ABSTRACT

One embodiment of a low to high temperature energy conversion system includes a decomposition chamber in which ammonia (NH₃) is decomposed into hydrogen and nitrogen by absorbing heat of decomposition from a low temperature, e.g., 300° C energy source. The separated hydrogen and nitrogen are then supplied to a recombination chamber wherein they recombine to produce ammonia. The recombination process is associated with a significant increase in temperature, used to increase the temperature of a fluid to temperatures on the order of 500° C.

6 Claims, 6 Drawing Figures
**FIG. 1**

- 300°C HEAT SOURCE
- DECOMPOSITION TANK
- N₂ TANK
- H₂ TANK
- RECOMBINATION CHAMBER
- UTILIZATION DEVICE

**FIG. 2**

<table>
<thead>
<tr>
<th>TEMP. °C</th>
<th>PRESSURE (ATMOS. ABS.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>200</td>
<td>50.66</td>
</tr>
<tr>
<td>250</td>
<td>28.34</td>
</tr>
<tr>
<td>300</td>
<td>14.73</td>
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<tr>
<td>350</td>
<td>7.41</td>
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<tr>
<td>400</td>
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<td>450</td>
<td>2.11</td>
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<td>550</td>
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<tr>
<td>650</td>
<td>0.33</td>
</tr>
<tr>
<td>700</td>
<td>0.23</td>
</tr>
</tbody>
</table>
LOW TO HIGH TEMPERATURE ENERGY
CONVERSION SYSTEM

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85–568 (72 Stat. 435; 42 USC 2457).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to temperature conversion and, more particularly, to a system for producing high temperatures from sources of relatively low temperature energy sources.

2. Description of the Prior Art

There are many processes which require high temperatures for their efficient operation. For example, for a large number of chemical reactions there is a practical lower limit of temperature, below which a desired reaction will not proceed, or below which it proceeds too slowly to be of technical value. In another example, the efficiency of the process by which electrical power is generated by turbines, driven by vapor, is critically dependent on the vapor temperature. Higher vapor temperatures produce more electrical power output from the same energy content, and permit smaller equipment, at a lower capital investment to be used, compared to those required to generate the same power using lower temperature vapor. Modern turbine-driven electrical generators operate at an input temperature of about 550° C, using super-heated steam. While there are many potential sources of energy which can be used to heat a fluid to produce vapor, most of the economical sources do not provide sufficiently concentrated energy to vaporize a continuously flowing fluid to the desired high temperatures, assumed to be on the order of 500° C or higher.

For example, while solar energy concentrators of the tracking type are capable of producing vapor at sufficiently high temperatures, such concentrators are very expensive because of the need for tracking mechanisms of substantial accuracy and the need for large and precise energy concentrators, such as parabolic reflectors with associated optics, in order to project a very small concentrated sun image on the collector targets. To date, the less demanding and less costly non-tracking type solar energy concentrators are only capable of producing steam at lower temperatures on the order of 300° C. Geothermal energy can also be used to produce steam or vapor in about the same temperature range of 300° C. Such temperatures are too low for efficient vapor turbine electrical energy generation.

Thus, a need exists for a system and process to recover heat energy from low temperature heat sources and to convert the recovered energy to higher temperatures.

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a system and method for converting at least some heat energy from low temperature heat sources to higher temperatures. Another object of the present invention is to provide a system and method for recovering heat energy from low temperature heat sources, such as solar collectors or geothermal sources, and converting it to high temperatures on the order of 500° C or more.

A further object of the present invention is to provide a system and process for the conversion of low temperatures from low temperature heat sources to higher temperatures for the efficient operation of compact or low capital investment turbine-driven electrical generators, or in other applications, to enable chemical reactions that have a critical lower temperature limit, which is itself higher than the temperature of the primary low temperature source, to be used.

Theses and other objects of the invention are achieved by a system and process in which a working substance such as a chemical compound is decomposed into simpler substances at relatively low temperature and low pressure. The low temperature heat which is absorbed is effectively stored in the form of chemical potential in the simpler substances. The simpler substances are subsequently recombined into the original compound, generally at higher pressure. During the recombination heat of recombination is released which raises the environment in which the recombination takes place to a substantially higher temperature. A substantial portion of the released heat of recombination is extracted to perform useful work, such as for example, produce vapor at high temperatures for driving a turbine in an electrical generator. The working substance is then led back to be decomposed by the absorption of low temperature heat and the process is repeated. The system can be thought of as a temperature converter, or low-to-high temperature energy conversion system.

The novel features of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of an embodiment of the invention using a gas as the working substance;
FIGS. 2 and 3 are a table and graph respectively, related to the equilibrium percentages of NH₃ at different temperatures and pressures;
FIG. 4 is a partial diagram of another embodiment of the invention;
FIG. 5 is a diagram relating energy consumption to gas compression; and
FIG. 6 is a diagram of an embodiment of the invention utilizing a metal-hydride as the working substance.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention makes use of complex chemical compounds, hereinafter also referred to as the working substances, which upon absorption of heat from a relatively low temperature source are decomposable into their constituents or into simple chemical substances. Such constituents can subsequently be recombined to form the original complex chemical compounds. During recombination, heat of recombination is released, raising significantly the temperature of the chamber in which the recombination takes place. The high temperature in the recombination chamber is used to heat a transport fluid or material to a relatively high temperature, approaching the recombination chamber temperature, which is appreciably higher than the temperature of the primary heat source which serves to decompose the working substance.
Finally, the recombined working substance is lead from the recombination chamber, its residual thermal energy utilized in an appropriate expansion engine, and the now-cool recombined working substance led to the decomposition chamber. The primary (low temperature) heat source causes decomposition and the cycle is repeated.

Before proceeding to describe specific embodiments of the invention, the types of working substance, which can be used, and the manner of their decomposition, will be discussed.

Useful working substances for the present invention are those in which input shifts the equilibrium toward the decomposition of the substances into their constituents. Such decomposition may or may not involve the use of catalysts to hasten the equilibrium shift. If the decomposition products, i.e., the constituents, can be separated from the undecomposed working substance, such separation or removal promotes further shift of equilibrium toward further decomposition. If one of the decomposition products (constituents) can be physically removed from the decomposition zone, the complex chemical compound can be completely decomposed into its constituents, and a maximum amount of heat at the decomposition temperature will be absorbed by the system to effect the decomposition.

It is relatively easy to accomplish such separation if the original chemical compound is a solid, and one of its constituents is a gas, as in metal hydrides. One example is the decomposition of magnesium hydride, represented by the equation,

\[ \text{MgH}_2(\text{Solid}) \rightarrow \text{Mg}(\text{Solid}) + \text{H}_2(\text{gas}) \]

The decomposition goes to completion if the separated hydrogen gas is merely allowed to flow away from the reaction, in which case only the Mg solid remains.

If, however, one starts with a gaseous working substance, where the decomposed constituents are also gases, gas separation is needed for complete decomposition. Otherwise, we get only partial decomposition and a shift in the equilibrium amounts until the decomposed gas-gas separation is needed for complete decomposition. This reaction in connection with NH3 as the reaction medium where the decomposed constituents are also gases, gas separation is needed for complete decomposition into its constituents, and a maximum amount of heat at the decomposition temperature will be absorbed by the system to effect the decomposition.

For explanatory purposes, let it be assumed that the temperature in tank 30 is on the order of 300°C.

Arrows 12 represent thermal energy or heat provided by a low temperature heat source 15, such as a solar collector or a source of geothermal energy. Generally, such sources are capable of delivering heat at temperatures on the order of 300°C. Thus, source 15 is assumed to provide heat at 300°C so as to maintain the tank at 300°C. The function of the system of the invention is to use the heat at 300°C from source 15 in order to raise a fluid (or other material) to higher temperatures on the order of 500° to 600°C. Attached to tank 10 and shown as forming one of the sides thereof is a separator 16 which is capable of separating H2 from the other gases in the mixture in tank 10. Separator 16 may be a membrane type separator. In FIG. 1, numeral 17 designates a pipe or line through which NH3 in equilibrium with H2 and N2, hereinafter referred to as the gas mixture is supplied to tank 10. Valve 18 controls the flow of the gas mixture into tank 10.

For explanatory purposes, let it be assumed that the inlet valve 18 is closed and that the gas mixture in tank 10 is in equilibrium at 300°C at a given pressure. As H2 is withdrawn through separator 16 into a hydrogen (H2) tank 20 an imbalance in the equilibrium is created in the tank 10 due to the absence of the separated hydrogen. A higher concentration of NH3 is present than is necessary for the proper equilibrium. As a result, additional heat is absorbed by the mixture to decompose some of the working substance of the types which can be used in the present invention are given herein:

\[ 2\text{NH}_3(\text{gas}) = \text{N}_2(\text{gas}) + 3\text{H}_2(\text{gas}) \]
\[ 2\text{SO}_2(\text{gas}) = \text{3SO}_2(\text{gas}) + \text{O}_2(\text{gas}) \]
\[ \text{C}_6\text{H}_{12}(\text{liquid}) = \text{C}_2\text{H}_4(\text{gas}) + 3\text{H}_2(\text{gas}) \]
\[ \text{CaH}_2(\text{solid}) = \text{Mg}(\text{solid}) + \text{H}_2(\text{gas}) \]
\[ \text{C}_4\text{H}_6(\text{solid}) = \text{C}_2\text{H}_4(\text{solid}) + 5\text{H}_2(\text{gas}) \]

Appropriate separation methods, for the removal of one of the constituents of the decomposed working substance have to be chosen individually to the best advantage of the chemical nature of the reactions. In general, for gas-gas separation, diffusion membranes, such as Pd for H2 or Ag for O2 are best suited, but a molecular skin may be better suited to produce other gas-gas separations. For the liquid-gas separation molecular sieves may be used, while for the solid-gas separation the phase separation is inherently complete.

As an example, the utilization of a particular working substance, ammonia (NH3) gas, will be described, although it should be realized that a similar description can be made for any one of a great number of other possible working materials.

Useful working substances for the present invention are given herein:

- Ammonia (NH3) gas
- Zinc hydride (ZnH2)
- Sodium hydride (NaH)
- Magnesium hydride (MgH2)

In order for this decomposition to proceed toward the right to a large extent, it is necessary to remove at least one of the gaseous products, N2 (gas) or H2 (gas) from the reaction zone where all three gases (including NH3) are present. Such a separation can be done by methods to be described in connection with the present disclosure.

Alternatively, one can start with a working substance which is a liquid, such as cyclohexane, which can be decomposed by the absorption of relatively low-temperature heat, according to the reaction

\[ \text{C}_6\text{H}_{12}(\text{liquid}) = \text{C}_2\text{H}_4(\text{gas}) + 3\text{H}_2(\text{gas}) \]

Again, if one of the products, say C2H4, is separated from the mixture of the three species, present in the reaction zone, the decomposition of the complex compound cyclohexane, using low temperature heat input, can proceed to completion. Thus, the decomposable complex chemical compound for use in the present invention may be a solid, a liquid or a gas. Several examples of working substance of the types which can be used in the present invention are given herein:

\[ 2\text{NH}_3(\text{gas}) = \text{N}_2(\text{gas}) + 3\text{H}_2(\text{gas}) \]
\[ 2\text{SO}_2(\text{gas}) = 3\text{SO}_2(\text{gas}) + \text{O}_2(\text{gas}) \]
\[ \text{C}_6\text{H}_{12}(\text{liquid}) = \text{C}_2\text{H}_4(\text{gas}) + 3\text{H}_2(\text{gas}) \]
\[ \text{CaH}_2(\text{solid}) = \text{Mg}(\text{solid}) + \text{H}_2(\text{gas}) \]
\[ \text{C}_4\text{H}_6(\text{solid}) = \text{C}_2\text{H}_4(\text{solid}) + 5\text{H}_2(\text{gas}) \]
the NH₃ to re-establish the proper equilibrium. The heat which is absorbed is known as the heat of decomposition which is for all practical purposes equal to the heat of recombination, which is the heat evolved when synthetic ammonia is produced by the direct reaction of H₂ and N₂. The heat of decomposition or recombination is on the order of 12,000 calories per gram mole of NH₃. As more and more of the H₂ in tank 10 is separated from the rest of the mixture, more heat of decomposition is absorbed to decompose more of the NH₃. In FIG. 1, numeral 22 designates a tank to which the N₂ present in the tank is supplied. Theoretically, all of the NH₂ in the gas mixture in tank 10 can be decomposed and all the H₂ and N₂ in the original mixture, as well as those produced by the decomposition of the NH₃ can be stored in tanks 20 and 22, respectively. However, complete decomposition of all the NH₃ in tank 10 is not practical nor required. In practice, membrane-separator 16 permits only the flow of H₂ to tank 20 while the content of tank 22 does not change. The pressure of the system is maintained constant and all undecomposed NH₃ as well as small quantities of H₂ and N₂ remaining will be stored in tank 22.

The pressure of tank 10 is assumed to be 12,000/8.2 = 1460 atmospheres, which is higher than the operating temperature of the fluid exiting the chamber. As is appreciated by those familiar with ammonia and as diagrammed in FIG. 5, the power required to compress ammonia-forming gases at several hundred atmospheres to higher pressures is relatively small. Thus, the amount of power needed to increase the pressure is small compared with the more efficient recombination of ammonia in the chamber 25, thereby increasing the system's efficiency.

The gas mixture including the recombined NH₃ at an assumed temperature of 550°C exits chamber 25 via conduit 17 for recirculation into the decomposition chamber 10. Thus, the system can be viewed as a closed loop system in which heat from a low temperature (300°C) source 15 is used to decompose NH₃ into its constituents H₂ and N₂, which are thereby recombined to produce NH₃ in a recombination chamber in which the temperature is considerably higher, e.g., 550°C enabling fluid, e.g., steam, to be heated up to the higher temperature.

Since the gas mixture exiting chamber 25 is assumed to be at 550°C which is higher than the operating temperature of 300°C in tank 10, the mixture can be cooled by passing conduit 17 through a heat exchanger to extract heat from the mixture and lower its temperature from 550°C to 300°C. If desired, the inlet end of pipe 32 may form part of the heat exchanger to use the heat extracted from the gas mixture in pipe 17 to first raise the fluid in pipe 32 to 300°C and thereafter feed it through the chamber for subsequent additional heating.
in chamber 25 to 550° C. In addition, if the pressure of the gas mixture exiting chamber 25 is higher than that in tank 10 the gas mixture pressure may be reduced to the required pressure in tank 10 by passing it through a power-producing turbine 47. The produced power may be used to supply at least part of the power required for compressor 40 as well as to regulate the pressures in the other tanks if required.

The process employed in the embodiment utilizing NH₃ as the working substance may thus be summarized as follows:

a. providing a source of heat at a relatively low temperature, e.g., 300° C,

b. utilizing the heat to decompose NH₃ into its constituents,

c. separating the constituents of the decomposed NH₃ and then recombinating the separated constituents in a recombination chamber at a controlled higher temperature, e.g., 550° C,

d. producing synthetic NH₃ by the direct recombinating of the separated constituents in a recombination chamber at a controlled higher temperature, e.g., 550° C,

e. passing matter, e.g., a fluid through the chamber using, e.g., a heat exchanger, to raise the temperature of the fluid to the higher temperature in the reaction chamber.

The invention is not intended to be limited to one in which the working substance is NH₃ nor to the specific temperature and pressure values, but rather it is intended to be used in a closed loop system, operable in continuous mode rather than in a batch mode, and then recombinating again under different conditions as represented by the following expression:

\[ \text{Metal-hydride} + \text{H}_2 \rightarrow \text{Metal} + \text{H}_2 \]

As is known, some metal hydrides can be decomposed into a metal and H₂ and then recombinated again under different conditions as represented by the following expression:

\[ \text{Metal-hydride} \rightarrow \text{Metal} + \text{H}_2 \]

As is known, some metal hydrides can be decomposed into a metal and H₂ by absorbing heat from a low temperature source at low pressure. The decomposed constituents can be recombinated at higher pressure into the original metal-hydride while releasing heat at higher temperatures which can be used to heat fluid to the higher temperatures. Such properties may be used in another embodiment of the invention which may best be described in connection with FIG. 6, wherein elements like those previously described are designated by like numerals. In FIG. 6, numeral 50 designates a decomposition-recombination tank or chamber in which a metal hydride 52 is contained. A H₂ tank is connected to chamber 50 by a pressure regulator 40, which controls the pressure in the chamber. CHamber 50 is filled with H₂ from tank 20, the pressure being controlled by the pressure regulator 40. Valve 54 is open and valve 52 is closed. Then valve 54 is closed and H₂ is fed back from tank 20 to chamber 50, at a higher pressure, provided by compressor 60. At the higher pressure the hydrogen entering chamber 50 combines with the metal therein, to form again the metal-hydride. The recombinating is accompanied by a significant increase in temperature which is used to heat the fluid flowing through pipe 52.

As is appreciated, different metal-hydrides combines under different temperature and pressure conditions. In the particular example, depending on the particular metal-hydride used, the flow of the fluid in pipe 52 may be controlled by valve 56 and the pressure regulated by valve 58 and/or compressor 60 so as to cause the recombinating to occur at a temperature significantly greater than the 300° C provided by source 15. Thus, the fluid can be heated to the higher temperature, e.g., 500° C or more.

For example, MgH₂ is decomposable into Mg and H₂ at a temperature of 300° C and a pressure of about 1.5 atmospheres, while at a temperature of about 500° C it is recombinatable at a pressure of about 100 atmospheres. Other metal-hydrides have different dissociation pressure-temperature properties. For example, palladium deuteride PdD dissociates at 300° C in an atmosphere of about 12 atmospheres or less, while at 500° C it can be recombinated at pressures on the order of 300 atmospheres. The above stated temperatures and pressures are approximate, and are based on interpolation of values appearing in FIG. 4-2 in a book entitled "The Solid State Chemistry of Binary Metal Hydrides" by G.G. Libowitz, published in 1965. In practice, the metal-hydride should be chosen based on the least amount of power needed for the pressure change in chamber 50.

It should be stressed that the embodiment shown in FIG. 6 is not merely one in which H₂ is extracted from a metal-hydride into which the H₂ can be restored. Rather, it is based on the decomposion of the metal-hydride at a low temperature (300° C) to separate the H₂ from the metal and thereafter recombinating the H₂ with the metal to recreate the original metal hydride at a higher temperature and thereby heat a fluid to the higher temperature.

Although hereinbefore the invention has been described in connection with embodiments utilizing working substances which are gases or solids, it should be apparent that the basic principles of the invention may be employed in connection with a liquid working substance. In summary the invention is based on the utilization of thermal energy from a source of relatively low temperature to decompose a working substance into its...
constituent is hydrogen and said second constituent is
removed from said chamber with part of undecom-
posed working substance and wherein the first and
second constituents are recombined in said second
chamber with some undecomposed working substance
present therein.
3. The method as described in claim 2 wherein said
working substance is ammonia and said second constitu-
ent is nitrogen.
4. A method of utilizing geothermal energy to pro-
duce superheated steam, the steps comprising:
introducing into a first chamber at a first selected
pressure a gaseous working substance which de-
composes into first and second gaseous constituents
at a temperature on the order of 300° C at said first
pressure;
heating said first chamber with the working sub-
stance therein with geothermal energy to a temperature on
the order of 300° C, whereby said working sub-
stance decomposes into said first and second con-
stituents;
continuously separating and removing said first con-
stituent from the second constituent and the unde-
composed substance and its constituents, present in
said first chamber, to thereby facilitate the contin-
ued decomposition of said substance;
removing from said first chamber at least part of the
second constituent;
recombining the first and second constituents, which
were separated and removed from said first cham-
ber, in a second chamber to reform the gaseous
working substance at a second pressure, higher than
said first pressure, the recombination being accom-
plished by the release of heat which raises the tem-
perature in said second chamber to a temperature on
the order of not less than 500° C; and
passing through said second chamber steam which
absorbs heat present in said second chamber and is
heated thereby to a temperature on the order of not
less than 500° C to form superheated steam, for use
in turbine electrical energy generation.
5. The method as described in claim 4 wherein said
first constituent is hydrogen and said second constituent
is removed from said chamber with part of undecom-
posed working substance and wherein the first and
second constituents are recombined in said second
chamber with some undecomposed working substance
present therein.
6. The method as described in claim 5 wherein said
working substance is ammonia and said second constitu-
ent is nitrogen.