Pressurised Combustion Of Biomass Derived Low Calorific Value Fuel Gas

J. Andries, J. Cao, M. Donne

Delft University of Technology
Alstom Gas Turbines Ltd.
Fluent Europe Ltd.

Contract JOR3-CT95-0027

Publishable final report

May 1999

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

Pressurised combustion of biomass derived low calorific value fuel gas

ABSTRACT

The section Thermal Power Engineering of the Delft University of Technology is operating a rig which is used for research on pressurised fluidised bed gasification. This rig has been used for about 9 years to conduct combustion experiments and was extensively modified during 1995 to enable gasification experiments using coal, biomass and coal-biomass mixtures as fuels and air and air-steam mixtures as the fluidisation/ gasification medium. The installation has a maximum thermal capacity of 1.5 MW_{th} and can operate at pressures up to 10 bar and temperatures of 900 °C.

Alstom Gas Turbines Ltd has designed manufactured and supplied a pressurised, high temperature combustor for the biomass derived, LCV, fuel gas matched to the Delft gasifier. The combustor has been installed in the Delft test rig and experiments have been carried out to gather experimental data on the steady state and dynamic behaviour of the combustor. The experimental results have been compared with the simulation results obtained from the mathematical models describing the steady state and dynamic behaviour of the combustor and used to refine and validate these models.

A mathematical model which simulates the steady state behaviour of the combustor has been developed by Delft University of Technology in collaboration with Fluent Europe Ltd. The experimental results obtained in the Delft test rig were used to refine and validate the model.

A mathematical model which simulates the dynamic behaviour of the combustor has been developed by Alstom Gas Turbines Ltd. The experimental results obtained from the Delft test rig were used to refine and validate the model using empirical relationships where no theory has been developed.

The refined and validated steady state and dynamic combustor models have been used by Alstom Gas Turbines Ltd to develop a gas turbine model which is incorporated in a plant layout for an advanced biomass-fuelled IGCC plant. The plant layout is developed by Delft University of Technology and Alstom Gas Turbines Ltd and has been used for the simulation of the steady state and dynamic behaviour of the system.

1 PARTNERSHIP

The groups participating in this project are:

Section Thermal Power Engineering
Delft University of Technology
Mekelweg 2
2628 CD Delft, The Netherlands
contact: drs. J. Andries

Alstom Gas Turbines Ltd. (formerly EGT)
Energy Technology Centre
Cambridge Road, Whetstone
Leicester LE8 6LH, England
Contact: Dr. M. Donne

Fluent Europe Ltd.
Holmwood House
Cortworth Road,
Sheffield, S11 9LP, England
Contact: dr. P. Wild

2 OBJECTIVES

The objectives of the project are:

- to design, manufacture and test a pressurised, high temperature combustor for biomass derived, LCV, fuel gas obtained from the Delft 1.5 MW_{th} pressurised fluidised bed gasifier.
- to develop a mathematical model of the combustor which will be used to simulate the steady state behaviour of the combustor in the Delft test rig. This model will be incorporated into a gas turbine model to be included in the plant layout of an advanced biomass-fuelled IGCC plant.
- to develop a mathematical model which will be used to simulate the dynamic behaviour of the combustor in the Delft test rig. This model will be incorporated into a gas turbine model to be included in the plant layout of an advanced biomass-fuelled IGCC plant.
- to gather reliable experimental data on the steady state and dynamic behaviour of a pressurised, high temperature, combustor in the Delft test rig by analysing the fuel gas quality and the combustor behaviour. The results will be used to refine and validate the models.
- to design the plant layout of an advanced biomass-fuelled IGGC system, which includes component models enabling the simulation of the steady state and dynamic behaviour of such a system.

3 TECHNICAL DESCRIPTION

The section Thermal Power Engineering of the Delft University of Technology is operating a rig which is used for research on pressurised fluidised bed gasification. This rig has been used for about 9 years to conduct combustion experiments and was extensively modified during 1995 to enable gasification experiments using coal, biomass and coal-biomass mixtures as fuels and air and air-steam mixtures as the fluidisation/ gasification medium. The installation has a maximum thermal capacity of 1.5 MW_{th} and can operate at pressures up to 10 bar and temperatures of 900 °C. A 2 m high bed zone with a diameter of 0.4 m is followed by an adiabatic freeboard approximately 4 m high with a diameter of 0.5 m.

Alstom Gas Turbines Ltd has designed manufactured and supplied a pressurised, high temperature combustor for the biomass derived, LCV, fuel gas matched to the Delft gasifier. The combustor has been installed in the Delft test rig and experiments have been carried out to gather experimental data on the steady state and dynamic behaviour of the combustor.

4 RESULTS AND CONCLUSIONS

4.1 Design, manufacture and testing of the combustor

The combustor, designed for use in the TU Delft test facility, was a development of a design provisioned by ALSTOM as part of the British Air Blown Gasification Cycle development programme. The tubo-annular type combustor is based on the staged combustion design principle, which has been shown to be successful in reducing NO_x emissions without compromising other aspects of combustor performance, such as combustion efficiency and exhaust temperature profile. To enable the performance of the combustor to be accurately assessed, apertures for radially traversible gas sampling and temperature probes were included in the combustor.

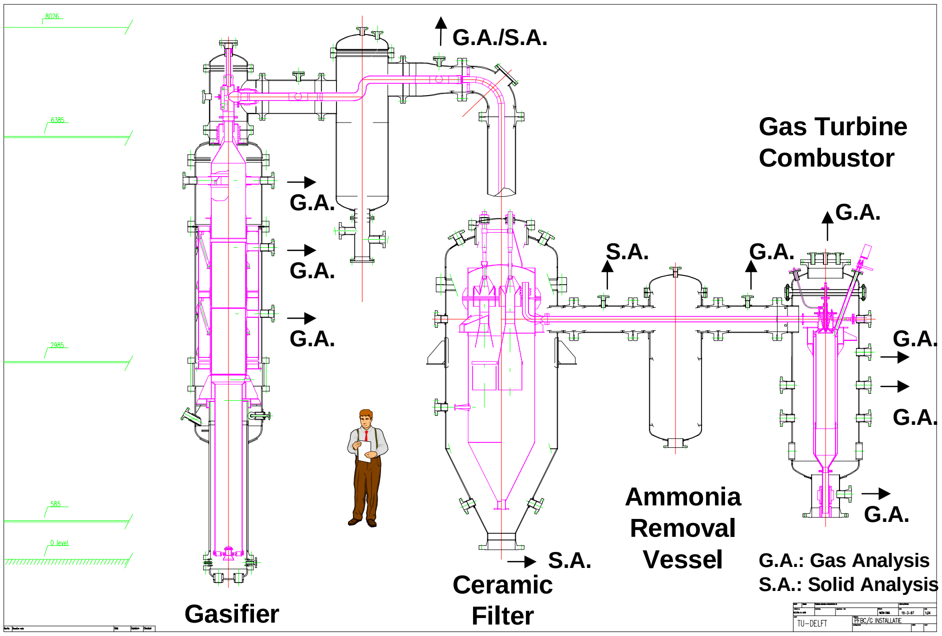
The combustor was designed to ensure that the Mach number and loading conditions were representative of those found in typical industrial gas turbines. The design operating conditions are shown in table 1

The combustor developed for this programme can be used in an ALSTOM Typhoon gas turbine with only minimal modifications. The steady-state and dynamic modelling data produced within this project are therefore representative of a production gas turbine, thus ensuring maximum commercial benefit from the project. The Typhoon, at a size of 4.5-5.0 MW_e, is ideally suited to typical European fully-fired biomass fuelled combined cycle applications. ALSTOM have also established a scale relationship between this size of gas turbine and medium sized industrial gas turbines at around 40 MW_e to cover larger plant applications.

The combustor was designed, manufactured and delivered in Delft in March 1998 and the integration in the Delft test rig was completed in June 1998 (figures 1,2 and 3). The fuel feed was modified, a steam supply has been installed and a electrical heating system to supply combustion and cooling air to the gas turbine combustor has been built. Experiments have been done to assess the steady state behaviour of the combustor (table 2). The dynamic behaviour of the combustor was determined by measuring the response of the combustor to a step change on the fuel feed. The experimental results have been used to develop and validate the steady state and dynamic models of the combustor.

TU Delft
Delft University of Technology

Experimental test facility



Laboratory for Thermal Power Engineering

Figure 1. The Delft test facility.

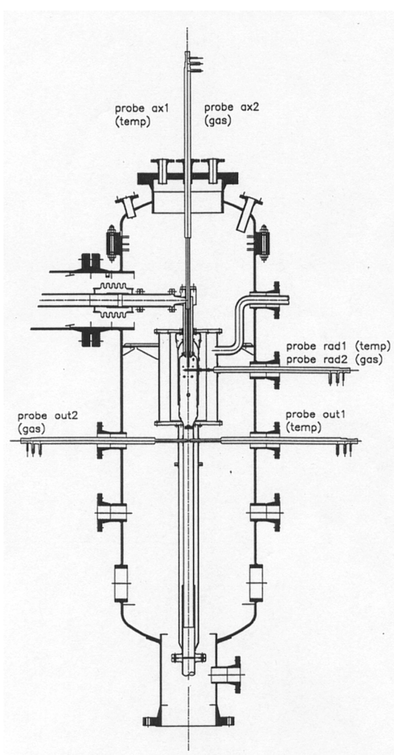


Figure 2. The combustor.

System Pressure	4 bar
Mass Flow LCV gas	557 kg/h
Temperature LCV gas	800 °C
Heating Value LCV gas	4.06 MJ/kg
Mass Flow Air	2200 kg/h
Temperature Air	350 °C
Auxiliary Fuel (start-up)	Methane

N_2 (+Ar)	37.5 vol%
H_2O	24.0 vol%
CO_2	15.6 vol%
CO	8.90 vol%
H_2	7.38 vol%
CH_4	5.22 vol%
C_2H_4	1.44 vol%
C_2H_6	0.26 vol%

Table 1. Design conditions.

Exp.	press.	λ gf.	St/air	Date/Exp.nr
	[bar]	[-]	[-]	
1	5	0.3	0.10	980708, 980715
2	5	0.4	0.10	980623
3	5	0.5	0.10	981002B
4	5	0.4	0.05	981019
5	4	0.3	0.10	981007A
6	4	0.5	0.10	981123
7	7	0.3	0.10	981007B
8	7	0.5	0.10	990121

Table 2. Operating conditions steady state experiments.

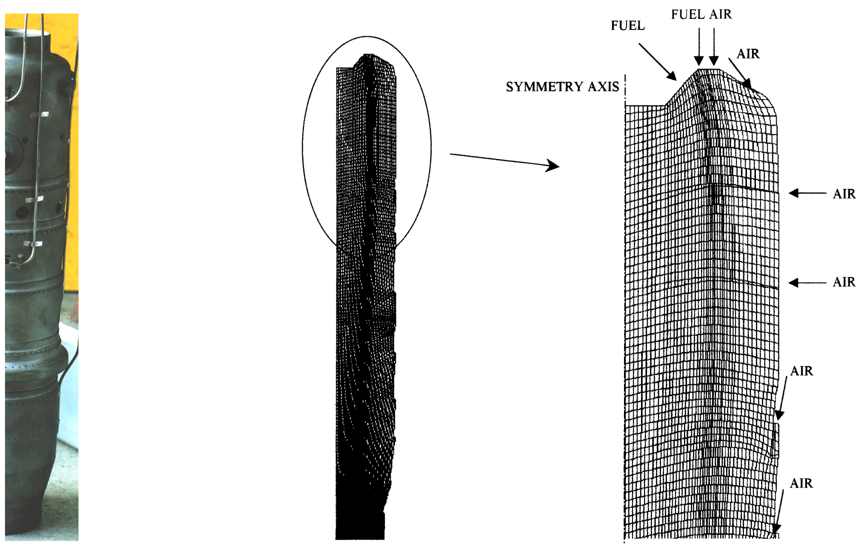


Figure 3. The modified Typhoon combustor and the 2D grid.

4.2 Numerical simulation of the steady state and dynamic behaviour of the combustor

The flow within the combustor has been modelled by solving governing equations for the conservation of mass and momentum in the gas phase.

The effects of turbulence are modelled using the k - ε model, which solves transport equations for turbulence kinetic energy and dissipation rate of the kinetic energy. The model is chosen for its robustness, economy and reasonable accuracy for a wide range of turbulent flows. Details of the model can be found in the work of Launder [1].

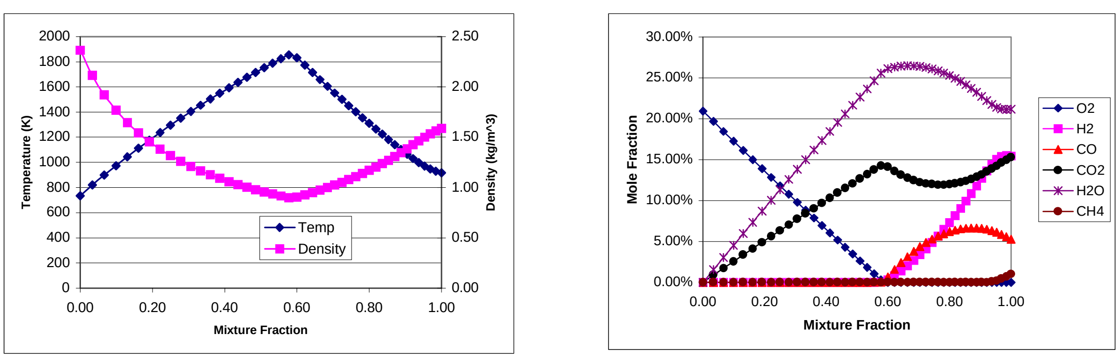
For the simulation of gas phase reacting flows, three approaches are used. They are Generalised Finite Rate model, Equilibrium Mixture Fraction/PDF model and Non-equilibrium Flamelet model.

In the generalised finite rate approach, the species transport equations are solved for each species participating the chemical reaction. The source terms of the species transport equations are expressed by the net rate of production of the species concerned. The Arrhenius model and the eddy break-up model [2] are used in evaluating the species rate of reaction.

The generalised finite rate approach is suitable for modelling flows where the reaction scheme is simple with the number of reactions small and the reaction chemistry well defined. However, for LCV fuel combustion the number of reactions and the species participating the reaction are large, and the reaction scheme complex and not well defined. Using the generalised finite rate approach would be computationally expensive.

The equilibrium mixture fraction/PDF approach does not require the solution of transport equations for individual species within the system. Instead the transport equation for the mixture fraction is solved. The concentrations of individual species, the mixture density and temperature in the system are derived from the predicted mixture fraction distribution.

The species concentrations, the mixture density and temperature as functions of mixture fraction are determined prior to the reacting flow simulation from the chemical equilibrium solutions.In the chemical equilibrium approach, the detailed reaction mechanism of the reacting flow is not required. With the specified species involved, the inlets and operating



(a) (b)

Figure 4. Equilibrium state of a LCV system.

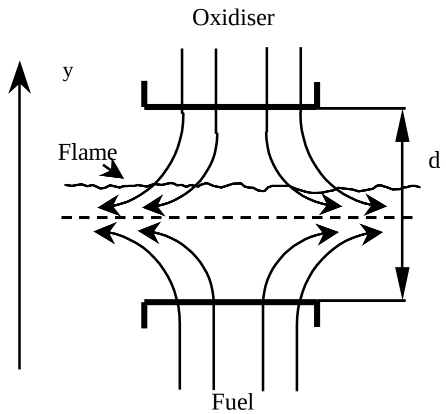


Figure 5. Laminar counter flow diffusion flamelet.

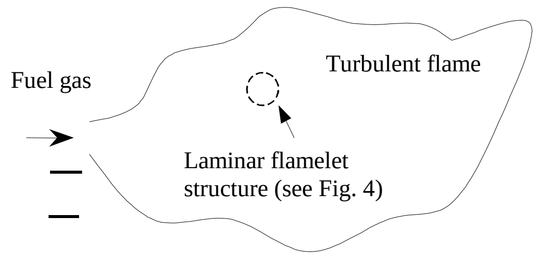


Figure 6. Turbulent diffusion flame.

conditions in the system, the state of chemical equilibrium of the system is solved based on the minimisation of the Gibbs free energy. The assumption is that the species reach chemical equilibrium as soon as they are mixed, i.e. an infinitely fast chemistry. Figures 4 (a) and (b) show the mixture density, temperature and the concentration of the main species of a typical LCV system (test condition for 08/07/98 experiment at Delft) as functions of mixture fraction.

The advantage of the Equilibrium Mixture Fraction/PDF approach is that no detailed knowledge of the reaction mechanism is required. Intermediate species formation, dissociation effects, and the coupling between turbulence and chemistry is taken into account. The approach is also computationally efficient as it avoids the solution of a large number of species transport equations. However, as mentioned earlier one major assumption of the approach is that of infinite fast chemistry. It assumes that the species reach thermal-chemical equilibrium as soon as they mix. This assumption can be invalid in many reacting systems where the reaction chemistry is not fast, i.e. the system is not in thermal-chemical equilibrium.

A flamelet is a 1-D representation of counter flow laminar flame. Within the flamelet structure a complete set of governing equations for the laminar flame are solved. These include the conservation of mass, momentum and energy, and the species transport equations. The inputs to the 1-D laminar flame solution include the boundary conditions in terms of fuel/oxidant stream velocities, temperature, species composition, the operating pressure, and the detailed reaction chemistry. Figure 5 shows the schematic representation of a flamelet structure.

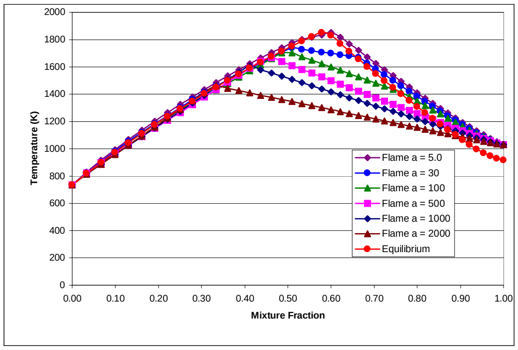
The Non-equilibrium Flamelet model views the turbulent flame as an ensemble of 1-D laminar flamelet structures embedded within the turbulent flow field [3, 4, 5], as depicted in figure 6.

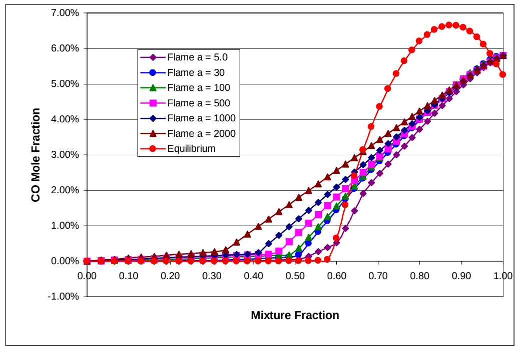
A flamelet is generally characterised by a characteristic strain rate. In turbulent flames the strain rate of a flamelet relates to the local turbulence kinetic energy, turbulence dissipation rate and mixture fraction variance via a scalar dissipation parameter.

In reacting flow simulation using the flamelet model, a set of flamelet solutions are generated based on the reaction systems to be used in the simulation. These solutions are stored as flamelet libraries in the space of mixture fraction, mixture fraction variance and scalar dissipation. These libraries are then used in the simulation of the combustion system.

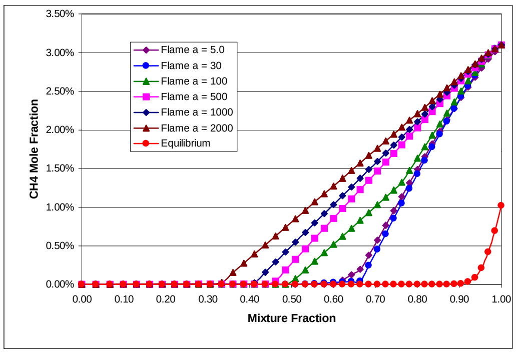
Figures 7(a) – (d) show the mixture temperature and the example of species concentration of a typical LCV system as functions of mixture fraction for a range of characteristic strain rates. The results of the equilibrium state are also show for comparison.

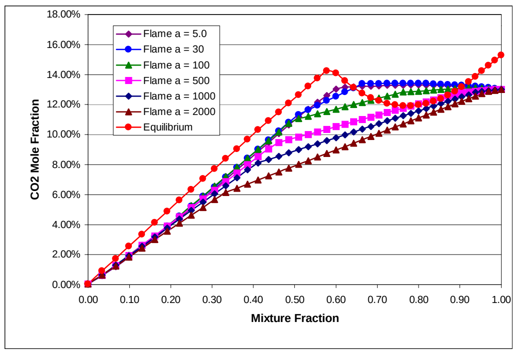
The figures show that as the flame strain rate increases, the flame temperature decreases as the result of flame stretching. The flame eventually extinguishes when the strain rate reaches a critical value. Notice also that the species concentration varies greatly with the strain rate. Comparison with the equilibrium results shows that at the fuel-rich region of the flame the equilibrium assumption can be invalid.





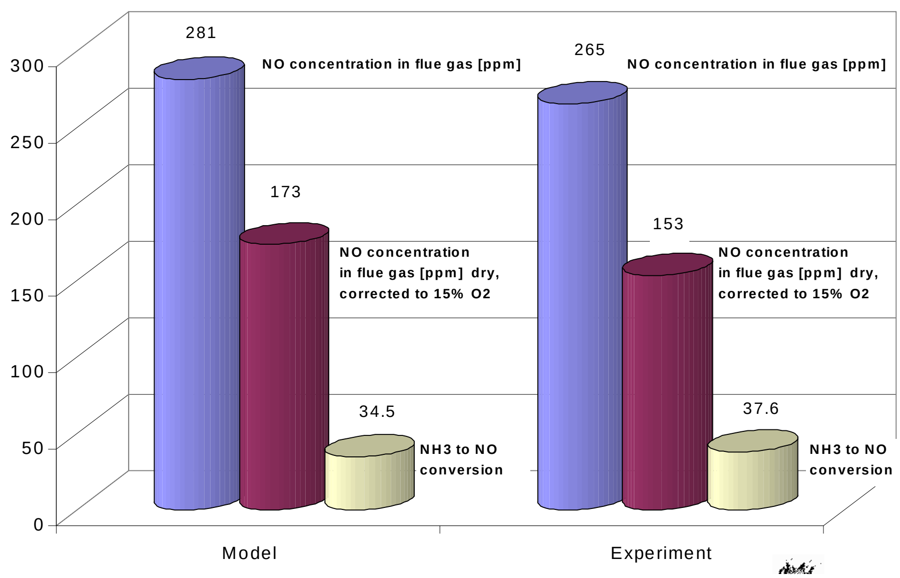
(a) (b)





(c) (d)

Figure 7. Flame temperature and species mole fraction at different strain rates.



980708 Figure 8. Comparison of calculated and measured NO emissions.

The steady state simulation was done based on the test conditions used in the experiments carried out at Technical University of Delft (Netherlands). The test conditions for the simulation results presented in this report are shown in Table 3.

Table 3. Test conditions (based on the experiment carried out on 08/07/1998).

System Pressure	**bar**	5.0
Inlet Temperature	**K**	
LCV Gas		1029.0
Combustion Air		734.0
LCV Gas Composition	**vol%**	
CO		5.8
H2		5.5
CH4		3.1
C2H4		0.4
CO2		13.0
H2O		28.2
N2		44.0

Table 4 shows the comparison of the flue gas conditions with the measured results.

Table 4. LCV flue gas composition and temperature.

		Measured	**Adiabatic PDF**	**Non-adiabatic PDF**	**Multi-strain Flamelets**
CO2	vol%	8.50	6.90	7.14	6.55
H2O	vol%	13.00	12.36	12.80	13.25
N2	vol%	69.50	69.70	69.37	69.37
O2	vol%	8.20	10.97	10.62	10.68
CO	ppm	10	371	442	500
NO	ppm	258			
Temp	K	1433	1403	1440	1434

There are a number of factors that may influence the degree of agreement between the simulation and the experiment data. These are listed as follows:

- Representation of combustor geometry by the computational grid. Certain simplifications have to be made on the meshing of cooling rings on the combustor. This may distort the secondary air inlet conditions used in the simulation.

- Choice of physical models for flow simulation. Correct use of physical models, especially the turbulence model, can have important implications on the flow field simulation and on the results of conserved scalars relating to the chemical reaction simulation, i.e. the system energy, and the mixture fraction and the mixture fraction variance.
- Choice of physical models for reaction simulation. The chemical equilibrium model assumes the instantaneous reach of thermal-chemical equilibrium of the reacting species. This may not be the case in the actual reacting system, especially in the fuel-rich region of the system. The flamelets model takes into account of the non-equilibrium effect of the chemical reaction. However, choice of reaction chemistry is critical in using the flamelets model. In particular, CH_4, CO chemistry will have major influence on the correct level of CO prediction. This is still an active research area.
- Disturbance of flow field by the sampling probe in collecting the experiment data. The influence of sampling probe is not included in the simulation.

The steady state behaviour of the combustor has also been simulated with the FLUENT CFD code using a 2D computational grid (figure 3). Turbulence, radiation and chemical reactions of the main fuel components have been modeled using respectively the k-ε turbulence model, the P1 radiation model and the PDF equilibrium and the laminar flamelet chemical models. The formation of NO_x from fuel nitrogen has been simulated using a newly developed model describing the conversion of ammonia into NO and NO_2 (figure 8).

In conclusion, the techniques of computational fluid dynamics (CFD) have been applied to the simulation of LCV gas fuel combustion inside a gas turbine combustor. Physical models, the flamelet model for chemical reaction simulation in particular, have been identified and used in the simulation of the LCV combustor.

The steady state simulation of the LCV gas turbine system based on the experiment conditions has been performed. The results are compared with the available experimental data. Reasonable agreements between the simulation and measurement have been achieved. It is believed that the techniques of CFD provide a powerful tool in assisting the design of energy efficient combustion system.

4.3 Simulation of a BIGCC plant

If biomass is to be successful as a fuel, it must not only be environmentally friendly, but also economically viable. Biomass integrated gasification combined cycle (BIGCC) is a particularly promising new technology. A major factor in developing and assessing the technical suitability of a BIGCC design is the availability of computer models of the power station, which enable designs to be rapidly evaluated. When developing a commercial scale BIGCC power station, it is essential that the design can be suitably controlled at all possible load factors and that the plant can operate safely during the occurrence of a fault. To enable this work to be undertaken, well documented and validated dynamic models of all the power station components are required. The Delft test facility provides an excellent opportunity to carry out model development and validation work for a biomass fuelled gasifier and for a low calorific value fuel gas turbine combustion can. The arrangement of the Delft facility allows many accurate measurements to be made and recorded, both during steady state operation and dynamic manoeuvres. The availability of these models enables plant performance calculations, control system design and safety analysis work to be carried out with a good degree of confidence in the quality of the results.

It was originally intended to modify an existing coal gasifier dynamic model to simulate the biomass gasifier. However, it was soon apparent that the chemistry of biomass gasification is significantly different to that for coal. This is mainly due to the significantly higher volatile content of biomass. Consequently, the chemistry of the biomass gasifier model was rewritten. Two approaches were taken; one relying on chemical reaction kinetics and the other an extension of a widely used semi-empirical model for coal. The models were validated against static and dynamic data from the Delft facility. During the steady state evaluation, it was found that the model based on reaction kinetics was very sensitive to initial data, such as the biomass volatile content and bed contents. The semi-empirical model performed well during both steady state and dynamic testing.

The combustor model consists of separate air nozzle, gas nozzle and combustion chamber modules. The model calculates the fundamental and frictional pressure drop of the combustion gas, the gas temperature rise due to combustion, the change in gas composition and the wall temperature. As this is a lumped parameter model, the wall temperature is assumed to be uniform throughout.

To validate the gasifier and combustor models, a dynamic test was carried out at the Delft test facility. After a steady state period of 5 hours, the biomass feed rate was reduced from 90% to 81% and all major control systems apart from the pressure control system were uncoupled. After a steady state period, the feed rate was further reduced to 72% before returning to 90%. Figure 9 shows a good agreement between the simulated and actual temperature in the bubbling bed and freeboard. The response of the combustor wall temperature to the change in gasifier feed rate is shown in figure 10. The variation of gas composition in the gasifier and combustor models also agreed well with experimental data. The validation tests show that the models describe the dominant characteristics of the actual plant and are therefore suitable for use during the development of control systems and for undertaking failure analysis studies. As a result of these tests, some areas for improvement in both models were also identified.

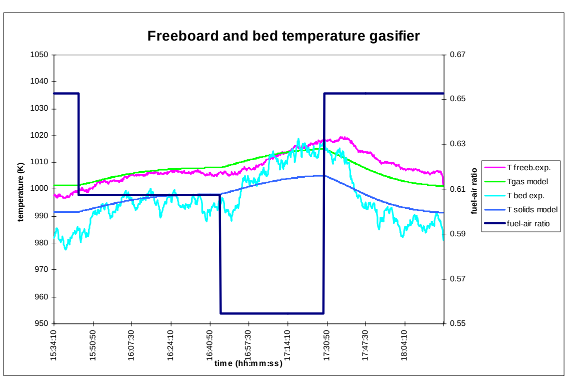


Figure 9. Gasifier response to a feed rate change.

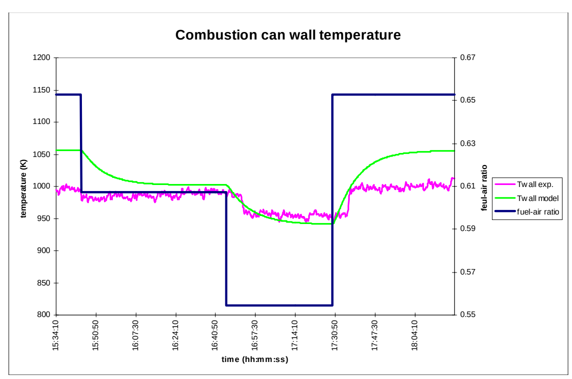


Figure 10. Combustor can wall temperature.

To investigate the steady state and dynamic performance of a biomass fuelled power station, a design based on a 76 MWe combined cycle power station was developed. This power output is considered to be sufficiently large to demonstrate biomass technology at a commercial level. To develop this design and derive certain fundamental parameters, a static model of the plant at design conditions was first written. The proposed plant layout and the corresponding steady state operating conditions are shown in figure 11. Using data from the static model, dynamic models of individual plant components were linked together and parameterised to produce a dynamic model of the complete plant. The graphical interface for this model is shown in figure 12. To enable the power station to operate dynamically, an overall control system was designed and implemented in the model. Once the model was complete, dynamic tests were carried out.

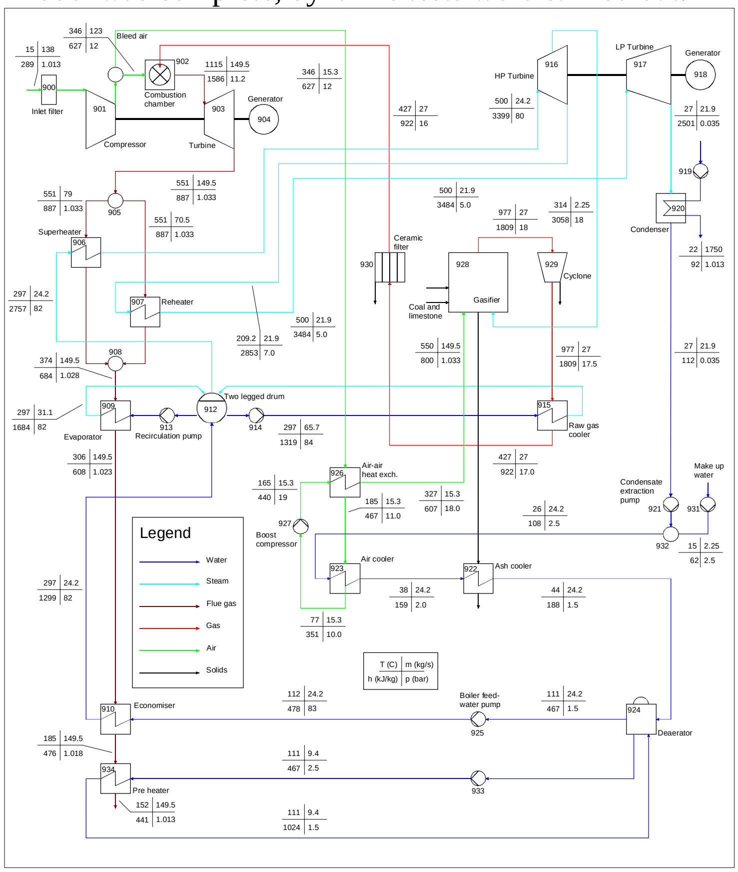


Figure 11. Layout of proposed BIGCC power station.

This design would incorporate a GE Frame 6B gas turbine converted to run on low calorific value fuel gas. This turbine would produce approximately 42 MW_e, with 34 MW_e being produced by the steam turbine.

To simulate the BIGCC power station, new models for a 2 leg evaporator with steam drum and a deaerator were written. Once the plant component models were assembled, control systems were added for the steam drum, gasifier, gas and steam turbines and overall load control. Additionally, safety systems to remove stored energy, in the form of steam or fuel gas, during an emergency shutdown were designed and added.

The behaviour of the plant during several operating scenarios was tested. These included full load acceptance, peak load acceptance, load reduction and full load rejection.Of all the dynamic tests, the most critical is a full load rejection. This test is characterised by a sudden opening of the grid circuit breakers in the gas and steam turbine generators and an instantaneous reduction in demanded power from full load to no load idle. As a consequence of the sudden disconnection from the grid, the gas turbine accelerates, which results in the control system closing the gas turbine fuel valve, thereby limiting the initial turbine overspeed to about 1% (figure 13). The result of closing the governor valve

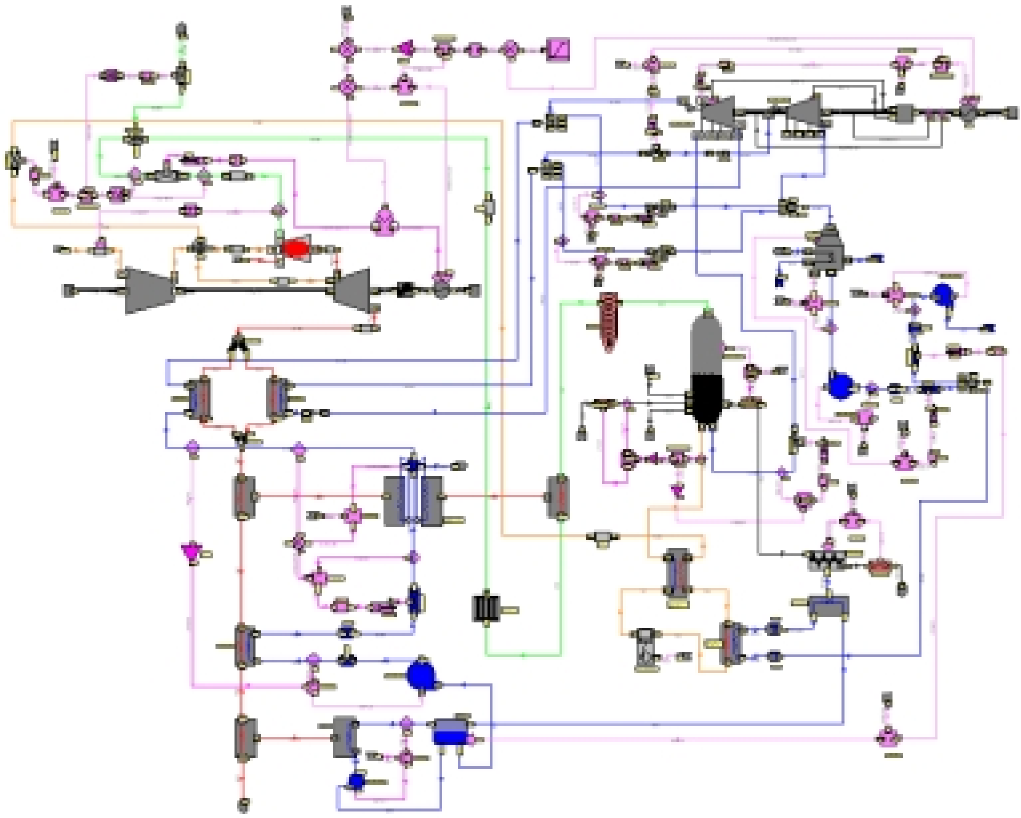


Figure 12. Dynamic model of BIGCC plant.

is a very fast build-up of pressure in the gasification system. This gas is vented to atmosphere through the flare valve, which opens as the gas turbine fuel valve closes.
Figure 14 shows that the flow rate through the flare valve is initially very high due to the momentary build up of gas upstream of the closed fuel valve. The flare valve closes when the gasifier fuel gas production rate is reduced down to that required by the gas turbine for operation at no load idle.

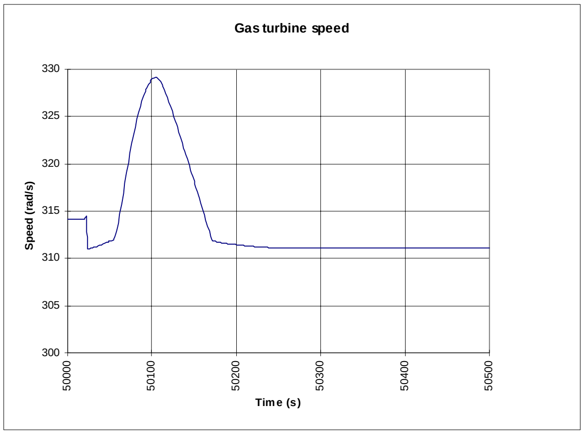


Figure 13. Gas Turbine Speed.

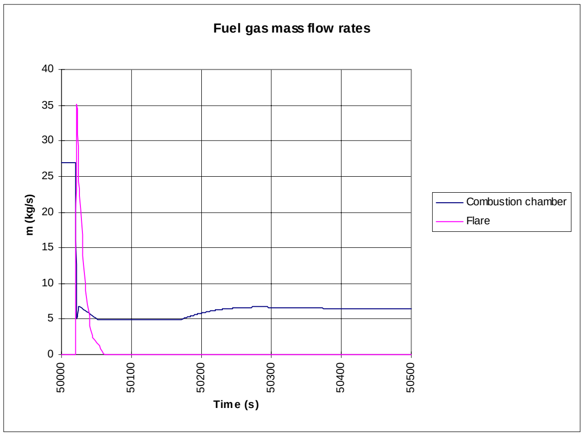


Figure 14. Flare Valve Operation.

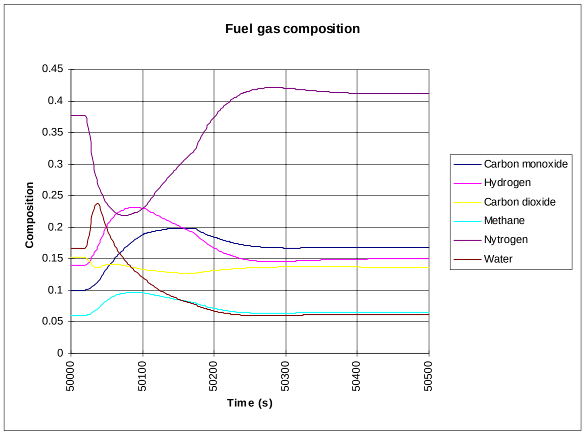


Figure 15. Fuel Gas Composition Changes.

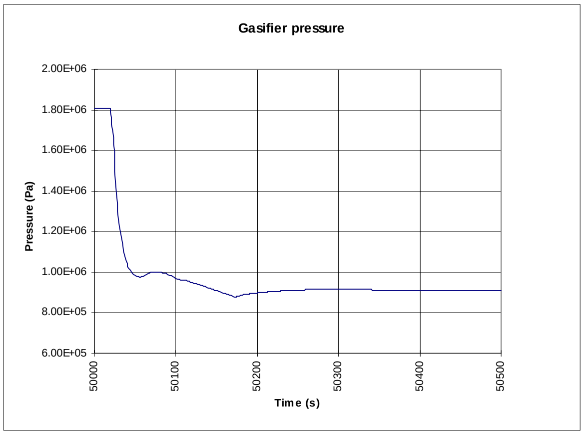


Figure 16. Change in Gasifier Pressure.

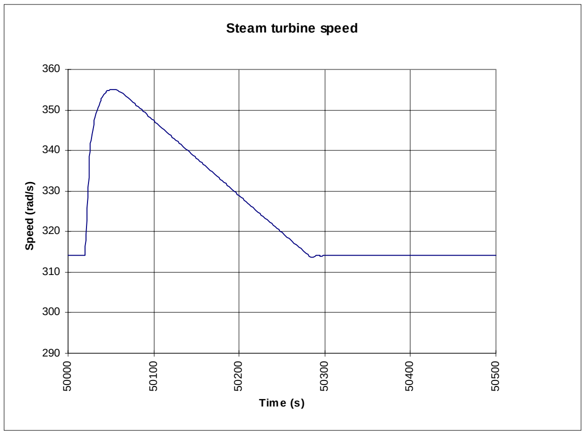


Figure 17. Steam Turbine Speed.

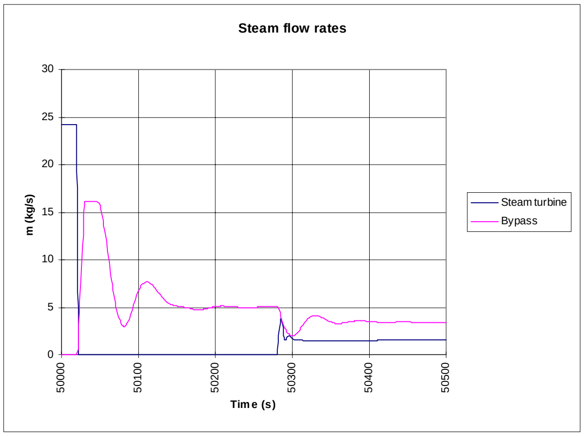


Figure 18. Steam Turbine By Pass Flows.

As figure 13 shows, the turbine accelerates after first slowing down. Figure 15 shows that this is due to a significant change in the fuel gas composition produced by the gasifier. The gasifier control system, as currently installed, is not able to prevent these effects. In control terms, the gasifier can be classified as a multiple input/multiple output system, with a strong degree of cross coupling between all inputs and outputs, which makes it very difficult to control using classical control techniques. Currently, work is underway to apply more advanced control techniques to gasifier control. Figure 16 shows that a major factor in the change in fuel gas composition is the change in the gasifier operating pressure from 18 to 9 bar.

During a load rejection, the steam turbine responds similarly to the gas turbine (figure 17). The control system acts quickly to close the steam inlet valve, resulting in the steam manifold pressure rising significantly. Figure 18 shows the protective action of the steam bypass facility, which dumps the live steam straight to the condenser. As the shaft speed falls, the steam inlet valve opens to maintain the no-load demand speed of the turbine; the bypass valve remains part open to dump excess steam.

This work has resulted in the development of a dynamic model of a 76 MWe biomass fuelled power station that is valid from no load idle to maximum load. The plant efficiency at 100 % load is predicted to be 44 % (LHV). The dynamic model has been used to develop and evaluate control schemes for individual plant components and for global plant control. Carrying out this process using a model rather than the actual plant is considerably easier, cheaper, faster and safer. The global control scheme developed here has been shown to be capable of controlling the complete plant in the event of a full load rejection - the most severe fault condition likely to be encountered.

The layout of a BIGCC plant has been determined for two different power output sizes: 7 MW_e based on an AGT Typhoon gasturbine and 77 MW_e based on a GE Frame 6B gasturbine. The steady state properties of two BIGCC plant layouts have been determined using flow sheeting programs.

5 EXPLOITATION PLANS AND ANTICIPATED BENEFITS

The experimental information obtained by TU Delft with regard to combustion of low calorific value fuel gas will be used to develop validated, mechanistic models which will be offered as tools to organisations engaged in the design, optimisation and assessment of energy production systems, bases on biomass utilisation. In order to dissiminate information concerning these models, presentations describing their application will be made at conferences and papers will be published in the open litterature.

TU Delft continues to be involved in a number of nationally funded multi-partner R&D projects in which the University's test rig is being used to provide data with regard to the fate of producer gas components (such as ammonia, tar and several trace compounds) during gasification, high temperature gas cleaning and gas turbine combustion issues.

Alstom Gas Turbines Ltd. will utilize the information on gas turbine combustion of LCV fuel gas obtained during this project to develop and exploit gas turbine technology for LCV fuel applications, particularly for those which contain fuel-bound nitrogen.

The knowledge with regard to steady state and dynamic system modelling of BIGCC systemes will be utilized for performance evaluation and control system design.

Fluent Europe Ltd, will implement the results in future products and apply the results in the services to its customers.

6 REFERENCES

1. B. E. Launder, D. B. Spalding. *Lectures in Mathematical Models of Turbulence*. Academic Press, London, England, 1972.
2. B. F. Magnussen, B. H. Hjertager. "On Mathematical Models of Turbulent Combustion with Special Emphasis on Soot Formation and Combustion", *16th Symposium (Int'l) on Combustion*. The Combustion Institute, 1976.
3. K. N. Bray, N. Peters. "Laminar Flamelets in Turbulent Flames". *Chemical Reacting Flows, Ed. P. A. Libby, F. A. Williams*, Academic Press, 1994.
4. N. Peters. "Laminar Diffusion Flamelet Models in Non-Premixed Combustion". *Prog. Energy Combust. Sci.*, 10:319 – 339, 1984.
5. N. Peters. Laminar Flamelet Concepts in Turbulent Combustion". *21st Symposium (Int'l.) on Combustion*, 1231 – 1250, The Combustion Institute, 1986.