FIXED-BED GASIFICATION OF AGRICULTURAL RESIDUES

Colomba Di Blasi, Project Co-ordinator, University of Napoli, Italy

Jesus Arauzo, University of Zaragoza, Spain

Ole Kristensen, Volund R & D, Denmark

Krister Sjostrom, KTH, Sweden

Emmanuel Koukious, National Technical University of Athens, Greece

Contract No. JOR3-CT95-0021

PUBLISHABLE PROJECT REPORT

Research funded in part by

THE EUROPEAN COMMISSION

in the framework of the

Non Nuclear Energy Programme

JOULE III

FIXED-BED GASIFICATION OF AGRICULTURAL RESIDUES

SUMMARY

The main purpose of this project is to provide the technical basis for the development of effective gasification technologies for the processing of agricultural residues. This is particularly important for Mediterranean countries where residues are widely available but dispersed over large or hardly accessible areas. Thus, this project is concerned with fixed-bed gasification of agricultural residues for decentralized heat and power production. The different aspects of the problem have been taken into account through the different stages of the process: availability, pre-treatment, transportation and storage of feedstocks, evaluation of their physico-chemical properties and thermo-chemical behaviour, conversion, model development, operation of a commercial plant and combustion tests of the producer gas.

Extensive laboratory-scale experiments have demonstrated that the heating value of the producer gas from agricultural residues is, in some cases, even higher than that from wood. However, pilot scale tests have also evidenced serious difficulties in the attainment of steady operation conditions, because of the very high reactivity and the low bed density (straw), the problematic ash behaviour (straw and olive waste), the high moisture content (grape residues), the high amount of tar produced and/or the very high bed density (almond shells, olive waste). Feedstock pre-treatments (in particular, fractionation and leaching) and co-feeding residues with different characteristics have been found to be effective tools to reduce or to eliminate such drawbacks. Detailed transport models of fixed bed gasification have been developed, which in conjunction with the measured reactivity and chemical kinetics, have been applied to clarify the complex interaction between physical and chemical processes and to optimize the operation of a commercial updraft plant.

PARTNERSHIP

The project has a European dimension, with contributions from Italy, Spain, Denmark, Sweden and Greece, countries that have common interests in the development of reliable gasification systems, based on the use of agricultural residues and industrial processing of agricultural products, for heat and power generation in rural areas. The main information on the project Partners is listed below:

Colomba Di Blasi, Project Co-ordinator,
Department of Chemical Engineering, University of Napoli "Federico II",
P.le V. Tecchio, 80125 Napoli, Italy
Tel: 39-081-7682232; Fax:39-081-2391800, email:diblasi@unina.it

Jesus Arauzo, Partner
Dept. de Ingenieria Quimica y Technologias del Medio Ambiente,
University of Zaragoza, Maria de Luna 3, E-50015 Zaragoza, Spain
Tel: 34-976-761878; Fax: 34-976-761861 email: qtarauzo@posta.unizar.es

Ole Kristensen, Partner
Volund R&D, Centervej 2, 6000 Kolding, Denmark
Tel: 45-75- 568874; Fax: 45-75-568873

Krister Sjostrom, Partner
Dept. of Chemical Engineering and Technology, KTH, Teknikringen 42, 10044 Stockholm, Sweden
Tel.: 46-8-7908248; Fax:46-8-108579; email:krister@ket.kth.se

Emmanuel Koukious, Partner
Dept. of Chemical Engineering,National Technical University of Athens, Zografou Campus, GR 15700 Athens, Greece
Tel: 30-1-7723191; Fax:30-1-7723163, email: koukios@chemeng.ntua.gr

OBJECTIVES OF THE PROJECT

The subject of this project is concerned with air, atmospheric pressure gasification of straw and other agricultural residues, typical of Mediterranean areas, for decentralized heat and power production. The different aspects of the problem are taken into account through the different stages of the process: availability, pre-treatment, transportation and storage of feedstocks, evaluation of their physico-chemical properties and thermo-chemical behavior, conversion, model development, operation of a commercial plant and combustion tests of the producer gas.

The project program is based on eight main tasks:

1) Data Collection,
2) Pretreatments,
3) Properties and Thermochemical Behaviour,
4) Model Development,
5) Numerical Simulation,
6) Laboratory Scale Tests,
7) Pilot Plant Tests,
8) Utilization.

The main objectives can be summarized as follows:

1.to quantify the potential use of agricultural residues (and residues of industrial processing of agriculture products) with a view of gasification for decentralized heat and power production in some areas of the South and North Europe (Denmark, Greece, Italy, Spain, Sweden),

2.to define the optimal pre-treatments for transportation, storage and conversion,

3.to determine the gasification characteristics of agricultural residues,

4.to improve the updraft and downdraft gasification technologies for the specific treatment of agricultural residues,

5.to develop mathematical models of fixed bed gasification for reactor optimization,

6.to test the producer gas characteristics through a Diesel engine (coupled with a downdraft gasifier), 7.to assess the applicability of a wood (updraft) gasification plant to feedstocks with different characteristics.

The activity of the Technical University of Athens (NTUA) is related to feedstock preteatment in order to improve gasification characteristics. The University of Napoli (U. Napoli) and KTH are involved with the evaluation of physico-chemical data and the study of the chemical kinetics of pyrolysis, gasification and combustion. Data are also collected in relation to devolatilization products under fixed-bed (U. Napoli) and fluid-bed (KTH) conditions. Kinetic mechanisms and constants are coupled to transport phenomena to model fixed-bed gasifiers (U. Napoli). The validation of the models is carried out through laboratory scale tests of updraft gasification (U. Napoli) and downdraft gasification (U. Zaragoza). In order to compare the gasification characteristics of agricultural residues in relation to different units, some tests are also made by a fluid-bed reactor (KTH). Volund (VRD) is responsible for the pilot scale tests of updraft gasification and the optimization of an industrial plant, while U. Zaragoza is involved with the pilot scale downdraft gasification and the combustion tests of the producer gas.

TECHNICAL DESCRIPTION OF THE PROJECT

Gasification is a widely studied technology to produce a mixture of combustible gases. It consists of several sequential processes which include: solid drying, solid pyrolysis to give gases, tars and char, cracking and oxidation of tars (and, to a certain extent, oxidation of volatile pyrolysis products) and gasification/combustion of char. Together with chemical reactions and evaporation of moisture, mass and heat transfer processes also play a fundamental role. However, while for coal numerous industrial plants are in operation, the problems associated with biomass conversion are not yet completely solved. Thus, this project is concerned with air gasification of agricultural residues for decentralized heat and power production.

The methodology applied for the project development is based on both experimental and theoretical investigations. Experiments have been carried out at different levels and for different purposes. The thermochemical gasification characteristics of the feedstocks, properly determined, are used to characterize the reactivity of the material and to "measure" kinetic data to be used in the numerical simulations of the mathematical models. Most of the experimental analyses have been conducted by means of fixed-bed chemical reactors, first on a laboratory scale, and then on a pilot plant scale. In the first stage, a fluidized bed reactor has also been used to compare the two different technologies. The feasibility has been tested of the application of the producer gas for an internal combustion engine as a way of generating electricity.

The methods applied for the theoretical part of the work deal with the formulation of mathematical models for the updraft and downdraft reactors and the subsequent numerical solution. The models are then used to optimize reactor performances, to understand the dependence of the gasification characteristics on feedstock properties, operating conditions, design parameters, etc., and to predict process dynamics.

Optimized gasification systems, the main objectives of this project, are not yet available on a commercial scale. Therefore, this aspect of the project is clearly innovative. Probably, among the different aspects, the most important is the development of detailed mathematical models, including multi-step chemical kinetics and transport phenomena. Indeed these, not available before the start of the project, are very effective tools for design and optimization of the gasification units of interest.

Additional components of the gasification plant, such as gas cleaning and treatments of the organic condensable components resulting from gas cleaning, the reduction in the pollution emission, which are partially investigated in this project, also represent areas where the technology is not fully developed.

RESULTS

Agricultural residues widely available in Northern and Southern European countries have been identified as straw, olive and grape waste, pruning cuts.

The primary degradation kinetics of wheat straw, corn stalks, vineyard prunings, olive husks, grape residues and xylan (taken as representative of hemicelluloses) have been investigated under isothermal conditions, established through a fast radiant heater (U. Napoli). In all cases, semi-global reaction mechanisms describe well the process, with kinetic constants that are comparable for the different biomasses. In order to explain the role played by the main components in the degradation of biomass, tests on the pyrolysis of cellulose, lignin and cellulose under thermogravimetric conditions have also been made. For these conditions, the behaviour of beech wood and agricultural residues has also been compared (U. Napoli). Degradation of the different biomass reflects the behaviour of the single components, however, quantitative predictions cannot be obtained from the degradation rates of the single components. The ratio of the cellulose content to the global content of hemicellulose and lignin only establishes the shape of the weight loss curve and its time derivative.

Product (char, gas, liquids) distribution and gas compositions from pyrolysis of wood and agricultural residues have been determined for conditions of interest in fixed bed gasification (U. Napoli) under fast external heat transfer rate, so that conversion characteristics are essentially the result of bed properties. For surface temperatures of the bed below 600°*C*, the char yield significantly decreases, while liquid and gas yields increase, as the external radiation intensity is increased. For higher temperatures, char tends to become constant while the gases continuously increase at the expense of liquids. These data, useful for mathematical modeling, show that, on the average, agricultural residues give rise to higher char and carbon dioxide yields and lower yields of liquid products. On the other hand, tests conducted for beds under very slow external heating rates (5-30*K/min*) (U. Zaragoza), though still characterized by significant intra-bed temperature gradients, do not show significant differences in the composition of the pyrolysis products.

Intra-particle gasification characteristics of straw, olive waste and wood have also been investigated through a free-fall reactor in the temperature range 800-1000°*C* (KTH). The dependence of the product distribution from the heating and temperature conditions is qualitatively similar to that observed for fixed-bed pyrolysis and again char yields are higher for agricultural residues. Another aspect investigated through this unit is related to particle size (Table 1).

Biomass	Olive Waste		Wood, Birch	
Rapid Pyrolysis				
Particle size, mm	0.5-0.8	0.8-1.0	0.5-0.8	0.8-1.0
Gas yield, wt % maf	61	51.8	81.1	77.7
Tar yield, wt % maf	1.1	0.9	1.1	1.1
Char yield, wt % maf	20	27.6	5.8	7.2
Final slow pyrolysis				
Char yield after total pyrolysis, wt % maf	17.1	18.3	4.6	5.5
Char removed by slow pyrolysis, wt%maf	14.6	33.7	20.7	23.6
Composition of the gaseous products (vol %. Nitrogen and waterfree basis)				
H2	15.8	12.8	17.3	16.8
CH4	24.1	24.1	15.7	16.2
C2H2,C2H4	3.9	3.4	5.8	6.2
C2H6	0.7	0.9	0.3	0.3
Benzene	0.6	0.5	1.2	1.2
CO2	15.7	18.2	9.6	8.3
CO	39.2	40.1	50	50.7

Table 1 - Influence of particle size in the rapid pyrolysis at 800 °C in a free fall reactor.

Reactivities of chars, derived from different agricultural residues, have been examined in both oxidizing and gasifying atmospheres (U. Napoli), by means of weight loss curves, measured for different sample heating rates and final temperatures. In all cases, the process is well described by a one-step global reaction, which takes into account the variation in the specific surface available for the heterogeneous reaction through a power law dependence on the solid mass fraction. Chars from grape residues appear to be the less reactive.

The gasification characteristics of agricultural residues, at a laboratory scale, have been determined through updraft (U. Napoli) and downdraft (U. Zaragoza) fixed-bed reactors and a pressurized fluid-bed reactor (KTH). A laboratory-scale updraft gasification system (1-3*kg/h*) has been specifically designed and constructed for this purpose (Fig.1).

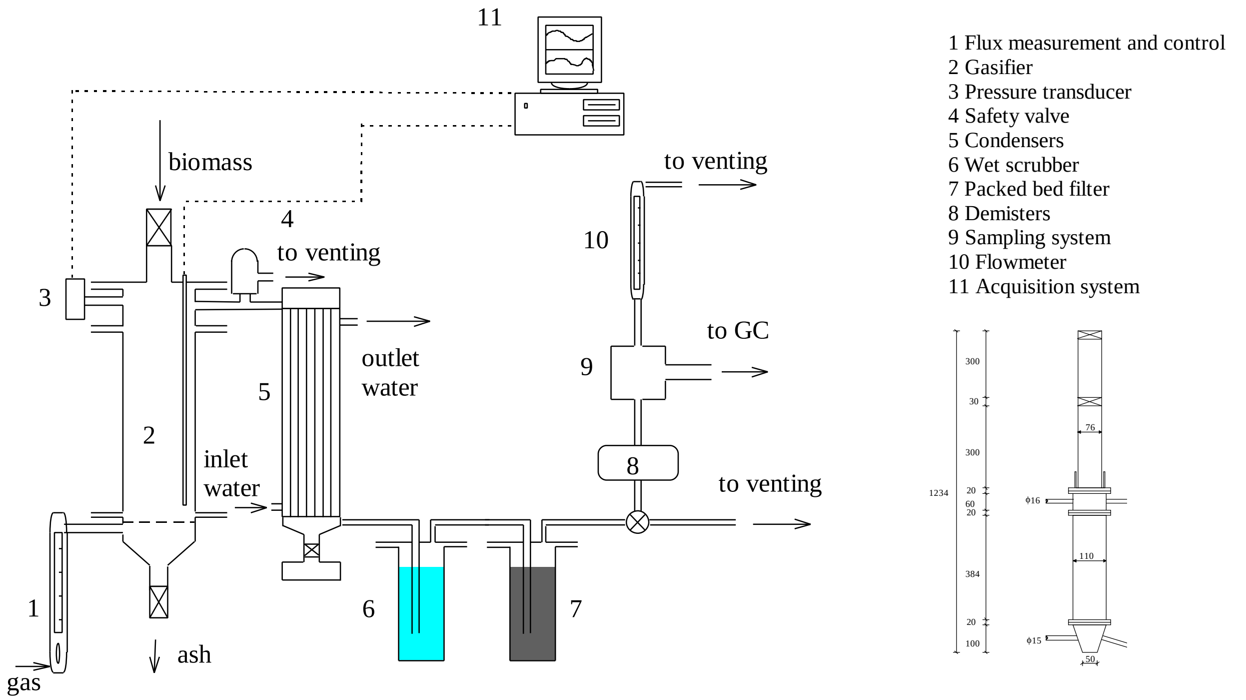

Fig.1 Laboratory-scale gasification plant

The core of the plant is a reactor (a thermally insulated cylindrical shaft 50 *cm* high above the grate and 8.4 *cm* i.d.), where pressure and temperature profiles are measured. The feeding system consists of a hopper including a double slide valve to prevent gas losses. The bottom zone of the reactor has a truncate conical shape to collect and to discharge ashes. The grate sustains the bed and acts as air distributor. At the top of the reactor, the gas stream enters two tube-shell heat exchangers, followed by a wet scrubber and a packed bed, which acts as demister. The gas flow measured is then analyzed through a gas-chromatograph. The liquids collected under steady operating conditions are also analyzed.

Laboratory scale updraft gasification (U. Napoli) has been carried out of beech wood (for comparison purposes), grape waste, olive husks and straw pellets. The wood has been cut in particles 0.5-2*cm* thick, whereas fines have been eliminated from the residues to avoid the partial transport of the bed at high flow rates, which interrupt the gasification process. The duration of the tests is 4-7*h* and steady conditions are achieved only after about 3-4*h*. The calorific value of the producer gas, the spatial temperature profiles, the product yields (solid, gas and liquids) and the gasification efficiency have been determined for different air flow rates. For all biomasses, the calorific value of the producer gas attains a maximum as a function of this variable. At low values, the heat released by the thin combustion zone causes biomass devolatilization but the temperature is too low for the gasification of the resulting char. Both the maximum temperature and the size of the reduction/devolatilization zone first increase with the air flow and then tend to become constant. Apart from very low temperatures, the air to fuel feed ratio remains roughly constant but it varies with the biomass (values of 1.4 for wood, 1.2 for olive husks and 1.5 for grape residues). The specific gasification rates attained by the system are in the range 100-550kg/m^2h. Significant differences are observed in the temperature profiles and gas composition but the gas heating value shows comparable values (about 5 MJ/Nm^3 for wood, 4.6 MJ/Nm^3 for grape residues and 5.6 MJ/Nm^3 for olive husks). For all feedstock tests, the GC analysis of the liquids has revealed components typical of low-temperature pyrolysis, as expected for updraft gasification. On the whole, from laboratory scale tests, Mediterranean agricultural residues appear to be good candidates for energy production, however several problems are still present for their gasification on a large scale. These have clearly appeared during pilot-scale (1 MW_{th}-600 kW_{th}) tests.

Pilot scale updraft gasification (VRD) tests indicate that cut straw is a very difficult feedstock mainly because of the low density, the high reactivity, the low ash melting point and the small size of char particles. As a consequence, it is very difficult to maintain steady conditions during gasification. The gasification performances are significantly improved by the use of straw pellets. However, to avoid char transport, the capacity of the reactor should be low. Given the high bed densities and the presence of fines, pretreatments are also required for olive husks and grape residues.

Downdraft gasification (U. Zaragoza) tests have been carried out with two different units, with capacities of 25-50 *kg/h* and 200-300 *kg/h*, by varying the air flow rate and rate of solid discharge. Steady conditions of gasification are easily achieved with woody residues. This is not the case of almond shells and olive stones which, however, produce a gas with a higher heating value. The main difficulties associated with the gasification of these two residues are due to the high density of the bed (olive husks) and the high yields of tars and content of alkalis (almond shells). Highly unstable is also the gasification of straw pellets, though the producer gas is cleaner. In order to overcome such drawbacks, cofeeding different biomasses has been tested. Thus, to reduce the density of the bed, pine bark has been associated with olive waste. The addition up to 25% of pine bark in the feed improves the bed characteristics without significant changes in the gas composition. Co-feeding almond shells and straw has also resulted in significant improvements in the global gasification characteristics. The heating values of the producer gas have not been found to depend on the size of the gasification plant. General characteristics of the process can be seen from Figs.2-3. Combustion tests of the producer gas have also been successfully accomplished (U. Zaragoza).

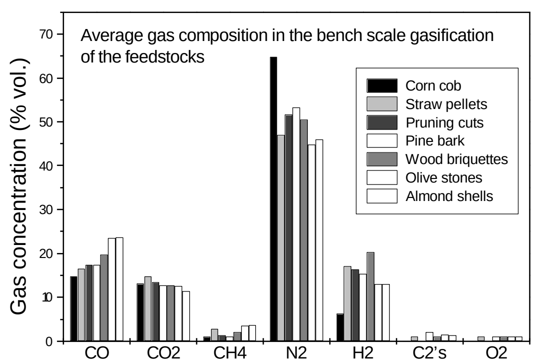

Fig. 2 - Gasification in the 25-50 kg/h plant: gas composition (average values).

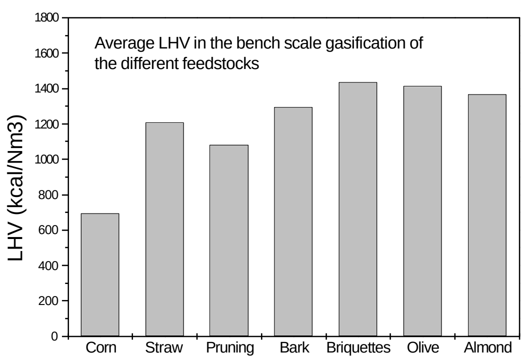

Fig. 3 - Gasification in the 25-50 kg/h plant: heating value of the gas (average values).

Fluid-bed, steam gasification of olive waste and straw has been carried out for temperatures in the range 700-900°*C* (KTH). The bed material was quartz or silver sand. Compared to wood, olive waste produced a gas with higher percentages of carbon dioxide and hydrogen and lower percentages of carbon monoxide. Also, ash from olive waste presents a lower melting point which is negatively affected by pressure increase.

Two types of pretreatments (NTUA) have been identified as promising for application to the selected residues, i.e., fractionation, and leaching. Optimisation of these pretreatments with respect to the selected feedstocks has shown that considerable upgrading of residues is possible, mainly due to a significant (i.e., of the order of 30-60 %) decrease of the ash content, in possible combination with an improvement of the treated ash thermal behaviour, especially a higher melting temperature zone. On the other hand, the energy value of the initial feedstock is more-or-less preserved in the pre-treated material. By laboratory tests on a high-temperature combustor and a downdraft gasifier, it has been observed that the highly problematic phenomenon of ash agglomeration can be controlled and, in some cases, even eliminated through the application of the appropriate pretreatment or combination of pretreatments, e.g., leaching or fractionation. Moreover, based on a combination of elemental and thermal analysis, the ash thermal behaviour during gasification can be predicted, especially with respect to in-bed agglomeration. The effects of the pretreatments on the logistic chain and, especially, the costs of biofuel supply have been evaluated with the help of a simple model.

Mathematical modelling (U. Napoli) has been applied to investigate the effects of properties on single-particle devolatilization and to simulate the fixed-bed gasification process. Thus the effects have been predicted of the widely variable physical properties (density, thermal conductivity, permeability to gas flow, specific heat) and initial moisture content on the devolatilization stage of agricultural residues gasification, by means of detailed mathematical models. A sensitivity analysis has shown that biomass density is the most important variable for the conversion time, whereas the thermal conductivity highly affects both conversion time and product distribution.

One-dimensional, unsteady mathematical models have also been developed for fixed-bed (updraft and downdraft) gasification of biomass (U. Napoli). The main physical and chemical processes taken into account include: 1) moisture evaporation/condensation, 2) finite-rate devolatilization kinetics of primary and secondary reactions, 3) solid (char) and gas phase (carbon monoxide, hydrocarbons, tars, hydrogen) combustion, 4) heterogeneous gasification of char, 5) homogeneous water gas shift, 6) heat and mass transfer through the reactor due to macroscopic and microscopic exchanges, 7) absence of local thermal equilibrium, 8) solid- and gas-phase heat transfer with the reactor walls, 9) heat losses through the bottom ash layer, 10) property variation, 11) solid movement, 12) tar vapours transport and condensation/evaporation, 13) variable gas flow rate along the reactor 14) unsteady solid and gas phase processes. Heterogeneous reactions are described by the unreacted core model with a constant particle size (constant solid velocity and variable density) or with a shrinking radius particle (variable solid velocity and density of the bed constant along the whole reactor or only along the char region).

Results have been obtained, for the time and space evolution of solid and gas temperature, moisture content, concentration of gaseous species (O_2, N_2, H_2O, H_2, CH_4, CO, CO_2, tar, pyrolysis gas), densities of biomass and char, for both updraft and downdraft gasification. Simulations have been made by varying biomass properties (initial moisture content, particle size, ash content) and the operating conditions. The simulations for both updraft and downdraft gasifiers predict the correct physical behaviour. Predicted and measured gas compositions are in agreement, given the proper composition of the pyrolysis gas. Also, temperature profiles are in good agreement with measurements carried out through laboratory-scale plants, using as adjustable parameter the wall heat losses. Given the better thermal insulation achieved in industrial plants, the assumption of adiabatic walls results in a close distribution of the temperature profiles along the bed axis (Fig.4), as predicted (U. Napoli) and measured for the Harboøre gasifier owned by Volund. For the conditions reported in Fig.4 the measured gas composition (molar basis) consists of 5.7% CO_2, 18% CO, 12% H_2, 32% N_2, 2.9% hydrocarbons 29.5% H_2O while the tar content is 12 g/Nm^3.

Modelling has also been applied (U. Napoli) to investigate the stabilization mode of reaction fronts through stratified downdraft reactors, as the air to fuel ratio is varied. For very low values of this, both heterogeneous and homogeneous combustion rates do not attain values sufficiently high for the stabilization of the reaction front. The two processes are closely positioned and give rise to a front propagating with a constant speed towards the bottom of the gasifier, where eventually extinction takes place. For intermediate values of the air to fuel ratio and fast pyrolysis rates, associated with the prompt formation of char, heterogeneous combustion also occurs at some extent near the top of the reactor. However, because of the reduced temperatures, the subsequent gas phase combustion and char gasification zone moves downward. After unsteady propagation, this front

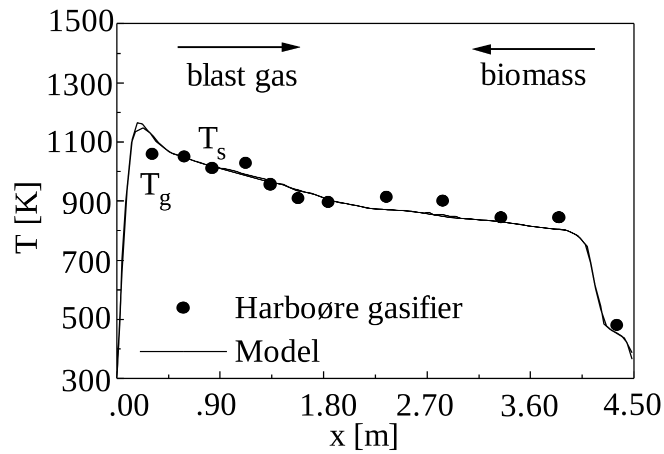

Fig. 4 - Axial profiles of temperature (steady state) for industrial scale gasification (steam 27%, oxygen 15%,ID=2m, L=4.5m, W=300kg/h, blast gas to fuel ratio 1.4).

stabilizes at a certain distance from the grate (Fig. 5). This mode of stabilization, observed also in the experiments and indicated as grate-stabilization, is not effective. Indeed, because of the reduced size of the reaction zone, the tar content of the gas is high and the char conversion low. As expected, for sufficiently high air to fuel ratios, the process becomes top stabilized and the quality of the gas improves significantly. The mode of stabilization of the reaction front is still largely determined by the combustion of volatile pyrolysis products and thus by biomass species, among others.

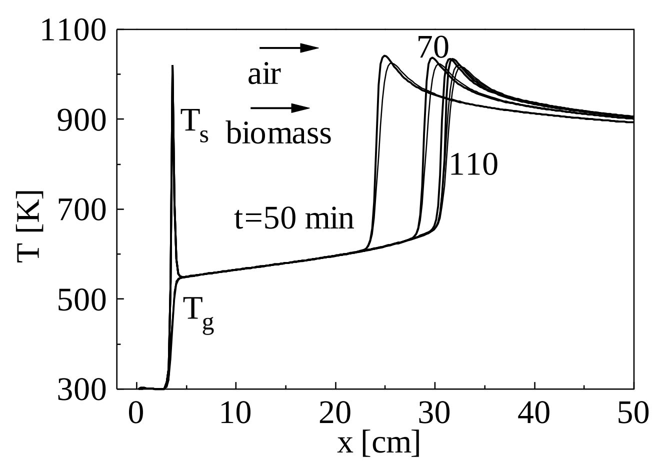

Fig. 5 - Temperatures profiles for downdraft gasification (ID=45 cm, W= 10 kg/h and air to fuel ratio 1.1).

The simulation results have been used mainly to understand the biomass gasification behaviour, to choose the optimal operating conditions in the experimental tests and to optimize the operation of a commercial updraft gasification plant. In particular, more accurate temperature measurements (VRD) have resulted in a better control of the gasification process, with a reduction in dust emissions and an increase in the heating value of the gas. The better temperature control has also made possible the injection of tar to the glowing zone of the gasifier (VRD), after wet scrubbing of the producer gas.

CONCLUSIONS

The first objective of the project, to quantify the potential use of agricultural residues for decentralized heat and power production through gasification in the countries of the Partners, has been fulfilled. The analysis of data collected has shown that the most available feedstock for all countries is cereal straw. This is also the only feedstock, whose amounts are interesting for energy conversion, in Denmark and Sweden. As expected, a larger variety of residues is available in the Southern countries, such as corn stalks and cobs, orchards and vine-yard pruning-off cuts, residues from olive and grape processing. For all countries involved in the project, agricultural residues can contribute significantly to energy needs (for instance, 8 % of the current electricity need in Italy and Greece).

The second objective of the project was to define the optimal pre-treatments for transportation, storage and conversion. Different pretreatments have been examined, in particular fractionation, leaching and densification. In all cases, the energetic characteristics of feedstock and, apart from densification, the thermal behaviour of ashes are improved, permitting a stable operation of the gasification plants. By a simple model, quantification of the overall net effects of pretreatments has been simulated. Furthermore, the logistic chain and its main stages, the energetic and economic costs of feedstock supply have been computed and the major problems with agro-residues have been identified. It has been found that these problems are mostly related to the transportation costs and that the application of pretreatments is, in many cases, positive.

Another import objective was the determination of the gasification characteristics of agricultural residues. The numerous activities have produced results on the pyrolysis and gasification characteristics of agricultural residues as well as on the chemical kinetics of the reactions taking place during biomass gasification. Conditions considered are those of both fixed-bed and fluid-bed reactors.

Pyrolysis of agricultural residues has been investigated under the control of chemical reactions (chemical reaction kinetics) and transport phenomena (product yields and gas composition). In the first case, semiglobal reaction mechanisms have been found to describe well the dynamics of weight loss for different thermal conditions. In agreement with previous findings, pyrolysis in the presence of significant heat and mass transfer resistances is largely affected by temperature, heating rate and solid and volatile residence times. Compared to wood, agricultural residues give rise to the formation of higher char yields. Also, the gas composition is characterized by higher carbon dioxide contents. Numerical predictions have indicated that conversion times and product distribution depend on the physical properties of biomass particle, in particular density, thermal conductivity and initial moisture content. The reactivities of chars, derived from agricultural residues under fixed-bed pyrolysis conditions, are comparable to those of wood. These have been analyzed again through weight loss curve measurements by varying the heating rate and the final reaction temperature.

Gasification characteristics for countercurrent fixed-bed reactors have been evaluated by means of a laboratory scale plant, specifically constructed for this purpose. Tests, carried out for different air to fuel ratios, have shown that the steady temperature profiles are significantly dependent on the type of feedstock (different physical characteristics of the bed) but the gas heating value shows comparable values. Comparable values of the heating value of the producer gas for the different residues have also been found through concurrent fixed-bed and fluid-bed reactors. However, pilot-scale tests have evidenced serious difficulties in the attainment of steady operation conditions, because of the very high reactivity and the low bed density (straw), the problematic ash behaviour (straw and olive waste), the high moisture content (grape residues), the amount of tar produced and/or the very high bed density (almond shells, olive waste). Feedstock pre-treatments and co-feeding residues with different characteristics have been found to be effective tools to reduce or to eliminate such drawbacks.

An important objective was to improve the updraft and downdraft gasification technologies for the specific treatment of agricultural residues. Modification in the feeding system and the insulating material have been studied for downdraft gasification. As for the pilot-scale updraft tests, it has been found that accurate temperature measurements are required for the control and regulation of the gasification process. Measurements have shown the existence of significant radial gradients. Radial and axial temperature measurements have allowed a better control, so that the particle content in the produced gas has been decreased, formation of melted ash has been prevented and the heating value of the gas has been raised. It has been demonstrated that it is possible to reinject tar, washed out in a wet scrubber, into the zone of glowing char so that thermal and oxidative cracking takes place. This has been possible because of the much better temperature control which is a condition for tar injection.

The fifth objective was to develop mathematical models of fixed bed gasification for process optimization. One-dimensional, unsteady mathematical models of stratified updraft and downdraft gasifiers have been developed. These models, which represent a significant advancement with respect to the current state of the art, include the description of all the main physical and chemical processes taking place during gasification. Validation has been made through comparison with experimental measurements at both laboratory and industrial scale. Simulations have been carried out by varying model parameters, kinetic constants, operational variables, and design parameters for both configurations. In all cases, the trends observed, as consequence of the variations in the physical parameters, reproduce well the experimental behaviour and allow the optimal gasification conditions, in terms of thermal efficiency, to be evaluated. The unsteady character of the models has also allowed the different stabilization modes (top- and grate-stabilized reactor) of the reaction zone for downdraft gasification to be determined.

Activities have been carried out to test the producer gas characteristics through a Diesel engine (coupled with a downdraft gasifier). It has been found that, compared with gasoline, when using producer gas, the maximum torque of the engine is reduced by 50 %; the thermal strengths in the engine decrease; HC and CO emissions achieve low levels. The decrease of the thermal strength improves the lifetime of the engine, while the lower emissions make the process more acceptable from the environmental point of view.

In accordance with the project objective concerning the assessment of the applicability of a wood (updraft) gasification plant to feedstocks with different characteristics and the availability of straw in the Northern European countries, a careful analysis has been made of the numerous tests carried out by Volund by two pilot scale gasifiers. The main problems associated with the fixed-bed gasification of straw are the unstable structure of the bed and char transport. Tests carried out with different kinds of straw pellets indicate that the way the pellets are produced is very important for the further use in an updraft gasifier. Moreover, updraft gasification of other agricultural residues, such as olive husks and grape residue, is very problematic and demands pretreatment before use as gasification fuels. These pretreatments should made so as to transform the residue in a wood-like fuel and therefore include densification and leaching. Only in this case it is possible to apply these fuels on a commercial scale.

From the analysis of the gasification tests conducted with fixed-bed reactors it can be concluded that the following basic requirements are needed for an efficient process:

I) Bed density > 300 kg/m^3 and <500 kg/m^3,

II) Moisture content 10-50 % on a dry basis for updraft gasification and below 10-25 % for downdraft gasification,

III) Particle size >10*mm*,

IV) Fines <15 %,

V) Ash melting temperature >1000°*C*.

Gasification of straw is very difficult even in the form of briquettes, unless these maintain their shape as undergoing the gasification process. Olive waste from oil production consist of particles in the range 0.1-10 *mm*. The high content of fines (about 30 %) causes a very high powder content in the gas and a relatively high bed density. This condition does not allow a uniform flow through the bed, but channelling and large pressure drops are established with consequent instabilities. Grape residues could be gasified in an updraft reactor but their high moisture level (about 50 %) does not make them suitable for downdraft gasification. For all the agricultural residues considered, ashes are present in higher amounts and, because of their composition, present lower softening points than wood. However, feedstock pre-treatments (densification, leaching, drying and fractionation) are effective tools to reduce or to eliminate the drawbacks reported above. Furthermore, in relation to downdraft gasification, adequate mixing of different residues can also be another mean to solve many operating problems, without loosing efficiency.

EXPLOITATIONS PLANS AND EXPECTED BENEFITS

In general, the use of agricultural residues for decentralized heat and power production is associated with an increase in the profits of agricultural areas, a reduction in the unemployment in rural areas through jobs in the new sector of electricity production from biofuels, a development in decentralized activities, thus avoiding depopulation of areas already neglected. From the economical point of view, the use of (low cost) agricultural residues for energy production is competitive. Moreover, there is the possibility of reducing the costs associated with environment conservation because of the low pollution emissions associated with these fuels.

Some specific tools and expertise have been developed in this project and include:

1) Devolatilization and gasification characteristics of agricultural residues through fixed-bed reactors (U. Napoli),

2) Transport models of updraft and downdraft gasifiers (U. Napoli),

3) Database of downdraft gasification characteristics of agricultural residues (U. Zaragoza),

4) Adaptation of gasoline and gas commercial engines to LHV gas from downdraft gasification (U. Zaragoza),

5) Advanced gasifier temperature measuring and control system (VRD),

6) Tar injection and control system (VRD),

7) Ash sintering behaviour in the fluid-bed gasification of olive husks (KTH),

8) Biomass pretreatments prior to gasification (NTUA).

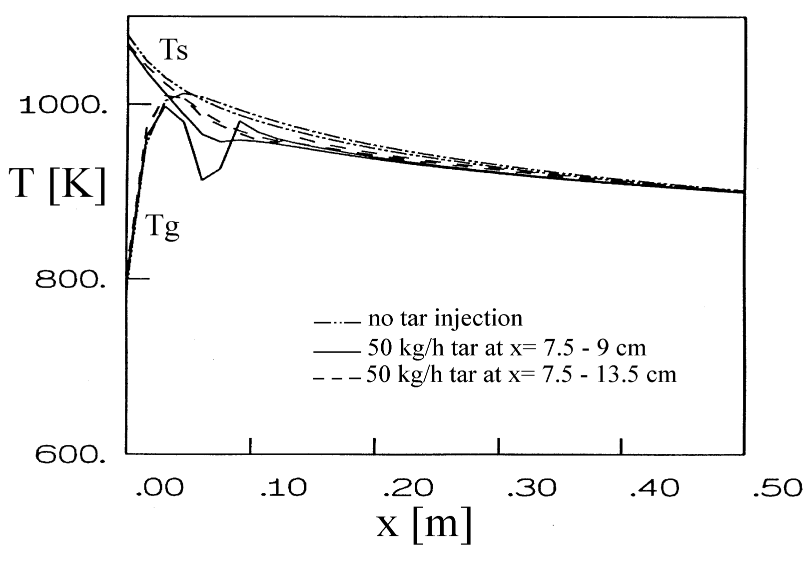

Fig. 6 - Simulated steady temperature profile along the first 50 cm of the gasifier axis with and without tar injection (steam 27%, oxygen 15%,ID=2m, L=4.5m, W=300kg/h, blast gas to fuel ratio 1.4).

Large part of the understanding of the gasification process, gained in this project, has already been applied to improve a commercial, wood-chip, updraft gasification plant (VRD), through points 5) and 6). All the data produced on the thermochemical behaviour of agricultural residues (points 1), 3),7)) and their optimal pretreatments in relation to gasifications (point 8)) are being published, so that the information can be used for the selection of the more appropriate conversion unit on dependence of the different agricultural residues. Also, these data can be applied in conjunction with the detailed transport models (point 2)), developed in this project, for design, scale-up and optimization of fixed bed gasifiers. As an example, the updraft gasifier model can simulate the effects of tar injection on the process characteristics and thus the optimal position for the injection zone and its size can be determined (Fig.6).