

## [54] HYDROLIQUEFACTION OF COAL

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C10G 51/06; B01J 8/18[52] U.S. Cl. .... 208/10; 208/49;  
208/78; 208/80; 422/140; 422/141; 422/142[58] Field of Search ..... 208/10, 49, 78, 80;  
422/140, 141, 142

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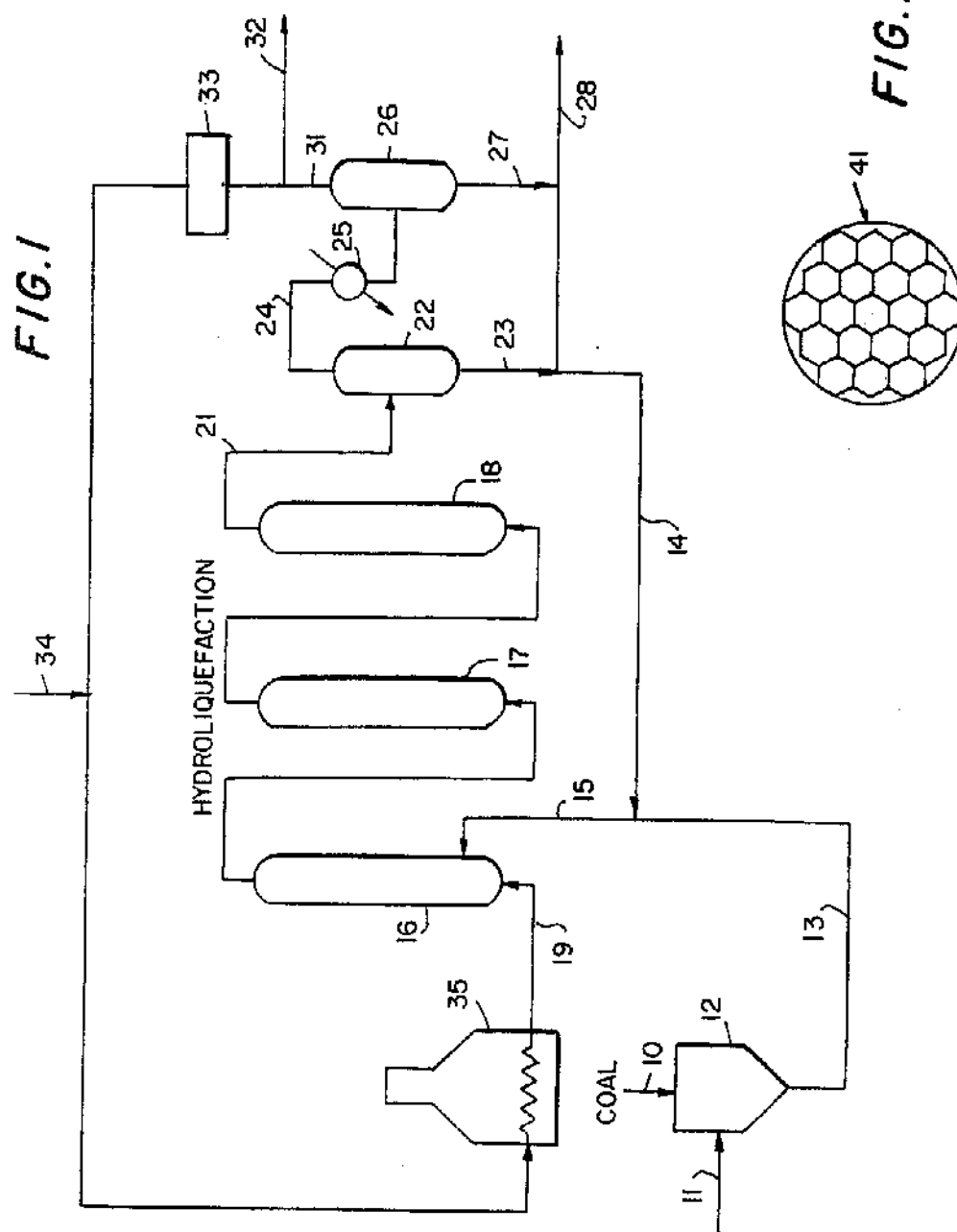
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## [57] ABSTRACT

Coal is catalytically hydroliquefied by passing coal dispersed in a liquefaction solvent and hydrogen upwardly through a plurality of parallel expanded catalyst beds, in a single reactor, in separate streams, each having a cross-sectional flow area of no greater than 255 inches square, with each of the streams through each of the catalyst beds having a length and a liquid and gas superficial velocity to maintain an expanded catalyst bed and provide a Peclet Number of at least 3. If recycle is employed, the ratio of recycle to total feed (coal and liquefaction solvent) is no greater than 2:1, based on volume. Such conditions provide for improved selectivity to liquid product to thereby reduce hydrogen consumption. The plurality of beds are formed by partitions in the reactor.

— ~ 18"  
Diameter

21 Claims, 2 Drawing Figures



## HYDROLIQUEFACTION OF COAL

The Government of the United States of America has rights in this invention pursuant to Contract No. EX-76-C-01-2514 awarded by the U.S. Energy Research & Development Administration.

This invention relates to the hydroliquefaction of coal.

Hydroliquefaction of coal to valuable liquid products is currently of great interest. In one such process, coal dispersed in a suitable liquefaction solvent is hydroliquefied in an upflow expanded or ebullated hydroliquefaction catalyst bed. Such a process is described, for example, in U.S. Pat. No. 2,987,465.

Applicant has found that such an upflow expanded or ebullated bed hydroliquefaction process has poor selectivity to liquid products, whereby there is an inefficient use of hydrogen and the production of light products, such as methane, ethane, propane, butane and light oils boiling below 400° F. Such products contain a higher percentage of hydrogen than heavier distillates.

In accordance with the present invention, applicant has provided a new and improved process and system for the hydroliquefaction of coal in an upflow expanded or ebullated catalyst bed which increases the selectivity to liquid products and thereby efficiently uses its hydrogen to provide a more economical process.

In accordance with one aspect of the present invention, there is provided a process for the catalytic hydroliquefaction of coal by passing coal dispersed in a coal liquefaction or pasting solvent and hydrogen through at least one reactor which has at least two parallel upflow expanded catalyst beds, in separate streams, each stream having a cross-sectional flow area of no greater than 255 square inches, with the streams through each of the catalyst beds having a length and a gas and liquid superficial velocity to maintain an expanded bed and provide a Peclet Number of at least 3. If recycle is employed, the ratio of recycle to total feed (coal and liquefaction solvent) does not exceed 2:1, by volume.

In accordance with another aspect of the present invention, there is provided a reaction system for the catalytic hydroliquefaction of coal which includes at least two upflow expanded or ebullated bed catalytic hydroliquefaction reaction zones in series, with each of the at least two reaction zones including at least two parallel expanded catalyst beds, each of the expanded catalyst beds providing for flow therethrough in a stream which has a cross-sectional flow area of no greater than 255 square inches and a flow length whereby the superficial velocities of gas and liquid therethrough maintain the expanded or ebullated catalyst bed and provides a Peclet Number of at least 3. The at least two parallel catalytic beds in each of the reaction zones are provided by the use of partitions in the reaction zones.

Peclet Number is defined as follows:

$$\text{Peclet No.} = \frac{(V_L)(L)}{(73.5 \text{ hr.}^{-1})(1 - E_G)(D)^{1.5}(V_G)^{0.5}}$$

wherein

$V_L$  is liquid velocity, ft/hr.

$L$  is length of the reactor, ft.

$D$  is the equivalent diameter of the catalyst reaction zone

$V_G$  is the gas velocity, ft/hr

$E_G$  is the fraction of the total catalyst bed volume which is occupied by the gas, as disclosed by Hughmark, G. A., "Hold-Up and Mass Transfer in Bubble Columns" *I&EC Process Design and Development* 6 (2), pp 218-20, 1964.

Peclet Number is a measure of the approach to plug flow, with a Peclet Number of infinity corresponding to perfect plug flow. In accordance with the present invention, the higher the Peclet Number the better the hydrogen efficiency, and as a result, although a Peclet Number of at least 3 provides a beneficial increase in hydrogen efficiency, the Peclet Number should preferably be as high as possible, consistent with other reaction conditions. Thus, the Peclet Number is preferably at least 3, and most preferably at least 10. The Peclet Number is preferably as high as possible; however, as a result of design limitations the Peclet Number generally does not exceed 70, and in most cases does not exceed 50. The selection of an optimum Peclet Number for a particular feedstock and other design considerations should be apparent to those skilled in the art from the teachings herein.

The cross-sectional flow area of the stream in each of the catalyst beds is no greater than 255 square inches, with the cross-sectional flow area generally being at least 10 square inches. In most cases, the cross-sectional flow area is at least 28 square inches. The selection of an optimum cross-sectional flow area will vary, and the selection of such an optimum cross-sectional flow area is deemed to be within the scope of those skilled in the art from the teachings herein.

The other parameters included in the calculation of Peclet Number are reaction zone length and superficial gas and liquid velocities through the expanded catalyst beds. The velocity of gas and liquid through the beds must be at a value sufficient to maintain the ebullated or expanded catalyst bed state, and as a practical manner, such expansion is primarily related to the superficial liquid velocity. Thus, the reactor length and the superficial liquid and gas velocities are coordinated to provide a Peclet Number, as hereinabove described, as well as sufficient velocity to provide for the expanded or ebullated catalyst beds. In general the reaction zone lengths is in the order of from 20 to 130 feet, and most preferably in the order of from 40 to 90 feet, with the superficial liquid velocity generally being in the order of from 0.04 to 0.3 foot per second. The superficial gas velocity is generally in the order of from 0.04 to 1 foot per second. The selection of optimum values is deemed to be within the scope of those skilled in the art from the teachings herein.

In accordance with the invention, recycle is limited, with the ratio of recycle to total feed (coal and liquefaction solvent) being no greater than 2:1. Although in some cases it may be possible to operate the process without any recycle; i.e., a recycle ratio of 0:1, in most cases, some recycle is required in order to maintain a sufficient liquid velocity for expanding the catalyst beds. As a result, in most cases, the recycle ratio is at least 0.2:1, with the recycle ratio generally not exceeding 1:1. In accordance with the preferred embodiment, all of such recycle is provided externally; i.e., no internal recycle, which thereby eliminates the necessity for an internal recycle pump as generally employed in the ebullated bed coal liquefaction process. It is to be under-

stood, however, that it is possible within the scope of the invention to provide some internal recycle, provided that the recycle ratio (internal and/or external recycle) does not exceed 2:1.

In accordance with the present invention by providing hydroliquefaction in a reactor having a plurality of parallel expanded catalyst beds it is possible to achieve efficient use of hydrogen in a reactor of a size suitable for commercial applications. Thus, for example, in accordance with the present invention, it is possible to employ a reactor having a total cross-sectional area in the order of at least 65 ft<sup>2</sup>, and up to 155 ft<sup>2</sup> or greater, and to achieve improved hydrogen efficiency by providing for a plurality of separate parallel flow streams having the flow parameters, hereinabove described in separate parallel expanded beds in the reactor.

The parallel flow through separate expanded beds in the reactor is achieved by providing appropriate partitions in the reactor which are designed and arranged to achieve cross-sectional flow areas as hereinabove described. The number of partitions and the number of parallel flow streams in part will be dependent upon the total cross-sectional area of the reactor in that there must be a sufficient number of partitions and resulting flow streams to provide parallel flow streams each of which has a cross-sectional flow area, as hereinabove described. In part, the total number of partitions and the resulting number of flow streams is dependent upon the desired cross-sectional flow area within the cross-sectional flow areas hereinabove described. The selection of partitions to provide a desired cross-sectional flow area is deemed to be within the scope of those skilled in the art from the teachings herein.

The partitions for the reactor may take any one of a wide variety of forms, with a preferred form of partition being a vertical honeycomb type of structure. It is to be understood, however, that the partitions may provide for flow passages of other shapes; e.g., round, square, rectangular, etc. The selection of an optimum partition pattern is deemed to be within the scope of those skilled in the art from the teachings herein.

In accordance with a preferred embodiment of the present invention, there are at least two catalytic hydroliquefaction zones of the type hereinabove described in series, and preferably at least three such zones in series. The additional hydroliquefaction zones are employed to provide the desired hydroliquefaction without an unacceptable increase in temperature; i.e., the exothermic heat of reaction is controlled by providing a series of reaction zones, rather than by providing large quantities of recycle. The selection of an optimum amount of reaction zones, in series, is deemed to be within the scope of those skilled in the art from the teachings herein. In most cases, it is not necessary to provide any more than 4 of such hydroliquefaction zones in series. In most cases, the number of hydroliquefaction zones in series is selected to limit the temperature increase of each of the zones to no greater than 150° F., and preferably to no greater than 100° F.

The hydroliquefaction, as known in the art, is conducted at elevated temperatures and pressures. In general, the hydroliquefaction temperature is in the order of 650° F., to 900° F., and preferably from 750° F. to 850° F. The pressures are generally in the order of from 1800 to 3000 psig, and most generally in the order of from 2000 to 2700 psig. The selection of optimum temperatures and pressures are deemed to be within the

scope of those skilled in the art from the teachings herein.

Hydrogen is introduced into the hydroliquefaction zone in an amount, which when coordinated with the other processing conditions, provides an amount of hydrogen addition or absorption to provide the desired liquefied product. In addition, hydrogen is provided for effecting hydrodesulfurization and hydrodenitrification of the feedstock. In general, by proceeding in accordance with the present invention, it is possible to achieve a conversion of 90% or more of the MAF coal feed with hydrogen consumptions in the order of from 2 to 4 lbs. of hydrogen per 100 lbs. of coal.

The hydroliquefaction is conducted with a catalyst suitable for liquefying the coal, and in addition, such catalyst should have desulfurization and denitrification activity. Such catalysts are generally known in the art; e.g., cobalt molybdate, nickel molybdate, tungsten-nickel sulfide, etc., and are generally supported on a suitable support such as alumina. The selection of a suitable catalyst is deemed to be within the scope of those skilled in the art from the teachings herein.

The catalyst is maintained in the hydroliquefaction zone as an expanded or ebullated bed. As known in the art, such expanded or ebullated bed differs from a fluidized bed in that, in the expanded or ebullated bed, catalyst particles are not maintained in fluidized random motion. Such expanded or ebullated beds are known in the art, and as a result, no further details in this respect are deemed necessary for a complete understanding of the present invention.

The coal, as known in the art, is dispersed in a suitable pasting or coal liquefaction solvent or oil for passage through the catalytic hydroliquefaction zone. Such pasting or liquefaction solvents are known in the art, and is preferably a solvent derived from the coal liquefaction product, although other pasting solvents or oils may also be employed for the hydroliquefaction. The selection of a particular pasting oil is well within the scope of those skilled in the art, and forms no part of the present invention. In general, as known in the art, the pasting solvent is provided in an amount to provide a pasting solvent to coal weight ratio in the order of those generally used in the art; e.g., from 1:1 to 20:1.

The coal employed as a hydroliquefaction feed may be a bituminous coal, sub-bituminous coal or a lignitic coal. The selection of a suitable coal for producing a desired product forms no part of the present invention, and as a result no further details in this respect are deemed necessary for a complete understanding thereof.

The invention will be further described with respect to the accompanying drawings, wherein:

FIG. 1 is a simplified schematic flow diagram of an embodiment of the present invention; and

FIG. 2 is a top cross-sectional view of a reactor to illustrate a form of the partitions.

It is to be understood that the embodiment is only schematically shown, and various equipment, such as pumps, heat exchangers and the like have been omitted for simplifying the description of the embodiment. The use of such equipment at suitable places is well within the scope of those skilled in the art from the teachings herein.

Referring now to the drawing, coal in line 10 and a suitable pasting solvent in line 11, generally recovered from the hydroliquefaction product, are introduced into

a slurry tank 12 to disperse the coal in the pasting solvent. A slurry of coal in pasting solvent is withdrawn from tank 12 through line 13, combined with recycle in line 14, as hereinafter described, and the combined stream in line 15 is introduced into the first of three hydroliquefaction reactors 16, 17 and 18, respectively. Heated hydrogen in line 19 is also introduced into the first of the three hydroliquefaction reactors 16, 17 and 18.

Each of the hydroliquefaction reactors 16, 17 and 18 includes at least two parallel expanded or ebullated beds of hydroliquefaction catalyst, each of which is designed and operated to provide for upward flow of hydrogen and coal dispersed in solvent through the bed as a stream having a cross-sectional flow area through the catalyst bed of no greater than 255 square inches, and a Peclet Number of at least 3. As shown in FIG. 2, such parallel beds in reactors 16, 17 and 18 are formed by a honeycomb shaped partition 41, which as particularly shown defines 19 parallel beds. It is to be understood that more or less parallel beds could be employed and/or the parallel beds could be formed by other than honeycomb shaped partitions. Reactors 16, 17 and 18 are operated without any internal recycle. Thus, as hereinabove described, the length of each of the catalyst beds in each of the reactors as well as the liquid and gas superficial velocities are coordinated with the stream cross-sectional flow area through each of the catalyst beds in each of the reactors to provide a Peclet Number of at least 3. The hydroliquefaction reactors 16, 17 and 18 are operated at the temperatures and pressures hereinabove described to effect hydroliquefaction of the coal, and in addition, hydrodesulfurization and hydrodenitrification thereof. The coal dispersed in the pasting solvent is passed in parallel flow streams through the catalyst beds in reactor 16, the combined effluent from reactor 16 is passed in parallel flow streams through the catalyst beds in reactor 17, and the combined effluent from reactor 17 is passed in parallel flow streams through the beds in reactor 18.

Hydroliquefaction effluent, withdrawn from reactor 18 through line 21, is introduced into a gas-liquid separator 22 to recover a portion of the liquid product in line 23, with the remaining portion of the effluent in line 24 being passed through a suitable cooler 25 and introduced into a second separator 26 to recover further liquid product through line 27. The net hydroliquefaction product is recovered through line 28 for further treatment, as known in the art.

Recycle product is recovered through line 14, and as hereinabove noted, the recycle in line 14 is primarily for the purpose of providing sufficient liquid in the hydroliquefaction reactors 16, 17 and 18 to maintain the catalyst as expanded beds. The recycle amounts are limited as hereinabove described.

Gas is recovered from separator 26 through line 31 and a portion thereof is purged through line 32. The remaining portion is compressed in compressor 33, combined with make-up hydrogen in line 34 and the combined stream passed through a suitable heater 35 to provide heated hydrogen to the hydroliquefaction through line 19.

The hereinabove described embodiment is only illustrative of the present invention, and as a result, such an embodiment may be modified within the spirit and the scope of the present invention. Thus, the hydroliquefaction may be effected in more or less than three zones, as

particularly described. Similarly, product recovery may be effected other than as particularly described.

These and other modifications should be apparent to those skilled in the art from the teachings herein.

The invention will be further described with respect to the following Example; however, the scope of the invention is not to be limited thereby:

#### EXAMPLE

The following is illustrative of a reaction system and conditions for practicing the present invention. The system includes three reactors in series using cobalt molybdate supported on alumina as catalyst. The system is suitable for hydroliquefaction of Illinois No. 6 coal, as a representative example. Each of the reactors has the following characteristics and is operated at the following conditions:

Height of each reactor	75 ft.
Diameter	11.05 ft.
Cross-sectional area of each reaction zone	255 in <sup>2</sup>
Number of parallel Reaction zones per reactor	40
Superficial velocities:	
Liquid	250 ft./hr
Gas	300 ft./hr
Temperature	820° F. (max.)
Pressure (system)	2100 psig
Peclet Number	8.9
Reaction Stages	5.0 per reactor

The present invention is particularly advantageous in that there is provided improved selectivity to liquid product which increases overall hydrogen efficiency. As a result, the present process is more economic than the hydroliquefaction processes previously employed in the art. In addition, such increased hydrogen efficiency may be obtained in reactors having total cross-sectional areas suitable for commercial applications.

Thus, by proceeding in accordance with the invention it is possible to achieve a 90% or greater conversion of moisture ash free (MAF) coal with hydrogen consumptions of 2-4 lbs. hydrogen per 100 lbs. coal, as compared to previous hydrogen consumptions in excess of 4%, and in most cases in excess of 4.5%.

These and other advantages should be apparent to those skilled in the art from the teachings herein.

Numerous modifications and variations of the present invention are possible in light of the above teachings and, therefore, within the scope of the appended claims, the invention may be practiced otherwise than as particularly described.

We claim:

1. A process for the catalytic hydroliquefaction of coal, comprising:

catalytically hydroliquefying the coal by passing the coal dispersed in a coal liquefaction solvent and hydrogen upwardly through at least one reactor having at least two parallel expanded hydroliquefaction catalyst beds, said passing being in separate streams through each bed, each stream through each bed having a cross-sectional flow area of no greater than 255 square inches, each of said streams through each catalyst bed having a length and a liquid and gas superficial velocity to maintain an expanded catalyst bed and provide a Peclet Number of at least 3, said hydroliquefaction being effected with a ratio of hydroliquefaction

product recycle to total hydroliquefaction feed to the at least one reactor of from 0:1 to 2:1.

2. The process of claim 1 wherein the Peclet Number is at least 10.

3. The process of claim 1 wherein the cross-sectional flow area is at least 10 square inches.

4. The process of claim 3 wherein the cross-sectional flow area is at least 28 square inches.

5. The process of claim 3 wherein the hydroliquefaction is effected by passage through at least two reactors in series, each of which has at least two catalyst beds in parallel through which said stream has a cross-sectional flow area of no greater than 255 square inches, and a length and a liquid and gas superficial velocity to maintain an expanded catalyst bed and provide a Peclet Number of at least 3.

6. The process of claim 5 wherein the hydroliquefaction is effected with sufficient catalyst beds in series, to limit the temperature increase in each of the catalyst beds to no greater than 150° F.

7. The process of claim 3 wherein the hydroliquefaction is effected without internal recycle to the catalyst bed.

8. The process of claim 1 wherein the total hydrogen consumption for the hydroliquefaction is from 2 to 4 lbs. of hydrogen per 100 lbs. of coal to achieve at least 90% conversion of moisture ash free coal.

9. The process of claim 8 wherein the ratio of hydroliquefaction product recycle to total hydroliquefaction feed is from 0.2:1 to 1:1.

10. The process of claim 8 wherein the hydroliquefaction is effected at a temperature of from 650° F. to 900° F. and a pressure of from 1800 to 3000 psig.

11. The process of claim 5 wherein the hydroliquefaction is effected without internal recycle to the catalyst beds, and the hydrogen consumption for the hydroliquefaction is from 2 to 4 lbs. of hydrogen per 100 lbs. of coal to achieve at least 90% conversion of moisture ash free coal.

droliquefaction is from 2 to 4 lbs. of hydrogen per 100 lbs. of coal to achieve at least 90% conversion of moisture ash free coal.

12. The process of claim 5 wherein each reactor has a cross-sectional flow area of at least 65 ft<sup>2</sup>.

13. The process of claim 8 wherein each reactor has a cross-sectional flow area of at least 65 ft<sup>2</sup>.

14. The process of claim 11 wherein each reactor has a cross-sectional flow area of at least 65 ft<sup>2</sup>.

15. A system for the catalytic hydroliquefaction of coal in an expanded catalyst bed, comprising:

at least two hydroliquefaction reactors connected in series, each of said at least two reactors including at least two parallel flow passages containing expanded catalyst beds, each of the flow passages providing for flow therethrough in a stream having a cross-sectional flow area of no greater than 255 square inches and a flow length whereby the superficial velocities of gas and liquid maintain the expanded catalyst bed and provide a Peclet Number of at least 3.

16. The system of claim 15 wherein the cross-sectional flow area is at least 10 square inches.

17. The system of claim 16 wherein the cross-sectional flow area is at least 28 square inches.

18. The system of claim 16 wherein the Peclet Number is at least 10.

19. The system of claim 16 wherein each of said reactors is free of means for providing internal recycle to the catalyst bed.

20. The system of claim 15 wherein each reactor has a cross-sectional area of at least 65 ft<sup>2</sup>.

21. The system of claim 19 wherein each reactor has a cross-sectional area of at least 65 ft<sup>2</sup>.

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