

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
9 December 2010 (09.12.2010)

(10) International Publication Number
WO 2010/141496 A2

(51) International Patent Classification:

C01B 3/04 (2006.01) *B01J 19/08* (2006.01)
C01B 17/04 (2006.01) *B01D 53/32* (2006.01)

(21) International Application Number:

PCT/US2010/036941

(22) International Filing Date:

1 June 2010 (01.06.2010)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/182,867 1 June 2009 (01.06.2009) US
12/790,250 28 May 2010 (28.05.2010) US

(71) Applicants (for all designated States except US):

CHEVRON U.S.A. INC. [US/US]; 6001 Bollinger Canyon Road, San Rafael, CA 94852 (US). **DREXEL UNIVERSITY** [US/US]; 3141 Chestnut Street, Philadelphia, PA 19104 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **GUTSOL, Alexander** [RU/US]; 2375 Magnolia Bridge Drive, San Ramon, CA 94582 (US). **POTTER, R., William** [US/US]; 207 Heritage Lane, Pleasanton, CA 94566 (US). **GUTSOL, Kirill** [RU/US]; 3516 Spring Garden Street, #B24, Philadelphia, PA 19104 (US). **NUNNALLY, Thomas** [US/US]; 4007 Lauriston Street, Philadelphia, PA 19128

(US). **STARIKOVSKI, Andrei** [RU/US]; 3 Wimbledon Way, Marlton, NJ 08053 (US). **FRIDMAN, Alexander** [US/US]; 36 John James Audubon Way, Marlton, NJ 08053 (US). **RABINOVICH, Alexander** [US/US]; 235 Garden Park Blvd., Cherry Hill, NJ 08002 (US).

(74) Agents: **GESS, Joseph, E.** et al.; Merchant & Gould PC, 80 S. 8th Street, Minneapolis, MN 55402 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: METHODS FOR LOW TEMPERATURE HYDROGEN SULFIDE DISSOCIATION

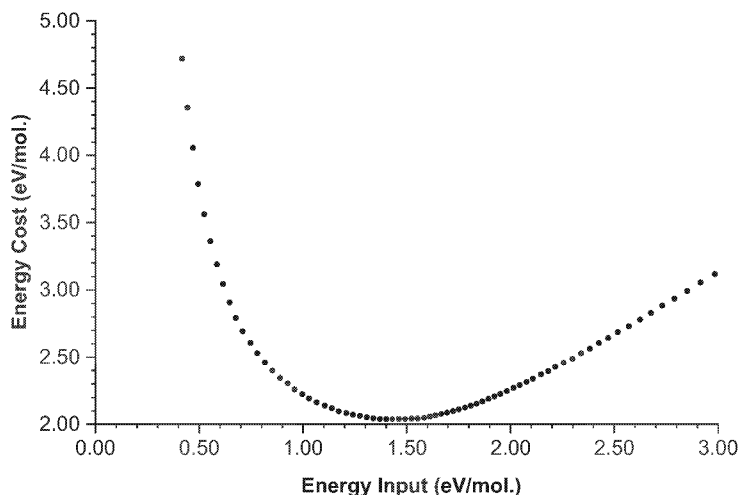


FIG. 1

(57) Abstract: A method Of H₂S dissociation comprises generating radicals or ions. H₂S dissociation is initiated at relatively low temperature, e.g., of less than 1875 K. The residence time for dissociation generally ranges from about 0.01 s to 10 s. In one embodiment, plasmas are used to generate ions for use in the H₂S dissociation.

WO 2010/141496 A2

Published:

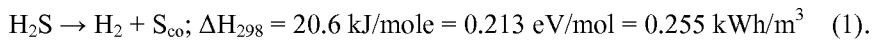
- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

1 **Methods for Low Temperature Hydrogen Sulfide Dissociation**

3 BACKGROUND

4 Hydrogen sulfide, H₂S, is a byproduct of oil refinement. Therefore, efficient H₂S
5 treatment and utilization is crucial to the oil and gas industry. In particular, H₂S dissociation
6 into sulfur and hydrogen is commercially important for the oil and gas industry, which
7 consumes large amounts hydrogen in oil hydrotreatment.

8 Rising fuel costs and more stringent restrictions on CO₂ emissions have resulted in
9 increasing interest in the weakly endothermic process of H₂S dissociation, which can be
10 arranged in a chemical or thermo-chemical reactor and carried out via the following reaction:

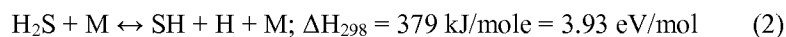


14 From the standpoint of thermodynamics, H₂S is a cost effective source of hydrogen, as the
15 disassociation energy of H₂S is only 0.2 eV per molecule. Therefore, the possibility to
16 dissociate H₂S into sulfur and hydrogen is important commercially. It has been estimated
17 that if plasma dissociation of H₂S can be industrially realized with Specific Energy
18 Requirement (SER) lower than 1 eV per H₂ molecule, the refining industry can save up to
19 70·10¹² Btu/yr.

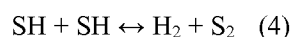
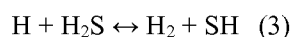
20 Several plasma-chemical systems have been utilized for H₂S dissociation: microwave
21 (MW) discharge, radio frequency (RF) discharge, gliding arc (GA) discharge, gliding arc in
22 tornado (GAT), and a nitrogen plasma jet. Such plasma-chemical systems however, have
23 significant drawbacks. Powerful MW systems are not readily available and are complicated
24 and expensive. Both MW and RF discharges are difficult to arrange at relatively high
25 pressure with the presence of hydrogen in the plasma. Scaling up of these systems is also
26 problematic. GA and conventional arc discharges have relatively low efficiencies. GAT and
27 conventional GA have potential problems with electrode deterioration and also problems with
28 scaling. Dissociation in the nitrogen plasma jet also has relatively low efficiency and creates
29 unnecessary byproducts (NH₃).

30 The existing theoretical basis for H₂S dissociation was developed in the 1980's, when
31 detailed kinetic simulation was difficult because of low computational power. It was

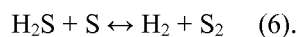
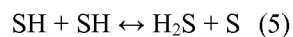
1 concluded that the process is defined by equilibrium heating. The traditional kinetic scheme
2 of H₂S dissociation includes one endothermic reaction:



5
6 which is the limiting reaction in the scheme, and several fast exothermic reactions:



9
10 or



13
14 As a result, it is necessary to spend 3.93 eV to dissociate two molecules of H₂S, which
15 is equivalent to SER of hydrogen production at least 1.965 eV/mol. Thermodynamic
16 equilibrium modeling with the assumption of plug flow reactor with fast product quenching
17 shows the lowest SER that can be expected is 2.04 eV per molecule (see Figure 1), which is
18 achieved at 1875 K. Table 1 shows the composition of an equilibrium H₂S mixture at the
19 point of minimum SER (species with mole fraction lower than 0.1% omitted).

20
21 Table 1

Mixture Species	Mole Fraction (%)
H ₂ S	21.99
SH	1.91
H ₂	50.98
S ₂	24.98

22
23 More efficient and effective processes for H₂S dissociation would therefore be of
24 great benefit to the oil and gas industry.

1 SUMMARY

2 Provided is a method of H₂S dissociation comprising generating radicals or ions,
3 wherein H₂S dissociation is initiated at a relatively low temperature, *e.g.*, of less than 1900 K,
4 for example, less than 1875 K, or less than 1700 K.

5 In one embodiment, the process involves reactions with the accumulation of H₂S₂ as
6 product and using a reaction chain that is triggered with a small amount of H and SH radicals.
7 In another embodiment, plasma catalysis is used. Ions are produced in or introduced into a
8 reaction zone of relatively low temperature. Positive and negative charges can be prevented
9 from recombining by creating a DC corona discharge in the reaction zone, or by applying a
10 biased voltage.

11

12 BRIEF DESCRIPTION OF THE FIGURES OF THE DRAWING

13 Figure 1 shows SER of dissociation per H₂S molecule as a function of energy input
14 according to a thermodynamic equilibrium simulation with the assumption of plug flow
15 reactor with fast product quenching.

16 Figure 2 illustrates the presently disclosed chemical kinetics mechanism of H₂S
17 dissociation and formation of H₂S₂ as a product.

18 Figure 3 shows the modeling results of H₂S and H₂ mass fraction as a function of
19 temperature.

20 Figure 4 shows SER of dissociation as a function of energy input for thermodynamic
21 equilibrium and kinetics modeling.

22 Figure 5 is a diagram of a basic reactor schematic.

23 Figure 6 is a diagram of a dissociation reactor with a heating element.

24 Figure 7 is a diagram of a dissociation reactor with corona discharge.

25 Figure 8 is a diagram of a dissociation reactor with glow discharge.

26 Figure 9 is a diagram of a dissociation reactor with DC corona.

27 Figure 10 is a diagram of a dissociation reactor with DC plasma and biased cylindrical
28 wall.

29

30 DETAILED DESCRIPTION

1 Methods for H₂S dissociation are provided based on modeling and the analysis of
 2 high efficiency results obtained in MW, RF, and GAT systems. According to the presently
 3 disclosed methods, H₂S dissociation can be initiated at temperatures that are significantly
 4 lower than those that are needed to reach the minimum SER according to thermodynamic
 5 equilibrium modeling with the assumption of plug flow reactor.

6 The presently disclosed methods are based upon presently disclosed chemical kinetics
 7 mechanisms for H₂S dissociation that enable low temperature dissociation. One mechanism
 8 replaces the major dissociation product S₂ with H₂S₂, which can further release hydrogen and
 9 leave sulfur as a final product at lower temperatures. Other mechanisms involve molecular or
 10 cluster ions for plasma catalysis.

11 **Chemical Kinetics Mechanism**

12 The presently disclosed chemical kinetics model shows the possibility of low SER for
 13 H₂S dissociation at temperatures that are significantly lower than in earlier models. The
 14 presently disclosed chemical kinetics mechanism, with a list of parameters, is shown in Table
 15 2.
 16

17
 18 Table 2

Reaction	<i>A</i>, cm³/molecules	<i>n</i>	<i>E_a</i>, kcal/mole
H ₂ S + M ↔ SH + H + M	2.92E-08	0.00	66.21
H ₂ S ↔ H ₂ + S	3.16E-10	0.00	65.49
H ₂ S + H ↔ H ₂ + SH	2.31E-07	1.94	0.90
H ₂ S + S ↔ 2SH	1.38E-10	0.00	7.392
SH + S ↔ H + S ₂	4.00E-11	0.00	0.00
SH + H ↔ H ₂ + S	3.01E-11	0.00	0.00
SH + SH ↔ H ₂ + S ₂	1.00E-14	0.00	0.00
SH + SH ↔ H ₂ S + S	1.50E-11	0.00	0.00
SH + H ₂ S → H ₂ S ₂ + H	3.32E-10	0.50	27.00
H ₂ S ₂ + M ↔ SH + SH + M	3.43E-07	1.00	57.12
S ₂ + M ↔ S + S + M	7.95E-11	0.00	76.96

$S_2 + S_2 + M \leftrightarrow S_4 + M$	2.23E-29	0.00	0.00
$H_2 + M \leftrightarrow H + H + M$	3.70E-10	0.00	96.02
$HSS + HSS \leftrightarrow H_2S_2 + S_2$	3.46E-15	2.37	-1.67
$HS + HSS \leftrightarrow H_2S + S_2$	3.66E-13	3.05	-1.10
$H + HSS \leftrightarrow S + H_2S$	7.32E-11	0.00	6.32
$H + HSS \leftrightarrow H_2 + S_2$	2.51E-12	1.65	-1.10
$S + HSS \leftrightarrow HS + S_2$	2.00E-2	2.20	-0.60

1

2 Main features of the presently disclosed chemical kinetics mechanism are
 3 accumulation of H_2S_2 as product and the reaction chain that is triggered with a small amount
 4 (~1%) of H and SH radicals (see Figure 2). Another main feature is that the process yields
 5 significantly higher degree of H_2S dissociation than the thermodynamic equilibrium modeling
 6 with the assumption of plug flow reactor with fast product quenching. The modeling results
 7 of dependence of mixture composition from the initiation temperature are illustrated in Figure
 8 3.

9 The thermodynamic equilibrium mixture composition is also shown for comparison.
 10 The modeling was performed on Chemkin® 4.1.1 software suite using a single adiabatic plug
 11 flow reactor with the initial mixture composition kept constant at 98% H_2S , 1% SH, and 1%
 12 H.

13 The above features contribute to the very low SER of H_2S dissociation using the
 14 presently disclosed chemical kinetics mechanism. The minimum SER corresponding to the
 15 initiation temperature of 1175K is 0.609 eV/mol, which is more than three times lower than
 16 minimum SER predicted by thermodynamic equilibrium modeling with the assumption of
 17 plug flow reactor with fast product quenching. A comparison of the results from both
 18 kinetics and thermodynamic equilibrium modeling is shown in Figure 4. H_2S_2 should be
 19 considered as a final product of gaseous phase kinetics. Further dissociation of sulfanes
 20 (H_2S_n) with hydrogen and sulfur release takes place at much lower temperatures in the
 21 condensed phase.

22 The presently disclosed chemical kinetics mechanism shows significant improvement
 23 over previous models (*e.g.*, conventional thermodynamic equilibrium model with the
 24 assumption of plug flow reactor with fast product quenching) and provides a potential

1 explanation for the low dissociation SER observed in MW, RF, and GAT experiments, in
 2 which energy consumption was half of the SER = 2.04 eV per molecule expected according
 3 to conventional thermodynamic equilibrium modeling with the assumption of plug flow
 4 reactor with fast product quenching.

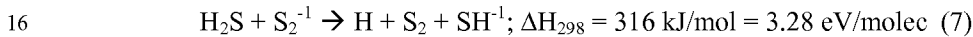
5 H₂S dissociation at low temperatures is possible and leads to significantly higher
 6 dissociation rate than in previous models. H₂S dissociation at low temperatures requires
 7 rather long residence time ranging from 0.01 to 10 seconds (s), for example, from 0.1 to 1 s,
 8 depending on the temperature of the process. The residence time drops sharply with
 9 temperature increase.

10

11 Plasma-Catalytic Mechanism

12 Another presently disclosed mechanism involves so-called plasma catalysis. The
 13 simplest example is an introduction of the ion-molecular reactions (that usually do not have
 14 any energy barriers)

15

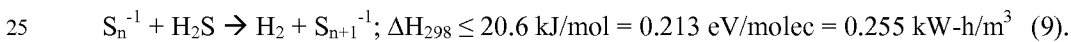


18

19 together with reaction (3) allows to decrease the enthalpy of the limiting reaction (compare
 20 reactions (7) and (2)).

21 Much more significant decrease of the reaction temperature can be expected if it is
 22 assumed that negatively or positively charged sulfur clusters play a catalysis role for the gross
 23 reaction (1), for example:

24



26

27 While there is no available data to estimate possible rate and efficiency of this
 28 reaction, a similar reaction plays a key role in the mechanism of Si nano-particles formation
 29 in SiH₄-Ar plasma. Therefore, non-equilibrium plasma processes may play key roles in
 30 effective H₂S dissociation, and reaction control should be possible through the control of
 31 plasma parameters. For effective realization of this mechanism it is necessary to produce

1 ions in (or introduce into) the zone of relatively low temperature where the reaction (9) is
2 much faster than the reverse reactions. Also it is important to separate positive and negative
3 charges to prevent their fast recombination. This can be arranged, for example, by creating
4 DC corona discharge in the reaction zone (Fig. 9) or by applying biased voltage between
5 central plasma zone and a cylindrical wall (Fig. 10).

7 **Apparatus and Method for Low Temperature H₂S Dissociation**

8 Based on the presently disclosed numeric modeling results and analysis of the
9 presently disclosed plasma-catalytic mechanisms, there are several ways of organizing an
10 H₂S dissociation reactor (see figures 5-10). For most cases, a reactor will operate with the
11 following general parameters: relatively low reaction zone temperature (less than 1900 K, in
12 particular, less than 1875 K, for example, less than 1700 K), long residence time (from 0.01
13 to 10 s, for example, from 0.1 to 1 s), and a low power dissociation source for generation of
14 H and SH radicals or ions. The first two parameters are common for all the reactors and can
15 be organized almost identically for all the reactors. The dissociation source is the main factor
16 distinguishing the reactors and requires significant changes from one reactor to another.

17 The long residence time in the reactor can be achieved by extending the length of the
18 reaction zone proportionally with desired operational flow rates. For example, the laboratory
19 size reactor designed to operate at 1 l/min of pure H₂S can have the reaction (hot) zone of 1 m
20 with a residence time of 1 s, which corresponds to cross-section of 0.167 cm² or, in the case
21 of cylindrical reactor, the diameter of 0.46 cm. Such system, even under laboratory
22 conditions, can be scaled to accept 10 times higher flow rate by increasing the diameter of the
23 reactor a little more than 3 times to 1.45 cm.

24 The uniform temperature of the mixture in the range from 800 K to 1700 K can be
25 maintained throughout the reaction zone by heating the reaction zone externally with a
26 convenient and efficient power source, *e.g.*, heat exchanger, or by mixing with hot hydrogen.
27 For example, a high quality tube furnace can be used for this purpose (Figures 5-9). Still,
28 special care should be taken while choosing the main reaction chamber due to the heating
29 requirements. For example, the reaction tube can be made out of quartz or ceramic, which
30 share high melting temperature, and both can be used as a dielectric, which is one of the
31 requirements for the local dissociation source. Figure 5 shows a general schematic of a

1 simple plug-flow reactor with external furnace and without local dissociation source
2 comprising reactor tube 1, inlet flange 2, inlet 3, closed end flange 4, and heating elements 5.

3 Several types of the reactors (Figures 6-9) can be distinguished based on the type of
4 the source that is used for local H₂S dissociation. Even though some of the reactors have
5 significantly different underlying principles, all of the reactors share a low power
6 requirement. In general, power for the local dissociation should not exceed 50%, for
7 example, 10%, of total power of the process: local dissociation plus external heating. Low
8 current less than 5A, e.g., less than 1A, arc or glow discharge is also appropriate at pressures
9 between 0.01 MPa and 1MPa.

10 The concept of radical production through localized heating is based on the presently
11 disclosed chemical kinetics mechanism, but with the consideration that relatively high
12 temperatures (of less than 2000 K, in particular, less than 1875 K) are reached in a very small
13 volume with minimal energy input. Such high temperatures allow for very fast (one to two
14 orders of magnitude faster than in the rest of the reactor volume) H₂S dissociation on H and
15 SH radicals or generation of ions that sequentially trigger the chain reactions in the entire
16 volume of the reactor. Figure 6 shows a schematic of a reactor based on localized heating
17 comprising high temperature heating element 11 (hot wire) and power supply 12. Other
18 sources of radicals, e.g., small hydrogen dissociator or hydrogen plasma injection can be
19 used.

20 A possible plasma source for low power radical production is corona discharge. It is
21 organized along a thin conductive wire placed along the axis of the reactor. The physical
22 properties of the wire are important due to the relatively high temperatures that the wire will
23 be exposed to. It is recommended to use thin (~0.25 mm) molybdenum wire, which has both
24 very high melting point (2896 K), low thermal expansion coefficient (4.8 μm·m⁻¹·K⁻¹), and
25 does not react with H₂S. Still a certain care should be taken to prevent the exposure of the
26 molybdenum wire to oxygen containing mixtures (e.g., air) at the temperatures exceeding
27 700°C because fast oxidation reaction happens at 760°C. Figure 7 shows a schematic of a
28 dissociation reactor with Alternative Current (AC) corona discharge comprising high voltage
29 power supply 21 and conductive wire 22.

30 Very similar reactor is presented in Fig. 9, however Direct Current (DC) power
31 supply in this case allows charge separation that promotes ionic catalysis.

1 Another possible plasma source for low power radical production is glow discharge.
2 It is organized between high voltage cathode and grounded anode, which are located on the
3 flanges of the reactor tube. Unlike the corona discharge, there are no strict physical
4 requirements on the anode and cathode materials as they are located outside of the heating
5 zone, but some non-corrosive metal is recommended (*e.g.*, stainless steel) due to constant
6 exposure of both electrodes to H₂S. The major requirement for glow discharge is low
7 pressure that has to be maintained on the level of 10 Torr or less. Figure 8 shows a schematic
8 of a dissociation reactor with glow discharge comprising high voltage power supply 31,
9 cathode 32, and anode 33.

10 It is possible to use other plasma sources, like dielectric barrier discharge, pulsed
11 corona, micro-discharges, etc. Figure 10 demonstrates the use of low-current arc or
12 atmospheric pressure DC glow discharge (similar to that used in Gliding Arc Tornado
13 reactor). Plasma can be generated inside H₂S gas, or separately (*e.g.*, discharge in hydrogen
14 or in gaseous sulfur) with further injection into H₂S gas.

15 The reactor presented in Fig. 10 is similar to that presented in Fig. 9, however it use
16 DC discharge combined with the biased voltage instead of corona. In that case ions
17 generated inside the discharge can promote dissociation outside the discharge zone using
18 ionic catalysis.

19 It is possible to combine key features of the disclosed relatively low-temperature
20 reactors with additional features like product separation, *e.g.*, separating hydrogen and sulfur,
21 using, for example, centrifugal forces (gas or reactor rotation) or electrical forces (*e.g.*, radial
22 electric field for separation of charge clusters). Also, the presently disclosed processes can be
23 realized inside a system with effective thermal energy recuperation, *e.g.*, the reverse-vortex
24 reactor. High energy efficiency of H₂S dissociation can be accomplished with a GAT reactor,
25 which is an example of a relatively low-temperature reactor with generation of radicals and
26 ions. GAT reactors utilize a gliding arc plasma discharge in reverse vortex flow. The GAT,
27 like many other plasma discharges, can be used as a volumetric catalyst in various chemical
28 processes. Some main features that make the GAT attractive are that it ensures uniform gas
29 treatment and it has rather long residence times. Also, the reverse vortex flow creates a low
30 temperature zone near the cylindrical wall of the reactor and a high temperature zone near the
31 reactor axis. This, in combination with a centrifugal effect, allows sulfur extraction from the

1 high temperature zone to the low temperature zone. As a result, sulfur quenching can occur
2 within the reactor. Since H₂S is quite susceptible to plasma decomposition, GAT is not only
3 a viable method but may also be a cost-effective method for H₂S dissociation. Further details
4 of the GAT can be found in U.S. Patent Application Publication 2006/0266637, the contents
5 of which are hereby incorporated by reference in their entirety.

6 Accordingly, provided is a method of H₂S dissociation comprising providing a plasma
7 reactor. The plasma reactor comprises a wall defining a reaction chamber; an outlet; a
8 reagent inlet fluidly connected to the reaction chamber for creating a vortex flow in the
9 reaction chamber; a first electrode; and a second electrode connected to a power source for
10 generation of a sliding arc discharge in the reaction chamber. The method further comprises
11 introducing H₂S into the reaction chamber in a manner which creates a vortex flow in the
12 reaction chamber and dissociating the H₂S using a plasma assisted flame.

13 In the method, the vortex flow can be a reverse vortex flow, which can be created by
14 feeding H₂S into the reaction chamber in a direction tangential to the wall of the reaction
15 chamber. The plasma reactor can comprise first and second ends, the reagent inlet can be
16 located proximate to the first end, the reactor can further comprise a second inlet fluidly
17 connected to the second end of the reactor, and at least some of the H₂S can be provided to
18 the reaction chamber via the second inlet. The plasma reactor can comprise a movable
19 second electrode and the method can further comprise the steps of igniting an electrical arc
20 with the movable second electrode in a first position, and moving the movable second
21 electrode to a second position farther from the first electrode than the first position for
22 operation of the reactor.

23 While various embodiments have been described, it is to be understood that variations
24 and modifications may be resorted to as will be apparent to those skilled in the art. Such
25 variations and modifications are to be considered within the purview and scope of the claims
26 appended hereto.

WHAT IS CLAIMED IS:

1. A method of H₂S dissociation comprising generating radicals or ions in a reaction zone and adding H₂S to the reaction zone to initiate H₂S dissociation at a temperature of less than 1900 K.
2. The method of claim 1, wherein H₂S dissociation is initiated at a temperature of less than 1875 K.
3. The method of claim 1, wherein H₂S dissociation is initiated at a temperature of less than 1700 K.
4. The method of claim 1, comprising maintaining a temperature of 800 K to 1700 K.
5. The method of claim 1, wherein the method comprises a residence time of 0.01 to 10 s.
6. The method of claim 1, wherein the method comprises a residence time of from 0.1 to 1 s.
7. The method of claim 1, wherein the radicals or ions comprise H and SH.
8. The method of claim 1, wherein radicals or ions are generated using corona discharge.
9. The method of claim 1, wherein radicals or ions are generated using glow discharge.
10. The method of claim 1, wherein radicals or ions are generated using dielectric barrier discharge, pulsed corona, or micro-discharges.
11. The method of claim 1, comprising using a gliding arc in a tornado reactor.

12. The method of claim 1, comprising using a low current <5 A arc or glow discharge at pressures between 0.01 MPa and 1 MPa.
13. The method of claim 1, wherein H_2S dissociation results in formation of H_2S_2 .
14. The method of claim 1, wherein a plasma is used to create ions.
15. The method of claim 14, wherein the ions are negatively charged sulfur ions.
16. The method of claim 14, wherein a DC glow discharge is combined with a biased voltage to create the ions.
17. The method of claim 14, wherein the residence time in the reaction zone ranges from about 0.01 to 10 s.
18. The method of claim 17, wherein the residence time in the reaction zone ranges from about 0.01 to 1.0 s.
19. A method of H_2S dissociation comprising:
 - providing a plasma reactor, said plasma reactor comprising:
 - a wall defining a reaction chamber;
 - an outlet;
 - a reagent inlet fluidly connected to the reaction chamber for creating a vortex flow in said reaction chamber;
 - a first electrode; and
 - a second electrode connected to a power source for generation of a sliding arc discharge in the reaction chamber;
 - introducing H_2S into said reaction chamber in a manner which creates a vortex flow in the reaction chamber; and
 - dissociating said H_2S using a plasma assisted flame to create ions, with the dissociation being initiated at a temperature of less than 1900 K.

20. The method of claim 19, wherein the residence time in the reaction chamber for dissociation ranges from about 0.01 to 10 s.
21. The method of claim 20 wherein the residence time in the reaction chamber for dissociation ranges from about 0.1 to 1.0 s.
22. The plasma reactor of claim 19, wherein said vortex flow is a reverse vortex flow.
23. The method of claim 22, wherein said reverse vortex flow is created by feeding H₂S into said reaction chamber in a direction tangential to the wall of said reaction chamber.
24. The method of claim 23, wherein said plasma reactor comprises first and second ends, the reagent inlet is located proximate to the first end, the reactor further comprises a second inlet fluidly connected to the second end of said reactor, and wherein at least some of said H₂S is provided to the reaction chamber via the second inlet.
25. The method of claim 24, wherein the plasma reactor comprises a movable second electrode and said method further comprises the steps of igniting an electrical arc with said movable second electrode in a first position, and moving the movable second electrode to a second position farther from said first electrode than said first position for operation of said reactor.

1 / 6

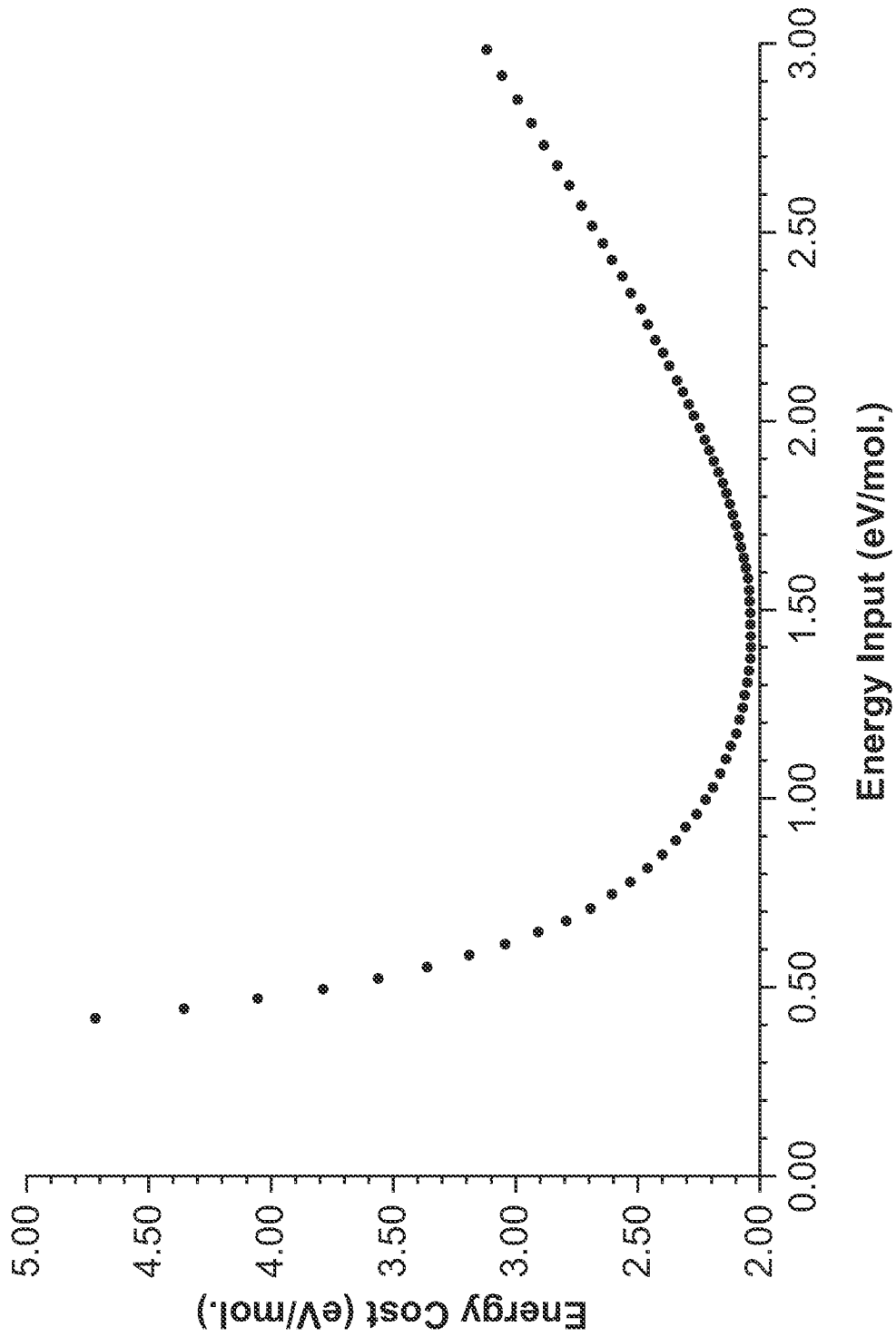


FIG. 1

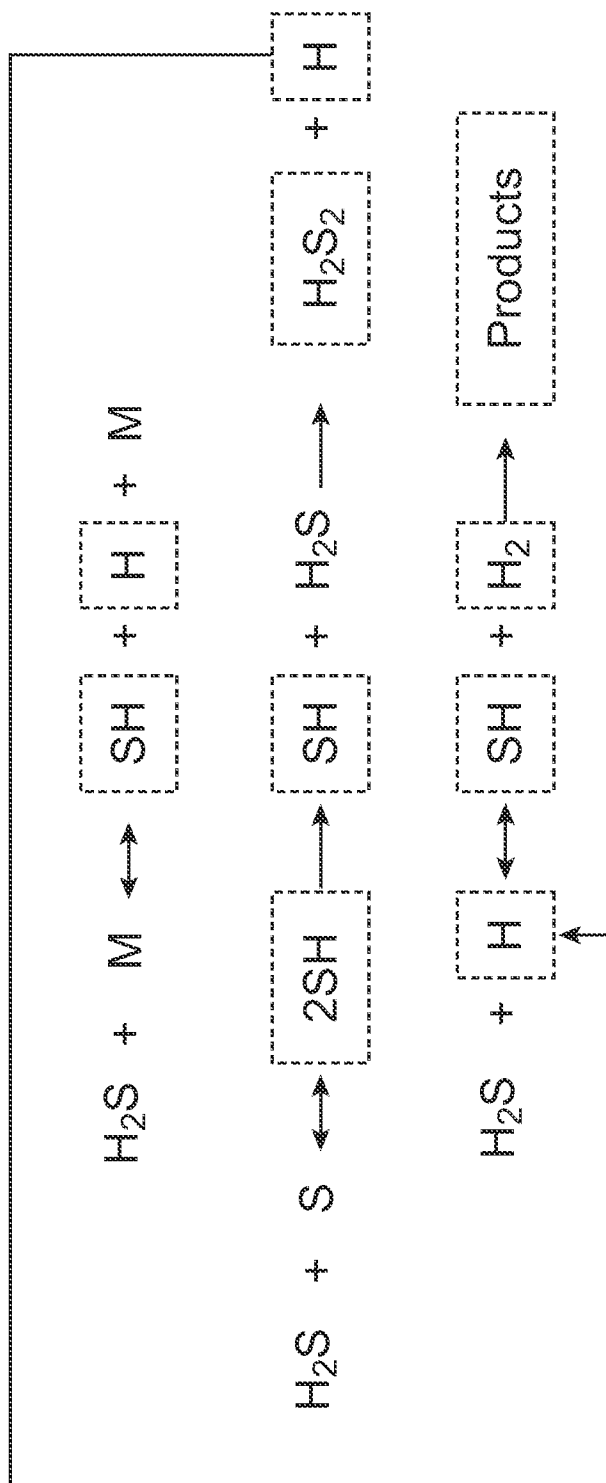


FIG. 2

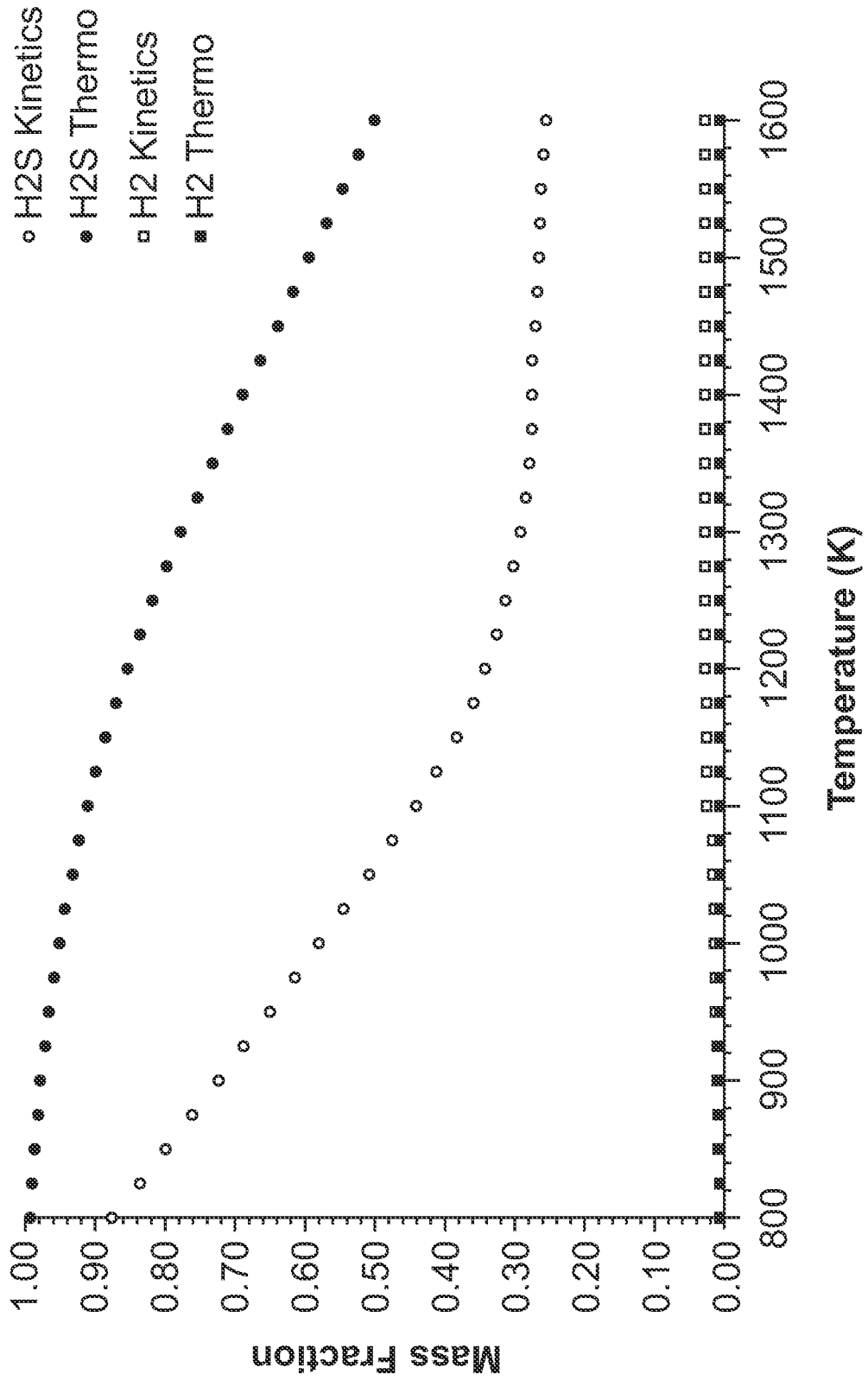


FIG. 3

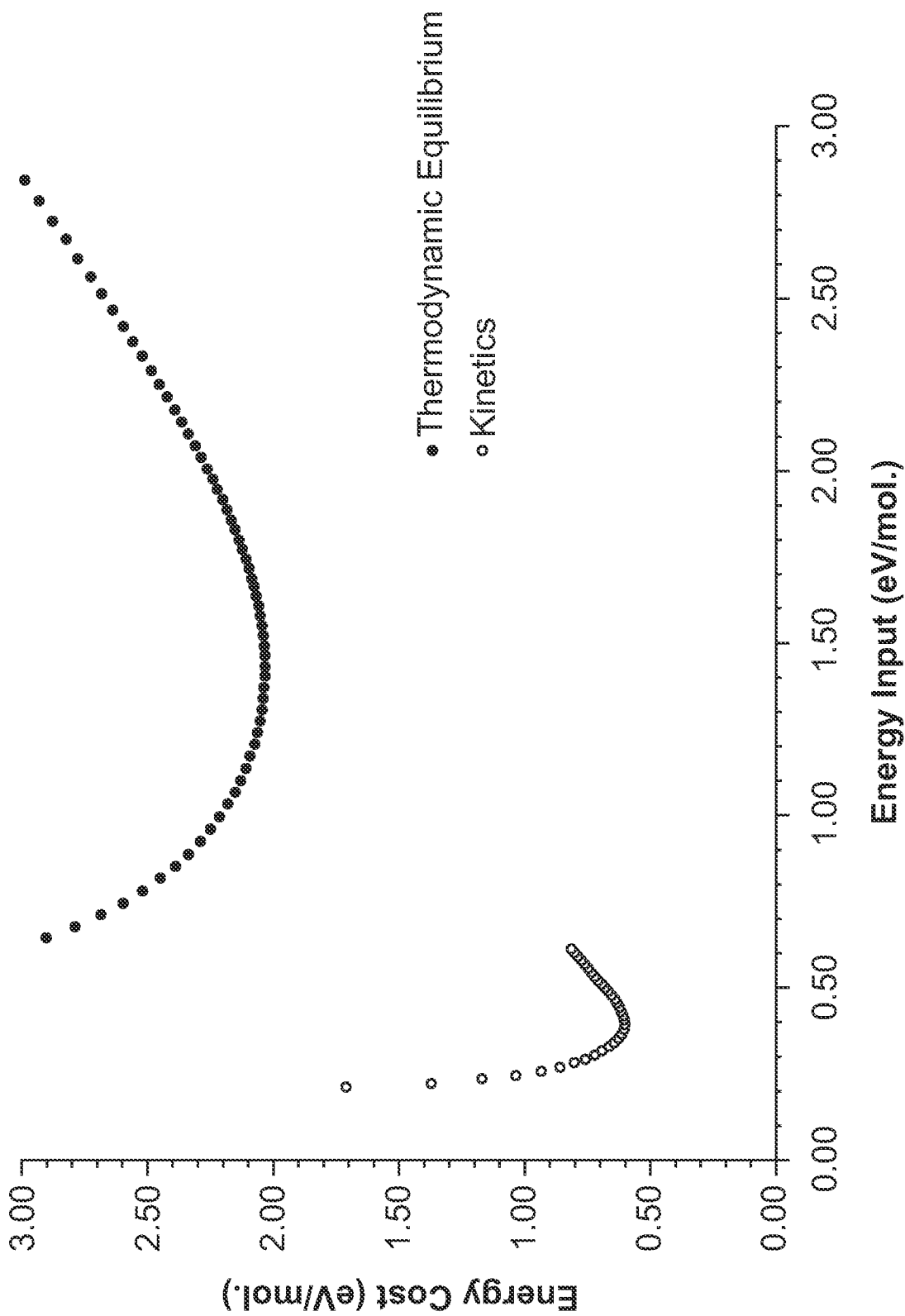


FIG. 4

5 / 6

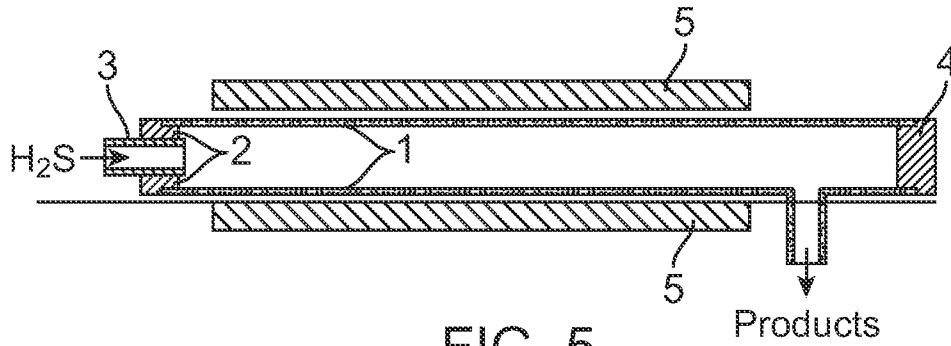


FIG. 5

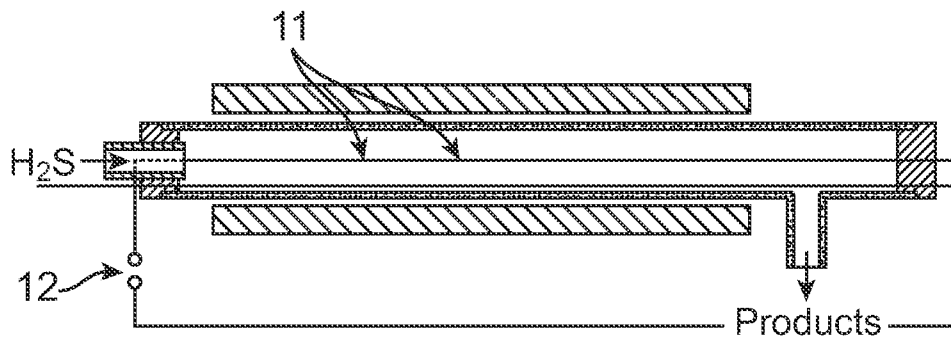


FIG. 6

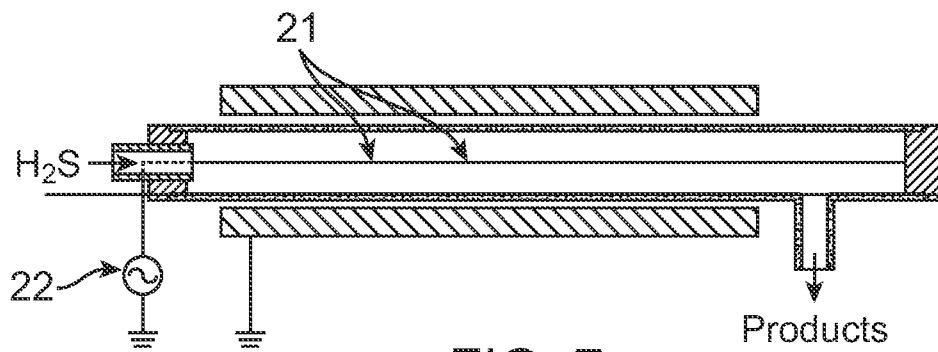


FIG. 7

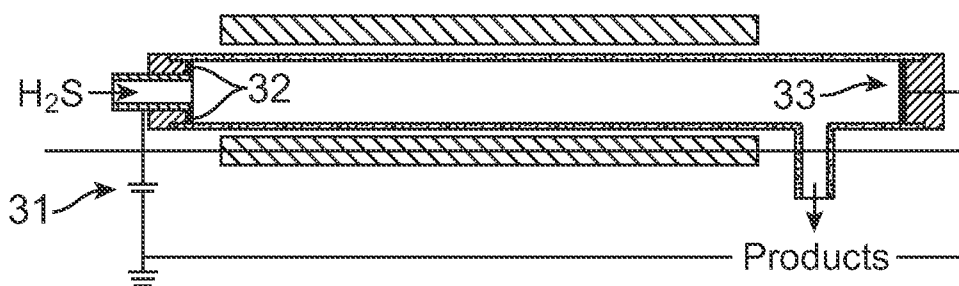


FIG. 8

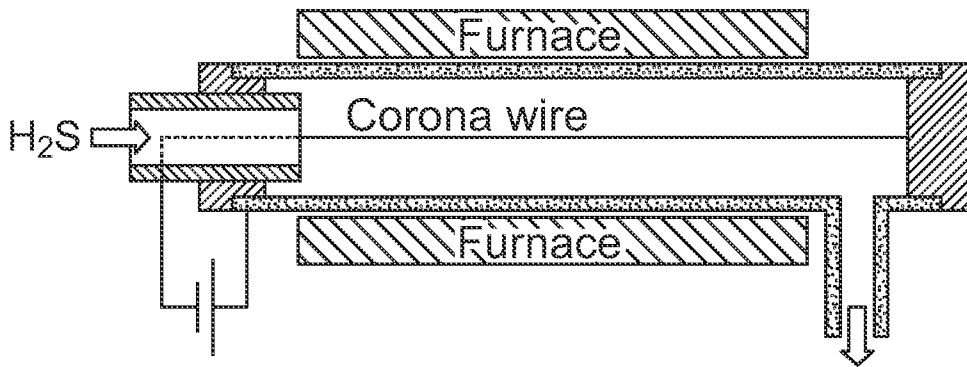


FIG. 9

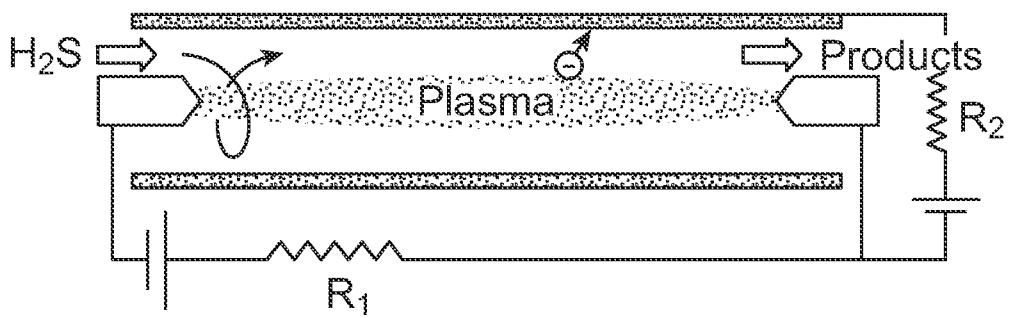


FIG. 10