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Modelling as an Aid to Biomass Combustion in Plant Design

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Solid biomass materials are recognized as a sustainable energy source worldwide. In particular, lump biomass has considerable potential for exploitation as fuel in small-size underfeed stokers. The paper considers the design features of the underfeed stoker and its advantages in the burning of biomass. Some experimental results are given to indicate the plant parameters to be modelled. An initial modelling approach is described for single-particle solid fuel combustion to predict flow patterns using the FLUENT Computational Fluid Dynamic (CFD) code. Predictions are compared against available experimental results showing reasonable qualitative and quantitative agreement. The paper concludes with information on the constraints on the modelling study and proposals for new work.

Keywords: Biomass, modelling, plant design, *and* underfeed stoker.

INTRODUCTION

Biomass may be defined as grown, organic material having the capability to undergo conversion to liquid, gaseous, or solid fuels with or without significant pretreatment processes. The focus of this paper is on lump-size dried forest wood fuel for use in small stoker boiler systems. The assumption is that fuel woods are derived from sustainably managed forests and are substantially neutral regarding net carbon dioxide emission.

Total biomass usage (including wastes) amounts to some 14% of the world energy supply. This is skewed heavily towards developing countries; for example, 84% in Cambodia and 26% in the Philippines. Current biomass utilization in the European Union is less than 3% of primary energy but with provision for an increase of about 5% by 2025. The attraction of biomass is due not only to its availability as a fossil fuel substitute but also to its lower air pollution potential compared to conventional oil and coal.

Boiler plants fuelled by biomass vary widely in size from a few kW to 50 MW. There is a need in many developing countries for low-output boilers (<500 kW) to supply steam/hot water to small process industries such as textiles, metal finishing, and food. Since the early 1990s, research at the University of Portsmouth has considered the design and operation of such equipment. Likewise, staff from De La Salle University in Manila, have made essential inputs to the work involving both experimental and modelling studies. Modelling for process parameters, such as thermal efficiency and air pollutants, is necessary due to the large number of independent variables affecting the combustion process—a modest estimate identifies 26 factors.

The current paper presents a background of the biomass study, starting with a description of the fuels and combustion plants. This leads to an outline of the modelling approach and to associated results to identify current progress.

PROPERTIES OF WOOD FUELS

Table 1 compares the properties of a typical wood fuel with that of a typical steam-raising coal. For the biomass, the table shows the relatively high concentrations of oxygen and volatile matter. Some 70% of the total heat release of the biomass is contained in the volatile matter and this must be accounted for in a substantially gas phase modelling procedure. A large difference is apparent in the energy intensity values (HCV) for the two fuels meaning that for equal energy, input feeder systems should be upsized for biomass in relation to coal. It is seen that the biomass contains no measurable sulphur and only a small amounts of nitrogen. This gives the potential for low emission of SO_x and fuel NO_x.

Table 1. The Properties of Wood and Coal

Content	Softwood	Coal
Carbon	50.6	78.7
Hydrogen	6.2	5.0
Oxygen	43.0	8.9
Nitrogen	0.1	1.7
Sulphur	0.0	1.5
Ash	0.1	3.7
Volatile Matter	87.3	36.1
HCV *(MJ/kg)*	20.4	33.6

Ash burdens appear much lower for biomass than in the case of coal. However, biomass ash is very light and friable and is liable to pass through the boiler system as entrained particles in the gas stream. In addition some biomass fuels contain relatively high concentrations of alkali compounds. These can provide low melting point ashes causing fouling of heat transfer surfaces. Moisture content will have a substantial effect on combustion rate and thermal efficiency. Raw wood fuels can have moisture contents approaching 60% and, for this reason, need to be dried to values below 30%.

It is evident that fuel properties need to be carefully matched to style of combustion plant. In the case of high volatile matter content biomass fuels the underfeed principle can be used to limit smoke emissions and is well suited to the design of simple, small scale boilers.

FEATURES OF UNDERFEED STOKER DESIGN

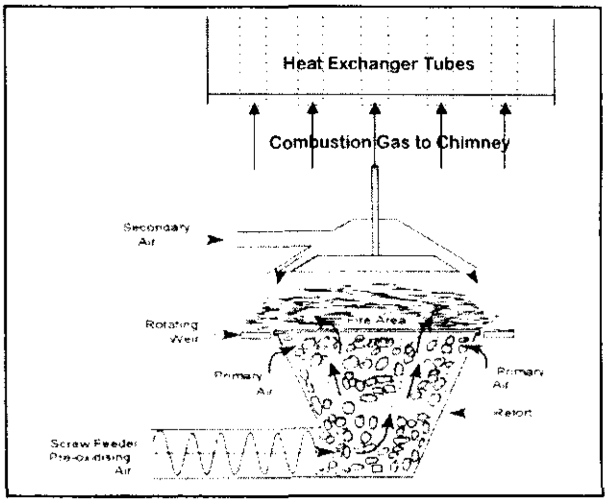

Figure 1. Schematic Diagram of the Underfeed Stoker

A schematic diagram used in the experimental work for this study is shown in Figure 1. The lump solid fuel of hydraulic size about 25 mm is contained within the cone shaped retort. Two air supplies enter the fuel bed namely; pre-oxidizing air and primary air admitted near the top of the bed. The fire area is at the top of the retort. Since the fuel is fed at the base of the retort the evolving volatile gases are consumed within the high temperature bed surface region. Partially burnt gases escaping the bed surface are burnt with secondary air. Ash is removed at the top of the retort by means of a rotating weir plate. Hot combustion gases are passed to the inlet of the gas/liquid heat exchanger. In the steady state the rate of combustion at the fuel bed surface is equal to the fuel feed rate.

A substantial series of experiments have been undertaken using the equipment shown in Figure 1. Fuels fired have included bituminous coal, anthracite, oak wood chips and coal/chip blends. The main measurements of interest were thermal efficiency, combustion efficiency and NO_x emission. A typical set of results for coal combustion is shown in Figure 2. The long-term aim of the modelling study is to attempt simulations of these results.

MODELLING APPROACH

The broad features of the system to be modelled comprise the flow pattern and air distribution in the fuel bed and beyond; the heating of the lump fuel, volatile release, pyrolysis, cracking, and gas phase reaction; combustion of the char; heat release to the working fluid and discharge of gaseous and solid products to the surroundings. Various submodels may be used to account for these effects coupled to computational fluid dynamic (CFD) systems of equations for mass, energy, and momentum conservation. Numerical methods are used to solve the equations and the extent of computation depends upon whether steady state can be assumed and on the required dimensionality. Even for simple geometric models and chemical kinetics, 3D transient situations can consume many days of computational time using advanced machines. There is a considerable skill attached to the choice of data, boundary conditions, computational domain and submodel to mitigate such efforts.

Complex models are usually solved in a step wise fashion; for example the geometry of the combustion chamber is discretized, isothermal flow fields may be solved followed by imposition of temperature effects; these solutions may be used as input conditions for various stages of combustion and pyrolysis; models for the formation of trace pollutants may be added to the CFD simulations. It is important that the model results are compared against simple experiments wherever possible. Sensitivity analysis on data should be undertaken to access accuracy of predictions. Problems of scale up should be addressed, particularly with regard to the extrapolation of bench top equipment results to the performance of full scale plant.

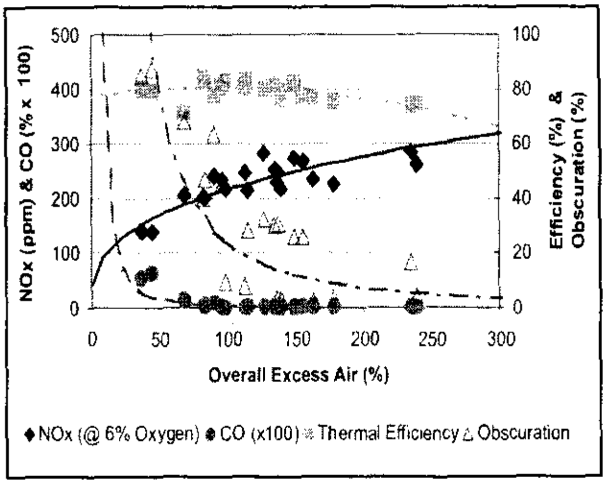

Figure 2. Experimental Results for Bituminous Coal Combustion in the Underfeed Stoker

A number of comprehensive reviews consider the basis, structure and capability of modern numerical models. Abbas et al. (1996) have described the combustion process for coal and biomass fuels and factors influencing thermal plant performance. A detailed explanation of combustion modelling and use of equations is given by Eaton et al. (1999). Comparisons of experimental and model results are found in Bruch et al. (2003) and Yang et al. (2003). Santos (2002) presented substantial experimental results for the combustion of coal and biomass and initiated a comprehensive mathematical study. Some of the results of this work are reported in the following sections.

COMBUSTION MODEL STRUCTURE

Based on the description given in the section on Modelling Approach, the first stages in the procedure arise as (a) single particle model for devolatilization, (b) single particle combustion model including devolatilization, (c) the use of a CFD model to describe flow patterns in the zones of the underfeed stoker. For present purposes model outcomes are restricted to high volatile coal

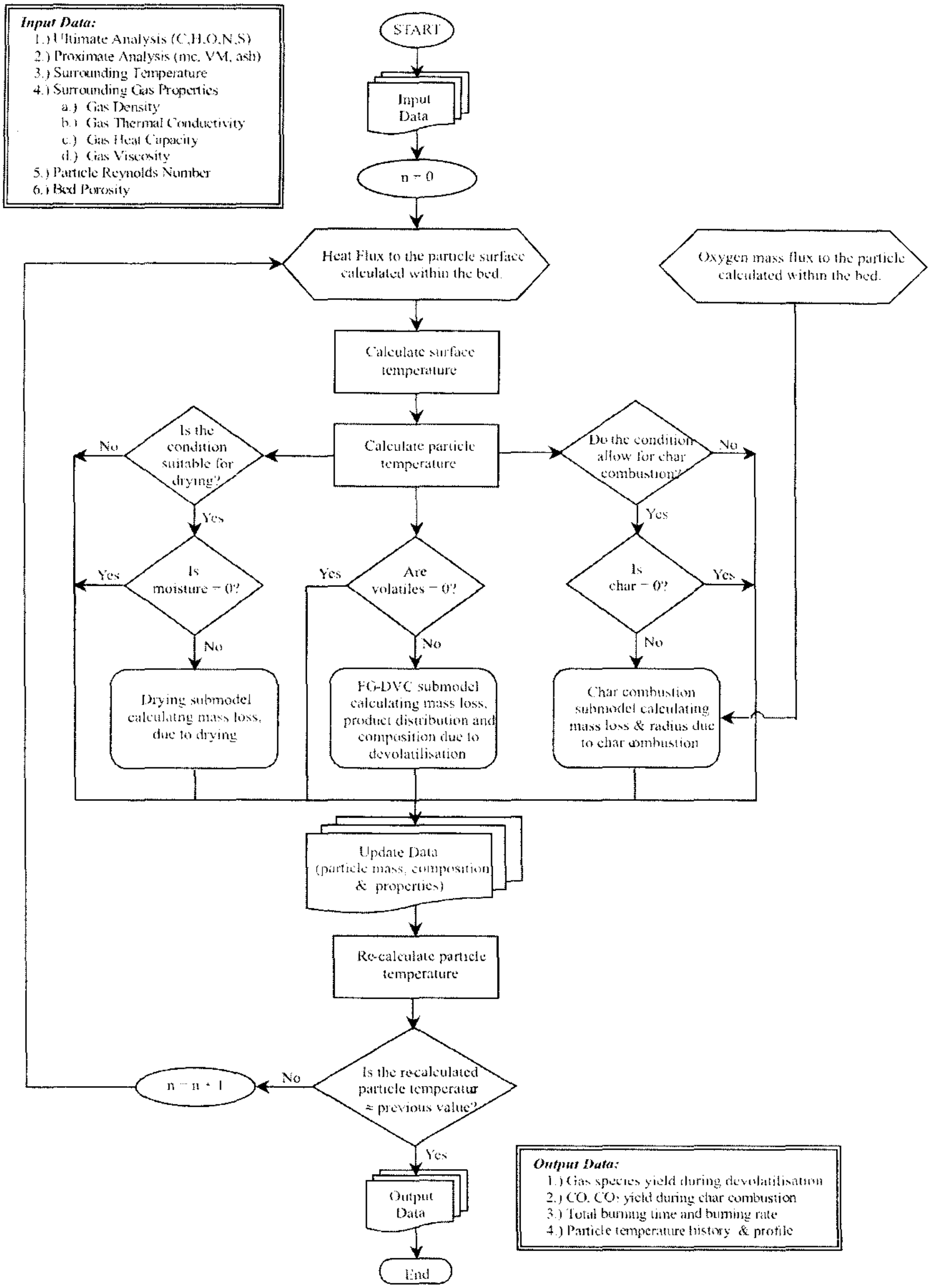

Figure 3. Algorithm for Solution of Particle Combustion Model

since, in this case, substantial data exists in the literature. Current work by Lim is considering extensions of results to biomass. The outcomes of this phase of the research to plant design relate to the prediction of fuel feed rates and air flow distribution which influence fuel combustion efficiency and NO_x formation.

Devolatilization submodel

This is based on the FG–DVC network model described by Solomon et al. (1992). Inputs to the model comprise the elemental composition and the particle temperature profile or heating rate. Outputs from the model include product distribution of char, tar, and gas as well as mass loss profiles and gaseous species emission rates for such species as CO_2, CO, H_2, H_2O, and HCN. The FG–DVC model is combined with drying and char combustion models to assemble a single particle combustion model.

Single-particle combustion model

The model considers a single, spherical coal particle of 20 mm in diameter at an initial temperature of 298 K and surrounding temperature of 1,273 K. The ambient gas contains prescribed values of excess oxygen and effects of forced convection and particle combustion are taken into account. Heat and mass transfer effects within the pore structure are neglected. A shrinking core model is assumed with diffusion-controlled combustion. The full assumptions and solution procedure are given in Santos (2002). Figure 3 presents an algorithm for the overall combustion model.

CFD model of the underfeed stoker

The geometry of the underfeed stoker was created using GAMBIT software (1998). Both 2D and 3D representations were assembled of a somewhat complex geometry. Zones of the stoker required very different detail in mesh definition. For example, the heat exchanger was assembled from 30 upright cylinders whereas the secondary air ports required special meshing facilities. A geometric model is shown in Figure 4.

The arrangement in Figure 4 was modelled for representative flow parameters using FLUENT CFD code (1998). In the first instance isothermal conditions were assumed and a modified k–e turbulence model applied. Predictions for flow distributions were obtained for 2D geometry in an empty bed.

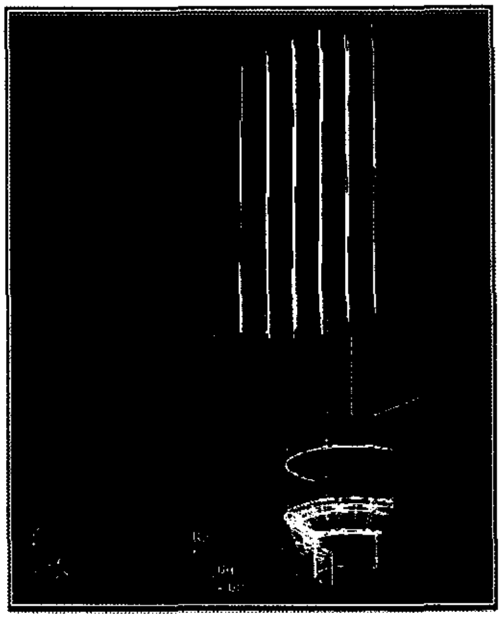

Figure 4. Geometric Model of Underfeed Stoker

SOME MODEL RESULTS

Sample model results are given for devolatilization, particle combustion rate, and stoker airflow distribution.

Devolatilization

Figure 5 shows the mass loss due to devolatilization with time for a 20-mm diameter coal particle subjected to a surrounding temperature of 1,273 K and a heat flux of 50 kW/m^2.

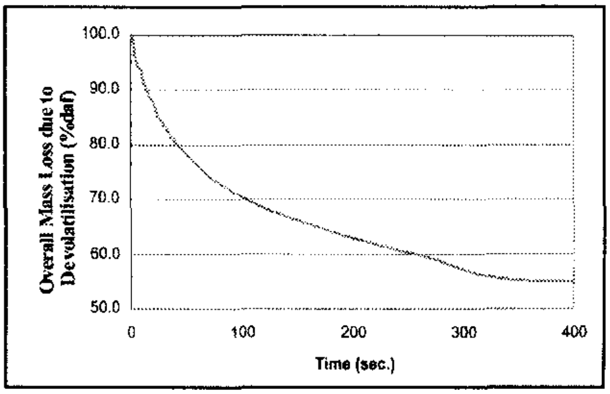

Figure 5. Mass Loss and Devolatilization for 20-mm Coal Particle

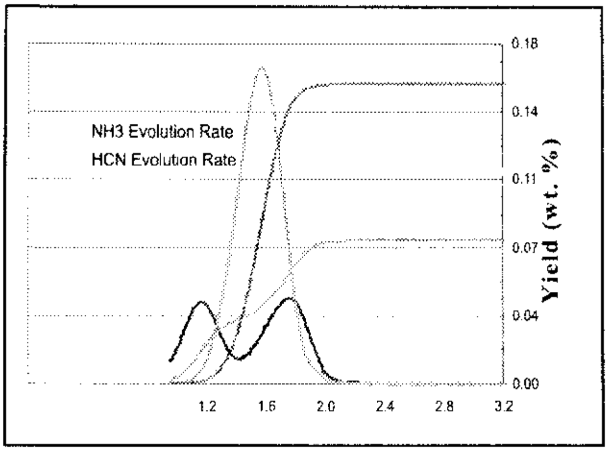

Figure 6. Evolution Rate and Yields for NH_3 and HCN for Coal at a Heating Rate of 10°C/min

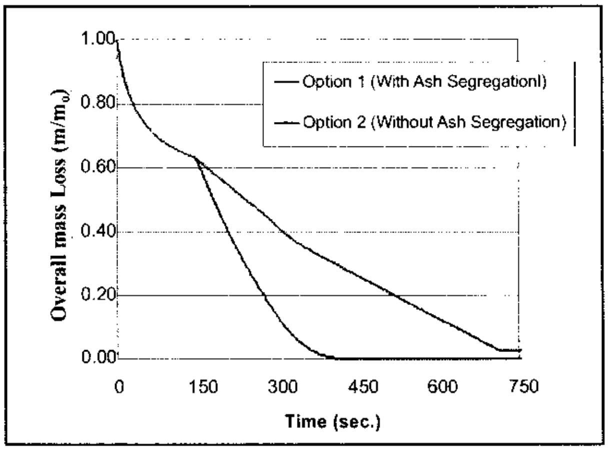

Figure 7. Mass Loss for 20-mm Coal Particle With and Without Ash Segregation

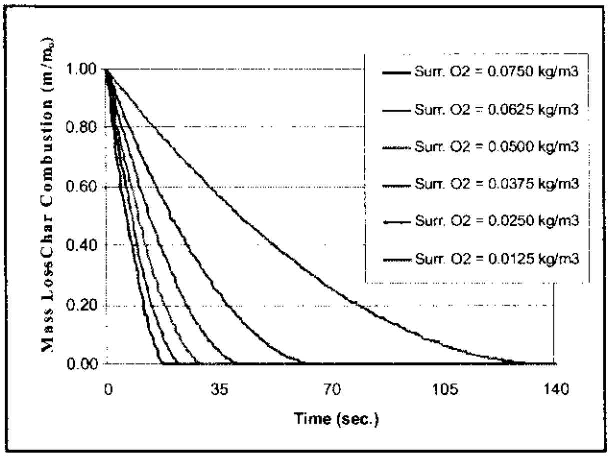

Figure 8. Mass Loss for Char Combustion With O_2 Concentration

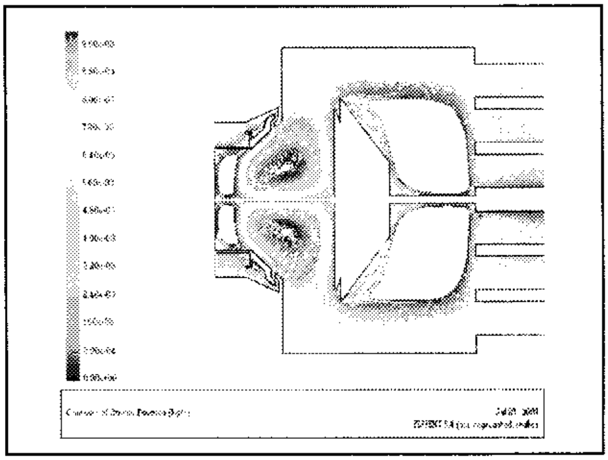

Figure 9. Flowrate Distribution for Underfeed Stoker Using the FLUENT Code

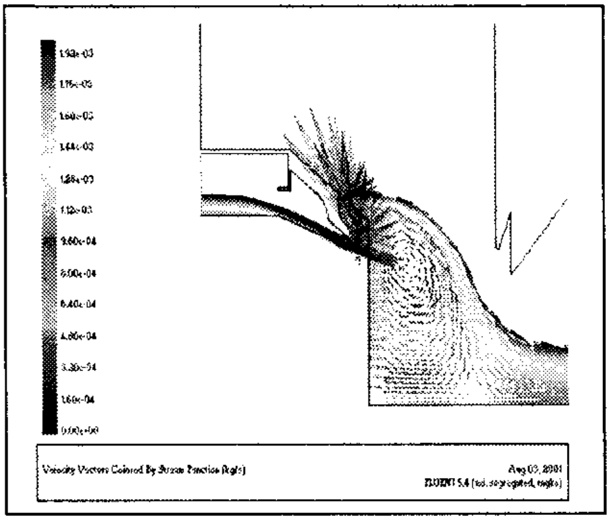

Figure 10. Secondary Airflow Distribution for the Underfeed Stoker

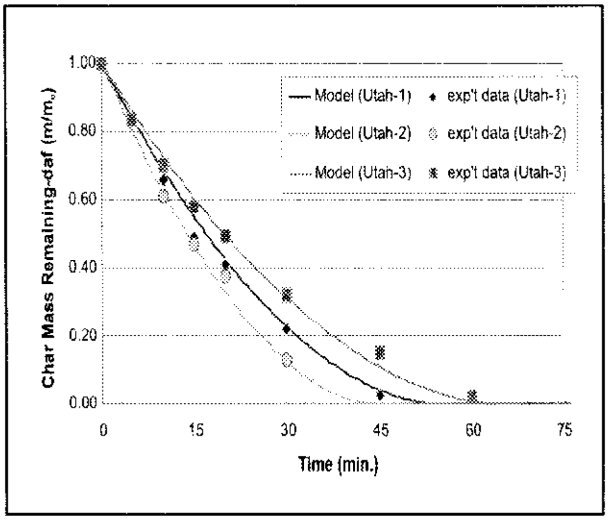

Figure 11. Comparison of Model Results for Char Burnout (Blackham et al. 1994)

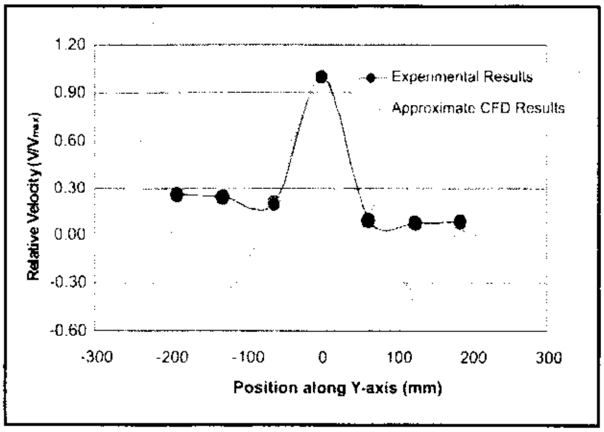

Figure 12. Comparison of Experimental Results for Axial Bed Velocity Profile Against the FLUENT Code Prediction

Figure 6 shows the evolution rate and yields for NH_3 and HCN formation for a heating rate of 10°C/min. These species are important in the prediction of NO_x formation.

Particle combustion

Figure 7 identifies the overall mass loss of the 20-mm coal particle with and without segregation of the coal ash.

Figure 8 shows the sensitivity of the mass loss in the char combustion model to changing external oxygen concentration.

Stoker Airflow distributions

Figure 9 identifies the stream function (kg/s) for flow in the combustion chamber using the FLUENT software.

Figure 10 shows detail of the secondary airflow in the stoker for conditions similar to Figure 9.

VALIDATION OF MODEL RESULTS

Searches within the literature revealed satisfactory agreement between the results of the current model and the experimental data reported elsewhere. Figure 11 compares model results for Utah coal char burnout with furnace heating experimental data at 1,230 K obtained by Blackham et al. (1994).

Similarly, Figure 12 compares the FLUENT Code predictions of normalized velocity along the axis of the underfeed stoker with experimental measurements. These and other results lend credibility to the modelling approach adopted.

CONCLUSIONS

Biomass materials, either from wastes or energy crops, will become an increasingly important sustainable energy source worldwide. There is considerable potential for the improved design of small-size biomass-fuelled thermal plants for use in process industries.

Such improvements are considerably aided by the use of comprehensive combustion models to predict combustion, thermal efficiencies, and pollutant emissions. However, initial model development requires considerable effort and the need for continuous upgrading to accommodate new data sources and improved computational hardware and software.

Validation of results for model components is an essential feature of this process. Compatibility between various submodels and large CFD codes is a problem that requires close cooperation between software developers and engineers.

The current paper has demonstrated the potential of modelling studies to produce useful predictions for limited conditions of solid-fuel combustion. New work is concerned with flow prediction for 2D- and 3D-lump fuel-packed beds. A substantial review of the biomass property database is necessary. Extensions to the solid fuel combustion model outlined here will then be undertaken.

New computer hardware have been purchased with parallel processing capability to shorten lengthy computations.

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