Producer gas fuelling of a 20kW output engine by gasification of solid biomass (ODNRI Bulletin No. 17)

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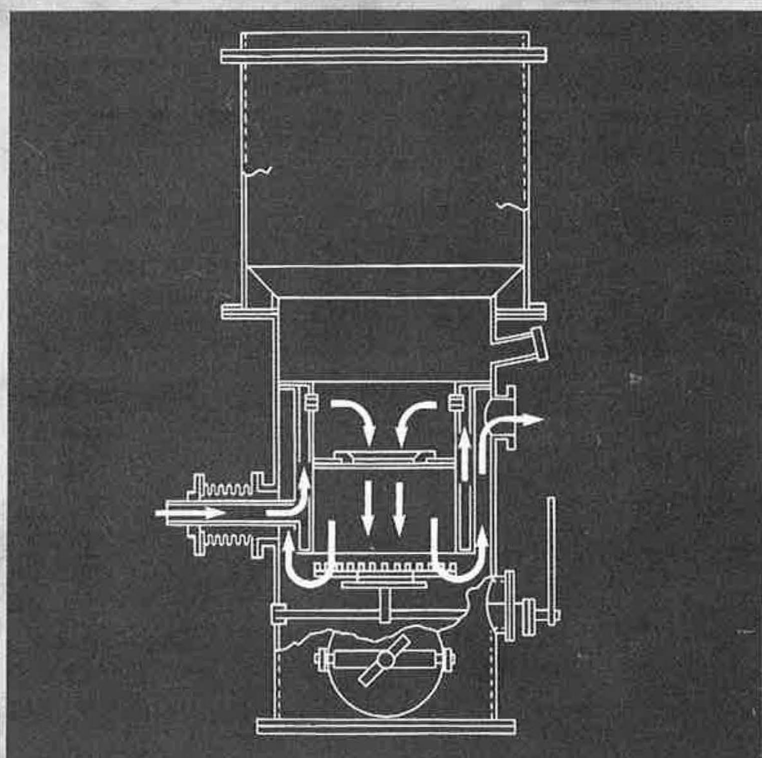

OVERSEAS DEVELOPMENT NATURAL RESOURCES INSTITUTE

BULLETIN

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PRODUCER GAS FUELLING OF A 20kW OUTPUT ENGINE BY GASIFICATION OF SOLID BIOMASS

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Summaries

SUMMARY

Motive power requirements in the range up to 100 kW shaft power are common in developing country processing operations. Producer gas-fuelled systems based upon a relatively cheap and simple manually operated gasifier or reactor using readily available biomass feedstock can offer in some cases an attractive alternative to fossil-fuelled power units.

This bulletin outlines research and development work by the Industrial Development Department of the Overseas Development Natural Resources Institute for 20 kW shaft power output from producer gas derived from solid biomass. Biomass materials such as wood or shells can be carbonized to form charcoal or left in their natural uncarbonized state. In this work both carbonized and uncarbonized biomass fuel has been used to provide producer gas to fuel a Ford 2274E engine, an industrial version of a standard vehicle spark-ignition engine. Cross-draught and down-draught reactor designs were evaluated during trials with this engine. Also different gas cleaning and cooling arrangements were tested. Particular emphasis was placed on practical aspects of reactor/engine operation. This work follows earlier work with a 4 kW shaft power output system using charcoal-derived producer gas.

RÉSUMÉ

Les besoins en source énergétique offrant une puissance à l'arbre allant jusqu'à 100 kW sont courants dans les opérations de traitement des pays en voie de développement. Les systèmes alimentés en gaz de gazogène basés sur un gazéificateur ou réacteur manuel relativement bon marché, simple de fonctionnement et utilisant le substrat des biomasses disponibles peuvent, dans certains cas, se présenter comme une solution intéressante pour remplacer les unités de puissance alimentées par matière fossile.

Ce rapport présente dans ses grandes lignes les travaux de recherche et de développement entrepris par le Départment de développement industriel de l'Institut du développement des ressources naturelles outre-mer relativement à la production d'une puissance à l'arbre de 20 kW obtenue à partir de gaz de gazogène dérivé de biomasses solides. Des biomasses telles que le bois ou les coques peuvent être soit carbonisées pour former du charbon, soit laissées dans leur état naturel. Au cours de ces travaux, du combustible de biomasses carbonisées et non-carbonisées a été utilisé pour fournir du gaz de gazogène afin d'alimenter un moteur Ford 2274E, lequel est la version industrielle d'un moteur de véhicule standard à allumage par étincelle. Des types de réacteurs à mouvement transversal ainsi qu'à mouvement vers le bas ont été évalués au cours des essais avec ce moteur. Divers méthodes de nettoyage du gaz et de refroidissement ont également été testées. Une importance particulière a été accordée aux aspects pratiques de l'opération réacteur/moteur. Ces travaux s'incrivent dans la ligne de ceux qui ont été précédemment conduits avec un système ayant une puissance à l'arbre de 4 kW fonctionnant au charbon dérivé de gaz de gazogène.

RESUMEN

Las operaciones de elaboración de los paises en desarrollo cuentan, a menudo, con requisitos energéticos de hasta 100 kW de potencia al eje. Los sistemas accionados por gas de aire, basados en un sencillo reactor o gasificador manualmente accionado y relativamente económico, que utiliza biomasa fácilmente obtenible, ofrecen, en algunos casos, una alternativa de interés en comparación con las unidades energéticas accionadas por combustibles fósiles.

En este informe, se ponen de relieve los trabajos de desarrollo e investigación realizados por el Departamento de Desarrollo Industrial del Instituto de Recursos Naturales para el Desarrollo Exterior con sistemas de 20 kW de potencia al eje, accionados por gas de aire derivado de biomasa sólida. La biomasa—madera o conchas, por ejemplo—puede carbonizarse para formar carbón vegetal o dejarse en su estado natural no carbonizado. En este trabajo se ha utilizado combustible de biomasa carbonizado y no carbonizado para obtener gas de aire

con que accionar un motor Ford 2274E, modelo industrial de un motor normal de encendido por chispa para vehiculos. Durante las pruebas llevadas a cabo con este motor se evaluaron diseños de reactor de corriente cruzada o descendente. También se realizó la prueba de distintos tipos de enfriamiento y limpieza. Se puso un énfasis particular en los aspectos prácticos del funcionamiento del reactor/motor. Estos trabajos son una secuela de trabajos anteriores con un sistema de 4 kW de potencia al eje, utilizando carbón vegetal derivado de gas de aire.

Producer gas fuelling of a 20 kW output engine by gasification of solid biomass

INTRODUCTION

Producer gas derived from coal and solid biomass fuels has a long history as a fuel for internal combustion engines. A resurgence of interest in this technology has occurred in recent years as alternative fuels to liquid and gaseous fossil fuels are being sought (Breag and Chittenden, 1979). Producer gas for motive power systems is particularly attractive up to about 100 kW shaft power and a number of commercial systems are available (Hollingdale, 1983).

The historical information available on this technology was reviewed by Foley and Barnard (1983) – particularly that relating to the World War II boom period of gasification. They noted that many designs were extant but that first-hand knowledge of the operation and maintenance of such systems had virtually disappeared. Work in the United Kingdom during World War II was primarily on cross-draught reactors using low-ash anthracite and coke as fuel. ODNRI recognized that this technology was relevant to the use of charcoal fuel and these designs have been tested for charcoal, both in this current work for 20 kW systems, and in the earlier work for a 4 kW system (Breag *et al.*, 1982). The wartime work on producer gas in Europe, especially in Germany and Sweden, placed more emphasis upon the use of uncarbonized fuels and the most commonly adopted reactors were of down-draught design. The construction of these units ultimately became standardized but there were working design methods evolved to determine nozzle and throat configuration. Some means of selection of suitable configuration is still necessary and this aspect has been investigated by the Institute.

In carrying out this work, cumulative running periods have totalled about 1,000 hours. Primarily this has involved running gasifiers with the Ford engine, but in some exploratory work an electric fan was used. Various combinations of reactor design and fuels were tested in association with this engine. Initially, a cross-draught reactor was used, running on graded charcoal. Subsequent work was done with down-draught reactors, running for various periods of time with different fuels, namely graded charcoal, wood blocks, crushed coconut shell and uncrushed coconut shell. During these trials certain potential improvements to the down-draught reactor design became evident. These were incorporated into a modified hearth section which was built and tested during the later stages of the test programme.

Apart from examining the use of charcoal with a cross-draught reactor the down-draught reactor was also run using charcoal. No difficulties were experienced when using this fuel and the remainder of the work was aimed at evaluating the potential use of a down-draught reactor with uncarbonized fuels. Initially, wood blocks were used as feedstock and problems with tar carry-over were encountered. In view of the need to prepare the wood to uniform sizes to obtain standard feedstock conditions, attention was then turned to the use of coconut shells, as they represent the kind of dense agricultural residue directly suitable for use in gasification; moreover, they have a similar elemental composition to wood with a carbon: hydrogen: oxygen ratio of 48.3 : 7.4 : 44.3. In addition, coconut shell is of potential interest as a quite widely available material in a number of developing countries at centralized copra production and coconut processing sites. Typical analysis for fuels used in this work are provided in Appendix 1.

This work has had four main objectives:

1. To acquire operating and maintenance experience using producer gas with 20 kW motive power systems designed according to World War II technology.
2. To examine the significance of various designs used in conjunction with different fuels, including selection of nozzle and throat configurations for down-draught reactors.
3. To investigate the potential use of coconut shells as a fuel for producer gas motive power systems.
4. To provide information as a basis for improved system designs, using currently available technology as appropriate.

SYSTEM DESIGNS

Cross-draught reactor

The cross-draught reactor construction is based upon United Kingdom World War II designs. It is made from 6 mm steel plate and consists primarily of a vertical cylinder 0.66 m in diameter with an extension hopper mounted above it. The unit can hold about 130 kg charcoal which is loaded through a removable hatch at the top. The arrangement and major dimensions of the reactor are shown in Figure 1. Combustion air enters through the stainless steel cross-draught nozzle near the reactor base. The 50 mm internal diameter nozzle projects 0.14 m into the reactor. Gas leaves the reactor through a screen fitted over the 38 mm-diameter outlet pipe on the reactor wall opposite the nozzle. Other features of the gas reactor are: a removable grate 0.12 m above the base; a 0.27 m-diameter discharge port and door, also at the base of the reactor; and a hand-operated shaker riddler bar spanning the reactor 0.56 m above the combustion zone. The nozzle has a water cooled annulus. The water is circulated using a small pump from a 360-litre storage tank.

Down-draught reactor

The down-draught reactor is designed using information both supplied by Statens Maskinprovinger, The National Swedish Testing Institute for Agricultural Machinery, Umea and that cited in the literature (Solar Energy Research Institute, 1979). The unit has a basic geometry similar to the 'Imbert' World War II design used for wood fuel. The hearth and throat dimensions are as indicated in Figure 2. Either 10 nozzles or 5 nozzles of different sizes are used and various nozzle number and size combinations can be adopted. Hearth rings of different diameter can be used also.

Beneath the reactor hearth, there is a hand-operated shaking grate. Hot gas, after passing through this grate, flows up outside an annular chamber containing the ingoing combustion air to the nozzles. This air is then preheated by heat transfer on both sides of the annular chamber: from the combustion zone on the inside, and from the product gases on the outside. The reactor is constructed from 6 mm mild-steel plate, apart from the nozzles and the hearth ring which are made in stainless steel.

Other features of the reactor include a 0.5 m^3 hopper fitted above the reactor zone. The hopper is partly lined internally with a conical section of

Figure 1

Cross-draught reactor

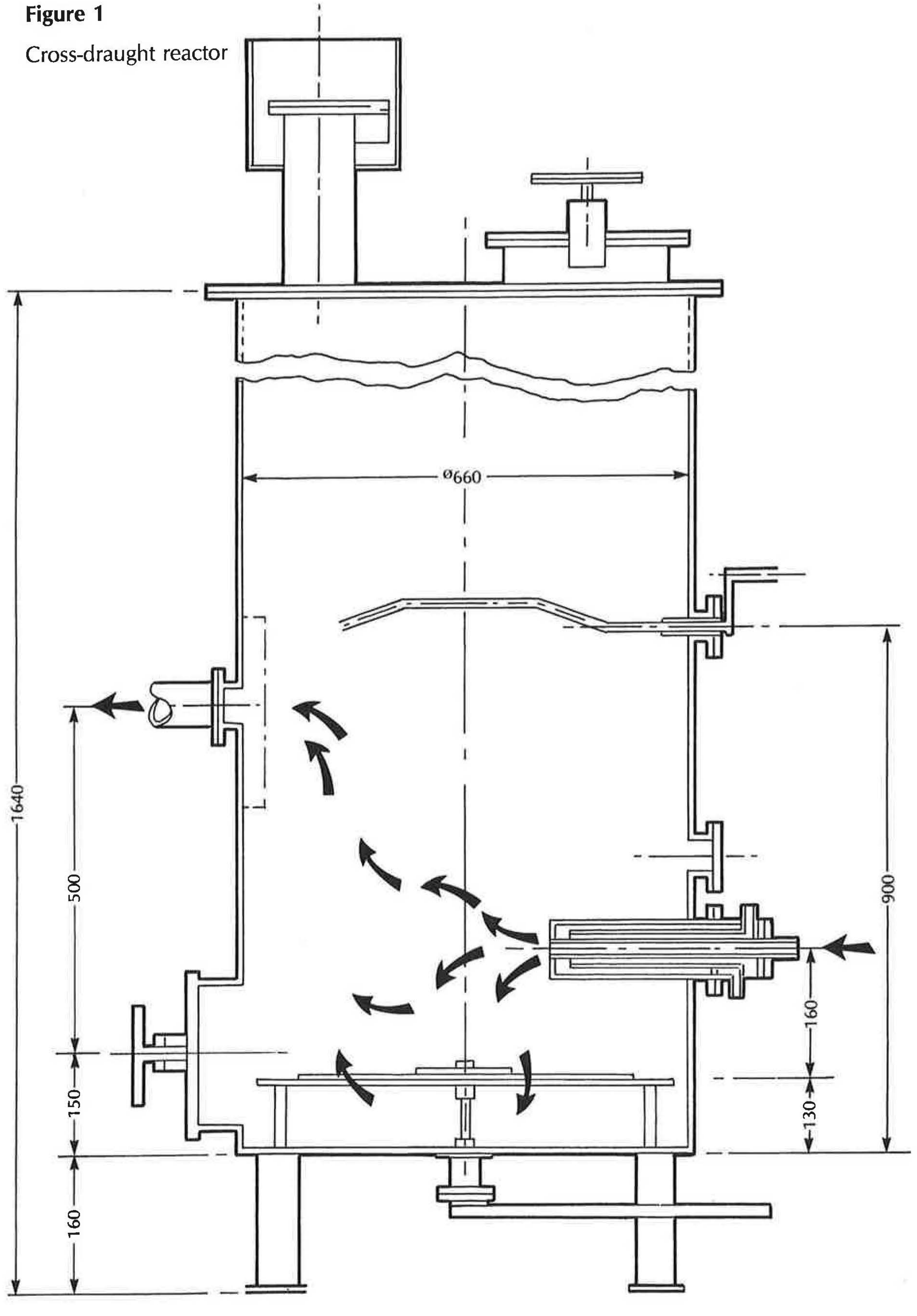
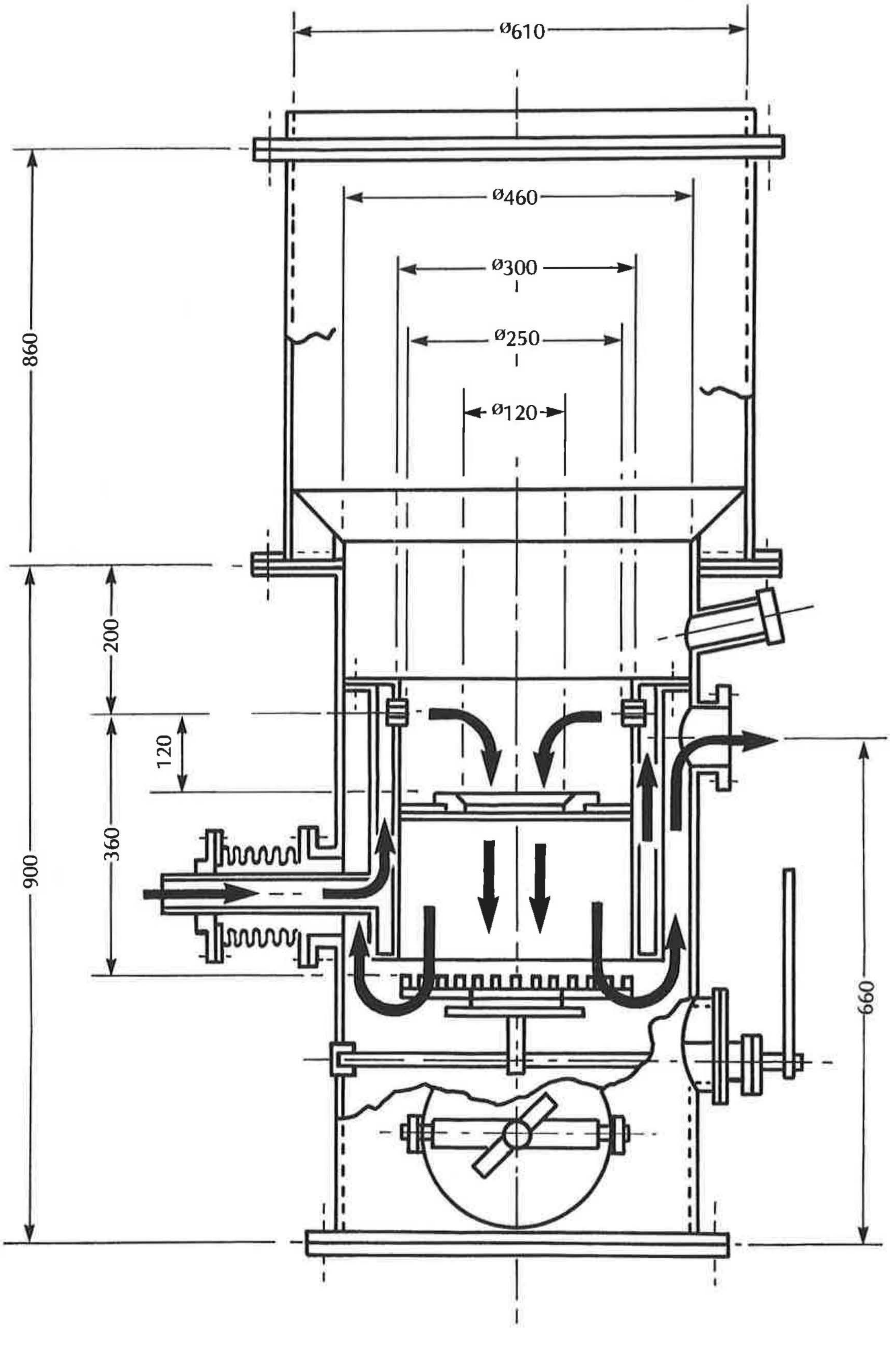


Figure 2

Down-draught reactor



perforated steel plate at the section just above the flange joining it to the reactor. Below this is located a tap to drain off any moisture or liquids condensing in the hopper. Fuel is loaded into the hopper through a hatch at the top.

At the base of the reactor there is another hatch for emptying and cleaning the reactor. A hand-operated paddle or agitator is fitted near to the base of the reactor hopper section in order to provide a means of movement within the charge. There is also an ignition port on the reactor wall positioned just above the nozzles.

Modified down-draught reactor

On the basis of running experience with the down-draught reactor described above, a modified hearth and nozzle assembly was built and tested during the latter part of the work. This is essentially of the same basic design as the down-draught reactor already described, but both the grate and the emptying port are altered to facilitate emptying of any charge remaining within the reactor. In addition, a rather different air entry and preheating arrangement is adopted such that the nozzles can be inspected or replaced without dismantling the reactor. This modified design is shown in Figure 3.

Gas cleaning/cooling system

Immediately upon leaving the reactor the hot gas enters a 144 mm-diameter cyclone. This has a chamber at its base for the collection of the separated dust. The dust is removed on a daily basis through a purpose-built emptying port. From the cyclone the hot gas passes to a fabric filter contained in a 0.41 m diameter and 1.11 m high vessel. The filter is made with three concentric cylindrical expanded metal elements of diameter 0.325 m, 0.225 m and 0.121 m, each covered in fibreglass cloth. Gas is ducted to flow simultaneously through these three elements which provide a total open area of filter cloth of 1.06 m^2. On leaving the filter chamber, the hot gas passes through a three-pass tube and shell heat exchanger unit where it is cooled by air flow through the shell, induced by a small axial fan. The cleaned and cooled producer gas is then ducted to the engine manifold. The mean particle sizes, as measured by Coulter counter, of the dust and ash material collected in the cyclone and on the filter are 20-30 μ and 3-4 μ respectively.

At one period in the development programme the dry gas filter system described here was temporarily removed and a water scrubber was used for the combined cleaning and cooling operation. As this was found to be less effective, the dry gas filter and cooler combination was reintroduced and run in conjunction with a modified reactor for the latter phase of the work.

Engine arrangement

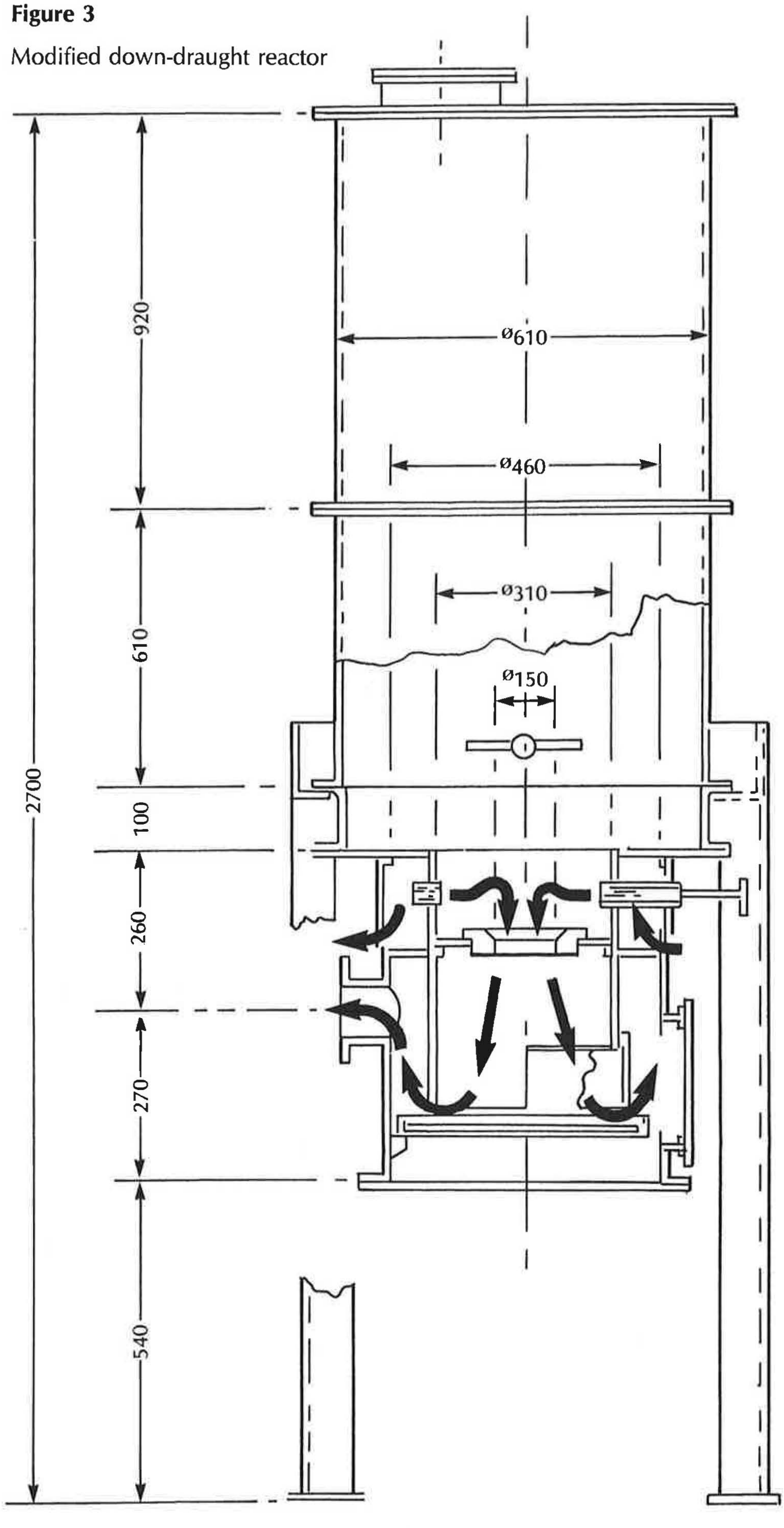
Producer gas and combustion air for the engine is mixed close to the engine manifold at a swept bend. The gas:air ratio is varied by throttling with a hand-adjusted butterfly valve in the air line. The combined gas/air flow can also be throttled immediately before the manifold with a governor-actuated butterfly valve. This valve is used for overspeed regulation and operated by a linkage from a mechanical governor which is belt driven off the engine crankshaft.

The engine itself is a standard 4-cylinder spark-ignition Ford 2274E industrial unit fitted with stellite valves and case-hardened valve seats, as used in natural gas-fuelled systems. Ignition timing is advanced to 35° before top dead centre (BTDC) in order to compensate for the low flame speed of producer gas. The essential engine specifications are given below:

No. cylinders	Running speed	Engine, cc's	Compression ratio	Ignition timing BTDC
4	3,000 r.p.m.	1,600	8:1	35°

Figure 3

Modified down-draught reactor



An engine load is coupled to the drive shaft. This is a hydraulic brake with a throttle valve and water cooling.

OPERATIONAL EXPERIENCE

Start-up procedure

Cold-starting of the engine after loading the cross-draught reactor with a fresh charcoal charge normally took only about 5 minutes from ignition of the charcoal using a burning wick inserted through the reactor nozzle. After a short period of fan-induced draught, the engine would be cranked by a battery powered starter. It would then pick up speed – running on producer gas – and sustain the gas supply through the reactor with the manifold suction pressure.

Experience of starting the down-draught reactor with uncarbonized materials was similar. When using uncarbonized feedstock the hearth section was filled either with wood charcoal or coconut shell charcoal for ease of ignition and in order to minimize tar carry-over.

Approximately 20 kg of charcoal were required to fill the hearth section of the reactor. Up to 100 kg of coconut shell or wood blocks could then be loaded above this in the hopper section of the reactor. At start-up the gas flow through the reactor induced by the fan was vented. This gas was normally combustible within 5-10 minutes and then the engine could be started. Sometimes the fan-induced combustion procedure had to be repeated before the engine would pick up with the producer gas as fuel.

Starting the engine directly on producer gas is not essential. Starting this engine on a conventional fossil fuel, for example, petrol, liquid petroleum gas (LPG) or natural gas with a subsequent change-over to producer gas could be adopted, but extra engine fittings would be necessary.

Engine running

Once the engine was operating under load its speed was quite steady and it could be left unattended. However, some difficulties with engine operation were experienced in these trials both in starting and during running on load. These were partly a consequence of the experimental nature of the system being used, and the extra maintenance requirements necessitated to sustain smooth running are described below. Engine power output and fuel efficiency details were measured and are described later; in both respects this engine seemed well suited to operation on producer gas.

Once running, the engine operation was sustained for runs of up to 8 hours on full load. Longer runs were possible with recharging during operation, but this was not generally practised in this work. Cumulative engine running time in these trials was 855 hours and the average run was of 3 hours duration.

An intermittent but troublesome disturbance in engine running of sporadic detonations in the inlet manifold arose occasionally when using uncarbonized biomass fuel. This resulted in a momentary loss of engine speed followed by a recovery surge due to the interruption of the fuel supply. A possible explanation of this was discovered through gas analysis work and it is described later. Remedial action was considered in collaboration with Ford engineers and an increased valve tappit clearance was tried. This did not wholly eliminate the problem and a further suggestion was made to fit a different profile camshaft, but such moves to a non-standard engine were avoided and have not been evaluated. The problem did not occur when using carbonized biomass fuel.

Loading reactor and filter system operations

For various reasons many of the runs were stopped before the fuel charge had been completely burnt. On most occasions the residual contents of the reactor were subsequently removed and the reactor refilled before the next run. This operation, rather than simply topping up with fuel, was necessary to facilitate start-up and for experimental record purposes. With the cross-draught reactor it posed no problem. In the initial down-draught reactor design it was envisaged that this emptying operation would be accomplished by removal of material through the ash port at the reactor base, but it was found that often this was not possible because of blockage in the hopper above the reactor grate or in the throat area. Emptying the reactor on these occasions required unbolting and removing the hopper section of the reactor. In order to obviate this problem a revised hearth and grate design was incorporated in the modified unit used for the latter part of this work.

Apart from the loading and emptying operations for each run, it was also necessary to empty the cyclone and drain the condensate from several collection points in the system. In addition, the condition of gaskets, seals, etc., had to be checked regularly, these being replaced as necessary in order to avoid difficulties with air leaks into the system. The reactor door and hatch seals were found to require re-gasketing at approximately 50-hour intervals.

Most of the fine particulate matter carried over from the reactor was removed in the cyclone which was emptied on a daily basis. After leaving the cyclone the producer gas flow then passed through the fibreglass cloth filter. The filter elements were removed for cleaning by brushing at about 20-hour intervals. After inspection the filter elements were normally replaced without changing the cloths, but at about 100-hour running intervals the cloths were renewed because of damage. It is possible that this period of effective use could be extended either by using different cloth material or by adopting alternative cleaning procedures; this is one practical feature which could receive more attention in future work.

Reactor maintenance

Cross-draught reactor: the cross-draught reactor design was originally adopted for a 4 kW power system using charcoal, since it is basically a simple device and offers advantages in ease of starting and in flexibility of operation. However, at the 20 kW power level there were initial difficulties experienced with nozzle burn-out because of inadequate water cooling. This was overcome by modifying the cooling water flow passage inside the nozzle annulus; for sustained long-term operation at 20 kW power output levels consideration should be given to a two-nozzle arrangement.

Down-draught reactor: short duration trials on the down-draught reactor using charcoal as feedstock suggest that it would be an equally effective option as the cross-draught reactor at the 20 kW power level, but the long-term effects on the engine and equipment would need to be confirmed. Since at this stage of the work programme the main objective of using the down-draught reactor was to test its use with uncarbonized fuel, further work with charcoal was not pursued.

Using uncarbonized feedstock for approximately 500 running hours, the only unexpected maintenance necessary with the down-draught reactor was once to replace the hearth ring which was found to have gradually bowed from the heat.

Engine maintenance

Frequent removal of the engine cylinder head was necessary during this work in order to clean tar-like deposits from the inlet manifold, the valve ports, the valve stems, the cylinder head chambers and the piston crowns. The longest cumulative period of running without the need for this maintenance was 360 hours with the cross-draught gasifier, cyclone and fibreglass cloth filter system using graded charcoal as fuel. When using uncarbonized fuel on the down-draught reactor the longest cumulative period of running was 124 hours, and under these conditions maintenance was required on average about every 50-100 hours.

The need for engine maintenance normally became evident from difficult starting and poor running performance. Sometimes ignition plug fouling was the cause and matters were improved by fitting cleaned or replacement plugs. Low cylinder compression was another indication, though this sometimes improved after short periods of operation. Visual inspection of the entry to the inlet manifold by removing the butterfly governor valve was also a quick guide. By removal of the manifold, the extent of deposition within the manifold, on the valve stems and on the valve ports was ascertained. Cleaning of the manifold with hot water and detergent was accomplished relatively quickly, but it was usually also necessary to remove the cylinder head in order to clean the valve stems and seats, etc. This then became a standard routine, necessitating draining of the engine coolant, removal of the cylinder head, removal of the valves, cleaning of the valves, piston crowns, cylinder head, etc., and relapping and sometimes regrinding the valve seats. The whole operation, including reassembly with a new cylinder head gasket and valve clearance adjustment took about one man-day.

After 855 hours total cumulative running of the engine (394 hours on charcoal fuel with the cross-draught reactor and 461 hours on uncarbonized fuel using down-draught reactors), a significant engine maintenance problem arose. Loss of compression was observed in one cylinder associated with a copious emission of fumes from the crank case. After inspection it was found that piston ring failure had occurred which had resulted in local burning of a piston crown. To repair this required a new piston assembly and honing of the cylinder. Subsequent examination of other pistons revealed a high level of ring stick which was almost certainly the reason for the piston ring failure and the damage to the piston crown.

The extra engine maintenance on producer gas operation compared to fossil fuel operation as described above was a consequence of various factors stemming from the carry-over of volatile and tarry material which deposits in the engine. This is markedly less of a problem with producer gas from the low volatile-content charcoal fuel and it is considered that in operation of such a system the extra engine maintenance would not be particularly burdensome. A contributory cause of the high frequency of maintenance necessary to clean the engine head, etc., when running on uncarbonized fuel was thought to be the relatively low capacity of the centrifugal priming fan. At very low gas production rates, insufficiently high reactor temperatures are obtained to crack the tars evolved, and whilst care was exercised to avoid such conditions, carry-over of tar did occur. Tar was deposited in pipelines, in the fan, sometimes either restricting or stopping its action, and in the engine. Introduction of a larger capacity priming fan appeared to have alleviated this difficulty, but as this was only used during the last 100 hours of work no firm conclusion was reached on this matter.

MEASUREMENTS AND PERFORMANCE

Measurements

Engine load and speed were measured using an electric speed and torsion sensor unit. The calorific value of the producer gas was monitored with a Sigma continuous-recording combustion calorimeter. Gas composition was measured with a Pye-Unicam gas chromatograph to provide component percentages of hydrogen, carbon dioxide, oxygen, nitrogen, methane and carbon monoxide. Gas flow rates were derived from orifice plate pressure-drop readings according to BS1042. In addition, pressures and temperatures at several points in the system were measured.

Gas analysis

During these runs two methods of gas analysis were used. Samples of the producer gas were taken directly after the reactor using a vacuum pump. The gas was fed via a sample line to both a gas chromatograph and to a calorimeter. With the chromatograph, samples could be analysed at approximately 15-minute intervals to give the percentage of the following components: hydrogen (H_2), carbon dioxide (CO_2), oxygen (O_2), nitrogen (N_2), methane (CH_4) and carbon monoxide (CO). On charcoal, the gas analysis was found to be H_2, 5.0%; CO_2, 2.1%; O_2, 0.9%; N_2, 62.5%; CH_4, 0.3%; CO, 29.2%; corresponding to a calorific value of 3.99 MJ/m^3. However, when running on coconut shell the analysis was found to have quite a large scatter and the component percentage ranged as follows: H_2, 7-13%; CO_2, 4.5-11%; O_2, 1.0-1.7%; CH_4, 0.6-1.6%; CO, 20-27%. This corresponded to calorific values in the range 3.5-5.4 MJ/m^3. No pattern to the variation in these results was evident until the gas calorimeter records were examined (*see* Figure 4).

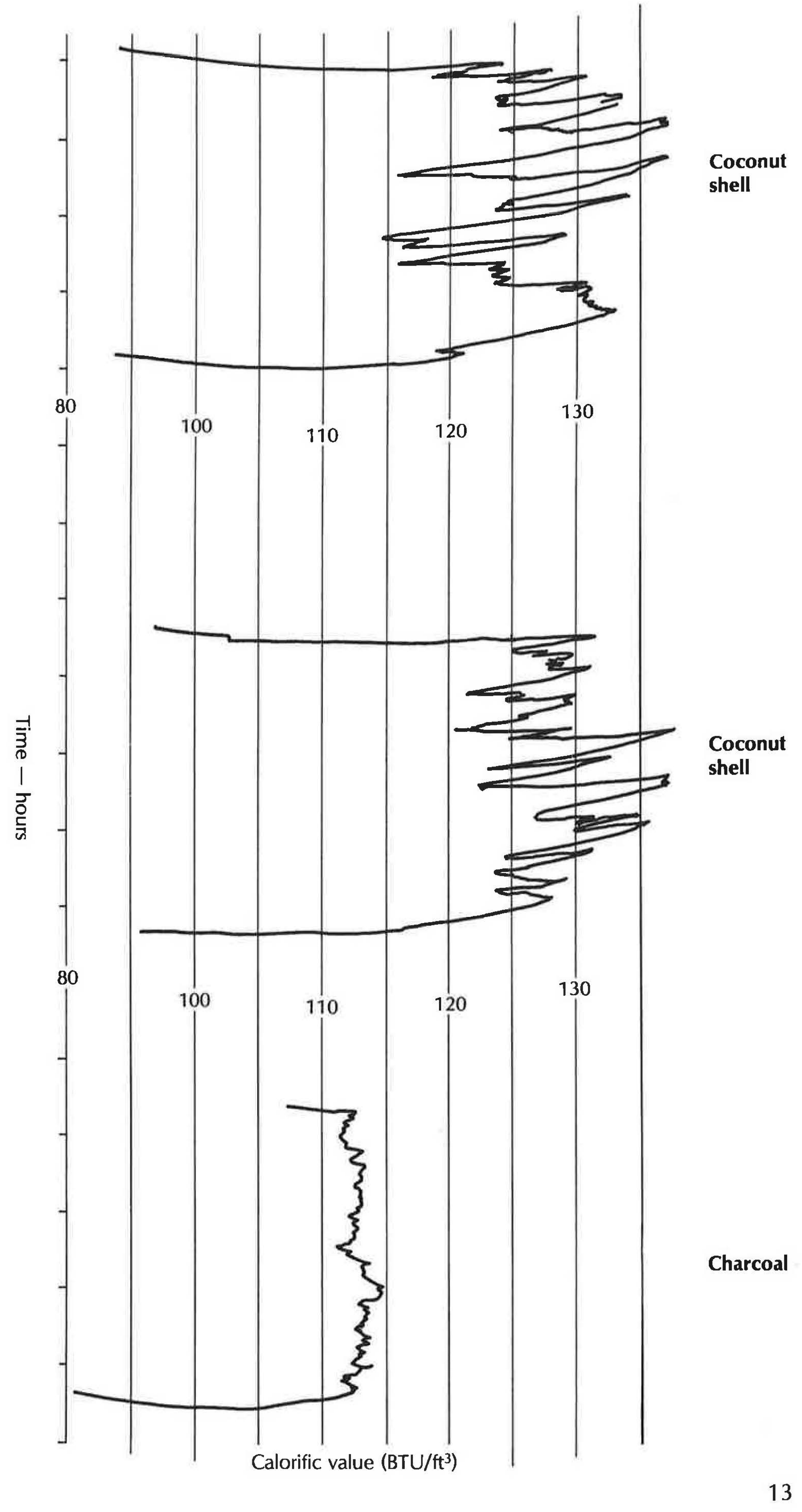
The calorimeter record was continuous and resulted from the combustion of a regulated supply of the producer gas. Heat from this combustion actuated a bimetallic element which was linked to a chart pen recorder. Though this measurement of gas calorific value was subject to some lag in response, the records obtained confirmed that significant fluctuations in the calorific value of the producer gas were occurring, as had been indicated from the gas chromatograph. However, the calorimeter record showed that the period over which changes occurred was of the same order as the sampling frequency time for the gas chromatograph, thereby explaining why no pattern could be found to the variations measured with the gas chromatograph. Traces for the recorded calorific value during two typical runs with coconut shell are shown in Figure 4. Also shown for comparison is a trace obtained whilst running on charcoal. On this record the range of recorded values with coconut shell is approximately $\pm$10% about a mean of 4.7 MJ/m^3. The thermal and mechanical inertia in the recorder undoubtedly damp this so the actual fluctuations are greater and probably of the order of $\pm$20%, as indicated by the gas chromatograph.

The cause of this fluctuation was found to be due to movement of material in the combustion bed, and sharp rises in calorific value could be observed when a drop in the reactor contents was induced by the manual paddle/agitator. It was apparent that the downward flow of coconut shell in the hopper was intermittent with irregular minor bridging. When these temporary bridges collapsed, either through the weight of the charge above or because of mechanical action, fresh unburnt shell dropped into the burning zone. This shell probably had on its surface some volatile tars and/or moisture which were quickly evaporated and passed immediately through the high-temperature zone of the hearth with a consequential rapid increase in calorific value of the gas.

This effect was not correlated with any direct output power variations on the engine, but short-term variation in gas composition was to some extent damped by the existing system due to the volume capacity of the filter vessels. However, an intermittent difficulty with inlet manifold detonation, described elsewhere, was observed to occur often when high calorific value gas was recorded. This may have therefore been a consequence of an increased percentage of hydrogen associated with the higher calorific value gas, since hydrogen has a much greater flame speed than the other combustible components (2.6 m/s for H_2 compared with 0.4 and 0.3 m/s for CO and CH_4 respectively).

Figure 4

Records of gas calorific value during runs



Down-draught reactor performance

Various empirical parameters relating to the nozzle and hearth arrangements are adopted in the design procedures for the World War II Imbert-type reactors. Different gasifier designs are compared on the basis of the value of these parameters. The following parameters are frequently used:

A_n = total of nozzle cross-section area (cm^2)
A_h = hearth ring cross-section area (cm^2)
V_h = average gas velocity through hearth ring area (gas flow taken at 15°C and one atmospheric pressure, and area assumed to be void of charcoal) (m/s)
V_n = air velocity through nozzles (m/s)

In this work a range of values for these parameters has been examined; this information is summarized in Appendix 2. Reactor gas output in all this work was taken as 56 m^3/h (at 15°C and one bar), equivalent to the gas requirement to supply a 1,600 cc, 4-stroke engine running at 3,000 r.p.m. and 80% swept volume efficiency using a 1:1 gas/air mixture.

A commonly quoted design parameter in the literature is the value for $\frac{A_n}{A_h} \times 100$, that is, a percentage measure of the ratio of the total nozzle area to the hearth area. High values of this quantity are used for small hearths, and vice-versa. Values of this area ratio between 2.84 and 10.0 have been examined in this work for hearth sizes ranging from 80 mm to 150 mm diameter. This has covered the range used in Imbert designs and some associated variations in performance have been observed which are broadly in line with former recorded experience.

Rating for a reactor is often based upon the average gas flow velocity through the hearth area, V_h, calculated from the NTP gas flow and assuming the hearth area is void of charcoal. It is reported that the maximum value of V_h which can be used is 2.5 m/s (Solar Energy Research Institute, 1979). A similar result was found in this work. On an occasion when a higher value of V_h was tried it was found that an excessively high overall pressure drop occurred across the reactor and the engine could not be started.

At lower values for V_h, lower hearth temperatures will result and it can be expected that the possibility for tar carry-over will increase. The World War II experience suggests that this starts to occur for values of V_h at about one-third of the maximum rating, that is, for V_h of about 0.8 m/s and below. In this work a slightly higher guideline seemed to apply. In the one run when tar was observed to have carried over onto the filter, a value of $V_h = 0.88$ applied, though in two other runs with the same V_h value this did not occur.

The work done in assessing these empirical design procedures has established their value in setting broad limits to the parameters that vary in a conventional down-draught reactor. However, within this general framework there remains a range of options which may be selected without apparently influencing performance.

Engine wear

Strip-down and measurement of the engine components after 855 hours running revealed no significant wear, for example, the inline bore diameters were found to be within the original manufacturing tolerances as were the main and big-end journal diameters.

Regular analysis of the engine oil for trace metals (*see* Appendix 3 and Figure 5) showed significantly higher levels for the period when the engine was operated on gas produced from uncarbonized coconut shell, that is, after 408 hours running. This would indicate a higher degree of engine wear and reduced engine lifetime in extended use.

Fuel efficiency on charcoal

The fuel consumption and power output of this reactor engine system when operated on charcoal has been reported previously (Hollingdale *et al.*, 1982). Average overall efficiency was 19.7%, equivalent to a specific fuel consumption of 0.58 kg charcoal per kWh shaft power. The corresponding reactor efficiency and engine brake thermal efficiency were 60.0% and 32.8% respectively.

Fuel efficiency on coconut shell

The fuel consumption rates and power output for the down-draught reactor/ engine system when operated at a constant full load on coconut shell were assessed in a series of runs. These data are tabulated in Appendix 4. In order to obtain average results, data from 11 runs of over 3-hour duration were analysed.

Gas flow rates and gas calorific values given are averaged values over the period of the runs. Values for engine torque and power are also averaged over the period of the runs. The average engine manifold depression pressure was a measure of the back pressure through the gasification equipment as well as being a parameter influencing the engine performance.

From these results it can be seen that an average overall efficiency of 21.2% was obtained for the system, equivalent to a fuel consumption of 0.82 kg shell per kW of shaft power developed by the engine. The corresponding reactor efficiency and brake thermal efficiency were 71.2% and 30.0% respectively.

CONCLUSIONS

This work has provided valuable direct experience of operating a 20 kW-shaft motive power system using producer gas to fuel a spark-ignition engine. The significance of various design features in relation to different biomass fuels has been investigated. An improved down-draught reactor design has been developed and this has been tested using uncarbonized feedstock.

The main conclusion from this work and earlier work is that the charcoal-fuelled systems tested offer an acceptable means of powering engines. The choice of reactor design for charcoal for 20 kW-shaft power systems has been considered and it is probable that the down-draught reactor is preferred to the cross-draught reactor at this power output level. However, as the most extended running period achieved on charcoal in this work was with a cross-draught reactor, further development work is desirable before the down-draught reaction design can be actively promoted for developing country application. The work is nevertheless at a sufficiently advanced state for it to be taken up for potential application, and future ODNRI involvement on design of charcoal systems of this power-output level is expected to take place in collaboration either with interested United Kingdom industrial organizations or with overseas development agencies.

In the work on uncarbonized materials, considerable progress has been made in acquiring first-hand experience of this technology. The value of traditional design procedures has been assessed and progress has been made in understanding the gasification process. With the systems tested using uncarbonized fuels, difficulties were experienced with excessive engine maintenance due to deposition of tar-like material in the engine inlet ports, valves and cylinder areas. Further work on the use of these fuels should concentrate on the measurement and improvement of gas quality from the gasifier and clean-up systems. In the meantime, it is recommended that claims in the literature minimizing the operational and maintenance difficulties of uncarbonized fuels such as coconut shell for gasifier engine systems should be treated cautiously.

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Appendices

APPENDIX 1 TYPICAL ANALYSIS OF FUELS USED DURING RUNS (DRY BASIS)

Component		Wood	Wood charcoal	Coconut shell
Carbon	%	48.9	76.9	53.6
Hydrogen	%	5.3	3.9	8.2
Oxygen	%	44.4	15.2	36.7
Nitrogen	%	0.1	0.3	0.2
Sulphur	%	0.1	0.1	0.2
Moisture	%	25.00	7.00	12.00
Ash	%	1.2	3.6	1.1
Gross calorific value	kJ/kg	19,850	31,220	20,480

APPENDIX 2 DOWN-DRAUGHT REACTOR PARAMETERS EXAMINED

Feed	Engine running hours	Cumulative hours run	Nozzle/hearth details			Design parameters			Comments
			Nozzle No.	Nozzle Ø mm	Hearth Ø mm		V_h m/s	V_n m/s	
Crushed coconut shell	408-470	62	5	13	150	3.75	.88	14.0	
	470-479	9	10	10	150	4.4	.88	12.2	Tar carry-over on filter
	479-539	60	10	8	150	2.84	.88	18.6	
	539-540	1	10	8	80	10.00	3.11	18.6	Very high reactor pressure drop (would not start engine)
	540-573	33	10	8	100	6.40	2.00	18.6	
	573-576	3	5	12	100	7.20	2.00	16.7	
Uncrushed coconut shell	576-646	70	10	10	100	10.00	2.00	12.2	Reactor pressure drop in range 10-50 in H_2O
	646-763	117	10	10	120	6.90	1.40	12.2	

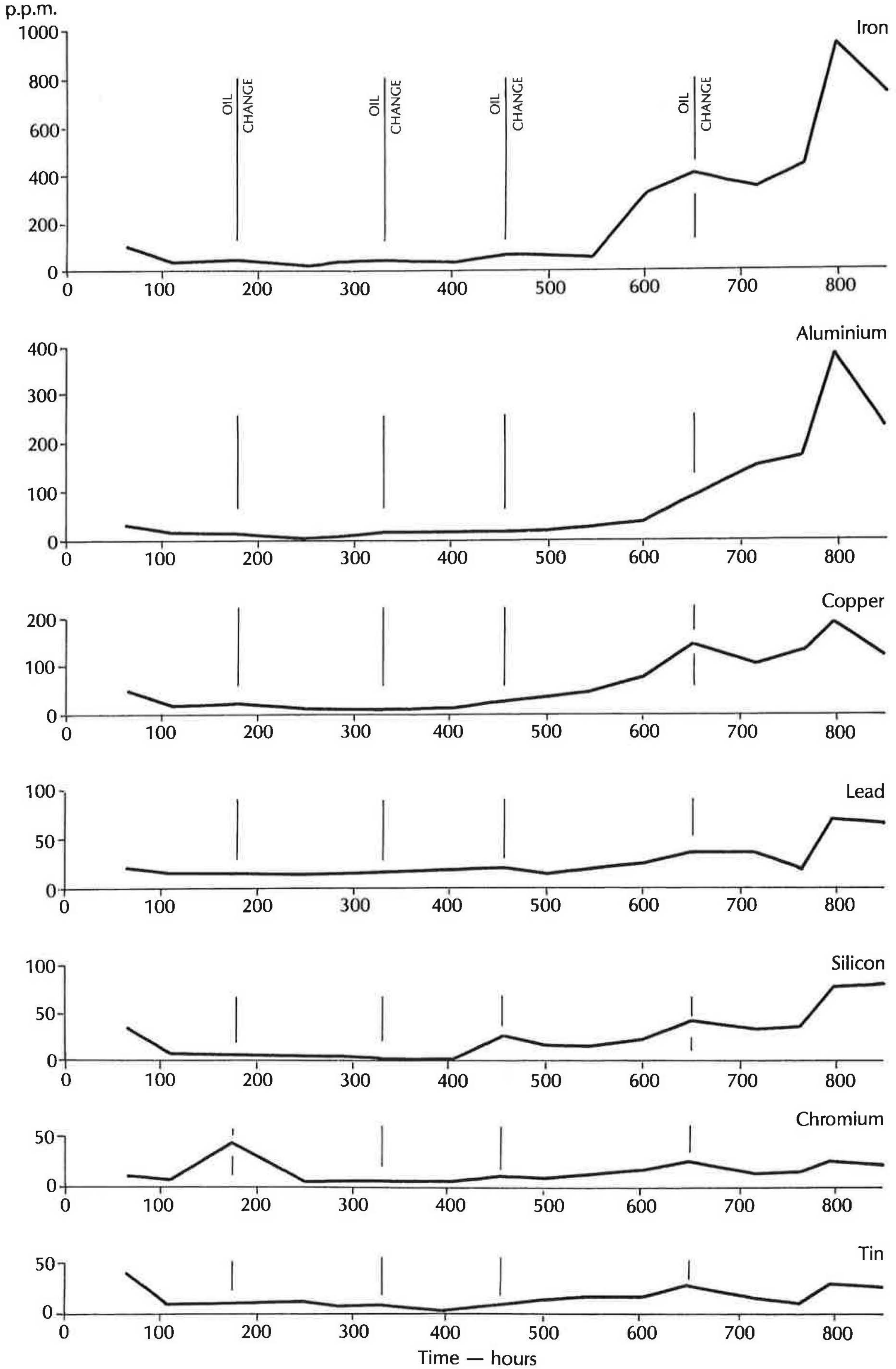
APPENDIX 3 ANALYSIS OF ENGINE OIL

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15*	16
Date	5/1	5/2	13/3	1/4	12/5	20/5	1/10	18/11	10/2	15/3	4/5	12/7	6/9	5/10	25/4	16/5
Total engine hours	63	110	177	246	285	330	404	454	497	546	598	650	717	763	794	850
Visc. @ 100°C, poise	15.6	–	9.5	–	9.2	–	–	9.8	–	9.9	–	10.0	–	10.0	–	10.2
Total base No.	8.4	9.5	8.7	8.7	8.4	7.1	7.0	7.0	6.8	6.7	6.4	6.5	6.3	6.0	5.9	7.0
Weighings																
Iron (p.p.m.)	104	39	43	18	41	40	39	67	65	249	324	904	347	434	938	733
Aluminium (p.p.m.)	28	3.5	3.7	0	1	2	3	3	6	11	17	84	149	166	341	218
Copper (p.p.m.)	50	21	24	8	10	8	6.5	24	38	53	80	145	103	130	184	117
Lead (p.p.m.)	20	14	14	13	16	14	18	20	15	20	30	34	33	19	78	74
Silicon (p.p.m.)	36	7	6	2	3	1	0	25	16	17	21	40	27	32	75	78
Chromium (p.p.m.)	11	4	45	1	2	2	2	8	5.5	9	13	26	11	14	24	22
Tin (p.p.m.)	41	8.5	9	1.5	4	1	0	6	12	17	18	27	16	10	30	28
Calcium (p.p.m.)	–	–	–	–	–	–	.31	.31	.26	.29	.30	.30	.26	.28	.29	.31
Zinc (p.p.m.)	–	–	–	–	–	–	.16	.16	.15	.17	.17	.18	.16	.17	.19	.19
Phosphorus (p.p.m.)	–	–	–	–	–	–	.20	.21	.23	.25	.26	.28	.25	.26	.28	.28
Magnesium (p.p.m.)	–	–	–	–	–	–	2	5	0	0	0	.006	.002	.002	.004	.003
Barium (p.p.m.)	–	–	–	–	–	–	21	18	2	1	1	3	01	6	8	7

Note: * Engine not operated for 3 months before taking this sample.

Figure 5

Oil sample analysis graphs (in parts per million)



APPENDIX 4 OPERATING RESULTS FOR REACTOR/ENGINE SYSTEM USING COCONUT SHELL FUEL

Date	Weight of coconut shell used kg	Hours run	Average hourly consumption kg/h	Energy into reactor kW	Average engine torque NM	Average engine power kW	Average engine manifold depression in " of Hg	Producer gas flow m^3/h	Producer gas calorific value MJ/m^3	Energy into engine kW	Reactor efficiency %	Engine brake thermal efficiency %	Overall efficiency %	kg shell per kWh (shaft)
26.8.82	78	5.25	14.9	85.5	71.0	22.2	2.75	55.8	4.46	69.1	80.1	32.0	26.0	0.67
02.9.82	62	3.5	17.7	101.6	57.6	17.9	5.0	49.9	4.28	59.3	58.4	30.2	17.6	0.99
09.9.82	70	3.75	18.7	107.3	72.6	22.7	2.5	52.3	4.69	68.1	63.5	33.3	21.2	0.82
10.9.82	69	3.75	18.4	105.6	71.0	22.2	3.0	55.3	4.65	71.4	67.6	31.1	21.0	0.83
13.9.82	77	4.5	17.1	98.1	70.7	22.1	4.0	57.8	4.87	78.2	79.7	28.3	22.5	0.77
15.9.82	84	4.5	18.7	107.3	72.0	22.6	2.6	50.4	4.72	66.1	61.6	34.2	21.1	0.83
20.9.82	72	3.5	20.6	118.2	71.5	22.4	2.2	51.7	4.65	66.8	56.5	33.5	19.0	0.92
22.9.82	74	3.75	19.7	113.1	70.5	22.0	3.4	61.4	4.65	79.3	70.1	27.7	19.5	0.89
23.9.82	70.5	4.5	15.7	90.1	69.0	21.6	4.3	60.6	4.76	80.1	88.9	27.0	24.0	0.73
24.9.82	64	3.75	17.1	98.1	65.5	20.4	4.4	60.3	4.65	77.9	79.4	26.2	20.8	0.84
27.9.82	82	4.5	18.2	104.4	69.5	21.8	3.6	61.4	4.65	80.7	77.3	27.0	20.9	0.83
Average	–	–	17.7	102.7	–	21.6	–	56.1	4.64	72.5	71.2	30.0	21.2	0.82

Notes: Based on a gross CV for shell of 20,660 kJ/kg.
Reactor hearth diameter 120 mm, 10 nozzles of 10 mm diameter.

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