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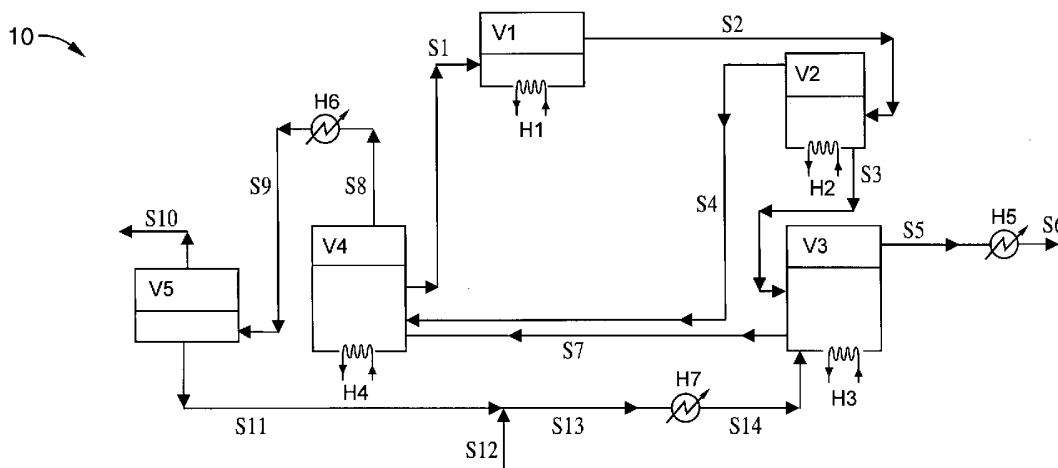
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(54) Title: HYDROGEN PRODUCTION BY A THERMOCHEMICAL WATER SPLITTING CYCLE



(57) Abstract: A novel thermochemical cycle for the decomposition of water is presented. Along with water, hydrogen, and oxygen, the cycle involves an alkali or alkali earth metal based catalyst and a variety of intermediates. The cycle is driven by renewable energy sources, and can have a maximum operating temperature below 1173 K (900°). The kinetics of the cycle are based on the reactant behavior as well as the separability characteristics of the chemicals involved.

HYDROGEN PRODUCTION BY A THERMOCHEMICAL WATER SPLITTING CYCLE

CROSS-REFERENCE TO RELATED APPLICATIONS

5 **[0001]** This application claims priority from U.S. provisional application serial number 60/637,048, filed on December 16, 2004, incorporated herein y by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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[0002] Not Applicable

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BACKGROUND OF THE INVENTION

25

1. Field of the Invention

[0004] This invention pertains generally to the production of hydrogen from water, and more particularly to a thermochemical cycle using a renewable energy source that efficiently separates water into its components.

2. Description of Related Art

30

[0005] Hydrogen is mainly produced from natural gas through steam reforming and dry reforming of methane and other fossil fuels, and from coal through gasification. Hydrogen is also produced through electrolysis. These production

methods consume fossil fuels, electricity, or both, and produce unwanted carbon dioxide as a byproduct. In addition, the hydrogen product usually requires separation from other by-products, such as carbon monoxide and carbon dioxide.

- 5 **[0006]** Thermal decomposition of water typically requires temperatures greater than 2273 K (about 2000°C).

BRIEF SUMMARY OF THE INVENTION

- 10 **[0007]** The present invention provides a novel thermochemical cycle for the decomposition of water. Along with water, hydrogen, and oxygen, the cycle involves an alkali or alkali earth metal based catalyst and a variety of reaction intermediates. The cycle is driven by renewable energy sources, and can have a maximum operating temperature below 1173 K (900°C). Alternatively, the cycle can operate at much higher temperatures. The kinetics of the cycle are based on the reactant behavior as well as the separability characteristics of the chemicals involved.

- 15 **[0008]** An aspect of the invention is a method, comprising using an alkali metal based or alkali earth metal based process intermediate in a thermochemical cycle for water splitting. In one embodiment, the thermochemical cycle operates in the absence of solids. In another embodiment, the thermochemical cycle operates at temperatures at or below about 1173 K.

- 20 **[0009]** Another aspect of the invention is a method for water splitting, comprising: introducing water into a system, introducing an alkali metal based or alkali earth metal based process intermediate into the system, separating the alkali metal based or alkali earth metal based process intermediate to produce reaction intermediates, reacting a subset of the reaction intermediates with water to produce hydrogen and hydroxide, combining a subset of the reaction intermediates with the hydroxide to produce water and oxygen, reforming the alkali metal based or alkali earth metal based process intermediate for continued use in the system, and removing the hydrogen and the oxygen from the system.

[0010] One embodiment further comprises removing heat from the system, and generating power, electricity, or both from the heat. In another embodiment, the generating step uses fuel cells or turbines to generate the power, electricity, or both.

5 **[0011]** A still further aspect of the invention is a system for water splitting, comprising: a plurality of interconnected reaction vessels, wherein the plurality of interconnected reaction vessels is configured to receive water from a source of water, wherein the plurality of interconnected reaction vessels is configured to admit an alkali metal based or alkali earth metal based process intermediate into the system, wherein water undergoes a series of
10 thermochemical reactions with said alkali metal based or alkali earth metal based process intermediate, and wherein hydrogen and oxygen are recoverable from the system.

[0012] In one embodiment, the alkali metal based or alkali earth metal based
15 process intermediate is combined with a transition metal. In other embodiments, the alkali metal based or alkali earth metal based process intermediate comprises a carbonate or a hydroxide, or comprises more than one type of alkali metal or alkali earth metal. In another embodiment, the system is operated in a polytropic manner. In another embodiment, the
20 system operates at temperatures at or below about 1300 K. In still another embodiment, the system operates in the absence of solids within the system.

[0013] In yet another embodiment, heat generated by the series of thermochemical reactions is used to produce power, electricity, or both. In another embodiment, heat required for the series of thermochemical reactions
25 is derived from solar or non-solar energy sources.

[0014] Further aspects of the invention will be brought out in the following portions of the specification, wherein the detailed description is for the purpose of fully disclosing preferred embodiments of the invention without placing limitations thereon.

30 BRIEF DESCRIPTION

OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0015] The invention will be more fully understood by reference to the

following drawings which are for illustrative purposes only:

[0016] FIG. 1 is one embodiment of the thermochemical water splitting cycle according to the present invention.

5 **[0017]** FIG. 2 is a second embodiment of the thermochemical water splitting cycle according to the present invention.

[0018] FIG. 3 is a third embodiment of the thermochemical water splitting cycle according to the present invention.

[0019] FIG. 4 is a thermochemical water splitting cycle associated with data in Tables 1-9.

10 **[0020]** FIG. 5 is a steam cycle used in conjunction with the cycle of FIG. 4 to produce power and/or electricity.

DETAILED DESCRIPTION OF THE INVENTION

[0021] Referring more specifically to the drawings, for illustrative purposes the present invention is embodied in the system generally shown in FIG. 1 through FIG. 5. It will be appreciated that the system may vary as to
15 configuration and as to details of the parts, and that the method may vary as to the specific steps and sequence, without departing from the basic concepts as disclosed herein.

[0022] The overall water decomposition reaction is given by the equation:

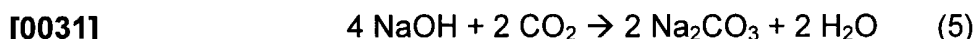
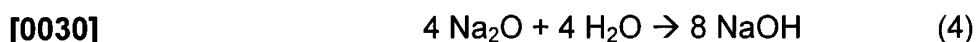
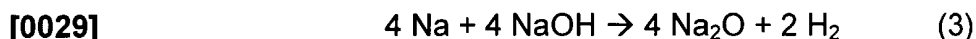
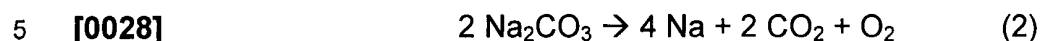
20 **[0023]**
$$2 \text{ H}_2\text{O} \rightarrow 2 \text{ H}_2 + 2 \text{ O}_2 \quad (1)$$

[0024] The present invention is a novel thermochemical cycle 10 that accomplishes the water decomposition reaction. The following examples detail various embodiments of the instant invention.

[0025] In each embodiment, temperatures shown are shown by way of
25 example, and are not intended to limit the invention. The maximum operating temperature can be less than or equal to 1173 K, but operating temperatures in the range of 298 K to 1300 K are within the scope of the invention. The choice of operating temperature is driven by several factors, including capital costs for the reactors and associated material movement equipment,
30 operating cost for the cycle, and costs related to available high temperature energy sources.

[0026] Example 1

[0027] One embodiment of the thermochemical cycle can involve sodium, sodium bicarbonate, sodium carbonate, sodium hydride, sodium hydroxide, sodium monoxide, and carbon dioxide as intermediates.



[0032] A process according to this embodiment is shown in FIG. 1.

10 **[0033]** Sodium carbonate is first placed in vessel 22 and heated. The sodium carbonate decomposes to a gaseous mixture of sodium, oxygen, and carbon dioxide. The gas mixture is then cooled to liquefy the sodium. The mixture enters vessel 24, where separation takes place. The sodium is sent to vessel 26, where it reacts to completion with sodium hydroxide (molten) to produce sodium monoxide and hydrogen (gas). The sodium monoxide is sent to vessel 15 28, where it is placed in contact with water to form sodium hydroxide.

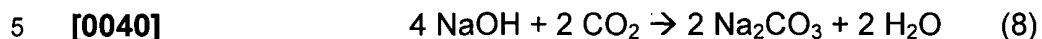
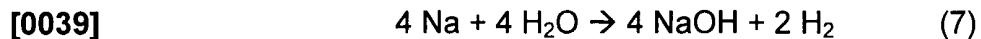
[0034] Some of the sodium hydroxide from vessel 28 is recycled back to vessel 26 to react with the sodium and to facilitate transport of both heat and sodium monoxide. Some sodium hydroxide is also sent to vessel 30, where it is placed in contact with oxygen and carbon dioxide from vessel 24. The carbon dioxide is adjusted so that the reaction proceeds to completion to form sodium carbonate (molten). The molten sodium carbonate is then fed to vessel 22.

25 **[0035]** The heat produced in vessels 26 and 28, the heat from the exit streams containing hydrogen and oxygen, and the heat from the exit of reaction vessel 22 can be heat and power integrated with the heating needs of the system (e.g., heating of carbonate in and before vessel 22, heating of inlet water), and outside hot utilities (e.g., solar, nuclear, fossil fuel based, geothermal, etc.) and cold utilities (e.g., cooling water) to produce electricity.

30 **[0036]** Example 2

[0037] Another embodiment of the thermochemical cycle involves sodium, sodium carbonate, sodium hydroxide, and carbon dioxide as intermediates

that help facilitate water decomposition. A process according to this embodiment is shown in FIG. 2.



[0041] The reactions can be carried out at a variety of temperatures. Reaction (6) is endothermic and can typically be carried out around 1173 K, where all its products are gases. Kinetic rate information at 1173 K is given in Hughes et al., "Production of the Boranes and Related Research", Academic Press,
10 New York, 1967. Reaction (7) is exothermic and can be carried out at room temperature or even around 1133 K. Care must be taken to control the rate of reaction (7). This can be accomplished by running the reaction with excess steam. Reaction (8) is also exothermic and can also be carried out around 1133 K. The choice of operating temperature for these reactions depends on
15 several factors including capital costs for the reactors and reactors and associated material moving equipment, operating cost for the cycle, as well as the available high temperature energy source. Stable operation requires efficient heat removal from reactions (7) and (8).

[0042] Referring to FIG. 2, sodium carbonate is first placed in vessel 42 and
20 heated. The sodium carbonate decomposes to a gaseous mixture of sodium, oxygen, and carbon dioxide. The gas mixture is then cooled to liquefy the sodium, and the mixture is sent to vessel 44, where separation takes place. The sodium is sent to vessel 46, where it reacts to completion with water (steam) to form sodium hydroxide (molten) and hydrogen (gas). Heat must be
25 removed from vessel 46 to ensure stable operation. The sodium hydroxide is sent to vessel 48, where it is placed in contact with the oxygen and carbon dioxide from vessel 44. The carbon dioxide is adjusted so that the reaction proceeds to completion and forms sodium carbonate (molten). The molten sodium carbonate is then sent to vessel 42.

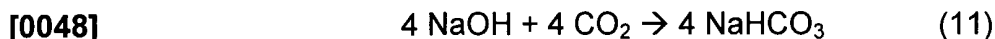
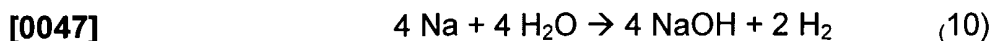
30 [0043] The heat from the reactions in vessels 46 and 48, the heat from the exit streams containing hydrogen and oxygen, and the heat from the exit of reaction vessel 42 can be heat and power integrated with the heating needs of

the system (e.g., heating of carbonate in and before vessel 42, heating of inlet water), and outside hot utilities (e.g., solar, nuclear, fossil fuel based, geothermal, etc.) and cold utilities (e.g., cooling water) to produce electricity.

[0044]

Example 3

5 [0045] A third embodiment is given by the system of equations:



10 [0050] Referring to FIG. 3, sodium carbonate is first placed in vessel 62 and heated. The sodium carbonate decomposes to a gaseous mixture of sodium, oxygen, and carbon dioxide. The gas mixture is then cooled to liquefy the sodium, and the mixture is sent to vessel 64, where separation takes place. The sodium is cooled and sent to vessel 66, where it reacts to completion with
15 water to form sodium hydroxide and hydrogen. Although FIG. 3 shows the reaction in vessel 66 with liquid water, the reaction can take place with liquid water or with steam. Heat must be removed from vessel 66 to ensure stable operation. The sodium hydroxide and some water are then sent to vessel 68, where it is placed in contact with the oxygen and carbon dioxide from
20 vessel 64. The carbon dioxide is adjusted so that the hydroxide reacts to completion and forms sodium carbonate and sodium bicarbonate. The sodium bicarbonate and sodium carbonate solution is fed to vessel 70, where the bicarbonate decomposes to carbonate, water, and carbon dioxide, the water is vaporized, and the carbonate melts. The carbon dioxide and water gases
25 are then separated and recycled, while the sodium carbonate is sent to vessel 62.

[0051] In each example, heat integration is possible, but not shown. All reaction vessels shown can be operated in an adiabatic or in a polytropic manner throughout the applicable temperature range. In addition, the process
30 can be operated in a manner that avoids the presence and/or movement of solids anywhere in the cycle. Finally, although temperature-based separations are disclosed, other types of separations can be utilized according to the

present invention.

[0052] Example 4

[0053] FIG. 4 shows a thermochemical cycle utilizing reactions (2) through (5), much like that in FIG. 3. FIG. 5 is a standard reheat steam cycle associated with the cycle of FIG. 4. The data associated with the cycles shown in FIG. 4 and FIG. 5 are presented in Tables 1-9.

[0054] Tables 1A-1B show the characteristics of each stream shown in Fig. 4 and Fig. 5, including temperature, flow rate, and composition. Note that the composition of streams S15-S20 is water only, as these streams comprise the steam cycle.

[0055] Tables 2-4 provide thermodynamic data for the individual components at 1173 K, 1133 K, and 298 K, respectively.

[0056] Tables 5A-5B provide the operating conditions for each heat exchanger H1-H10, turbine T1-T2, and pump P1.

[0057] Table 6 indicates the heat load for the heat exchangers in the two systems, and Table 7 indicates the work load for the turbines and the pump.

[0058] Tables 8 and 9 quantify the cost coefficients (\$/GJ) and the utility cost (\$/s), respectively, for the cycle shown in FIG. 4 and FIG. 5. The value of the Hot Utility (HU) Cost for Groups 1-3 reflects the cost of natural gas.

Fluctuations in the cost of natural gas will directly affect the cost efficiency of the cycle. For Group 4, the cost coefficient is zero, reflecting the use of solar power as the hot energy source. Note that the use of solar power realizes the greatest benefit in terms of cost. Table 9 also indicates the cost to produce hydrogen using the cycle of FIG. 4.

[0059] In the cycle shown in FIG. 4, sodium carbonate enters reaction vessel V1 as stream S1. In vessel V1, sodium carbonate is separated into sodium, oxygen, and carbon dioxide, which exits in stream S2. Stream S2 enters vessel V2. Sodium is separated out into stream S3, and enters vessel V3. Meanwhile, the carbon dioxide and oxygen from vessel V2 exit as stream S4, entering vessel V4.

[0060] Water enters the system at stream S12, and is also recycled from vessel V5. Streams S11, S13, S14 are composed of water, and are directed

into vessel V3 to combine with the sodium from stream S3. Hydrogen is produced in vessel V3, and exits the system in streams S5, S6. Vessel V3 also produces sodium hydroxide, which enters vessel V4 via stream S7 and reacts with the carbon dioxide and oxygen from stream S4.

5 **[0061]** The reaction in vessel V4 produces sodium carbonate, which is routed back to vessel V1 via stream S1. The reaction in vessel V4 also produces water and oxygen, which enters vessel V5 through stream S9. Oxygen exits the system through stream S10, and the water is recycled to vessel V3 by way of streams S11, S13, S14.

10 **[0062]** FIG. 5 shows a standard reheat steam cycle utilizing streams S15-S20, which generates power or electricity from a thermochemical cycle such as that shown in FIG. 4. Heat exchangers H8 and H10 pick up energy from heat exchangers H2, H3, H4, H5, H6, shown in FIG. 4, and utilize turbines T1 and T2 to generate power and/or electricity. Note that the heat load, shown in
15 Table 6, for H8+H10 is equal in magnitude to that of H2+H3+H4+H5+H6.

[0063] The steam cycle shown in FIG. 5 is intended only as an example, and other elements may be used to achieve similar or better results. For example, fuel cells can be utilized instead of turbines for energy generation.

[0064] FIGS. 4 and 5, and their associated data, represent one example of the
20 use of the present invention and does not represent the maximum system efficiency possible. Other embodiments of the present invention could achieve efficiencies of 75-80%.

[0065] Other systems of equations can be generated that involve the same intermediates. In addition, other alkali metals and alkali earth metals can be
25 used in place of sodium. Finally, mixtures of these metals, their carbonates, and/or their hydroxides can be used according to the present invention, as can combinations of these materials with transition metals.

[0066] Although the description above contains many details, these should not
30 be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention.
Therefore, it will be appreciated that the scope of the present invention fully encompasses other embodiments which may become obvious to those skilled

in the art, and that the scope of the present invention is accordingly to be limited by nothing other than the appended claims, in which reference to an element in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." All structural, chemical, and functional equivalents to the elements of the above-described preferred embodiment that are known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the present claims. Moreover, it is not necessary for a device or method to address each and every problem sought to be solved by the present invention, for it to be encompassed by the present claims. Furthermore, no element, component, or method step in the present disclosure is intended to be dedicated to the public regardless of whether the element, component, or method step is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for."

Stream #	1	2	3	4	5	6	7	8	9	10
Flow (mol/s)										
Pressure (kPa)	1	3.5	2	1.5	1	1	2	1.5	1.5	0.5
Temperature (°K)	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3
H ₂ O (mol/s)	1133	1173	1133	1133	1133	298	1133	1133	298	298
H ₂ (mol/s)	0	0	0	0	0	0	0	1	1	0
O ₂ (mol/s)	0	0	0	0	1	1	0	0	0	0
Na (mol/s)	0	0.5	0	0.5	0	0	0	0.5	0.5	0.5
NaOH (mol/s)	0	2	2	0	0	0	0	0	0	0
Na ₂ CO ₃ (mol/s)	0	0	0	0	0	0	2	0	0	0
CO ₂ (mol/s)	1	0	0	0	0	0	0	0	0	0
H (kJ/s)	0	1	0	1	0	0	0	0	0	0
H (kJ/s) (Hysys)	100.9963	92.01492	32.6428	54.76664	25.16037	-0.00431	99.38876	33.44491	-12.1357	-0.00196
Phase	Liquid	Vapor	Liquid	Vapor	Vapor	Vapor	Liquid	Vapor	Liquid/Vapor	Vapor

Table 1-A

Stream #	11	12	13	14	15	16	17	18	19	20
Flow (mol/s)	1	1	2	2	0	0	0	0	0	0
Pressure (kPa)	101.3	101.3	101.3	101.3	25330	1818	1818	2.55	2.55	25330
Temperature (°K)	298	298	298	1133	873.15	481.65	1011.15	295.2	294.99	295.26
H ₂ O (mol/s)	1	1	2	2	0	0	0	0	0	0
H ₂ (mol/s)	0	0	0	0	0	0	0	0	0	0
O ₂ (mol/s)	0	0	0	0	0	0	0	0	0	0
Na (mol/s)	0	0	0	0	0	0	0	0	0	0
NaOH (mol/s)	0	0	0	0	0	0	0	0	0	0
Na ₂ CO ₃ (mol/s)	0	0	0	0	0	0	0	0	0	0
CO ₂ (mol/s)	0	0	0	0	0	0	0	0	0	0
H (kJ/s)	-12.1338	-12.1338	-24.2676	39.28542	0	0	0	0	0	0
H (kJ/s) (Hysys)					0	0	0	0	0	0
Phase	Liquid	Liquid	Liquid	Vapor	Vapor	Vapor	Vapor	Vapor	Liquid	Liquid

Table 1-B

T °K (298.15-1300)	1173											
	CO ₂	H ₂	H ₂ O	O ₂	Na	Na ₂ CO ₃	NaOH	CH ₄				
Melting Point °K	216.55	13.95	273.15	54.25	371	1127	595	90.65				
Boiling Point °K	194.65	20.45	373.15	90.15	1154.5	1300	1651	111.75				
ΔH°f (kcal/mol)	-94.052	0	-68.3174	0	0	-269.46	-101.96	-17.889				
ΔG°f (kcal/mol)	-94.26	0	-56.6899	0	0	-249.55	-90.06	-12.14				
ΔHf (cal/mol)	1900	28	1436	106	630	7000	2000	224				
ΔHv (cal/mol)	6030	216	9729	1629	23120			2040				
Cps (cal/mol °K)					11.29728	28.9	14.22					
Cpl (cal/mol °K)			18		7.5	28.9	14.22					
Cpg (cal/mol °K)	13.41193	7.57013	11.82324	8.436217	4.97			18.8295				
H (T) (kcal/mol)	-83.7319	6.312756	-49.8732	6.931505	30.21382	-237.177	-87.5196	-5.81685				

Table 2

T °K (298.15-1300)	1133												
	CO ₂	H ₂	H ₂ O	O ₂	Na	Na ₂ CO ₃	NaOH	CH ₄					
Melting Point °K	216.55	13.95	273.15	54.25	371	1127	595	90.65					
Boiling Point °K	194.65	20.45	373.15	90.15	1154.5	1300	1651	111.75					
ΔH°f (kcal/mol)	-94.052	0	-68.3174	0	0	-269.46	-101.96	-17.889					
ΔG°f (kcal/mol)	-94.26	0	-56.6899	0	0	-249.55	-90.06	-12.14					
ΔHf (cal/mol)	1900	28	1436	106	630	7000	2000	224					
ΔHv (cal/mol)	6030	216	9729	1629	23120			2040					
Cps (cal/mol °K)					11.08288	28.9	14.22						
Cpl (cal/mol °K)			18		7.5	28.9	14.22						
Cpg (cal/mol °K)	13.29212	7.53773	11.63964	8.416095	4.97			18.3695					
H (T) (kcal/mol)	-84.2659	6.010599	-50.2802	6.594456	6.840622	-238.333	-88.0884	-6.56083					

Table 3

[illegible]

Table 4

Unit	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
Temperature IN (°K)	1173	1133	1133	1133	1133	1133	298	481.65	295.2	295.26
Temperature OUT (°K)	1173	1133	1133	1133	298	298	1133	1011.15	294.99	873.15
Q (kJ/s)	914.6174	-198.622	-348.64	-117.92	-25.1647	-89.3193	151.0303	199.4494	-426.574	580.2165
Q/ΔT (kJ/(°K*s))					0.030137	0.106969	0.180875	0.376675	2031.303	1.004026
W (kJ/s)										

Table 5-A

Unit	T1	T2	P1
Properties			
Temperature IN (°K)	873.15	1011.15	294.99
Temperature OUT (°K)	481.65	295.2	295.26
Q (kJ/s)			
Q/ΔT (kJ/(°K*s))			
W (kJ/s)	-105.928	-251.936	4.771517

Table 5-B

Heat Loads (kJ/s)	9.543035	← flow
H2+H3+H4+H5+H6	-779.666	
H1+H7	1065.648	
H8+H10	779.666	
H9	-426.574	

Table 6

5

Work Loads (kJ/s)	
T1+T2	-357.864
P1	4.771517

Table 7

Cost Coeffs (\$/GJ)	Group 1	Group 2	Group 3	Group 4
Hot Utility Cost (\$/GJ)	8.825	8	9.298	0
Cold Utility Cost (\$/GJ)	0.5	0.5	1.85	1.85
Electricity Cost (\$/GJ)	25.3	26	23.8889	23.8889

10

Table 8

Utility Costs (\$/s)	Group 1	Group 2	Group 3	Group 4
HU Cost (\$/s)*10 ³	9.404341	8.525182	9.908393	0
CU Cost (\$/s)*10 ³	0.213287	0.213287	0.789161	0.789161
E Cost (\$/s)*10 ³	-8.93324	-9.1804	-8.43499	-8.43499
Total Cost (\$/s)*10 ³	0.684393	-0.44193	2.262567	-7.64583
H ₂ Cost (\$/kg H ₂)	0.342197	-0.22097	1.131284	-3.82291

15

Table 9

CLAIMS

What is claimed is:

1. A method, comprising:
5 using an alkali metal based or alkali earth metal based process intermediate in a thermochemical cycle for water splitting.
2. A method as recited in claim 1, wherein the thermochemical cycle operates in the absence of solids.
- 10 3. A method as recited in claim 1, wherein the thermochemical cycle operates at temperatures at or below about 1173 K.
4. A method for water splitting, comprising:
15 introducing water into a system;
introducing an alkali metal based or alkali earth metal based process intermediate into said system;
separating said alkali metal based or alkali earth metal based process intermediate to produce reaction intermediates;
20 reacting a subset of said reaction intermediates with water to produce hydrogen and hydroxide;
combining a subset of said reaction intermediates with said hydroxide to produce water and oxygen;
reforming said alkali metal based or alkali earth metal based process
25 intermediate for continued use in said system; and
removing said hydrogen and said oxygen from said system.
5. A method as recited in claim 4, further comprising:
removing heat from said system; and
30 generating power, electricity, or both, from said heat.

6. A method as recited in claim 5, wherein the generating step uses fuel cells or turbines to generate said power, electricity, or both.

7. A system for water splitting, comprising:
5 a plurality of interconnected reaction vessels;
wherein said plurality of interconnected reaction vessels is configured to receive water from a source of water;
wherein said plurality of interconnected reaction vessels is configured to admit
an alkali metal based or alkali earth metal based process intermediate into the
10 system;
wherein water undergoes a series of thermochemical reactions with said alkali metal based or alkali earth metal based process intermediate; and
wherein hydrogen and oxygen are recoverable from said system.

15 8. A system as recited in claim 7, wherein said alkali metal based or alkali earth metal based process intermediate is combined with a transition metal.

9. A system as recited in claim 7, wherein said alkali metal based or alkali earth metal based process intermediate comprises a carbonate.

20 10. A system as recited in claim 7, wherein said alkali metal based or alkali earth metal based process intermediate comprises a hydroxide.

11. A system as recited in claim 7, wherein said alkali metal based or alkali
25 earth metal based process intermediate comprises more than one type of alkali metal or alkali earth metal.

12. A system as recited in claim 7, wherein the system is operated in a polytropic manner.

30 13. A system as recited in claim 7, wherein the system operates in the absence of solids within the system.

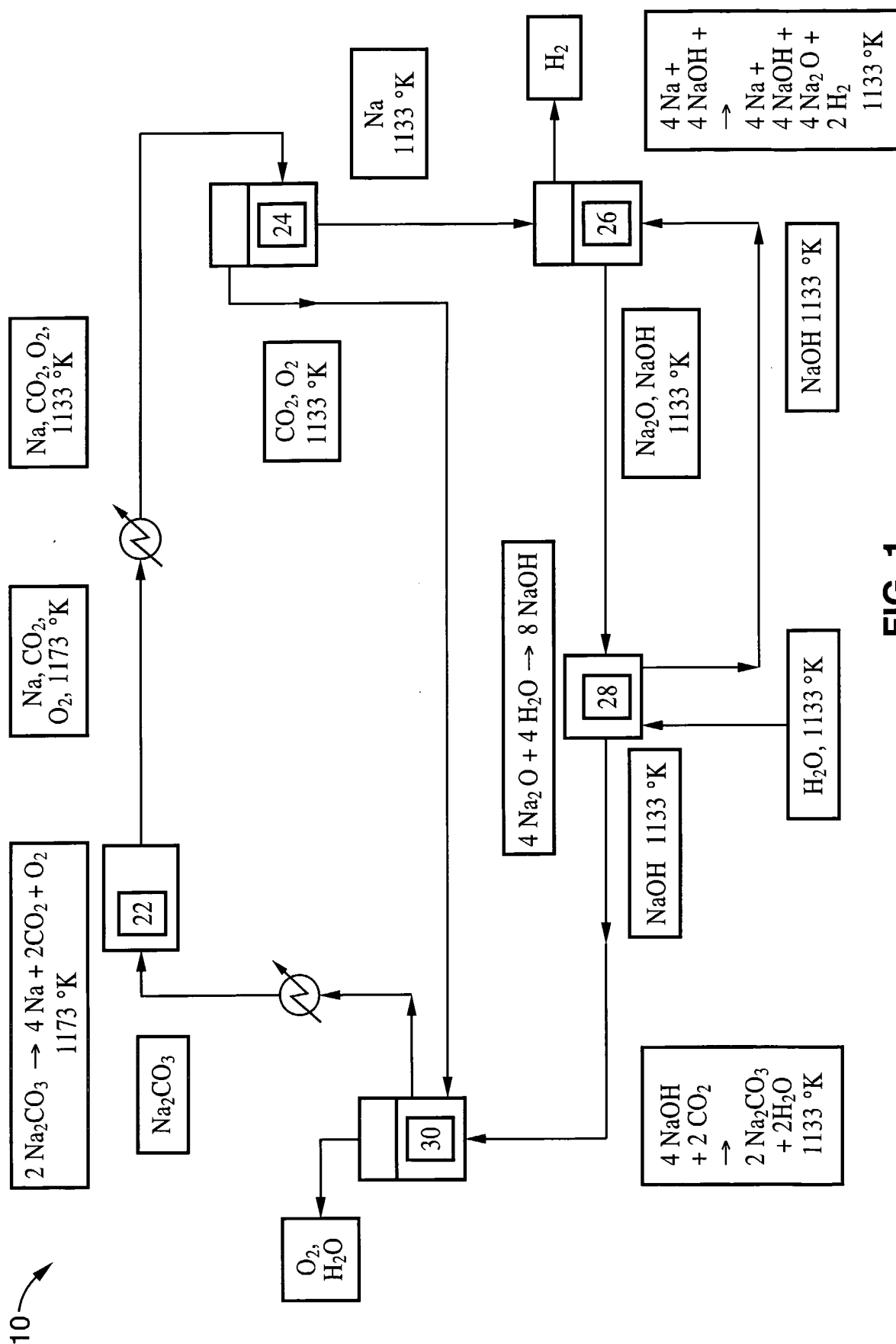
14. A system as recited in claim 7, wherein the system operates at temperatures at or below about 1300 K.

5 15. A system as recited in claim 7, wherein heat generated by said series of thermochemical reactions is used to produce power, electricity or both.

16. A system as recited in claim 7, wherein heat required for said series of thermochemical reactions is derived from solar energy sources.

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17. A system as recited in claim 7, wherein heat required for said series of thermochemical reactions is derived from non-solar energy sources.



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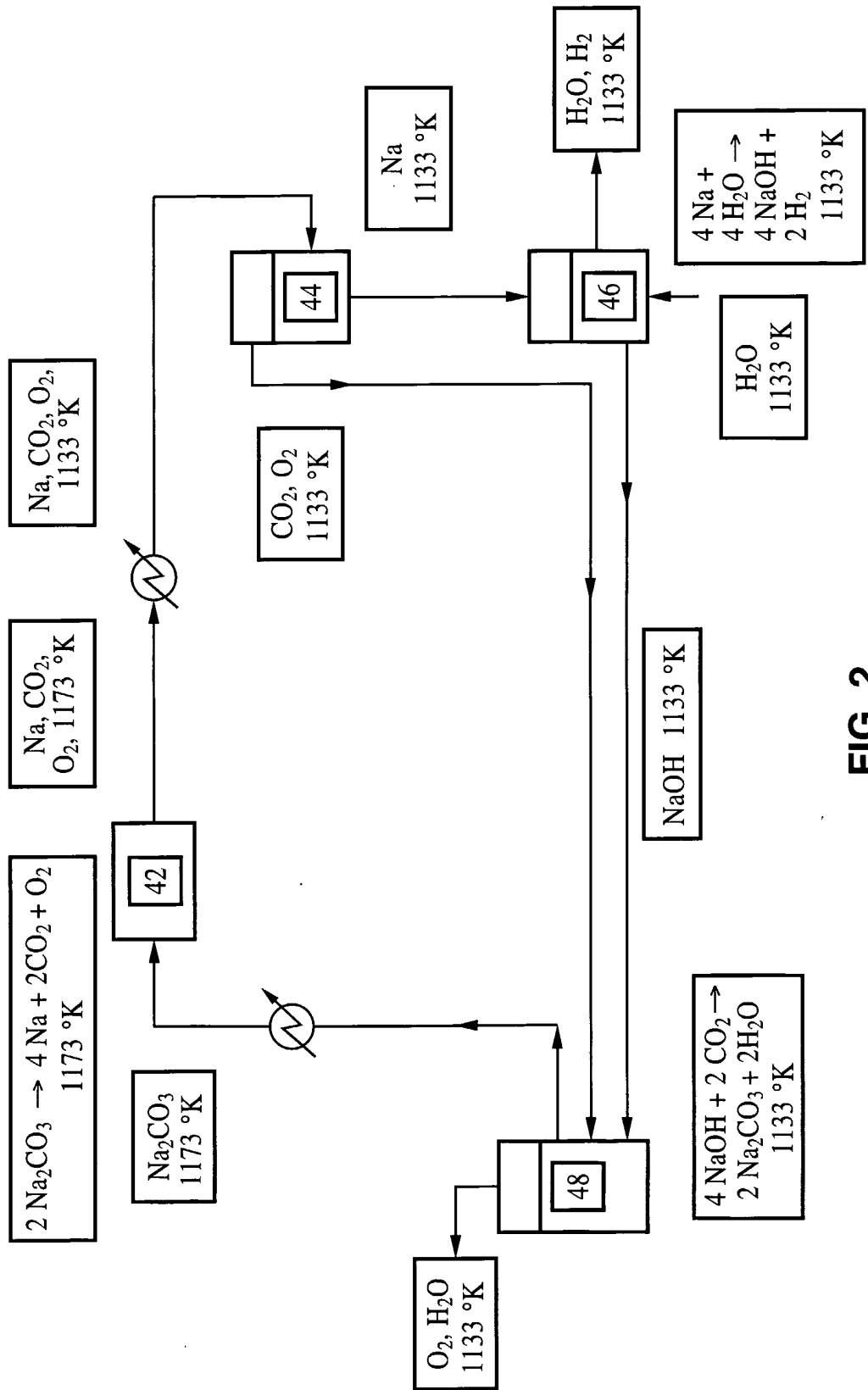


FIG. 2

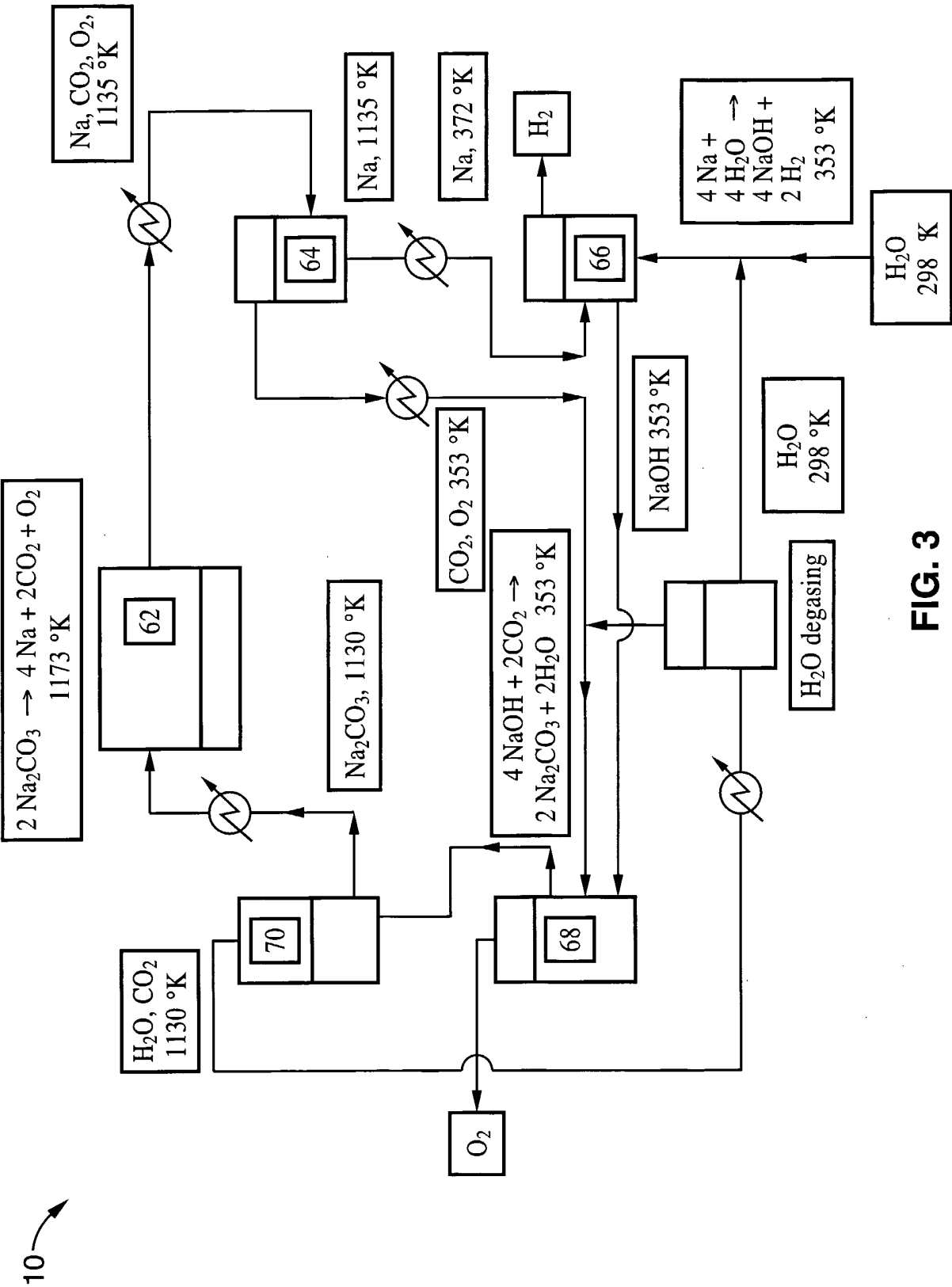


FIG. 3

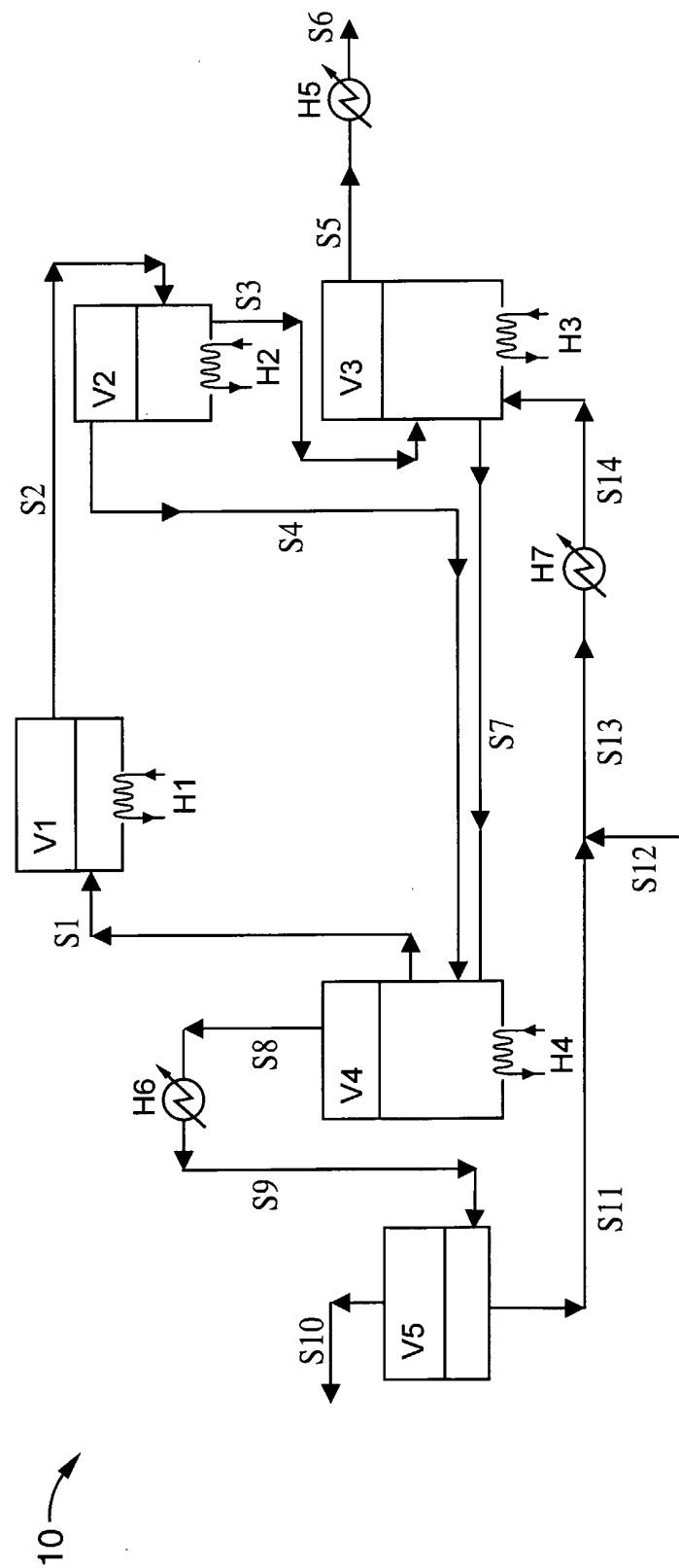


FIG. 4

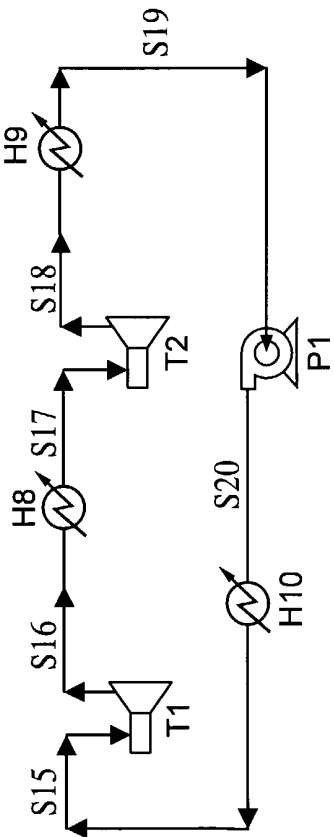


FIG. 5