A Conceptual Process for the Production of Hydrogen from the Organic Fraction of Municipal Wastes and Biomass

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Abstract

This paper describes a process to produce hydrogen economically from local waste materials as a fuel for vehicles. It is now urgent to deal with two problems that will become more pressing in the coming decade: the current excessive level of carbon dioxide emissions released to the atmosphere from the fossil fuels and the higher prices for oil and natural gas likely to result from the impending peak in the world production of oil from conventional sources. These problems are inter-related in the sense that higher energy prices facilitate the introduction of alternate techniques on either the supply or the demand side. Nevertheless, it would be particularly helpful to devise a technological approach that addressed both issues at once. As a step in this direction, a new technique is proposed in this paper for the economical production of hydrogen from Municipal Solid Wastes (MSW) together with any available biomass for use in fuel cell-equipped vehicles. MSW is the only fuel with a negative cost due to the need for expensive landfill sites for its safe disposal and the generally high trucking costs to reach those at acceptable locations. Hydrogen is costly to transport and thus there is an incentive for its production near markets in such a way that fossil fuels are not consumed and emissions of greenhouse gases are reduced.

The advent of membrane technology for the separation of hydrogen from process gas streams opens new opportunities for the production of this benign fuel gas. In effect, only a proportion of the gas resulting from a prior pyrolysis or gasification stage need consist of hydrogen because the other fuel gases remaining after its separation are required to meet the thermal requirements of the process. The approach proposed here involves the introduction of the waste hydrocarbon fraction of the MSW or biomass into a rotary kiln in such a way that both the external heat supplied in the form of hot sand and the water inevitably present in the charge (whose presence leads to a high thermal burden on the process for its evaporation) is conserved for effective use in the pyrolysis/gasification reactions. After separation of the product hydrogen from these gases, the fuel gas is combusted to heat the sand employed as the heat-carrying medium.

One of the objectives in publishing this paper is to emulate the ‘Open Source’ movemenst in the field of information technology. It is hoped that others will evaluate the proposal made here and suggest possible improvements with the aim of developing a realistic approach to develop this technology with the object of speeding its development.

Introduction

Two quite different but equally pressing problems afflict the transportation sector at present. First, more aggressive measures are needed to reduce the release of greenhouse gases to the atmosphere to combat climate change and other emissions that lead to poor local air quality particularly in cities. Second, the production of oil from conventional sources is reaching a peak. This author expects this peak around 2020[1]. Other estimates prepared by *The Association for the Study of Peak Oil and Gas* (ASPO) anticipate this peak as early as 2008 though the *Energy Information Administration* (EIA) of the U.S. Department of Energy places it later at 2037 for their most probable case. Even if the peak in conventional oil production does not occur much before 2050, there is not that much time available to replace the present supply system given the enormity of the problem that is now compounded by the rapid adoption of cars in such populous countries as China and India.

In this paper, a conceptual process for the local production of hydrogen to power vehicles is proposed that addresses these two problems together. It is applicable at most locations in the world but is particularly useful in Canada with its high per capita availability of biomass.

Hydrogen does not travel well. It costs twelve to fifteen times more to move energy in the form of this gas by pipeline as it does in oil, and there is a corresponding increase in costs for other modes of transport. It is therefore attractive to produce hydrogen near its immediate market. The logical starting fuel for local production of this gas is Municipal Solid Waste (MSW) because it is available at negative cost at most population centres in the sense that a fee is normally charged for its transportation and safe disposal in landfill sites. A process that produces hydrogen locally from the organic fraction of MSW together with any biomass available within acceptable distance of the conversion facility would therefore be attractive. The conceptual process is therefore aimed at the supply of the hydrogen necessary to power local vehicles equipped with fuel cells from such locally available materials. No fossil fuels are thus necessary; the emissions of greenhouse gases are reduced; and the transportation problem is short-circuited.

In 2000, there were 304 waste-to-energy plants operting in Europe of which perhaps six could be classed as based mainly upon pyrolysis as opposed to combustion or gasification.[3] Generally an oil is co-produced in the pyrolysis case. To produce hydrogen, it is desirable to operate at a higher temperature than when oil or electrical energy usually generated in combined heat and power mode is the desired end product. There has been less emphasis on recovering energy from MSW in North America perhaps due to generally lower costs of both energy and landfill operations.

The main option for the small-scale supply of hydrogen for local markets at present is the electrolysis of water. This process may be attractive in the early phases of the introduction of hydrogen-fuelled vehicles. During this initial introductory period, off peak power may well be available at sufficiently attractive rates, say less than three cents per kilowatt-hour. Nevertheless, it is difficult to justify this option when new generating facilities must be built to supply this expanding market when the lowest on peak cost is likely to be in the range of 6 cents per kilowatt-hour or even higher. Moreover, it is difficult to find a use for the oxygen always co-produced in electrolysis facilities. These early electrolysis facilities could be integrated later with the proposed process to increase hydrogen production in such a way the co-product oxygen could be used to advantage.

The conceptual process owes much to developments in the classical field of the coking of coal. Every city of any size had its own gas works by the early twentieth century. This gas contained about fifty per cent hydrogen by volume and thus could serve as a source of hydrogen though it was used mainly at first for illumination and later for domestic purposes such as cooking and heating well into the twentieth century. Coke ovens are now confined to steelworks where the coke derived from the coking grades of coal is essential as a fuel for the iron blast furnace process. The gas always produced as a by-product of coke production is used as a general purpose fuel throughout these plants.

A cryogenic technique was used to separate hydrogen from coke oven gas at a steelworks in Hamilton in the 1960s as an intermediate step in a chemical complex producing urea. With the advent of less costly membrane technologies for the separation of hydrogen from the bulk gas, there are proposals in Japan to supply gas from this source for the initial phase of the introduction of fuel cell-equipped vehicles. (In that country, coke oven gas is partly derived from Canadian coal.) Given that the coke has to be produced for the iron blast furnace process in any case, it may be shown that hydrogen derived from coke oven gas is cheaper than that obtained from the conventional technique based upon the reforming of natural gas up to the limit of the quantity of this gas available. Nevertheless, there is no reason that appreciable quantities of hydrogen derived from coke oven gas could not be supplied economically for vehicles in steelmaking centres in Ontario such as Hamilton and Sault Ste. Marie. It is somewhat ironic that the lowest cost hydrogen available in Ontario for this purpose is produced from coal mainly of U.S. origin.

Sand Coking Processes

The conceptual process proposal follows logically from the developments in the classical carbonization field over the years. Any pyrolysis process requires an external source of sensible heat. In the usual case, the heat requirement is supplied by conduction through a refractory wall as in conventional ovens for the coking of coal. This is inherently a slow step. From time-to-time, however, externally heated sand has been used as the heat transfer agent. Such sand-based processes have been operated on a small scale off and on for over one hundred years in the carbonization of coal for specialized purposes such as the production of 'smokeless' fuels. Sand is normally used as the heat carrier because of its low cost, widespread availability, uniform characteristics, good heat capacity, and physical and chemical stability.

There are major efforts underway at present to pyrolyze or gasify wood in fluid beds using sand as a heat carrier. For example, in the facility demonstrating the Battelle Process in Burlington, Vermont, fine dried wood is gasified in a bed of sand fluidized with steam. Sand containing residual organic matter is continuously transferred from the gasification stage to a second fluid bed in which it is re-heated by the combustion of the residual matter inside the bed with air. After heating, the sand is continuously transferred back to the gasification stage to supply the necessary energy.[2] The fuel gas resulting from the gasification is intended for the generation of electricity in gas turbines arranged in combined cycles.

In general, fluid bed processes have the advantage of fast reaction because of the fine size of the feed but it must be quite uniform in size and other properties. Despite prior drying, there is always water present in this type of feed that must be vapourized which requires energy. When hydrogen is the desired product, it is desirable that this water vapour be released in such a way it can participate in the gasification and reforming reactions. This is difficult to achieve in fluid bed processes. The Battelle process is typical of pyrolysis (or gasification) processes in which the lighter fraction of the gases released from the fuel become part of the product gas stream whereas the remaining carbon-rich fraction serves as the source of energy. This technique obviates the need for expensive oxygen to produce a useful fuel gas that would otherwise contain as much as fifty per cent nitrogen were the biomass simply gasified with air. This cycle is to be contrasted with conventional coke making from coal where the necessary energy for the process is provided by the combustion of a fraction of the coke oven gas with air in combustion chambers separated from the coal. If hydrogen is separated from the coke oven gas in membranes or by other methods, the remaining gas could still serve as the necessary fuel.

The question as to whether the fuel gas is produced by pyrolysis or by gasification mechanisms is one of degree: some processes lie closer to one end of the spectrum while others lie at the other. Gasification occurs in all pyrolysis processes and pyrolysis in all gasification processes.

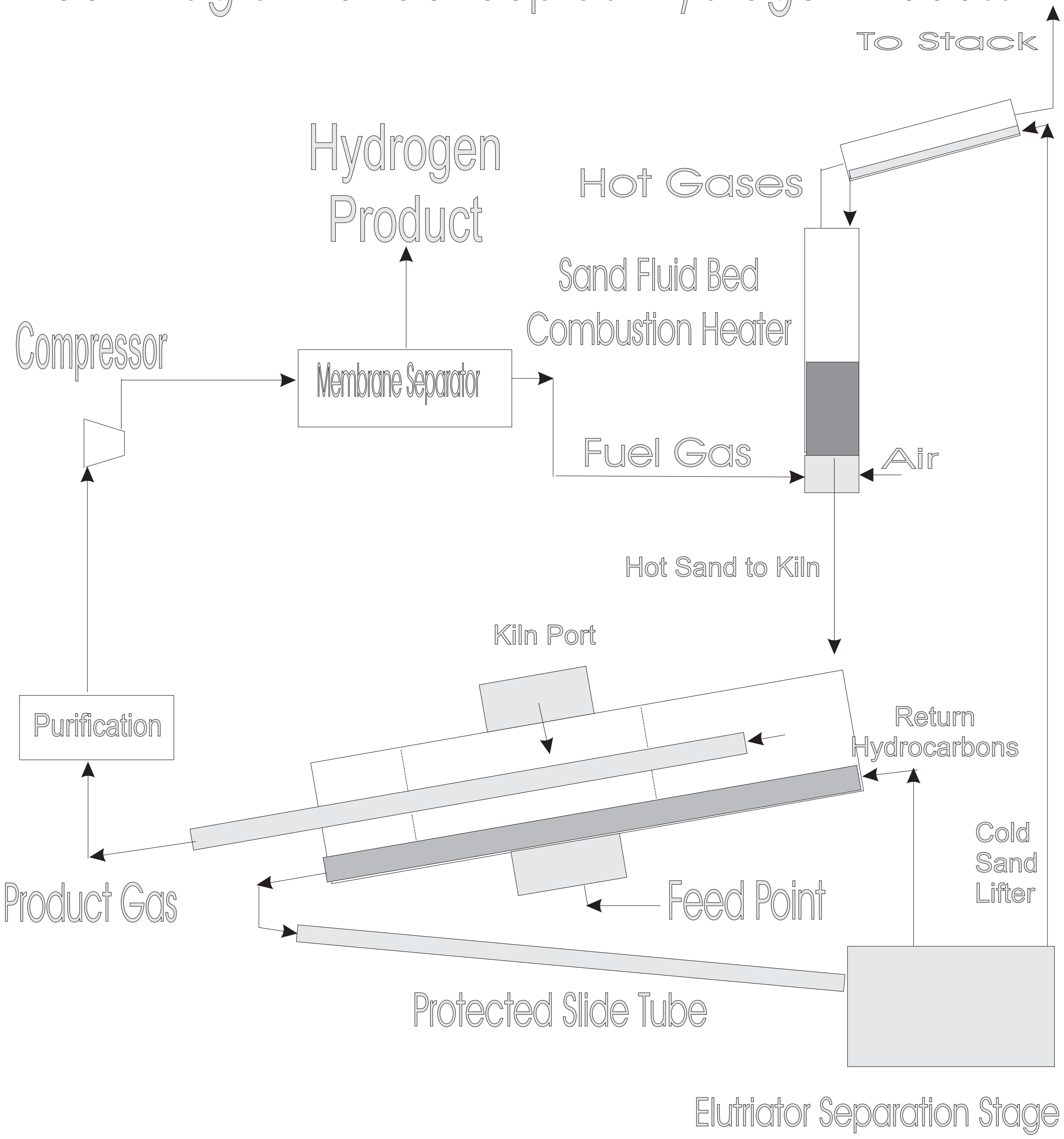
The major difference between the traditional coal coking technologies and the pyrolysis/gasification of MSW/biomass materials is the high water content of the latter even when a prior drying stage is provided. Nothing can be done about the quantity of heat required to change the state of a given amount of water contained in the feed to vapour but because of the high thermal burden this imposes on the process, it is important to use energy of the lowest grade possible for this purpose. In several processes, high-grade heat is employed which is an inefficient use of energy.

Outline of Conceptual Process

In the conceptual process advanced here, hot sand is added to a long rotating inclined lined tube or kiln at its hot end and the MSW/biomass charge is fed at an intermediate point along the vessel. The sand and the organic material are continuously tumbled as the charge proceeds down the kiln towards the discharge point at the low-temperature end. Unlike a cement kiln, there is no flame in the centre of the kiln.

In the proposed process, the MSW/biomass is fed onto the sand through a porting system located about mid-way along the kiln where it is tumbled with the cooling sand. The gases generated in the colder end of the kiln consist of water vapour and that portion of the volatile matter released from the charge at low temperature. These gases pass up the kiln to the hotter end because there is no other avenue of escape. The sand containing the residual organic material is discharged through the cold end bulkhead possibly by the use of a screw-type device. After discharge, it is transferred under a protective atmosphere to a location near the hot end of the kiln. This

Block Diagram of Conceptual Hydrogen Process



step might be carried out in a downward sloping covered duct. The unreacted remaining organic residual matter is then elutriated from the sand and blown through the bulkhead pressure seal into the hot end of the kiln with a carrier gas. After this separation stage, the remaining sand is then transferred to a heating device that may be a conventional kiln or fluid bed. This separation need not be perfect: some sand will inevitably be blown back into the kiln with the lighter elutriated residual organic matter and some of this organic matter will remain with the sand. That remaining with the sand becomes part of the fuel for this heating stage though most of the energy required will be supplied by the combustion of that fraction of the fuel gas remaining with air after separation of the hydrogen in the membrane stage. There are thus two sources of fuel for the re-heating of the re-circulated sand.

The gas at the hot end of the kiln is extracted through a concentric pipe mounted in the centre of the kiln extending back through the cold end. This arrangement makes it possible to recover sensible heat from the product fuel gas as it passes through the kiln to the cold end. This sensible energy is transferred to the rising gas stream in counter-current flow. There is a second counter-current flow between the outer ring of rising gases and the falling stream of solids.

Notes on Specific Steps in the Conceptual Process

The Development of Membrane Separators

It is now possible to buy membrane devices that operate at low temperature to separate hydrogen from mixed gas stream. To date, these have mainly found application to recover relatively minor hydrogen flows in oil refineries and other process industries. Most operate at elevated pressure. There is also active research into the development of membranes to separate hydrogen from high temperature streams of dirty gases such as might result from the gasification of coal. Here the problem is to deal with the presence of difficult impurities such as sulphur. Palladium in bulk form has long been considered for this class of operation but is too expensive for routine applications and is subject to fouling. Active work has been underway at Argonne National Laboratory for a number of years to develop robust and cheaper substitute materials with every prospect that a reasonable degree of success will be achieved.

The conceptual process proposed here depends upon the successful development of membranes to separate hydrogen. The selection of hydrogen as a product for direct use in fuel cells is the step that distinguishes it from other processes in the pyrolysis/gasification field. There are three considerations of importance to the proposed process. First, a compression stage will no doubt be needed prior to the membrane separation stage because the proposed process cannot be operated much over atmospheric pressure. This implies that the product gas from the kiln will have to be cooled and cleaned sufficiently to be an acceptable input to standard compressors.

Second, after the separation of the hydrogen, the residual fuel gas (the so-called ‘retainate’) will still be under high enough pressure to meet the requirements of a fluid bed stage employed to re-heat the sand. This gas would be combusted with air in the bed to supply the necessary heat along with that released by combustion of any carryover solid residual hydrocarbon material not separated from the cooled sand exiting the kiln.

The third aspect arises from the temperature at which the membrane separation stage will be operated. Were the incoming gas to consist only of a mixture of hydrogen/water vapour and carbon monoxide/carbon dioxide, and given a high enough temperature and the presence of a suitable catalyst, there would be a continuous shift in the composition of the residual gas as hydrogen is removed through the membrane. This so-called ‘shift’ reaction of carbon monoxide with water vapour to form hydrogen and carbon dioxide is somewhat exothermic. In the more likely case, some residual hydrocarbons will also be present in the feed gas. If so, reactions with water vapour of the reforming type will tend to occur at higher temperatures, but given that these are strongly endothermic, external heat would have to be supplied to allow continuing reaction.

It is an important issue as to whether chemical reactions of any kind should be encouraged in the membrane separator to increase the quantity of hydrogen produced.

The Nature of the Feed Materials

In principle, virtually all hydrocarbon-based materials may be charged to the process. It is a major advantage of the conceptual process that the feed may also be in a variety of physical forms though the size should not be reduced so fine as to lead to high gas-borne flows of solids in the kiln. In the ideal situation, all the charge would be heated and decomposed during tumbling with the sand though some will inevitably be entrained in the evolving gases.

The mid-kiln feeding device is assumed to be a scoop that opens near the bottom of the rotation. This scoop is retracted as the rotating motion causes it to rise and, after full closure of the external scoop, a second interior gate opens as the kiln approaches the top position to allow the feed material to fall through the port down onto the sand below. Some compacting of the feed is to be expected in the charging equipment and it may not fall out easily or completely without an assist of some kind. To deal with this eventuality, a positive discharge mechanism will probably be required such as a short-action punch rod capable of fully cleaning out the port holding chamber. The feed assembly may be powered from the motion of the kiln by a system of levers and cams. For a kiln of large diameter, several feed assembly modules may be mounted around the circumference at the same longitudinal position with each filling in turn at the bottom position to provide an almost continuous feed falling on to the sand.

Small proportions of waste hydrocarbon liquids could also be charged by admixture with the bulk solid charge fed though the scoop. The feed might also include a limited fraction of crushed tires and other such difficult materials mixed with the bulk MSW/biomass. It may be necessary to reduce different materials to their own characteristic sizes as they are fed together, but individual pieces should be as small as possible without leading to excessive entrainment by the flowing gases in the kiln.

The ash-forming content of the waste hydrocarbon feed is likely to be as high as five per cent and constituents in this material may tend to fuse with the sand. For this reason, there may be advantage in adding some standard iron ore pellets with the hot sand to act as a minor grinding medium to help break up such agglomerations. These pellets may be screened from the cold-end discharged product of sand and partly reacted hydrocarbon material for separate heating and re-charging to the hot end of the kiln along with new re-heated sand.

Though the kiln system is tolerant of a wide range of hydrocarbon materials in both chemistry and in form, it is desirable to avoid the presence of chlorine-containing plastics and some other impurities. Despite precautions to separate these materials in the charge preparation stage, the hydrogen-containing product gases will no doubt have to be passed through a protective chlorine trap.

There will be a certain minimum water content required to operate the kiln successfully to produce hydrogen. In the case of a feed high in biomass content, the problem may be to dry the charge down to a desired level of the order of 20 per cent of the weight of the dry charge material. In the case of some MSW materials, there may be insufficient water present. In the latter case, some steam may have to be introduced through the cold end of the kiln. In general, however, it should be possible to find an acceptable blend of MSW and biomass without the need to resort to such measures.

Design of the Exit Tube

The product gases leave through an exit tube mounted along the length of the kiln in its centre with the intake extended as far as possible into the hot zone. The tube leaves through the cold end bulkhead. These gases enter this interior tube at their maximum temperature which is expected to be in the range of 700/800 degrees C. It is important to recover as much of the heat content of the leaving product gas stream as possible to reduce the overall energy requirements of the process. For this reason, it may be necessary to place longitudinal fins on both the inside and the exterior of the centre tube to improve heat transfer from the hot product gas to the gases proceeding in the opposite direction along the length to the hot zone. Alternatively, the tube could be in the form of a spiral to increase the area of heat transfer. The centre tube may be supported by a series of three members mounted 120 degrees apart at each supporting location and anchored to the kiln circumference at intervals from the cold end of the kiln. The tube might be cantilevered as far as possible into the hot zone employing high temperature materials for this last section. If this tube rotates with the kiln, this cantilevered tube would tend to stay straight, as the tendency to sag would be cancelled by the rotating motion.

The issue arises as to whether the exhaust tube should rotate with the kiln or instead remain stationary as the kiln rotates and turn inside supporting ring bearings. Rotating the tube with the kiln is a simpler design since the extension through the cold end bulkhead would permit a cold connection to the external continuing stationary piping though a revolving joint located outside the kiln. Nevertheless, maintaining the tube stationary in the kiln may be possible since the rotation speed is low enough that no lubrication may be required for the supporting ring bearings. This latter arrangement has the advantage that the inlet to the tube in the hot zone could be in the form of a permanently upward-facing elbow to minimize the content of suspended fine solids entering along with the product gas stream. There would be no need for a rotating coupling linking the centre tube to the external continuing tubing in this case.

Both options face the problem of a build-up of solids both inside and outside the tube that would reduce heat transfer. It is possible to conceive of a cleaning device that would be periodically pushed through the inside of the tube from the cold end access point through seals whether longitudinal fins had been installed within the tube or not. It is more difficult to conceive of such a device that could be used to clean the exterior of the tube.

Safety

It is important that the conceptual process be examined by safety experts because the hydrogen content of the product gas may be expected to be about 30% by volume. The bulkheads sealing the end of the kiln should be designed as explosion relief doors with the continuing path left clear of critical components along the extended axis of the kiln. Though the volume of the kiln is large, it operates only slightly above atmospheric pressure at a sufficiently high temperature that it may prove not to be inherently dangerous.

Discharge System

The cooled sand would be extracted from the cold end of the kiln with the partially reacted residual hydrocarbon material possibly using a screw mechanism. The kiln pressure is low enough that such a simple system may be adequate to provide a gas seal. This partly reacted hydrocarbon material will need to be protected from combustion with air by a protective gas atmosphere. This small flow of protective gas could be obtained from the retrained fraction of the gas remaining after hydrogen recovery in the membrane stage. The simplest procedure to transfer the discharged sand and unreacted hydrocarbon material to the hot end of the kiln is to let it fall through a protected chute to the elutriation stage. The light elutriated material is composed mainly of the unreacted MSW/biomass but would contain some entrained sand. This light fraction would be blown into the kiln through the hot end bulkhead. The heavier separated sand (which would contain some unseparated residual MSW/biomass) would be transferred to the re-heating stage. Compressed air would be used for fluidization to which would be added the retained flue gas from the membrane separation stage since the pressure of the latter gas would likely be adequate. Should the pressure be inadequate, the sand might be re-heated in a standard kiln fired by the residual flue gas combusted with air.

Burning the residual fuel gas would be the main source of energy but this would be augmented by the combustion of carry over solid hydrocarbon material that was not separated in the elutriation stage. The sand should be heated as hot as possible with an object of reaching 1000 degrees C or even higher but this limit is set by the fusion characteristics of the mixture of the sand and the ash-forming constituents in the MSW/biomass feed materials. When a fluid bed is used as the heating stage, the hot sand could be returned to the kiln through a standard ‘downcomer’ that would pass through the hot end bulkhead where it will be tumbled with the returned hydrocarbon solids from the elutriation stage.

Scaling Factors

The target selling price to the public for the hydrogen required to fuel individual vehicles is assumed here to be no more than $20/GJ (essentially equal to $20/mmBtu) on a tax-free basis. The object is to compete with crude oil trading on the NYMEX Market at $US 40/barrel. When $US 10 is added to cover the cost of refining and delivery, the energy in gasoline is priced at about $US 8.60/barrel before taxes. The implicit assumption is that the efficiency of conversion of the energy in the hydrogen supplied to the wheels for propulsion in fuel cell-equipped vehicles will be at least twice that of gasoline in the conventional internal combustion engine.

Though it is possible fewer people would be required, the conservative assumption here is that as many as fifty people will be needed to staff the hydrogen facility on the basis of three shifts operating 7000 production hours per year. The average cost per employee is placed at $100,000 per year to cover salaries and all related employment benefits. Total employment costs per year would thus be $5 million. Given that the plant would be paid to accept MSW, this source of revenue is assumed to about equal the expenditures to purchase locally surplus biomass. Given this situation, the total cash flow needed per year is assumed by rule-of-thumb to be four times the total employment cost. On this basis, the cash flow requirement from the sale of hydrogen would be $20 million per year.

With the energy content in the hydrogen taken as 325 Btu/scu. ft. (HHV), the value of the hydrogen produced will be $ 6.50/1000 standard cubic feet (Scf) for the target selling price of $20/mmBtu. The total quantity of hydrogen that must be sold in one year at this price to meet the need for $20 million in cash flow is then 3,077 million Scf. The production of hydrogen per operating hour on the basis of 7000 hours per year is then 0.44 million Scf/hour

Given that the kiln gas contains one-third hydrogen content by volume before entering the membrane separation stage, the total gas flow becomes 1.32 million Scf per hour.

With an internal diameter of the kiln of 20 feet, the working area of the cross section is 314 ft. If the tumbling solid charge occupies one-quarter of the cross section of the kiln, the superficial velocity becomes 1.55 ft/second at standard conditions. Even allowing for the expansion of the gases produced on heating, the velocity appears within acceptable operating limits.

Based upon an approximate carbon balance, a charge consisting of 30 tonnes per hour MSW plus biomass assumed to approximate dry cellulose in composition would produce the desired 0.44 million Scf of hydrogen per hour.

The sand-to-charge ratio is taken as 5/1 with the water content of the MSW/biomass set at 20% or 6 tonnes of water per hour. The total solids feed is thus 30 + 5 x 30 + 6 = 186 tonnes per hour which is approximated here as 200 tonnes per hour. (Should the charge be drier than expected, any additional water requirement should be made in the form of steam.)

Given a kiln of twenty feet internal diameter one hundred feet in length with one-quarter of the cross section occupied by tumbling solids, the weight of charge in the kiln at a density of 100 lb/cubic ft. is 356.2 tonnes. With a total solids feed rate of 200 tonnes per hour, the retention time would be 1.78 hours which is judged adequate if not too long.

Other Process Possibilities

Link to Electrolysis Processes

If off peak electricity were available, it may be attractive to link the proposed process to electrolysis techniques particularly if a small-scale facility of this kind had been installed first as an introductory measure to provide the smaller quantities of hydrogen needed when fuel cell-equipped vehicles were first introduced. There would be little difficulty in blending the two sources of hydrogen.

The oxygen co-product of the electrolysis process could be introduced in the hot zone of the kiln to both increase the temperature and to reduce the sand re-circulation ratio. Though this oxygen would consume some of the energy potential of the kiln gas, it would result in a gas of higher hydrogen content by partial oxidation of some of the hydrocarbon gases. With less sand needed to be re-circulated per unit of output, less energy be would be needed for its heatiheat it and thus less retained fuel gas would be required.

The linkage of electrolysis techniques to the proposed process thus improves the economic acceptability of the electrolysis process by providing a local outlet for the oxygen. Unit capital requirements may also be reduced because the introduction of oxygen in the kiln would allow higher charge rates because less sand is needed which would lead to higher output from the kiln.

Alternatively, the oxygen could be used to autogenously reform the kiln gas in a separate stage to increase its hydrogen content before the membrane separation stage. This practice would reduce the quantity of hydrogen-depleted flue gas remaining to heat the sand. Natural gas could be used to make up this thermal deficit and this option may be attractive during periods of low natural gas prices.

Alternative to the Use of Rotary Kilns

If a shorter retention time is adequate to release the gases from the MSW/biomass charge, it is possible a simple vertical tube could be used in which the hot sand mixed with the solid charge would be passed downwards over a stack of delaying internal devices such as metal coils whose purpose would be to increase the pathways open to the gases as they to rise. Two towers might be used, with the raw MSW/biomass fed to the lower or cooler unit and the elutriated fraction returned to the hotter tower with re-heated sand as before.

Conclusion

The advent of fuel cell-equipped vehicles and the development of membranes to separate hydrogen from process gas streams provides an opportunity to produce this gas locally from Municipal Solid Wastes and biomass. A successful process of this type would address both climate change concerns and economic problems resulting from higher oil prices. The high cost of transportation of hydrogen from large centralized production facilities and MSW to landfill sites provide an incentive to a local approach to meeting the hydrogen needs of the regional fleet of vehicles.

The proposed process is based upon the pyrolysis of a wide variety of available hydrocarbon materials - MSW and biomass - in a rotary kiln with the thermal requirement supplied internally by a flow of hot sand. This sand is heated by combustion of the residual fuel gas remaining after the separation of hydrogen in a membrane stage. The charge to be pyrolyzed is fed to the kiln in mid-length to improve thermal performance and to ensure the participation of the water vapour always released from such materials in the kiln reactions.

The full process details are disclosed in this paper in the hope of attracting interest and further development based upon the ‘open source’ techniques now prevalent in the field of information technology.

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