Research into the Possibilities of Burning Hydrogen and Fossil Fuel with the Aim of Reducing its Carbon Footprint

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Abstract— *Requirements for increasing the environmental friendliness of electricity and heat production to reduce the emission footprint are increasing the demands on the used fuels. For the replacement of conventional fuels in the process of combined production of electricity and heat, it is possible to use synthetic gases, which are created during processes of thermal recovery of biomass and waste. The presented article discusses the possibilities of using synthesis gas obtained by thermal recovery of waste in a plasma reactor in cogeneration units. For the experiment, different ratios of mixtures of natural gas and synthesis gas were used to reduce the consumption of fossil fuel without significantly reducing the performance of the cogeneration unit. The primary combustibles in the synthesis gas were hydrogen and carbon monoxide, the calorific value of which differs from that of methane, causing changes in fuel consumption to maintain the required unit performance. For the full possibility of using synthesis gas as a replacement in cogeneration units, further research is necessary both in the field of its use in combustion engines and in the field of its acquisition and primary purification.*

Keywords— Hydrogen, Cogeneration Unit, Syngas, Renewable Fuels.

I. INTRODUCTION

Between 2010 and 2020, it is possible to observe a total decrease in the production of greenhouse gases in the form of CO_2. This decrease is caused by many factors, including the global COVID-19 pandemic, which caused a significant slowdown in the economy in 2020, and the associated lower amount of CO_2 emissions produced. In addition to this sudden drop in production, the EU's commitment to meeting the requirements of the Kyoto Protocol and the provisions on the decarbonization of Europe by 2050 has a significant impact on reducing CO_2 emissions.

The decrease in the amount of CO_2 produced in Slovakia between 2010 and 2020 was around 19%, while to meet the EU requirements for the overall reduction of CO_2 production, an increase in efforts and thus more significant changes in the field of industry and transport are necessary. The total amount of CO_2 produced by transport in Slovakia in 2020, including both passenger and freight transport, amounted to 31.163 mil. tons. According to the data of the Statistical Office of the Slovak Republic, the share of CO_2 production by transport in the total amount of CO_2 produced is increasing, which increased from 6.08% to 12.52% between 2010 and 2020 [1]. Due to the significant increase in the share of transport in the total production of CO_2, it is necessary to focus on reducing CO_2 not only in industry, but also in transport. Increasing the use of hydrogen in transport has a significant impact on the elimination of CO_2 production and increases the possibilities of meeting the EU's decarbonisation goals.

Hydrogen transport, as well as alternative gaseous mixed fuels containing a significant proportion of hydrogen, are based on the idea of using hydrogen as a basic energy carrier. Vehicles that use hydrogen fuel for their propulsion are generally referred to as hydrogen vehicles. Hydrogen vehicles are divided into two basic categories according to the method of converting the chemical energy of hydrogen into mechanical energy. Hydrogen fuel cell vehicles (HFCV - Hydrogen Fuel Cell Vehicle) belong to the first and currently the most widespread category of hydrogen vehicles. The second category consists of vehicles with a hydrogen combustion engine (HICEV - Hydrogen Internal Combustion Engine Vehicle), whose representation on the automobile market is currently almost zero. The process of burning hydrogen is like that of other high-temperature fuels, such as petrol, diesel or natural gas. However, the achieved efficiency of a hydrogen-burning engine is fundamentally lower compared to a fuel cell. However, the investment costs of a hydrogen combustion engine are also lower compared to a fuel cell. At the same time, it is possible to use already existing equipment, which, after transformation, enables adaptation to the new ecological fuel.

Assuming the combustion of only pure hydrogen in the exhaust gases, there are no carbon-based pollutants, such as carbon monoxide CO or carbon dioxide CO_2, just like when using a fuel cell. Due to the combustion of hydrogen in an atmosphere containing nitrogen and oxygen, however, undesirable nitrogen oxides, also known as NO_X, can be produced during the combustion process. Despite the shortcoming, internal combustion engines burning gaseous fuel based on hydrogen can be one alternative facilitating the transition of industry and transport to 100% clean and green technologies.

In 2011, a team led by Iwasaki Hideyuki from “Tokyo City Univ.” published the results of implementing direct combustion hydrogen propulsion in turbocharged engines into two city vehicles, namely a small city bus and a small city van. The result of the implementation were two functional prototypes of vehicles with direct hydrogen combustion, while each of them used a partially different approach to the given issue. Both vehicles were equipped with the N04-H2 combustion engine, with one of the engines using TCI (transistor coil ignition) technology, while the other engine used CDI (Capacitor discharge ignition) technology. In both cases, the fuel was hydrogen compressed at high pressure. Research on real vehicles has proven the suitability of using hydrogen in direct combustion, with the addition that many sub-problems in the process of direct hydrogen combustion still need to be solved [2].

Following the research carried out at “Tokyo City Univ.” It is also worth mentioning the work of a team led by S. Natarajan from the “Indian Institute of technology – Delhi” created 15 three-wheeled hydrogen vehicles of the “Rickshaw” type by Mahindra, which were equipped with a single-cylinder four-stroke engine with a volume of 395 cm^3. As a result, it was found that at full load there was a decrease in performance compared to the gasoline variant by about 25%, while this decrease was caused by a depleted fuel mixture. During the test run, small shares of CO and CO_2 were recorded at the output due to the partial combustion of oil by the engine, and at the same time negligible shares of NO_X compared to conventional combustion engines. Experimental measurements also proved that the given types of internal combustion engines can be rebuilt to burn hydrogen without major interventions in the overall structure of the engine and without significant performance losses [3].

In addition to the use of diesel and possibly gasoline as a moderator of hydrogen combustion in direct combustion engines, the use of CNG and compressed natural gas can also be considered. These are combustion engines marked HCNG. In this case, there is a need to address the excessive amount of NOx generated due to high operating temperatures in the combustion chamber, as reported by R.K. Mehra and the team from "State Key Laboratory of Automobile Safety and Energy, Tsinghua University, Beijing 100084, People's Republic of China" [4]. The laminar burning speed of hydrogen/air is about six times that of gasoline/air. Due to this higher burning rate, the actual indicator diagram has moved closer to the ideal, resulting in a higher thermal efficiency of the engine [5]. The synthesis of air and a small amount of hydrogen gas produced a combustible mixture that can be burned in a conventional spark-ignition engine below the limit of a lean gasoline/air mixture. Combustion of gasoline/air and hydrogen in a very lean mixture provides a lower flame temperature, resulting in less heat transfer, higher thermal efficiency and reduced NOx emissions [6].

In view of the definitive approval of the ban on the sale of new vehicles with a conventional drive in the territory of the EU states from 2035 and the EU's goals in the field of decarbonization of industry, it is necessary to intensify research in the search for ecological and at the same time effective low-emission fuel alternatives and think rationally about the possibility of transforming already existing technologies into devices using hydrogen as fuel. The submitted contribution analyses the possibility of energy recovery of synthesis gas produced in the process of high-temperature gasification of waste using a combustion engine recovering a mixture of natural gas and synthesis gas.

II. CO-COMBUSTION OF SYNTHESIS GAS AND NATURAL GAS IN A SPARK-IGNITION ENGINE

Synthesis gas produced in the process of high-temperature gasification of waste in a plasma reactor can be considered as an alternative secondary fuel, which is created e.g. in the process of energy recovery of unusable and otherwise non-recyclable waste. With a significant representation of the plastic fraction of the input mixture of wastes entering the plasma gasification process, the calorific value of syngas is at the level of 12-15 $MJ \cdot m^3$ of the gas mixture, while hydrogen can have up to 50 vol. % representation in syngas. Based on the results of high-temperature gasification of various types of waste, the artificially mixed mixture of synthesis gas, which was used in the experiments, consisted of the four most dominant gas elements (CH_4, CO, H_2, N_2) represented in real samples of synthesis gas. Their percentage representation in the mixed gas mixture is adapted to the composition of the collected samples of syngas generated from RDF and municipal waste and to the technological and safety requirements associated with the storage of explosive gas mixtures in pressure vessels. The percentage of components represented in the mixed mixture of gases corresponds to the values of 45 vol. % H_2, 40 vol. % CO, 5 vol. % CH_4 and 10 vol. % N_2. The mixture of syngas and natural gas prepared in this way is then, after passing through the mixing chamber, energy-enhanced in the cogeneration unit, the drive unit of which is a converted four-cylinder spark-ignition combustion engine with a working volume of 1584 cm3. Engine power at 5,000 rpm is 55 kW. Its compression ratio is 8,8:1, the number of valves per cylinder - 2, while the original fuel was 95 octane gasoline. The original system used to prepare the fuel mixture for a spark-ignition combustion engine from easily vaporizable liquid fuels (carburettor) was modified to a system enabling the combustion of gaseous fuel mixtures (by installing a gas fuel mixer). The mechanical power of the four-cylinder spark-ignition combustion engine to the asynchronous generator (TGL 11856/01, type KHR 132 M4) is transmitted by means of a shaft. An asynchronous generator, used mainly in cogeneration units with a small power (up to 100 kW), works in parallel with the superior electrical system. The start of the cogeneration unit is provided by the generator by starting the combustion engine in motor mode. When the nominal speed is reached, the combustion engine takes over the load and automatic phasing of the generator to the network starts. The produced electrical energy is then supplied to the grid. The wiring diagram of the cogeneration unit is shown in fig. 1.

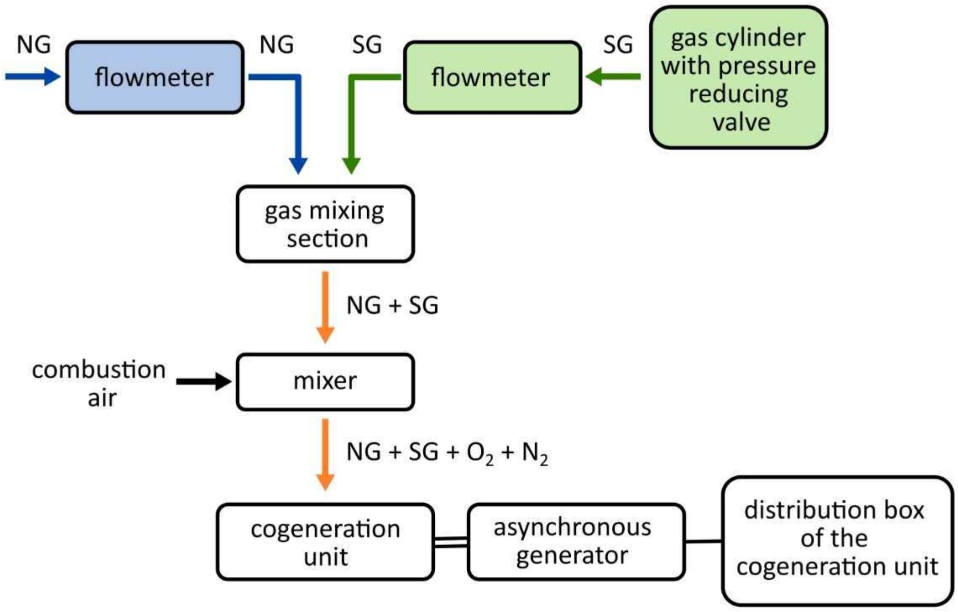

FIGURE 1: Wiring diagram of the measuring stand

Both natural gas and a mixture of natural gas (NG) and syngas (SG) were recovered in the cogeneration unit during the experiments. Mixing natural gas with syngas was carried out in the ratio shown in tab. 1.

TABLE 1
THE COMPOSITION OF THE FUEL MIXTURE

Fuel flow ($l \cdot min^{-1}$)			The composition of the fuel mixture (vol. %)			
natural gas	synthesis gas	total flow rate	CH_4	H_2	CO	N_2
86,0	0	86,0	100,0	0,0	0,0	0,0
81,2	4,8	86,0	94,70	2,51	2,23	0,56
76,8	9,2	86,0	89,84	4,81	4,28	1,07
68,5	17,5	86,0	80,67	9,16	8,14	2,03
60,9	25,1	86,0	72,27	13,13	11,67	2,92
52,5	33,5	86,0	62,99	17,53	15,58	3,90

In addition to the development of the change in the power of the electric generator depending on the composition of the fuel mixture (Fig. 2), the values of gaseous emissions arising from the co-combustion of NG and SG were also monitored (Table 2).

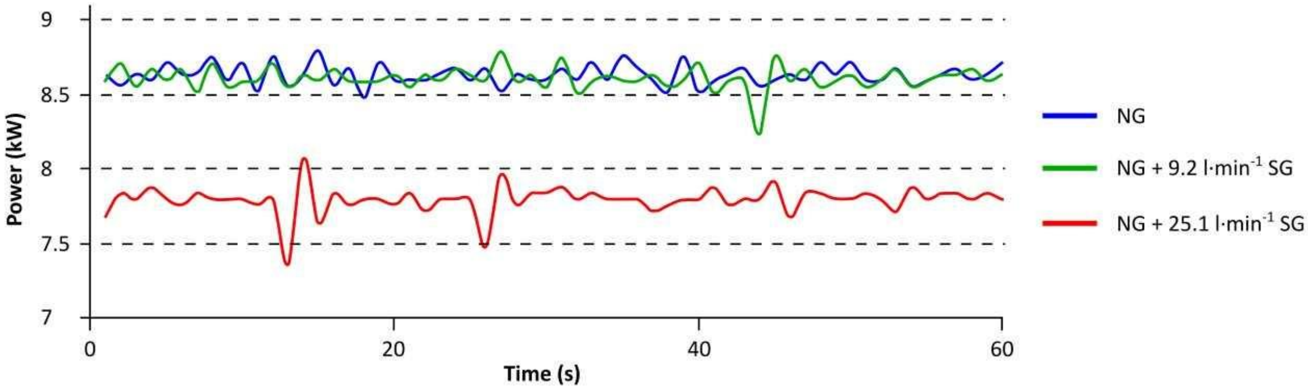

FIGURE 2: Power of the electric generator depending on the composition of the fuel mixture

The results from the flue gas analysis are shown v tab. 2.

TABLE 2
CONTENT OF O_2, CO, CO_2 IN FLUE GAS DETERMINED DURING THE EXPERIMENTS

Measured quantities for	Fuel					
	N+G	NG+SG	NG+SG	NG+SG	NG+SG	NG+SG
Flow of natural gas ($l \cdot min^{-1}$)	86	83.4	78	70	58.7	52
Flow of synthetic gas ($l \cdot min^{-1}$)	0	4.8	9.2	17.5	25.1	33.5
O_2 (%)	6.9	7	6.9	6.5	6.9	8.4
CO (ppm)	690.1	655.6	501	430	399	461
CO_2 (%)	6.74	6.91	6.87	7.11	6.92	6.18
T_S (°C)	198.4	201.8	201.5	207.8	205.9	203.4
T_V (°C)	16.2	16.5	16.7	17	17.2	17.5

III. DISCUSSION

An important property that plays an important role in determining the energy parameter of motor fuel is the calorific value, the value of which is defined by the concentration of combustible components and inert gas components contained in the fuel. Inert gases present in the fuel further affect the gas constant of the fuel, meaning on its density under the conditions of filling the cylinder engine with a fresh dose of fuel. The percentage of the individual gaseous components of the mixture also determines the resistance of the fuel against knocking, meaning transition of the normal course of combustion of the gas mixture in the cylinder to an uncontrolled state, characterized by self-ignition of the fuel before closing the top dead centre. The resistance of gaseous fuel against this unwanted phenomenon is expressed by the methane number, which can be determined by the sum of the methane numbers of the individual combustible components in the fuel reduced according to the volume share of the individual combustible components in the total content of combustibles in the fuel [7]. The presence of H_2 in the gas mixture causes a reduction in the knock resistance of the fuel, while inert gases such as CO_2 and N_2 increase the methane value. The high concentration of CO_2 and N_2 in the fuel also poses a risk for the quality of combustion [7].

During the measurement, the proportion of synthesis gas in the dosed mixture of gaseous fuel entering the cogeneration unit (tab. 2) increased, which resulted in a reduction of CO emissions in the flue gas. The increase in the CO emission value occurred at a synthesis gas flow rate of 33.5 $l \cdot min^{-1}$. The given mixing ratio of gaseous fuels also caused an increase in the oxygen represented in the flue gas, with a simultaneous decrease in the share of CO_2. Taking these facts into account, it is possible to state that the excess air for a specific gas mixture ratio is at a higher level compared to the optimal amount. However, the CO emissions arising in the volume of 461 ppm are still below the value of the CO emission limit in exhaust gas defined for gas engines. The development of CO emission production, depending on the synthesis gas flow, is shown in fig. 3.

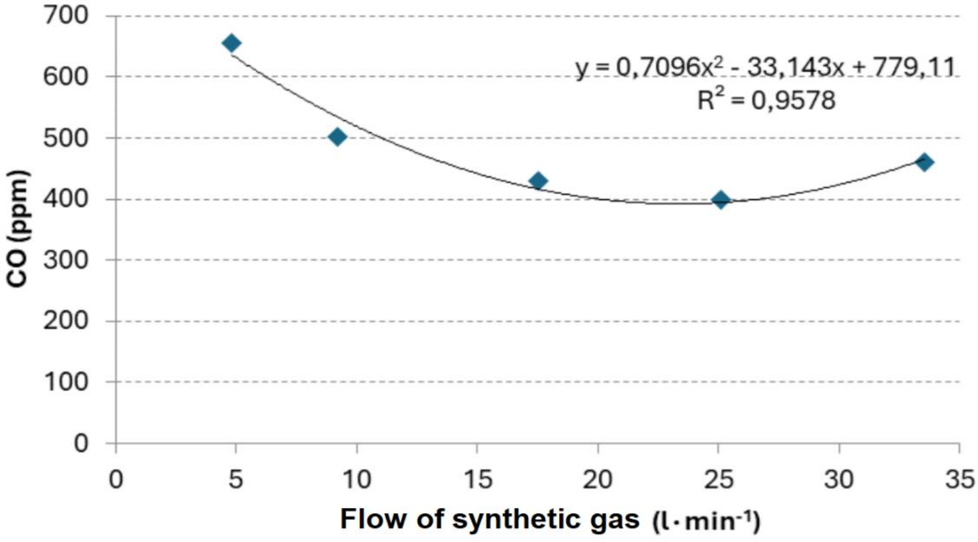

FIGURE 3: Development of CO emission production depending on synthesis gas flow

The CO emission limit in exhaust gases for stationary gas engines is set at 650 mg·Nm^{-3}. In the case of burning natural gas, as well as a mixture of natural gas and synthesis gas, on equipment directly intended for burning such fuel mixtures, together with the use of catalysts, it would be possible to suppress CO emissions to much lower values (compared to the results determined in the experiment). It is important, however, that the purified mixture of gaseous components forming the synthesis gas does not contain, or only contains a negligible amount of sulphur, fluorine and chlorine compounds. The increased value of carbon monoxide in the exhaust gases is caused by the incomplete combustion of the mixture of fuel and air in the cylinder of the experimental spark-ignition four-cylinder engine.

Other emissions in the flue gas are NOx emissions, whose emission limit for 1 Nm^3 of flue gas is 250 mg. This value is achievable in most cases for gas engines operating on natural gas. In the case of the production of a larger proportion of NOx emissions, the reduction can be achieved by a suitable change in the engine setting, which may consist in reducing the ignition advance or by depleting the fuel mixture. When burning a gaseous fuel mixture with a high content of inert gas, to achieve a high-quality course of the combustion process at n >> 1 (excess air), measures of a design nature consisting in the optimization of the combustion space and the ignition system in the engine cylinder are also required. The available type of flue gas analyser used did not allow the measurement of the amount of NOx in the flue gas (the basic equipment of the device does not have a probe for measuring NOx) produced in the experimental trial of energy recovery of synthesis gas using a cogeneration unit.

The aim of the energy recovery of the mixed synthesis gas mixture was also to monitor the change in the power parameters of the electric current generator depending on the change in the composition of the gaseous fuel (Fig. 2). By dosing the volume of 4.8 and 9.2 l of synthesis gas per minute into the flow of synthesis gas, it is possible to state that the changes in the power of the electric current generator are negligible. At the given flow rates, the volume of methane in the fuel mixture is above 89% and compared to the generator output when operating a cogeneration unit on natural gas, a decrease in the output of the electric power generator by 0.02 kW is recorded to a value of 8.62 kW. A more pronounced decrease in performance occurred when the synthesis gas flow rate was increased to 17.5 l·min^{-1}. In this phase of the measurement, the average value of the generator power was calculated at 8.2 kW. By increasing the proportion of synthesis gas in the fuel mixture, as was expected even before the experiment itself, the output of the cogeneration unit is further reduced. A leaner gas fuel mixture at a flow rate of 25.1 l·min^{-1} caused a drop in power to an average level of 7.8 kW. For a flow rate of 33.5 l·min^{-1}, the average power of the generator was calculated to be 7.2 kW. At the given output, the methane content in the fuel was approximately 63%. The efficiency of electricity production for the used fuel mixture was determined as the ratio of the energy content of the fuel to the electricity produced.

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{elG}}}{\frac{Q_{\mathrm{pal}} \cdot Q_v}{t}} \cdot 100 \qquad (1)$$

Where:

Qpal is the calorific value of the fuel mixture ($J \cdot m^{-3}$),

Qv - volumetric flow of fuel ($m^3 \cdot s^{-1}$),

t - time of measurement (s),

PelG - average power of the electric power generator (W).

The dependence of the efficiency of electricity production on the synthesis gas flow is shown in fig. 4.

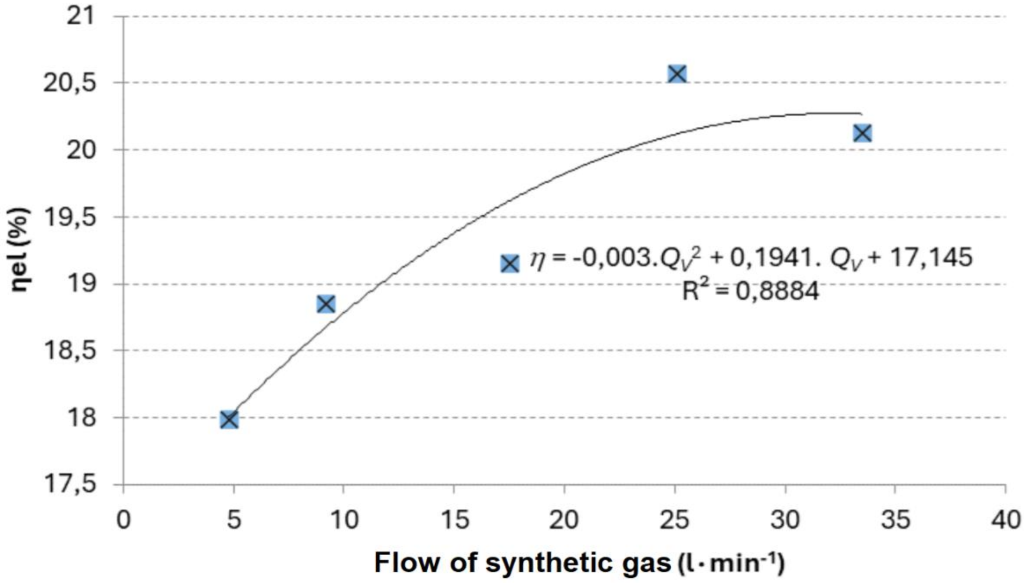

FIGURE 4: Dependence of the efficiency of electricity production on the synthesis gas flow

Based on the calculated values of the efficiency of electricity production, it can be concluded that the efficiency increases with the increasing proportion of synthesis gas in the gas fuel mixture. This tendency is visible until the moment of dosing of synthesis gas with a flow rate of 25.1 $l \cdot min^{-1}$. A further increase in SG flow will cause a breakdown and decrease in the efficiency of electricity production. This decrease is caused by the deterioration of the combustion process in the engine cylinder, which is also evidenced by the data measured using the flue gas analyser shown in tab. 2.

IV. CONCLUSION

In many cases, attention to the alternative energy market is devoted to solar energy, water and geothermal energy, while the energy stored in waste and their negative impact on the environment are often forgotten. The production of a gas mixture, with most of the hydrogen and carbon monoxide, represents a possible available source of energy and a high-quality input raw material for the chemical industry. Hydrogen, which forms a significant percentage of the gas mixture generated during high-temperature gasification, is also considered an alternative to replace fossil sources.

The significant deployment of hydrogen as a fuel requires a perfect mastery of technological and safety aspects and the creation of a sufficient portfolio of offered solutions, which will be based on modern hydrogen storage systems and alternative gaseous fuels with a high proportion of H2, as well as variable methods of hydrogen valorisation. One of the mentioned solutions enabling the transition of continuous transformation of technologies based on fossil fuels to green technologies is also the use and valorisation of secondary gaseous fuels. The conclusions valid for the implemented experimental trial can be defined in the following points.

Mixing the cleaned synthesis gas into the natural gas stream offers a real possibility of energy recovery of the synthesis gas produced in the gasification process. Gasification of waste with a high proportion of organic fraction, in addition to hygienic disposal and reduction of waste volume, also brings benefits in the form of energy recovery of otherwise unused waste, which usually ends up in managed or black landfills.

Dosing synthesis gas into the natural gas stream resulted in a reduction of CO emissions in the exhaust gases. By burning a mixture of synthesis gas and natural gas in cogeneration units, with fully automated control of the dosing of combustion air, fuel and the control of emerging emissions, it is possible to assume a more ecologically favourable operation of electricity production,

No operational problems were noted when burning the gaseous fuel mixture in accordance with tab.1. Reduced resistance to knocking in the engine cylinder was not noted at the volume fraction of hydrogen in the fuel at the level of 17.6 vol. %.

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REFERENCES

[1] PUŠKÁR, M., BRESTOVIČ, T., JASMINSKÁ, N.: Numerical simulation and experimental analysis of acoustic wave influences on brake mean effective pressure in thrust-ejector inlet pipe of combustion engine. In: International Journal of Vehicle Design, 2015, Vol. 67, no. 1, p. 63-76., ISSN 0143-3369

[2] IWASAKI, H., SHIRAKURA, H., ITO, A.: A Study on Suppressing Abnormal Combustion and Improving the Output of Hydrogen Fueled Internal Combustion Engines for Commercial Vehicles. In: SAE Technical Paper Series, 2011. Available on: https://doi.org/10.4271/2011-01-0674.

[3] NATARAJAN, S., ABRAHAM, M., RAJESH, R., DAS, L.: DelHy 3W - Hydrogen Fuelled Hy-Alfa Three Wheeler, In: SAE Technical Paper Series. 2013. Available on: < https://doi:10.4271/2013-01-0224

[4] [4] MEHRA, R. K. et al.: Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines - A comprehensive review, In: Renewable and Sustainable Energy Reviews, 2017, Volume 80, p. 1458-1498. Available on: https://doi.org/10.1016/j.rser.2017.05.061

[5] KOROLL, G. W. et al.: Burning velocities of hydrogen-air mixtures, In: Combustion and Flame, 1993, Volume 94, Issue 3, p. 330-340. Available on: < https://doi.org/10.1016/0010-2180(93)90078-H

[6] SCHROEDER, V., HOLTAPPELS, K.: Explosion Characteristics of Hydrogen-air and Hydrogen-Oxygen Mixtures at Elevated Pressures, In: International Conference on Hydrogen Safety, 2005, Available on: https://www.h2knowledgecentre.com/content/conference216#abstract_content

[7] BEROUN, S., ŠTECHR, V.: Výkonové a emisní parametry plynových motorů kogeneračních jednotek při provozu na paliva různékvality. [cit. 2014-03-20]. Dostupné na internete: www3.fs.cvut.cz/web/.../12241.../2006_100_01.pdf.