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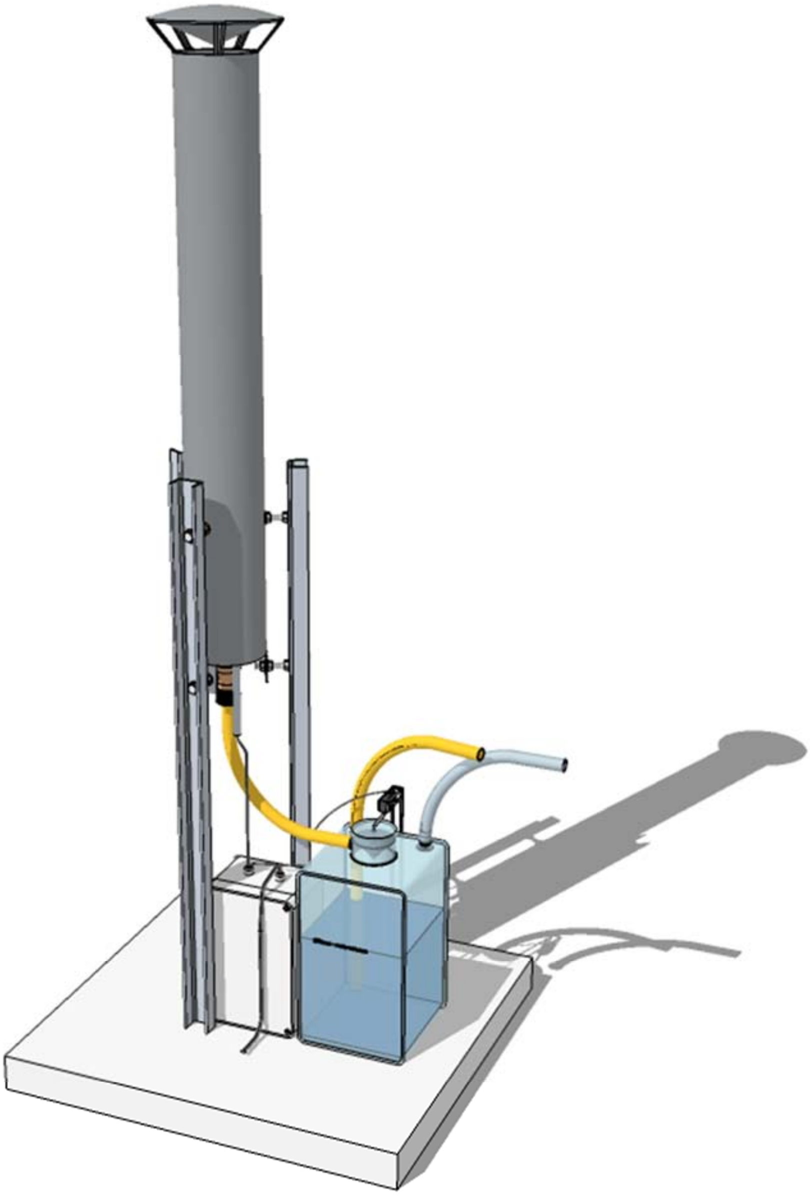
FACT

Internship FACT Foundation

Design of a flaring system for small and medium scale biogas installations in rural Mali



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August 2012

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Design of a flaring system for small and medium scale biogas installations in rural Mali

Name course	:	Internship Farm Technology at FACT Foundation
Number	:	FTE-70424
Study load	:	24 ECTS
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Preface

This report describes the work I have done during my internship at FACT Foundation. When I started, I was hoping to be able to produce not only a design, but also a prototype of a flaring system. Time limits prevented me from doing so, but I hope that my work, as presented in this report, is interesting and useful for FACT and a good basis for further development of a small flaring system.

My time at FACT Foundation was a pleasure to me. I enjoyed the friendly and open atmosphere, the flexibility and the lunches. Therefore I want to thank everyone I worked with: all FACT employees, interns and student, for conversations and discussions, whether or not related to work. I also want to thank FACT Foundation for giving me this internship opportunity and especially Bart Frederiks for his supervision, helpful suggestions and cooperation. I wish FACT all the best with keeping up the good work.

Bart Slager

Wageningen, August 2012

Summary

FACT Foundation promotes the use of bioenergy for energy supply in developing countries, because bioenergy can provide an affordable and reliable energy supply. In cooperation with local partners and NGOs, FACT executes projects in several countries. In Mali, relatively small anaerobic digester systems for production of biogas are installed. Biogas production of these systems is not always level with consumption, resulting in biogas surpluses.
Current practice is to simply vent surplus biogas, which is not the best solution with regard to environment and safety. Better is to combust the surpluses with a flare, but flaring systems for such small systems are not available. The goal of this study is to develop a flaring system for these small and medium sized biogas installations, which does not only function autonomous and reliable, but which is also low-cost.

In this study, the process of flaring and the alternatives to flaring were studied. From literature, methods were found with which a flaring system could be designed and a graphical design was made, taken into account the functionality, reliability and costs.

An enclosed flare was developed, of which the main components are a pressure monitor, a mechanical, spring loaded gas valve, a gas injector with passive air supply, a burner head and an enclosure. Ignition is performed with electronic spark ignition and the flame is monitored with a temperature switch. Separate components were tested, in order to relate theory to practice and to test their functionality.

The proposed design is a first step towards implementation of flaring systems by FACT Foundation. Recommended next steps are to construct and test a prototype and to evaluate and improve its functioning.

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1. Introduction

Problem background

The Republic of Mali is a West-African country with about 14.5 million inhabitants. The country is land-locked and can be divided into three natural zones: the southern, most populated and cultivated Sudanese, the central, semi-arid Sahelian and the northern, arid Saharan. See figure 1 for geographic images of Mali. The country has significant climatic, infrastructural and economic constraints, with only about 4% of the surface being arable land. The rural population comprises the largest part of the population and lives in villages which are often remote and isolated. Agriculture and fishing are the most important economic activities. Main agricultural products are cotton, millet, rice, corn, gardening vegetables, groundnuts, cattle, sheep and goat (Rodriguez-Sanchez 2009; Brew-Hammond and Crole-Rees 2004; Wikipedia 2012b).

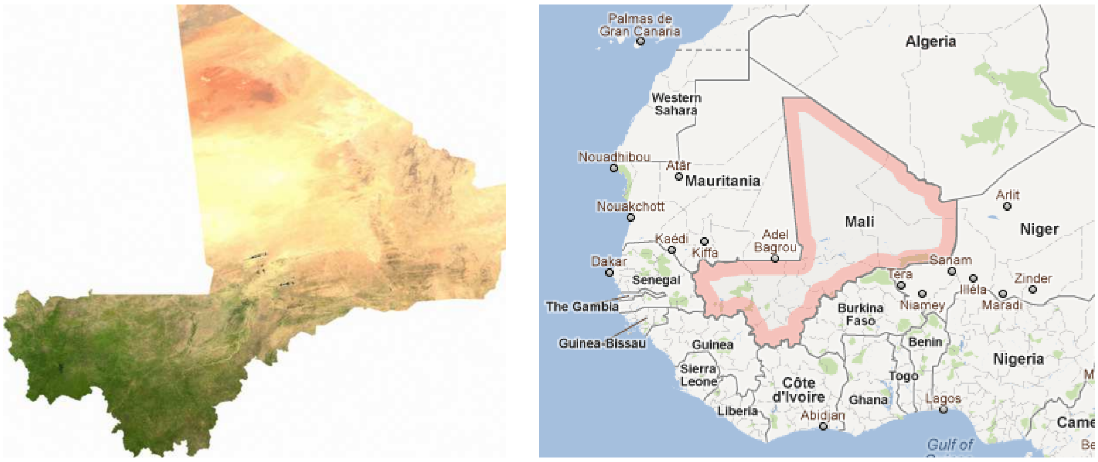


Figure 1: A satellite image of the republic of Mali (left, (Wikipedia 2012b)) and a geographical map (right, (GoogleMaps 2012))

Mali ranks 175 out of 187 on the Human Development Index of 2011, which means high poverty and illiteracy levels (UNDP 2011). Also access to modern energy sources is very limited in most parts of the country, especially in rural areas. Often there is no connection to the grid and fire wood is used as energy source for cooking and lighting. Also car batteries are used to supply electricity for a small number of electrical devices. The lack of access to energy sources is a critical burden to Mali's development, with the rural women being especially vulnerable, since traditional roles and lack of tools and resources makes them the suppliers of labour for multiple activities with little or no remuneration. Promotion of Multi-Functional Platforms (MFPs) through the Multi-Functional platform Program is one way to address the needs of the Malian women. The core of the MFP is a small and simple Lister diesel engine of 8 to 12 horsepower, delivering mechanical energy. The Lister engine can also be (partially) fuelled with Jatropha oil or with biogas, and it can power a variety of end-use equipment. This can be for post-harvest processing, but also for pumping or electricity generation. The MFPs can improve the lives of particularly rural women and from that improve the lives in their communities, by reducing the burden of labour intensive tasks and providing additional sources of income and local employment (Rodriguez-Sanchez 2009; Verkuijl 2011a; Brew-Hammond and Crole-Rees 2004).

FACT-Foundation is a Dutch non-governmental organisation (NGO) that promotes the use of bioenergy for energy supply in rural communities in developing countries, because bioenergy can provide an affordable and reliable energy supply. At the same time it can reduce dependence on fossil fuels, stimulate local entrepreneurship, increase farmers' income and improve quality of life. FACT executes projects in several countries, in cooperation with local partners and with other NGOs (FACT-foundation 2012). One of these projects is "Biogas from agro-residues: Decentralised energy production serving rural communities in Mali". This project is accomplished in cooperation with the company Mali Biocarburant SA and the Malian national agency for development of biofuels (ANADEB) (Frederiks 2011). The aim of the project is production of biogas through anaerobic digestion, so that with this biogas, consumption of costly diesel fuel for the MFPs and OESs can be cut down.

Current and desired situation

A number of anaerobic digestion systems are already functioning and more will be installed in the future. Biogas is produced, but biogas production and consumption are not always in equilibrium. This results in frequent biogas surpluses. Currently these surpluses are simply vented to the environment. Both with regard to safety and environment, venting is not a good solution. In the desired situation, the surplus biogas is minimised, but when occurring, it is combusted through flaring. The flaring system should be able to do this autonomous, safe and reliable, with minimal installation and running costs.

Research objective

The objective of this internship project for FACT-Foundation is to design a biogas flaring system which can be implemented on biogas installation in rural Mali, so that surplus biogas can be disposed of in a proper way. The biogas flaring system should suit the Malinese environment and conditions and the characteristics of the anaerobic digestion systems.

Research questions

Following from the research objective, the research is based on a main research question and seven sub-questions:

Is it possible to design a robust and low-cost flaring system for small and medium scale biogas installations in rural Mali?

1. What are the characteristics of the anaerobic digestion systems in Mali?
2. What is the function of a flaring system (for anaerobic digestion systems)?
3. What (type of) flaring systems are used/available in practice and what are they used for?
4. What are the requirements for a flaring system under mentioned conditions?
5. How could a flaring system be designed for mentioned conditions?
6. How should the designed flaring system be constructed?
7. How should the designed flaring system be tested and tuned?

Methods

The engineering design method of Van den Kroonenberg (1998) was used as a guideline during this study. Methods deriving from this design method are for example the use of a brief of requirements and the morphologic chart.

Information and working methods were obtained from diverse sources. Scientific literature was studied, but a lot of useful and practical information and ideas were also acquired from more informal websites, from companies and product information.

In the design process, literature study was alternated with testing. In that way it was possible to determine the characteristics of separate components and expand the design step by step.
For testing purpose, a test setup was built with which a gas mixture, similar to biogas, could be prepared and provided to the components of the flaring system. With the test setup, also gas pressure and flow could be measured and regulated.
Graphical designs and sketches were constructed in Trimble SketchUp (formerly known as Google SketchUp), a freeware 3D modelling program.

Demarcation of the work

When this project was started, the idea was that the study would consist of the design, construction and testing of a flaring system. Available time proved to be too limited to come to the construction of a complete prototype. Therefore the work was limited to the design of a flaring system and testing of separate components.

Report structure

The report consists of eight chapters. After this first introductory chapter, chapter 2 elaborates more on the characteristics of the anaerobic digester systems as to be implemented in Mali. Chapter 3 contains a literature study on flaring and flaring systems. The core of the work is contained in chapters 4 and 5, where the fourth chapter describes the design process and the fifth chapter shows the results of this process. In chapter 6 the process and results are discussed and the main research question is answered in chapter 7. Recommendations for further research are given in chapter 8.

Declaration of used variables

The most important variables used in following chapters, the used symbols and units are displayed in table 1.

Table 1: Nomenclature of all parameters and variables

Quantity	Symbol	Unit
Daily gas flow rate	Q_{day}	$m^3 day^{-1}$
Hourly gas flow rate	Q	$m^3 hour^{-1}$
Volumetric gas velocity	F_v	$m^3 s^{-1}$
Orifice discharge coefficient	C_d	-
Gas Volume	V	m^3
Specific weight of gases	V_{spec}	$m^3 kg^{-1}$
Number of moles of a gas	n	-
Molar mass of gases	M	$kg\ mole^{-1}$
Volumetric share of a gas	$\%\ v/v$	%
Surface area	A	m^2
Gas (over)pressure	p	$mbar$
Specific gravity of gases	s	-
Air entrainment rate	r	$m^3 m^{-3}$
Diameter of a circle	d	m
Gas velocity	v	$m\ s^{-1}$
Temperature of the flare	T	$°K$
Ambient temperature	T_a	$°K$
Gravitational acceleration	g	$m\ s^{-2}$
Vertical flame length	L	m
Net heat release of the burned gases	q_n	kW
Pressure	P	Pa

Subscripts

Concerning oxygen	O_2
Concerning methane	CH_4
Concerning biogas	$biogas$
Concerning air	air
Concerning the burner throat	$throat$
Concerning the burner orifice	$orifice$
Concerning the burner port	$port$
Concerning the stack exit	$exit$
Concerning natural gas	$NatGas$

2. Literature study on flaring

In this chapter the concept of (bio)gas flaring is explored. Firstly the reasons for flaring of biogas and the process itself are described. Then the alternatives to flaring are studied. Finally, the use of flares in practice and the way they are constructed is described.

2.1 Why flaring?

Venting is a very simple method to get rid of the surpluses of biogas. But there are two reasons to use flaring instead of venting. The first one is safety.

Although biogas has a lower mass density than air, venting of large amounts of biogas can result in high concentrations of methane around the anaerobic digester. This can potentially lead to dangerous situations, because when methane concentration comes within the range of 5-15% in air, there is risk for explosion or open fire (Nikiema *et al.* 2007). Although the volumes of biogas vented are relatively small and normally the gas will quickly disperse, it is better to reduce the risks to a minimum.

A second reason is the environment. The temperature on earth is, among others, dependent on the concentration of a group of gases in the atmosphere, which absorb and emit thermal infrared radiation. These gases are generally termed greenhouse gases (GHG). Since the industrial revolution, human activities have strongly increased the concentrations of GHG in the atmosphere, which results in an intensified greenhouse effect and a temperature rise on earth. Reduction of GHG-emission is part of most countries policies (Vellinga 2011). The global warming potential (GWP) is a relative measure of the effect of different GHGs compared to carbon dioxide. Table 2 shows that methane is a much stronger GHG than carbon dioxide (Forster *et al.* 2007; Slager 2009). Current practice of venting the surplus biogas, resulting in emission of methane, results in a 25 times higher emission of CO_2-equivalents than when the biogas is combusted or flared, resulting in the emission of carbon dioxide. The methane is from non-fossil origin and one could argue that the methane as such is thus renewable. But when the agro-residues would not have been anaerobically digested but aerobically composted, only carbon dioxide and no methane would be produced. Best practice for the environment is thus to oxidise the methane to carbon dioxide.

Table 2: Global warming potential of three important greenhouse gases (Forster et al. 2007)

Gas Name	Chemical term	GWP [CO_2-equiv.]
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298

2.2 What is flaring?

Flaring is a method typically used in the oil producing sector to get rid of unwanted gases. Drilling for oil at oil deposits and wells most times goes with occurrence of (unwanted) natural gas. Sometimes this gas is re-injected for later recovery, but more commonly it is released to the environment. This is usually done by flaring rather than by venting, because venting can result in high methane concentrations around the oil drilling site, which can potentially lead to explosions or open fires (Blasing and Hand 2007). The Dutch emission guidelines (NeR) indicate that flaring is used in a number of sectors, namely:

The (petro-)chemical industry, the oil and gas industry, melting and cokes furnaces, flaring of gas originating from landfills and flaring of surpluses of biogas originating from anaerobic digestion and water treatment systems. Safety is the primary reason for flaring in all these sectors, it is a relatively cheap and simple way to treat large amounts of gases occurring accidental or incidental. Besides that flaring is also suitable for gases with fluctuation in composition and volatile organic solids content (AgentschapNL 2008).

Chemical process of biogas flaring

From a chemical viewpoint, flaring of biogas is basically oxidation of methane in an open flame. The basic reaction is depicted in equation 1. Complete combustion of one mole of methane requires two moles of oxygen. But when biogas is combusted with plain air, both the methane content of the biogas and the oxygen content of air determine how many volumes of air are needed to combust one volume of biogas (Caine 2000). Following calculations are done for a biogas containing 60% v/v methane and for air with 21% v/v oxygen. The stoichiometric volume ratio of air and biogas can be calculated according to equation 2.

$$CH_4 + 2 \cdot O_2 \rightarrow CO_2 + 2 \cdot H_2O \qquad mole \qquad \text{Equation 1}$$

$$\frac{V_{air}}{V_{biogas}} = \frac{\frac{1}{0.21} \cdot V_{spec\,O_2} \cdot n_{O_2} \cdot M_{O_2}}{\frac{1}{0.60} \cdot V_{spec\,CH_4} \cdot n_{CH_4} \cdot M_{CH_4}} \qquad m^3 m^{-3} \qquad \text{Equation 2}$$

With V the volume in m^3, V_{spec} the specific weight in $m^3 kg^{-1}$, n the number of moles as determined in Equation 1 and M the molar mass in $kg\ mole^{-1}$ of either methane or oxygen. Equation 3 displays the values used and the actual stoichiometric ratio. In this situation, 5.83 volumes of air are theoretically needed for complete combustion of 1 volume of biogas. An increase of the methane percentage in the biogas results in a higher volume ratio.

$$\frac{0.2301}{0.0395} = \frac{\frac{1}{0.21} \cdot 0.755 \cdot 2 \cdot 0.032}{\frac{1}{0.60} \cdot 1.48 \cdot 1 \cdot 0.016} = \frac{5.83}{1.00} \qquad m^3 m^{-3} \qquad \text{Equation 3}$$

Providing less air than required will result in incomplete combustion and thus release of unburned methane and formation of unwanted products like carbon monoxide. Providing excess air can result in complete combustion and besides that also cools the flame and results in more turbulence and better mixing. So within certain ranges it is possible to play with the air intake to tune the burning behaviour. Usually, large biogas flares, burning good quality biogas, operate at an air to biogas ratio of 10 – 15 volumes of air to 1 volume of biogas. Which thus is more than double the stoichiometric ratio (Caine 2000). But according to Fulford (1996), small burners and gas stoves indeed are usually run with a small excess of air, but are designed in such a way that the amount of primary air added to the gas before the flame is usually around 50% of the total air requirement.

Burning methane results in the production of heat. Pure methane has a Lower Heating Value (LHV) of 36 [MJ m^{-3}]. Biogas with 60% methane has a LHV of 21 [MJ m^{-3}]. The flare should be designed in such a way that the conversion of methane is maximised, in order to minimise the release of unburned methane and products of incomplete oxidation. Table 3 gives an overview of these undesirable products and the reason of their occurrence. For advanced flares, two parameters form the performance specifications, namely the temperature and the residence time. The optimal temperature range is 800 – 1200°C, with a minimal residence time of 0.3 seconds. Performance standards for flares in the Netherlands are a temperature of 900°C with a residence time of 0.3 seconds (Caine 2000).

Table 3: Undesirable products which could originate from flaring of biogas (Caine 2000)

Undesirable product	Mechanism of formation
Carbon monoxide (CO)	Complete oxidation requires T>850°C and a residence time of >0.3 s throughout the flame
Partially oxidised hydrocarbons (HC) Dioxins and Furans Poly-aromatic hydrocarbons (PAH)	T>850°C throughout the flame to prevent formation of these species through unwanted molecular rearrangements
NO_x	Formed at >1200°C by oxidation of N_2. Also formed within the flame by the oxidation of nitrogenous non-methane volatile organic compounds

According to Caine (2000), when designing a flare, it is important to consider the following interrelated factors, in order to reach the wanted burning characteristics:
The air requirement of the flame:
The temperature of the flame is mainly dependent on the amount of air added to the biogas and the heat loss to the environment. When the biogas contains more than 50% methane, usually the air to biogas ratio is in the range of 10-15 m^3 of air to $1m^3$ of biogas, so that the air functions both to oxidise the biogas, to cool the flame and to create more turbulence and mixing. Mixing is crucial for uniform and complete burning of the methane.
The stack exit velocity:
The velocity with which the gases leave the flare must be sufficiently high, in order to prevent the flame front to travel backwards down the burner, but not too high, because that could result in extinguishment of the flame. The exit velocity can be calculated from the exhaust gas flow rate and the surface area of the enclosure opening. The exhaust gas flow rate can be calculated based on the inflow of fuel and gas, the equimolar combustion reaction, and the temperature of the gas at the exit.
The energy release by the flame:
The calorific value of the major fuel components and the gas flow determine how much heat is potentially released to the environment.
The residence time of the biogas in the flame:
The exit velocity of the gas in combination with the height of the flare at the working temperature, which is determined empirically, are needed to be able to calculate the residence time of the biogas in the flame.

2.3 Alternatives to flaring

The goal of the current project is to design a flaring system. But for FACT it is interesting to investigate if there are alternatives to flaring. Other promising methods could show up, which may for example be cheaper, or fit better within certain systems and which can be investigated more thoroughly in another project.
In their review paper on biofiltration, Nikiema *et al*. (2007) mention a number of processes through which biogas can be used or removed and also indicate the characteristics of the processes, including an estimation of the related costs. The paper is focused on biogas originating from landfills. Five methods are mentioned and described, namely combustion, catalytic flow reversal reactor technology, transformation to methanol, flaring and biological oxidation.

Combustion
When the biogas quantity and quality is high enough, combustion of the biogas is an option and in that way the biogas can be turned into electricity or generate hot water or steam. Assuming an energy recovery efficiency from the landfill of 50%, Nikiema *et al*. (2007) estimate that investment costs (installation and operation) are 3.1 US$/ton CO_2-equivalent of CH_4 removed. This method is currently not universally economic because of the low costs of natural gas. In the biogas project in Mali, combustion is off course the primary goal of biogas production. But it might be an option to use the surplus biogas within a small combustion system.

Catalytic flow reversal reactor technology
This process is developed to eliminate methane when its concentration is in the range of 0.1-1% v/v in air. It is developed for treatment of methane in coal mine ventilation air. The methane is oxidised in a packed bed reactor. The auto-ignition temperature of the methane is strongly reduced to around 350°C with help of a catalyst. Product gases with a temperature ranging from 600 to 800°C are produced and this heat can be recovered and used for heating or for production of electricity. An increased concentration of methane in the air results in higher percentages of energy recovered (Nikiema et al. 2007; Hristo and Gilles 2003).

Transformation to methanol
It is also possible to transform the methane in the biogas into methanol. This process is derived from the Lurgi-process for natural gas and consists of three steps. Firstly synthesis gas is produced, from which crude methanol is produced and in the last step, the methanol is purified. The process needs a high temperature of around 840°C and a high pressure of 8 bar (Nikiema et al. 2007; Kovac Kralj and Kralj 2009).

Flaring
Flaring of biogas is mostly done with minimal facilities and without energy recuperation. The objective is mainly to avoid the risk of explosion caused by the presence of CH_4 in the air. The method can be environmentally harmful, because dioxins and other dangerous compounds can be generated. Investment costs are about 1.2 US$/ton CO_2-equivalent of CH_4 removed. Nikiema *et al.* state that minimum amounts of biogas is in the range of 10-15 m^3h^{-1}, with a methane concentration of 20% v/v. This method is under investigation in this study.

Biological oxidation
For old or small landfills, it is usually economically not feasible to use any of above mentioned valorisation techniques for biogas, due to low gas production rates. A biological oxidation process, called biofiltration could be a solution here. The process often occurs naturally in landfills already, where methanotrophic bacteria in the upper layers of the landfill degrade 10-100% of the produced methane. A biofilter can be seen as a three-phase bioreactor, with a solid, a liquid and a gaseous phase. The filter bed represents the solid phase, the biofilm the liquid phase and the biogas the gas phase. Contact between methane and microorganisms takes place in the biofilm. Both closed and open biofilters exist. The closed system works with forced ventilation, which supplies both air and biogas to the biofilter. Methane removal may reach values of above 90%. Open systems work with passive ventilation and are more commonly used for landfills. Methane flows upwards through the biofilter covering the landfill, while oxygen diffuses downwards. Lack of oxygen in lower layers of the filter can lead to lower methane removal. A maximum methane elimination capacity (EC) in the range of 325-400 g CH_4 $m^{-2}d^{-1}$ was achieved with a biofilter consisting of compost of leaves. The inlet load (IL) was approximately 500 g CH_4 $m^{-2}d^{-1}$, thus the methane

conversion ranges from 65 to 80% in this particular experiment. Too low biogas flow rates in combination with low filter bed porosity can lead to poor performance. Nikiema *et al*. (2007) present a table with data from a large number of studies on biofilter. Table 4 displays some interesting data from this table. There is large variation in the material used as biofilter, and the performance of the filters. The size of a biofilter should be at a scale of at least 1 m^3 of filter bed for achieving flow rates of CH_4 in the range of 0.01 – 2.5 m^3h^{-1}. And when passive ventilation is applied, the height of the open filter must be lower than 1 m to assure proper diffusion of both methane and oxygen. Installation costs for open systems were between 0.25 and 0.40 US$/$m^3$/day of biogas treated. The Empty Bed Retention Time (EBRT) for methane in the biofilter lies in the range of a few minutes to several hours, because of the low biodegradability of methane.

Table 4: Characteristics of the results of a number of studies on biofiltration (Nikiema et al. 2007)

Filter bed	Operating Conditions	Inlet load [g $m^{-2}d^{-1}$]	Elimination Capacity [g $m^{-2}d^{-1}$]	Conversion [%]
Compost and soil Clay and landfill cover Soil and sand Soil	Aerated at the top, mixture of 45% CH_4 and 45% CO_2 v/v	202	80-90 40-50 15-20 5-7	40-45 20-25 7-10 2-3
Multi-layers: Compost + sand (top) and sand (0.9 m)	Aerated at the top, mixture $50CH_4/50CO_2$ v/v	288	164-283	57-98
Agricultural soil	Aerated at the top, mixture $50CH_4/50CO_2$ v/v	214	171	80
Compost	Aerated at the bottom	590	530-590	90-100
Compost of leaves Compost of municip. waste Compost of garden residues Compost of wood chips	Aerated at the top, pure methane, 99% v/v	~500	325-400 200-250 200-250 <50	65-80 40-50 40-50 <10
Inorganic material Compost	Aerated at the bottom, 7000-7500 ppmv methane	~1700	~700 ~300	41 18
Soil	Aerated at the top, pure methane, optimal conditions	525	435	83
Compost Compost+Peat+Wood fiber	Large-scale open biofilter	288-3120	max.960 max.480	max.31 max.15

The bacteria which are able to biologically oxidise the methane are known as methanotrophs and this group consists of a large number of specific species. The process of methane decomposition has three steps. The first reaction step is the oxidation of methane to methanol, with help of the enzyme methane monooxygenase (MMO). Subsequently, the methanol is transformed into formaldehyde. The bacteria can use formaldehyde either via a dissimilatory pathway, in which it is converted to CO_2, or via different assimilatory pathways, leading to the synthesis of cell components necessary for the growth of the methanotrophs. Optimal growth temperatures of the methanotrophs strongly varies for the different species and varies between 0°C and 62°C. Maximum growth rates are reached in media with a pH range of 5 to 5.5. The methanotrophic species also differ in their CH_4 needs. Some species reach optimum growth rates at low methane concentrations of less than 1000 ppmv, while other species grow best at methane concentrations higher than 1% and low oxygen concentrations (<1%). But in general, the methane conversion rate is mainly influenced by oxygen concentration. O_2-concentrations lower than 3% result in strong decrease of the conversion rate. A biofilter will not function optimally from start-up on. Initially, the conversion of methane will be weak, at 0-10% of the steady state conversion. This time is needed to activate and build a culture of bacteria. When high concentrations of methane (10000 ppmv) are maintained in the biofilter, this induction time step will take about 6 days, lower concentrations result in a longer induction time step. At concentrations of 1000 ppmv, it took 19 days to obtain steady state methane conversion. The biofilter is often inoculated with a culture of selected bacteria. It is important that the biofilter also contains enough nutrients to support bacterial growth. Copper, nitrogen and phosphorus are mainly important. If not yet present in the biofilter material, these nutrients should be added.

Methane oxidation is an exothermic reaction, which theoretically releases about 880 kJ per mole CH_4. In bio-oxidation, most of this energy is used for the anabolic reactions during CH_4 degradation. The rest is transferred to both the filtering material and to the gases emitted from the biofilter. A temperature gradient will exist over the biofilter, which is mainly dependent on the gas flow, the methane conversion and the filter material.

Nikiema *et al.* (2007) conclude that methane biofiltration is both a simple and a complex process at the same time. The overall phenomenon of the reaction seem to be well known, but many aspects are still misunderstood and contradictory theories are proposed.

Analysis

Three new methods for methane removal are described additional to combustion and flaring, namely catalytic flow reversal reactor technology, transformation to methanol and biological oxidation. As an alternative to flaring, biological oxidation seems most promising. Mainly because this is a relatively simple and low cost method. Disadvantages are the sometimes incomplete methane removal and the need for a rather continuous flow. And, as mentioned, many aspects are still misunderstood. But a deeper investigation of this method might be worthwhile. The other two methods have a much higher system complexity and are also more suitable as methods to process all biogas produced.

2.4 Flaring in practice

Often flares are roughly divided into two groups: Open flares and enclosed flares.

Open flares are very basic, simple systems, consisting of a burner from which the flame is protected by a small windshield. The simplicity of the system results in relatively low costs but also in rather poor mixing, lack of protection and insulation of the flame, which results in high radiant heat losses and cool areas in the flame. This in turn leads to uncontrolled and incomplete burning and undesirable reaction products (Caine 2000).

Enclosed flares can again be divided in several types, differing mainly in the amount of added equipment for measurement and control of burning. Typical for enclosed flares is that the burner is enclosed by a cylindrical enclosure of a refractory material. This enclosure protects the flame from wind and isolates it, resulting in a much more uniform flame and low emission of undesirable reaction products. Added monitoring and control equipment also makes it possible to properly flare gases with different compositions and flows (within certain ranges), because for example the flow can be adapted according to measurements of flame temperature or composition of the exhaust gases. Table 5 compares the features of open and enclosed flares, from the perspective of use under European conditions (Caine 2000).

Table 5: Comparison of the features of open and enclosed flares used under European conditions (Caine 2000)

Open Flares	Enclosed Flares
Cannot meet performance or emission standards	Meet performance and emission standards
May be skid mounted and collapsed for transport	Permanent systems, 10-15 meter high
Costs are 20-75% of equivalent enclosed flares	Capable of operation over a wide range of combustion conditions
Suitable for temporary or test uses only	Can be further engineered to meet specific site

Caine (2000) sub-divides the enclosed flares for biogas flaring in two sub-groups, based on the method with which air is introduced to the biogas.

Aeration through diffusion means that air is mixed with the biogas at the burner, resulting in slow propagation of the flame and thus high enclosures to achieve burn-out. This method can be compared with a Bunsen burner with the air-port closed.

Pre-aeration of the biogas, mostly achieved through a venturi. This is done before the flame is reached and the use of the venturi results in an added volume of air proportional to the volume of the biogas. This method can be compared with a Bunsen burner with the air-port open in a fixed position.

In the information related to the Dutch regulation for emissions to the air (NeR), flares are divided in 4 variations according to how the gas is mixed and delivered to the flame.

The simplest version is a flare with passive air diffusion. This can be compared with above mentioned ‘aeration through diffusion’, but for both open and enclosed flares. It is mentioned that these flares are used for gases with low heating values, because these need less air. A second variation are high-pressure flares, in which the kinetic energy of the burned gases is used to bring more air to the flame and create more turbulence. In a third variation, air is actively injected in the zone of the flame for the same purpose. The last variation are flares with steam injection. For mixing and turbulence purposes, steam with a pressure of around 7 bar is injected in the zone of the flame. This type of flare is widely used in the chemical and petrochemical industry (AgentschapNL 2008).

Caine (2000) mentions a number of established suppliers of flares for biogas production systems. These are: Biogas (UK), Haase Energie Technik (Germany), Organics (UK), Hofstetter (Switzerland) and John Zink (USA).

Flaring systems are used in numerous processes in which gases are produced or occur as a by-product. Main user of flaring systems is the petrochemical industry, but flares are also used to treat gases arising from other chemical processes and from waste-treatment, landfills or anaerobic digestion. Due to the nature of all these processes, the flares will most-times be used in a (semi-)industrial environment, on a relatively large distance from residential areas.

Scale of the systems

Commercially available flaring systems are often intended for large scale systems, like the large anaerobic digestion systems used on West-European farms. Biogas production in these systems is much higher compared to the systems implemented in Mali. Often suppliers offer a range of flaring systems with different capacities. The capacity is expressed as the gas flow which can be treated by the system. `

Gas Treatment Services is a Dutch company, active in the petrochemical and biogas industry. The company provides (bio)gas utilisation, upgrading and flaring systems. For biogas they produce three types of flares: An open flare, which is used as emergency flare only, with a range of capacities from 100 to 1500 Nm^3 h^{-1}. An enclosed flare which can work permanently and meets the Dutch NeR regulations. Capacities range from 100 to 1500 Nm^3 h^{-1}. An enclosed Eco flare, mainly used when the produced biogas cannot be completely used. Capacities range from 100 to 900 Nm^3 h^{-1}. Smaller capacities can be built on request.

Himmel Gastechnik is specialised in the design and production of components for biogas and landfill gas stations, including gas flares. They produce three types of flares: Low-, middle- and high-temperature flares. The respective capacity ranges of these flare types are: 20 – 2000 Bm^3h^{-1}, 25 – 2000 Bm^3h^{-1} and 25 – 1500 Bm^3h^{-1}. Bm^3 indicates the gas flow rate in cubic metres at operating pressure. Again the scale of the capacities is much higher than needed for the biogas installation in Mali.

2.5 Components of flaring systems

The number of components of which a flaring system consists, is dependent on the type of flare, increasing with increased sophistication. Therefore it is interesting to define what are the essential components to build a working flare. When these are known, the non-essential components can be defined and evaluated on their necessity for our purpose. Finally the lay-out and dimensions can be chosen in such a way that they fit the requirements.

Following the flow of the gas from the source to the flame, we encounter the following essential components: Firstly the gas inlet pipe or tube, then a pressure monitor and a valve. In the gas-tube, close to the flame, a flame-arrestor is essential. A flame arrestor should be capable of extinguishing a flame in case of flashback. Subsequently, the gas reaches the burner head, where actual flaring takes place. There, also an ignition system (whether or not in combination with a pilot flame) is needed. Finally a flame detector is needed to assure proper functioning of the ignition. To support all these components, some construction is needed(Gastechnik_Himmel_GmbH 2009; Caine 2000; AgentschapNL 2008).

Extra components can be added to improve the reliability, safety and effectivity of oxidation of the gas. Firstly, the construction supporting the flare can be extended, the flare can be elevated from the ground and the flame can be protected and isolated, either by only a windshield, or by an enclosure of certain height, which can also be isolated. In the gas supply tube, before the flame arrestor, a gas booster can be placed to increase the gas pressure at the burner to 30 – 150 mbar. The burner head can be extended with more burners, which can all be fitted with their own (automatic) gas valves, so that they can be made active or inactive, dependent on the gas flow. When a pilot burner is installed, it should be fitted with its own gas-tube, which then needs a flame arrestor and a valve as well. The pilot burner can either work on biogas, or can have its own lpg or natural gas supply to assure a constant flow. As mentioned before, the flare can be equipped with extra air or steam injection. It is also possible to supply a support fuel to the flare. This can be especially useful when the quality or the energy content of the main fuel is low. Finally, equipment for metering and measurements can be added: gas meters to measure gas flows in and out, thermocouples for temperature measurement placed at the stack gas exit, flashback detection and equipment for analysis of the exhaust gas (Gastechnik_Himmel_GmbH 2009; Caine 2000; AgentschapNL 2008).

3. The design process: materials and methods

In the foregoing chapter, the principle and use of flares in practice is analysed. In this chapter the design process is described in detail. The design process was started with investigating the context in which the flaring system has to be developed, by studying the used anaerobic digester systems, the process of biogas production and the occurrence of biogas surpluses. Subsequently, the requirements to the flaring system were determined. After that, a shortlist of required components is set up, deducted from previous chapter. For these components, specific requirements were formulated and a search for suitable methods and components was started. Two or three of the most promising are placed in a morphologic chart and analysed with regard to the requirements. The following part describes a more detailed study on the separate components, starting from the core of the flaring system. For many parts of the burner, theoretical study is interspersed with testing. In that way, a feeling for the relation between theory and practice was developed and the effect on the overall system could be seen. This alternation can also be found back in the way this chapter is ordered. Finally, the costs related to the proposed system are analysed.

3.1 Biogas projects and process

The project "Biogas from agro-residues: Decentralised energy production serving rural communities in Mali" was started in June 2011 and is planned to end in September 2013. The aim of the project is to produce energy from agro-residues through implementation of anaerobic digestion systems. Agro-residues are for example animal manure and residues from Jatropha nut processing (Verkuijl, Proj.Plan). These agro-residues are fed to the anaerobic digester, and the organic matter in it is partly converted to biogas. Biogas is a mixture of several other gases, with methane and carbon dioxide taking the largest share. The composition of the substrate largely defines the composition of the biogas. Table 6 gives an indication of the composition of biogas. The methane can be used as an energy source by burning it, to obtain either heat or power (mechanical and/or electrical) or both (Caine 2000).

Table 6: Typical ranges regarding the composition of biogas (Caine 2000)

Typical Bulk Biogas Components		Trace Components (<2%)
Methane	50 – 60%	Hydrogen
Carbon Dioxide	38 – 48%	Hydrogen Sulphide
Trace Components	2%	Non methane volatile organic carbons NMVOC
Water vapour	saturated	Halo Carbons

Besides biogas, also a digestate/effluent is produced. This digestate contains all nutrients from the feedstock and can be used as a fertiliser in agriculture or gardening.

In the project, as implemented by MBSA, ANADEB and FACT, the goal is to couple anaerobic digesters to five Oil Extraction Sites (OES) and five Multifunctional Platforms (MFP) (Frederiks, 2011). Bag-type, plug-flow anaerobic digesters are implemented, varying in reactor volume and thus in biogas output. Bag-type digesters are cost effective and relatively easy to install and manage (Verkuijl 2011b). Table 7 gives an indication of the characteristics of the anaerobic digestion systems as implemented in the project.

Table 7: Characteristics of anaerobic digestion systems in the FACT-project (Verkuijl 2011a; Frederiks 2011)

Anaerobic digestion systems in Mali

Scale of digester	Digester coupled to:	Number of systems	Volume AD [m^3]	Expected gas flux [$m^3 day^{-1}$]	Max. pressure in system[mbar]	Gas used in:
Small	MFP	5	25	5-10 (5)	20	Diesel engine (dual-fuel)
Large	OES	5	2x300	200-250	20-40	Gas generator

Anaerobic digestion systems in FACT-projects elsewhere

Country	Volume AD [m^3]	Expected gas flux [$m^3 day^{-1}$]
Uganda	200	70
Mozambique	60	20

Figure 2 contains a picture of one of the anaerobic bag digesters, which is already installed and functioning.

Figure 2: A bag-type anaerobic digestion system, as implemented in Koulikoro, Mali (Mali_Biocarburant 2012)

For the anaerobic digesters both incidental and accidental surpluses can occur. Production of biogas is a more or less continuous process, while the engine in which the biogas is combusted is used only part of the time, which can result in incidental surplus. Failure or maintenance of the engine or other parts of the system can result in accidental surplus.

When no gas is used, the produced biogas is initially stored in the digester bag. The digester bag allows for a certain maximum volume of biogas to be stored, dependent on the volume of the bag, the amount of substrate in it and the maximum pressure tolerated. Currently, the maximum pressure is set by using an over-pressure relief system, consisting of a plastic bottle filled with water, in which the gas-tube is submerged. The height of the water in relation to the exit of the gas-tube determines the counter-pressure. Every 0.01 m of water results in a counter pressure of 1 mbar. When the maximum pressure is reached, while biogas production goes on, biogas is vented through the water and emitted to the environment without further treatment. The anaerobic digestion system is schematised and depicted in figure 3. Also the system boundaries for this study are indicated in the scheme.

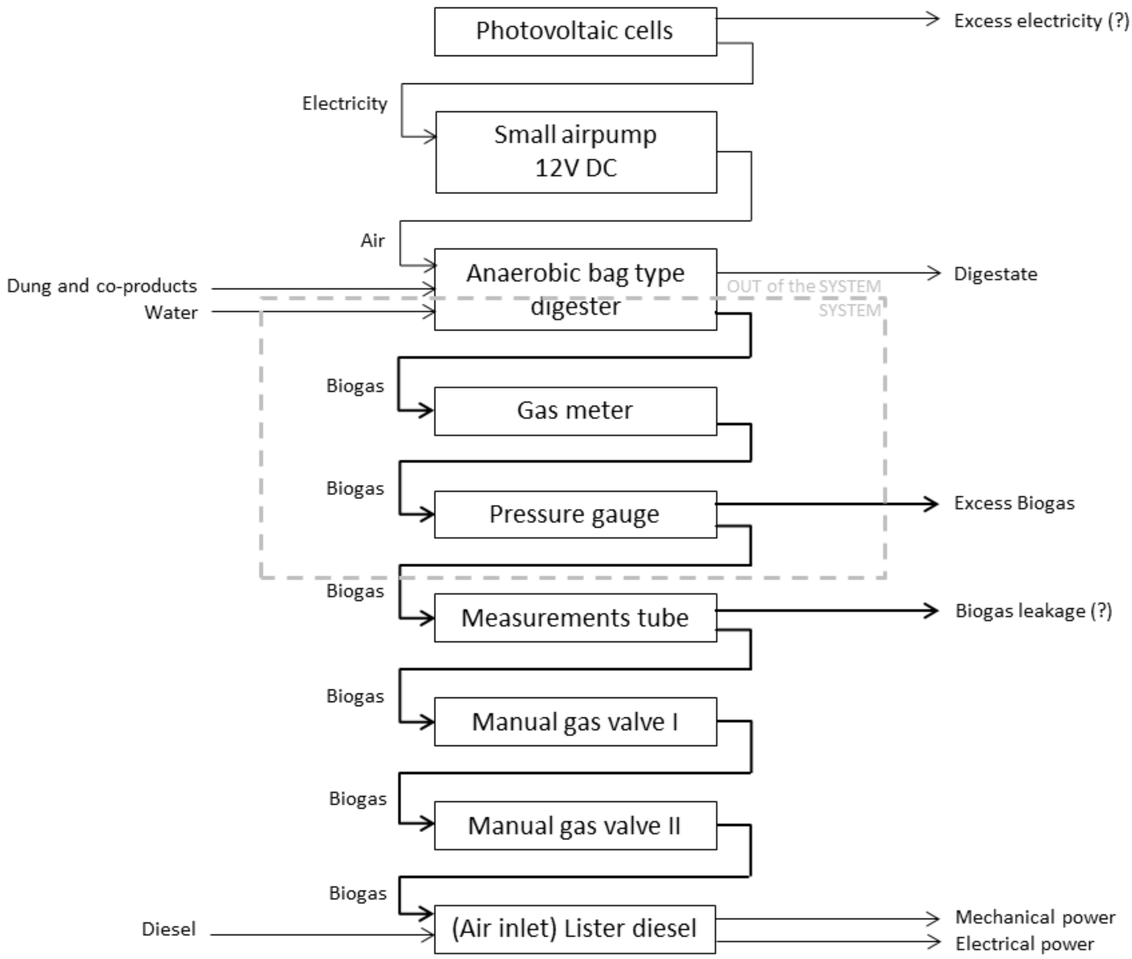


Figure 3: Process chart of the biogas production system in Koulikoro, Mali (determined from video produced by FACT)

3.2 Prediction of biogas surpluses

The bag-digester is made of fibre reinforced PVC, which makes it strong and slightly elastic. Generally it is assumed that the substrate occupies approximately two thirds of the volume of the bag, so that one third of the volume can be used as gas storage. So, for a 25 m^3 digester, a maximum of approximately 8.3 m^3 of biogas can be stored. Pressure in the digester is kept rather constant, even when little biogas is stored, by placing weights on top of the bag. These weights result in a pressure of about 10-15 mbar. When the digester is completely filled, pressure starts to build up and simultaneously the bag will slightly increase in volume, because of its elasticity. The pressure will build up until the it reaches a value equal to the counter-pressure applied by the water (20 mbar). Then venting of the biogas through the water will start, while pressure in the system will be constant at 20 mbar and the flow rate of biogas through the water will be equal to the production rate of biogas in the system.
It is uncertain what the frequency of occurrence of gas venting will be exactly. This will be very dependent on the volume of the system, the biogas productivity, the frequency and amount of gas taken off by the MFP or the OES, the type of engine in which the gas is used and the number of days per week the gas is used. Thus set-up and management of both the

anaerobic digestion system and the MFP or OES will determine the frequency of occurrence of biogas surplus.

Modelling

To obtain insight in the occurrence of biogas surplus occurrence, a simple model was developed, with which scenarios can be set up, by varying aforementioned parameters. The scenarios are listed in Excel and are read from Matlab. Table 8 shows the parameters which can be varied and a number of the resulting scenarios. In practice, there is not much certainty about the exact values of the parameter biogas production, biogas consumption, engine working hours and days, due to recent start up and little monitoring. Besides that, these parameters can also vary strongly during the year. Biogas production will probably increase with increasing temperature in the hot season and decrease in the cooler season. Availability of substrates is also partly dependent on the season. The working hours of the engine are also dependent on the seasons, the MFP will for example be used more intensive after harvest, for treatment of agricultural products as rice de-hulling. Besides set-up and management variations of the system, also accidental surpluses can occur, most likely this can occur due to break-down of the engine.

Table 8: Scenarios for occurrence of surplus biogas, with a number of varying parameters

Scenario	1	2	3	4	5	6	7	8
Volume anaerobic digester [m^3]	25	25	25	25	600	600	600	600
Biogas production rate [m^3/day]	5	10	5	5	200	250	200	200
Maximum pressure in the bag [mbar]	20	20	20	20	20	20	20	20
Biogas consumption by engine [m^3/h]	0.8	0.8	1.0	1.0	200			
Working hours engine [h/day]	5	5	5	3	12	12	12	6
Number of days engine is used [day/week]	5	5	5	5	5	5	5	5

The developed model can be used to analyse the scenarios on an hourly basis and a prediction can be made about the amount of biogas vented and the moment of venting. All parameters in the model can be varied and simulations can be performed for short or longer periods, from one week to one year. The core routine of the model is basically a mass balance over the biogas storage of the anaerobic digester, as displayed in equation 4, which is recalculated for every hour, based on the input.

$$Storage = Input - Output + Production - Consumption \qquad m^3$$ Equation 4

$Input$ is the input of biogas into the biogas storage in m^3/hr, which is always zero. $Production$ is the biogas produced in the digester in m^3/hr and $Consumption$ the biogas consumption in m^3/hr by the biogas end users, like the MFP. And finally, $Output$ is the amount of biogas vented in m^3/hr, starting when the biogas storage is full and maximum pressure is reached. Simulation is started with the biogas storage half full. It can occur that consumption is so much larger than production that the storage is empty during certain hours. In the model, consumption is then impossible.

The developed model can be helpful as a tool to match biogas production and consumption of future anaerobic digestion systems. Besides that its development was very useful to acquire insight in the functioning of the biogas systems and in the moments and quantities of gas surplus occurrence.

3.3 Requirements to the design

An important step in the development of a well-functioning system is setting up the requirements to that system . Often requirement fall within five groups, namely performance, reliability, safety, costs and exterior (Kroonenberg and Siers 1998). In Table 9 requirements are listed for a flaring system connected to a anaerobic digestion system of 25 m^3. For every requirement it is indicated whether this requirement must be fulfilled completely (fundamental), or fulfilled within certain ranges (variable) or if this requirement does not have to be fulfilled per se (wish). When it is relevant, also the values and units are indicated. In this study, most attention will be paid to the requirement groups performance and reliability, followed by costs and safety, with exterior being treated as the least important group.

For reason of lay-out, table 9, referred to in this section and table 10, referred to in following section, are displayed directly after each other on the following pages.

Table 9: Brief of requirements for a flaring system to be implemented for anaerobic digestion systems with a volume of 25 m^3 in Mali

Index	Group	Requirement	Type	Value Min.	Value Max.	Value Desired	Unit
	Safety						
1		Emission of CH4 to environment is minimal	Variable				
2		Emission of CO and NO_x is minimal	Variable				
3		The flare facilitates complete and clean combustion	Variable				
4		The flare cannot cause direct or indirect scalding of bystanders	Fundamental				
5		The flare cannot cause direct or indirect scalding of animals	Fundamental				
6		It must be clear when the flare is active	Wish				
7		No unwanted/uncontrolled fire can originate from the flare	Fundamental				
8		The flare is located in a safe place	Fundamental				
	Performance						
9		Biogas can be burned at varying biogas flow rates	Variable	2	10	5	m^3/day
10		Biogas with a varying methane-content can be burned	Variable	50	80	60	% v/v
11		The flare functions autonomous	Fundamental				
12		Ignition of the flare is autonomous	Fundamental				
13		The flare should be used as little as possible to avoid wasting energy	Wish				hr/wk
14		The heat energy originating from the flare is utilised	Wish				
15		Odour emission to the environment must be low	Wish				
	Reliability						
16		Ignition of the flare is reliable	Fundamental			100	%
17		Malfunctioning of the system is detected and indicated	Fundamental				
18		Most parts are locally available	Variable			90	%
19		The flare can stand all local weather conditions	Fundamental				
20		The flare can function in all local weather conditions	Variable				
21		The flare requires little maintenance	Variable	0	1	0.5	hr/wk
22		Regular maintenance can be done by local staff	Fundamental				
	Costs						
23		Total costs of the flare are only a small part of the total AD system	Variable	2	20	4	%
24		Total costs of the flaring system are low (total AD= 2500 €)	Variable	50	500	100	€
25		Costs of installation of the flaring system are low	Variable				€

26		Costs of maintenance of the flaring system are low	Variable	€/yr
27		Costs of most spare parts are low	Variable	€
	Exterior			
28		The dimensions of the flare match the dimensions of the AD system	Wish	
29		The flare is not too dominantly present	Wish	
30		The flame is not disturbingly visible	Wish	

Table 10: Brief of requirements for specific components of the flaring system

Index	Component	Requirement	Type	Value			Unit
				Min.	Max.	Desired	
	Tubing & Connections						
1		The diameter of the tube should fit the gas flow range	Variable				m
2		The length of the tubing is minimised	Variable				m
3		Tube and connections should be and stay air tight	Fundamental				
	Pressure monitor						
4		Over-pressure is monitored accurately	Variable	0.5	5	1	mbar
5		The pressure monitor drives gas venting	Fundamental				
	Gas valve						
6		The valve can be opened and closed manually	Wish				
7		The valve can be opened based on a set value for the over-pressure	Variable	15	25	20	mbar
8		Once the valve is opened, it allows for constant gas flow	Variable				
	Flame arrestor						
9		No flashback can occur	Fundamental				
10		The flame arrestor should be durable and resistant to rust etc.	Fundamental				
	Burner head						
11		The burner head can be used to burn varying gas flow rates	Variable				
12		The burner head can be used to burn gas with varying composition	Variable				
13		Air is passively delivered to the burner head	Fundamental				

	Ignition			
14		Ignition functions autonomous	Fundamental	
		A gas with varying flow rate and composition can be ignited	Fundamental	
15		The ignition can function at 12VDC	Wish	
16		Whenever gas is vented, it is ignited quickly	Fundamental	
17		The parts of the ignition positioned nearby the flame should be temperature resistant (temperature shock res. + high melting T)	Variable	°C
18		Ignition components should be resistant to oxidation	Fundamental	
19		Ignition components should be resistant to shocks and breakage	Variable	
22		The ignition system is low cost	Variable	€
23		The design of the ignition system is simple	Variable	
24		Energy use of the ignition system is as low as possible	Variable	W
	Flame detector			
27		The flame detector rapidly detects a flame	Variable	s
28		The flame detector is connected to the ignition	Fundamental	
29		The flame detector can function at 12 VDC	Wish	
30		The flame detector can stand high temperatures	Variable	°C
31		The flame detector only detects the flame, not the increased temperature caused by solar radiation	Fundamental	
32		The flame detector is not sensitive to fouling	Fundamental	
	Electronic circuit			
33		The electronic circuit connects sensors and actuators in a functioning way	Fundamental	
34		The electronic circuit contains as little complexity as possible	Variable	
35		The electronic circuit functions with a car battery as power supply	Variable	
36		Little energy is used by the electronic circuit	Variable	W
37		The electronic circuit is reliable	Fundamental	
38		A signal is given when the circuit is malfunctioning	Wish	
	Enclosure			
39		The enclosure protects the flame against wind	Fundamental	
40		The enclosure isolates the flame from the environment/people	Fundamental	
		The enclosure protects the flame against rain	Fundamental	

41		Exhaust gases can exit the enclosure properly	Fundamental	
42		The material can stand high temperatures	Variable	°C
43		The height of the enclosure is limited	Variable	m
44		The width of the enclosure is related to the characteristics of the burning	Variable	m
45		The enclosure results in good combustion temperature	Variable	°C
	Construction			
46		The construction supports the flare under all (normal) circumstances	Fundamental	
47		The construction elevates the flare from the ground	Variable	m
48		The construction separates the flare from humans and animals for safety	Wish	

3.4 First selection

The main goals in the design of the flaring system are simplicity and minimal costs. Therefore it is possible to already partly indicate which components will be needed, which might be needed and which are not needed. It is also possible to give a first indication of why certain components are (not) needed and what further considerations will be required later on.

A good starting point is the Bunsenburner, depicted in figure 4, which can be seen as a very basic flaring system and was indeed used in this study to start research, designing and testing.

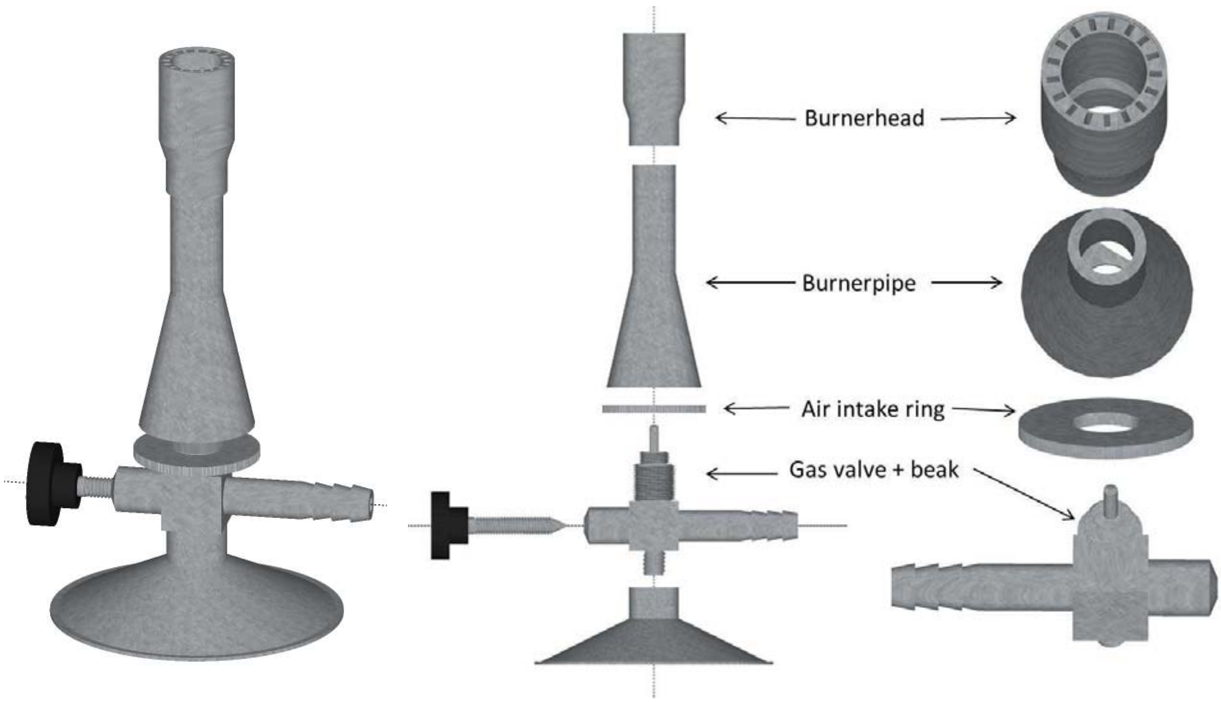


Figure 4: Bunsenburner (complete at left, disassembled at right) as used for preliminary testing

A gas tube is needed to transport the biogas from the main tube to the flare. This gas tube should be scaled according to the expected gas flows and the length is determined by the position of the flare itself. Keeping all tubes as short as possible is important to minimise the pressure losses and the risk for defects, but the flare should have a safe position. Pressure monitoring in current anaerobic digestion systems is performed with help of a tube immersed in water. The water height above the tube-exit determines the maximum pressure build up in the system. This method could still be used when the gas is not vented but flared. Advantageous is that at the moment the water functions both as pressure monitor and as valve, and besides that it could also function as a flame arrestor. Disadvantageous is that when the gas flows through the water, all over-pressure is lost, while some over-pressure might be necessary for the flare to function or ignite properly. Besides that, it is difficult to measure if and when gas is flowing through the water, making it difficult to decide when to ignite the flare. As mentioned, the water could also function as a flame arrestor, but it might be best to also have a flame arrestor close to the flame. A flame arrestor can consist of just a metal wire mesh. The type of flame arrestor, its location and dimensions should be decided according to the system dimensions, the expected gas flow and the flammability of the biogas. A burner head is needed, of which the dimensions are also dependent on the gas flow rates. Besides that it is also important to consider the way air reaches the burner head. No forced air supply will be implemented, so a passive air supply should be considered. The design of the burner head can have a function in this. It should be decided whether or not a pilot flame will be implemented. The advantage of a pilot flame is, that whenever gas passes through the water, it probably can directly be burned. The gas does not have to be detected in order to ignite it. Disadvantage of a pilot flame is that it always uses gas. Estimates of gas use vary strongly, but are at least around 40 litre per hour. Besides that, a separate gas tube, flame arrestor, air supply and a small burner head would be needed and a rather constant gas supply should be guaranteed. A pilot flame cannot replace ignition either, because the pilot flame itself needs ignition as well. Probably a flame detector is needed for proper functioning, either to detect the pilot flame or the main flame. Flame detection is commonly done either with an optical sensor (UV) or with a bi-metallic strip. The optical sensor needs more maintenance, because the photocell is rather sensitive to dust and soot. Both sensors need an electrical circuit and coupling to the ignition system. The main functions of the construction are safety and protection of the flame from the environment to ensure proper flaring. At the same time the flare must be well accessible for maintenance and check of functioning. Probably, an enclosure is good practice for the circumstances in Mali, but the dimensions of the enclosure are dependent on the gas flow, the wished quality of combustion and requirements of the users. A lot of heat is generated during flaring, so the material of the enclosure should be capable of standing and releasing this heat in a proper way. It might be interesting to utilise the heat in a useful way. A gas booster will not be implemented. There is over-pressure in the system already and a booster will increase complexity and costs of the system. The same goes for air or steam injection. This will not be needed, because overpressure exists and air can be sucked in in a passive way with help of a venturi.

In table 11, a first selection of components is done. Per essential component, two or three options are depicted. Often more options were found, but the options displayed came forward as most promising after a first selection. Also, different types and brands are available for most options. In this phase, such a specific selection is not yet done. Some positive and negative points are indicated and based on these points, options are chosen to be further analysed. These options are underlined in the morphologic chart and will be worked out in following section.

Table 11: Morphologic chart with 2 or 3 options and their (dis-)advantages displayed for the most important components. Underlined options are current first choice and will be further analysed.

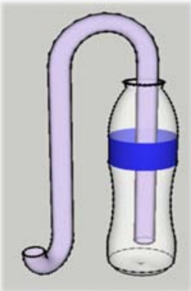
Component	
Tubing	
1. Garden hose	2. Steel gas pipe
	
+ Flexible and simple assembly + Flexible placement	+ Durable + Maintenance free - Low flexibility

+ Low cost
- Higher risk of defects

- Higher cost

Pressure monitor

1. <u>Bottle with water column</u>



+ Simple construction
+ Widely available
+ Quite accurate
+ Low cost
- Higher risk of defects

2. Mechanical safety relief valve

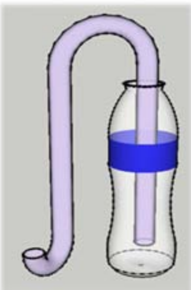
+ Adjustable pressure
+ Durable
+ Maintenance free
- Either low price but too low flow rate or high flow rate and high price

3. Electronic pressure sensor

+ Pressure can be monitored continuous
+ Accurate measurement
- Need for electronic circuit and controller
- Quite high price

Gas valve

1. <u>Bottle with water column</u>



+ Autonomic functioning
+ Low cost
- Risk for irregular venting
- No signal at gas flow

2. Mechanical safety relief valve

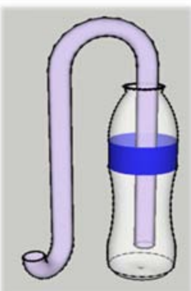
+ Autonomic functioning
+ Simple implementation
- No signal at gas flow

3. Electronic gas valve

+ Adjustable gas flow
+ Durable material
- Needs electronic circuit
- Thus increased complexity and risk for failure

Flame arrestor

1. <u>Bottle with water column</u>

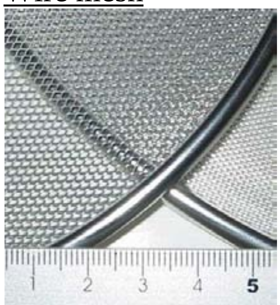


+ Gas flow is irreversible thus no flash back possible

2. Witt flame arrestor

+ Reliable
+ Simple implementation
- Relatively expensive

3. <u>Wire mesh</u>

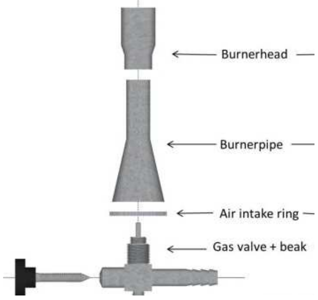


+ Low cost
+ Simple but well-functioning
- In time, the flame might damage the mesh

- Mesh diameter has to fit the gas flow

Burner head

1. Bunsenburner configuration



- + Fulfils all required functions
- - Needs to be adapted

Gas detection

1. Gas sensor

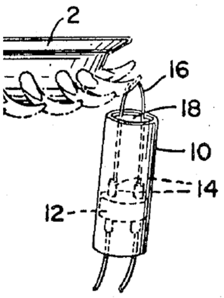
- + Reliable gas detection
- - Relatively expensive
- - Continuous energy use
- - More complex electronic circuit needed
- - More difficult to obtain

2. Switch contact

- + Simple electronic circuit
- + No energy use
- + Widely available
- - More complex mechanical construction
- - Lower reliability

Ignition

1. Hot wire/coil



- + Effective ignition
- + Low cost solution
- + Uncomplicated electronics
- - Relatively high energy use
- - Lifetime of wire unsure

2. Spark ignition

- + Low energy use
- - More complicated electronics
- - Ignition less reliable

3. Pilot flame

- + Reliable ignition method
- + Durable solution
- - Needs ignition itself
- - Constant gas use

Flame detector	
1. UV/IR flame scanner  + Rapid flame detection + Reliable flame detection - Sensitive to fouling - More difficult to obtain	2. <u>Temperature sensor</u>  + Low cost solution + No fouling problems - Needs tuning for right switching moment - Too high temperatures might damage sensor - Environment might result in false detection
Enclosure	
1. <u>Circular steel enclosure</u>  + Protects and isolates + Temperature resistant + Simple and low cost + Widely available - May become dangerously hot	

In table 9 a brief of requirements is set up for the complete flaring system. In order to have a guideline in choosing the separate components and to be able to check their performance, specific requirements are set up and displayed in table 10.

3.5 Component design, dimensioning and testing

In this section, the separated components of the flaring system are studied, starting from the most prominent ones. For some components, first a theoretical description is given, followed by results obtained from testing and an analysis of both.

Fulford (1996) extensively describes the theory of biogas stove design. Figure 5 schematically shows the basic elements of a stove or burner, namely the injector orifice, the air inlet ports, the throat and mixing tube and the burner port. The basic elements can be seen as what in table 10 is called the burner head, fulfilling most of the basic requirements. Figure 5 also shows the elements of the flame itself and the way air is supplied to the flame. Primary air is air mixed with the gas before the flame is reached, while secondary air is air sucked on by the flame itself.

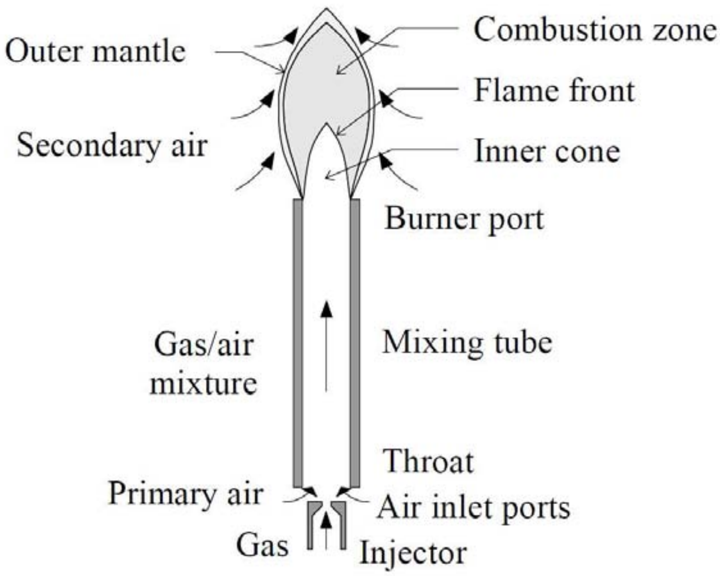


Figure 5: Schematic drawing of the elements of burner and flame (Fulford 1996)

Gas flow through injector orifice

Biogas is introduced into the burner through the gas injector or injector orifice. A simple orifice is just a hole in a plate. In the burner, this orifice has four important functions: As mentioned, it introduces the biogas into the burner, but it also separates the burner from the gas supply, so that it is impossible for a flame to enter the gas supply tube. Factually, the injector orifice thus functions as a flame arrestor. Besides that, the orifice increases the biogas flow speed, resulting in a pressure drop just after the orifice, which again results in (primary) air being sucked in and mixed with the biogas. Finally, the orifice can also be used to control the gas flow rate. Figure 6 shows an orifice in a tube. One can see that the air is forced through a small hole, where the speed will strongly increase. Maximum velocity is reached in the vena contractor, some distance after the hole, were compression of the gas is at its maximum. After that the gas speed will decrease again. When the orifice is placed at the end of a pipe, the same effect will occur.

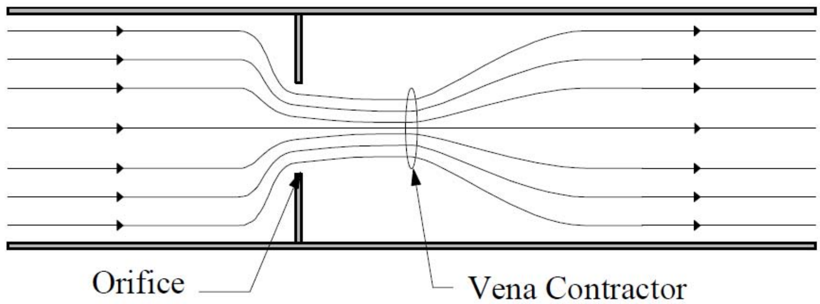


Figure 6: Schematic image of an orifice in a tube (Fulford 1996)

At a known pressure, the gas flow rate through an orifice with a defined diameter is limited and can be calculated with an empirical version of Bernoulli's theorem, displayed in equation 5 (Fulford 1996).

$$Q = 0.0467 \cdot C_d \cdot A_{orifice}\sqrt{\frac{p}{s}} \qquad m^3h^{-1} \qquad \text{Equation 5}$$

With Q the gas flow rate $[m^3h^{-1}]$, C_d the discharge coefficient [-], which accounts for the vena contractor and the friction losses over the orifice, $A_{orifice}$ the area of the orifice $[mm^2]$, p the gas pressure before the orifice $[mbar]$ and s the specific gravity of the gas [-]. Both calculations and measurements are performed to determine the flow rate over orifices with different orifice diameters and varying pressure before the orifice. The goal is to be able to choose the right orifice for the expected gas flows. Measurements were in the first stage performed with air, so the specific gravity of the gas is 1. Five orifices were available for testing. The first one is the Bunsenburner which is depicted in figure 4, having an orifice of 1 mm diameter. Four others were prepared by drilling holes in brass caps, normally used in the central heating system. Caps with one hole of 1.5 and 2 mm respectively, a cap with two holes of 1 mm and a cap with five holes of 1 mm were prepared. The discharge coefficients of the orifices is unknown, therefore calculations are performed for a range of coefficients, from 0.75 to 0.95. Measurements were closest to the theoretical calculations for a C_d of 0.75, therefore this value is used in further calculations. Figure 7 shows the calculated air flow rates for the five different orifices at varying pressure and the related measurements for the orifices, excluding the Bunsenburner. One can see that measured values are quite close to the calculated values. It is also interesting to mention that the calculation for the caps with two and five 1mm orifices is taken as a multiplication of the calculation for the 1mm orifice with 2 and 5 respectively.

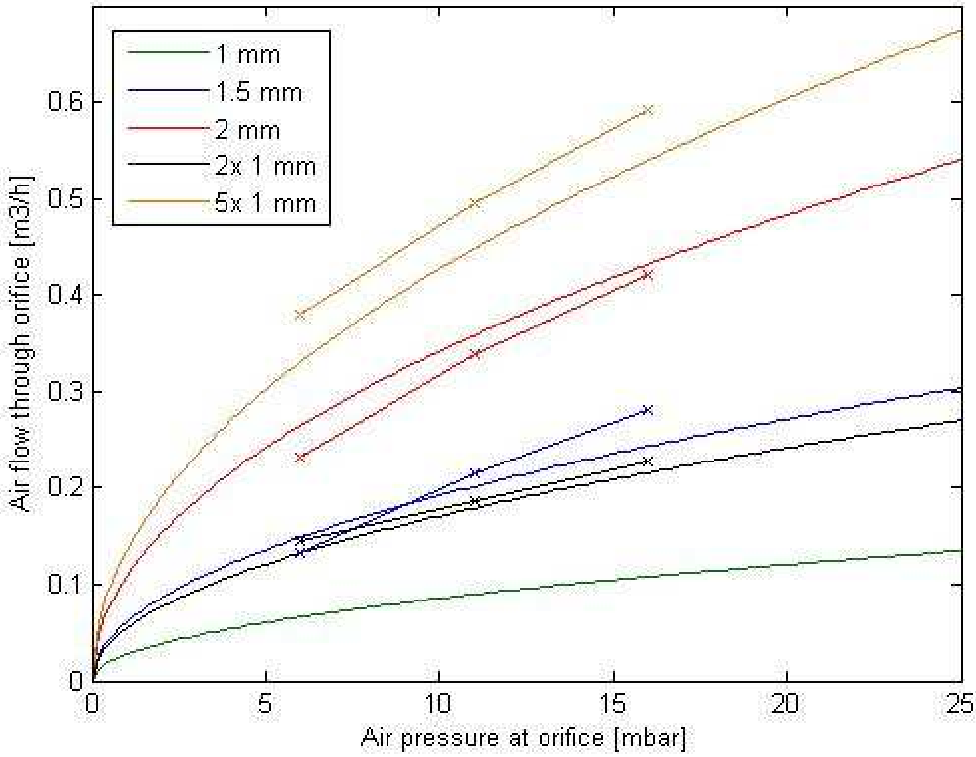


Figure 7: Theoretical and measured (+) flow rates through orifices for air with Cd set to 0.75

The measurements were performed for air, but the orifices are meant to be used for biogas. The specific gravity for biogas is equal to 0.858. Performing the calculations again using this value and a C_d of 0.75, results in a estimation of the biogas flows through the different orifices, as is shown in Figure 8. Two lines were added to the figure, indicating the biogas flow at a biogas production rates of 5 and 10 m^3 per day.

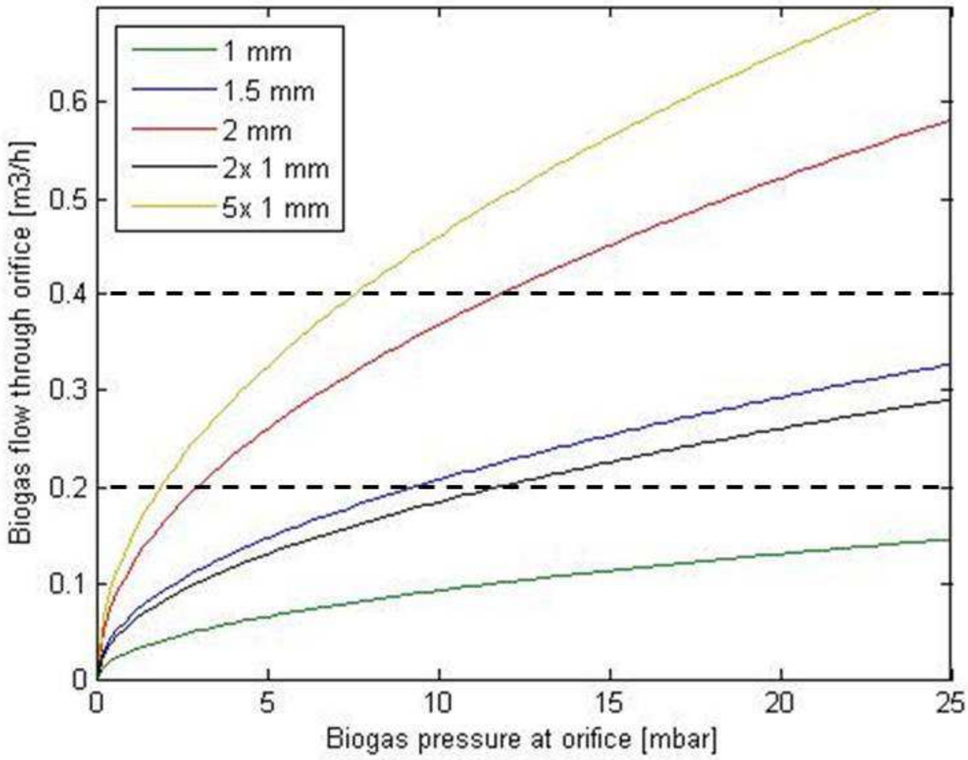


Figure 8: Theoretical biogas flow rate through orifices with Cd is 0.75 and lines indicating biogas production of 5 and 10 m^3/day

It can be seen that one orifice of 1 mm is too small to be used for gas flows of both 5 or 10 m^3 per day at this low pressures. The caps with the 1.5 mm and the two times 1 mm orifices could be used for gas flows of 5 m^3 per day when pressure is above 10 mbar. The caps with the 2.0 mm and the 5 times 1 mm orifices can be used for gas flows of 5 m^3 per day at very low pressure already, and for flows of 10 m^3 per day when pressure is around or above 10 mbar.

Throat dimensioning for air entrainment

As mentioned before, one of the functions of the orifice is to create an underpressure resulting from increased gas velocity. This underpressure results in the entrainment of primary air via the air inlet ports or throat. Fulford (1996) indicates that the amount of primary air added to biogas is usually around 50% of the total stoichiometric air requirement, although dependent on the design of the burner. Testing showed that although flame temperature increased and the flame became more compact, indeed adding a high amount of primary air increases the risk for blow off of the flame, therefore an entrainment ratio of 4 is chosen. This means that four volumes of air are entrained per volume of biogas, where the stoichiometric air requirement is around 5.8. The amount of primary air entrained can, within certain ranges of pressure drop and tube dimensioning, be calculated according to equation 6 (Fulford 1996). The wished entrainment ratio is known, therefore the equation is modified, so that the diameter ratio can be calculated, as shown in equation 7.

$$r = \sqrt{s} \cdot \left(\sqrt{\frac{A_{throat}}{A_{orifice}}} - 1 \right) = \sqrt{s} \cdot \left(\frac{d_{throat}}{d_{orifice}} - 1 \right) \quad [-] \qquad \text{Equation 6}$$

$$\frac{d_{throat}}{d_{orifice}} = \frac{r}{\sqrt{s}} + 1 = \frac{4}{\sqrt{0.86}} + 1 = \frac{5.3}{1} \qquad [-] \qquad \text{Equation 7}$$

With r the primary air entrainment ratio, s the specific gravity of the gas, A the surface area and d the diameter of the throat and orifice. So with given diameter of the orifice, the diameter of the throat has to be taken 5.3 times larger to obtain the right air entrainment. This ratio was confirmed by calculations according to the method of Jones (1989), which takes a slightly different approach. There are several ways to design the orifice/throat area of the burner. The throat diameter mentioned before suggests that the air inlet has to have one hole with certain diameter, but in the end, the air inlet area is decisive. So it is also possible to use several air inlet holes which together have the calculated surface area. The amount and size of the air inlet holes is in a practical setup dependent on the design of the rest of the flare construction and the drill sizes available. A suitable size and number has to be chosen in such a way that the total air inlet area is close to the calculated area.

Dimensioning of the burner port

The burner port or flame port is where actual combustion takes place. Biogas has a relatively low stoichiometric flame speed of 0.25 m/s, which means that a biogas flame easily lifts from the port or even goes out when the gas velocity through the flame port is too high (Fulford 1996). Therefore the size of the flame port must be chosen in such a way that the velocity of the gas/air mixture is considerably lower than this value. The gas mixture velocity at the burner port is dependent on the gas mixture flow rate and the surface area of the burner port. Equation 8 displays this relation explicitly. This equation can be transformed to equation 9. The diameter of the burner port can then be determined for a given flow rate and a wished mixture velocity. A safe mixture velocity of 0.10 m/s is chosen in order to prevent lift off and have some tolerance in real flow rate and entrained air.

$$v_{port} = \frac{Q \cdot (1 + r)}{{d_{port}}^2} \cdot \frac{4}{\pi \cdot 3600} \qquad m \cdot s^{-1} \qquad \text{Equation 8}$$

$$d_{port} = \sqrt{\frac{Q \cdot (1 + r)}{v_{port}} \cdot \frac{4}{\pi \cdot 3600}} \qquad m \qquad \text{Equation 9}$$

With v_{port} the gas mixture velocity, Q the volume flow rate through the port in $m^3 \cdot h^{-1}$ and d_p the diameter of the burner port in meter. One should notice that for this calculation, there is no relation with the dimensioning of the biogas injector and air inlet ports. It is just a relation between the gas volume flow and the area of the burner port. Tests were performed for biogas flows of 2.4 and 5 m^3/day, to find out if the given theoretical relation above indeed resulted in a stable flame,. According to equation 9, the diameter of the burner port d_p should then be 4.2 and 6.1 cm respectively. Figure 9 shows the test setup, mixing tubes (and thus the burner port) of 3.4 and 4.9 cm inner diameter were available and used. This means that the gas velocity at the burner port is higher than 0.1 m/s, namely 0.15 m/s. This is still lower than the biogas flame speed, and indeed a stable flame could be obtained in both situations.

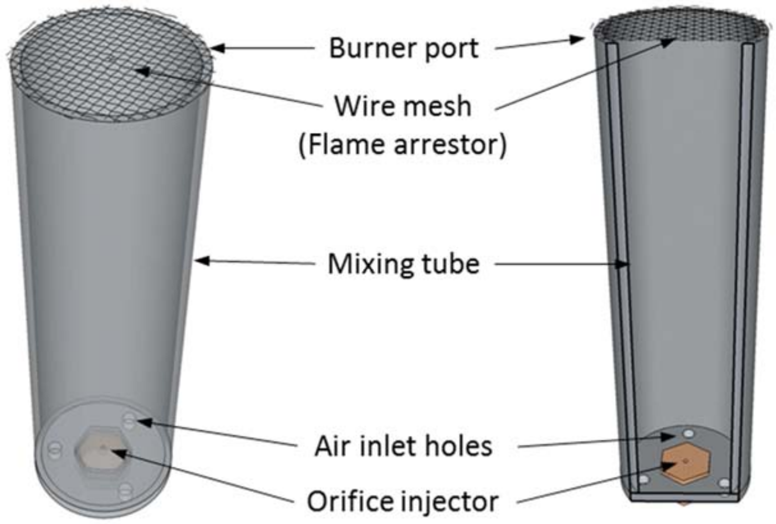


Figure 9: Drawing of the setup used for testing of the port dimensioning

Fulford (1996) indicates that the length of the mixing tube is usually taken to be ten times the diameter of the throat to allow for proper mixing of fuel and air. During testing, in both situations, the length was taken to be 25 cm, which seems to allow for proper mixing under these flow rates. Air inlet holes were drilled which theoretically should provide an air entrainment of 4. It is rather difficult to measure air entrainment, so for this element there is some uncertainty in the relation between theory and practice.
As can be seen in figure 9, the flame was separated from the mixing tube by a wire mesh, which adequately functioned as a final flame arrestor.

Dimensioning of the flare enclosure

The components treated in foregoing parts together function as the burner head, where the actual flaring takes place. It is important to protect the biogas flame from influences of the environment, to be able to create proper flaring conditions, no matter the weather conditions for example. Usually, an enclosure is basically a tubular construction surrounding the burner head. Secondary air is sucked in through the bottom opening, while exhaust gases are released through the upper opening called the stack exit. A small flaring system also needs to be protected against rain by a hood on top of the enclosure. This hood should be designed in such a way that the flame is protected adequately, but gases can escape with little hinder to the environment.
The dimensioning of the stack exit is mainly dependent on the exit gas volume flux and velocity. The Texas Air Control Board (TACB) developed a method to determine the dimension of the stack exit (Ruggeri 2004), on which these calculations are based. The method is based on two equations for calculating the buoyancy flux of the burned gases Equation 10 is dependent on four parameters, namely stack temperature ($T, [°K]$), ambient temperature ($T_a, [°K]$), stack gas velocity ($v, [m\ s^{-1}]$) and stack diameter ($d, [m]$), with g the gravitational acceleration of 9.81 $[m\ s^{-2}]$. Equation 11 calculates the buoyancy flux based on the heat of the stack gases only, with q_n the net heat release by the burned gases $[cal\ s^{-1}]$.

$$F_1 = g \cdot v \cdot \frac{d^2}{4} \cdot \frac{T - T_a}{T} \qquad m^4 s^{-3} \qquad \text{Equation 10}$$

$$F_2 = (3.7 \cdot 10^{-5}) \cdot q_n \qquad m^4 s^{-3} \qquad \text{Equation 11}$$

The two equations can be aligned and solved for the stack diameter, by using reasonable values for the unknown parameters. For the exit temperature, according to Ruggeri (2004), a reasonable value for a flare with good burning characteristics is 1273 ˚K (1000 ˚C). For the ambient temperature, under Malian conditions, a value of 303 ˚K (30 ˚C) is reasonable. According to Ruggeri (2004), the stack gas exit velocity should be taken sufficiently high in order to prevent down wash of the gases, even at reasonably high wind speeds. Down wash of the gases will result in incomplete burning or even suffocation of the flame. The gas exit velocity is taken 1.5 times a reasonably high wind speed of 50 km/h, resulting in a velocity of 75 km/h, which is approximately 20 m/s. The net heat release of the burned gases, q_n, is a function of the lower heating value of the biogas, the mass density and the mass flow. Besides that, the unit has to be converted from J/s to cal/s, as can be seen in equation 12. Equation 13 shows the units related to equation 12 and equation 14 shows the values used for LHV and mass density.

$$q_n = LHV \cdot 10^6 \cdot \rho \cdot F_v \cdot \frac{1}{4.1868} \qquad cal\ s^{-1} \qquad \text{Equation 12}$$

$$\frac{cal}{s} = \frac{MJ}{kg} \cdot \frac{J}{MJ} \cdot \frac{kg}{m^3} \cdot \frac{m^3}{s} \cdot \frac{cal}{J} \qquad \text{Equation 13}$$

$$q_n = \frac{20.4 \cdot 10^6 \cdot 1.04}{4.1868} \cdot F_v \qquad cal\ s^{-1} \qquad \text{Equation 14}$$

Aligning equation 10 and equation 11, with the constant variables filled out, results in equation 15 and can be simplified to equation 16, which gives a direct relation between the stack exit diameter and the biogas flow rate, with the biogas flow rate in m^3/s.

$$\frac{9.81 \cdot 20}{4} \cdot \frac{1273 - 303}{1273} \cdot d^2 = \frac{3.7 \cdot 10^{-5} \cdot 20.4 \cdot 10^6 \cdot 1.04}{4.1868} \cdot F_v \qquad \text{Equation 15}$$

$$d = \sqrt{5.016 \cdot F_v} \qquad m \qquad \text{Equation 16}$$

At a biogas flow rate of 5 m^3/day, a stack exit diameter of 1.7 cm is calculated. This seems a rather small number, especially when compared to the dimensions of the burner head. Therefore, the effect of the important parameters on the diameter of the stack exit was tested. Figure 10 shows that both the biogas flow rate and the assumed stack exit velocity have a large influence on the required diameter. A higher biogas flow rate requires a larger exit diameter. Assuming a lower required exit velocity means that a smaller exit diameter is required.

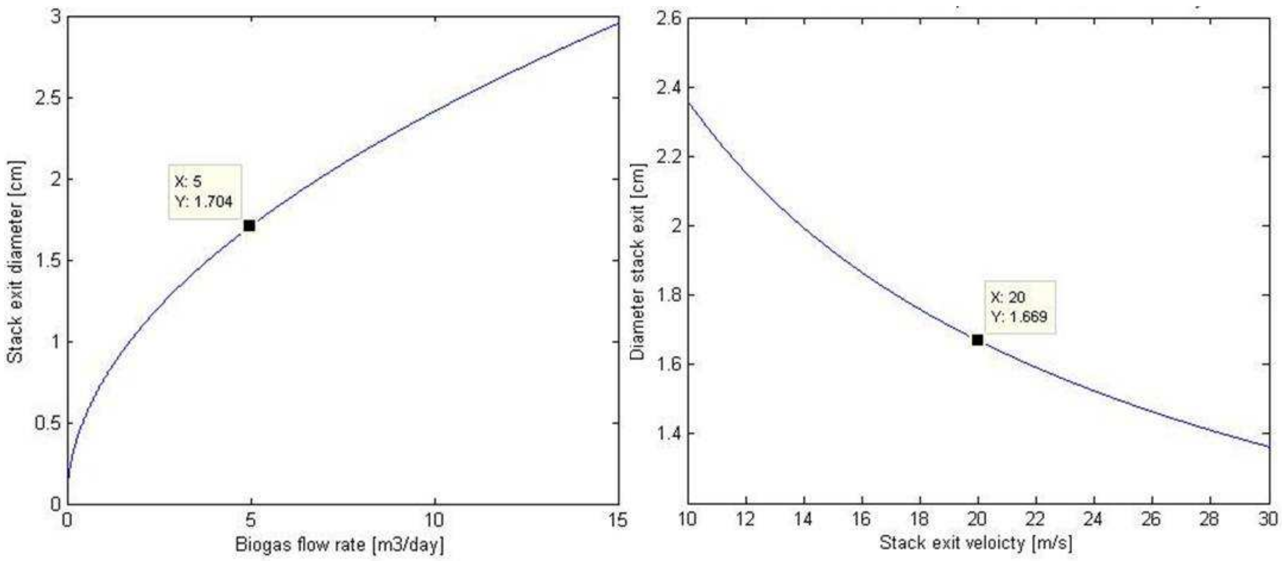


Figure 10: The stack exit diameter as influenced by the biogas flow rate (left) and the stack exit velocity (right)

Assuming 1273 ˚K for a small flare might be a too high estimation, because of the relatively low energy dissipation and high energy losses due to a small system. Figure 11 shows that the effect of the exit gas temperature is rather small, a decrease of the diameter of 2 mm would be required when the temperature is assumed to be 500˚K lower. The ambient temperature has an even smaller influence.

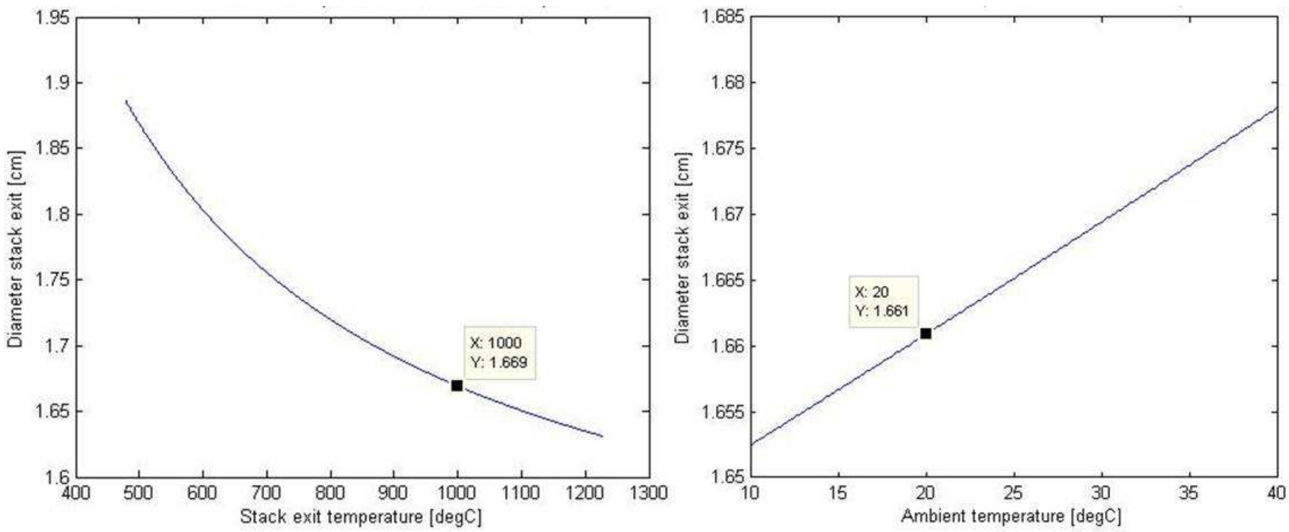


Figure 11: The stack exit diameter as influenced by the gas temperature (left) and the ambient temperature (right)

The calculated diameters are smaller than expected. Therefore it is useful to compare the calculated diameter with existing flaring systems. Detailed drawings of three flare stacks of Himmel Gastechnik also contain the dimensioning of the gas stack and the gas flow range. The smallest of these systems is designed for gas flows of 20 -50 m^3/hr. In figure 12 the dimensioning of the high temperature and the low temperature flaring systems are compared with the theoretical values. It is clear that in this case the theoretical values strongly underestimate the diameters used in practice, which are on average about 40% larger.

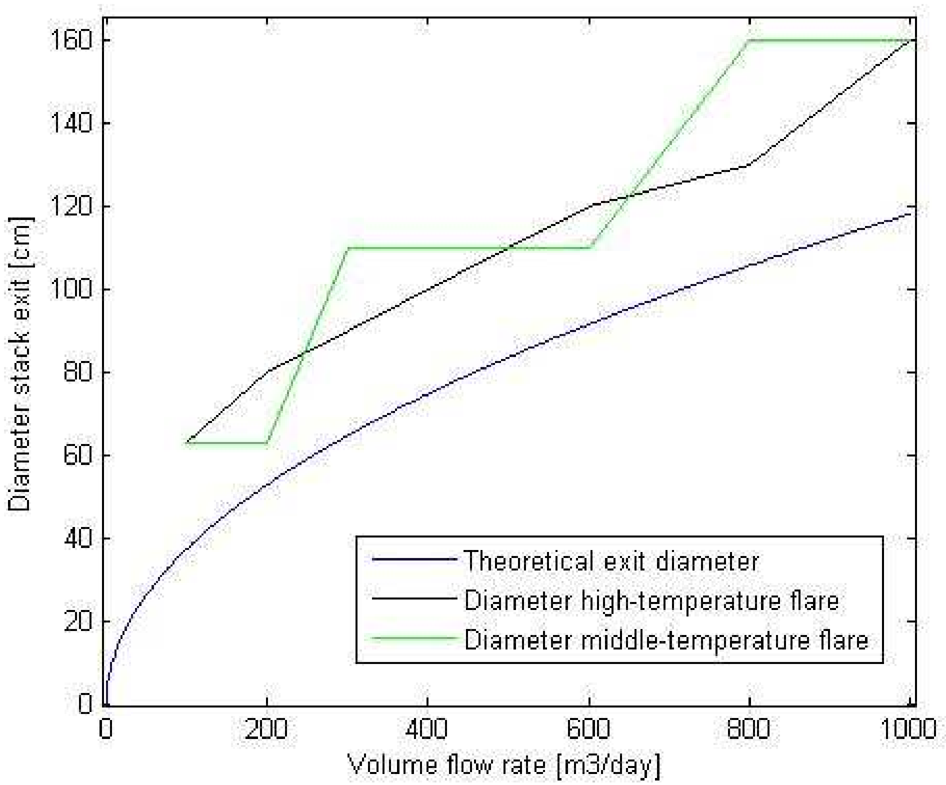


Figure 12: Comparison of theoretical values for the stack exit diameter and dimensions of flare stacks of Himmel Gastechnik

The TACB method does not directly give satisfactory results. This can have several reasons: the used method is not useable for these low amounts of gas, or cannot be used for biogas, or the used parameters do not apply for a small flaring system. Therefore an approach is taken based on first principles, as indicated by Caine (2000), so that the two methods can be compared.

The flue gas originating from combustion in the flame, has a much higher temperature than the biogas and air before the flame. This results in expansion of the gases. The combustion equation is equimolar, so an adapted version of the ideal gas law can be used to determine the volume increase and with that the velocity increase of the gases. The gas law is shown in equation 17 and by assuming that pressure before and after the flame is equal and the total air entrainment is 10 (sum of primary and secondary air), equation 18 calculates the volume increase resulting from temperature increase.

$$\frac{P_1 \cdot V_1}{T_1} = constant = \frac{P_2 \cdot V_2}{T_2} \qquad Pa \cdot m^3 K^{-1} \qquad \text{Equation 17}$$

$$\frac{100000 \cdot 11}{300} = \frac{100000 \cdot V_2}{1000} \rightarrow V_2 = \frac{11 * 1000}{300} = 36.67 \qquad m^3 \qquad \text{Equation 18}$$

With P the pressure in Pa, V the gas volume in m^3 and T the temperature of the gas. The subscripts 1 and 2 indicate the characteristics of the gas before and after the flame respectively. The added air and the 700 °C temperature increase results in a volume increase of 36.7 times the gas input. The real expansion coefficient of the gases is equal to 3.33 $m^3 m^{-3}$, when comparing the flue gases with the sum of biogas and entrained air ($36.67/(1+10)$). With this expansion coefficient, the gas flow through the stack exit can be calculated at a biogas flow rate of 5 m^3/day and a total air entrainment of 10. And from the gas flow rate and the area of the stack exit, the gas velocity can be determined, as shown in equation 19.

$$v_{exit} = \frac{Q_{day} \cdot (1+r)}{24 \cdot 3600} \cdot \frac{4}{\pi \cdot d_{exit}{}^2} \qquad m \cdot s^{-1} \qquad \text{Equation 19}$$

With v_{exit} the gas velocity through the stack exit in $m \cdot s^{-1}$, Q_{day} the gas flow rate in $m^3 day^{-1}$, r the entrainment rate and d_{exit} the effective diameter of the stack exit in m. Figure 13 shows the relation between the diameter of the stack exit and the flue gas velocity. It can be seen that indeed a rather small diameter is needed to obtain gas velocities as high as 20 m/s and that current method gives comparable results as the TACB method.

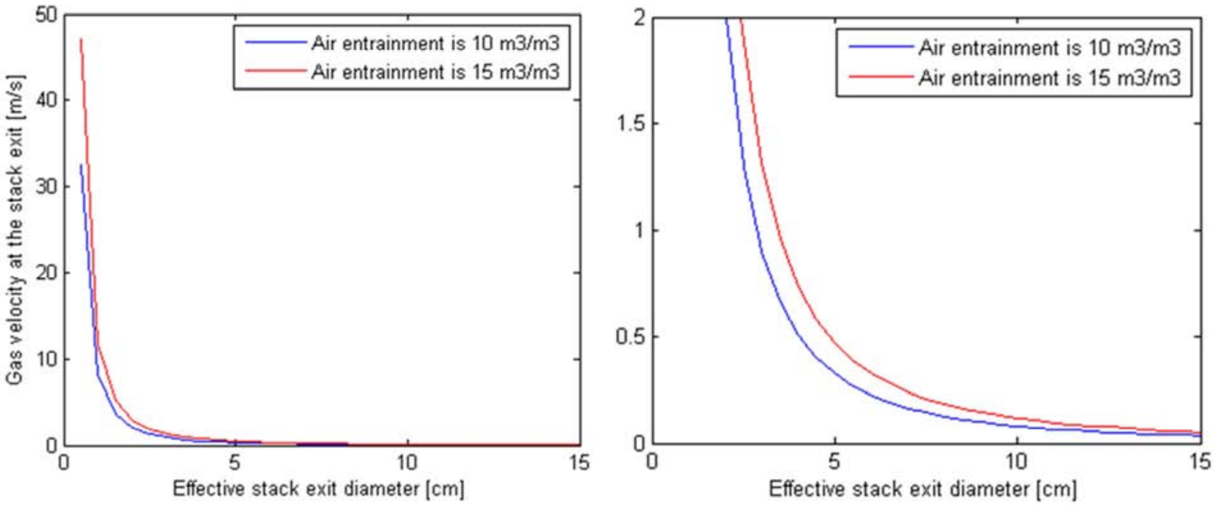


Figure 13: The influence of the diameter of the stack exit and the air entrainment rate on the gas velocity

For a biogas flow of 5 m3/day, the diameter of the burner port was calculated to be 6 cm, in order to obtain a gas velocity of 0.10 m/s. Compared to this velocity, the exhaust velocity of 20 m/s as proposed in the TACB method is very high. But it is unknown what would be a good exhaust velocity to maintain a good flame. Therefore it is proposed to determine this in duration tests. In figure 14 a suggestion is done of a combination of enclosure and hood which makes it possible to vary the effective stack exit area. This is a convenient solution, not only because it is possible to adapt the stack exit area, but the diameter of the enclosure can be chosen suiting the diameter of the burner port. It is useful to have an enclosure with a diameter about 4 cm larger than the diameter of the burner port. In that way there is about 2 cm space for the additional equipment like the ignition and the cables.

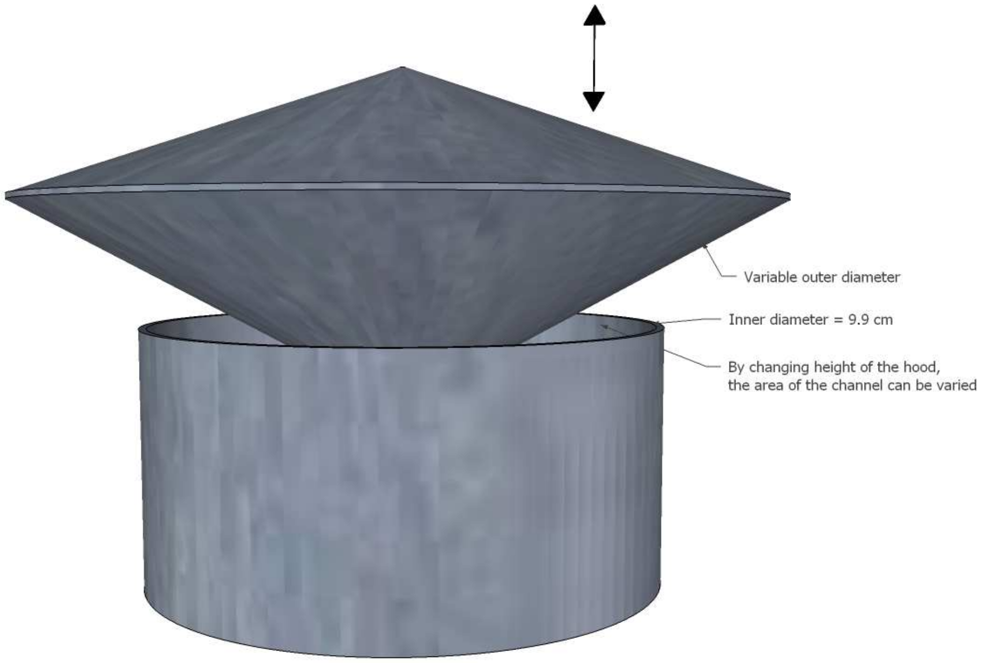


Figure 14: The surface area of the enclosure can be chosen by varying the distance between hood and enclosure

The enclosure should be high enough to keep the flame within. From the dimensions provided by Himmel Gastechnik for their enclosed flares , a linear relation can be deducted, but this does not result in useful values, minimum height deducted is about 3.8 meter, which is much too high. A regularly mentioned equation is the flame height correlation equation by Heskestad, which is presented in equation 20. With this equation, the flame vertical flame length can be calculated for an open fire.

$$L = -1.02 \cdot D + 0.235(Q^{\frac{2}{5}}) \qquad m \qquad \text{Equation 20}$$

With L the flame length in m, D the diameter of the base of the flame in m and Q the energy dissipation of the flame in kW. Assuming a lower heating value of 20.4 MJ/kg and a mass density of 1.04 kg/m^3 for the biogas and taking the diameter of the burner head as the base of the flame, the flame length is 19.4 and 24.8 cm for a biogas flow rate of 5 and 10 m^3/day respectively. In the flare, the flame is enclosed, which might slightly increase the length of the flame, but the flame lengths most probably will be within 20 to 30 cm. The length of the mixing tube is about 25 cm, resulting in a minimum height of the enclosure of about 60 cm.

Pressure monitor and gas valve

A device is needed which triggers gas flaring at the moment that the gas pressure in the digester bag reaches the maximum tolerated value. This device should be simple but reliable. Currently, venting is triggered by submerging the venting tube in a bottle filled with water. The water column supplies the wished counter pressure. This is a very simple and effective system, but for flaring it needs to be known when venting takes place and the gas needs to be guided to the flare. Besides that, some gas pressure is needed to be able to flare, while when the gas flows through water all over pressure will be lost. An interesting alternative to this system is a mechanical safety relief valve. This is basically a spring loaded valve. The spring keeps the valve closed as long as the gas pressure is lower than the counter pressure of the spring. This counter pressure is adjustable within certain ranges. These safety relief valves could have been a great solution. Low cost valves are available, but their gas flow capacity in the required pressure range was not sufficient, while a valve with enough capacity at low pressure, turned out to be far too expensive (Wittgas). Therefore it was decided to use a water column as pressure monitor and to add functionality so that the gas is lead to the flare and a signal is given when gas flow occurs. Two options were considered for this function. The cheapest and simplest option is to imitate the method used in the safety relief valve, with a spring loaded valve. The extra pressure provided by the spring should be minimal in comparison with the water column, but enough to close the valve. When pressure builds up above the water column, the spring is pushed up, giving way to the gas and at the same time activating a microswitch. Activating the microswitch results in an electronic signal which at its turn activates the flare ignition. Figure 15 contains a drawing of the proposed implementation of this option. Most difficult in this setup is to tune the spring loaded valve in such a way that it gives applies very little counter pressure to the gas, but at the same time closes the valve properly and accurately activates the microswitch. As mentioned before, the water column can also function as flame arrestor, but with the proposed setup, two components closer to the flame already fulfil this function.

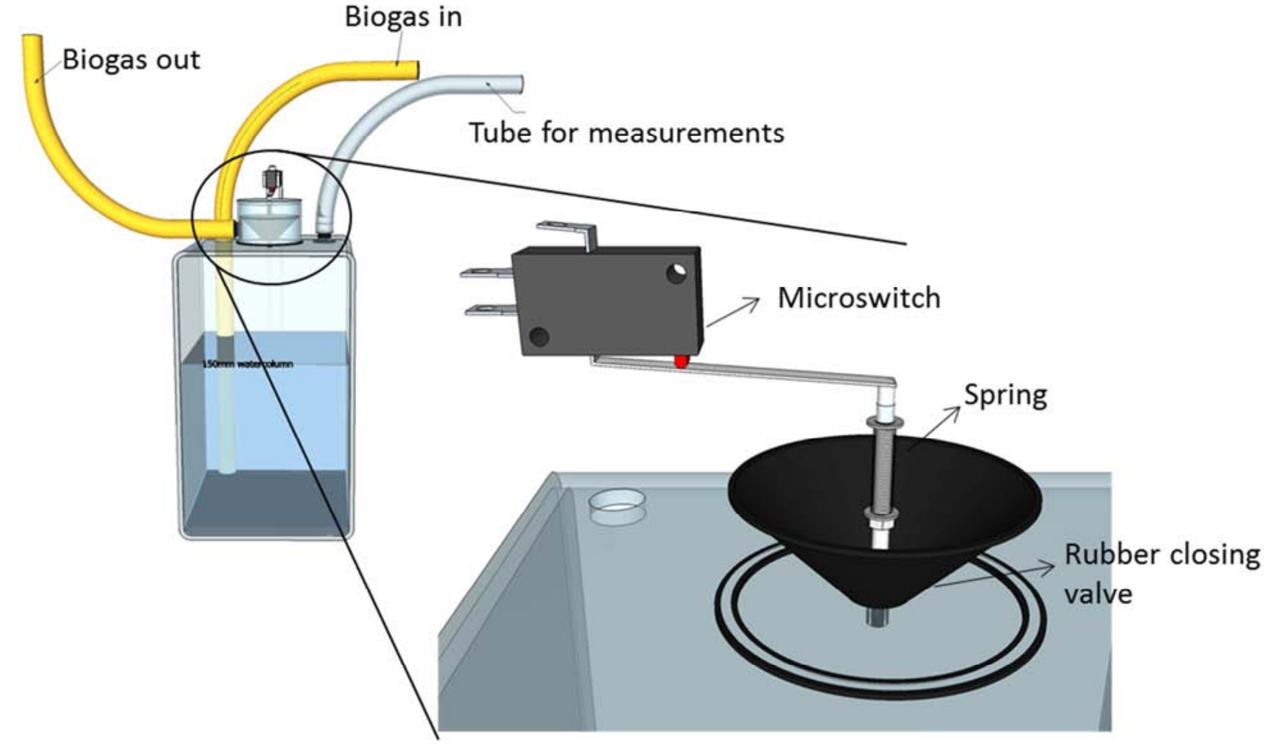


Figure 15: Drawing of the pressure monitor and gas valve with details of valve and microswitch

The second option is a combination of the water column as pressure monitor and a gas sensor indicating gas flow. The gas sensor is an electronic device with a high sensitivity to methane, propane and butane, which makes it ideal for monitoring of both biogas and natural gas. In clean air, the resistance of the sensing element is high, but when one of the gases is present, the resistance decreases with increasing concentration (Figaro 2012). From this changing resistance, a signal can be obtained, in order to start ignition. Best location for the gas sensor would be in the mixing tube. Placing it closer to the water column will probably result in a non-reliable signal because gases will remain present for some time after the gas flow has stopped, while gas present in the mixing tube will be burned or replaced by air. In general, this sensor can result in reliable gas flow detection. Though there are two disadvantages. The first is that the electronics circuit needed is more complex than for the microswitch. Secondly, the gas sensor has a continuous energy use. It contains an heating element which provides proper conditions for gas sensing and requires, dependent on the electronic circuit, between

0.8 and 2 Watt of electricity. The basic scheme required for the gas sensor is displayed in figure 16 (Figaro 2012), where V_H is the voltage applied to the gas sensor heater and V_c the sensor voltage, which is maximum 24 V, but in this case 12 V. A voltage divider is created by the resistance of the gas sensor and R_L, so that the output voltage is dependent on the resistance of the gas sensor. When no gas is present, sensor resistance is high, thus V_{RL} is low, increasing with decreasing sensor resistance. This scheme is meant to actually measure gas concentration. When the gas sensor has to be used as a switch, the scheme needs extension.

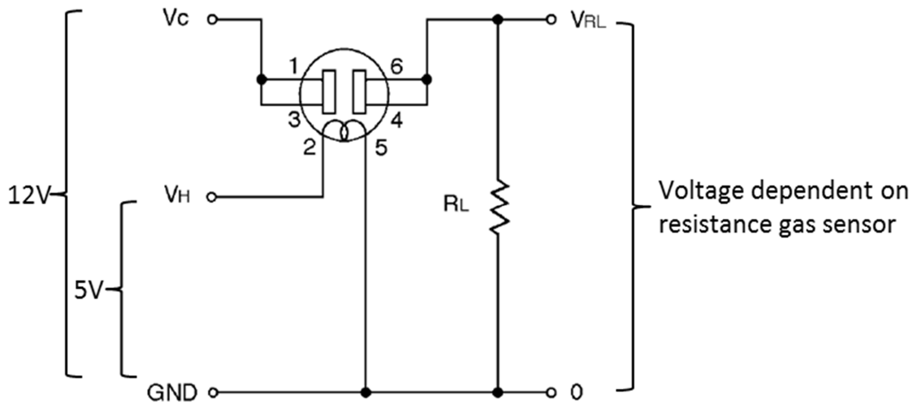


Figure 16: Basic scheme of the Figaro TGS-813 gas sensor (Figaro 2012)

Ignition of the flame

By either the microswitch or the gas sensor, a signal is produced when gas is vented. This gas needs to be ignited as quickly as possible at the burner head. Two methods are promising, namely ignition with a hot wire or coil and spark ignition.

In the first method, a wire is electronically heated to a temperature above the auto ignition temperature of the biogas, which is about 600 ˚C. This can be done by applying a voltage over a metal wire, which is partly in contact with the gas stream. Ideally the wire is resistant to high temperatures of up to 1000 ˚C, to some shear and shock and to corrosion. Besides that, the resistance of the wire should be high, in order to quickly increase its temperature, but the electronic energy dissipated should be as low as possible, to minimize energy use. Isabellenhütte is a producer of a range of resistance wires, varying in material used, thickness and resistivity (Isabellenhütte). The material also determines the maximum temperatures at which the wires can be used. When the wire is used to ignite biogas, the temperature for ignition should be around 600˚C and the temperature of the flame can reach about 1000˚C. Wires made of the material Iso-chrom can be used up to a temperature of 1150˚C, unlike the other wire types, which mostly can be used up to a maximum temperature of 600˚C. An Iso-chrom 60 wire is available from www.conrad.nl. Isabellenhütte provides technical information regarding their wires, with which currents, resistance and dissipated power can be calculated. Table 12 contains a selection of a table provided by Isabellenhütte for a wire of the material Isotan. It displays how much electrical current should flow through a wire of certain diameter in order to reach a certain temperature increase.

Table 12: The current needed to obtain a certain temperature increase for Isotan wire of different diameter (Isabellenhütte)

Temperature increase	60 [˚C]	100 [˚C]	300 [˚C]	600 [˚C]
Diameter [mm]	I [A]	I [A]	I [A]	I [A]
0.020	0.034	0.048	0.096	0.144
0.050	0.097	0.136	0.274	0.431

0.100	0.216	0.302	0.610	0.966
0.250	0.629	0.880	1.79	3.08
0.500	1.44	2.01	4.13	7.39
1.000	3.37	4.72	9.78	18.1

These values are only valid for Isotan, but can be converted to the current for other materials, like Isochrom 60, through equation 21 (Isabellenhütte). When the needed current is known, the required resistance of the wire and through that its length can be calculated, dependent on the voltage applied, as shown in equation 21, equation 22 and equation 23respectively. When a car battery is used, the applied voltage is 12 V. The lower the used voltage, the shorter the wire can be. From the current through and the resistance of the wire, the amount of energy dissipated can be calculated according to equation 24.

$$i_x = i_{Isotan} \cdot \sqrt{\frac{\rho_{Isotan}}{\rho_x}} \qquad A \qquad \text{Equation 21}$$

$$R = \frac{V}{i} \qquad \Omega \qquad \text{Equation 22}$$

$$\ell = \frac{R}{R_{spec}} \qquad \text{m} \qquad \text{Equation 23}$$

$$P = i^2 \cdot R \qquad \text{W} \qquad \text{Equation 24}$$

With i the current needed $[A]$ to reach a temperature increase, ρ the resistivity of the material $[\Omega \cdot mm^2 m^{-1}]$, which is 0.49 for Isotan and 1.20 on average for Isochrom (temperature dependent), V the applied voltage, R the resistance [Ω] and R_{spec} the specific resistance of the wire [Ω/m], ℓ its length [m] and P the dissipated electric energy [W]. Table 13 displays the results of calculations regarding the needed current, resistance, length and dissipated power for heating wire of different diameter and material. The voltage applied over the wire is also varied. One can see that a larger diameter requires a longer wire and dissipates more energy. When the applied voltage is decreased, also the length of the wire and through that the energy requirement is reduced. From the table can be concluded that, when only the material is taken into account, Isochrom 60 is more effective as heating coil compared to Isotan. But one can also see that a rather large current of almost 5 ampere is needed for an Isochom wire of 0.50 mm diameter. A convenient wire length will be between 5 and 10 cm. With 2 volt, a length of 7 cm is calculated. Power dissipation is than approximately 10 Watt.

Table 13: Characteristics of and calculations on wires which can be used as heating coil

Material:	**Isotan**					
Diameter [mm]	R_{spec} $[\Omega \cdot m^{-1}]$	i (600°C) $[A]$	V $[V]$	R [Ω]	ℓ [cm]	P $[W]$
0.08	100	0.76	12	15.8	16	9.1
0.08	100	0.76	1	1.3	1.3	0.8
0.50	2.5	7.39	12	1.62	65	88.5
0.50	2.5	7.39	**1**	0.14	5	7.7

Material:	Isachrom 60					
0.05	565	0.28	12	42.9	8	3.4
0.10	141	0.62	12	19.6	14	7.5
0.25	22.6	1.97	12	6.1	27	23.7
0.50	5.65	4.72	12	2.5	44	58.1
0.50	5.65	4.72	**5**	1.06	19	23.6
0.50	5.65	4.72	**2**	0.42	7	9.4
0.50	5.65	4.72	**1**	0.21	4	4.7

The second method is a better method, at least with regard to energy consumption. With an electronic circuit, sparks are created, which can ignite the biogas. In principle, the electronic concept is rather simple and widely used in petrol and gas engines. Figure 17 displays the electronic principle of a car bobbin. A voltage of 12 VDC is applied over a coil with a few copper windings (L_p) and a capacitor, which is loaded in this way. Every time the switch (s) is opened, the voltage collapses very rapidly and as a result of induction a high voltage is generated over the secondary coil (L_s), which consists of a lot of windings. This voltage is so high that a spark can jump the gap between two points (Wikipedia 2012a).

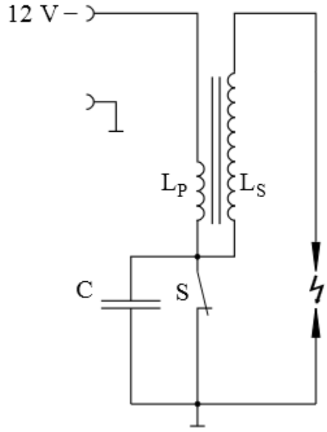


Figure 17: Scheme of the electronic principle of a car bobbin (Wikipedia 2012b)

A miniature version of this car bobbin was found in an electronic lighter for household purpose. This lighter contains a small electronic circuit, functioning on a 1.5 V battery and delivering multiple sparks per second of about half a centimetre length. This implies that the generated voltage is about 6000 V (Ridders 2012). Energy use is in the range of 0.3 Watts, at a spark frequency of approximately 20 Hz. When the electrodes are well positioned in the gas stream, most times the gas will be ignited within five seconds of sparking, but the total sparking time is dependent on how quick the temperature sensor reaches its switching temperature, and the frequency of gas occurrence. The electronic circuit can be used directly by reducing the car battery voltage to 1.5 Volt. It can also be replicated by obtaining the separate electronic components. Finally, it might be interesting to modify the circuit, to obtain a slightly stronger spark (Ridders 2012). One challenge is to mount the wires and spark ends in such a way that sparks occur at the right place instead of jumping to another closer low voltage spot, while the wires are not damaged by the flame. Figure 18 contains the electronic scheme of the spark generator. In the oscillator/load circuit, the 1.5 VDC is firstly converted to alternating current and the voltage is increased to 100 V with the transformer. The capacitor C1 is charged until diode D3 lets through a reverse current at a reverse voltage of about 70V. At that moment, the capacitor is unloaded over the thyristor D4 and the transformer T2, resulting in a voltage peak in the secondary coil of the transformer (Ridders 2012).

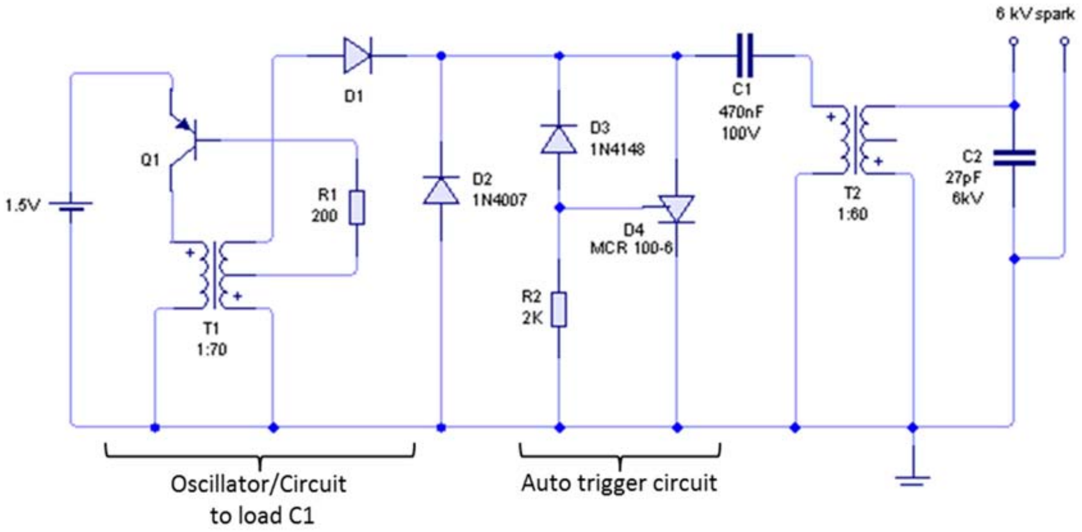


Figure 18: Scheme of the 1.5 Volt spark generating circuit (Ridders 2012)

Flame detection

As a result from ignition, combustion of the biogas will be initiated. As soon and as long as the gas is burning, ignition is not necessary anymore. For reasons of durability and energy consumption, it is best to switch of the ignition as soon as possible. A device is needed which can quickly recognise a flame. In advanced systems, often an UV or IR scanner is used for that, which is an electronic device detecting the radiation resulting from the flame. Disadvantage of such scanners is their sensitivity to fouling of the lenses by particles and sooth from the flame. Besides that, an electronic system will be needed, comparable to that of the gas sensor, resulting in increased complexity and energy use. Another option is to detect the heat resulting from the flame with a temperature sensing element. Numerous devices are available, mostly meant to measure and display a range of temperatures. But also a component was found which functions as a switch. When the temperature of the component rises above a trigger value, the switch opens and when temperature drops again under that value, the switch closes. These low cost switches are called klixon or clixon and are available for several switching temperatures, see figure 19 for a picture. Klixons were obtained with a switching temperature of 70 and 100˚C (EOO 2012). The klixon should be mounted on the mixing tube, close to the flame. Tuning is needed in order to obtain a short reaction time, but the switch should not become too hot.

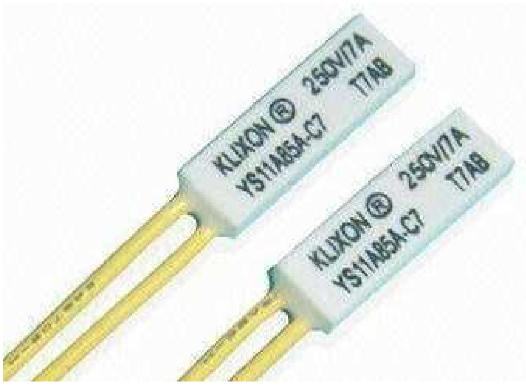


Figure 19: Klixon/clixon temperature switches

Electronic circuit

To connect and control the described sensors and actuators, an electronic circuit is needed. In the best case with regard to simplicity and energy use, gas detection is done with the microswitch, ignition with spark ignition and flame detection with a klixon temperature switch. Power is delivered by a car battery, therefore an extra resistance of 70 Ohm is needed to apply 1.5 V over the ignition. In this case, the electronic circuit can be schematised as shown in figure 20. The total energy dissipation in this case is in the range of 1.8 Watt. This could be reduced by either using a 1.5V battery or a DC/DC voltage converter in combination with a resistance, which can convert the voltage from 12V to 1.5V with more efficiency (Conrad 2012).

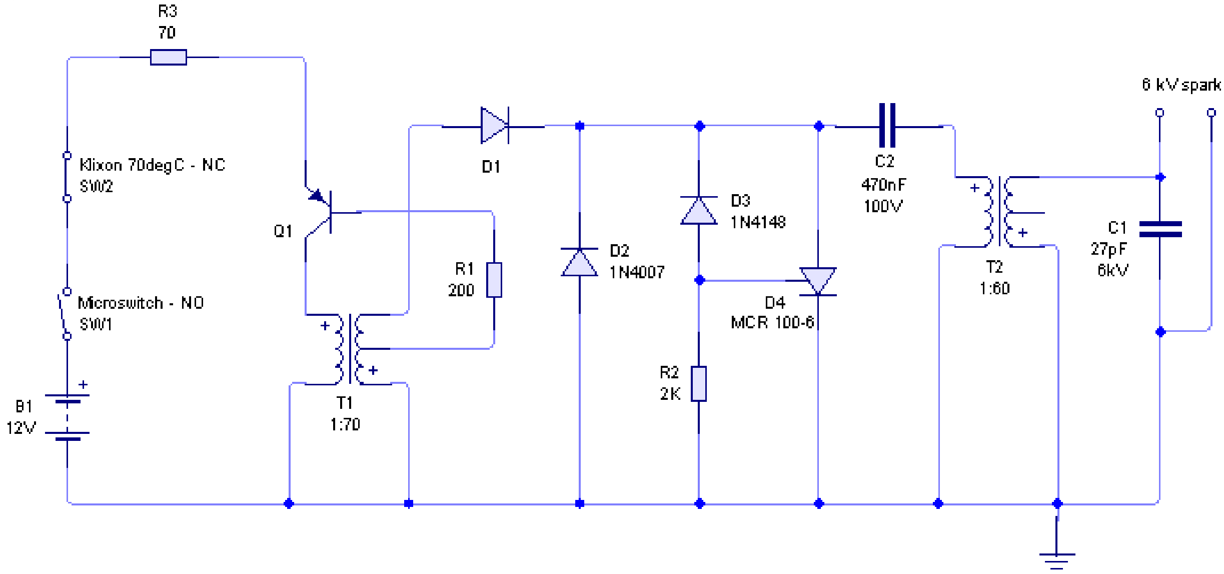


Figure 20: Scheme of the electronic setup for the combination of microswitch, klixon and spark ignition

Testing

As mentioned before, theoretical study was interspersed with testing, in order to be able to relate theory to the real world and to check the functioning of components. For tests related to gas flows, a setup was built with which a (bio)gas mixture could be prepared and provided to the components of the flaring system. The setup was equipped with a gas pressure monitor and a gas flow meter and different equipment which have to be supplied with gas, can be coupled to it.

Biogas is a gas consisting of several gases, but mainly methane and carbon dioxide. No actual biogas was available for testing. Therefore a gas mixture resembling biogas had to be composed by mixing natural gas and carbon dioxide. In the Netherlands, natural gas is available from the gas grid while a pressurised 2 litre CO_2 cylinder was bought to supply the carbon dioxide. To obtain a biogas with known methane content, it is necessary to know the composition of the natural gas. The gas from the Dutch grid is a mixture of gasses obtained from different gas wells. The composition of these gasses varies per source, but is blended in such a way that the gas reaching the end users is of almost constant quality. This quality is based on the gas obtained from the Slochteren gas field, which is the largest and most important field of the Netherlands. After condensation and carbon dioxide removal, the gas contains 86% v/v methane and 14% v/v nitrogen. With this methane content, the heating value is about 35 MJ/Nm^3 (Anonymous 2012). In the test setup, biogas can be simulated by mixing natural gas with carbon dioxide. The ratio of natural gas and carbon dioxides to be mixed to reach a certain biogas quality, can be calculated with equation 25.

$$\frac{V_{NatGas} \cdot C_{CH_4\,NatGas}}{C_{CH_4 Biogas}} - V_{NatGas} = V_{CO_2} \qquad L \qquad \text{Equation 25}$$

With V the gas volume $[L]$ of either natural gas or carbon dioxide and C_{CH_4} the methane content $[\%v/v]$ of either the natural gas or the resulting biogas. In table 14, the mixing ratios of natural gas and pure carbon dioxide for obtaining four biogas qualities are depicted.

Table 14: Mixing ratio of natural gas and pure carbon dioxide to obtain a biogas with a certain methane content

$C_{CH_4Biogas}$	V_{NatGas} $[m^3]$	V_{CO_2} $[m^3]$
40 %	1	1.15
50 %	1	0.72
60 %	1	0.43
70 %	1	0.23

For testing and development of the electronics, most important equipment were a variac, which is an adjustable transformer to supply power in the range of 1 to 240 Volt, a car battery of 12 Volt, a multimeter, a temperature sensor, and a breadboard, which is a board on which electronic circuits can be built and tested without soldering.

4. Results

In this fourth chapter the results will be presented. The chapter consists of three sections. In the first section, some results from the model developed to predict biogas surpluses are presented. In the second section, the actual design will be presented and explained on the basis of 3d-drawings. While in the third section the costs of such a design are estimated.

4.1 Biogas surplus modelling

In chapter 3.2, the development of a model for prediction of biogas surpluses was described. In table 8, the combination of parameters for eight scenarios were shown. The results of the analysis of the first four will be discussed, therefore these four scenarios are displayed in table 15.

Table 15: Repetition of the first four model scenarios

Scenario	1	2	3	4
Volume anaerobic digester [m^3]	25	25	25	25
Biogas production rate [m^3/day]	5	10	5	5
Maximum pressure in the bag [mbar]	20	20	20	20
Biogas consumption by engine [m^3/h]	0.8	0.8	1.0	1.0
Working hours engine [h/day]	5	5	5	3
Number of days engine is used [day/week]	5	5	5	5

Some of the results of simulating the scenarios 1 to 4 for two weeks (336 hours), can be seen in figure 21, figure 22 and table 16. Figure 21 shows all graphs generated by the model, which are the hourly biogas production, the biogas consumption by the dual fuel engine, the amount of gas stored in the bag digester and the occurrence of biogas surpluses. The simulation is started with the gas storage being half full. One can see after about 100 hours, regular venting will start. Venting then takes place during the weekend, when no biogas is consumed, and also a few hours per day. Daily venting in this situation starts in the early morning, around 3 o'clock, and stops when consumption is started again.

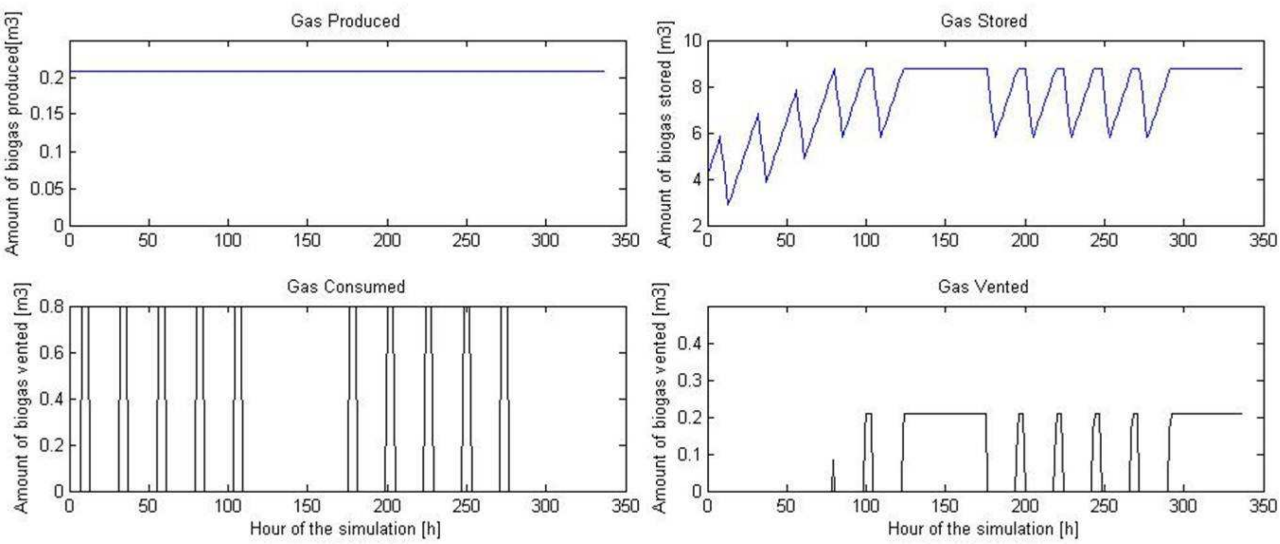


Figure 21: Hourly biogas production, consumption, amount of biogas in storage and vented for scenario 1

Figure 22 shows the prediction of the amount of gas stored and vented in scenarios 2 and 3. It is interesting to compare these graphs. One can see that in scenario 2 venting occurs much more often than in both scenario 1 and 3. For scenario 3, venting only occurs during the weekend. One can say that in this scenario there is a very good balance between production and consumption.

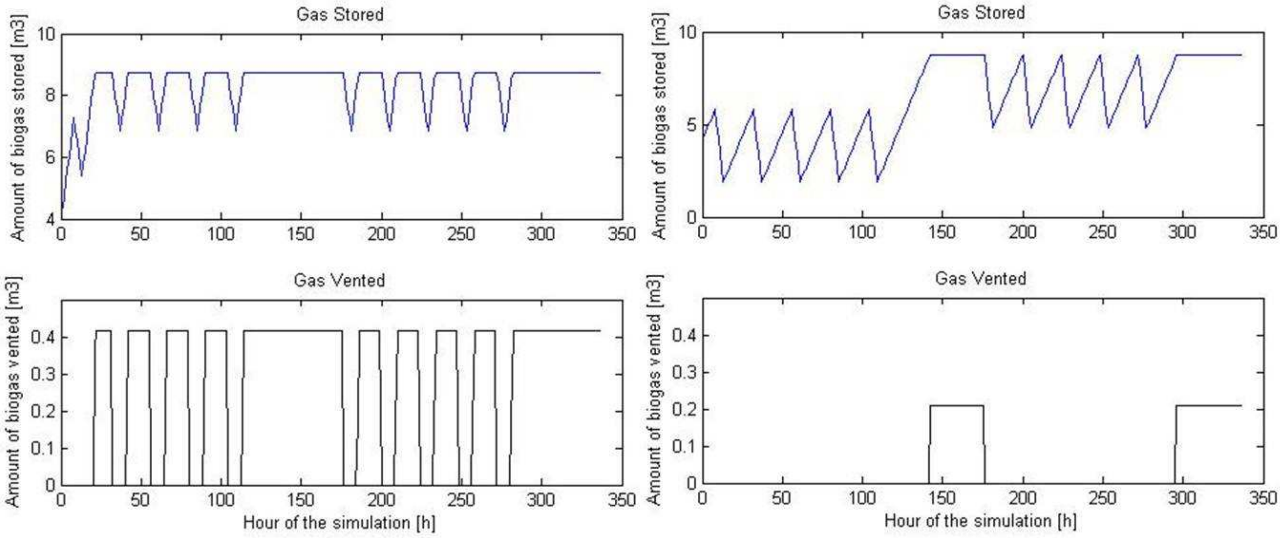


Figure 22: Hourly prediction of the amount of biogas stored and vented for scenario 2 (left) and scenario 3 (right)

For every simulation, also the absolute biogas production, consumption and venting, and the venting as percentage of production are calculated.
One could say that when biogas consumption and production are relatively well balanced, venting may occur for a short time every day, just before consumption will start again, and in periods when little consumption takes place for a longer time. The gas flow rate is equal to the production rate, although when maximum pressure is just reached, the flow rate can be expected to be a bit irregular. One can see that in the situation with lowest biogas venting, 15.6 m^3 biogas is vented, which is equal to about 400 m^3 per year. Assuming a methane content of 60% v/v and a methane mass density of 0.68 kg/m^3, about 165 kg of methane is vented yearly.

Table 16: Further results of the analysis of scenarios 1 to 4. All values are for a period of two weeks.

Scenario	1	2	3	4
Total amount of biogas produced [m^3]	65.6	135.6	65.6	65.6
Total amount of biogas consumed [m^3]	40.0	40.0	50.0	30.0
Total amount of biogas vented [m^3]	25.6	95.6	15.6	15.6
Vented as percentage of production [%]	39.0	70.5	23.8	54.3

4.2 Design

Based on the equations mentioned in the previous chapter, the dimensions of the components of the flaring system can be determined. Table 17 displays the dimensions of the orifice, throat, burner port and enclosure, for two different biogas flow rates, namely 5 and 10 m^3 per day and two pressures before the orifice, namely 5 and 15 mbar. In the table, two diameters are displayed for the enclosure, indicated with $d_{enclosure}$ and $d_{e\ eff}$, were the latter is the enclosure calculated with the method of TACB. The first is the actual diameter of the enclosure pipe, chosen to be approximately 4 cm larger than the diameter of the burner port.

Table 17: Possible dimensioning of the flare: diameter of orifice, throat, flame port and enclosure, related to gas flow rate and pressure

Q [m^3/day]	P [mbar]	$d_{orifice}$ [cm]	d_{throat} [cm]	d_{port} [cm]	$d_{enclosure}$ [cm]	$d_{e\ eff}$ [cm]
5	5	0.20	1.06	6.1	10	2.5
5	15	0.15	0.80	6.1	10	2.5
5	15	2x 0.10	0.75	6.1	10	2.5
10	5	3x 0.15	2.60	8.6	12.5	3.5
10	15	0.20	1.06	8.6	12.5	3.5

Based on design requirements, calculations and testing, components were chosen with which a low-cost but robust flaring system could be build. In SketchUp a complete design was drawn for a flare, designed to combust biogas flows of up to 5 m^3 per day. This design will be presented and explained by means of the drawings. With regard to all pipes, dimensioning is according to DIN2448 and NEN2323. So when for example, the diameter of the enclosure was calculated, no pipe with exactly that diameter was available, but a pipe was chosen with a diameter close to it.
As tubing for gas transport, garden hose with an inner diameter of a ½ inch was chosen. Garden hose is flexible in use and easy to connect. For gas transport over these relatively short distances, the chosen diameter is large enough to prevent disturbing influence on gas flow and pressure. Figure 23 displays the pressure monitor and spring loaded gas valve plus the tubing for gas transport and measurements. The measurement tube can also be used to increase or decrease the water column.

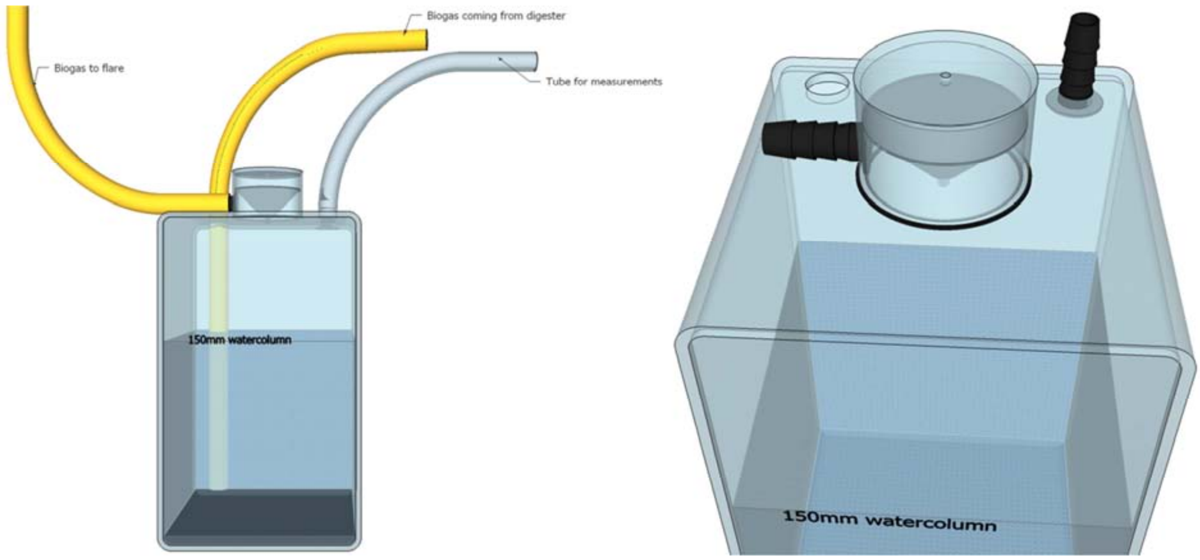


Figure 23: Drawing of pressure monitoring, gas valve and tubing

In the drawing, a water column of 15 cm is depicted, corresponding to a maximum system pressure of 15 mbar. Tubes are connected with hose connectors, which need to be sealed to guarantee gas tightness of the system. More details of the spring loaded gas valve are displayed in figure 24. The spring and microswitch apply a pressure on a rubber sheet and in this way close the valve. When gas pressure exceeds the applied counter pressure, the valve is pushed open and gas can flow through the water and the valve, via the tube connector and tube to the flare. The rubber sheet seals the valve, so that the spring can move freely up and down, without need for a seal. As visible, the microswitch is fixed securely, so that a reliable signal can be obtained. The microswitch has three contact points, of which the top one is the ground. With the other two contact points, the switch can either be used as normally closed or as normally open. For current situation, ‘normally open’ should be used. All contact points should be protected from influences of the environment by proper isolation with tape or shrink wrap.

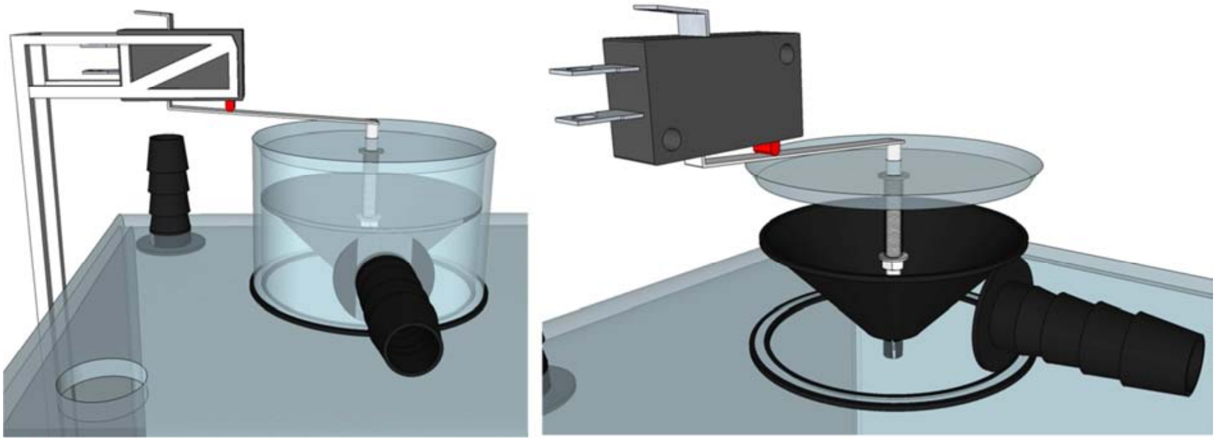


Figure 24: Spring loaded gas valve with microswitch and details of the spring loaded valve

The spring loaded valve is connected to the actual flare. As basis of the flare, a device normally used for the filling and emptying of central heating systems is implemented, shown in figure 25. Advantageous of this component are the valve, which makes it possible to stop gas flow manually, and the closing cap, which is replaceable and in which the orifice can be drilled. Around the end cap, a disc is placed, in which the air inlet holes are drilled and which at the same time functions as the bottom of the mixing tube. The diameter of the orifice is 2 mm and the three air holes are 6 mm each, which should result in a primary air entrainment of 4 m^3 per m^3. In the drawing, the disc is made of steel, but in practice it can be more convenient to make it out of plastic, because this simplifies fitting the orifice cap in. The disc is not influenced by the flame, so plastic is well possible. Figure 25 also shows how the orifice and the disc close the bottom opening of the mixing tube.

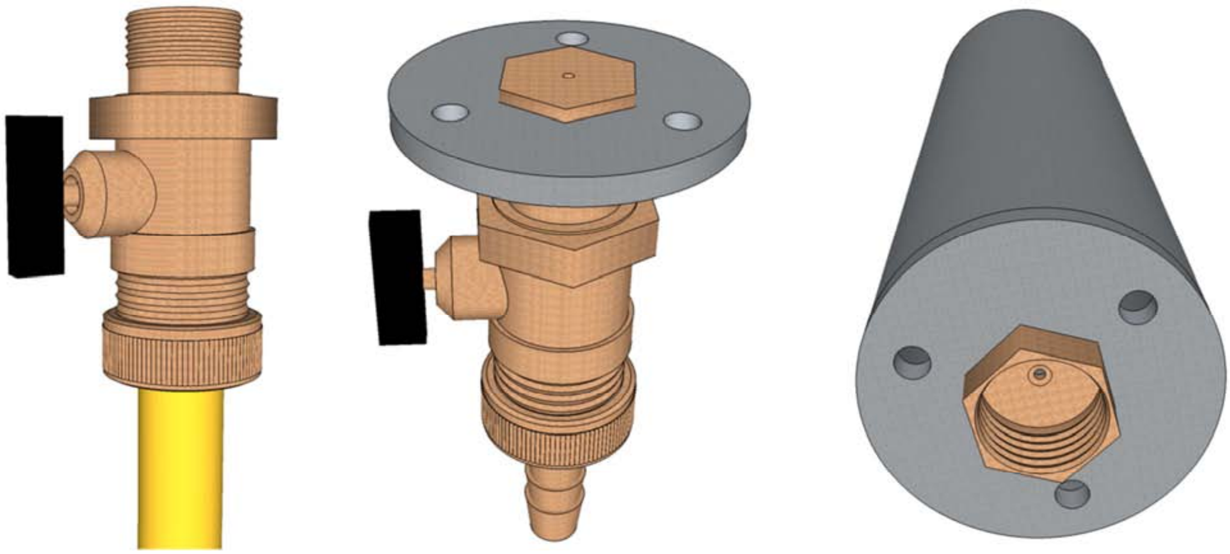


Figure 25: Manual gas valve, orifice and primary air holes (left) and cap with injector orifice, air holes and mixing tube (right)

The mixing tube is a steel tube with an outer diameter of 60.3 mm and an inner diameter of 54.5 mm, in which biogas and air become completely mixed to form a combustible gas mixture. As shown in figure 26, the height of the mixing tube is 20 cm. The top of the mixing tube forms the burner head, where a wire mesh separates the unburned gases in the mixing tube from the flame above it. The wire mesh is clamped over the top of the mixing tube with a small piece of pipe having a slightly larger inner diameter than the outer diameter of the mixing tube, namely 60.4 mm. Outer diameter is 63.4 mm. At a biogas flow rate of 5 m^3 per day, a stable flame of approximately 20 cm will be present at the burner head.

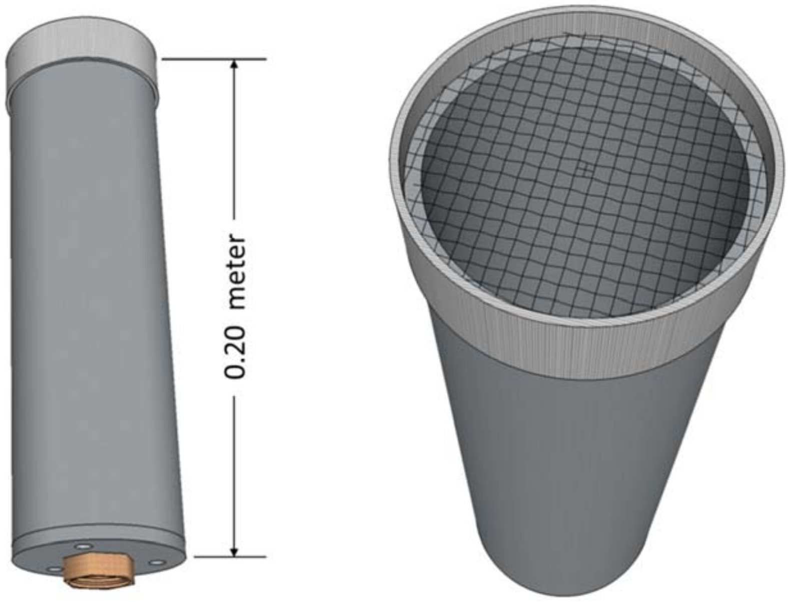


Figure 26: Side and top view of the mixing tube and burner head

In the proximity of the burner head, also ignition and flame detection takes place. Ignition is performed with a spark, generated with a high voltage over two electrodes. The two electrodes are clearly visible in figure 27. The positive electrode should be properly isolated, so that no sparks will jump to for example the mixing tube at the wrong place. The klixon temperature switch, switching at 70°C, is also mounted close to the burner head. Cables are led through a small diameter pipe, which is fixed to the mixing tube.

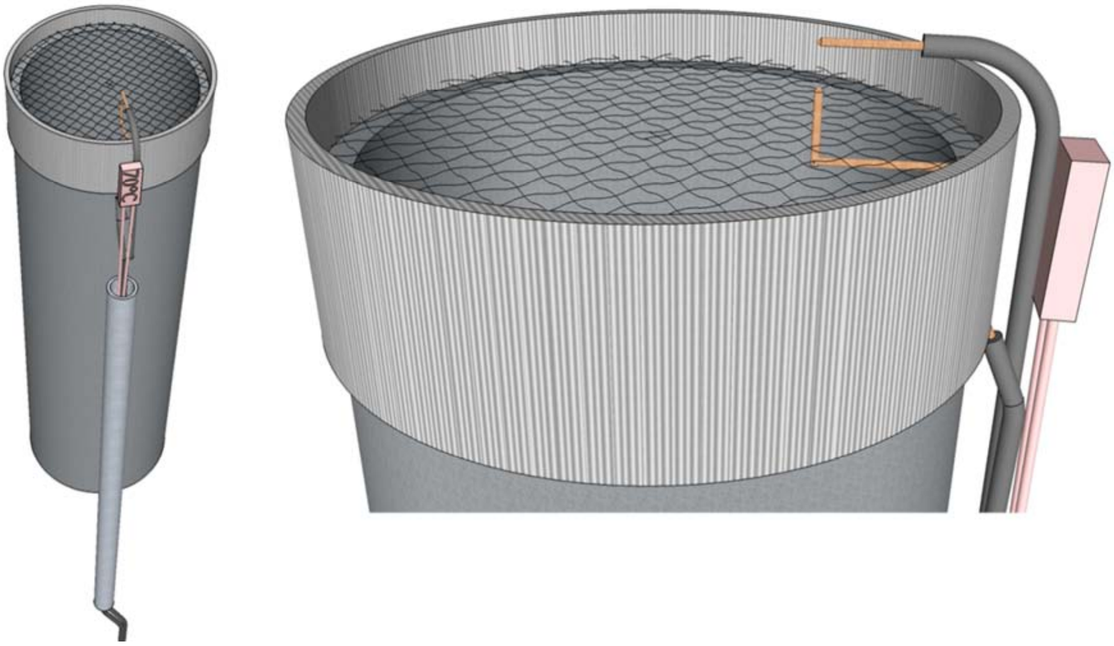


Figure 27: Fixation of ignition system, temperature switch and cables to mixing tube and burner head

The mixing tube is enclosed by a second steel pipe. Its diameter is chosen in such a way that space is left besides the mixing tube for the electronics. Also secondary air needs to be sucked in through this space. The outer diameter of the enclosure is chosen to be 101.6 mm, resulting in an inner diameter of 93.8 mm, leaving approximately 17 mm of space around the mixing tube. The height of the enclosure is 75 cm. Figure 28 depicts the enclosure, with the enclosed components visible in the cross section. A hood with a conical shape is place on top of the enclosure. As mentioned in chapter 4, the hood determines the effective exit area for the flue gases. From this study it did not become completely clear what this area needs to be in order to be able to maintain a flame under all weather conditions. Further tests need to sort this out. In the current design, a fixed hood is placed on top of the enclosure, resulting in an effective diameter of approximately 7 cm.

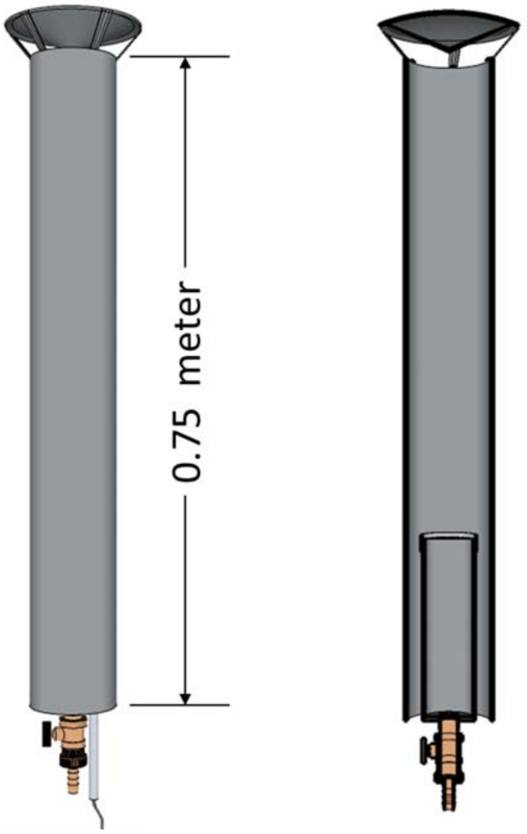


Figure 28: Side view and cross section of the flare enclosure and hood

The flare needs to be properly supported for safe and correct functioning. Three steel u-profiles have to be anchored in the ground, best practice is to anchor them in concrete. The enclosure and mixing tube, as heaviest components, are mounted to the u-profiles with bolts, as shown in figure 29.

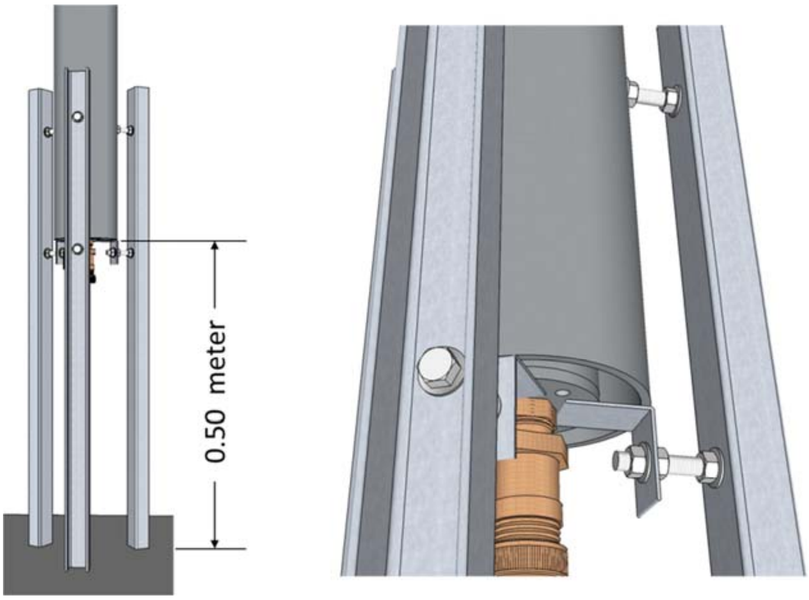


Figure 29: Flare support construction

The construction lifts the flare 50 cm from the ground, so that the other components can be placed underneath, as can be seen in figure 30. This drawing shows the complete design of the flaring system, including the pressure monitor and the box for the electronic circuit. Total height of the flare, from floor to the top of the hood, is approximately 131 cm.

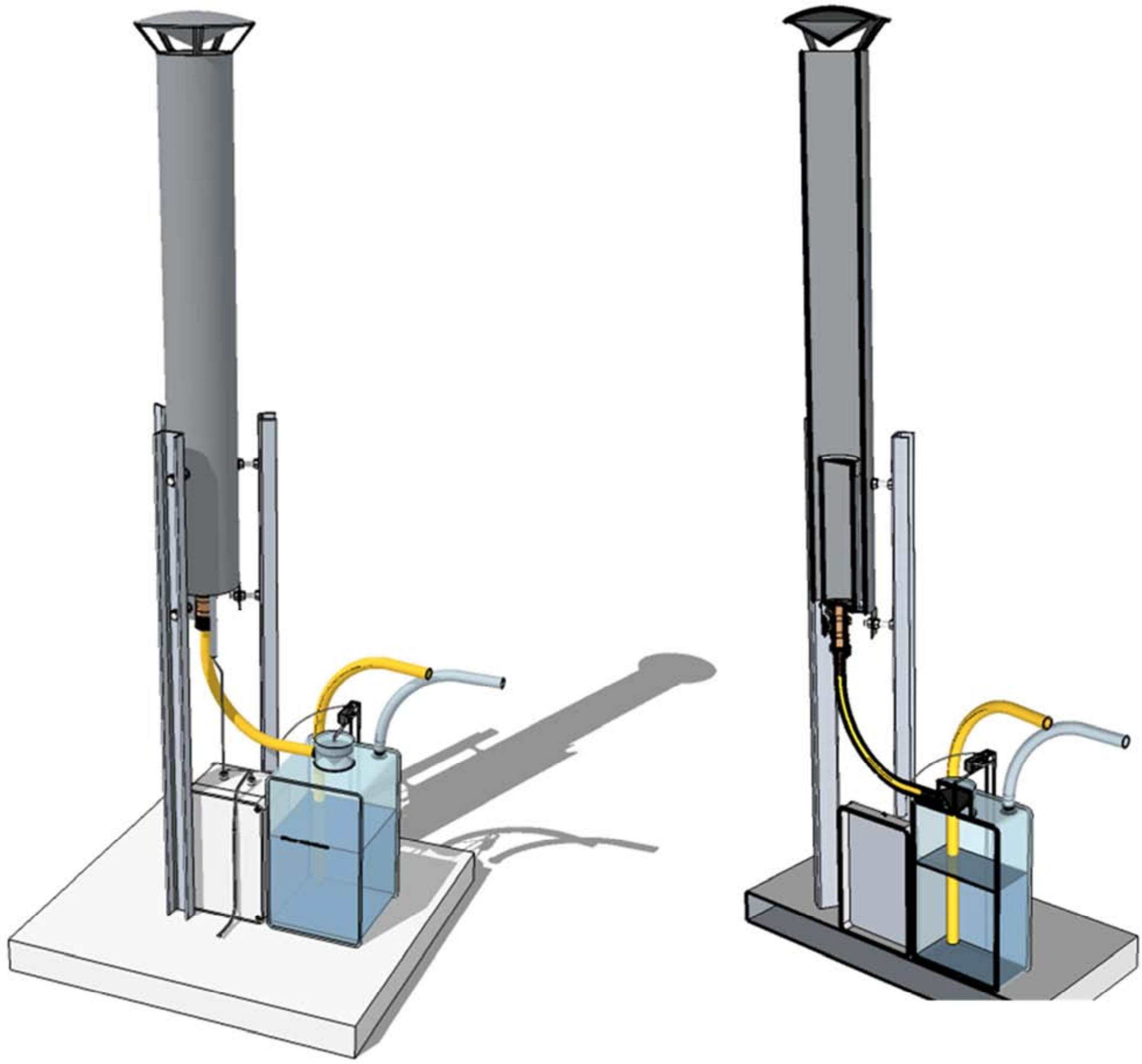


Figure 30: Overview and cross section of the complete flaring system

4.2 Calculation of costs

Goal of this study is to design a flaring system which is also low cost. In the design process which led to the design as presented in the previous section, the component costs were therefore taken into account and minimised. Table 18 presents the costs of the components needed to build the flaring system, including a short description and a reference. When no reference is given, the price of the component is known from its purchase in local shops. Three things need to be taken into account. Firstly, the prices mentioned are consumer prices for the Netherlands, including VAT. For a company, lower prices could be applicable or negotiable. Besides that, prices in other (developing) countries differ from these prices. Secondly, although most components are commonly available, some components, like the temperature switch, might be difficult to obtain. Finally, prices for new products are mentioned, while some components can be made from used or scrap materials, like for example the steel piping.

Table 18: Prices of the flaring system components

Component	Reference	Specific price	Total price [€]
Tubing	(Deltaline 2012)	1.96 €/m	**7.84**
Description	Dependent on system setup, approximately 4 m of garden hose is needed to connect the digester to the flare, via the gas valve. Hose of the brand Tricoflex with ½ inch inner diameter is assumed.		
Tube connectors		3.69 € pp	**7.38**
Description	Two plastic or brass tube connectors are needed to connect tubes to the pressure monitor and gas valve. Brass connectors are more expensive, but can be fixed more secure.		
Plastic boxes		3.99 € pp	**7.98**
Description	Two plastic boxes are needed, one transparent, airtight box for the pressure monitor and one smaller box for the electronics.		
Plastic cap		*Estimation*	**0.20**
Description	The gas valve is made of a plastic cap with a diameter of approximately 6 cm, fixed on the plastic box.		
Spring, threaded rod, nuts and rings			**0.59**
Description	For the spring loaded valve, a threaded rod, a spring, 4 nuts and 4 rings of size M3 are used.		
Rubber sheet		*Estimation*	**2.00**
Description	The rubber sheet is glued in the plastic cap. A piece with a diameter of maximum 10 cm is needed. This can be rubber normally used for inner tire repair.		
Sealant		1.98 € per tube	**1.98**
Description	To make several parts gas tight, a silicon sealant can be used.		
Shrink wrap	(Conrad 2012)	Set	**3.59**
Description	Shrink wrap is used to isolate and protect all electronic connections.		
Microswitch	(Conrad 2012)		**2.28**
Description	A microswitch with a trigger pressure of 30 gram is used		
Microswitch fixation		*Estimation*	**1.00**
Description	The microswitch needs to be fixed securely to the plastic box		
U-profiles	(IJzershop 2012)	23.88 € per 2 meter	**26.87**
Description	Three vertically placed U-profiles keep the flare in place. Profiles with dimensions 30x60x60x3 mm will be strong enough. Each profile is 0.75 m high.		
Bolts, nuts and rings	(IJzershop 2012)		**5.19**
Description	Three bolts, 9 nuts and 9 rings of size M8 are needed to attach the actual flare to its supporting construction.		
Steel angle brackets	(IJzershop 2012)	0.68 € pp	**2.04**
Description	Three angle brackets are needed to couple the pipes to the profiles.		
Wiring		0.71 € per 1 m	**1.78**
Description	2.5 m cable with 2x0.75 mm^2 wire can connect the sensors and actuators.		
Small pipe	(IJzershop 2012)	7.10 € per 2 m	**1.78**
Description	A small pipe with a maximum diameter of 1.5 cm is needed to guide the electronic wires from the electronics box to the burner head. The material is not too important. Mentioned price is for steel. Length is 50 cm.		
Klixon switch	(EOO 2012)		**3.89**

Description	A klixon switch, switching at 70˚C is used for flame detection.		
Spark ignition	(Conrad 2012)		**4.29**
Description	The spark ignition is obtained from an electronic gas lighter, which costs 4.29 € at “Blokker”. The electronic circuit can be copied and its separate components cost approximately 2.25 €.		
Hot wire ignition	(Conrad 2012)	3.59 € per 10m	**0.36**
Description	Approximately 10 cm of Isachrom 60 wire can be used for hot wire ignition. Hot wire ignition was tested, but not included in the design.		
Gas sensor	(Conrad 2012)		**14.37**
Description	The Figaro TGS 813 gas sensor detects combustible gases. The gas sensor was considered, but not included in the design.		
Brass manual valve + closing cap			**8.68**
Description	For the manual valve and closing cap, a component normally used in central heating systems can be used. It exists of a tube connector, manual valve and closing cap.		
Air inlet ring		*Estimation*	**0.50**
Description	A plastic or steel ring with a diameter of 60 mm and minimally 3mm thick can be used as air inlet ring. Plastic is most easy to fix and drill. A scrap piece of steel or plastic can be used		
Steel pipe (mixing tube)	(IJzershop 2012)	24.13 € per 2 m	**2.41**
Description	A steel tube with dimensions of 60.3x2.9x200mm is used as mixing tube.		
Steel pipe (burner head)	(IJzershop 2012)	24.13 € per 2 m	**0.60**
Description	Approx. 5 cm of tube with dimensions 63.4x2.9 mm is used to form the burner head and clamp the wire mesh over the mixing tube.		
Steel pipe (enclosure)	(IJzershop 2012)	51.12 € per 2 m	**19.17**
Description	The enclosure has a height of 75 cm with dimensions 101.6x3.6 mm.		
Wire mesh			**1.99**
Description	A wire mesh with small holes is needed, but the wire must be sturdy in order to withstand the high temperatures. A wire mesh was obtained from “Blokker” for a price of 1.99, normally used as a flame divider for cooking purposes, which functioned well.		
Hood	(IJzershop 2012)	22.93 € per plate	**2.29**
Description	The hood can be made from thin steel plate which can be cut and hammered in the right shape. A thickness of 2 mm will be strong enough, but still workable. A diameter of approximately 15 cm is necessary.		

From table 18 can be calculated that the sum of the material costs is 116.32 €, when the microswitch is used for gas detection and ignition is performed with spark ignition. The costs for an anaerobic digestion system with comparable capacity are approximately 2500 €. Thus the costs for the flaring system are about 5% of that. It is difficult to estimate at this stage what will be the lifetime of all components. FACT assumes a 15 year lifetime for an anaerobic bag digester system (personal information). This is also a reasonable assumption for the flaring system. But especially the electronic components, like the klixon switch and the spark ignition system, the rubber of the gas valve and the wire mesh might be sensitive to break down, due to the high temperatures or wear out. These components probably need more regular replacement. The other components, which account for most of the material costs, are quite sturdy. Besides these material costs, also installation and maintenance costs need to be taken into account when assessing the costs of this system. These costs are also difficult to estimate at this moment. Construction of a complete system and durability tests should provide more insight. Energy consumption is negligible when no gas is vented and very small during ignition, namely approximately 0.3 Watt. Costs for energy consumption are therefore negligible as well.

For a flaring system with a larger capacity, material costs will increase. Within a certain capacity range, a number of components need to be changed with increased capacity, namely the steel pipes of mixing tube, burner head and enclosure, the hood, and possibly the construction elements.

5. Discussion

Designing the system was started with formulation of requirements, both for the complete system and the separate components, therefore the fulfilment of these requirements will firstly be discussed. After that the other methods and results will be discussed in this chapter, in order to be able to draw conclusions.

5.1 Fulfilment of requirements

In chapter 4, table 10, requirements were set up for all essential flare components. The design fulfils requirements set with regard to tubing and connections, the pressure monitor and the burner head. But discussion is needed with respect to fulfilment of a number of other requirements.

Functioning of the spring loaded gas valve

A low cost and (electronically) simple solution was chosen to function as gas valve and gas sensor. This component was not tested and doubts remain with respect to whether or not this idea will indeed result in reliable functioning. Both the spring and the microswitch apply pressure on a rubber sheet, in order to close a hole as long as pressure underneath is smaller than the sum of the pressure of spring and switch. The applied pressure should ideally be enough to keep the hole closed when no gas is flowing, but small enough to open up at gas pressures of between 1 and 3 mbar. The valve should also open enough to activate the switch. This requires accurate tuning of spring and microswitch. Rubber is a product sensitive to temperature, dust and drying out. Therefore it might be difficult to make a valve which works maintenance free for a long period.

Endurance of flame arrestor

The wire mesh, which functions as a flame arrestor will become rather hot when the flare is functioning. Its temperature may rise to approximately 600°C. In time, this high temperatures might result in damage and crumbling of the wire mesh. When the wire mesh is damaged too much, it loses its functionality. Both the injector orifice and the pressure monitor will still function as a flame arrestor, so there is no risk for flashback, but probably no stable flame can be established anymore. A wire mesh consisting of thin wires will be damaged more quickly, so a thicker wire mesh should be used. But the relation between thickness and durability should be determined.

Temperature switch placement

In current design, flame detection is performed with a temperature switch, switching at 70°C. The switch is best mounted on the mixing tube, close to the burner head, but the exact position is not yet determined. In positioning the sensor, there is a trade-off between quick reaction to temperature change due to combustion of biogas and the tolerance of the sensor to high temperatures. The switching temperature of 70°C might be not the best choice in this trade-off.

Reliability of the electronics

The electronic system has an important role in the flaring system. When the electronic system fails, no combustion will take place and the biogas will simply be vented again. Currently there is no automatic monitoring of the functioning of the electronic system. This reduced reliability of the complete system.

Diameter enclosure

The diameter of the enclosure is currently taken to be slightly larger than the diameter of the mixing tube, so that space is available for ignition and temperature switch and so that secondary air can be sucked in. The surface area of the bottom and the top of the enclosure influences the amount of secondary air provided to the flame and the flue gas velocity, which in turn influences the flame temperature and the flue gas exit velocity. Best is to have flame temperature of around 900°C, and an exit velocity high enough to keep the flame going in difficult weather conditions. No solution was yet found to solve this problem. Besides that it was also difficult to find clear information about the effect of the length of the enclosure on the quality of combustion.

Complete system requirements

Table 9 in chapter 4, displays the requirements set up for the complete flaring system. Focus in this study has mainly been on the requirement-groups performance and costs.
Requirements in the group reliability are taken into account in the design process, but it was impossible to assess them properly, because no prototype was built and no durability tests could be performed. This means that although separate components were tested satisfactory, it is unknown if the combination indeed results in a working system. Main concerns are for the electronic sensors and actuators; reliable gas detection and ignition.
Also not all requirements in the group safety are fulfilled. Mainly the safety for humans and animals is not really taken into account. Although the flame itself will stay within the enclosure, components of the flaring system will become hot. The construction does not prevent humans or animals to approach or touch the system. It is also not indicated whether or not the flare is functioning.

5.2 Flare design

This study was focused on development of a flare for small and medium scale anaerobic digesters. A design was presented for a gas flow of 5 m^3 per day. Separate components were tested successfully for gas flows up to 10 m^3 per day. Theoretically, a flare for larger gas flows can be developed, using the same equations and methods. But it is uncertain for what range of gas flows the equations are valid and can result in a working flaring system. At some point, certain components will not be able to fulfil their function properly anymore. The current spark ignition for example, might deliver to little energy to start combustion at larger gas flow rates. Even more limiting might be the gas valve, it could be more effective to use the gas sensor at larger gas flow rates.

Construction and maintenance

When the flaring system is in use, regular inspection and maintenance will be needed. Besides that, parts need to be replaced when they break down. Therefore it is necessary that the system and separate parts are accessible. In the current design, this factor is not yet considered enough. The way the mixing tube and the enclosure are mounted to the supporting construction can hinder inspection, maintenance and substitution of parts.

Costs

Material costs of the flaring system were determined, based on the new price of the separate components at the Dutch price level. Although costs under Malian conditions were not determined, it is probably possible to built such a flaring system for a lower price. Mainly because it is possible to utilize used materials for certain components. Costs for maintenance were not determined. The parts which will probably need regular replacement are listed as being not too expensive, but might be less easy to obtain and therefore more expensive under Malian conditions. Labour costs for maintenance are unknown, because it is unknown how often maintenance will be needed and how much time this will take. That is mainly dependent on the reliability of the components.

6. Conclusion

Based on the methods used and the results obtained, an answer can be given to the main research question as proposed in chapter 1, bearing the remarks made in previous chapter in mind. The main research question was posed as following:

Is it possible to design a robust and low-cost flaring system for small and medium scale biogas installations in rural Mali?

Methods were found with which a flaring system for small and medium scale biogas installations can be designed. A complete design was drawn, dimensioned for a biogas flow rate of 5 m^3 per day. Main components were tested for gas flows up to 10 m^3 per day and fulfilled their function as expected. The drawn design was not built and tested, so no conclusion can be drawn with regard to the robustness of the system, although most components are expected to be able to stand Malian conditions, expecting a lifetime equal to that of the anaerobic digestion system.

Assuming Dutch prices, material costs for the drawn flaring system add up to 116.32 €, which is equal to approximately 5% of the costs of an anaerobic bag digester system. In practice, this price could be decreased through building with used materials. The electronic sensors and actuators, the wire mesh and the rubbers of the valve seem most sensitive to breakdown and might need regular replacement. Energy consumption of the system is very low, which will result in low energy costs.

7. Recommendations

This study forms a basis for implementation of flaring systems by FACT foundation. At the same time, the discussion in chapter 6 revealed the limitations of this study. In this chapter, recommendations are done for further research on the topic and improvement of the design.

Prototyping
The first step towards a introducible flaring system should be the assembly of the separate components into a flare prototype. This system should then be tested and tuned for optimal functioning. Also duration tests are needed, to examine whether the flaring system can perform under more difficult conditions, like strong winds and rain. And also to determine if the sensors and actuators can function reliable for a long period. Part of these duration tests should be the determining of the best area of the stack exit, by varying the height of the hood, as depicted in figure 14, chapter 4, and a good flame temperature, which might require decreasing the enclosure bottom area.

Safety
Safety for humans and animals is essential when the flaring system is implemented. The requirements set with regard to safety in chapter 4 should be considered and with the situation in which the flare will be implemented in mind, the flaring system should be extended with components securing the safety of the environment.

Costs
Costs for a flare with a capacity of 5 m^3 per day were calculated with Dutch prices, adding up to 116 €. In Mali and other countries were the flare could be implemented, prices and availability of components will differ. Both the prices and the availability should be studied.

Biological oxidation as alternative
In chapter 3, alternatives to flaring were studied. One of these methods, namely biological oxidation, could be an interesting alternative to flaring for the small and medium scale anaerobic digester units. It is a low cost and simple method, but although a lot of literature is available, still many questions remain. Studying biological oxidation more deeply and testing it in combination with small scale anaerobic digestion systems

Effective use of produced heat
Flaring is a safe way to get rid of surplus biogas, but at the same time it is a waste of valuable energy. It might be interesting to find ways to make use of this energy. Combination with two recent projects of FACT foundation might be possible. In the first project, the possibilities for implementation of a heating system in the anaerobic bag digesters is studied. A second project, which is still in an early state, is focused on generating electricity from heat through a thermo-acoustic generator.

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