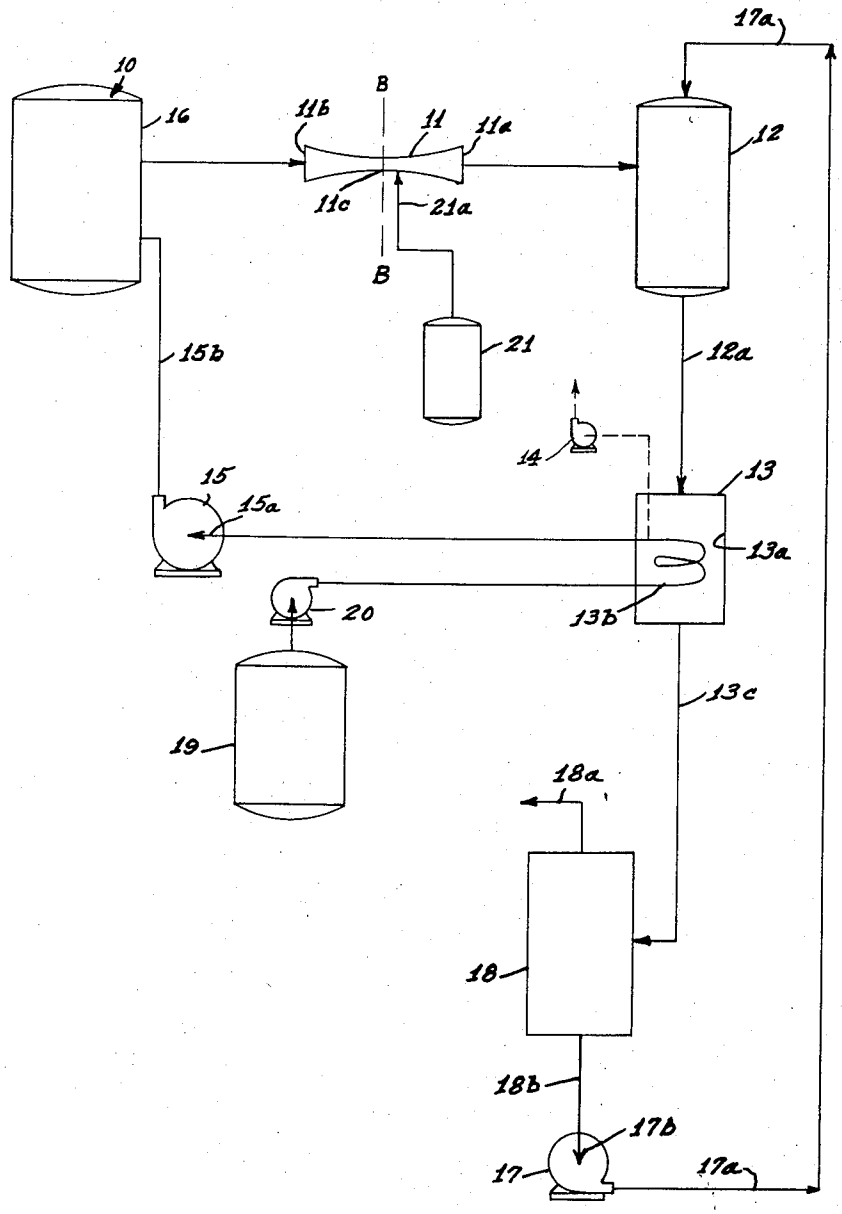
March 10, 1959 F. C. FOWLER ET AL 2,877,279

PROCESS AND APPARATUS FOR THERMAL DEHYDROGENATION

Filed Jan. 10, 1955



Inventors
Frank C. Fowler
James C. Seay

by Hill, Sherman, Meroni, Gross & Simpson Attys.

United States Patent Office 2,877,279 Patented Mar. 10, 1959

2,877,279

PROCESS AND APPARATUS FOR THERMAL DEHYDROGENATION

Frank C. Fowler and James G. Seay, Kansas City, Mo.

Application January 10, 1955, Serial No. 480,829

6 Claims. (Cl. 260—683)

Our invention relates to an improved method and apparatus for carrying out certain reactions requiring high temperatures and high vapor flow rates, and more particularly, to an improved method for the production of ethylene by pyrolyzing ethane in the presence of steam or the like heat transfer medium in vapor form.

Although the instant method and apparatus may be used advantageously in carrying out a number of reactions, the instant invention is particularly useful with respect to the pyrolysis of ethane to yield ethylene in accordance with certain critical conditions, and for the most part the instant method and apparatus will be described in connection with this particular process.

There have been increasing demands for ethylene, and for economic methods for the production thereof, in recent years in view of the increasing demands for vinyl plastics and synthetic alcohols, wherein ethylene derivatives are used. Commercial processes for the production of ethylene include those involving thermal dehydrogenation or pyrolysis of hydrocarbons including ethane, propane and the less volatile hydrocarbons or oils. Propane may soon be displaced as an available raw material because of its increased use in motor fuel. Various of the other less volatile hydrocarbons or oils also have a great number of industrial uses, and the number of impurities and the like present in crude forms of such oils make their use in delicately controlled processes difficult or impossible.

In general, the pyrolysis of ethane has heretofore been accomplished at temperatures below 1600° F. and in the presence of suitable dehydrogenation catalysts, in metal tubes in cracking furnaces. Reports in the art concerning the use of higher temperatures, which are impractical using the described apparatus, are, therefore, limited to a few bits of guess-work and even fewer experimental data. In general, the workers in the art believed that catalytic dehydrogenation of ethane could be carried out successfully at temperatures ranging from 1000° F. to 1200° F., and they believed that the presence of steam in the reaction medium resulted in the formation of a substantial amount of carbon monoxide, which is an undesirable by-product of the reaction.

In contrast, it has now been found that under certain specified conditions the pyrolysis of ethane in the presence of steam, and in the absence of a catalyst, may be carried out at temperatures substantially higher than those heretofore employed, so as to obtain distinctly superior ethylene yields under industrially economic conditions. The conditions which have been found to be uniquely advantageous include the use of temperatures in the range 1600–2400° F. and ethane-steam contact times in the range of 0.001–0.1 second, prior to rapid cooling of the ethane-steam reaction product mixture to below 1000° F. By such "contact time," we mean the time during which the ethane and steam are actually in contact, from the time the two gases are brought into contact and until the resulting mixture is cooled, or some other specified event takes place (which effects discontinuance of the pyrolysis reaction). We carry out our process by accomplishing very rapid heating of the ethane from below about 1000° F. (or the cracking temperature thereof) to the desired reaction temperature in the range 1600–2400° F. This rapid heating of the ethane is carried out by using superheated steam in sufficient volume for admixture with the ethane and using peculiar high flow rate conditions which will be described. We have also found that certain operating conditions are of critical importance in carrying out the process, and these various operating conditions include the maintenance of a relatively constant reaction temperature, the maintenance of reaction conditions for time sufficient to obtain a specified ethane volume expansion to obtain a corresponding amount of ethylene production in the reaction mixture, and/or the maintenance of specified flow rates and flow distances, all of which will be described in detail hereinafter.

It is, therefore, an object of our invention to provide an improved method and apparatus for producing ethylene by pyrolyzing ethane in the presence of steam.

In certain broader aspects, it is an object of our invention to provide an improved apparatus for carrying out vapor-phase reactions comprising a particular vapor-phase reactor structure and also a particular combination of elements for economic heat recovery. Also, it is an object of the invention to provide an improved method of controlling the heat cycle in such vapor-phase reactions and an improved method of controlling temperatures in the case of certain endothermic reactions.

Other objects, features and advantages of the present invention will become apparent to those skilled in the art from the following detailed disclosure thereof and the drawing attached hereto and made a part hereof.

Referring to the drawing, which is essentially a diagrammatic view of an apparatus embodying the instant invention, indicated generally by the reference numeral **10**, which comprises a vapor-phase reactor **11** in the form of a venturi tube having an exit **11***a* and an inlet **11***b* accommodating flow of gases therethrough, quenching means **12** at the reactor exit **11***a*, a heat-exchanger **13** having a steam condensing side **13***a* connected to the reactor exit **11***a* through the quenching means **12** and having a steam-generating side **13***b* (in the form of internal piping), vacuum-producing means **14** in the form of a pump connected to the steam-generating side for maintaining subatmospheric pressure therein, a steam compressor **15** having an inlet **15***a* connected to the steam-generating side **13***b* and a discharge **15***b*, and a steam superheater **16** interconnecting the compressor discharge **15***b* and the reactor inlet **11***b*.

In the quenching means **12** and heat-exchanger **13** system, quenching water is continuously forced through a pump **17** and a pump discharge line **17***a* into the top of the quenching chamber **12** where the cooling water engages the stream and reaction product being discharged from the reactor **11**. In actual practice, of course, the quenching tank **12** is positioned immediately adjacent the reactor **11** and is used to quickly terminate reaction, thereby controlling the actual reaction time as will be explained hereinafter. The quenching water in the quenching tank **12** reduces the overall temperature to less than about 1000° F. and the resulting steam-water-reaction product mixture passes downwardly through the quench tank discharge line **12***a* and into the "outside" section or steam condensing side **13***a* of the heat-exchanger **13**. It will be appreciated that a series of heat-exchangers (or waste heat boilers) may be used in order to effectively remove as much heat as possible; but the principal purpose of the heat-exchanger **13** is to substantially reduce the quenched mixture to water and the gaseous reaction products which will include ethane, ethyl-

ene, hydrogen and the like. Steam is substantially eliminated from the vapor-phase and the resulting mixture passes downwardly through the exchanger outlet 13*c* and into a gas-liquid separator 18. In the separator 18 the gaseous reaction products are permitted to flow out the top 18*a* and are recovered in the usual manner and the water flows out the bottom 18*b* and into the water pump suction 17*b* to complete the cycle for the quenching water.

In the fresh steam-generating system involving the steam-generating side 13*b* of the heat-exchanger 13 and the compressor 15, fresh water is delivered from a source 19 through a pump 20 and into the steam-generating side 13*b* of the heat-exchanger 13. The steam is generated within the pipes of the steam-generating side 13*b* and flows therefrom to the steam compressor intake 15*a*. If this system is operated at atmospheric pressure, however, the resulting steam temperature must be in excess of 212° F. and this means that the discharge temperature for the steam condensing side 13*a* of the exchanger 13 must be at least slightly in excess of 212° F. This results in a rather substantial loss of heat and the instant invention provides an apparatus and method for avoiding this loss of heat. Instead of operating at atmospheric pressure in the steam-generating side 13*b*, subatmospheric pressure is employed and this is obtained by the use of a vacuum pump 14 or similar vacuum producing means. Actually, effective operation of the steam compressor 15 may adequately serve to maintain subatmospheric pressure in the steam-generating side 13*b*. The operating pressure employed in the steam-generating side 13*b* is subatmospheric and it may range from only one or two pounds per square inch less than atmospheric pressure (about 15 pounds per square inch absolute) to as little as about 10 inches of water absolute pressure. Preferably, the vacuum employed is about 20–50 inches of water absolute pressure and, at such pressures, steam may be formed at temperatures as low as 140° F. or 150° F. In general, the pressure is reduced on the steam-generating side 13*b* to a subatmospheric pressure whereat water boils within the range of about 140° F. to about 200° F., in order to obtain adequate economic advantage by the use of the instant invention. The temperature in the quench tank, in contrast, is substantially below about 1600° F. (so that reaction is effectively discontinued) and the cooling is carried on rapidly to below about 1000° F. (so that side reactions including polymerization of ethylene may be effectively avoided. The temperature of the quenched mass entering the heat-exchanger 13 or a series of heat-exchangers (not shown) may thus range from about 1500° F. to about 1000° F. and this mixture is reduced in the heat-exchanger structure to as low as perhaps 200° F. and possibly lower, down to 175° or 180° F. In this manner, it is possible to effect substantially complete condensation of all of the steam in the quenched mixture, thereby effectively transferring the rather substantial amount of calories involved in the heat of vaporization of water to the steam-generating side 13*b* of the exchanger 13. In addition, because of the low pressure employed in operation of the steam-generating side 13*b* this heat transfer is effective in producing steam and making the conversion from liquid to vapor, which requires the relatively high heat of vaporization.

The steam thus generated, which is referred to as "fresh" steam (although it may be made from fresh water or water drawn from the separator 18) has a temperature of about 140° to 200° F. and a pressure of something less than atmospheric pressure, preferably about 20 to 40 inches of water absolute. This steam at subatmospheric pressure is then drawn into the steam compressor 15 and adiabatically compressed (or at least compressed without any cooling so as to prevent condensation) to a minimum of about 2 pounds per square inch gauge pressure and preferably not more than about 10 pounds per square inch gauge pressure. Most preferred operating conditions call for about 5 pounds per square inch gauge pressure. The steam discharged by the compressor 15 is still "dry" steam, because the temperature is increased correspondingly with the increase in pressure. Actually the steam at the compressor discharge 15*b* is approximately saturated steam under the usual operating conditions and the pressure thereof will determine the corresponding temperature, which in any case is above 212° F. The steam passes through the compressor discharge 15*b* and into the superheater 16.

The superheater 16 may, and preferably does, involve a superheater system including pebble heaters and comparable devices for externally heating the steam or supplying external heat thereto in order to superheat the steam. The steam is thus superheated to approximately 2000 to 3000° F. in the superheater system 16 and from there is flowed through the reactor 11 to the quench tank 12 (which is maintained at substantially atmospheric pressure).

A particularly important feature of the instant invention resides in the design of the reactor 11, which is in the form of a venturi tube. Ethane is injected into the steam flowing through the reactor 11 approximately at the venturi throat 11*c* (or along the dotted line B—B of the drawing), whereat the linear velocity of the steam is at a maximum. Ethane at temperatures below the cracking temperature of ethane (which is approximately 1000° F.) is fed from a source tank 21 through the usual metering system (not shown) and injected through the line 21*a* at the region of the venturi throat 11*c*, and preferably just downstream from the middle of the throat region (B—B), whereat a vacuum or subatmospheric pressure is created by the flow of steam through the venturi reactor 11. In the preferred embodiment of the invention, the superheated steam at about 2100 to 3000° F. and 4 to 6 pounds per square inch gauge is introduced into the reactor inlet 11*b*. The incoming flow rate is about 150 to 2500 feet per second at the reactor inlet, and preferably about 2000 feet per second. In order to take significant advantage of the venturi action, a minimum steam flow rate of about 100 feet per second is required (the maximum flow rate is, of course, that which may be obtained in practical operation). The general shape of a venturi tube is well understood by those skilled in the art. The generally cylindrical inlet 11*b* is substantially the size of the supply pipe and the upstream section from the inlet 11*b* to the throat 11*c* is a generally contracting portion that is a frustum of a cone with a vertex angle of about 25 to 30°. Such gradual contraction is preferable in order to avoid excessive friction losses. The throat 11*c* is a short generally cylindrical section which should have at least about three-quarters the diameter of the inlet in order to obtain a venturi effect and preferably has about one-quarter to one-half the diameter of the inlet. The throat 11*c* is about one-quarter to three-quarters of the diameter thereof in length. In the downstream section from the throat 11*c* to the outlet 11*a* there is a diverging passageway wherein the general shape is that of a cone frustum diverging from the throat diameter to the diameter at the discharge 11*a* at a recommended cone angle of 7° or less (usually about 5 to 7°). Using the velocities here involved the overall pressure drop across the venturi is ordinarily about 5 or 10 to 20%. Thus, using an upstream incoming pressure of 5 pounds per square inch gauge, which is approximately 20 pounds per square inch absolute, the pressure drop would be from 2 to 4 pounds per square inch, thereby giving a downstream gauge reading of 1 to 3 pounds per square inch (gauge). At the venturi throat, however, the pressure drop is much more severe and is in the neighborhood of about 50% of the incoming absolute pressure, thus resulting in a vacuum gauge reading of about 5 pounds (or 5 pounds less than atmospheric pressure). This serves to assist materially

in drawing the ethane into the steam stream and in effecting extremely rapid mixing of the ethane.

With respect to the linear velocities in the stream flowing through the reactor, it has been mentioned that the incoming linear velocity should be at least 100 feet per second and, preferably is in the range of 150 to 2500 feet per second. The cross-sectional area of the stream is restricted at the venturi throat at least to an extent necessary to effect about a 10% increase in linear velocity and preferably about 30 to 70% increase in linear velocity. From the venturi throat 11*c* downstream the cross-sectional area of the stream is gradually expanded in order to effect at least a 25% decrease in the linear velocity at the throat and preferably a 50 to 75% decrease in such linear velocity (or a decrease to from ¼ to ½ of the throat velocity). As previously mentioned, the velocities at all times in the reactor are relatively high; and the minimum inlet effective velocity is approximately 100 feet per second and the minimum exit velocity for effective operation is at least about 50 feet per second and preferably is in the range of 50 to 1500 feet per second. At flow rates in this region the very short contact time desired may be obtained by positioning quenching means 12 or similar rapid cooling means closely adjacent the venturi outlet 11*a*.

Besides the distinct advantage of having extremely high flow rates (by virtue of the use of the venturi reactor 11) so as to permit minimum contact times, there is another unusual advantage resulting from the practice of the instant invention. It has been found through numerous experiments that severe temperature variations in the reaction zone tend to cause excessive undesirable by-product formation and/or poor yields involving the principal reaction of pyrolysis of ethane to yield ethylene. This reaction is endothermic in that it requires heat or consumes heat as it takes place. This, of course, serves to assist in the temperature drop across the reaction zone which would ordinarily be obtained by heat losses. In view of the relatively poor heat conductivity properties of gases and the practical difficulty of employing heaters, it has been found that it is almost an industrial impossibility to supply external heat effectively, even in very small scale plants, so as to prevent noticeable temperature dropping across the reaction zone. The instant invention offers a unique solution to this problem, however.

When the fast flowing stream of superheated steam enters into the venturi it has an appreciable amount of "pressure" energy (as evidenced by the 5 pounds per square inch gauge pressure), but as the stream passes through the venturi throat this "pressure" energy is changed to velocity or "kinetic" energy (as evidenced by the distinct increase in linear velocity). At this point, the endothermic reaction is initiated by the introduction of the ethane into the steam stream; but the gradual expanding of the cross-sectional area of the stream from the throat downstream actually results in a conversion of kinetic energy back to "pressure" energy and the increase in pressure effectively increases the "heat" energy in the stream itself. In other words, the energy in the steam stream at the venturi throat is primarily kinetic energy, but the kinetic energy in the stream is materially decreased in the downstream side of the venturi and the pressure in the gas stream at this location is noticeably increased (from about 5 pounds vacuum gauge to from 1 to 4 pounds positive gauge pressure). This has the effect of actually compressing the steam under conditions which would be adiabatic, except for the endothermic reaction and frictional losses, so that there is a tendency to actually increase the steam temperature from that at the venturi throat. It should be mentioned that there is a steam temperature decrease effected in passing the steam from the venturi inlet to the venturi throat. This tendency to increase the steam temperature on the downstream side of the venturi serves to offset (partially) heat losses resulting from the endothermic reaction. The particular significance of this is that radical temperature drops may cause the endothermic reaction to be less effective or, in some instances, to even extinguish itself. In the pyrolysis of ethane radical temperature reductions in a reaction zone tend to cause poor yields and a number of undesirable by-product reactions. For this reason, the amount of steam used in conducting the instant pyrolysis of ethane is an amount sufficient to maintain the desired average reaction temperature throughout the reaction zone and to prevent a drop in the temperature in the reaction zone below the minimum effective reaction temperature of about 1600° F.

The savings in steam using the instant method and apparatus may best be shown by example. If a reactor having the form of a straight tube is used, with a stream velocity therethrough (which is substantially uniform) of 2000 feet per second, a superheated inlet steam temperature of 2000° F., and an ethane inlet temperature of 1000° F., it is found that 8 pounds of steam per pound of ethane injected must be employed in order to maintain a reactor exit temperature of 1604° F. In contrast, if the venturi reactor is used the steam requirements for obtaining substantially the same reaction conditions are almost 50% of those just described (i. e., 8 pounds of steam per pound of ethane injected). As a typical example, superheated steam at 2266° F. and a linear velocity of 2000 feet per second is directed into the venturi inlet, and at the venturi throat the steam has a temperature of 2000° F. and a linear velocity of 3000 feet per second. At the throat, ethane at a temperature of 1000° F. is injected and at the reactor discharge the temperature is 1604° F. and the velocity is only 1000 feet per second.

The table below summarizes the results here obtained:

Table A

	Tube Reactor	Venturi Reactor
Inlet:		
Amount of Steam, lbs.	8	4.36
Velocity, F. P. S.	2,000	2,000
Temperature, ° F.	2,000	2,266
Middle or Throat:		
Velocity, F. P. S.	2,000	3,000
Temperature, ° F.	2,000	2,000
Exit:		
Velocity, F. P. S.	2,000	1,000
Temperature, ° F.	1,604	1,604

It will be noted that only 4.36 pounds of steam per pound of ethane are required to obtain substantially the same exit temperature, and thus the same temperature drop from the temperature of 2000° F. when reaction was initiated. The reaction time in the two reactions is almost identical, since the linear velocity in the venturi averages 2000 feet per second. Such velocity changes in the reaction zone apparently have no effect whatsoever toward reducing the yield or creating unfavorable side reactions. It will also be noted that the steam inlet temperature of 2266° F. required in the venturi reactor in order to obtain a temperature of 2000° F. at the point of ethane injection involves a slight additional expenditure of heat. But there is no comparison between the relatively small amount of heat required to raise the temperature of 4.36 pounds of steam from 2000° F. to 2266° F. and the very substantial amount of steam that is required to heat the difference between 4.36 pounds and 8 pounds of steam up to 2000° F.

As hereinbefore mentioned, the product results and yield obtained in the above identified comparative reactions are substantially the same and the saving is primarily in the amount of heat employed to generate steam. On the other hand, better yields can be obtained in the practice of the instant invention by employing comparatively greater amounts of steam so as to reduce to a more substantial extent the tendency for the temperature to fall off in the reaction zone. For example, if 8 pounds

of steam were used in the venturi reactor instead of the 4.36 pounds, the yield is noticeably increased and the temperature at the exit is in the neighborhood of 1800° F.

Although the invention has been described primarily in connection with the endothermic reaction involved in the pyrolysis of ethane to obtain ethylene, it will be appreciated that the instant invention affords unique advantages in temperature control and similar critical process features for any endothermic vapor-phase reaction. If such reaction is initiated upon contact between two gases at an elevated temperature, a stream of one of such gases may be restricted to obtain the venturi effect hereinbefore described and increase the velocity while the endothermic reaction is initiated, for example, by injecting the other of such gases into the stream. If the endothermic reaction is initiated by something else, such as the presence of a catalyst, it would be possible to pass a mixture of such gases through a venturi reactor and over a catalyst bed positioned so as to initiate the reaction approximately at the venturi throat and in the form of catalytic wires, or comparable structures which would not disrupt the velocity and pressure energy changes taking place in the venturi reactor in accordance with the teachings of the instant invention. As will be appreciated, the venturi reaction chamber affords an additional advantage in the case of a reaction involving contact between a thermally stable gas (such as steam) and a thermally unstable gas (such as ethane) at a given elevated temperature, because of the superior mixing effect that is obtained at the high throat velocities. In such an arrangement, the stable gas provides the main basis for the stream (and the stable gas may be a reactant or it may merely be the heat carrier as in the case of steam in the instant pyrolysis action). The stable gas passes through the reactor at higher than the elevated temperature at which the unstable gas decomposes and the unstable gas may be injected at a lower temperature so as to reach the decomposition temperature almost instantly in the reaction zone.

Also the overall method of controlling the supply of heat to an endothermic vapor-phase reaction, which is taught herein, has unusual advantages. The instant method involves the use of pressure changes to accomplish the generation of fresh steam by recovery of a maximum amount of heat from the reaction product steam. Pressure changes are also used to actually add to the total heat content of such fresh steam by increasing the pressure and further to effect velocity changes in the flow of steam so as to obtain the advantages hereinbefore described in connection with the venturi reactor.

In general, the practice of the instant invention for producing ethylene by pyrolyzing ethane comprises contacting, at 1600–2400° F., ethane and steam and then rapidly cooling the resulting product below 1000° F., the total contact time prior to cooling being 0.001–0.1 second. A key to the instant invention involves the heating of the cold ethane (below cracking temperature) which is not diluted by steam or the like heating media, by contacting the ethane with superheated steam (at the venturi throat) so as to effect an intimate mixture thereof and to heat the ethane to the reaction temperature in preferably less than 10% of the total contact time between the ethane and the steam.

One of the requirements for the instant invention is a reaction temperature of at least about 1600° F., or a range of about 1600–2400° F. Higher temperatures tend to cause the production of an additional amount of acetylene, which is also a useful product. In the production of ethylene, we have found good yields may be obtained using the temperature range of 1600–2100° F., and preferably 1750–2000° F.

Another requirement for carrying out the instant process involves the use of the shortened reaction time. The contact time for ethane and steam should be within the range of about 0.001–0.1 second. Preferably such reaction time is the time ranging from the moment at which substantially undiluted ethane and steam come into contact until the time at which the ethane-steam reaction mixture is cooled to at least below 1000° F., at which temperature no appreciable side reactions take place. Also, we have found that for the preferred reaction temperature range of 1750–2000° F., the preferred reaction time is 0.01–0.02 second. Best results are obtained using about 1800° F. and about 0.015 second.

The steam to ethane volume ratios which may be used in the practice of the invention are 3 to 8 or 10:1, and preferably 4–6:1 (although as much as 15:1 can be used to obtain minimum temperature drop). Using the preferred operating conditions of temperature (1800° F. average) and contact time (0.014), the results obtained in the venturi run hereinbefore described are 70 mol percent ethylene yield, 1.99 volume expansion and 36 mol percent ethylene in the product gas. At temperatures of 2400–3500° F. the same apparatus produces predominantly acetylene. Water gas reactions in fuel gas generation may also be controlled using the instant method and apparatus.

Another method of determining best operating conditions in the ethylene reaction is by the use of volume expansion which is obtained by dividing the molecular weight of ethane by the molecular weight of the product gas (exclusive of the steam). Under perfect reaction conditions, the product gas would contain only ethylene and hydrogen, having an average molecular weight of 15 and the volume expansion would thus be 2.0, and in the instant process, the by-product formation should not bring about an expansion in excess of 2.1. The volume expansion is, of course, an indication of the extent to which any reaction has taken place in the instant system, since any of the reactions herein mentioned involves the formation of lower molecular weight materials and a greater total volume thereof. Under the particular reaction conditions, the principal reaction here involved is that of producing only ethylene and hydrogen, as previously mentioned, and it has been found preferable to carry out the instant reaction, employing the temperatures, times and flow rates within the ranges hereinbefore mentioned, at least until a volume expansion of about 1.2 is obtained and preferably until a volume expansion of at least about 1.5 is obtained.

The general changes in pressures and flow rates indicated hereinbefore for the steam flowing through the venturi reactor are the conditions which are required in order to obtain the particular advantages of the instant "venturi effect" in any type of endothermic reaction. In other words, the minimum flow rates should be obtained and the minimum changes in velocity at the throat and again at the venturi exit, hereinbefore mentioned, should be obtained in order to effect the unique advantages in mixing, controlled reaction time, kinetic-heat energy balance, and the like in the case of endothermic reactions which consume less heat, the amounts of carrier gas (or the overall kinetic-heat energy changes) may be reduced and just the opposite is true in the case of endothermic reactions which consume more heat than the instant pyrolysis of ethane reaction.

It will be understood that modifications and variations may be effected without departing from the scope of the novel concepts of the present invention.

We claim as our invention:

1. A method of controlling the supply of heat to an endothermic vapor-phase reaction which comprises (*a*) restricting the cross-sectional area of a fast flowing stream of superheated steam at superatmospheric pressure to effect at least a 10% linear velocity increase therein while initiating the endothermic reaction, and then gradually expanding the cross-sectional area of the gas stream while continuing the endothermic reaction to effect at least a 25% linear velocity decrease therein so as to convert kinetic energy in the stream to heat energy to offset heat

losses resulting from the endothermic reaction, (*b*) next effecting heat exchange between the resulting reaction product-containing steam and water at subatmospheric pressure to obtain maximum use of the heat of the reaction product-containing steam as heat of vaporization for the creation of fresh steam at subatmospheric pressure, (*c*) then compressing the fresh steam to superatmospheric pressure and (*d*) finally superheating the fresh steam of step (*c*) to provide steam for the fast flowing stream of step (*a*).

2. A method of controlling the supply of heat to an endothermic vapor-phase reaction which comprises (*a*) withdrawing heat from a fast flowing stream of superheated steam by carrying out an endothermic reaction therein, (*b*) next effecting heat exchange between the resulting reaction product-containing steam and water at subatmospheric pressure to obtain maximum use of the heat of the reaction product-containing steam as heat of vaporization for the creation of fresh steam at subatmospheric pressure, (*c*) then compressing the fresh steam to superatmospheric pressure and (*d*) finally superheating the fresh steam of step (*c*) to provide steam for the fast flowing stream of step (*a*).

3. Apparatus for carrying out vapor-phase reactions, comprising a vapor-phase reactor having an exit and an inlet accommodating flow of gases therethrough, a heat-exchanger having a steam-condensing side connected to the reactor exit and a steam-generating side, vacuum producing means connected to the steam-generating side, a steam compressor having an inlet connected to the steam-generating side and a discharge, and a steam superheater interconnecting the compressor discharge and the reactor inlet.

4. Apparatus for carrying out vapor-phase reactions, comprising a vapor-phase reactor having an exit and an inlet accommodating flow of gases therethrough, quenching means at the reactor exit, a heat-exchanger having a steam-condensing side connected to the quenching means and a steam-generating side, vacuum producing means connected to the steam-generating side, a steam compressor having an inlet connected to the steam-generating side and a discharge, and a steam superheater interconnecting the compressor discharge and the reactor inlet.

5. Apparatus for carrying out vapor-phase reactions, comprising a vapor-phase reactor in the form of a venturi tube having an exit and an inlet accommodating flow of gases therethrough, a heat-exchanger having a steam-condensing side connected to the reactor exit and a steam-generating side, vacuum producing means connected to the steam-generating side, a steam compressor having an inlet connected to the steam-generating side and a discharge, and a steam superheater interconnecting the compressor discharge and the reactor inlet.

6. Apparatus for carrying out vapor-phase reactions, comprising a vapor-phase reactor in the form of a venturi tube having an exit and an inlet accommodating flow of gases therethrough, means for injecting a reactant into said reactor at the throat of said venturi tube, a heat-exchanger having a steam-condensing side connected to the reactor exit and a steam-generating side, vacuum producing means connected to the steam-generating side, a steam compressor having an inlet connected to the steam-generating side and a discharge, and a steam superheater interconnecting the compressor discharge and the reactor inlet.

References Cited in the file of this patent

UNITED STATES PATENTS

2,158,869	Sperzel	May 16, 1939
2,208,123	Duncan	July 16, 1940
2,280,093	Kleinschmidt	Apr. 21, 1942
2,520,149	Keeling	Aug. 29, 1950
2,572,664	Robinson	Oct. 23, 1951
2,576,034	Myers	Nov. 20, 1951
2,656,307	Findlay	Oct. 20, 1953