



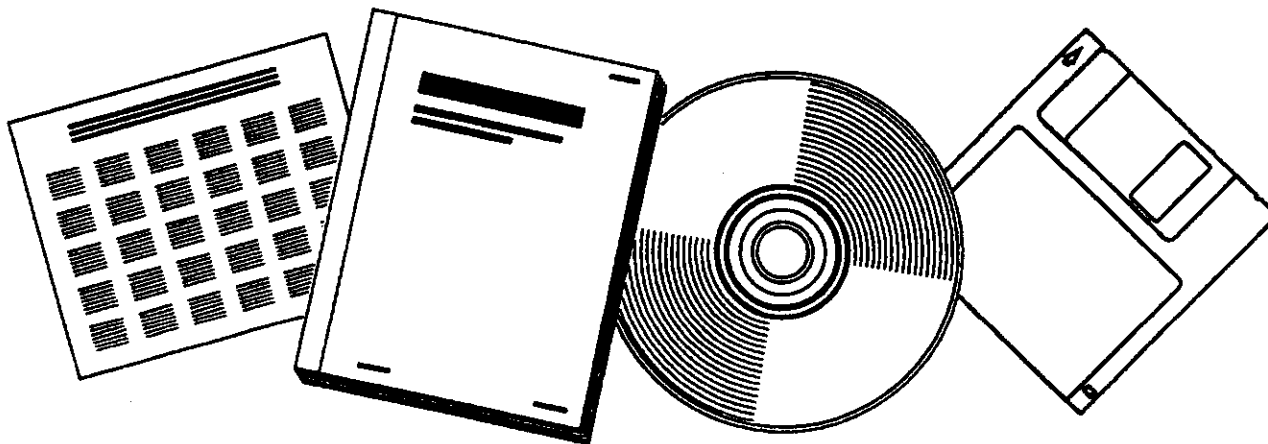
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**CONVERSION OF CELLULOSIC WASTES TO LIQUID
HYDROCARBON FUELS: VOL. 6, THE MODELING
AND DESIGN OF A STAGED INDIRECT
LIQUEFACTION REACTOR: FINAL REPORT**

ARIZONA STATE UNIV., TEMPE. COLL. OF
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VOL. 6: THE MODELING AND DESIGN
OF A STAGED INDIRECT LIQUEFACTION
REACTOR:

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Abstract

A staged reactor was designed to convert biomass to useful fuels. The reactor consists of three stages. The first stage is a concentric combustor/pyrolyzer system where the biomass is gasified in a fluidized bed at high temperatures in the absence of oxygen. The second stage is a cyclonic scrubber where particulates and condensable materials are removed from the gas stream while the gas is cooled. In the final stage the gas undergoes a Fischer-Tropsch synthesis in a fluidized bed or slurry reactor. Mathematical models of the system were developed and used to create computer programs that would predict the behavior of the bed. The models were based on fundamental phenomena and were used to predict key dimensions of the staged reactor system. A transparent plastic, full-scale, cold flow reactor simulator was built using the models' predictions. The simulator was used to refine the models and determine the operating characteristics of the reactor. The design was determined to be workable and potentially useful. The reactor was, however, difficult to operate and would require extensive automated control systems.

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NOTATION

- a = Liquid-gas interfacial area
 A = Cross-sectional area of the bed
 a_H = Specific heat transfer area
 a_s = Liquid-solid interfacial area
 Be = Dimensionless parameter
 Bo_g = Gas phase Bodenstein number
 Bo_l = Liquid phase Bodenstein number
 C = Concentration of species of interest
 C_b = Concentration of a species in the bubble phase
 C_{bc} = Concentration of species in combined bubble
and cloud phases
 C_{cat} = Catalyst concentration
 C = Concentration of a species in the emulsion
phase
 C_g = Concentration in the gas phase
 C_H^* = Equilibrium liquid concentration of hydrogen
 $C_{H,l}$ = Concentration of hydrogen in liquid
 $C_{H,s}$ = Concentration of hydrogen at the solid surface
 D_g = Diffusivity of species in gas
 d_b = Bubble diameter
 d_c = Diameter of cloud phase
 D_l = Diffusivity of hydrogen in slurry liquid

d_p = Diameter of a solid particle
 Da = Damkohler number
 E_A = Activation energy
 F_{BC} = Diffusive mass transfer coefficient for bubble
to cloud transfer (based on bubble volume)
 F_{CE} = Diffusive mass transfer coefficient for cloud
to emulsion transfer, (based on bubble volume)
 g = gravitational acceleration
 G_{BC} = Superficial velocity of gas moving from the
bubble to the cloud phase
 G_{CE} = Superficial velocity of gas moving from the
cloud phase to the emulsion phase
 h = Heat transfer coefficient
 He = Henry's law constant
 H_r = Molar enthalpy of reaction
 K_{bc} = Total mass transfer coefficient
 k_{be} = bubble to emulsion mass transfer coefficient
 k_{gc} = Mass transfer coefficient from cloud phase to
emulsion phase
 k_l = Liquid side mass transfer coefficient
 k_s = Mass transfer coefficient for liquid to solid
transfer
 P_{BC} = Velocity of gas flow from bubbles to cloud
 P_{CE} = Velocity of gas flow from cloud to emulsion
 Pe = Peclet number

q = bulk molar gas flow

r = Reaction rate

r_{H_2} = Rate of disappearance of hydrogen

R_{VB} = Rate of disappearance of component of interest per unit of bubble volume in the bubble phase

R_{VC} = Rate of disappearance of component of interest per unit of bubble volume in the cloud phase

R_{VE} = Rate of disappearance of component of interest per unit volume of the emulsion phase in the emulsion phase

Re_c = Reynolds number of cloud phase

S_{bc} = Mass transfer area of combined cloud and bubble phase

S_{be} = Mass transfer area between the bubble phase and the emulsion phase

Sc = Schmidt number

Sh_c = Sherwood number of cloud phase

St_g = Gas phase Stanton number

St_h = Heat transfer Stanton number

St_l = Liquid phase Stanton number

t = time

T = Temperature

T_w = Temperature of the reactor wall

U = Overall superficial gas velocity

- U_b = Gas flow rate in bubble phase
- U_{BS} = Superficial gas velocity in the bubble phase
- U_{CS} = Superficial gas velocity in the cloud phase
- U'_g = Dimensionless superficial gas velocity
- U_{ES} = Superficial gas velocity in the emulsion phase
- U_{mf} = Minimum superficial gas velocity required to fluidize a bed

- U_o = Overall superficial gas velocity
- V = Volume
- V_b = Volume of the bubble phase
- V_{bc} = Volume of bubble and cloud combined
- x = Height in reactor
- X = Mole fraction of component of interest in the liquid phase
- x' = Dimensionless liquid concentration
- y = Mole fraction of component of interest in the gas phase
- y' = Dimensionless gas phase concentration
- z = Dimensionless height

INTRODUCTION

Modern society has developed to the point where it is intimately dependant on the availability of large amounts of ready energy. In the past, the procurement of needed energy has been relatively easy. Petroleum currently fills the role of our principle energy source. It is, however a finite resource. In time, we will exhaust all our current reserves of oil. Eventually we will have to look elsewhere for the energy which our life styles demand.

Over the past decade, numerous alternatives for the use of petroleum have been examined. Some, like coal and nuclear power, are also based on finite reserves of raw materials. Thus they represent, at best, a temporary solution to the problem. Ideally, any new energy system to be developed would be based on reserves that can not be exhausted. These sources are those that are continually being renewed or are so vast that they can not be used up in the lifetime of this planet.

One potential energy source that is continually being renewed is biomass. The plants and animals on the Earth are constantly converting solar energy into energy-containing materials. These materials are known

collectively as biomass and are found in a wide variety of forms and locations. The vast majority of the material is currently unused. Much, in fact, is considered waste and disposed of at significant expense. If the potential of these materials were tapped, it would be possible to supply a large portion of the energy demands of society. It should be noted that the earth is not capable of producing sufficient quantities of biomass to both satisfy all our energy demands while at the same time meeting our demand for food. (Cheremisinoff et al., 1980) The use of biomass as an energy source, however, does have the capability of meeting a significant portion of our energy demands while at the same time reducing the load on our waste handling capabilities.

There are several barriers that must be overcome before the potential of biomass can be tapped. Foremost among the difficulties is the conversion of biomass into useful forms. In its naturally occurring forms, biomass is not suitable for most energy demanding activities. The materials have a low energy density containing around 5000 cal/g. (Bungay, 1981) This can be compared with 9560 cal/g, the value for gasoline. (Cheremisinoff et al., 1980) The amount of energy extracted from naturally occurring biomass would not even offset the amount required to transport it to the points where it is needed. The second

major difficulty stems from the fact that biomass is produced in a wide variety of forms. Each form has its own set of characteristics that must be considered in processing.

In order to overcome these problems, it is necessary to convert biomass from its naturally occurring forms into some other forms that are more convenient. Two general classes of conversion techniques have been examined. Figure 1 is a diagram of the classes and some of the techniques associated with each class. The first class of techniques makes use of biological processes. The principle techniques in this class are fermentation and anaerobic digestion. Fermentation converts specific types of biomass into liquid alcohols. The alcohols have a higher energy density than the biomass. Anaerobic digestion involves the production of gases containing mainly methane. Anaerobic digestion can handle a wider range of types of biomass than fermentation. The product, however, is more difficult to utilize. Biological processes in general are pollution free and use nearly ambient conditions. However, they are very sensitive to their operating conditions and are slow.

The second class of techniques involves the use of thermochemical processes. These techniques make use of much more extreme conditions than the biological processes