

GAS-STEAM EFFICIENT COGENERATION PROCESS AND SYSTEM BASED ON BIOMASS GASIFICATION AND METHANATION

TECHNICAL FIELD

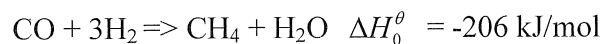
[0001] The invention relates to the field of biomass energy, and more particularly to a method and system for cogenerating gas-steam based on gasification and methanation of biomass such as rice husk, straw, and sawdust.

BACKGROUND OF THE INVENTION

[0002] In recent years, with the development of economy and society, the demand of natural gas rapidly grows, so the natural gas will become the energy with fastest consumption growth in the 21st century. But the natural gas supply capacity of China relatively lags behind, resulting in the sharp contradiction between supply and demand of natural gas. Therefore, it is still necessary to expand resource supply by multi-channels and in multimode based on the existing resources of China to meet the increasing market demand. It is still necessary not only to develop domestic natural gas resources and introduce overseas natural gas resources, but also to make use of the abundant biomass resources in China to actively develop substitute natural gas made from biomass and relieve the tense situation of natural gas supply, which has strategic significance to the

realization of gradual replacement of the oil and gas resources, energy security, energy conservation and emission reduction.

[0003] Crude syngas generated from biomass gasification contains a lot of CO, H₂, CO₂, etc., and is not suitable for direct use as a city gas and a fuel for combined cycle power plant because of its low calorific value and CO toxicity. Natural gas is suitable for use as a city gas and a fuel for combined cycle power plant because of its high calorific value and non-toxicity. In the presence of a catalyst, CO and CO₂ can be completely converted to methane, which is the synthetic substitute natural gas (SNG). Main reaction of the methanation is as follows:



[0004] Based on the characteristics of strongly exothermic reaction of methanation, methanation reaction route is designed mainly considering reaction heat control and recovery. The reaction heat can reach about 20% of the calorific value of syngas, so efficiently recycling the heat is very critical for any methanation technology.

[0005] Increasingly more importance is attached to biomass integrated gasification combined cycle power generation technology (BIGCC) as a new clean and high efficient biomass power generation technology with high power generation efficiency and CO₂ emission reduction advantages.

[0006] This can not only solve the problem that biomass is not suitable for long distance transportation, and promote efficient and clean use of biomass, but also effectively relieve

the contradiction between supply and demand of natural gas using the existing natural gas pipeline at lower economic costs, which is a strong measure for comprehensive utilization of the biomass.

[0007] In the patent number CN101245262 titled “Gas-steam combined cycle system and process based on coal gasification and methanation”, the raw material is derived from non-renewable coal of low calorific value; the methanation reaction uses a molybdenum sulfide catalyst, so that the syngas conversion efficiency is low, processing capacity is limited greatly, and it is difficult for practical application. It is harder for large-scale application because of the complex design, complex structure and high manufacturing costs of the isothermal reactor, difficult mechanical amplification, difficult loading and unloading of catalyst etc. Besides, the reaction occurs in a isothermal reactor at 210-280°C, so it is difficult to produce high quality steam and efficiently recycle the reaction heat.

[0008] In the patent number CN100582201C titled “Combined System and Process for Producing Electricity-Substituted Natural Gas Based on Coal Gasification and Methanation”, the raw material is derived from non-renewable coal of low calorific value; the methanation reaction is carried out in a high-temperature reactor and a low-temperature reactor. This process has harsh requirements for catalyst, low heat exchange efficiency between the product gas and steam circulation system in the process, and low recovery efficiency of methanation reaction heat.

SUMMARY OF THE INVENTION

[0009] On the basis of comprehensive utilization of gasification of biomass at high temperature and high pressure and methanation in a circulating adiabatic fixed bed, the invention provides a method and system for cogenerating gas-steam. Meanwhile, the method can generate a large amount of superheated steam and substitute natural gas with high efficiency.

[0010] The technical scheme of the invention is that: a method for cogenerating gas-steam based on gasification and methanation of biomass comprises the following steps:

[0011] 1) biomass gasification: mixing oxygen and water vapor produced from an air separation plant with biomass, transporting a resulting mixture via a nozzle to a gasifier, gasifying the biomass at a temperature of 1,500-1,800°C and a pressure of 1-3 MPa to yield crude gasified gas, and transporting superheated steam having a pressure of 5-6 MPa resulting from sensible heat recovery to a steam turbine;

[0012] 2) shift and purification: according to demand for a methanation reaction, adjusting a hydrogen/carbon ratio of the crude gasified gas generated from step 1) to 3: 1 using a shift reaction, and eluting the crude gasified gas using low-temperature methanol for desulfurization and decarburization, whereby yield purified syngas;

[0013] 3) methanation: introducing the purified syngas in step 2) to a methanation unit comprising a primary methanation unit and a secondary methanation unit, the primary methanation unit comprising a first primary methanation reactor and a second primary methanation reactor connected in series; allowing part of process gas from the second primary methanation reactor to return to an inlet of the first primary methanation reactor to mix with fresh feed gas, and then to enter the first primary methanation reactor, so that a concentration of reactants at the inlet of the first primary methanation reactor is reduced and a catalyst bed temperature is controlled by the process gas; introducing the syngas after primary methanation to the secondary methanation unit comprising a first secondary methanation reactor and a second secondary methanation reactor connected in series, where a small amount of unreacted CO and a large amount of CO₂ is converted into CH₄; and transporting intermediate pressure superheated steam generated in the methanation unit to the steam turbine; and

[0014] 4) methane concentration: concentrating methane of synthetic natural gas containing trace nitrogen and water vapor obtained from step 3) through pressure swing adsorption, so that a molar concentration of methane reaches 96%, and calorific value of the synthetic natural gas is up to 8,256 kcal/Nm³.

[0015] The mixture in step 1) is introduced to an airflow bed gasifier through the nozzle at a rate of 100-120 m/s for parallel flow gasification.

[0016] The crude gasified gas from a side top of the gasifier in step 1) is controlled to

have a temperature of 1,200-1,500°C; waste heat of the crude gasified gas is recycled by a waste heat boiler to produce intermediate pressure superheated steam, a part of which is mixed with oxygen as a gasification agent, and the remaining is sent to the steam turbine; after heat recovery, the gasified gas temperature drops to 220-280°C; the gasified gas is purified by a two-stage cyclone separator for removal of dust and is cooled by a washing tower, so as to reduce the gasified gas temperature to 50-55°C, reduce a dust content to below 50 mg/m³, and the gasified gas comprises CO, H₂ and N₂.

[0017] The purified syngas in step 3) is divided into two equal streams comprising a first feed gas and a second feed gas, which respectively enters a first primary methanation reactor and a second primary methanation reactor; the first feed gas is first mixed with the process gas and then enters a catalytic bed of the first primary methanation reactor for a methanation reaction, a temperature thereof is controlled at 300-330°C; an outlet temperature of the mixed gas is 600-630°C; the intermediate pressure superheated steam is generated through a first waste heat boiler and a first steam superheater; the process gas from the first steam superheater is mixed with the second feed gas, and then enters the second primary methanation reactor for methanation reaction at 300 -330°C; an outlet temperature of the process gas from the second primary methanation reactor is 600-630°C; the process gas from the second primary methanation reactor passes through a second waste heat boiler and a second steam superheater to generate intermediate pressure superheated steam; the process gas from the second primary methanation reactor is divided into two streams: one stream accounts for 30-40%, and flows to the first

primary methanation reactor via a recycle compressor; another stream accounts for 60-70%, and enters the first secondary methanation reactor; the process gas is cooled to 270-290°C and enters the first secondary methanation reactor for further methanation reaction; an outlet temperature of mixed gas of the first secondary methanation reactor is 440-460°C, and an inlet temperature of a feed gas of the second secondary methanation reactor is 270-290°C; and the intermediate pressure superheated steam generated from the methanation reaction is transported to the steam turbine.

[0018] A pressure of the intermediate pressure superheated steam that is generated by the first/second waste heat boiler and the first/second steam superheater in the primary methanation unit is 4.5-5 MPa.

[0019] The methanation reaction in step 3) employs high-load nickel as a catalyst, with a reaction temperature of 270-630°C, a pressure of 1-3 MPa, and a reaction formula of $\text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O}$, $\Delta H_0^\theta = -206 \text{ kJ/mol}$.

[0020] After the process gas from the second primary methanation reactor is cooled through the second waste heat boiler and the second steam superheater, a first stream flowing to the first primary methanation reactor through the recycle compressor accounts for 60-70%; and a second stream entering the first secondary methanation reactor accounts for 30-40%.

[0021] The system for cogenerating gas-steam based on gasification and methanation of biomass comprises: a gasification unit, a shift unit, a purification unit, a methanation unit,

and a methane concentration unit; a waste heat boiler is provided in an upper part of a gasifier of the gasification unit; waste heat of the crude gasified gas from the gasifier is recycled by the waste heat boiler to yield intermediate pressure superheated steam, which is transported to a steam turbine; an external thermostatic high-temperature heater is provided in an outlet segment of the gasified gas of the gasifier to keep a gasification temperature within the gasifier at 1,500-1,800°C; and a temperature of the crude gasified gas from the gasifier is controlled at 1,200-1,500°C.

[0022] The methanation unit comprises a primary methanation unit and a secondary methanation unit; the primary methanation unit comprises a first primary methanation reactor and a second primary methanation reactor connected in series; an outlet of the second primary methanation reactor is provided with two bypasses: one bypass is connected to an inlet of the first primary methanation reactor, so that the process gas therein is mixed with fresh feed gas, and then enters the first primary methanation reactor; the other bypass is connected to the secondary methanation unit, which comprises a first secondary methanation reactor and a second secondary methanation reactor connected in series; and the second secondary methanation reactor is connected to the methane concentration unit.

[0023] Reaction heat of the mixed gas at the outlet of the first primary methanation reactor is recycled by the first waste heat boiler and the first steam superheater, and that of the mixed gas at the outlet of the second primary methanation reactor is recycled by the second waste heat boiler and the second steam superheater; and the intermediate

pressure superheated steam generated therefrom is transported to the steam turbine.

[0024] The invention has the following advantages: (1) The gasifier uses an external thermostatic high-temperature heat source, which can significantly improve the active components of CO and H₂, and improve the biomass gasification efficiency; (2) Usually, the biomass gasification will produce a large amount of tar. High temperature of the gasification unit can greatly reduce the tar production, improve the carbon conversion, and save the investment in tar removal device. (3) The methanation reaction achieves the CO conversion rate of 100%, and the H₂ conversion rate of 99%; at the same time, produces a lot of by-product (intermediate pressure superheated steam), and reduces power consumption of the recycle compressor in the traditional methanation reaction; (4) The biggest advantage of the invention is that it can not only convert biomass energy into clean natural gas with high calorific value and convenient for use, but also efficiently recycle a lot of heat released from gasification and methanation of biomass by way of producing high grade superheated steam.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. 1 is a flow diagram of a method for cogenerating gas-steam based on gasification and methanation of biomass of the invention;

[0026] FIG. 2 is a schematic diagram of a gasification unit of the invention; and

[0027] FIG. 3 is a schematic diagram of a methanation unit of the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0028] The invention is further illustrated in more detail in the light of the drawings and embodiments, which are not intended to define the protection scope of the invention.

[0029] As shown in FIG. 1, FIG. 2 and FIG. 3:

[0030] Step 1): Rice straw, crop stalk and other biomass were dried, crushed and sorted. Biomass raw material with the diameter or maximum length below 2 mm was directly transported to the gasifier of the high-temperature airflow bed through a screw feeder. The pressure in the gasifier was 1-3 MPa. An external thermostatic high-temperature heater was provided in the outlet segment of the gasified gas of the biomass gasifier to keep the gasification temperature within the gasifier at 1,500-1,800°C, and guarantee the gasification intensity, gasified gas quality and strengthened heat transfer process. As the gasification agent, superheated water vapor and oxygen were premixed, and then fully mixed with the treated biomass. The mixture was injected into the gasifier with a special nozzle at a rate of 100-120 m/s for gasification by way of parallel flow. Due to small particle size and strong heat transfer ability of the airflow bed, raw material was heated to the furnace temperature as soon as it entered the furnace. Almost at the same time, there was moisture evaporation, volatile matter decomposition, tar cracking, carbon combustion and gasification. Alkali-containing metal ash was converted to liquid slag,

and then directly discharged. Small biomass particles were retained in the reaction zone for less than 3S, rapidly gasified before melting, and respectively separated by the high-speed gas flow without the phenomenon of bonding and cohesion etc. Crude gasified gas from the side top of the gasifier was controlled at a temperature of 1,200-1,500°C. The upper part of the gasifier was provided with a waste heat boiler. The crude gasified gas from the gasifier entered the waste heat boiler to recover waste heat, and produced a lot of steam. After heat recovery, the gasified gas temperature dropped to 220-280°C. Then most dust and water vapor in the gasified gas were purified and cooled through two stage cyclone separators and a washing tower, so as to reduce the gasified gas temperature to about 50-55°C, reduce dust content to below 50 mg/m³, and generate the gasified gas mainly containing CO, H₂ and N₂.

[0031] Step 2): After washing and dust removal, crude gasified gas entered the sulfur-tolerant shift process, the ratio of H₂, CO and CO₂ therein was adjusted to the hydrogen/carbon ratio of 3: 1, and the vast majority of organic sulfur therein was converted into inorganic sulfur. Then the gas was purified, and washed with methanol at low temperature, so that methanol was used to remove unwanted CO₂ and all sulfides from methanation reaction of the process gas, and the process gas composition achieved the methane production requirements. Methanol rich in CO₂, H₂S and COS was recycled by flash evaporation under reduced pressure and nitrogen stripping etc. and the cooling capacity therein was recovered for re-use.

[0032] Step 3) methanation: The purified syngas in step 2) at adjusted hydrogen/carbon

ratio can be divided into two approximately equal streams, which respectively entered the first primary methanation reactor and the second primary methanation reactor. Feed gas entering the first methanation reactor was first mixed with the recycle gas. The mixed gas at 300-330°C entered the catalytic bed of the adiabatic reactor, wherein the exothermic methanation reaction occurred. Outlet temperature of the hot gas was about 600-630°C, and the hot gas was used to produce intermediate pressure superheated steam in the first waste heat boiler and superheat intermediate pressure superheated steam in the first superheater. The process gas from the first superheater was mixed with another stream of fresh feed gas. The mixed gas at 300-330°C entered the second methanation reactor for further methanation reaction.

[0033] Outlet temperature of the gas of the second primary methanation reactor was about 600-630°C, which was used to produce steam in the second waste heat boiler and preheat recycle gas in the second superheater. Hot process gas from the second waste heat boiler was divided into two streams: one stream accounted for 30-40%, and flowed to the first primary methanation reactor via a recycle compressor; another stream accounted for 60-70%, and entered the first secondary methanation reactor.

[0034] Inlet temperature of the feed gas of the second secondary methanation reactor was 270-290°C, and further methanation reaction occurred in the second secondary methanation reactor, in order to achieve the specification of SNG product. Intermediate pressure superheated steam generated from the methanation reaction was transported to the steam turbine.

[0035] Pressure of the intermediate pressure superheated steam that was generated by the waste heat boiler and steam superheater using the recycling reaction heat in the primary methanation reaction stage was 4.5-5 MPa.

[0036] The methanation was carried out with high-load nickel as the catalyst, at the reaction temperature of 270-630°C, under the pressure of 1-3 MPa, and following $\text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O}$ $\Delta H_0^\theta = -206 \text{ kJ/mol}$.

[0037] Step 4) Methane concentration: After methane was concentrated through pressure swing adsorption of crude natural gas, substituent natural gas following national standard was obtained. In general, the natural gas enters the urban gas pipeline as domestic gas, and may also enter the gas turbine to generate electricity in case of power shortage.

[0038] As shown in FIG. 1, a method and system for cogenerating gas-steam based on gasification and methanation of biomass comprises a gasification unit, a shift unit, a purification unit, a methanation unit and a methane concentration unit.

[0039] As shown in FIG. 2, a waste heat boiler is provided in the upper part of the gasifier of the gasification unit. Intermediate pressure superheated steam is generated by the waste heat boiler using the recycling waste heat of the crude gasified gas from the gasifier, and is transported to the steam turbine. An external thermostatic high-temperature heater is provided in the outlet segment of the gasified gas of the biomass gasifier to keep the gasification temperature within the gasifier at 1,500-1,800°C. Crude gasified gas from the gasifier is controlled at a temperature of 1,200-1,500°C.

[0040] As shown in FIG. 3, the methanation unit comprises a primary methanation unit and a secondary methanation unit. The primary methanation unit is composed of two reactors connected in series with two reactors connected in parallel in either stage. The outlet of the second primary methanation reactor is provided with two bypasses: one bypass is connected to the inlet of the first primary methanation reactor, so that the process gas therein is mixed with fresh feed gas, and then enters the first primary methanation reactor; the other bypass is connected to the secondary methanation reactor, which comprises a first secondary methanation reactor and a second secondary methanation reactor connected in series. The second secondary methanation reactor is connected to the methane concentration unit. After the second stage primary methanation, a part of the process gas returns to the inlet of the first primary methanation reactor, is mixed with fresh feed gas, and then enters the first primary methanation reactor, in order to reduce the reactant concentration at the inlet of the primary methanation reactor. On the other hand, the recycle process gas is used for inert medium heating to control the catalyst bed temperature. The vast majority of methanation reaction is completed at the primary methanation stage. Reaction temperature of the secondary methanation is lower than that of the primary methanation. This stage is composed of two secondary methanation reactors connected in series, and converts a small amount of unreacted CO and most of the CO₂ into CH₄. Product gas from the methanation stage is transported to the methane concentration process.

[0041] Reaction heat of the mixed gas at the outlet of the first primary methanation

reactor is recycled by the first waste heat boiler and the steam superheater, and that of the mixed gas at the outlet of the second primary methanation reactor is recycled by the second waste heat boiler and the steam superheater. The intermediate pressure superheated steam generated therefrom is transported to the steam turbine.

Example 1

[0042] Calculation of the overall system performance under the basic load with 1,000 tons/day raw material biomass

[0043] Dry rice straw is used as the gasification biomass in Example 1. Its ingredients and calorific value are shown in Table 1.

Table 1 Ingredients and calorific value of biomass

Items	Content	Unit	Rice straw
calorific value	Qar, net	MJ/kg	11.346
Elements	Carbon Car	%	37.162
	Hydrogen Har	%	2.748
	Oxygen Oar	%	35.136
	Nitrogen Nar	%	0.905
	Sulfur Sar	%	0.029

[0044] In example 1, biomass 1000 tons/day, and the gasification agent comprising 93 vol. % of oxygen is employed for gasification.

Table 3 Material balance and performance parameters of gas product

	Example 1			
	Gasified as	Shift gas	Syngas	Gas product

Rate of flow Nm ³ /h	43960	53320	29300	7350
Percentage vol. %				
CO	43.41%	12.03%	20.36%	0.01
H ₂	16.42%	37.30%	67.53%	0.30
N ₂	5.77%	4.76%	8.04%	1.17
CO ₂	21.19%	41.23%	1.88%	1.13
CH ₄	1.92%	1.59%	2.16%	96.13
H ₂ O	9.29%	1.45%	0.03%	1.26
C ₂ -C ₄	1.92%	1.59%	0.00%	0.00
Caloric value of syngas kcal/m ³			2579	8227
Yield of syngas m ³ /d				176400
Chemical synthesis efficiency from biomass to syngas (chemical energy of SNG/biomass chemical energy of biomass)				47%
Steam from methanation	450°C, 4.7 MPa (t/h)			21.45

Example 2

[0045] Biomass 1000 tons/day, and the gasification agent comprising 98 vol. % of oxygen is employed for gasification.

Table 2 Material balance and performance parameters of gas product

	Example 1			
	Gasified as	Shift gas	Syngas	Gas product
Rate of flow Nm ³ /h	51140	64640	39670	10190
Percentage vol. %				
CO	52.10%	14.46%	21.91%	0.01%
H ₂	22.81%	44.81%	72.66%	0.20
N ₂	2.02%	1.60%	2.48%	2.00%

CO ₂	12.55%	36.70%	1.79%	0.28%
CH ₄	1.17%	0.92%	1.13%	96.47%
H ₂ O	9.27%	1.45%	0.02%	1.03%
C ₂ -C ₄	0.02%	0.01%	0.00%	0.00%
Caloric value of syngas kcal/m ³			8256	8227
Yield of syngas m ³ /d				244560
Chemical synthesis efficiency from biomass to syngas (chemical energy of SNG/biomass chemical energy of biomass)				64%
Steam from methanation	450°C, 4.7 MPa (t/h)			30.90

CLAIM

1. A method for cogenerating gas-steam based on gasification and methanation of biomass, the method comprising:
 - 1) biomass gasification: drying, crushing and sorting rice straw, crop stalk and other biomass so as to produce biomass raw material with diameter or maximum length below 2 mm; sending the biomass raw material to high-temperature entrained flow bed gasifier directly via a screw feeder; mixing oxygen and water vapor produced from an air separation plant with biomass, transporting a resulting mixture via a nozzle to a gasifier, gasifying the biomass at a temperature of 1,500-1,800°C and a pressure of 1-3 MPa to yield crude gasified gas, and transporting superheated steam having a pressure of 5-6 MPa resulting from sensible heat recovery to a steam turbine;
 - 2) shift and purification: according to demand for a methanation reaction, adjusting a hydrogen/carbon ratio of the crude gasified gas generated from step 1) to 3: 1 using a shift reaction, and eluting the crude gasified gas using low-temperature methanol for desulfurization and decarburization, whereby yield purified syngas;
 - 3) methanation: introducing the purified syngas in step 2) to a methanation unit comprising a primary methanation unit and a secondary methanation unit, the primary methanation unit comprising a first primary methanation reactor and a second primary methanation reactor connected in series; allowing part of process gas from the second primary methanation reactor to return to an inlet of the first

- primary methanation reactor to mix with fresh feed gas, and then to enter the first primary methanation reactor, so that a concentration of reactants at the inlet of the first primary methanation reactor is reduced and a catalyst bed temperature is controlled by the process gas; introducing the syngas after primary methanation to the secondary methanation unit comprising a first secondary methanation reactor and a second secondary methanation reactor connected in series, where a small amount of unreacted CO and a large amount of CO₂ is converted into CH₄; and transporting intermediate pressure superheated steam generated in the methanation unit to the steam turbine; and
- 4) methane concentration: concentrating methane of synthetic natural gas containing trace nitrogen and water vapor obtained from step 3) through pressure swing adsorption, so that a molar concentration of methane reaches 96%, and calorific value of the synthetic natural gas is up to 8,256 kcal/Nm³.
2. The method of claim 1, characterized in that the mixture in step 1) is introduced to an airflow bed gasifier through the nozzle at a rate of 100-120 m/s for parallel flow gasification.
3. The method of claim 1 or 2, characterized in that the crude gasified gas from a side top of the gasifier in step 1) is controlled to have a temperature of 1,200-1,500°C; waste heat of the crude gasified gas is recycled by a waste heat boiler to produce intermediate pressure superheated steam, a part of which is mixed with oxygen as a

gasification agent, and the remaining is sent to the steam turbine; after heat recovery, the gasified gas temperature drops to 220-280°C; the gasified gas is purified by a two-stage cyclone separator for removal of dust and is cooled by a washing tower, so as to reduce the gasified gas temperature to 50-55°C, reduce a dust content to below 50 mg/m³, and the gasified gas comprises CO, H₂ and N₂.

4. The method of claim 1 or 2, characterized in that the purified syngas in step 3) is divided into two equal streams comprising a first feed gas and a second feed gas, which respectively enters a first primary methanation reactor and a second primary methanation reactor; the first feed gas is first mixed with the process gas and then enters a catalytic bed of the first primary methanation reactor for a methanation reaction, a temperature thereof is controlled at 300-330°C; an outlet temperature of the mixed gas is 600-630°C; the intermediate pressure superheated steam is generated through a first waste heat boiler and a first steam superheater; the process gas from the first steam superheater is mixed with the second feed gas, and then enters the second primary methanation reactor for methanation reaction at 300-330°C; an outlet temperature of the process gas from the second primary methanation reactor is 600-630°C; the process gas from the second primary methanation reactor passes through a second waste heat boiler and a second steam superheater to generate intermediate pressure superheated steam; the process gas from the second primary methanation reactor is divided into two streams: one stream accounts for 30-40%, and flows to the first primary methanation reactor via

a recycle compressor; another stream accounts for 60-70%, and enters the first secondary methanation reactor; the process gas is cooled to 270-290°C and enters the first secondary methanation reactor for further methanation reaction; an outlet temperature of mixed gas of the first secondary methanation reactor is 440-460°C, and an inlet temperature of a feed gas of the second secondary methanation reactor is 270-290°C; and the intermediate pressure superheated steam generated from the methanation reaction is transported to the steam turbine.

5. The method of claim 4, characterized in that a pressure of the intermediate pressure superheated steam that is generated by the first/second waste heat boiler and the first/second steam superheater in the primary methanation unit is 4.5-5 MPa.
6. The method of claim 1 or 2, characterized in that the methanation reaction in step 3) employs high-load nickel as a catalyst, with a reaction temperature of 270-630°C, a pressure of 1-3 MPa, and a reaction formula of $\text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O}$, $\Delta H_0^\theta = -206 \text{ kJ/mol}$.
7. The method of claim 4, characterized in that after the process gas from the second primary methanation reactor is cooled through the second waste heat boiler and the second steam superheater, a first stream flowing to the first primary methanation reactor through the recycle compressor accounts for 60-70%; and a second stream entering the first secondary methanation reactor accounts for 30-40%.