2 inch. These circular openings are constructed with a welding flange (DN65) in order to mount measurement devices e.g. thermocouples. The three rectangular openings are for visual purposes. With a rectangular flange construction, two window panes of 300x120mm can be mounted. These window panes are realively large. This will have a major effect on the aerodynamics inside the reactor. More common in combustion reactors are small openings (2" to 3"). For optical measurement this size is enough. However a clear visual overview of the total flame is harder to get and the measurement areas are fixed. The reactangular large window panes give the possibility to do optical measurement over the entire length of the flame and gives flexibility with the area where you want to do measurements.
Between de Combustion zone and the exit there is a quench chamber. Four water inlets are connected with the option to enlarge to eight inlets in total. The exit of the reactor downstream consist of two 3" flanges and one 2-1/2" flange. Flue gasses will leave the horizontal 3" pipe leading to the heat exchanger and chimney. A flue gass fan mounted in the chimney ensures an slight underpressure in the reactor. Solid residues like char particles drop down the horizontal 3" pipe into a barrel. The 2" flange is used for mounting thermocouples to measure the flue gas temperature. On the top of the reactor there is a $\varnothing$ 200mm detachable opening for mounting burner equipment.

6.2 Burner

The burner used in this study is the one designed and used by Göptekes work on swirl[2]. It consist of three concentric tubes. The inner tube is for primary air mixed with wood particles. Secondary air flows trough the outermost tube. Four tangential aligned tubes are connected to the outermost tube in order to induce swirl. The middle tube is for propane in order to support the flame during start up.

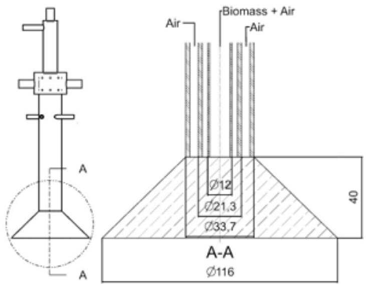


Figure 6: Swirl burner used in this study. Note: Dimension in mm.[2]

6.3 fuel feeder

The reactor is build for research on gasification of biomass. To be more specific wood particles. The object that will provide the wood particles is *K-Tron KT20 screw feeder*. This is a so called loss-in-weight feeder which means that it doses the massflow of woodparticles by continuously measuring the weight loss of the storage bin. It has an accuracy of 0.001 kg/h.

6.4 Pnuematic conveying

The reactor and the fuel feeder as described above are what was build so far. In this state the reactor has not been running with a real flame. In order to do so the fuel feeder has to be connected to the burner on top op the reactor. This seemed to have some hurdles to overcome. From the exit of the screw feeder to the burner covers a distance of 2 meters. The way to transport the wood particles is by pneumatic conveying. By mixing the wood particles with a driver gas (e.g. air) a mixed flow is created which in the right proportions is flowable.

Pnuematic conveying in general is a technique of transporting granular solids in a gas-solid mixture. The behaviour of solid-gas mixtures are difficult to simulate. Most of the knowledge existing on pneumatic conveying is experimentally obtained. No exact mathematical models, or software are accesible for simulating pnuematic conveying flows. There is some literature available on how to design pneumatic conveying systems. A usefull comprehensive book is "Pneumatic conveying of solids, a theoretical and practical approach" written by Klinzing et al [6]. As the title indicates it gives as well the practical approach as well tries it to use an theoretical approach. Although, in the end, the theory, is still based on experimental work and a lot of formulas and approaches should be considered more as a rule of thumb than as an exact calculation. Other usefull work is from D. Mills [7]. He sticks to a more practical approach with the use of basic formulas instead.

6.4.1 Flow velocity and flow regimes

One of the restrictions on pneumatic conveying is the velocity of the driver gas. Figure 7 gives the different flow regimes which occur in pipe flow. The mechanism of interaction between air and particles are complex and often difficult to predict exactly. In case of the flame reactor it is prefered to have a fully suspended flow (a). A good mixing is obtained resulting in less change of accumulation in comparison with the other flow regimes. Furthermore a good mixture is important for having a full and stable combustion of the particles at the burner exit. Determining the required velocity is a complex task and most of the knowledge is based on experimental and practical work. For the conveying wood particles the minimum velocity of the driver gas should be in the range of 12-17 m/s.

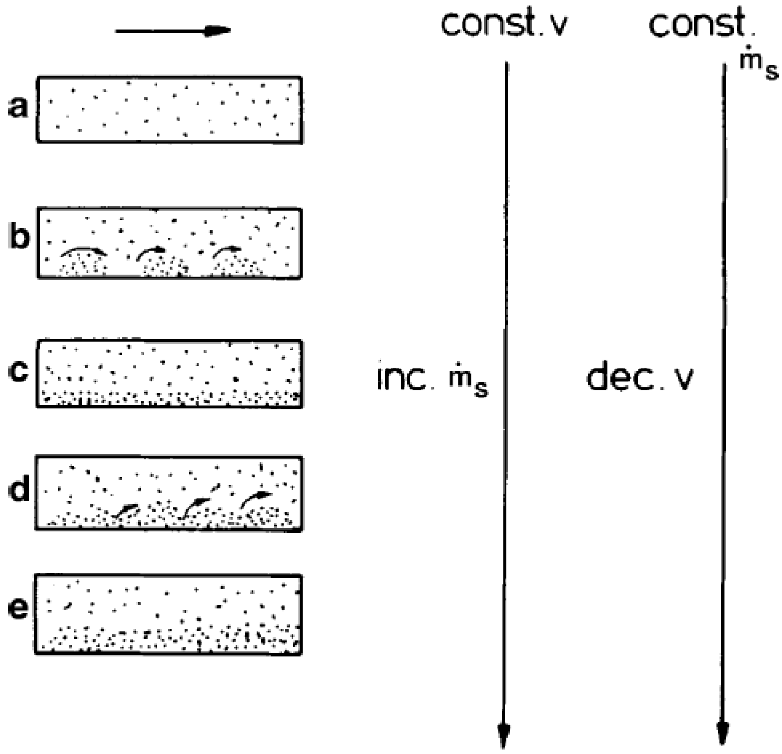


Figure 7: Flow phases for fine particle suspensions: (a) fully suspended, stable; (b) surging, unstable; (c) saltation point - stationary bed, stable; (d) moving bed, very unstable; (e) stationary bed, stable. [6]

6.4.2 Determining flow velocity

In building the conveying system there are several parameters to play with. The four most important ones to consider are:

- fuel mass flow
- pipe flow velocity
- stochiometry
- pipesize

These variables are all related with each other by the combustion theory. The pipe flow velocity is the parameter which gives the restriction. Too low velocities results in an improper conveying, too high flow velocities can result in flame blow-off phenomena. Therefore it is desirable to express the flow velocity is terms of the fuel mass flow, stochiometry and pipe dimension. Starting with the oxidation reaction of biomass.

$$C_\alpha H_\beta O_\gamma + A_{st} O_2 \rightarrow \alpha CO_2 + \frac{\beta}{2} H_2O \tag{7}$$

Assuming air consist of 21% oxygen and 79% Nitrogen

$$C_\alpha H_\beta O_\gamma + A_{st}(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2} H_2O \tag{8}$$

For woody biomass the weight percentage of the fuel is assumed:C 50wt%, H 6wt%,O 44wt%.

$$50wt\% \rightarrow 0.041667 \frac{kmol - C}{Kg - fuel} \tag{9}$$
$$6wt\% \rightarrow 0.06 \frac{kmol - H}{Kg - fuel} \tag{10}$$
$$44wt\% \rightarrow 0.0275 \frac{kmol - O}{Kg - fuel} \tag{11}$$
$$\tag{12}$$

equilize the combustion reaction gives:

$$A_{st} = \alpha + \frac{\beta}{4} - \frac{\gamma}{2} \approx 0.04292 \tag{13}$$

then the amount of kg of air needed for stochiometric combustion is:

$$Kg_{air\,required} = A_{st}(mass\,of\,air) \tag{14}$$
$$Kg_{air\,required} = (2 * 16 + 3.76 * 28) = 5.8916 \tag{15}$$

Written in the air-feul ratio (AFR):

$$AFR = kg - air/kg - fuel = 5.8916 \tag{16}$$

Then the massflow of air as function of the mass flow of biomass can be calculated

$$\dot{m}_{air} = AFR\lambda\dot{m}_{fuel} \tag{17}$$

With λ the equivalence ratio given as $\lambda = AFR_{real}/AFR_{stoich}$

A relation of the air flow speed in a pipe as function of the biomass flow, stochiometry and pipediameter D:

$$v_{air} = \frac{\dot{m}_{air}}{\rho_{air}(\frac{D^2\pi}{4})} = \frac{AFR\lambda\dot{m}_{fuel}}{\rho_{air}(\frac{D^2\pi}{4})} \tag{18}$$

In figure 8 the visualization of this relation is given. The blue flat surface represent the minimal velocity required of 15 m/s. From figure 8a it can be noted that for a fuel mass flow of 2 kg/h and pipe diameter of 14mm it is not possible to operate in gasification condition since at $lambda = 0.4$ the flow velocity is under 15 m/s. In figure 8b. the situation for $\dot{m}_{fuel} = 5kg/h$ is given. The lower velocity limit of 15m/s is not giving a problem. However at $lambda \geq 1.0$ the flow reached velocities over 50 m/s up to around 120 m/s. At these high velocities the problem of flame blow-off occurs. This in turn can be resolved by burner design and spreading the air supply.

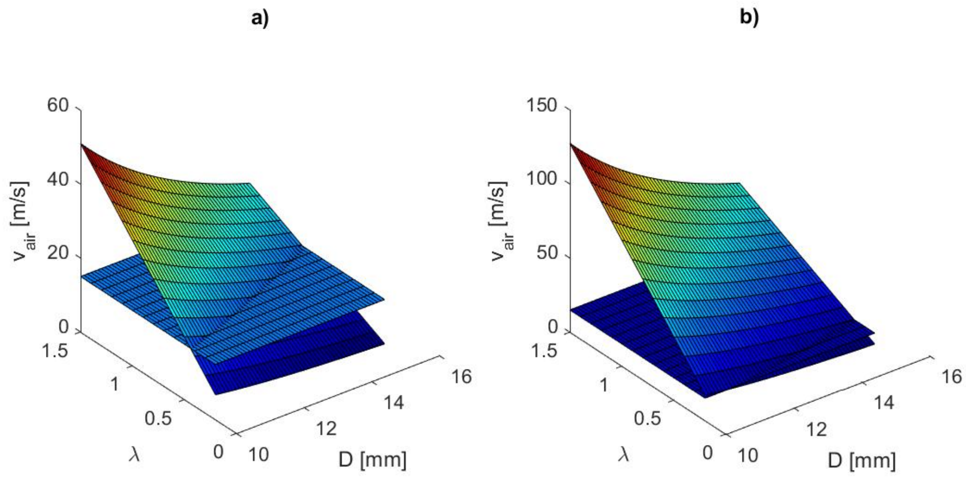


Figure 8: Flow velocity as function of equavalence ratio λ and pipediameter D $a)$ $\dot{m}_{feul} = 2kg/h$ $b)$ $\dot{m}_{feul} = 5$ kg/h

6.4.3 Pressure drop

An other important aspect to check in pneumatic conveying is the pressure drop. The pressure drop for only air in a straight pipe can be determined with the darcy's equation:

$$\triangle p = f\frac{\rho_{air}v_{air}^2 L}{2D} \tag{19}$$

Beside the pressure drop of the flowing gas stream the particles will also contribute to the pressure drop. The particle interaction due to particle collision and particle wall collision are such phenomena. Especially in a pipe bend the particle-wall collision plays an important role. In case of biomass and in particular wood particle there is another aspect involved called the tribo-electric effect. This will be neglected. Summarized, the three major contributions to the pressure drop taken into account are:

- $\triangle p$ due to friction of solid particles in flow
- $\triangle p$ due to accelaration of particles
- $\triangle p$ due to bends

The first two contributions to the pressure drop are caused by flow-solids interaction phenomena which cannot be adjusted. This is a result of the conveying air-fuel mixture which is a chosen fixed quantity. The third contributions, the pressure drop due to bend is something which can be modified by simply designig the conveying system with large bend radiuses and as less bends as possible.

In figure 9 for three different fuel mass flows at three different pipe bend radiuses the total pressure drop is given. For bend radius of 12mm which is used for gaspipe connections the inlet pressure needs to be over one bar.

m_{fuel} [kg/h]	Bend diameter [mm]	ΔP total [bar]
1	12	0.032
	75	0.005
	200	0.003
5	12	0.794
	75	0.138
	200	0.076
10	12	3.175
	75	0.550
	200	0.305

Figure 9: Pressure drop different size of bend diameters.

6.4.4 design criteria

Considering the above theory there are some points to consider in building the conveying system.

1. As less bends as possible and large bend diameters
2. For normal burning conditions $\lambda \geq 1.0$ velocity v_{air} takes high values, this can result in flame blow-off.
3. at low $\dot{m}_{fuel}$ gasification conditions are not possible since v_air is to low for proper conveying of woodparticles.

The first one is a design criteria which can be abided. The second one can be fulfilled by the design of the burner. The available burner consist of three concentric tubes of which two are for primary and secondary air streams. Therefore the total required air mass flow can be divided over two tubes resulting in a lower flow velocity. The latter point is more difficult to overcome. At low $\dot{m}_{fuel}$ rates and understochiometric conditions the air-flow speed is too low to ensure proper conveying. Decreasing the pipe diameter will partly solve the problem in the sense that its minimum critical equivalence ratio decreases. However smaller pipe diameters results in higher flow velocities which is case of stochiometric conditions gives the risk op flame blow-off.

6.5 Ignition

The flame reactor is designed for autoignition of the combustion reaction. With an electrical heating system the reactor can be heated up to 800 $^\circ C$. This is above the autoignition temperature of fuels to be used like wood shavings (350-400 $^\circ C$)[1], methane (620 $^\circ C$) and propane(490$^\circ C$)[8]. For cold reactor operations no ignition system is build in. The burner has to be ignited manually. The intention is to built an ignition system yet which can be automatically controlled. This also acts as a safety mechanism in case the burnerflame blows off. Since the pilot ignition is a critical part of the reactor and also act as safety mechanism it should be bought externally. Pilot ignition systems are widely used in industrial furnaces and there are companies specilized in pilot ignitors. Although most of the models are for large furnace applications ($\geq$ 45kW) the company Hegwein GmbH in germany produces models for smaller application. They have a compact 2 kW gas fired pilot burner. The pro's of the Hegwein Pilot Burner

- Premixed burner. It supplies its own air.
- It has its own spark ignitor with controller
- It can operate in intermittend state as wel as continuous state.
- Wood powder ignites better with a flame than with a ignition spark.

7 Building

7.1 conveying system

7.1.1 practical set-up

Ealier attempts to build a conveying system were unsuccesfull. Problem which occured were, clogging, bridge forming of the wood particles and pressure fluctuation. First attemps to get a working system were made with the present (not working) set-up. The most critical part was the venturi ejector and the "reduction cone". The venturi Ejector was sensitive to clogging of wood particles. In the "reduction cone" typical hopper problems like bridge and tunnel forming appeared. Little improvements we're made but not enough to get a steady reliable conveying flow. Furthermore the tube between the venturi ejector and burner had to be replaced. It was made of a flexible hose causing pressure fluctuations resulting in unsteady conveying. Keeping the theory in mind from chapter 6.4 and insights obtained from the practical tests a new set up was build with different parts.

After exit of the screw feeder the woodparticles are sucked into the venturi ejector. In here the particles are mixed with air and accelerated into the pipeline towards the burner. The pipeline consist of a 15x1.20mm steel tube leaving an inner diameter of 12.60 mm. From screw feeder to burner the pipeline bend two times with a bending radius of 75 mm and 300mm. To get a steady homogeneous flow in the pipeline the aim is to have no changes in diameter. The fuel feeder exit has a diameter of 50 millimeter and has to be reduced to the venturi inlet size of 13 mm. This reduction is realized over a length of 200mm Testing different sizes of reduction lengths, this appeared to have the best flowability. Reduction of diameter over a shorter length gave clogging problems.

This set-up gave much more steady conveying flows than before. The flow at the exit of the burner is much more continuous.

With a controlled air mass flow of $\dot{m}_{air} = 20Ln/min$ resulting in a total air mass flow of $\dot{m}_{air} = 115Ln/min$ (according to the ejector's datasheet) continuous flows of biomass rates were achieved. An air mass flow of $m_{air} = 115Ln/min$ in an inner pipe diameter of 12.6mm gives a flow velocity of 15.6 m/s. A total air mass flow of $\dot{m}_{air} = 90Ln/min$ gives a flow velocity of 12.02 m/s. Continuous conveying was not always acquired. especially with the higher biomass flow rates.

Although the flow in general was continuous and more steady than before there were still some irregularities. One reason for this is the fact the engineering of the system is not perfectly finished in the sense that there were some edges and grooves at the pipe connections. This results in accumulation and clogging with its consequence of unsteady biomass flow.

7.2 windows

The type of glass used for the windows is called Robax©. It is an ceramic type of glass which has high resistance to temperatures and is often used in industrial oven side panels. In continuous operation it is resistant to temperatures of 740 $°C$. It has a thermal expansion coefficient of nearly zero up to 800 $°C$ making it highly resistant to temperature shocks. An altenative which was considered is quartz glass. Quartz glass is resistant to temperature up to 1000 $°C$ which would be more suitable. In practical point of view, Robax is prefered above quartz. The windows panes should be removable for cleaning purposes. Quartz glass appeared to be more difficult to handle. It breaked quicker and in smaller sharper splinters than Robax. Furthermore the optical properties of Robax are suitable for optical measurements. At the SP Energy Technology Center in Piteå, where a lot of optical research on combustion is conducted, they have good experience with Robax and optical measurements.

In scope of the removability of the glass panes a new design is made. The present situation consist of two flanges, one fixed on the reactor and one detachable. The glass window is mounted betweed these two flanges and sealed with gaskets to prevent leakages. The force needed for proper sealing pressure of the gasket is too high for the glass pane to resist and often resulted in fracture. An alternative sealing was the use of (liquid) silicon gasket. This gives a reliable sealing. However it should be clear that this is not removable solution. In the new design an extra detachable flange is introduced. The window pane is mounted between the two detachable pane. These two panes are fastened with springs in between to give freedom to move under thermal influences. This whole assembly is mounted to the fixed flange on the reactor. In this way the glass is not subjected to excesive forces. In case the windows have to be cleaned it can be done without removing the glass from its position.

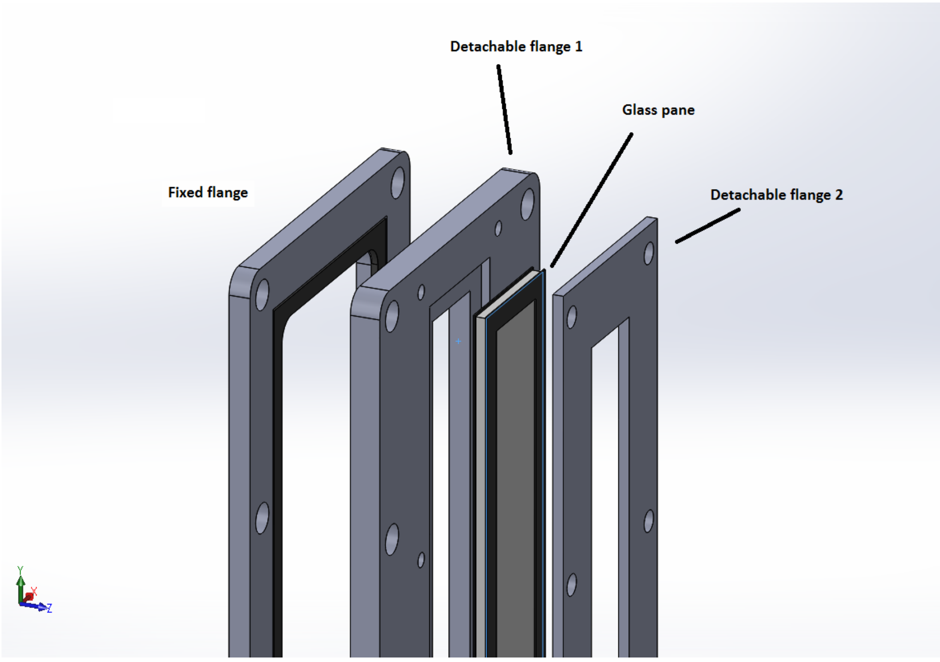


Figure 10: Improved window design; Fixed flange represent the flange welded to the reactor

7.3 Leakage of toxic gasses

The reactor is designed for research purposes. Therefore there are a lot of connections for thermocouples and measurement devices. Everyone of these connections give the possibility of leakages. The Flame reactor is tested for leakage by putting a small overpressure in the vessel and check the connection with a soap solution. By every adjustment of any connection the whole vessel should be tested for leakages. Furthermore to prevent leakage of toxic gasses a exhaust fan is mounted in de chimney resulting in an underpressure in the reactor during operating condition.

8 Running the reactor

8.1 test set-up

So far the reactor has not been operated with a flame inside. Therefore, the reactor has been run to get an impression on the operating condition and to get an insight in further improvements to be made.

Two main questions to answer here are:

- What flame temperature can be achieved?
- Is wood fired flame possible?

Tests have been run without the electrical pre-heating of the walls. Wood particles' sieve size is 710 μm. Ignition is manually realized. The reactor is operated with only propane. Flame temperature is measured with a thermocouple placed 30cm below the burner rim. A second thermocouple is placed 70cm below the burner rim. Snapshot are taken with a simple 8 Megapixel Camera.

8.2 results

The highest flame temperature which could be obtained (at 30cm from the burner rim) is 956 degrees celsius. The primary air supply from the center tube has a velocity of approximately 23m/s. No swirl is applied. A snapshot of the flame is given in figure 11.

At this condition wood particles are fed to the flame with a low mass flow rate of $\dot{m}_{wood} = 0.5kg/h$ Figure 12.The different flame which can be noticed indicates combustion of the wood particles. However not everything is burned. After operation partially burned and also unburned wood particles are found on the reactor's bottom.

In both figures. An instability at the burner rim can be noticed. On the left side the flame irregularly detaches from the burner rim while on the right side it is constantly attached. Also a small yellow ring can be seen indicating a region of lower temperature at the vicinity of the burner.

Test is conducted in a initially cold reactor. After ± 80 minutes of operating the wall temperature is measured to be around 180 $^{\circ}C$ The second thermocouple which is outside the flame region gives a temperature of 350 $^{\circ}C$

Figure 11: Propane fired flame

Figure 12: Propane fired flame with wood addition: $\dot{m}_{wood}$ 0.5kg/h

9 Conclusions

In this chapter the result from the test are discussed. Recommendations are given based on the finding from the test run and based on commisioning which is mainly discussed in chapter 6 and 7.

9.1 Discussion

The test operation show that it is was not possible to get a fully combustion of wood particles. The flame does get high temperatures which are far above the ignition temperature and partially combustion of wood is noticed. However the time wood particle are inside the flame region is too short for full combustion. Once outside the flame region particles cool down quickly since environmental temperature is much lower.

Part of the wood can be found in unfully combusted state at the bottom of the reactor. Particles which are found are in general bigger particles in the range >710 μm - 1000 μm. Wood is sieved to the size class of 710 μm. This does not mean al the particle are exactly this dimension but are distributed in a range of approximately 40 μm - 1000μm. The exact distribution of wood particles are not known. The fact only the larger wood particles are found on the bottom of the reactor gives the impression that the smaller particles are fully combusted. In case use will be made of a lower sieve size class performance is expected to be better.

The primary air velocity is approximated on thechnical data of the venturi ejector. The total amount of air the venturi eject is linearly interpolated with standard operating values. In order to know what the exact mass flows and air velocities are, more measurements devices are needed. With PIV for example a measurement can be done of the particle velocity at the exit of the burner. Furtermore a mass flow meter uppstream of the venturi ejector gives the amount of air sucked into the system.

The burner is designed without cooling application. During operation the tip of the burner gets extremely hot. When the burner reaches high temperatures wood particles can melt to the tube walls and cause clogging resulting is uncontrolled gasflows. The detachment of the flame constantly started at the same place at the burner exit. The propane flows trough the middle tube of the burner (see 6). The supply of the propane is by just one connection. This may result in an poor distributed flow at the burner exit. The outermost tube of the burner is designed with an annular settling chamber with twelve 2mm holes to ensure uniform distribution of the airflow. A similar kind of improvement could be usefull for the propaneflow to exclude it from inhomogeneous flows. Furthermore a quick glance of the effect of swirl is given. At different flame condition the swirl is applied. In almost al cases when the swirl was visible for the eye it resulted in unstable flames and in most cases in a blow off. Although this is a rough check it gives the impression that the design of the swirl burner is unsufficient.

9.2 recommendation

- Run test with electrical pre-heated walls. Preliminary test with initially cold reactor resulted in usefull insights. Same should be done to discover points of improvement on fully operating conditions uncluding pre-heated reactor walls.
- New burner design. The current burner is not sufficient. It lacks a cooling device preventing

the burner tip to reach high temperatures. A new design or probably a commercial available burner should be considered

- Test have been run to get insight in the performance of the reactor and discover point of improvements. Most parameters are roughly taken or approximated. In case of the air mass flow and velocity it is highly desirable to get exact flow values. Therefore more mass flow meter/controllers should be applied. Most important one is to mount one upstream of the venturi ejector as mentioned in 9.1. It was ascertained that not all the wood particles are fully combusted. By collecting the particles and analyse them on composition and size a more detailed view of the combustion rate will be obtained. So far there is no attempt made or opportunity to take flue gass samples. Analysing the flue gasses gives insight in the combustion performance.

- Pilot ignitor flame: Out of safety perspective the flame reactor should be equiped with a reliable ignition system according to safety regulations. In chapter 6.5 a proposal for such design is given.

- Fabricate new window design: In chapter 7.2 a new window design is made: due to time restrictions it has not been made yet.

- safety/risk assesment: The flame reactor is a potentially dangerous machine with realistic posibilities on severe accidents. According to swedish regulation it should comply with high safety standards. In further design and revision of the reactor these safety standards should always be followed. The ATEX 114 directory for objects in explosive environments should be the leading document. According to regulations, the flame reactor should be subjected to a risk and safety assesment by a external certified party.

- Furthermore there are minor improvement to be made concerning the total lab's lay out where the Flame reactor is situated. A brief summary without commentations: The electrical control box should be moved, the lab's piping system for gass supply should be extended for the Flame reactor, the position of the fuel feeder relative to the flame reactor should be changed. Cooling water supply should be independent from other units in the lab.

References

[1] M. Zachar et al. Determination of fire and burning properties of spruce wood. *Drv Ind*, 63(3):217–223, 2012.

[2] Burak Göktepe. *Entrained flow gasification of biomass: soot formation and flame stability.* PhD thesis, 2015.

[3] Burak Göktepe, Kentaro Umeki, and Rikard Gebart. Does distance among biomass particles affect soot formation in an entrained flow gasification process? *Fuel Processing Technology*, 141(1):99–105, 2016.

[4] Swedish Government. En sammanhållan klimat- och energiteknik - energi. *Regerings proposition 2008/09:0163*, 2009.

[5] Dr. Dmitri Kopeliovich. Combustion,pyrolysis and gasification of scrap tires., 2013.

[6] Klinzing G.E.; Rizk F. ; Marcus R.; Leung L.S. *Pneumatic convey of solids, a theoretical and practical approach.* Springer, 2010.

[7] D. Mills. *Pneumatic conveying design guide.* Elsevier, Oxford, UK., 2004.

[8] Frederik Norman. *Influence of process condition on the auto-ignition temperature of gas mixtures.* PhD thesis, 2008.

[9] Fredrik Weiland. *Pressurized entrained flow gasification of pulverized biomass: Experimental characterization of process performance.* PhD thesis, 2015.