LOW EMISSION COMBUSTION TECHNOLOGY FOR LANDFILLS

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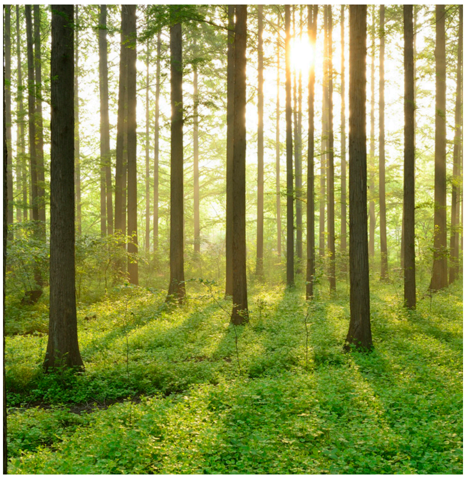

ENERGY GAS TECHNOLOGY

Energiforsk

New Technology for Low Emission Combustion for Landfill Gas

ABDALLAH ABOU-TAOUK, MARTIN NILSSON, PONTUS WETTRELL, JAN HOLMSTRÖM,
HÅKAN SANDBERG, LARS GUSTAVSSON

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Authors' foreword

This project evaluated the possibilities of low emission combustion technology for landfill gas with low energy content. The study has a strong focus on computer simulations and involves the optimization of a reduced global reaction mechanism for the landfill gas.

The report has been produced by Cleanergy AB and the author is Abdallah Abou-Taouk.

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The project was funded by the Swedish Energy Agency and Cleanergy AB. The study had a reference/working group with the following members: Jenny Rissler/Anton Fagerström (Energiforsk), Lars-Erik Eriksson and Ingemar Denbratt (Chalmers University of Technology) and Martin Nilsson and Lars Gustavsson (Cleanergy AB).

Sammanfattning

Förbränning i brännkammare är en viktig del av dagens elproduktion och med världens ökade energibehov samt en ökad mängd bioenergi i samhället genom användningen av förnyelsebara bränslen kommer energieffektivisering av förbränningsteknik fortsätta att vara viktig.

Företaget Cleanergy AB [1] har utvecklat en Stirlingmotor som drivs av en brännkammare (GasBox). Denna kan bränna både naturgas, vars främsta beståndsdel är metan, samt deponigas som har en mycket varierande gassammansättning. Det har på senare år blivit tydligt för Cleanergy att sammansättningen av deponigasen kan variera avsevärt, beroende på olika faktorer så som: plats, temperatur, tryck, deponisammansättning, tid etc. Dessa faktorer leder till variationer i gasens värmevärde och därmed variation i driften av GasBox-motorn. Detta ställer stora och hårda krav på flexibilitet i driften av brännkammaren.

Deponigasen har olika förbränningsegenskaper då dess sammansättning varierar. Ämnena i gasen ger olika flamhastigheter och vissa molekyler ger en högre diffusion jämfört med andra. Dessa egenskaper behöver undersökas mer i detalj och därmed är simuleringar av dessa deponigaser viktiga eftersom det ökar detaljförståelsen samt möjliggör undersökning av förhållanden som kan vara svåra, omöjliga och/eller kostsamma att utföra experimentellt.

Detta projekt handlar dels om att ta fram nya kinetikscheman för förbränning av metanbaserade lågvärdiga gaser. Den planerade metoden var utvecklad av bl. a Chalmers. I projektet togs det fram optimerade reducerade kinetikscheman som användes i förbränningssimuleringar av GasBox-brännaren. Ett viktigt syfte med simuleringarna var att undersöka vilken av flera kemiska mekanismer av olika komplexitet som bäst och mest tidseffektivt matchar de teoretiska resultaten. Exempelvis så utvecklades en optimerad reducerad global reaktionsmekanism, ett 4-stegs schema för deponigasen med gassammansättningen 24.2% CH_4, 21.6% CO_2, 2.0% O_2 och 52.2% N_2 baserat på volym. Denna gas var uppmätt i deponin placerad i Eslöv [2]. Den kemiska beräkningsmekanismen gav bra överensstämmelse med de teoretiska kemiska beräkningarna samt de uppmätta emissionerna ute på Eslövs deponi.

Den andra uppgiften i projektet var att Computational Fluid Dynamics (CFD) - modellera Cleanergys befintliga brännkammare med olika gaser och de nya framtagna reaktionsmekanismerna för att förstå nuläget med avseende på strömning och förbränning. Här har både metangas, propangas samt deponigaser simulerats. Generellt kan fastställas att CFD-simuleringarna var kapabla att någorlunda rätt prediktera flödes- och förbränningsstorheter jämfört med de experimentella resultaten, närmare bestämt emissioner, NOx och temperaturer.

Slutuppgiften var att föreslå modifieringar utifrån dagens brännkammare för att nå övergripande mål och ta fram konstruktionsunderlag samt bygga och testa en prototyp. Numerisk gjordes ett noga och gediget arbete där det konstruerades en ny typ av brännkammare baserad på ett roterande luft- och gasflöde. De

numeriska resultaten gav en djup förståelse och visade en ny typ av teknik som möjliggör en termisk effekt upp till 60 kW baserat på en 18 % metanhalt. Simuleringar på prototypen visar också att det är möjligt att nyttiggöra elproduktion ner till 15 % metanhalt baserat på en lägre effekt. Projektmålet var att tillverka och testa protypen. Att producera en fungerande fysisk prototyp på ett helt nytt brännarkoncept visade sig vara betydligt mera omfattande och resurskrävande än det var budgeterat och planerat. Detta resulterade i att denna slutuppgift inte kunde slutföras i form av en fysisk prototyp.

Strategiskt så borde nästa steg vara att kunna bygga en fysisk prototyp och testa denna i en Stirlingmotor (GasBox) med olika deponigaser samt lågenergigaser. Experimentella data i form av temperaturer, emissioner och hastigheter hade varit mycket värdefullt för att kunna validera beräkningsmetoden på Cleanergy samt verifiera de numeriska resultaten för den nya prototypen.

Summary

Combustion is an important part of electricity production. The energy need and the amount of bioenergy in society is likely to increase. Cleanergy AB has developed a combustion chamber located in a Stirling engine which is operated primarily on natural gas, whose main component is methane and landfill gas, which has a large varying gas composition. In recent years, it has been seen that the composition of the landfill gas has varied more, depending on various factors such as location, temperature, pressure, landfill composition and age of the landfill. These variations lead to variations in the heating value and thus variation in the operation of the Cleanergys GasBox engine. This requires flexibility in operation of the combustor.

The different composition of the landfill gas provide different combustion characteristics since the gas molecules varies between different species. The species gives different flame speeds and certain components gives a higher diffusion rate than others. These properties need to be investigated in more detail and thus are simulations of these landfill gases important because it increases understanding and enables detailed investigation of the circumstances that may be difficult or costly to perform experimentally. A 4-step reaction mechanism was developed for landfill gas 24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 by volume, this gas was measured in the landfill located in Eslöv. This chemical reaction mechanism gave good agreement with the theoretical results and the measured emissions out of Eslöv landfill.

The second task was to model Cleanergys existing combustion chambers with different fuels and new kinetic mechanisms to understand the current situation with regards to flow and combustion properties. Here, methane gas, propane gas and landfill gas were simulated. Generally, one can determine that the simulations could predict the correct flow and combustion properties reasonably well compared to the experimental results, such as major emissions, NOx and temperatures.

The final task was to propose modifications based on today's combustion chamber to reach the overall goal and to develop design documentation and to test this prototype. Numerically a major work was performed where a prototype was constructed based on a rotating air and gas flow (swirling flow). The result has shown and given a deeper understanding of a new type of technology that allows a thermal power up to 60 kW based on an 18% methane content. Simulations of the prototype also shows that it is possible to utilize electricity down to 15% methane content based on a lower power. The project goal was to manufacture and test the prototype. To produce a functioning physical prototype of a completely new concept proved to be considerably more extensive than initially budgeted and therefore could not be carried out.

Strategically, the next step would be to build a physical prototype and test it in a Stirling engine (GasBox) with landfill gas and low energy gas. Experimental data in terms of temperatures, emissions and velocities would have been very useful to validate the calculation method used in Cleanergy and verify the numerical results of the new prototype.

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1 Background

1.1 MOTIVATION

The growing trend today is that combustors for power production should be fuel flexible [3]. These different fuels may have relatively low energy content like landfill gas-mixtures. In a landfill gas extraction, the methane content decays with time. The gas mixture depends on different conditions, such as temperature, humidity, dryness of the earth, pressure, age of the landfill etc. This implies that the energy content of the gas mixture can vary typically from 20 MJ/kg (~60% CH_4) down to 5 MJ/kg (~20% CH_4). Once the LHV (Lower Heating Value) of the gas reaches a value below 10 MJ/kg (~40% CH_4) it has historically been the case that the gas is flared away since no available technology could utilize the gas for energy production. The low methane content is often a limitation for conventional techniques, typically gas turbines and internal combustion engines. This also implies today when a large quantity of methane gas is released from landfills around Europe.

1.2 PURPOSE AND AIMS

The Cleanergy Gasbox combustion chamber was constructed in its original version for natural gas as fuel supply. Since the last few years the combustion chambers have been continuously modified in several stages in order to handle lower heating value fuels such as biogas produced by anaerobic digestion. Lessons learned showed that the landfill was more interesting than biogas from anaerobic digestion since certain pollutants are present in lower concentrations in landfill gas.

A pilot plant consisting of two Stirling engines was installed 2012 on a landfill outside Eslöv in a project co-financed by the Swedish Energy Agency. The project has demonstrated that landfill gas with a methane content of over 40% can be used to power Stirling engines. Conventional techniques for generating electricity often have a lower limit of 40% methane. Cleanergy has estimated that the market has significant potential. According to the European regulations, the methane gas from landfills should be utilized for energy recovery as far as possible. The Cleanergy technology can be used and to better meet these regulations and take advantage of the methane gas for a very long time. In Europe, there are many thousands of landfills where Cleanergy technology is interesting. Below a certain methane level Cleanergy is today alone in the market.

The first markets for Cleanergy AB regarding landfill was developed in Scandinavia and the Baltics. Thereafter, the continued establishment took place in other regions of Europe, where the UK represents the single largest market. In the Baltic states, there are, for example, approximately 500 landfills that are potential customers for Cleanergy technology with an energy value corresponding to 850 gigawatt hours. This corresponds to approximately 2400 Stirling engines. This represents a huge export potential for Cleanergy. There is a great need of the Cleanergy AB's solution in many countries in the world. The long-term goal is to introduce Cleanergy AB's solution within the landfill globally.

The combustion chamber is in the current version of the Stirling engine adapted to more low-grade fuel, and to date, the major changes made is in the control system and the system of fuel supply. The combustion chamber has a further improvement, particularly in terms of flow field distribution since this burner was originally developed for methane-air gas. In the current situation, full power is not reached with methane-based fuels for 30% methane content and fuel with less than 20% cannot be burned at all, or only at very low power. However, it is desirable to reach full power even with only 20% methane content since the methane content slowly decays in landfills and with time will drop below 20%.

2 Implementation

2.1 WORK PACKAGE 1: KINETICS

The integration of detailed kinetics in turbulent flame simulations is one of the most difficult technical challenges that exist today. The complexity of combustion chemistry must be reduced to reduce both the number of degrees of freedom and the stiffness of the partial differential equations that are solved simultaneously with the flow and combustion. This is something that the turbulent reacting community has been focusing on for about 40 years and many different methods are proposed. Regarding industrial applications, eg a Stirling engine and gas turbine where the burner is often fed by multiple streams of fuel, cold and hot air, circulating burnt gases, and areas of premixed and partially premixed mixtures, implies a high complexity and modeling difficulty. In these complex flow situations, the chemistry reduction is needed since too large number of control parameters (fuel, air, EGR, heat loss, etc.) exists. A method to solve this is to use optimized reduced global reaction mechanisms ([4]-[15]) in CFD simulations, instead of tabulating the chemistry of a complex system. Using global mechanisms in CFD are advantageous because only a few components are of interest in many industrial applications.

The first work package contains a literature study on developed simplified reaction mechanisms. The focus of this work package was to develop and evaluate simplified global reaction mechanisms for different gas mixtures aiming for landfill gases. The method used was developed earlier at the Chalmers University of Technology [15]. Optimization strategy to optimize the global reaction mechanisms are based on ModeFrontier [16] as optimization program linked to the commercial software CHEMKIN [17] (chemistry tool). The method is based on an established set, where the Arrhenius parameters for a global schedule is determined from a set of reference detailed chemistry solutions [18]. The optimization is performed so that the balance equations for gas molecules and temperature involved in the reduced system matches the detailed chemistry solution. A 4-step optimized global reaction mechanism was developed for the landfill gas mixture 24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 based on volume. This gas was measured at the landfill located in Eslöv [2]. The chemical reaction mechanism gave good agreement with the theoretical results and the measured emissions from Eslöv landfill.

2.2 WORK PACKAGE 2: CFD OF THE CLEANERGY COMBUSTOR

The second work package was focusing on the numerical simulations. Ansys CFX CFD software [19] were used for all simulations. Numerical models of Cleanergy current combustion chambers have been built up using ICEM CFD [20]. A major effort has been made to construct and simplify the models in order to adapt them to the CFD simulations.

RANS simulations [21] have long been a very common approach for industrial simulation of reacting flows. However, the rapid increase in computer power in recent years has made feasible reacting flow simulations using more sophisticated turbulence models such as URANS/LES and LES [22]. The turbulence model SAS-SST [24] is an example of a hybrid URANS/LES model that switches to LES [22] if the resolution of the grid is sufficient and to URANS simulation mode in coarser grid regions and close to the walls. The Ansys CFX [19] uses a coupled solver and the solution approach uses a fully implicit discretization of the equations at any given time step. The high-resolution scheme (which is a bounded second-order upwind biased discretization) was applied for the discretization in space and time. The mesh is composed of 1.5 million hexahedral cells. The turbulence model k-ω-SST [23] has been used for all RANS simulations and the SAS-SST model [24] was used for the transient simulation. The chemistry was represented by the four-step global mechanism for landfill gas [2]. Results are presented with the inclusion of radiative heat transfer.

A combined turbulence-chemistry interaction model, the Finite Rate Chemistry/Eddy Dissipation Model (FRC/EDM), was chosen for all CFD analyses. The FRC model ([25], [26]) computes the reaction rate R_k from the following expression:

$$R_k = \left(F_K \prod_{I=A,B,..}^{N_C} [I]^{v'_{kI}} - B_K \prod_{I=A,B,..}^{N_C} [I]^{v''_{kI}} \right)$$

where $[I]$ is the molar concentration of component I and $F_K$and B_K are the forward and backward rate constants, respectively. v'_{kI} and v''_{kI} represents the reaction order of component I in the reaction k. The forward (F_k) and backward rate (B_k) constants assume Arrhenius temperature dependence as:

$$F_k = A_k \, T^{\beta_k} \, e^{-\frac{E_k}{RT}} \qquad\qquad B_k = \frac{F_k}{K_C}$$

where A_k is pre-exponential factor, β_k is the temperature exponent, E_k is the activation energy and K_C the equilibrium constant. The FRC model computes one reaction rate respectively for each reaction in the optimized global reaction mechanism. In the EDM model [27], the reaction rate of reaction k, is computed as:

$$R_k = A \frac{\varepsilon}{k} min \left(\frac{[I]}{v'_{kI}} \right)$$

where A is a constant, $\frac{\varepsilon}{k}$ is the turbulent mixing rate, $[I]$ is the molar concentration of component I and v'_{kI} represent the reaction order of component I in the elementary reaction k. The EDM model computes one reaction rate respectively for each reaction in the optimized global reaction mechanism. The combined FRC-EDM model thus gives two different reaction rates for each reaction, one from the EDM model and one from the FRC model. The minimum rate for each reaction is then chosen.

A schematic picture showing the burner is shown in Figure 1. Specified mass flow rates are imposed at the inlet boundaries for the air inlet and the fuel inlet. The preheated air inlet temperature is set to 1000 K and to 300 K for the fuel inlet. The outlet boundary condition is set to 1 bar and a no-slip adiabatic boundary condition is imposed on all walls. The P1 model for radiation was included in the CFD simulations leading to an additional transport equation to be solved. The heat exchanger is included in the CFD simulations and is modeled by a heat sink in order to represent the amount of heat that is extracted by the heat exchanger in the Stirling engine. For the transient simulations, the statistics are first converged for a non-reactive case, and the flow is then advanced in time with combustion for about 0.5 s (ten flow-through times) until the flame is well established and statistics are accumulated for another 0.5 s. The time step for the simulation was set to 1.0e-4 s which implies a mean CFL number of 1. Conservation checks were made for mass, momentum, energy, and major species.

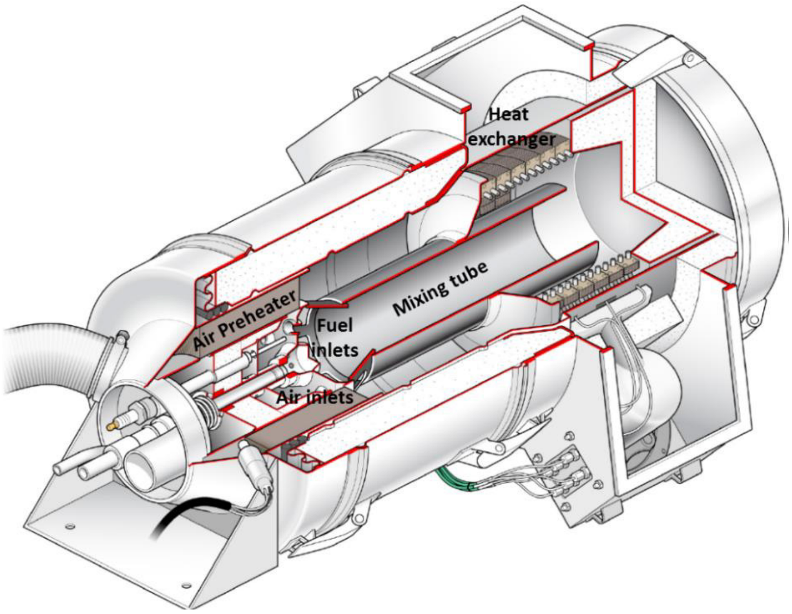

Figure 1: GasBox schematic cut showing the burner [1].

2.3 WORK PACKAGE 3: FUTURE COMBUSTOR

In the third work package the advanced engineering department at Cleanergy was developing a new prototype of the combustion chamber, which will enable a safer and more stable operation with potential to burn landfill gas with a methane content down to 18%.

The goal in this work package was to propose modifications based on today's combustion chamber to reach the overall goal and to create design documentation as well as build and test a prototype. From numerical point of view, the work was progressing very well where a solid model was designed and simulated using CFD. The present combustor chamber was a new burner based on a rotating air and gas flow. AE department at Cleanergy had the following philosophy when the combustion chamber was designed:

- Use the same geometry for "heater head" in the Stirling engine
- Create a rotating air / fuel flow upstream of the burner
- Improving mixture by improving the design of fuel mixing and at the same time provide that the fuel and air flow would "interact" with one another
- The velocity field in the burner should be independent on the mass flow variations and variations of the landfill gases
- Create an internal recirculation flow field before the heat exchanger instead of an EGR.

The above points were considered in the design loop and various design proposals were made. At the end, AE department in Cleanergy successfully designed and simulated a new burner named PAM burner that created a high rotation velocity of the gasses and expanded into a large chamber that created a negative axial movement in the center of the burner. In this way, the temperature variation in the burner was small, a very good mixing between air and gas was obtained, and an internal recirculation of hot gases was implemented. The advantage of the recirculation back to the combustion zone before the heat extraction implies a more stable operation and the ability to burn gas with a lower methane content.

3 Results

3.1 WORK PACKAGE 1: KINETICS

The optimization was performed by selecting a set of one-dimensional premixed flames simulated with the detailed GRI-Mech 3.0 mechanism [18]. This was performed for a quite a lot of set of operating conditions. The result was saved to provide reference solutions to the optimization setup. The same set of flames was simulated using the four-step mechanism shown in Table 1. This mechanism is designed for an operating pressure of one bar, inlet temperatures from 295 to 1000 K and equivalence ratios (air / fuel ratio) from 0.15 to 1. A function is further defined to measure and minimize the difference between the two solutions. The selected points are solved interactively with the chemistry tool CHEMKIN coupled to the optimization tool ModeFrontier, until the function reaches its minimum and the best set of parameters determined for the global mechanism is chosen, table 1.

Table 1. Kinetic rate data (units in cm, s, kcal and mol)

Reaction	A	Ea	B
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	2.2E15	40.5	− 0.1
$H_2 + 0.5O_2 \rightarrow H_2O$	2.08E18	42.0	0.5
$CO_2 \rightarrow CO + 0.5O_2$	1.0E11	42.75	− 0.5
$CO + H_2O \rightarrow CO_2 + H_2$	6.0E14	40.0	− 0.4

$$k_{f,1} = A_1 T^{B_1} e^{\frac{-E_{a1}}{RT}} [CH_4]^1 [O_2]^1 \quad (R1)$$

$$k_{f,2} = f_2(\emptyset) A_2 T^{B_2} e^{\frac{-E_{a2}}{RT}} [H_2]^{1.2} [O_2]^{0.9} \quad (R2)$$

$$k_{f,3} = f_3(\emptyset) A_3 T^{B_3} e^{\frac{-E_{a3}}{RT}} [CO_2]^1 \quad (R3)$$

$$k_{f,4} = A_4 T^{B_4} e^{\frac{-E_{a4}}{RT}} [CO]^{0.6} [H_2O]^{0.7} \quad (R4)$$

Figure 2 shows the laminar flame speed versus the equivalence ratio for the detailed GRIMech 3.0 mechanism (solid line) and the present optimized four-step mechanism (symbols). The agreement is acceptable despite some deviations close to the lean blow out limit. Figure 3 shows the autoignition delay time versus the temperature for one atmosphere pressure and using different global mechanisms (JL4 [8], M3 [10], WD2 [9] and the present four step named AAT4NR [2]). The present four-step mechanism predicts the ignition delay time well compared to the detailed GRIMech 3.0 mechanism and better than the other global mechanisms, Figure 3.

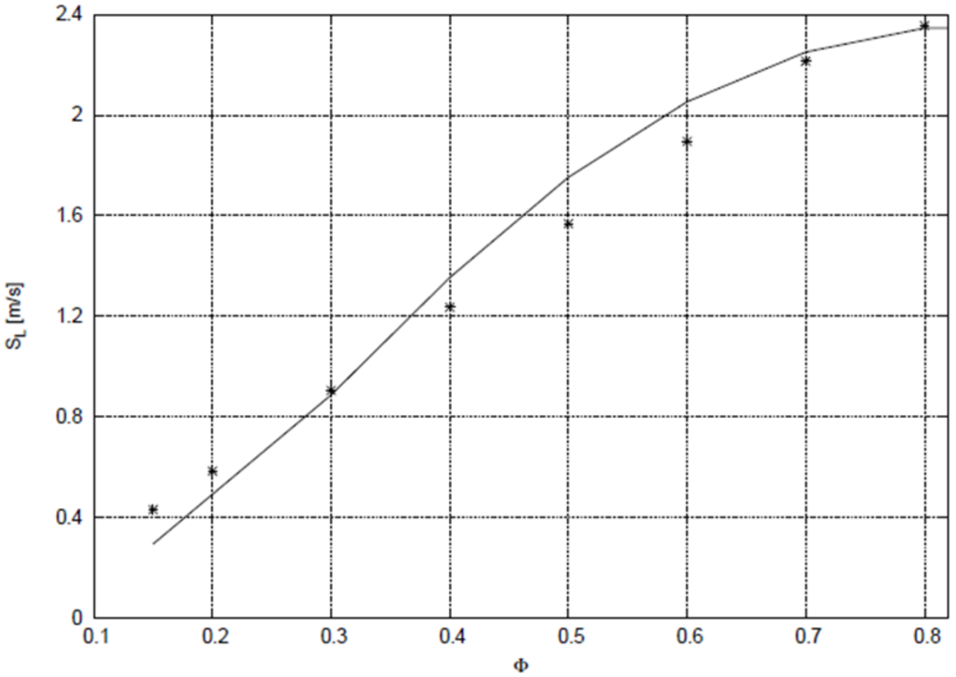

Figure 2: Laminar flame speed versus the equivalence ratio for the detailed GRIMech 3.0 mechanism (solid line) and the present optimized four-step mechanism (symbols).

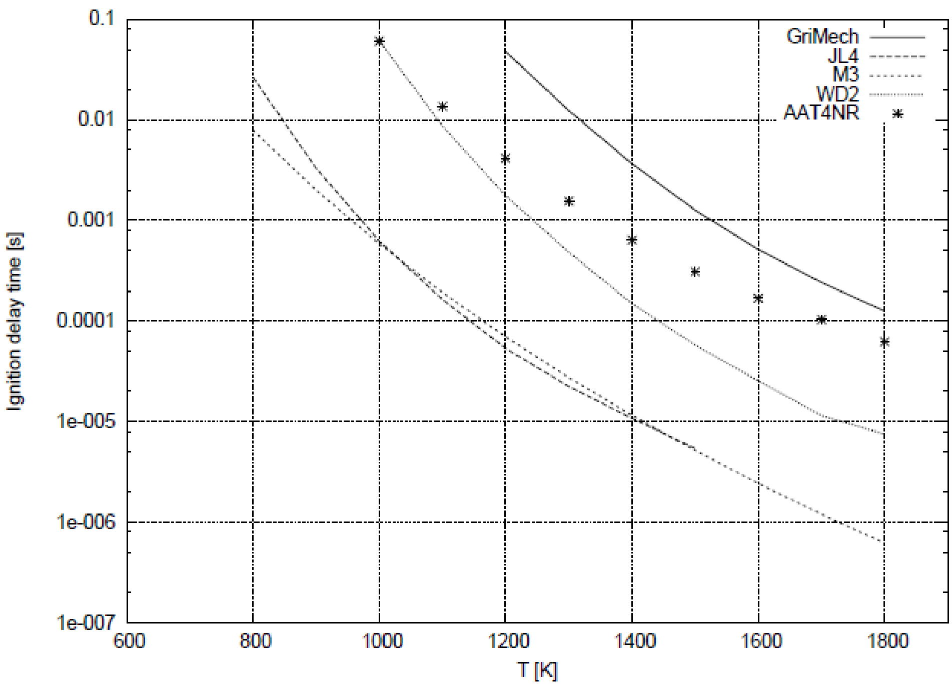

Figure 3: Ignition delay versus the temperature for the detailed GRIMech 3.0 mechanism (solid line), different global mechanisms and the present optimized four-step mechanism (symbols).

Figure 4 shows the detailed GRI-Mech 3.0 equilibrium species concentrations and the adiabatic temperature at different equivalence ratios, together with the reduced AAT4NR mechanism counterpart. It is seen that the AAT4NR mechanism captures the equilibrium conditions and the adiabatic temperature very well for the considered range.

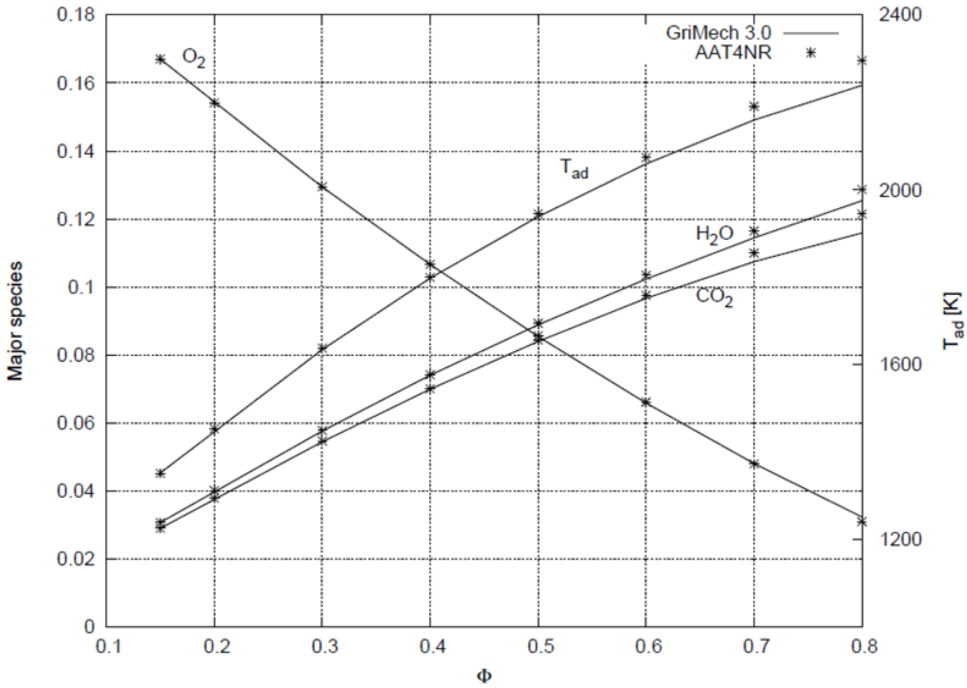

Figure 4: Equilibrium concentrations (mole fractions) of the species and the adiabatic flame temperatures vs. equivalence ratio using the present AAT4NRmechanism compared to the detailed GRI-Mech 3.0 mechanism; landfill mixture.

3.2 WORK PACKAGE 2: CFD SIMULATIONS

The GasBox burner, as shown in Figure 5, consists of a main burner and a heat exchanger. The gas is injected from one location and there are 6 main injection holes at the entrance of the burner. The main air is preheated above the auto-ignition temperature of the fuel. The air and the fuel are diluted by exhaust gas recirculation. The mixture then makes a 180 degree turn downstream the mixing tube and goes through the heater head. Finally, the exhaust gases pass upstream the mixing tube and is divided into two parts. One part passes the heat exchanger and one part is guided back into the combustion zone. The CFD model contains the main components, the inlet and the outlet, the heat exchanger, the cone, the air and the fuel cavities. To save computing time and memory a 60-degree sector of the combustion chamber is simulated rather than the whole geometry.

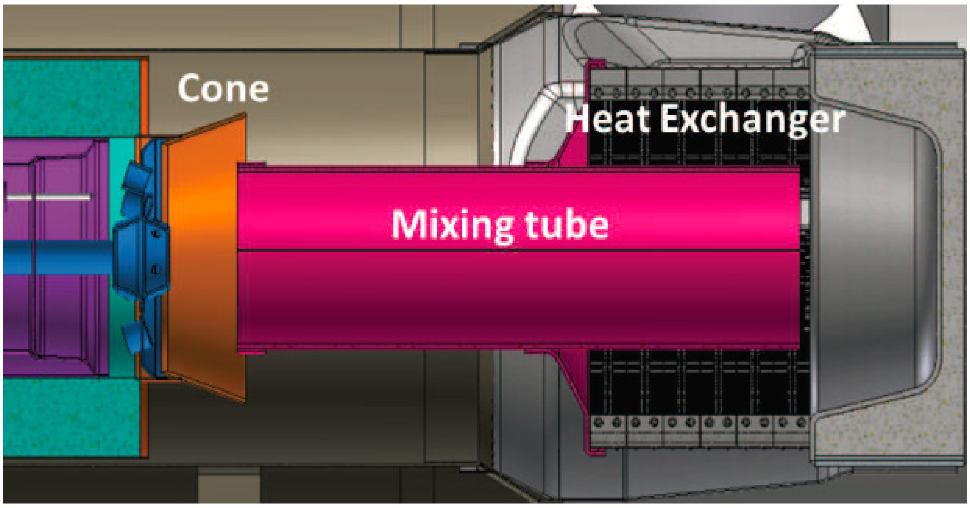

Figure 5: Cleanergy combustor.

The boundary conditions are very important for CFD simulations and is usually the ones that has the greatest uncertainty. Specified mass flow rates were set at the inlets for air intake and fuel inlet. The preheated air temperature was set to 1000 K. Radiation was included in the CFD simulations, which unfortunately leads to additional transport equation to solve. The global lambda values in the burner is around 0.2 including exhaust gas recirculation (EGR) mixing. The heat exchanger is part of CFD simulations and a heat sink is placed to represent the amount of heat extracted by the heat exchanger of the Stirling engine.

Table 2 shows a comparison between predicted CFD results (both k-w SST which is time-independent model and SAS model which is time-resolved) and measurements. The first thing to note is that the SAS model predicts emissions and NOx better than k-w SST. This is consistent with earlier studies [2]. The reason for this is because the time-independent model predicts an average temperature, which is lower than the peak temperatures, in comparison with the more transient calculations. A lower temperature gives lower NOx prediction because the NOx concentration is strongly correlated to the temperature. Generally, the CFD simulations with the optimized chemistry show a good agreement with measured data. A more detailed reading of the results can be found in reference [2].

Table 2: Major emissions and mean NO_X concentrations: experimental data compared to CFD.

Emissions	Experiment	CFD k-w SST	$CFD\ SAS\ SST$
$Landfill: CO_2$	17.4%	15.3%	16.1%
$Landfill: O_2$	7.3%	7.4%	7.0%
$Landfill: NO_x$	$<$ 10ppm	$<$ 1ppm	$<$ 10ppm
$Natural\ gas: NO_x$	150ppm	–	180ppm

3.3 WORK PACKAGE 3: FUTURE COMBUSTOR

Figure 6 shows the simulated CFD model of the PAM burner. The gas pipe is located upstream in the center. The first cavity creates a rotational flow that increases the velocity in the contraction. This rotational flow is then expanded largely in the entrance to the combustion chamber. Figure 7 shows a schematic picture of the PAM burner with the heat exchanger.

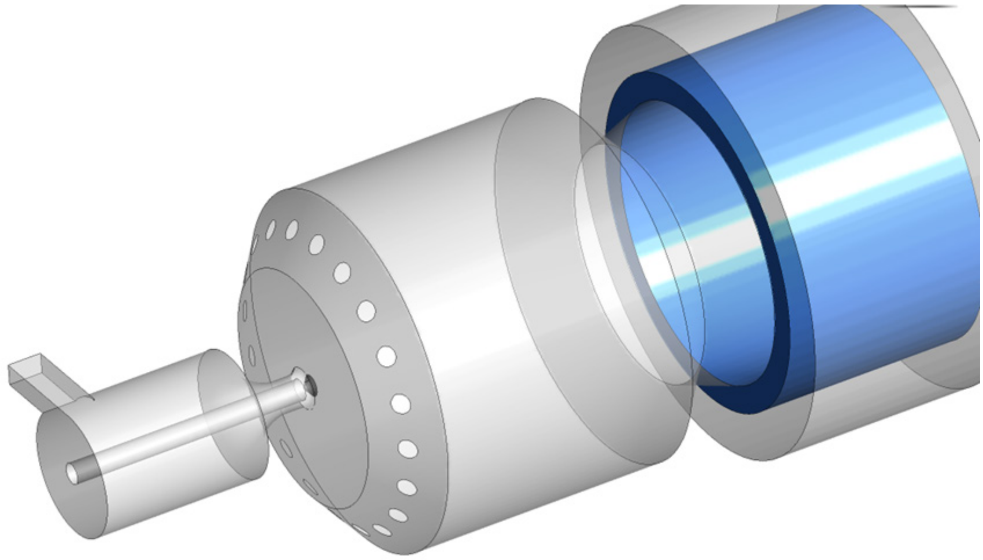

Figure 6: CFD model of the new PAM burner.

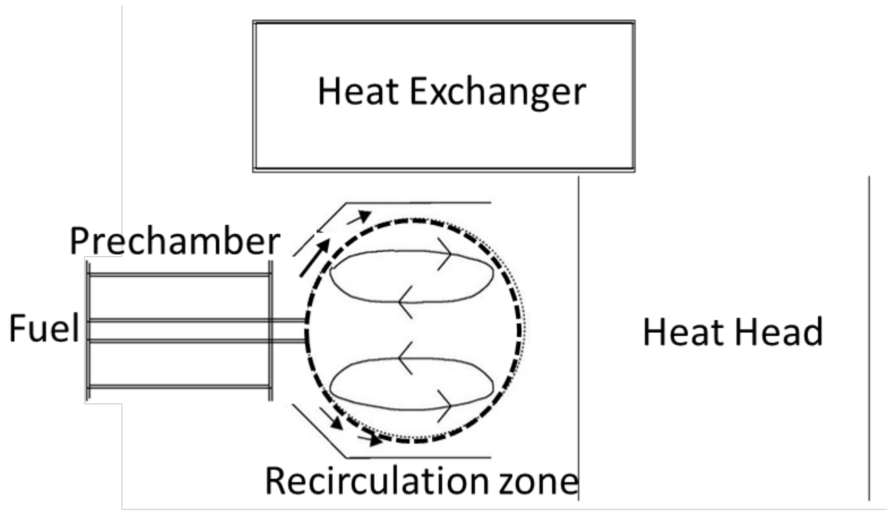

Figure 7: Schematic picture of the model of the new PAM burner

The numerical results provided a deep understanding of, and demonstrated, a new type of technology that allows a thermal power up to 60 kW based on a 18% methane content. Simulations of the PAM showed also that it is possible to produce electricity down to 15% methane content based on a lower power. Many different types of simulations have been run which contained various chemical reaction mechanisms, different turbulence models, gas mixtures, effects, operating modes, and geometries. Figure 8 provide temperature and velocity vectors for the new PAM burner. The CFD simulation is based on a time-resolved turbulence model. This gas is propane, and is used to simulate the startup of the burner. In general, the results are promising.

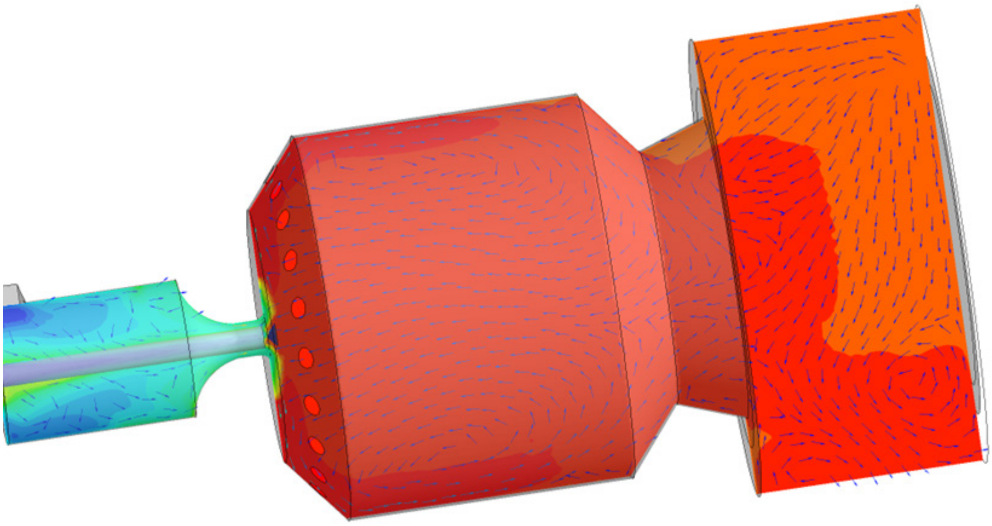

Figure 8: Propane gas at start-up of operating mode. The plot show temperature and velocity. Red depicts hot- and blue cold zones.

Figure 9 shows the temperature and velocity vectors for the new PAM burner simulated using a mixture consisting of 24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 based on volume. The new optimized reaction mechanism from work package 1 of this mixture was used in the simulation. The results are very positive regarding emission levels, flow field and temperatures.

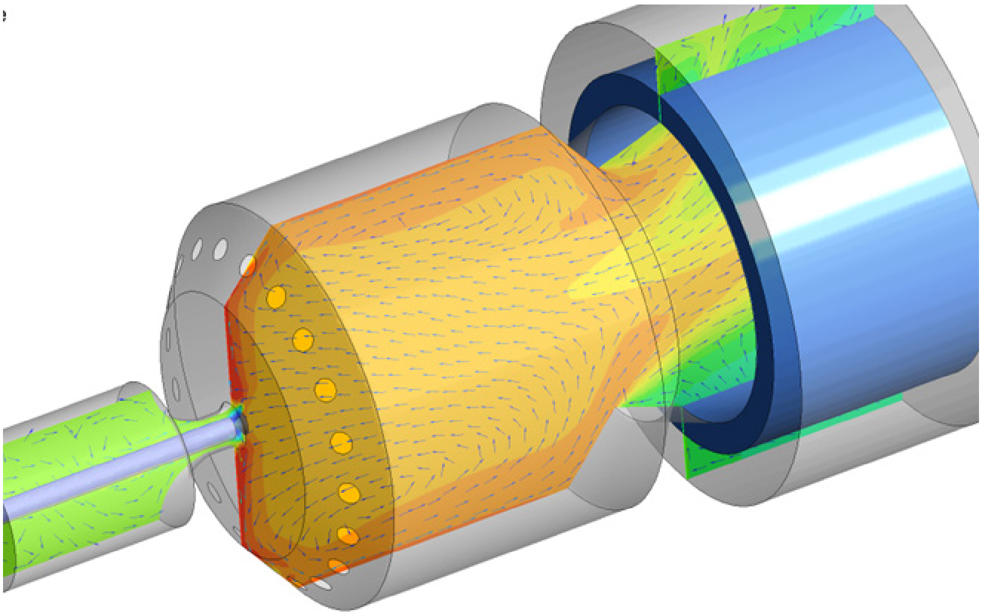

Figure 9: PAM burner simulated with of 24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 based on volume. The cross-sectional plane plot shows temperature and velocity vectors. Red depicts hot- and blue cold zones.

4 Summary

The results of the various work packages are positive. The method from work package 1 has been shown to work very well and can be used for various gas compositions for both landfills and biogas plants. This means that one can save a lot of computing time when designing new types of combustors which aims for more robustness and fuel flexibility. A new optimized global reaction mechanism, AAT4NR, was developed for the present landfill mixture (24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 by volume). The parameters of the 4-step AAT4NR global mechanism have been automatically obtained from the optimization loop for a range of equivalence ratios and inlet temperatures. The optimized Arrhenius rates allows for capturing the major species, the laminar flame speed, the adiabatic flame temperature and the ignition delay time for different equivalence ratio compared to a detailed reaction mechanism.

The results from the CFD simulations in work package 2 was satisfied. The new new optimized global mechanism from work package 1 was used in RANS and URANS/LES modeling applied to an industrial Stirling engine combustion chamber at atmospheric pressure. The flow and flame properties are compared to measurements and reasonable agreement is seen in terms of major emissions, NO_X and temperatures.

The experience and lessons learned from work packages 1 and 2 were used in the last work package which had the purpose to develop and test a more robust burner. A series production of the new PAM burner will have a very strong positive contribution and impact for a sustainable society. The new burner shows reduction of emissions (below 10ppm NOx) but what is more important is that many gases from landfills and other facilities that have a methane content of 15-30% could be utilized for electricity and heat production instead of being flared out in the atmosphere. In line with this, the construction of a physical prototype of PAM burner is extremely important, especially to perform experimentally testing and obtain experimental data.

Then, this new optimized global mechanism is used in RANS and URANS/LES modeling applied to an industrial Stirling engine combustion chamber at atmospheric pressure. The flow and flame properties are compared to measurements and reasonable agreement is seen in terms of major emissions, NOX and temperatures.

5 Publications

A. Abou-Taouk, P. Wettrell, L. E. Eriksson. CFD investigation of a Stirling engine flexi fuel burner based on MILD combustion. In 8th Inter. Symposium on Turbulence, Heat and Mass Transfer. (2015).

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Appendix

Turbulence, Heat and Mass Transfer 8

CFD investigation of a Stirling engine flexi-fuel burner based on MILD combustion

A. Abou-Taouk[1,2], P. Wettrell[2] and L. E. Eriksson[3]

[1,3] *Chalmers University of Technology,*
Hörsalsvägen 7A, SE-41296 Gothenburg, Sweden, abdallah@chalmers.se, lee@chalmers.se

[2] *Cleanergy AB,*
Therese Svenssons gata 15, SE-41755, Gothenburg, Sweden, pontus.wettrell@cleanergy.com

Abstract — This paper presents comparisons of results from tests and 3D CFD combustion simulations based on both RANS and hybrid URANS/LES (SAS-SST model) turbulence models applied to an industrial Stirling engine combustion chamber at atmospheric pressure. The combustor uses both air preheating and exhaust gas recirculation. Both methane gas and landfill gas (24.2% CH_4, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 by volume) were simulated. The combustor is designed to operate in the MILD combustion mode which is characterized by low flame temperatures and low NO_X emissions. A 4-step reduced reaction mechanism, named AAT4NR, involving seven species was developed to represent the landfill gas. The optimization was performed at atmospheric pressure for a range of fresh gas temperatures [300 K - 1000 K] and equivalence ratios [0.15 - 1]. Comparisons with detailed chemistry solutions of a planar propagating flame front show that the laminar flame speed, the adiabatic flame temperature, the ignition delay time and the species concentration at equilibrium are adequately predicted. There is good agreement between the quantities predicted with URANS/LES and experimental data, in terms of flow and flame dynamics, averaged temperatures, NO_X-levels and the concentrations of some major species.

1. Introduction

Combustion of fossil fuels has provided the major part of our energy needs in the past and will remain the dominating energy conversion process in the near future [1]. The reduction of pollutant emissions from practical combustion systems therefore is a major issue both in industry and in combustion research. Regulatory requirements for limiting emissions, such as nitrogen oxides (NO_X), carbon monoxide (CO) and unburned hydrocarbons (UHC), and the demand for higher efficiency combustion systems lead to new technologies of energy systems and combustors. These include, for example, premixed burners, air staging and exhaust gas recirculation (EGR). The growing trend today is that combustors should be fuel flexible. These different fuels are typically of Low Caloric Value (LCV), such as biofuels, syngas [2, 3] and landfill mixtures. The industrial company Cleanergy is the worlds's leading supplier of sustainable energy solutions based on the Stirling engine. The Stirling engine, described by [4], is a prime mover with energy input in the form of externally supplied heat. This can be done via e.g. a combustion chamber or a solar concentrator. Cleanergy has found a market niche towards LCV type of fuels and currently focuses on renewable, gaseous mixtures that are relatively difficult to burn since the energy content is small compared to natural gas. One such gas is Landfill gas. In a landfill gas extraction the methane content is decaying with time. The low methane content is often a limitation for conventional techniques, typically gas turbines and IC engines. Cleanergys newly developed and manufactured burner has shown capabilities to burn landfill gas and other types of LCV mixtures with very low energy content. The new burner (named GasBox, see Figure 1) is driving an alfa type Stirling engine where the burner is designed and manufactured at Cleanergy AB, Sweden. The engine power output is 7.2 kW electric power and 16 kW

LOW EMISSION COMBUSTION TECHNOLOGY FOR LANDFILLS

This report describes the optimization of a reduced global reaction mechanism for landfill gas aiming for the gas composition CH_4 24.2%, 21.6% CO_2, 2.0% O_2 and 52.2% N_2 based on volume. The chemical reduced mechanism gave good agreement with the theoretical kinetic calculations. The report also includes CFD combustion results using the Cleanergy existing combustion chambers with different gases and the new reaction mechanism for understanding the flow and combustion. Finally, the CFD result of a new developed combustion chamber based on a swirling air and gas flow are presented. One of the main factors affecting the combustion result is the mixing of fuel and oxygen. The numerical results provide a deep understanding of the technology that enables a thermal power up to 60 kW based on a 18% methane content. Simulations of the prototype also shows that is possible to provide electricity down to 15% methane content based on a lower power.

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