Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2020, 63 (135), 39–47
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/438

Received: *19.06.2020*
Accepted: *29.09.2020*
Published: *30.09.2020*

Liquid methanol energy storage technology

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Key words: methanol, energy storage, renewable energy sources, hydrogen, carbon dioxide, methanol reactor

Abstract

The paper presents technologies currently being developed for methanol production and its applications. Particular attention was paid to energy storage technology in the form of "renewable" methanol, which is produced from hydrogen generated from surplus energy from renewable energy sources and from captured CO_2. The global methanol market was characterized, i.e. global demand, major producers and global demand for products made from methanol. The installation of methanol production and purification with stoichiometry as well as the methodology for assessing the efficiency of such an installation are also presented. The results of the analysis of such an installation were discussed in accordance with the methodology given.

Introduction

There are noticeable opportunities in the transport and energy sector to use alternative fuels replacing oil-derived fuels due to growing concerns about climate change, air quality and, most importantly, energy security. An example of such an alternative fuel is produced using surplus electric energy from Renewable Energy Sources (RES) – "renewable" methanol. It can be successfully used as a replacement or addition to diesel and gasoline (Pirola, Bozzano & Manenti, 2018).

The development of RES is based on the adopted Directive 2009/28/EC, which shows that the European Union member states should increase the share of electricity produced from RES to 20% by 2020. The directive contains mandatory targets for an individual member state until 2020. In the case of Poland, this is an achievement of 15% in the entire renewable energy sector and 10% in the transport fuels sector (Directive, 2009).

The production of "renewable" methanol is based on four primary sources: biomass, municipal waste, industrial waste and carbon dioxide. The first three options are based on gasification technology and catalytic conversion. The main producers in the global market who use these technologies include Chemrec and Varmlands Methanol (Sweden), Blue Fuel Energy and Enerkem (Canada), BioMCN (the Netherlands) and Carbon Recycling International (Iceland) (Law, Rosenfeld & Jackson, 2013; Svenberg et al., 2018). The last option uses carbon dioxide, water and surplus electricity from RES. Catalytic hydrogenation of carbon dioxide is currently the technology with the largest development prospects and a relatively high probability of being introduced as a large-scale commercial technology in the near future.

The electrolysis process is powered by surplus electricity from renewable sources. The hydrogen generated in this way is used in catalytic reactions. The conversion of hydrogen gas to liquid methanol as a form of energy storage whose energy re-use efficiency is estimated at around 45%, i.e. by 8 p.p. more than in the case of secondary energy use from the obtained methane (Wilk et al., 2016).

Methanol and its synthesis products, such as DME (*dimethyl ether*), MTBE (*tert-butyl methyl* *ether*) and MTG (*Methanol-to-gasoline*) are both used in the energy and fuel sectors. The literature of the subject (Gumber & Gurumoorthy, 2018; Ullmann's Encyclopedia of Industrial Chemistry, 2017) promoting this approach introduces the so-called "Methanol economy" based on the production of methanol from coal, CO_2, biogas or other sources for use in transport as well as energy based on the methanol combustion process. An alternative technology for the energetic use of methanol is DMFC (*Direct Methanol Fuel Cell*) and RMFC (*Reformed Methanol Fuel Cell*) fuel cells.

The use of "renewable" methanol provides the opportunity to achieve the environmental goals such as greenhouse gas reduction, promote renewable energy sources and to improve the functioning of the energy system by storing energy.

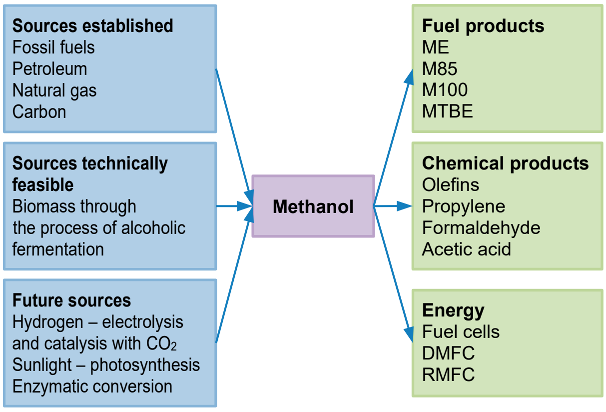

Figure 1. Products of methanol synthesis

Methanol market in Poland across the world

Methanol as a commercial product can be treated as a raw material for the synthesis of fuels and chemical compounds, but also as a fuel source for DMFC or RMFC fuel cells. Figure 1 presents the sources of methanol production as well as the products of its use.

In 1988, the global production of methanol amounted to 19 million tons, while in 2010, production is approximately 46 million tons. This means that the average annual increase in methanol production in the world is around 9% (Figure 2). Methanol as a chemical raw material is used for the production of the following: formaldehyde (about 30% of the world consumption of methanol), acetic acid (about 10%), chloromethane (about 3.5%), MMA – methyl methacrylate (about 2.5%) and methylamines (about 2%). Formaldehyde is mainly used in the construction industry, where this substance is used in adhesives for the production of building boards (OSB boards). In addition to strictly chemical applications, the role of methanol as an additive or raw material for the production of fuel components increases. As an additive to gasoline, it can be used in pure form (about 12% of world production) or in the form of MTBE – methyl tert-butyl ether (12% of world production), now more and more often replaced by ETBE – ethyl-tert-butyl ether. Methanol also has its use as ship fuel (Svenberg et al., 2018). In the literature on the subject, expectations are visible that the demand for methanol converted to fuel products will increase significantly in the coming years. The average annual increase in the demand for products produced from methanol across the world is about 6.2% over the period 2014–2019 and is presented in Figure 3 (Methanol Institute, 2019).

The largest methanol producers in the world are as follows: Methanex (4 million tons/year), Qatar Fuel Additives Company (1 million tons/year), Metafrax and Atlantic Methanol Production Company (1 million tons/year). The current price of methanol acc. Methanex for the European market is

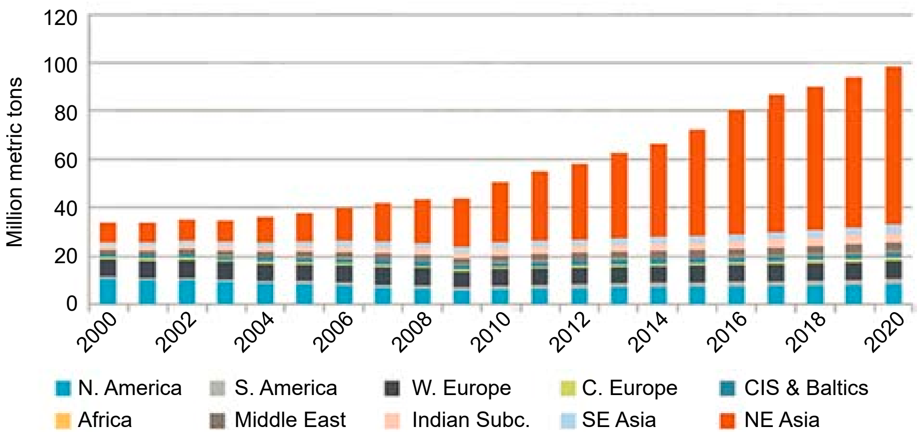

Figure 2. World demand for methanol acc. Methanol Institute

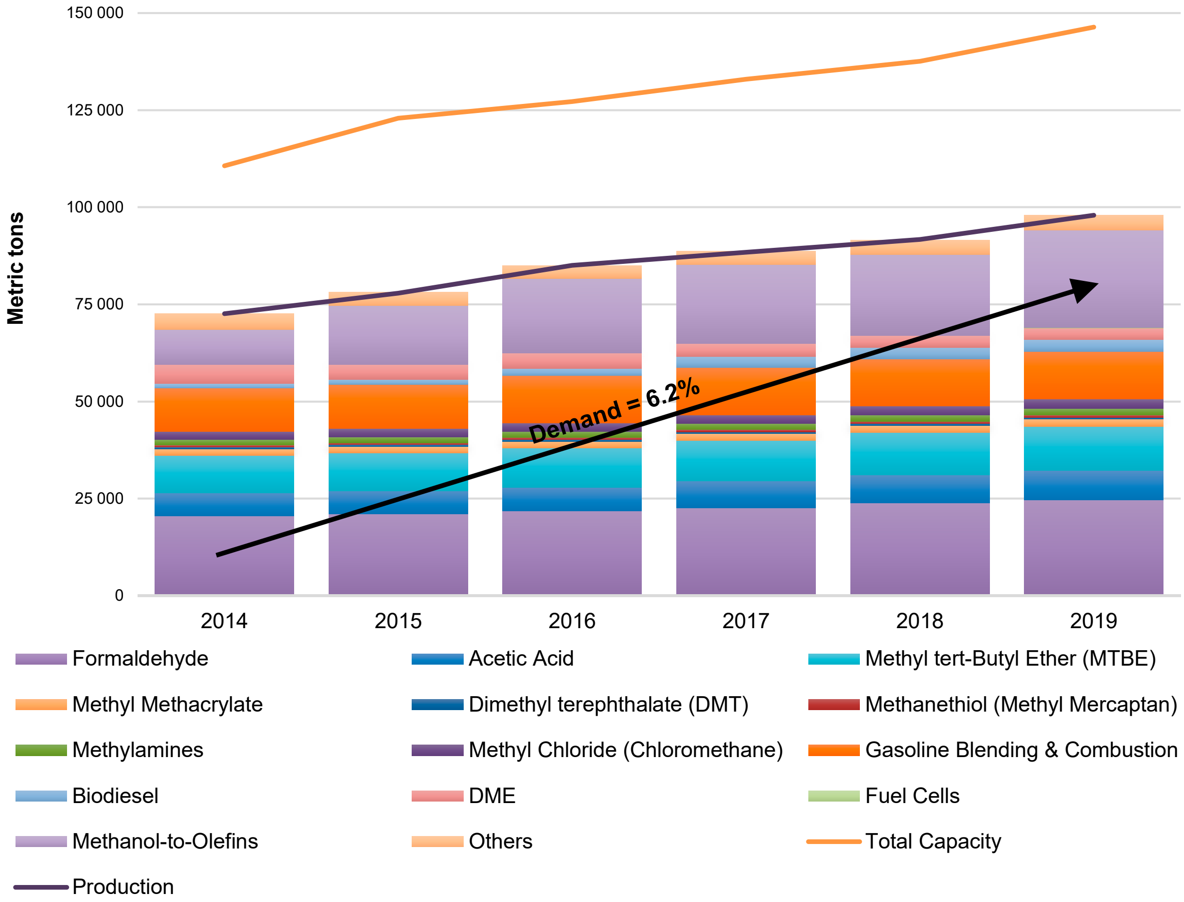

Figure 3. Global demand for products produced from methanol in the period 2014–2019 (Methanol Institute, 2019)

360 €/Mg (June 2019), for the Asian market 350 €/Mg (June 2019) and for the US market 419 $/Mg (June 2019). The change in the methanol price for individual markets in the period 2003–2019 is shown in Figure 4. Methanol, despite its valuable properties as a raw material for chemical syntheses and as a fuel additive, is still not produced in Poland, although in 2010 Zakłady Azotowe Kędzierzyn announced a methanol production plan in Poland on an industrial scale. The situation may change due to the joint project of TAURON and Grupa Azoty (2017) aimed at building a coal gasification plant

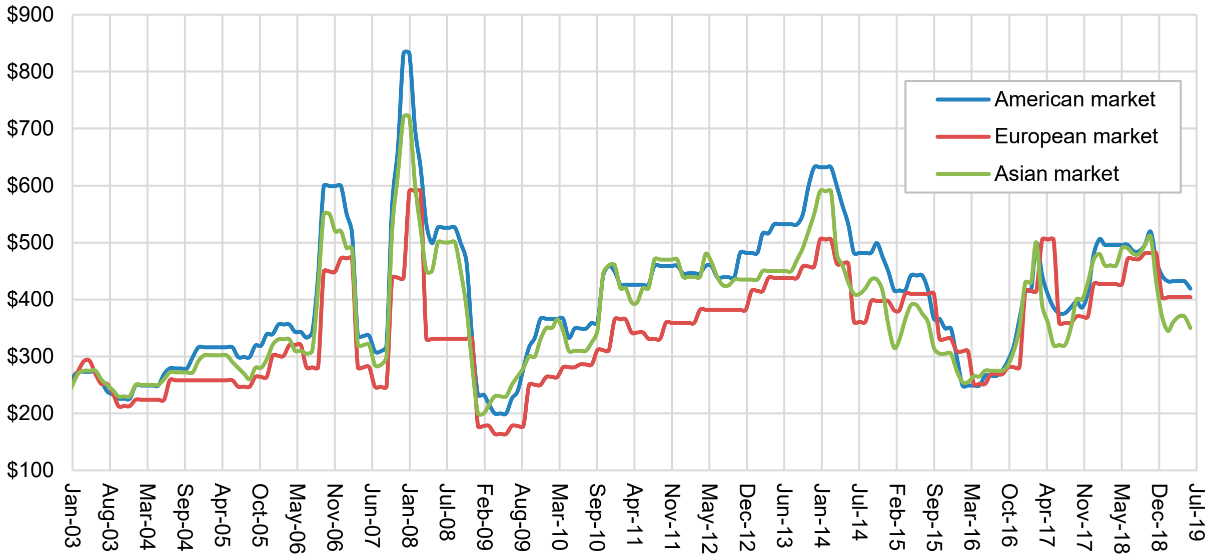

Figure 4. The price of methanol in world markets in the period 2003–2019 in $/Mg (for the European market the price was converted according to the rate of 1 € = 1.12 $)

for the production of chemical products, including methanol.

Production of methanol from CO_2 and H_2

The largest functioning commercial methanol plant from CO_2 is George Olah (owned by Carbon Recycling International) established in Svartsengi near the 76.5 MW geothermal power plant in Iceland (Carbon Recycling International, 2019). This installation produces 5 million dm^3/year using 5500 Mg of CO_2 per year. This methanol unit is sold on the fuel market under the trade name Vulcanol™.

A commercial methanol production plant was also created at the Lünen coal-fired power plant in Germany, where the captured carbon dioxide is converted into methanol. An installation at the Lünen power plant belongs to Mitsubishi Hitachi Power Systems Europe and produces 1 Mg of methanol per day, consuming 1.4 Mg of CO_2 and 1 MW of electricity. The unit is the first-ever attempt to integrate a commercial coal-fired power plant operating at variable load with the generation of liquid methanol.

The CO_2 used for the production of methanol can not only be sourced from power plants but also from industrial plants, ironworks, chemical plants, refineries and cement plants. Carbon Recycling International (CRI) oversees the FreSMe project aimed at the construction of an installation producing methanol from CO_2 from steel mills. The installation is to be implemented in the Swerea MEFOS facility in Sweden. The methanol produced will be entirely used by the Swedish ferry operator Stena, which operates the passenger ferry called Stena Germanica, driven by liquid methanol.

Due to the potential of the methanol production technology described in this article, the authors will present an analysis of the installation of production and purification of methanol produced from CO_2 and of hydrogen produced from surplus electricity from RES.

Methodology for determining the efficiency of the entire system

Figure 5 presents a schematic diagram of a methanol installation and purification with balance shields.

The efficiency of the hydrogen generator (η_{HG} and η'_{HG}) was calculated as the product of the mass stream of hydrogen produced ($\dot{m}_{\mathrm{H_2}}$) and its lower heating value ($\mathrm{LHV_{H_2}}$) (Eq. (1)) or the higher heating value ($\mathrm{HHV_{H_2}}$) (Eq. (2)) related to the power supplied to the generator (N_{HG}):

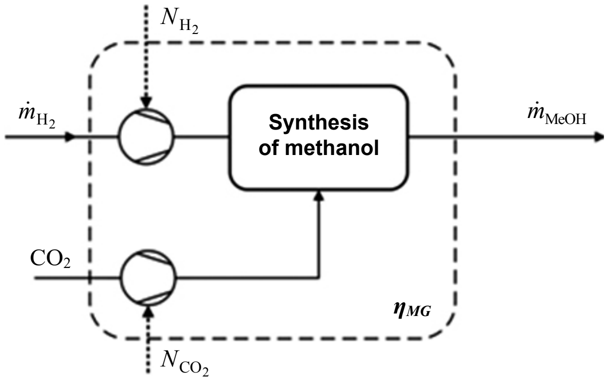

Figure 5. Thermal diagram of production installation and methanol purification with balance shields

$$\eta_{HG} = \frac{\dot{E}_{ch\,\mathrm{H_2}}}{N_{HG}} = \frac{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV_{H_2}}}{N_{HG}} \tag{1}$$

$$\eta'_{HG} = \frac{\dot{E}'_{ch\,\mathrm{H_2}}}{N_{HG}} = \frac{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV_{H_2}}}{N_{HG}} \tag{2}$$

The efficiency of the methanol generator (η_{MG} and η'_{MG}) was determined as the product of the mass stream of methanol produced ($\dot{m}_{\mathrm{MeOH}}$) and its lower heating value ($\mathrm{LHV_{MeOH}}$) (Eq. (3)) or higher heating value ($\mathrm{HHV_{MeOH}}$) (Eq. (4)) related to the sum of hydrogen chemical energy ($\dot{E}_{ch\,\mathrm{H_2}}$ and $\dot{E}'_{ch\,\mathrm{H_2}}$) and own power of individual installations (N) (equation (5) and (6)):

$$\eta_{MG} = \frac{\dot{E}_{ch\,\mathrm{MeOH}}}{\dot{E}_{ch\,\mathrm{H_2}} + N} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{LHV_{MeOH}}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV_{H_2}} + N} \tag{3}$$

$$\eta'_{MG} = \frac{\dot{E}_{ch\,\mathrm{MeOH}}}{\dot{E}'_{ch\,\mathrm{H_2}} + N} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{HHV_{MeOH}}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV_{H_2}} + N} \tag{4}$$

The power of the individual installations own needs (N) is understood as the sum of the power needed to drive a hydrogen compressor ($N_{\mathrm{H_2}}$), a carbon dioxide compressor ($N_{\mathrm{CO_2}}$) and two fans in a methanol purification installation ($N_{W1} + N_{W2}$):

$$N = N_{\mathrm{H_2}} + N_{\mathrm{CO_2}} + N_W \tag{5}$$

$$N_W = N_{W1} + N_{W2} \tag{6}$$

The efficiency of the entire unit (η) shown in Figure 1 takes the form of the quotient of the chemical energy of the produced methanol ($\dot{E}_{ch\,\mathrm{MeOH}}$ and $\dot{E}'_{ch\,\mathrm{MeOH}}$) and the sum of the power supplied to the generator (N_{HG}) together with the power of the needs of the individual installations (N):

$$\eta = \frac{\dot{E}_{ch\,\mathrm{MeOH}}}{N_{HG} + N} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{LHV_{MeOH}}}{N_{HG} + N} \tag{7}$$

$$\eta' = \frac{\dot{E}'_{ch\,\mathrm{MeOH}}}{N_{HG} + N} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{HHV}_{\mathrm{MeOH}}}{N_{HG} + N} \tag{8}$$

Using the above equations on the efficiency of individual installations (η_{MG}, η_{HG} and η'_{MG}, η'_{HG}) and considering the power supplied to the hydrogen production plant (N_{HG}) and the power of the individual installations own needs (N), the efficiency of the entire unit can also be demonstrated as follows:

$$\eta = \eta_{MG} \cdot \eta_{HG} \cdot \frac{\alpha + \frac{1}{\eta_{HG}}}{\alpha + 1} \tag{9}$$

$$\eta' = \eta'_{MG} \cdot \eta'_{HG} \cdot \frac{\alpha + \frac{1}{\eta'_{HG}}}{\alpha + 1} \tag{10}$$

where:
$$\alpha = \frac{N_{HG}}{N} \tag{11}$$

The efficiency of the methanol generator ($\eta_{MG.\eta}$ and $\eta'_{MG.\eta}$) (equations (3) and (4)) can also be defined considering the efficiency of electricity transmission (η_{tr}) from the reference power plant to the methanol production and purification installation and the efficiency of electricity generation in the reference power plant ($\eta_{el,R}$) in accordance with the formula:

$$\eta_{MG.\eta} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{LHV}_{\mathrm{MeOH}}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV}_{\mathrm{H_2}} + \frac{N}{\eta_{tr} \cdot \eta_{el,R}}} \tag{12}$$

$$\eta'_{MG.\eta} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{HHV}_{\mathrm{MeOH}}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} + \frac{N}{\eta_{tr} \cdot \eta_{el,R}}} \tag{13}$$

In the case of heat recovery from the carbon dioxide compression installation (preparing it for the methanol synthesis reactor), the methanol generator takes the form ($\mathrm{LHV_{MeOH}}$) for equation (14), and for ($\mathrm{HHV_{MeOH}}$) equation (15) (for equations (16)–(17) the sub-indexes according to Figure 6):

$$\eta_{MG.Q} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{LHV}_{\mathrm{MeOH}} + \sum_{i=1}^{n} \dot{Q}_i}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV}_{\mathrm{H_2}} + N} \tag{14}$$

$$\eta'_{MG.Q} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{HHV}_{\mathrm{MeOH}} + \sum_{i=1}^{n} \dot{Q}_i}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} + N} \tag{15}$$

$$\eta_{MG.QE} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{LHV}_{\mathrm{MeOH}} + \dot{m}_{14} \cdot \mathrm{LHV}_{14}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV}_{\mathrm{H_2}} + N} + \frac{\dot{m}_{22} \cdot \mathrm{LHV}_{22} + \sum_{i=1}^{n} \dot{Q}_i}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{LHV}_{\mathrm{H_2}} + N} \tag{16}$$

$$\eta'_{MG.QE} = \frac{\dot{m}_{\mathrm{MeOH}} \cdot \mathrm{HHV}_{\mathrm{MeOH}} + \dot{m}_{14} \cdot \mathrm{HHV}_{14}}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} + N} + \frac{\dot{m}_{22} \cdot \mathrm{HHV}_{22} + \sum_{i=1}^{n} \dot{Q}_i}{\dot{m}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} + N} \tag{17}$$

($\sum_{i=1}^{n} \dot{Q}_i$) is the sum of the heat streams received in intersectional coolers, where (n) are the number of intersection coolers:

$$\sum_{i=1}^{n} \dot{Q}_i = \dot{Q}_i + \dot{Q}_{i+1} + \cdots + \dot{Q}_{n-1} + \dot{Q}_n \tag{18}$$

where:

$$\dot{Q}_i = \dot{m}_i \cdot \left(h_{\mathrm{temp}.x} - h_{hx.\mathrm{zal}}\right) \tag{19}$$

Stoichiometry of methanol production

The production of methanol is based on exothermic reactions of hydrogen synthesis with carbon dioxide or with carbon monoxide in accordance with reactions:

$$\mathrm{CO_{(g)} + 2H_{2(g)} \leftrightarrow CH_3OH_{(l)}}$$
$$\Delta \mathrm{H} = -128\ \mathrm{kJ/mol\ (298\ K)} \tag{20}$$

$$\mathrm{CO_{2(g)} + 3H_{2(g)} \leftrightarrow CH_3OH_{(l)} + H_2O_{(g)}}$$
$$\Delta \mathrm{H} = -87\ \mathrm{kJ/mol\ (298\ K)} \tag{21}$$

At the same time, there is also an endothermic reaction of the reverse conversion of water gas:

$$\mathrm{CO_{2(g)} + H_{2(g)} \leftrightarrow CO_{(g)} + H_2O_{(g)}}$$
$$\Delta \mathrm{H} = +41\ \mathrm{kJ/mol\ (298\ K)} \tag{22}$$

The mass of substrates and products in the methanol synthesis reaction (21) for 1 kg H_2 looks as follows:

$$7.277\ \mathrm{kg\ CO_{2(g)}} + 1\ \mathrm{kg\ H_{2(g)}} \leftrightarrow$$
$$5.298\ \mathrm{kg\ CH_3OH_{(l)}} + 2.979\ \mathrm{H_2O_{(g)}} \tag{23}$$

where: $M_{\mathrm{CO_2}} = 44.00950$ g/mol; $M_{\mathrm{H_2}} = 2.01588$ g/mol; $M_{\mathrm{CH_3OH}} = 32.04190$ g/mol; $M_{\mathrm{H_2O}} = 18.01528$ g/mol (NIST, 2019).

Installation of methanol production and purification

The structure of the methanol production plant and its purification is shown in Figure 6. It should be noted that it is necessary to prepare both hydrogen and CO_2. The hydrogen pressure behind the generator is about 2.5 MPa. In the case of captured CO_2

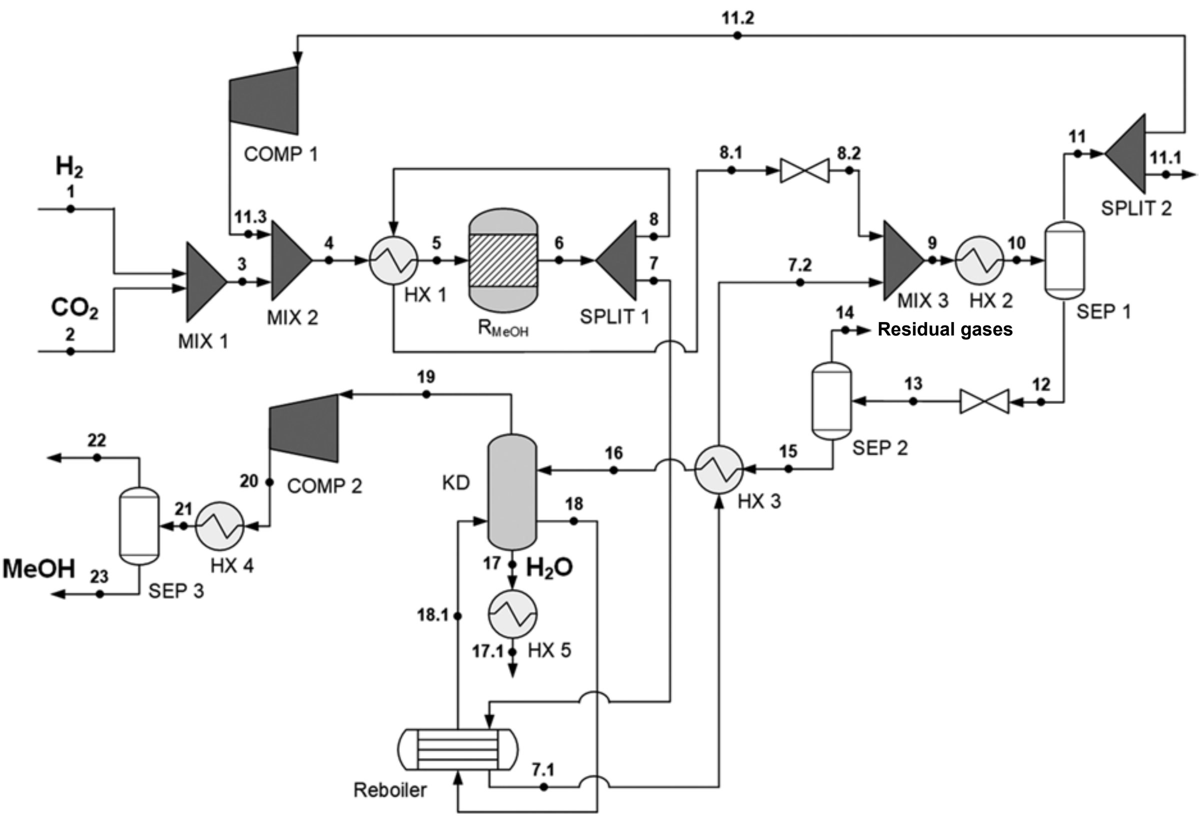

Figure 6. Installation of methanol synthesis and its purification

from the carbon dioxide separation plant in the power plant, the gas pressure is roughly 0.1 MPa. Both gases should be compressed to a pressure of approximately 7.8 MPa. The pressure depends on the catalyst used in the methanol reactor. For Cu/ZrO_2, $Au/Zn/ZrO_2$ and $Cu/Zn/ZrO_2$ catalysts, the pressure in the reactor should be within the range of 7.8–8 MPa (Wilk et al., 2016).

The analysis assumes that gas compression (CO_2 and H_2) takes place in a one-section compressor. However, it should be noted that by reducing the energy consumption of CO_2 compression and using waste heat, we improve the energy balance of the entire installation. However, reducing the number of compressors, and thus the number of heat exchangers, results in a decrease in capital costs with possibly a large increase in energy costs. Assumptions for the part of gas compression are presented in Table 1.

Table 1. Assumptions for the CO_2 and H_2 compression installation

Parameter	Symbol	Value		Unit
		H_2	CO_2	
Gas mass flow	$\dot{m}_{H_2}$	1	1	kg/h
Gas pressure at the installation inlet	p_{in}	2.5	0.1	MPa
Gas temperature at the installation inlet	t_{in}	25	25	°C
Isentropic efficiency of the compressor	$\eta_{i.S}$	0.88	0.88	–
Mechanical efficiency of the compressor	$\eta_{m.S}$	0.99	0.99	–
Electrical efficiency of the motor	$\eta_{el.motor}$	0.85	0.85	–
Mechanical efficiency of the motor	$\eta_{m.motor}$	0.998	0.998	–
Gas pressure at the installation outlet	p_{out}	7.8	7.8	MPa

Analysis of the production and methanol purification installation was conducted for 1 kg/h of $H_2(g)$. This means that the amount of CO_2 supplied to the installation is consistent with the stoichiometry of equation (23) and amounts to 7.227 kg/h. The analyzed installation is based on the reaction (21), which takes place in the methanol synthesis reactor (R_{MeOH}). Table 2 presents the main assumptions for this installation.

Both gases are mixed in (MIX1) and then mixed again with the recycle gas stream in (MIX2). The stream is then heated (HX1) to 210°C and injected into a fixed bed adiabatic reactor. Gases leaving the reactor are split (SPLIT1) into two streams: the first (60% of the initial stream) is used to preheat (HX1) the gas mixture at the reactor inlet while the other is directed to the reboiler (Reboiler) and the stream supplying the distillation column (HX3). The two

Table 2. A set of assumptions for production installations and methanol purification

Parameter	Symbol	Value	Unit
The pressure loss of medium on the cold side of the heat exchanger HX1	ζ_{4-5}	0.23	MPa
The pressure loss of medium on the hot side of the heat exchanger HX1	$\zeta_{8-7,1}$	0.3	MPa
The temperature of the medium at the outlet of HX1 (at the inlet to the methanol synthesis reactor)	t_5	210	°C
The operating temperature of the methanol synthesis reactor	t_6	284	°C
Mass stream of the refrigerant at the inlet to HX1	m_8	$m_6 \cdot 0.6$	kg/h
Pressure of the medium at the throttling valve outlet	$p_{8,2}$	7.36	MPa
The temperature of the medium at the reboiler outlet	$t_{7,1}$	156	°C
Pressure loss of the medium at the outlet from the reboiler	$\zeta_{7-7,1}$	0.05	MPa
The temperature of the medium at the outlet of HX3 (at the inlet to the distillation column KD)	t_{16}	75	°C
The pressure loss of medium on the cold side of the heat exchanger HX3	ζ_{15-16}	0.01	MPa
The pressure loss of medium on the hot side heat exchanger HX3	$\zeta_{7,1-7,2}$	0.1	MPa
The temperature of the medium at the outlet of the HX2	t_{10}	35	°C
The temperature of the medium at the outlet of HX5	$t_{17.1}$	40	°C
The pressure loss of medium on the hot side heat exchanger HX2	ζ_{9-10}	0.02	MPa
Operating temperature of SEP1 separator	$t_{11} = t_{12}$	35	°C
Mass flow of recirculating medium	$m_{11,2}$	$m_{11} \cdot 0.01$	kg/h
Isentropic efficiency of the compressor COMP1	$\eta_{i.\mathrm{COMP1}}$	0.75	
Mechanical efficiency of compressor COMP1	$\eta_{m.\mathrm{COMP1}}$	0.99	
Isentropic efficiency of the compressor COMP2	$\eta_{i.\mathrm{COMP2}}$	0.75	
Mechanical efficiency of compressor COMP2	$\eta_{m.\mathrm{COMP2}}$	0.98	
Pressure of the medium at the outlet of COMP1	$p_{11,3}$	7.8	MPa
Pressure of the medium at the outlet of COMP2	p_{20}	0.12	MPa
Pressure of the medium at the throttling valve outlet	p_{13}	0.12	MPa
Operating temperature of SEP2 separator	$t_{14} = t_{15}$	22	°C
The mass ratio of the distillate to the supply medium		0.99	
The temperature of the medium at the outlet of HX4	t_{21}	40	°C
The pressure loss of medium on the hot side heat exchanger HX4	ζ_{20-21}	0.02	MPa
Operating temperature of SEP3 separator	$t_{22} = t_{23}$	40	°C

streams are again mixed (MIX3) where the water is cooled to 35°C (HX2). Water and methanol, which were condensed in the heat Exchange (HX2), are separated from the unreacted gases in the separation tank (SEP1). Some of the unreacted gases (1%) are purified to minimize the build-up of inert substances and byproducts in the reaction loop.

The liquid stream leaving the separation tank (SEP1), called crude methanol, consists of methanol, water and other dissolved gases. The crude methanol is expanded to 1.2 bar in the throttling valve. Then the residual gases are almost completely removed in the separation tank (SEP2). The remaining stream is heated to 80°C in the heat exchange (HX3) and then directed to the distillation column (KD). Water flows from the bottom of the column at 102°C, containing 23 ppm weight of methanol. Methanol exits the upper part of the column at a pressure of 1 bar and a temperature of 64°C, in gaseous form, containing 69 ppm by weight water and unreacted gases. Then methanol is compressed (COMP2) and cooled (HX4) to 40°C. In the separation column (SEP3), unreacted gases exit from the top of the column, while "clean" methanol emerges from the bottom of the column in liquid form.

In the analyzed installation, simulation of the KD distillation column (responsible for methanol purification) takes place in a more realistic manner due to the lack of perfect separation of liquid and gas in the tank. The column consists of 44 rectification stages and 13 stripper stages. The mass ratio of reflux was assumed to be equal to 1.2. Table 2 presents a set of assumptions for the methanol synthesis plant and its purification.

The hydrogen heating value was adopted at the level of LHV = 119 986 kJ/kg (HHV = 142 327.7 kJ/kg), while for methanol LHV = 19 346.4 kJ/kg (HHV = 22 137.5 kJ/kg).

Table 3. Results of the analysis of the work of the methanol production plant

Parameter	Symbol	Value	Unit
Compressor unit work H_2	L_{H_2}	2238.48	kJ/kg
Compressor unit work CO_2	L_{CO_2}	530.17	kJ/kg
Power required for the compressor CO_2	N_{CO_2}	1071.68	W
Power required for the compressor H_2	N_{H_2}	621.8	W
Power required for the fan $COMP_1 = W_1$	N_{W_1}	124.31	W
Power required for the fan $COMP_2 = W_2$	N_{W_2}	27.62	W
Heat recovery from the heat exchanger HX2	$\dot{Q}_3$	2915.65	W
Heat recovery from the heat exchanger HX4	$\dot{Q}_4$	79.80	W
Heat recovery from the heat exchanger HX5; $t_{17.1} = 40°C$	$\dot{Q}_5$	401.86	W
Generator efficiency MeOH based on LHV (Eq. (3))	η_{MG}	0.7094	–
Generator efficiency MeOH based on HHV (Eq. (4))	η'_{MG}	0.6900	–
Efficiency based on LHV; $\eta_{tr} = 0.95$; $\eta_{el,R} = 0.42$ (Eq. (12))	$\eta_{MG.\eta}$	0.6574	–
Efficiency based on HHV (Eq. (13))	$\eta'_{MG.\eta}$	0.6465	–
Production efficiency MeOH and heat utilization $Q_{3–5}$ (Eq. (14))	$\eta_{MG.Q}$	0.8060	–
Production efficiency MeOH and heat utilization $Q_{3–5}$ (Eq. (15))	$\eta'_{MG.Q}$	0.7721	–

Analysis results of the methanol production installation operation

The methanol production and purification installation is characterized by the methanol yield with respect to 4.643 kg CH_3OH/kg H_2 hydrogen and the methanol yield at the level of 0.638 kg CH_3OH/kg CO_2. Table 3 presents the results of the analysis of the work of the methanol synthesis installation and its purification.

The analysis showed a relatively high unit work of gas compression, which means that multi-section compression with interstage cooling of compressed gases or isothermal compression is worthwhile. The efficiency of the MeOH generator relative to LHV is approx. 71%. If the efficiency of electricity transmission from the reference power plant to the methanol purification installation (η_{tr}) and the efficiency of electricity generation in the reference power plant ($\eta_{el,R}$) are taken into account, this efficiency is lower by 5.2 p.p. Using heat from HX2, HX4 and HX5 unit efficiency is 80.6%.

Conclusions

The production of liquid methanol (and its use as an energy carrier) from CO_2 (separated from industry and energy) and H_2 (produced from surplus electricity from RES) is currently the technology with the most significant potential for commercialization. The dynamic development of "methanol economy" and the growing interest in "renewable" methanol in the near future may increase the competitiveness of this product on the fuel and energy markets.

The methanol production and purification plant is characterized by the methanol yield of 4.643 kg CH_3OH/kg H_2 and the methanol yield of 0.638 kg CH_3OH/kg CO_2 with a reactor efficiency of 71%.

In the case of production installations and methanol purification, it is crucial to conduct research in the field of assessing the potential of the unit's integration with both wind and solar farms. Due to the specificity of the photovoltaic farm (energy production during the day), integration may turn out to be less profitable than in the case of wind farms.

Regarding the preparation of methanol production substrates, it should be noted that by reducing the energy consumption of CO_2 compression and using the heat of compressed gas, we improve the energy and economic balance of the entire installation. However, by reducing the number of compressors, and thus the number of heat exchangers, consequently results in a reduction of capital expenditures if not possible a large increase in energy costs. In light of the above, it is reasonable to conduct research in the field of optimization of the structure of CO_2 and H_2 compression systems.

The use of waste heat from a methanol synthesis plant and its purification by using organic Rankine cycle modules (ORCs) or Stirling engines will further improve the efficiency of the installation. However, due to the high unit costs of these technologies, it is necessary to conduct economic analyses identifying the optima for each solution, taking into account the impact of macro and micro-economic factors and conducting investment risk analyses.

Acknowledgements

Scientific work financed by the National Science Center as part of the research project: "Research on various structures of systems for the energetic use of methanol and its production based on H_2 from the electrolysis process and CO_2 from CCS installation" (project No. UMO2018/29/B/ST8/02244).

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