A mathematical model of the carbon dioxide production unit for a cogeneration power station

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Abstract. A mathematical model is presented of a unit for carbon dioxide production using an absorption-desorption method on the basis of a generation facility with a cogeneration steam turbine unit (STU).

1. Introduction

Carbon dioxide finds wide commercial application. It is used for production of synthetic substances in the chemical industry. In medicine, pharmaceuticals and the food industry, CO\textsubscript{2} is used to create a specific environment as well as for cooling or freezing. Carbon dioxide is employed in iron and steel industry, pulp-and-paper industry, and electronics. A characteristic feature of the CO\textsubscript{2} is that it can be used as gas, liquid, or solid.

The absorption-desorption method for the production of carbon dioxide can be profitably used in cogeneration power facilities since the process requires heating steam for its implementation. This brings about the opportunity to increase the efficiency of both the cogeneration power plant (CPP) proper and the carbon dioxide production unit through operating the CPP main equipment under conditions close to rated ones offering reduced specific fuel consumption [1].

2. Energy supply to the consumer from a generation facility based on a cogeneration steam turbine and a unit for production of carbon dioxide by the absorption-desorption method

2.1. Process Flow Diagram

Figure 1 shows a process flow diagram of a system of energy supply to consumer from a generation facility with a cogeneration steam turbine unit (STU) and a unit for the production carbon dioxide by the absorption-desorption method [2].

This process flow diagram is for a system which can produce all types of carbon dioxide (gaseous, liquid, or solid). However, combined production of all types of commercial CO\textsubscript{2} in a single unit is not always required. Therefore, the system in question can have various configurations as applicable to produce one or several types of CO\textsubscript{2}.

The considered scheme of energy supply provides the consumer with electricity, heat, and carbon dioxide in a gaseous, liquid, or solid state.

The main feedstock required for proper operation of this generation facility is fuel for the steam turbine unit, the combustion products of which are flue gases becoming, in their turn, a feedstock for production of carbon dioxide.
Required utilities and their consumption:
- Cooling water flow to the turbine exhaust steam condenser;
- Network water flow to deliver heat to consumer;
- Water flow for treatment of the flue gases in scrubbers;
- Steam flow to the desorber;
- Power to drive compressor, pump, and other auxiliary equipment;
- Cooling water flow.

The basic processes are the stages of conversion of the primary feedstock energy in the unit whose process flow diagram is shown in Fig. 1:

1) Fuel treatment at the power plant. Fuel treatment station.
2) Steam generation. Boiler unit.
3) Conversion of working fluid energy into mechanical work. Turbine.
4) Power generation. Electric generator.
5) Heat generation. Network water heaters.
6) Flue gases treatment at the inlet to the carbon dioxide production unit. Scrubber treatment system.
7) Absorption of CO₂ by an absorbent solution.
8) Desorption of CO₂ from the saturated absorbent solution with steam supply. Desorber.
9) Cooling of the obtained mixture of CO₂, water, and absorbent. Gas cooler.
10) Treatment and production of gaseous CO₂ delivered to consumers. Gaseous CO₂ treatment unit.
11) Production of liquid CO₂ delivered to consumers. Compressor train.
12) Production of solid CO₂ delivered to consumers. Throttling system.
13) Accumulation of carbon dioxide in gaseous, liquid or solid form.
14) Delivery of gaseous, liquid, or solid carbon dioxide to consumers.

Fig. 1 – Process flow diagram of supplying utilities to consumers from a generation facility with a cogeneration steam turbine unit and an adsorption-desorption carbon dioxide production unit

2.2. An Adsorption-Desorption Carbon Dioxide (Gaseous, Liquid, or Solid) Production Units
A principle of production of commercial carbon dioxide is described in [3].
Flue gases are fed to a carbon dioxide production unit. They flow through a cooling and washing plant containing a multistage scrubber system. The treated and cooled flue gases enter an absorber where carbon dioxide is absorbed from the flue gases with an absorbent solution. Nitrogen and nitrogen dioxide which have not been absorbed, are discharged to the atmosphere. The carbon dioxide-rich absorbent solution is routed to the stripper (desorber) where \( \text{CO}_2 \) is desorbed from the absorbent solution by its heating and boiling using heating steam fed to the desorber. The vapor-gas mixture of carbon dioxide, water, and absorbent is fed to a gas cooler which can be a shell-and-tube or sectional heat exchanger. Cooling of the vapor-gas mixture yields condensate of secondary water vapor saturated with gaseous \( \text{CO}_2 \) and containing absorbent. To recover the initial concentration and amount of the solution, the condensate is returned to the absorber. After cooling, wet \( \text{CO}_2 \) is directed to the treatment unit for purification and compression, where it is washed in the washing columns with potassium permanganate and water. The treated gaseous \( \text{CO}_2 \) is delivered to consumers. Liquid \( \text{CO}_2 \) can be produced from gaseous carbon dioxide in a liquefaction unit where it is compressed to the condensation pressure with heat removal to the environment. Liquid \( \text{CO}_2 \) is delivered to consumers in transportable reservoirs (such as cylinders or isothermal tank cars). To make dry ice (or solid \( \text{CO}_2 \)), liquid carbon dioxide is fed to a special package where multistage throttling yields snow-like mass which is compacted to obtain dry ice.

The absorption-desorption method for producing carbon dioxide includes the following operations:

- flue gas treatment;
- \( \text{CO}_2 \) absorption with absorbent solution;
- desorption of \( \text{CO}_2 \) from saturated absorbent solution;
- cooling of obtained mixture of \( \text{CO}_2 \), water, and absorbent;
- treatment and production of gaseous \( \text{CO}_2 \) delivered to consumers;
- production of liquid \( \text{CO}_2 \) delivered to consumers;
- production of solid \( \text{CO}_2 \) delivered to consumers.

### 2.3. A mathematical Model of a System for Supplying Energy Carriers (Utilities) to Consumers from a Generation Facility Based on a Cogeneration Steam Turbine Unit (STU) and an Absorption-Desorption Carbon Dioxide Production Unit

**Adopted assumptions:**

- burned fuel type and its characteristics;
- cogeneration STU type and performance;
- STU load curve;
- carbon dioxide production unit characteristics:
  - flue gas flowrate and composition;
  - flue gas characteristics (pressure, temperature, moisture content);
  - absorbent type;
  - flowrate and conditions of steam fed to desorber;
  - carbon dioxide production unit capacity with respect to gaseous, liquid, and solid \( \text{CO}_2 \);
  - liquefaction unit compressor power;
- characteristics of the main and auxiliary equipment.

**Adopted restrictions:**

- carbon dioxide production units is supplied with electricity and extracted steam not demanded by the consumers and generated in STU operation under rated conditions;
- carbon dioxide production unit operates under variable conditions.

**System of equations.**

Mathematical relationships describing operation of a generation facility, which is a cogeneration steam turbine unit, are as follows [4]:

1) The overall heat balance, kW, for a turbine can be written as:

\[
Q_h = Q_{\text{in}} + Q_{\text{out}} + Q_c
\]
where \( Q'_e \) is the amount of heat in the total heat input to the turbine which is used to generate electricity, kW; \( Q_h \) is the heat delivered with the extracted steam, kW; \( Q_c \) is the steam condensation heat in the condenser, kW.

2) The generated electric power, kW, can be calculated by the following expression:

\[
N_e = D_0(h_0 - h_p) + (D_h - D_c)(h_h - h_c)
\]

where \( D_0 \) is the steam flow fed to the turbine in its operation with steam extraction and condensation, kg/s; \( D_h \) is the steam flow to the steam extraction assembly, kg/s; \( h_0, h_h, h_c, h_p \) are the steam enthalpies at the turbine inlet, points of heating steam extraction, and the condenser inlet, respectively, kJ/kg.

3) Fuel consumption, kg/s, for electricity generation is:

\[
B_e = \frac{Q'_e}{\eta_w \eta_tr \eta_b
\}
\]

where \( Q'_e = Q_h - Q_c \) is the amount of heat consumed for electricity generation, kW; \( Q'_w \) is the lower working calorific value of fuel, kJ/kg; \( \eta_w \) is the heat transport efficiency; \( \eta_b \) is the boiler gross efficiency.

4) The electrical efficiency of a turbine unit is:

\[
\eta^e_e = \frac{N_e}{Q'_e}
\]

5) The fuel rate for electricity generation, g/(kW h), is:

\[
b_e = B_e / N_e
\]

6) The heat, kW, delivered from the steam extraction assemblies to an external consumer is:

\[
Q_{h,ex} = Q_h \eta_h^h = D_h(h_h - h_h) \eta_h^h
\]

where \( h_h \) is the enthalpy of the extracted steam condensate.

7) The thermal efficiency of a cogeneration turbine unit is:

\[
\eta^h_h = Q_{h,ex} / Q_h
\]

8) The fuel consumption, kg/s, for generation of the heat delivered to an external consumer is:

\[
B_h = \frac{Q_{h,ex}}{\eta^h_h \eta_w \eta_tr \eta_b
\}
\]

9) The fuel rate, kg/Gcal, for generation of heat delivered to an external consumer is:

\[
b_{h,ex} = B_h / Q_{h,ex}
\]

10) The total fuel consumption, kg/s, is:

\[
B = B_e + B_h
\]

\[
B = \frac{Q_h}{\eta^w_w \eta_w \eta_tr \eta_b
\}
\]

The relationships describing operation of a carbon dioxide (gaseous, liquid, or solid) production unit using the absorption-desorption method [3] are given below [3]:

1) The rate of carbon dioxide production of complete combustion of fuel (kg/kg for solid fuel or nm3/kg for liquid fuel) is:

\[
g_{CO_2} = 3,67 C_f^w / 100
\]

\[
v_{CO_2} = 3,67 C_f^w / 100 p_{CO_2} = 0,02 C_f^w
\]

for gaseous fuel, kg/nm3 and nm3/nm3:

\[
g_{CO_2} = v_{CO_2} / \rho_f
\]

\[
v_{CO_2} = 0,01(CO_f^w + CH_f^w + \Sigma mC_m H_m^f + CO_2^f)
\]

where \( C_f \) is the fuel carbon content, wt%; \( CO_f^w, CH_f^w, \Sigma mC_m H_m^f, CO_2^f \) are the carbon-containing combustible components, vol%.

2) The theoretical fuel flow required to produce gaseous \( CO_2 \) (in kg/h) with its complete recovery from the flue gases is:
where $G_{\text{CO}_2,g}$ is the gaseous CO$_2$ flow.

3) The actual fuel flow depending on the fraction of CO$_2$ recovery is:

$$B_f = kG_{\text{CO}_2,g}C_1 / g_{\text{CO}_2}(C_1-C_2)$$

(16)

where $k$ is the CO$_2$ loss coefficient; $C_1$ and $C_2$ are the CO$_2$ content in the flue gases upstream and downstream of the absorber, respectively.

4) Total flue gas volume is:

$$V_{f,g}^t = B_fV_g$$

(17)

where $V_g$ is the flue gas volume formed on combustion of 1 kg of fuel, nm$^3$/kg [3].

5) The specific fuel rate is:

$$g_f = 1/g_{\text{CO}_2}$$

(18)

6) Water flow, kg/s, to cool the flue gases in the scrubber is:

$$G_w = Q/c_w(t_{w2}-t_{w1})$$

(19)

where $c_w$ is the water heat capacity, kJ/(kg·K); $t_{w1}$ and $t_{w2}$ are the water temperatures at the scrubber inlet and outlet, respectively; $Q$ is the amount of heat, kW, removed by water and determined from the flow and composition of the flue gases and the inlet and outlet temperatures [3].

7) The power consumption of the exhauster or other blowers is calculated by the expression:

$$N = V_wH/\eta$$

(20)

where $V_w$ is the working fluid flow; $H$ is the total head of the exhauster or blower; $\eta$ is the exhauster or blower efficiency.

8) The disrober heat balance, kJ/kg, is

$$q = q_r + q_s + q_{s,v} + \Sigma q_{\text{los}}$$

(21)

where $q$ is the total specific amount of heat inputted in the desorber from the heating steam and which is equal to the total specific heat consumption; $q_r$ is the reaction heat consumption; $q_s$ is the specific amount of heat required to heat up the solution to the desorption temperature; $q_{s,v}$ is the specific amount of heat removed with secondary water vapor flowing from the reflux condenser to a cooler; $\Sigma q_{\text{los}}$ is the specific heat losses.

9) The area of heat transfer surface in the used heat exchangers is calculated using the well-known heat transfer equation.

2.4. Determination of the Efficiency of an Energy (Utility) Supply System. Selection of a Thermodynamic Efficiency Criterion

The energy supply system under consideration generates, in addition to electricity and heat, another product, which, on the one hand, can be used as an energy carrier for cold supply the consumer, and, on the other hand, this is a useful demanded in various process, for example, in the food industry. When determining the thermodynamic efficiency of energy supply for the system generating only produced energy carriers (or utilities), it is recommended to adopt the following conditions:

1) The exergy efficiency should be taken as a criterion of thermodynamic efficiency for energy supply (or utility) systems [5]. This selection is determined by the features of operation of energy supply (or utility) systems based on multi-generation technology where various types of energy are to be generated.

2) The exergy efficiency should be determined as the ratio of the sum of incoming exergy flows to the sum of outgoing exergy flows.

3) The outgoing exergy flows should include only those which can be used further for any purpose, while the remaining ones should be considered as losses.

4) The exergy efficiency should be calculated by the black box method, i.e., considering the exergy of various energy carriers (or utilities) at the inlet and outlet of the energy (or utility) supply system.

When a product generated in the energy supply system in addition to electricity and heat cannot be considered as an energy source, the energy (or thermodynamic) efficiency cannot be significant, the
economic efficiency of implementation of a system based on the multigeneration technology and improvement of the environment performance of the energy (or utility) supply system should be used as the selection criteria.

Let us analyze the thermodynamic efficiency criterion for an energy supply system comprising a cogeneration steam-turbine unit and a carbon dioxide production unit based on the absorption-desorption method.

The assumptions adopted for the considered energy supply systems are as follows:

1) Inlet streams:
- fuel at the boiler inlet;
- air at the boiler inlet;
- return network water flow from the consumer at the network water heater;
- return flow of the circulating water at the condenser inlet;
- water flow at the inlet to the flue gas scrubbing system;
- return cooling water flow at the gas cooler inlet;
- water flow at the inlet to the gaseous dioxide treatment plant.

2) Outlet flows:
- electricity delivered to the consumer;
- heat of the direct network water flow at the inlet of the network water heater;
- flue gases at the boiler inlet a percentage of which enters the carbon dioxide production unit, while the remaining gas is discharged into the atmosphere;
- direct circulating water flow at the condenser outlet;
- sludge-containing water flow at the outlet of the flue gas scrubbing system;
- flow of elements (such as nitrogen and nitrogen dioxide) that have not been absorbed, at the absorber outlet;
- direct cooling water flow at the gas cooler outlet;
- water flow with impurities at the inlet of the gaseous carbon dioxide treatment unit;
- gaseous carbon dioxide flow to the consumer;
- liquid carbon dioxide flow to the consumer;
- solid carbon dioxide delivered to the consumer.

Thus, the exergy efficiency of an energy supply system comprising a steam-turbine unit (STU) and a carbon dioxide production unit based on the absorption-desorption method can be written as:

$$\eta_{ex} = \frac{E_f + E_{w.f} + E_{w.re} + E_{w.re.gc} + E_{w.re.w} + E_{w.re.w.scr} + E_{w.re.w.tr} + E_{f.gCO2}}{E_f + E_{air} + E_{w.re} + E_{w.re} + E_{w.re} + E_{w.re} + E_{w.re} + E_{w.re} + E_{w.re}}$$

where $E_f$ is the fuel exergy at the STU boiler inlet; $E_{air}$ is the air flow exergy at the STU boiler inlet; $E_{w.re}$ is the exergy of the return network water flow from consumer at the network water heater inlet; $E_{w.re}$ is the exergy of the circulating water return flow at the condenser inlet; $E_{w.re.w}$ is the exergy of the water flow at the inlet to the flue gas scrubbing system; $E_{w.re.gc}$ is the exergy of the return cooling water flow at the gas cooler inlet; $E_{w.tr}$ is the water flow exergy at the inlet of the gaseous carbon dioxide treatment unit; $E_{f.gCO2}$ is the exergy of electricity delivered to consumer; $E_{w.re}$ is the exergy of the direct network water flow to consumer at the network water heater outlet; $E_{f.gCO2}$ is the exergy of the flue gas flow to the carbon dioxide production unit; $E_{CO2.g}$ is the exergy of the gaseous carbon dioxide flow to consumer; $E_{CO2.l}$ is the exergy of the liquid carbon dioxide flow to consumer; $E_{CO2.s}$ is exergy of the solid carbon dioxide delivered to consumer.

### 3. Conclusions

The presented mathematical model of a system for supplying energy (or utilities) to consumer from a generation facility based on a cogeneration steam turbine unit and a carbon dioxide production unit on the basis of the absorption-desorption method can be used to determine the efficiency and select the best scheme for supplying energy to consumer.
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