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(54) COMBUSTION APPARATUS

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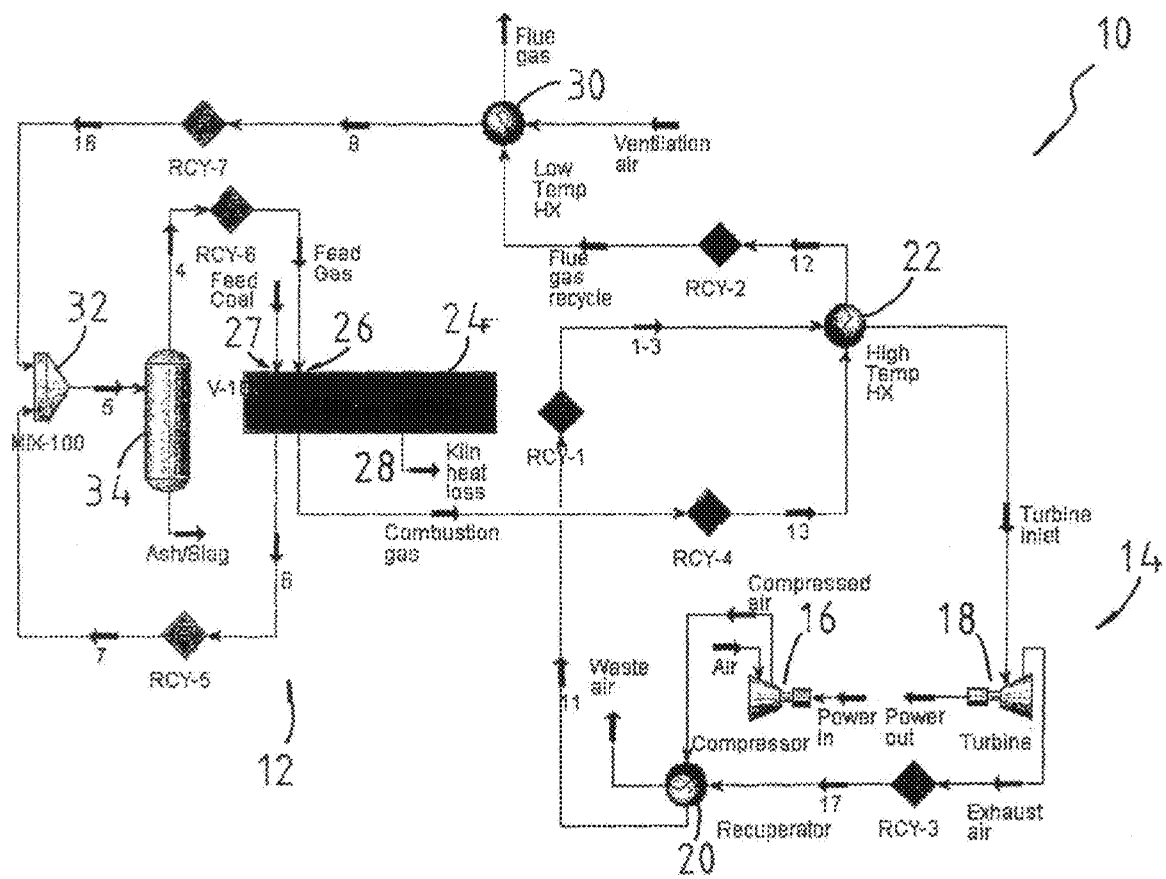
(57) **ABSTRACT**

Provided is a combustion apparatus (**10**) for combusting one or more combustible media such as mine methane and waste coal. The apparatus has a combustion unit (**24**) with a fuel inlet (**26**,**27**) through which the combustible media enters the combustion unit for combustion therein, and a gas outlet (**28**) for gases formed during combustion to flow out of the combustion unit to provide heat energy to a downstream apparatus such as a turbine engine(**14**). The combustion unit is arranged to provide a volatile release reaction, a char combustion reaction and a gas phase reaction



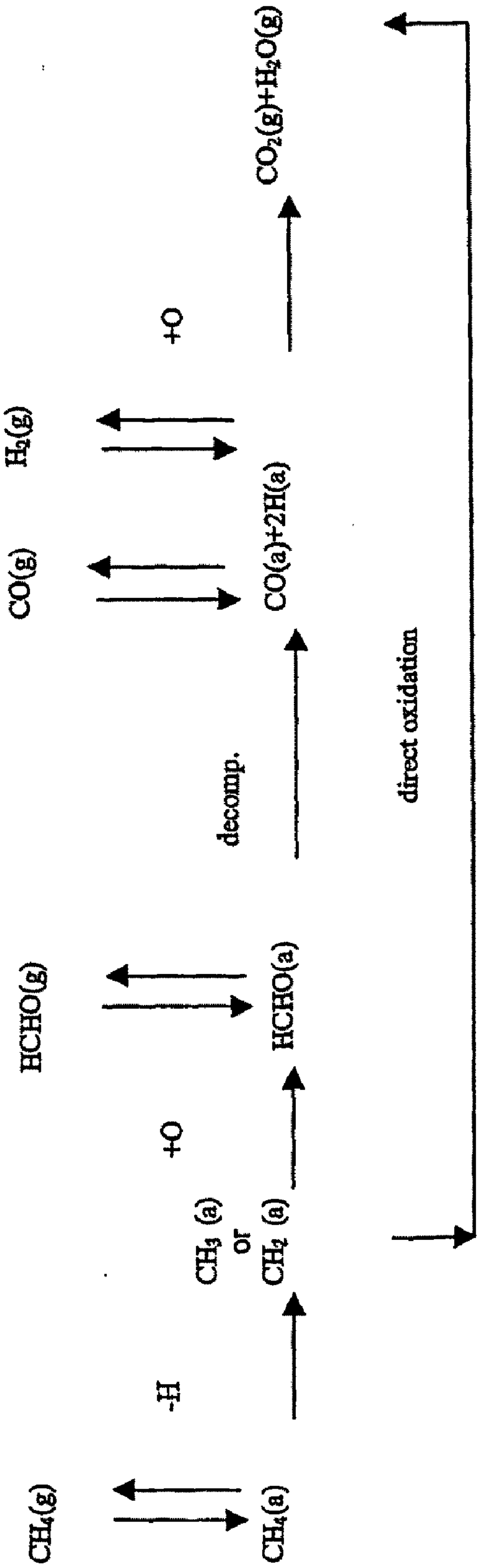

CH4(g)
CH4(a)
-H
CH3 (a)
or
CH2 (a)
+O
HCHO(g)
HCHO(a)
decomp.
direct oxidation
CO(g)
CO(a)+2H(a)
H2(g)
+O
CO2(g)+H2O(g)

FIG. 1

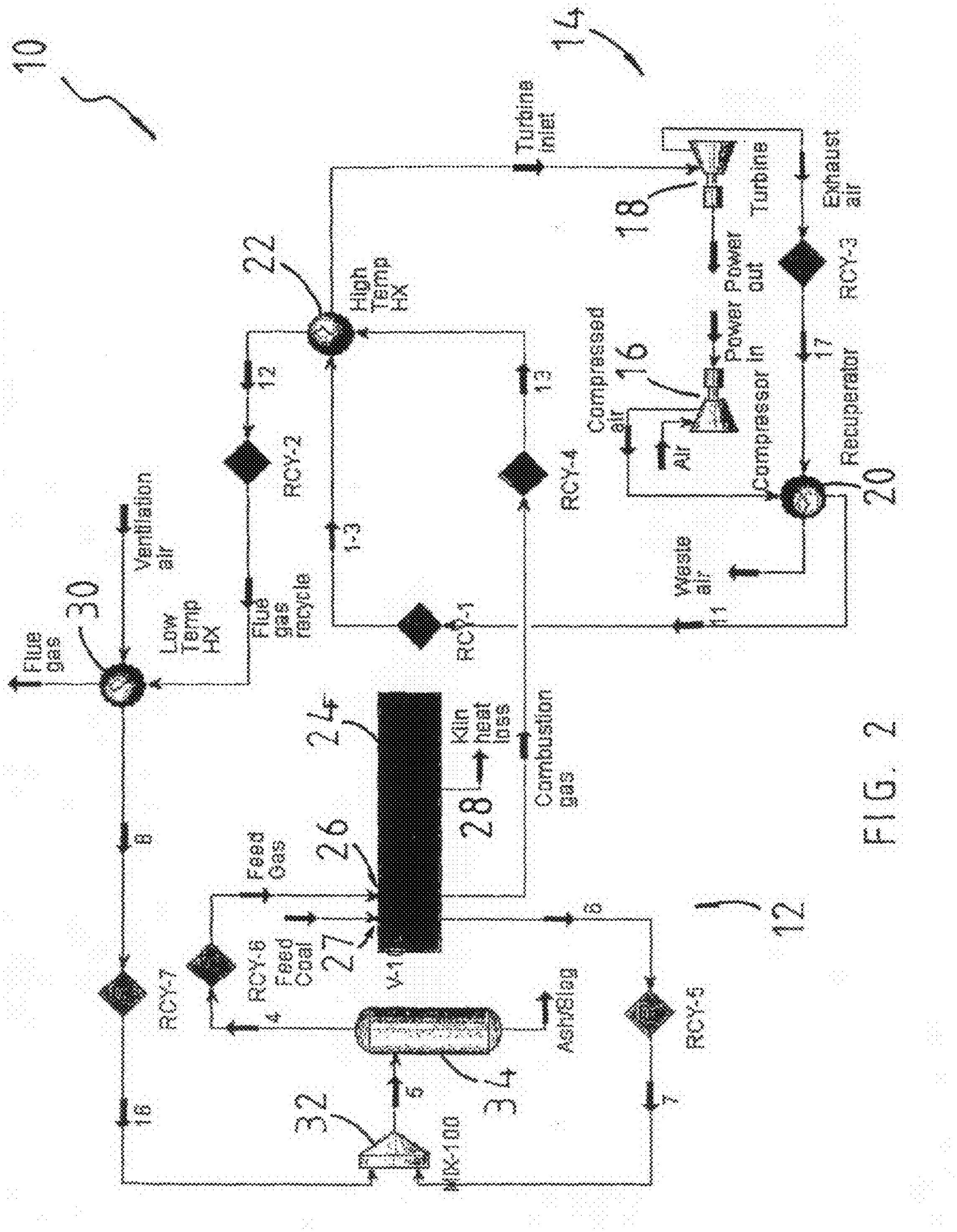

10
14
Turbine inlet
Exhaust air
Turbine
18
Power out
22
High Temp HX
Compressed air
16
Power In
Compressor
Air
RCY-3
17
Recuperator
20
12
RCY-2
13
RCY-4
1-3
Ventilation air
Waste air
11
RCY-1
Flue gas recycle
Low Temp HX
30
Flue gas
24
Kiln heat loss
28
Combustion gas
8
Feed Gas
26
Feed Coal
27
V-1
RCY-6
RCY-7
4
Ash/Slag
RCY-5
12
34
32
5
16
7
MIX-100

FIG. 2

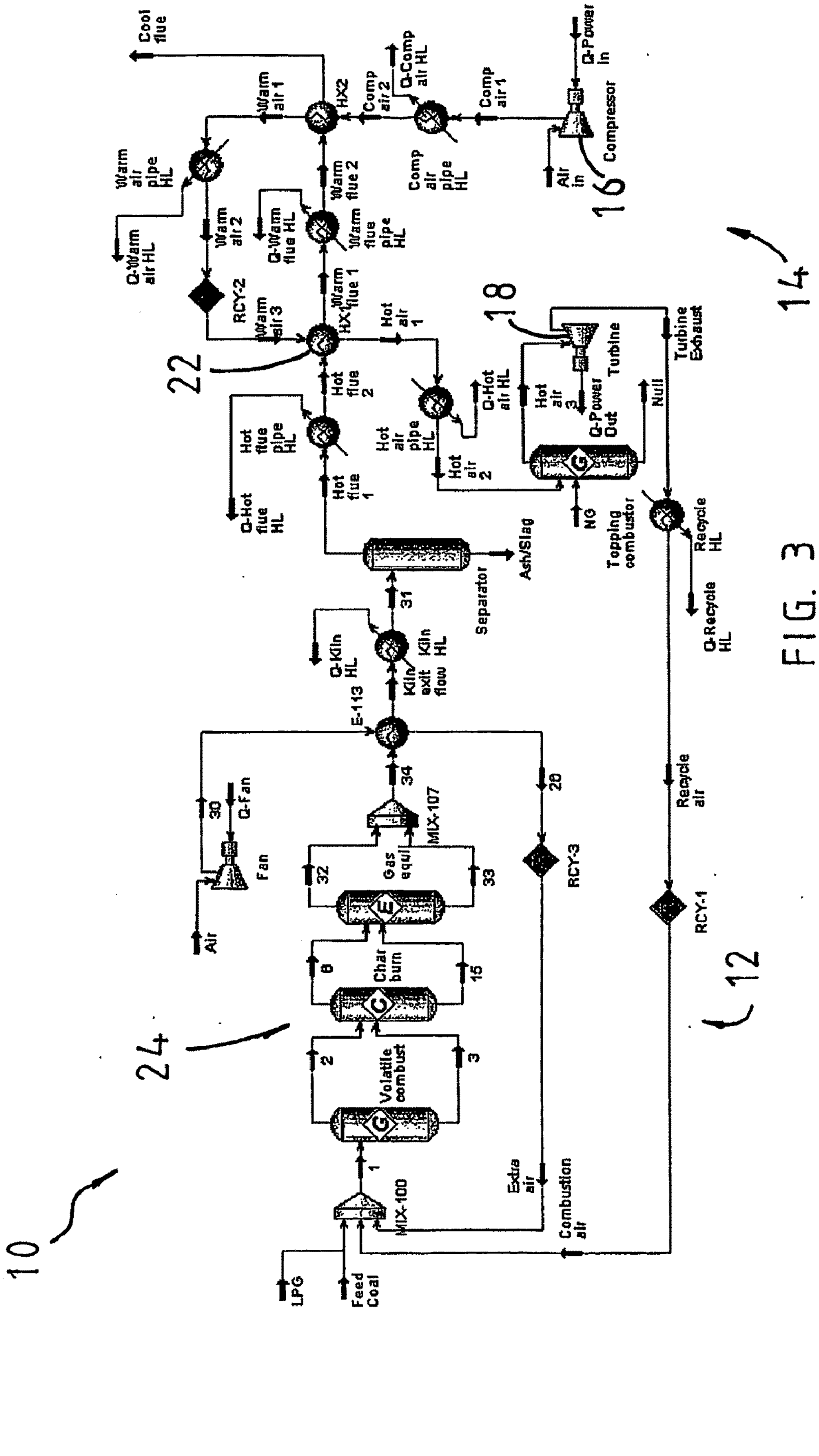

10
LPG
Feed Coal
MIX-100
Combustion air
Extra air
1
Volatile combust
2
3
24
Char burn
6
15
Gas equil
32
33
MIX-107
34
Air
Fan
30
Q-Fan
E-113
28
RCY-3
Kiln exit flow
Kiln HL
Q-Kiln HL
31
Separator
Ash/Slag
Hot flue 1
Hot flue pipe HL
Q-Hot flue HL
Hot flue 2
22
HX1
Warm air 3
RCY-2
Warm air 2
Q-Warm air HL
Warm air pipe HL
Warm flue 1
Warm flue pipe HL
Q-Warm flue HL
Warm flue 2
HX2
Warm air 1
Cool flue
Comp air 2
Q-Comp air HL
Comp air pipe HL
Comp air 1
Compressor
Q-Power In
Air in
16
Hot air 1
Hot air pipe HL
Q-Hot air HL
Hot air 2
NG
Topping combustor
Hot air 3
Q-Power Out
Turbine
18
Null
Turbine Exhaust
Recycle HL
Q-Recycle HL
Recycle air
RCY-1
12
14

FIG. 3

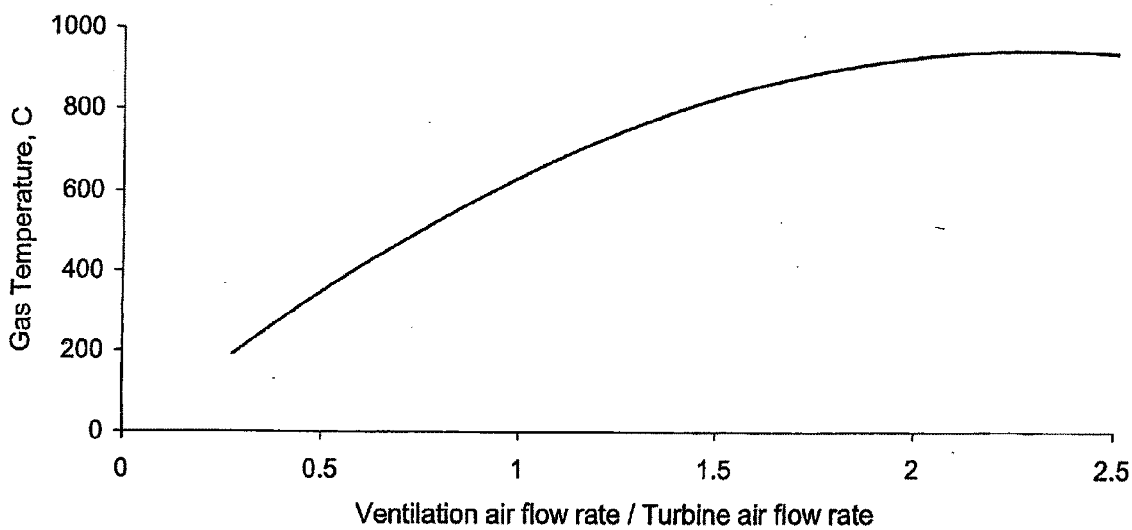

1000
800
600
400
200
0
Gas Temperature, C
0
0.5
1
1.5
2
2.5
Ventilation air flow rate / Turbine air flow rate

FIG. 4

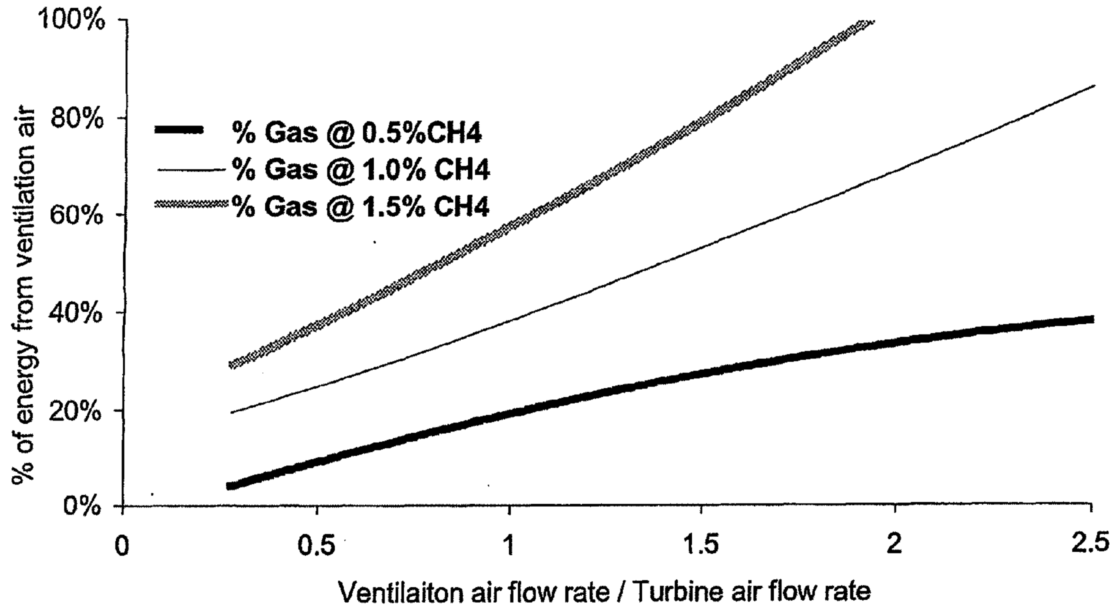

100%
80%
60%
40%
20%
0%
% of energy from ventilation air
% Gas @ 0.5%CH4
% Gas @ 1.0% CH4
% Gas @ 1.5% CH4
0
0.5
1
1.5
2
2.5
Ventilaiton air flow rate / Turbine air flow rate

FIG. 5

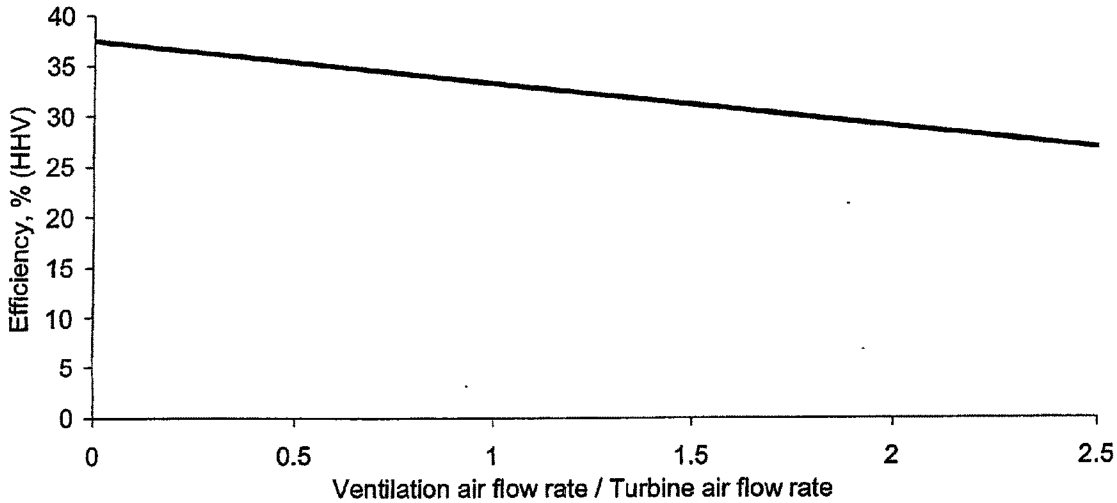

40
35
30
25
20
15
10
5
0
Efficiency, % (HHV)
0
0.5
1
1.5
2
2.5
Ventilation air flow rate / Turbine air flow rate

FIG. 6

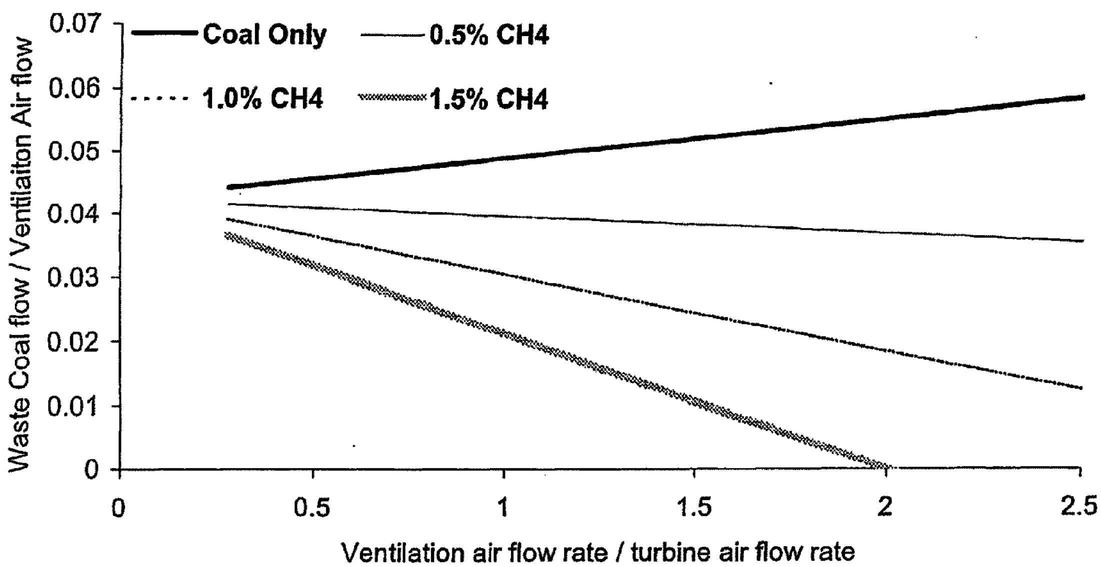

0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Coal Only
0.5% CH4
1.0% CH4
1.5% CH4
Waste Coal flow / Ventilaiton Air flow
0
0.5
1
1.5
2
2.5
Ventilation air flow rate / turbine air flow rate

FIG. 7

# COMBUSTION APPARATUS

## FIELD OF INVENTION

**[0001]** THIS INVENTION relates to a combustion apparatus for combusting fuel media and in particular but not limited thereto a thermodynamic system having a combustion apparatus for combusting one or more relatively low grade fuel media, and a thermodynamic apparatus adapted to receive heat energy from the combustion apparatus.

## BACKGROUND OF THE INVENTION

**[0002]** Known thermodynamic apparatus general have a turbine with a built in combustion chamber. The combustion chamber is configured to burn a relative high grade fuel such as high yielding coal. Consequently there is abundance of relatively low grade resources such as low grade coal, biomass, municipal waste and the like, which are unused and considered waste materials. These waste materials are normally left in the open and generally looked upon as environmental scars.

**[0003]** Coal mine vVentilation air methane ($CH_4$) contributes approximately 64% of coalmine $CH_4$ emissions, and is difficult to use as an energy source, as the air volume is large and the methane resource is dilute and variable in concentration and flow rate. The low concentration of methane in mine ventilation air is a major problem, and mitigation requires either treatment in its dilute state, or concentrating up to levels that can be used in conventional methane fueled engines. Effective technology for increasing the concentration of methane is not available but it is being developed, and most work has focussed on the oxidation of very low concentration methane. These processes are complex and not cost effective.

**[0004]** Methane is a homogonous gas that requires large amounts of heat energy to oxidise at low concentrations <1% in air. This is normally accomplished by exposing low concentration to very high temperatures >1000° C. for 0.3 of a second. The combustion mechanism of methane may be overall represented by the following equation:

$$CH_4+2O_2=CO_2+2H_2O\ DH_{(298)}=-802.7\text{ kJ/mol}$$

**[0005]** This is a gross simplification, since the actual reaction mechanism involves many free radical chain reactions. The combustion of methane may produce CO or $CO_2$ depending on the air/methane ratio by the reactions.

$$CH_4+2O_2=CO_2+2H_2O$$

$$CH_4+3/2O_2=CO+2H_2O$$

Other reactions may also be present, such as:

$$CH_4+H_2O=CO+3H_2$$

$$2H_2+O_2=2H_2O$$

$$CO+H_2O=CO_2+H_2$$

**[0006]** Studies of the kinetic mechanisms of methane catalytic combustion are quite involved when multi-step surface reactions are considered. As described in the reference entitled Numerical Studies of Methane Catalytic Combustion inside a Monolith Honeycomb Reactor Using Multi-Step Surface Reactions, Combustion Science and Technology 2000; 150:27-58, the authors used 23 different reactions in their numerical study of methane catalytic combustion in a monolith honeycomb reactor. The situation becomes even more complicated when considering heterogeneous reactions. FIG. **1** shows a possible mechanism for methane catalytic oxidation proposed in the article entitled Methane oxidation over noble metal catalysts as related to controlling natural gas vehicle emissions, In: Silver JE and Summers (Eds), Catalytic control of air pollution: mobile and stationary sources, 202" National Meeting of the American Chemical Society, 25-30 Aug. 1991, ACS Series, Vol. 495, pp 12-25. In this Figure, "a" indicates an adsorbed phase and "g" a gas phase.

**[0007]** In general, catalytic combustion is a multi-step process involving diffusion to the catalyst surface, adsorption onto the catalyst, reaction, and desorption of the product species from the catalyst surface and diffusion back into the bulk. Most kinetic investigations have been performed in conditions where methane is present in excess of the stoichiometric ratio. The result of this is that the reaction has generally been found to be independent of the oxygen concentration. The reaction order with respect to methane is generally found to be between 0.5 and 1. The activation energies are quite variable, being dependent on the catalyst and operating temperature. Platinum and palladium are generally accepted as the most active catalysts for low temperature total oxidation. Other catalysts have been tested but are less active.

**[0008]** Accordingly, there is a need to address one or more of the areas of existing and developing technologies for coal mine ventilation air methane ($CH_4$) mitigation and utilisation, particularly the field of $CH_4$ oxidation, with respect to technical feasibility, engineering applicability, and potential to recover the heat released from $CH_4$ oxidation.

## OBJECT OF THE INVENTION

**[0009]** An object of the present invention is to provide a combustion apparatus which will at least reduce one or more of the above prior art disadvantages.

**[0010]** A further object of the present invention is to provide an indirect fired thermodynamic system which may be adapted to use relatively low grade fuel resources.

## SUMMARY OF THE INVENTION

**[0011]** In one aspect therefore the present invention resides in a combustion apparatus for combusting one or more combustible media. The apparatus comprises a combustion unit having a fuel inlet adapted to receive said one or more combustible media for combustion therein, and a gas outlet adapted for combustion gas formed during combustion to flow out of said combustion unit to provide heat energy to a down stream apparatus. The combustion unit is arranged to provide a volatile release reaction, a char combustion reaction and a gas phase reaction.

**[0012]** It is preferred that the fuel inlet is configured to receive gaseous and solid combustible media, and the apparatus includes a preheating arrangement adapted to preheat the gaseous medium or any of said gaseous media.

**[0013]** It is also preferred that the heating arrangement is arranged to receive the combustion gas before or subsequent to reaching said down stream apparatus.

**[0014]** The apparatus may have a mixing unit arranged upstream of said combustion unit. The mixing unit is adapted to mix the gaseous fuel media and solid waste fuel media from said combustion unit, and the mixed media are then conveyed to the combustion unit.

**[0015]** Preferably, said one or more fuel media include a low grade fuel in the form of low grade coal, biomass or municipal waste.

**[0016]** More preferably, said combustion unit is a kiln. Desirably, said combustion unit is a rotary kiln.

**[0017]** Said down stream apparatus may be a thermodynamic apparatus comprising a compressor, an expander and heat exchange means connecting the compressor and the expander in an open or closed cycle, and a compressible working medium arranged to flow in the open or closed cycle. In preference, said combustion gas is arranged to heat said working medium at the heat exchange means.

**[0018]** The expander may release exhaust gas and the exhaust gas is conveyed to the combustion unit or the mixing unit for heating media therein.

**[0019]** Desirably, said solid fuel medial is a low grade coal and the kiln is adapted to convert said coal into flue gas and ash which can be formed as a by-product such as closed or open cell spherical nodules for lightweight building materials. Limestone may be added to convert any sulphur dioxide to calcium sulphate. This should at least reduce the amount of low grade coal which poses environmental problems.

**[0020]** In one form, said gaseous fuel media is methane gas. This is specially advantageous as very low concentration methane from an underground mine can be put into good use while at the same time removing it from the mine.

**[0021]** In one form the heat exchange means includes a first heat exchanger arranged for receiving said combustion gas from said combustion unit.

**[0022]** The combustion apparatus according to the present invention thus not only mitigates mine methane and utilises waste coal, but also to recover waste energy for power generation. The waste coal could be combusted with mine methane from both drainage gas and ventilation air inside a rotating kiln, in particular, drainage gas flame could play a role in stabilising combustion process inside the kiln. The rotary kiln has an "open structure" which earmarks it for mass burn applications involving bulky and "gooey" fuels and wastes.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0023]** In order that the present invention be more readily understood and be put into practical effect, reference will now be made to the accompanying drawings wherein:—

**[0024]** FIG. **1** is a schematic diagram of known reaction processes in methane catalytic oxidation;

**[0025]** FIG. **2** is a schematic diagram of an embodiment of the thermodynamic system according to the present invention;

**[0026]** FIG. **3** is a schematic diagram of another embodiment of the thermodynamic system according to the present invention;

**[0027]** FIG. **4** is a specific form of the apparatus shown in FIG. **3** being adapted to use low grade coal and waste methane as fuel sources;

**[0028]** FIG. **5** is a graph showing variations in gas temperatures with flow ratios;

**[0029]** FIG. **6** is a graph showing percentage variations in energy versus flow ratios;

**[0030]** FIG. **7** a graph showing variations in efficiency versus flow ratios; and

**[0031]** FIG. **8** is a graph showing variations in the ratios waste coal to ventilation air versus flow ratios.

## DETAILED DESCRIPTION OF THE INVENTION

**[0032]** Referring initially to FIG. **2** there is shown a block diagram of a thermodynamic system **10** according to an embodiment of the present invention. The system **10** has a combustion apparatus **12** and a closed cycle thermodynamic apparatus **14**. In this embodiment the apparatus **14** is for powering a turbine engine.

**[0033]** The apparatus **14** has a compressor **16** for compressing a working medium which in this case is air. The compressed air from the compressor **16** is preheated in a recuperator **20** with exhaust air from a turbine **18**. The preheated compressed air is then conveyed to a high temperature heat exchanger **22** from which it returns to the turbine **18** where it expands to provide energy (power output) to perform work at the turbine **18**. The turbine in this case turns a generator (not shown) to generate electricity.

**[0034]** The combustion apparatus **12** has a combustion unit in the form of a rotary kiln **24** having an inlet **26** with a port for feed gas and another port **27** for feed coal.

**[0035]** Combustion gas in the combustion unit **24** travels from the outlet **28** to provide heat energy to the high temperature heat exchanger **22** for heating the compressed gas. The combustion gas then travels further to a low temperature heat exchanger for preheating ventilation air or drain air from a coal mine or any location in which methane is generated, before being put to flue. The preheated ventilation air is mixed with solid wastes from the kiln **24** at a mixing unit **32** and the mixed materials are then subject to further heating at a recuperator **34** prior to feeding into the combustion unit **24**.

**[0036]** The combustion unit **24** represents the reactions occurring between feed coal and pre-heated feed gas, including volatile release, char combustion and gas phase reaction. Char burnout is estimated using an empirical correlation dependent on the temperature of reaction, as given in the equation below. This is for an arbitrary kiln and should be modified to correlate with experimental results for a specific kiln, operating conditions and feed coal. The product gas from the kiln is taken to be at equilibrium at the kiln exit. An estimate of heat loss from the kiln is determined from experimental data. Two products exit the kiln, one is a hot combustion gas and the other solid wastes comprising of char and ash. These are used to pre-heat the feed gas by mixing and re-separating the solids and gas;

$$X_C=-32+0.1168<T-2596E-5\times T^2$$

**[0037]** The net power output of the system **10** is calculated by subtracting the power requirements for the compressor and fan from the power generated by the turbine. The efficiency is determined by dividing the net power output by the sum of the calorific values of the feed coal and ventilation air. In the system shown the calculated efficiency is 26.1%, with the coal being 50% ash content (heating value 10.1 MJ/kg) and the ventilation air containing 0.37% methane

**[0038]** Referring to FIG. **3**, the second embodiment of the thermodynamic apparatus **10** as shown is substantially similar to that shown in FIG. **2** and the same numeral references are used for the same components. Some of the components shown on the schematic diagram are symbolic only and are used to break the process up into sub-processes that can be more readily shown. For example, there are 8 units on the left of the Figure that are used in the model to replicate distinct processes that occur in the real kiln. A description of how the model describes the kiln through these separate unit operations is given below.

**[0039]** MIX-100' is a mixer that combines all the feeds to the kiln, namely air streams, coal and liquefied petroleum gas (LPG);

**[0040]** 'Volatile combust' is a reactor that transfers the volatile component of the coal into the gas phase and allows reaction of the volatiles with the other gases. Volatile release is typically the first stage of coal combustion and is the only stage likely to compete with the LPG in the consumption of oxygen;

**[0041]** 'Char burn' is a reactor that estimates the proportion of the coal char that will react with the remaining oxygen given the reaction temperature, where the temperature and proportion of char burnt are calculated iteratively. A quadratic expression is used to estimate the percentage of the char burnt based on the peak temperature reached during reaction, as given below where $X_C$ is the percent of char combusted and T is the resultant temperature in Kelvin. The equation is entirely empirical and was designed on the basis that the conversion will be low at low temperatures (~0% at 300K) and approach 100% at 2000K. It is for an arbitrary kiln and should be modified to correlate with experimental results for a specific kiln, operating conditions and feed coal;

$$X_C=-32+0.1168<T-2596E-5\times T^2$$

**[0042]** 'Gas equil' is a reactor that allows the gases to react so that an equilibrium composition and temperature at the exit of the kiln is calculated. This will only be a significant operation when the feeds to the kiln are close to stoichiometric ratios, so carbon monoxide and hydrogen may be produced in small quantities. Under typical combustion conditions, the gases will be fully oxidised to carbon dioxide and water vapour;

**[0043]** 'MIX-107' is a mixer that recombines solid and gas phases;

**[0044]** 'E-113' is a heat exchanger that transfers some heat from the kiln to preheat air that is being blown through the outer jacket of the kiln to be used as extra combustion air in the kiln;

**[0045]** 'Kiln HL' is a fictional heat exchanger that represents the heat loss from the kiln and associated pipework to the atmosphere. This can be used to adjust the exit temperature of the kiln to match experimentally acquired values; and

**[0046]** 'Separator' represents the separation of the solid materials from the kiln product gases at the exit of the kiln.

**[0047]** The indirectly fired turbine system constitutes the right half of the process diagram. This is comprised of two heat exchangers that transfer heat from the kiln product gas to compressed air, a topping combustor to heat the air to the required temperature and a turbine-compressor set (shown as a separate turbine and compressor units). The diagram also includes a number of fictional heat exchangers that are used to represent heat losses from pipework and unit items of equipment. The topping combustor burns methane in the compressed air to maintain the turbine inlet temperature at the target temperature. The net power output of the system is calculated by subtracting the power requirements for the compressor and fan from the power generated by the turbine.

**[0048]** By inputting measured values of feed flows, temperatures and gas compositions measured, it can tune the model to identify the heat losses for the major components, the performance of the rotating plant and the unknown flow rates using the model. Besides allowing verification of the system performance and identifying flaws in the experimental apparatus, the model can then be used as a tool for predicting the performance of the experimental plant under different operating conditions and developing designs for improved configurations.

**[0049]** The combustion unit **24** of the apparatus **12** is in the form of a rotary kiln adapted to receive low grade coal which has been ground to a size about 6-8 mm. The rotary kiln **24** is also designed so that the low grade coal has a relatively long residence time therein and a relatively large surface area of high temperatures, for ensuring combustion of very low concentration mine methane.

**[0050]** The apparatus **24** shown in FIGS. **2** and **3** can therefore be utilised to burn reject coal (low grade coal) and waste mine methane.

**[0051]** The ash from the burnt coal can be processed so that it is converted into a useful by-product such as closed or open cell spherical nodules ideal for manufacture of lightweight building materials and gravel substitutes. In this manner, little or no fly ash or slag is produced from combustion of low grade coal with extremely high ash contents.

**[0052]** Limestone can be added to convert any sulphur compound to calcium sulphate.

**[0053]** Greenhouse benefits can be maximised by sizing the plant to use all the mine ventilation air and rejects. This utilises carbonaceous waste that may eventually become carbon dioxide emissions by spontaneous combustion if stockpiled on the surface. Having separate flow paths provides the system with the flexibility to vary the proportion of ventilation air to gas turbine flow rate. This is managed by setting the temperature at which the gas is exhausted from the high temperature heat exchanger. FIG. **4** shows the ratio of ventilation air to gas turbine flow rate as a function of the primary heat exchanger exit temperature. This value has a practical range for 0.5 to 2.5, with the minimum value set by the energy value of the waste coal.

**[0054]** Changing the kiln/turbine flow ratio alters the proportion of energy derived from ventilation air compared to the waste coal and this is illustrated by FIG. **5** for a number of different methane concentrations. FIG. **5** also demonstrates how the system flexibility allows it to be used from a range of 0% to 100% ventilation air. This allows the system performance to be matched to the mine's requirements. In this figure, variation in methane concentration occurs in a plane parallel to the vertical axis of the plot. Variability in methane concentration is compensated for by an increase in coal flow rate and not by a change to the turbine/kiln flow ratio.

**[0055]** If full utilisation of rejects is not the primary consideration, then by increasing the kiln/turbine flow ratio, the size, output and, hence, capital cost of the gas turbine can be reduced. As the HTHx and gas turbine are related by size, and are the main capital cost items for the system, the overall capital cost of the system is reduced for a given ventilation flowrate. However, FIG. **6** shows that increases to the kiln/turbine flow ratio result in a decrease in the efficiency system because more energy travels out of the kiln recuperator for a given amount of electricity generated.

**[0056]** Alternatively, if maximum utilisation of waste coal is a priority, the flow rate of coal can also be maximised by changing the kiln/turbine ratio. FIG. **7** shows the mass ratio of coal to ventilation air with changes to the kiln/turbine flow ratio. It demonstrates that the facility can also be operated in a coal only manner for applications where no ventilation air is available or the operation of the mine has ceased. This system is a candidate for remediation of waste coal stockpiles from older mines.

**[0057]** Whilst the above have been given by way of illustrative examples of the present invention many variations and modifications thereto will be apparent to those skilled in the art without departing from the broad ambit and scope of the invention as herein set forth in the following claims.

**1-14**. (canceled)

**15**. A combustion apparatus for one or more combustible media, comprising a combustion unit having a fuel inlet adapted to receive said one or more combustible media for combustion therein, a gas outlet adapted for combustion gas or gases formed during combustion to flow out of said combustion unit to provide heat energy to a downstream apparatus, and a preheating arrangement adapted to preheat the combustible media and arranged to receive the combustion gas or gases before or subsequent to said gas or gases reaching said down stream apparatus; the combustion unit being arranged to provide a volatile release reaction, a char combustion reaction and a gas phase reaction.

**16**. The apparatus according to claim **15** wherein said one or more combustible media include gaseous fuel media and solid waste fuel media, and the apparatus further comprising a mixing unit arranged upstream of said combustion unit, the mixing unit being adapted to mix the gaseous fuel media and the solid waste fuel media to be conveyed to said combustion unit.

**17**. The apparatus according claim **15** wherein said downstream apparatus is a thermodynamic apparatus comprising a compressor, an expander and heat exchange means connecting the compressor and the expander in an open or closed cycle, and a compressible working medium arranged to flow in the open or closed cycle.

**18**. The apparatus according claim **16** wherein said downstream apparatus is a thermodynamic apparatus comprising a compressor, an expander and heat exchange means connecting the compressor and the expander in an open or closed cycle, and a compressible working medium arranged to flow in the open or closed cycle.

**19**. The apparatus according to claim **17** wherein said combustion gas or gases are arranged to heat said working medium at the heat exchange means.

**20**. The apparatus according to claim **17** wherein the expander is arranged to release exhaust gas and the exhaust gas is conveyed to the combustion unit or the mixing unit for heating media therein.

**21**. The apparatus according to claim **19** wherein the expander is arranged to release exhaust gas and the exhaust gas is conveyed to the combustion unit or the mixing unit for heating media therein.

**22**. The apparatus according to claim **17** wherein the heat exchange means includes a first heat exchanger arranged for receiving said combustion gas from said combustion unit.

**23**. The apparatus according to claim **15** wherein the fuel inlet is configured to receive gaseous and solid combustible media.

**24**. The apparatus according to claim **15** wherein said one or more combustible media include a relatively low grade fuel in the form of relatively low grade coal, and/or biomass and/or municipal waste.

**25**. The apparatus according to claim **16** wherein said combustion unit is a kiln or a rotary kiln.

**26**. The apparatus according to claim **25** wherein said solid fuel medial is a relatively low grade coal and the kiln or rotary kiln is adapted to convert said coal into flue gas and ash for forming a by-product.

**27**. The apparatus according to claim **25** wherein said gaseous fuel media are methane gas.

**28**. The apparatus according to claim **26** wherein said gaseous fuel media are methane gas.

**29**. The apparatus according to claim **27** wherein the methane gas is mine methane and the low grade coal is waste coal could be combusted with mine methane.

**30**. The apparatus according to claim **25** wherein the rotary kiln is configured with an "open structure" for mass burning applications involving bulky and "gooey" fuels and wastes.

* * * * *