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LABORATORY TESTS OF HYDROGEN PRODUCTION THROUGH COAL GASIFICATION WITH REDUCTION OF CO_2 EMISSION WITH CaO

ADAM SMOLIŃSKI

Central Mining Institute, Department of Energy Saving and Air Protection, Laboratory of Coal Processing
pl. Gwarków 1, 40-166, Katowice, Poland

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Abstract: The paper presents the results of laboratory-scale tests of Polish hard coal steam gasification process combined with CO_2 capture by absorption on CaO in a single step. Polish coal mine Piast was selected as a coal samples supplier based on the coal resources, quality, price and reactivity which makes it a potential supplier for a future full-scale gasification system. Steam gasification tests were conducted in a vertical fixed bed reactor at the temperature range of 948–1173K in three series: with addition of CaO layered on a coal sample (II), mixed with a coal sample (III) and without adding CaO (I). The CaO increased both the hydrogen yield and content in gaseous products mixture in comparison with series I. As expected, mixing of CaO with coal sample improved the effects in terms of hydrogen yield and concentration in outlet gas when compared with CaO layered on a coal sample. An effective CO_2 absorption was observed in tests with CaO mixed with a coal sample and at relatively low temperatures. At higher temperatures a reaction resulting in CO_2 concentration increase in the produced gas mixture was observed.

INTRODUCTION

The European economy dependence on natural gas and crude oil, imported from geo-politically unstable world regions, creates a severe risk for its energy security. It is expected that without fundamental changes in energy base structure the European dependence on imported energy resources will have risen from present 50% to 70% by 2030 (of which crude oil will constitute 94%) [8]. The increasing energy demand and resulting increase in fossil fuels consumption contribute to environment contamination and climatic changes. Rising awareness in terms of sustainable development in the greatest economy powers brought about more restrictive regulations regarding greenhouse gases emission and an increasing interest in the research focused on fossil fuels-based energy generation technologies of improved efficiency and combined with CO_2 capture as well as on new, economically competitive and environmental friendly energy carriers. The natural consequence of the above circumstances are research activities oriented on the production of hydrogen which is more and more commonly considered to be an energy carrier fulfilling all economic and environmental requirements, with a particular focus on the development of an integrated coal-based hydrogen and electricity generation technology with CO_2 capture [11, 14].

THERMODYNAMIC ANALYSIS OF THE PROCESS OF HYDROGEN PRODUCTION THROUGH COAL GASIFICATION

The paper presents the process of hydrogen production from syngas generated from coal gasification with CO_2 absorption. Two main steps of this process can be distinguished. In the first one, called the gasification step, coal is gasified to synthesis gas and CO is converted into CO_2 in a water gas shift reaction (WGS) and Boudouard reaction in which CO disproportionate into amorphous carbon and CO_2. In the second step CO_2 is removed from the outlet gas in the CaO carbonation reaction. The main reactions of this process and the free Gibbs energy at the temperature of 298K are presented bellow [7]:

– steam reforming of coal $C + H_2O_{(g)} = CO_{(g)} + H_{2(g)}$ $\Delta G_{298} = 91.4$ kJ/mol (1)
– WGS reaction $CO_{(g)} + H_2O_{(g)} = CO_{2(g)} + H_{2(g)}$ $\Delta G_{298} = -28.6$ kJ/mol (2)
– Boudouard reaction $2CO_{(g)} = CO_{2(g)} + C$ $\Delta G_{298} = -120.0$ kJ/mol (3)
– steam reforming of methane $CH_{4(g)} + H_2O_{(g)} = CO_{(g)} + 3H_{2(g)}$ $\Delta G_{298} = 142.2$ kJ/mol (4)
– methanation reaction $C + 2H_{2(g)} = CH_{4(g)}$ $\Delta G_{298} = -50.8$kJ/mol (5)
– dry reforming of methane $CH_{4(g)} + CO_{2(g)} = 2CO_{(g)} + 2H_{2(g)}$ $\Delta G_{298} = 170.8$ kJ/mol (6)
– CaO carbonation $CaO + CO_{2(g)} = CaCO_3$ $\Delta G_{298} = -130.9$ kJ/mol (7)

For the above reactions, calculations of the free Gibbs energy were conducted using HSC Chemistry software [6] (Fig. 1). The results presented show that in the first step of the process the major reactions are steam reforming of coal, Boudouard reaction producing C and CO_2 (leading to CO_2 syngas enrichment) and steam reforming of methane, whereas the water-gas shift reaction is the reaction of minor importance. CO_2 removal during CaO carbonation results in a hydrogen content increase in the outlet gas.

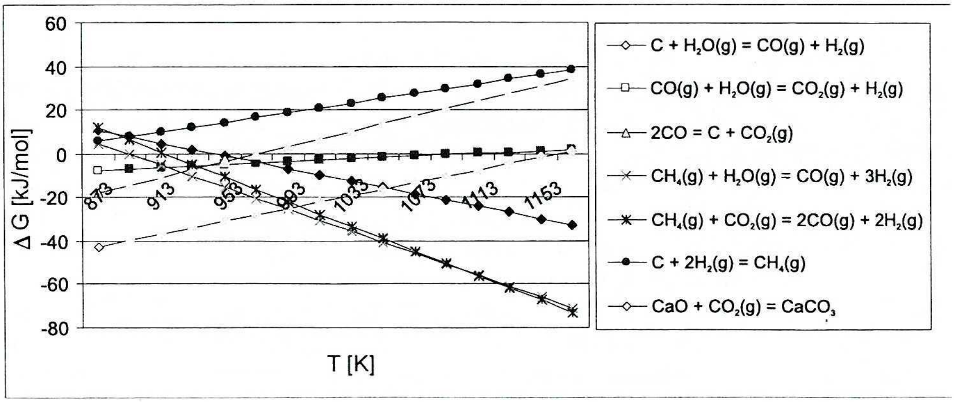

Fig. 1. The free Gibbs energy for the main reactions in the hydrogen-rich gas production through coal gasification

Based on the results presented in Figure 1 the considered temperature range may be divided into three levels:

- the temperature range of 948–973K,
- the temperature range of 973–1073K and
- the temperature range of 1073–1173K.

At the temperature range of 948–973K, the observed coal conversion rate is low. At a temperature higher than 903K, methane steam reforming is observed and at a temperature over 923K, methane is consumed in the reaction with CO_2, and CO and H_2 is produced.

The free Gibbs energy calculated for the main reactions in the hydrogen-rich gas production process through coal gasification at the temperature range of 973–1073K shows the immediate coal conversion and a minor influence of the water-gas shift reaction on the CO/CO_2 ratio. Moreover, at a temperature higher than 993K, the reverse Boudouard reaction is observed during which amorphous carbon and CO_2 are consumed, which results in CO gas enrichment.

The last temperature range, of 1073–1173K, shows high coal conversion. At the temperature higher than 1073K the reverse reaction to water-gas shift reaction takes place and CO_2 is consumed to produce CO and steam. Calculations of free Gibbs energy for the reaction of CaO carbonation indicate that the absorption of CO_2 on CaO is preferred at a relatively lower temperature range as calcination starts at the temperature of 1165K. The problem of limestone calcinations is widely discussed in literature, but still there is no consensus on $CaCO_3$ calcinations mechanism [2, 3, 9, 10]. However, it is recognized that CO_2 concentration, which considerably inhibits the reaction, particle size, limiting the thermal and mass transfer, and the catalytic or inhibiting effects of impurities such as Li_2CO_3 considerably accelerating the reaction, may have all great impact on the calcination kinetics [13]. The calcination process is usually conducted at the temperature range of 1023–1173K, whereas the carbonation at 823–1023K [10].

At the same time, the temperature of the process discussed should be maximum 1123K, which is the maximum temperature at which Boudouard reaction and carbonation reaction are thermodynamically favorable [1, 4, 5].

MATERIALS

Hard coal samples from Piast coal mine which is considered to be a potential future supplier of coal for a full scale gasification system in terms of resources, quality and price were used in the laboratory tests of hydrogen-rich gas production through coal gasification with addition of CaO [12]. For the coal samples tested, the basic analyses of the selected physical and chemical parameters of fundamental importance for the gasification process were conducted, such as: content of C, H, N, S, total moisture, ash and volatile matter. The characteristic temperature of fusibilities of ash, namely sintering point, softening point, melting point and flow temperature, were determined both in the oxidizing and reducing atmosphere. Moreover, the combustion heat and calorific value of the analyzed coal samples were determined. Results of these analyses are presented in Table 1. A commercial grade highly reactive CaO from Lhoist Bukowa Plant, a leading Polish lime producer were used in the experiments.

Table 1. The basic analysis of the selected coal sample from the Piast coal mine

Parameter	Value	
As-received		
Total moisture W_t^r [%]	8.58	
Ash A^r [%]	5.54	
Total sulfur S_t^r [%]	0.49	
Calorific value Q_i^r [kJ/kg]	26798	
Analytical		
Total moisture W^a [%]	6.02	
Ash A^a [%]	5.69	
Volatiles V^a [%]	31.12	
Heat of combustion Q_s^a [kJ/kg]	28805	
Calorific value Q_i^a [kJ/kg]	27616	
Ash melting points:	oxidation	reduction
Sintering point t_s [°C]	990	960
Softening point t_A [°C]	1270	1160
Melting point t_B [°C]	1350	1180
Flow temp. t_C [°C]	1370	1210
Total sulfur S_t^a [%]	0.50	
Carbon C_t^a [%]	70.64	
Hydrogen H_t^a [%]	4.08	
Nitrogen N^a [%]	0.98	
Dry		
Ash A_d [%]	6.05	
Total sulfur S_t^d [%]	0.53	
Volatiles V^{daf} [%]	35.25	
Heat of combustion Q_s^{daf} [kJ/kg]	32625	

EXPERIMENTAL PROCEDURE AND APPARATUS

The experiments were conducted in a laboratory-scale fixed bed reactor presented in Figure 2. The maximum reactor operating pressure was 5 MPa and the maximum operating temperature was 1173K. The gasifying medium in the process of hydrogen production through coal gasification was steam generated in a steam generator (2) and transported by a pump (3). The mixture of steam and an inert gas was supplied to the vertical fixed bed gasifier (5) located inside a resistance furnace (4), whose temperature was controlled by a computer (11). The temperature and pressure inside the reactor were controlled via a thermocouple (6), manometer (7) and pressure valve (8). The outlet gas was cooled and dried in a water trap (9). The composition of the outlet gas mixture was analyzed via a gas chromatograph (12) and the amount of gas produced in the gasification process was measured by a flow meter (10) every 3.2 minutes.

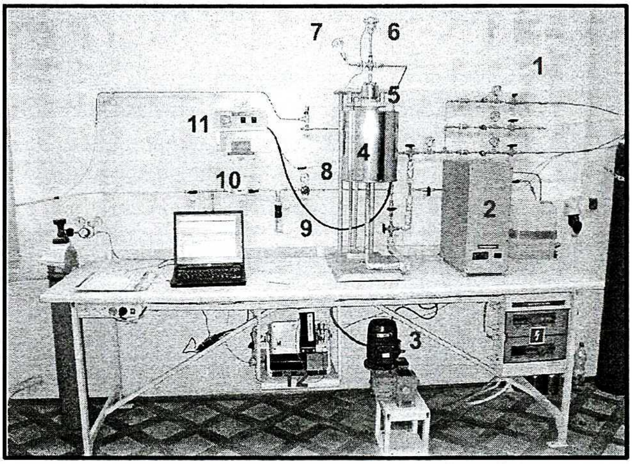

Fig. 2. The laboratory-scale fixed bed reactor installation for coal gasification: 1 – gases inlets (valves, flow regulators), 2 – steam generator, 3 – pump, 4 – resistance furnace, 5 – fixed bed reactor, 6 – thermocouple, 7 – manometer, 8 – pressure regulator, 9 – water trap, 10 – flow meter, 11 – furnace temperature control, 12 – gas chromatograph

Three series of experiments were conducted. In the first series the sample of 3.1 g of coal was fed into the fixed bed reactor (Fig. 3a), whereas in the second and third series 3.1 g of coal and 50 g of CaO were used: in layers (Fig. 3b) and mixed (Fig. 3c), respectively, and the reactor was heated in an inert gas atmosphere to the temperature of 948, 973, 1023, 1073, 1123 and 1173K. After the temperature stabilization, the steam was injected upwards the gasifier with a flow rate of 3.2 cm^3/min and the outlet gas cooled and dried in a water trap was analyzed on-line via GC and its flow was measured by a flow meter.

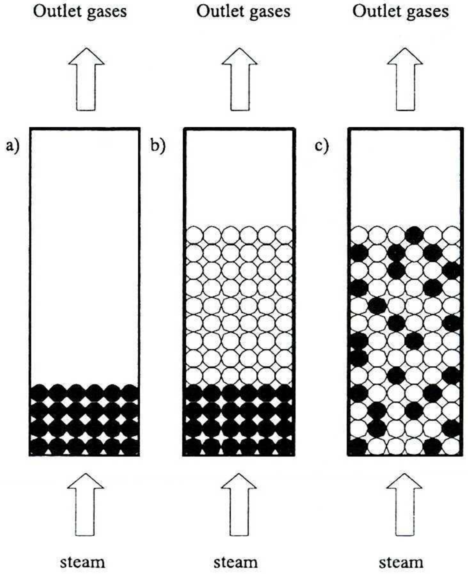

Fig. 3. The samples tested in the experiments: (a) sample of coal, (b) coal sample and CaO layered (c) coal sample and CaO mixed

RESULTS AND DISCUSSIONS

In Figure 4 the main gaseous products flows and percentage composition of the gaseous product mixture produced in the process are presented. Hydrogen is the main syngas component obtained in the process of coal gasification at the temperature range of 948–1173K. The lowest value of hydrogen (48%) was observed at the temperature of 948K and the highest one (67%) at the temperature of 1123K. The theoretically achievable total amount of hydrogen from Piast coal sample was 8175 cm^3. The ratio of hydrogen amount obtained in one-hour test duration (Tab. 2) to the total theoretical amount was as follows:

- at the temperature of 948K – 0.30,
- at the temperature of 973K – 0.46,
- at the temperature of 1023K – 0.51,
- at the temperature of 1073K – 0.50,
- at the temperature of 1123K – 0.59,
- at the temperature of 1173K – 0.65.

The relatively higher amounts of hydrogen produced (4805 cm^3 and 5345 cm^3) and the highest average percentage of hydrogen in the product mixture (67% and 65%) were observed for the tests at the temperatures of 1123K and 1173K, respectively.

The remaining gaseous products, mainly CO_2, CO and small amounts of CH_4 constituted about 33% and 52% of the gaseous products mixture at the temperature of 1123 and 948K, respectively. Next series of experiments aimed at CO_2 separation from the products mixture in the process of absorption on CaO. Coal samples and CaO were put in layers or mixed and the gasification tests were conducted at various temperatures. The main gaseous products flows and percentage composition of the gaseous products mixture in a steam gasification process of Piast coal mine samples with CaO at the temperature range of 948–1173K are presented in Figures 5 and 6.

The percentage compositions of the gaseous products mixture obtained in coal gasification with CaO are presented in Tables 3 and 4. Gasification with CaO, layered and especially mixed with coal samples led to a significant increase in hydrogen content at the whole temperature range.

The ratio of hydrogen volume obtained in one-hour test duration (Tabs 3 and 4) to the total theoretically achievable in test with CaO addition was as follows:

CaO in layers

- at the temperature of 948K – 0.41,
- at the temperature of 973K – 0.53,
- at the temperature of 1023K – 0.60,
- at the temperature of 1073K – 0.62,
- at the temperature of 1123K – 0.61,
- at the temperature of 1173K – 0.67.

CaO mixed

- at the temperature of 948K – 0.48,
- at the temperature of 973K – 0.56,
- at the temperature of 1023K – 0.69,
- at the temperature of 1073K – 0.61,
- at the temperature of 1123K – 0.65,
- at the temperature of 1173K – 0.72.

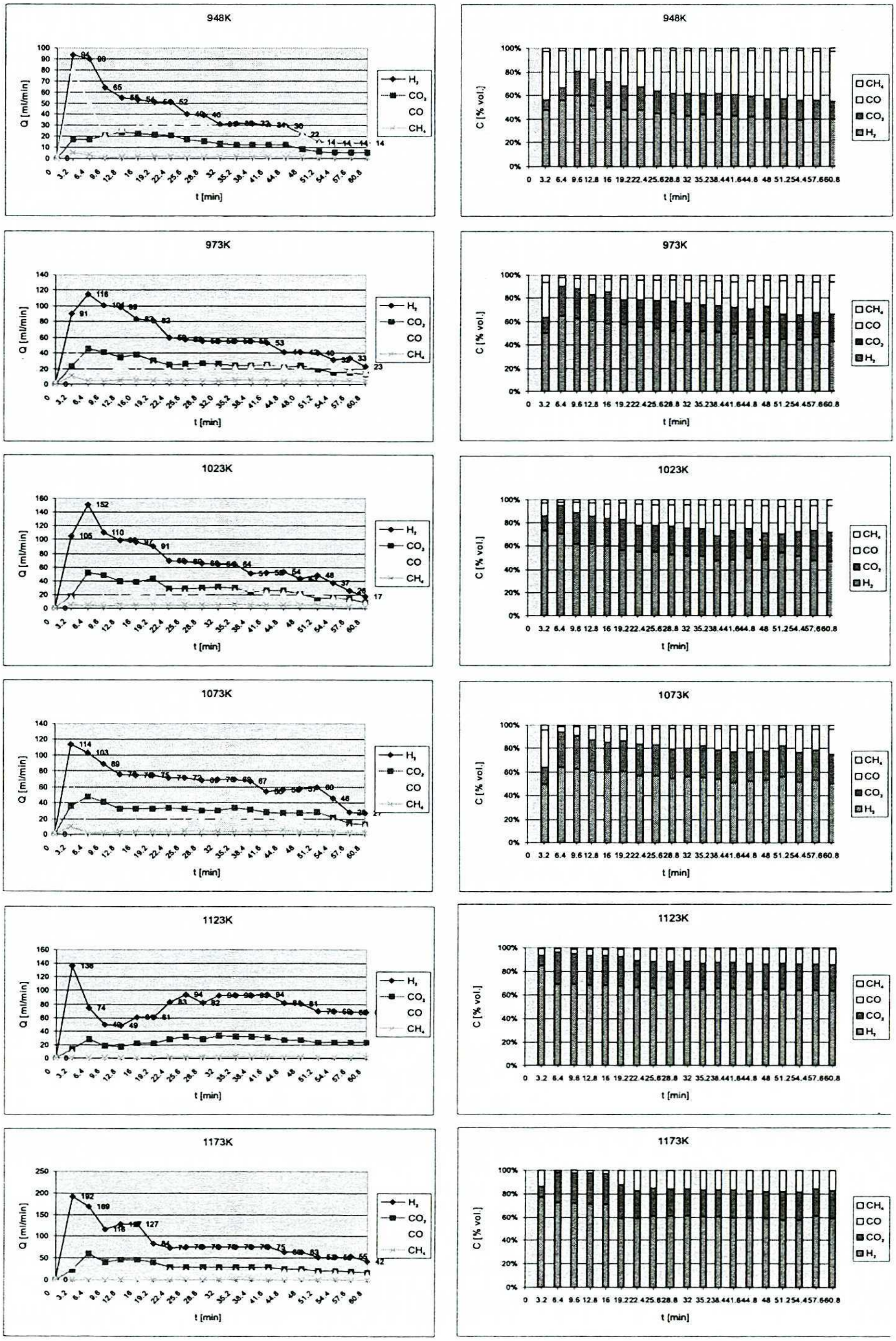

Fig. 4. (a) The main gaseous products flows and (b) percentage composition of the gaseous product mixture in a steam gasification process of Piast coal mine samples at the temperature range of 948–1173K

Table 2. The amounts of gaseous products generated in steam gasification process of Piast coal mine samples at the temperature range of 948–1173K

		948K				973K				1023K				1073K				1123K				1173K			
		CO2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]
No	t [min]																								
1	0-3.2	54	256	18	301	74	171	36	290	56	49	15	337	113	233	31	366	44	29	5	436	78	107	2	613
2	3.2-6.4	54	162	10	288	147	41	13	370	165	20	16	485	154	24	6	330	93	9	4	237	190	12	0	541
3	6.4-9.6	68	65	3	207	130	48	14	322	157	52	11	352	131	32	8	286	60	8	3	158	133	10	0	371
4	9.6-12.8	77	85	5	176	111	68	18	317	126	57	14	317	105	41	10	244	57	12	3	156	151	12	0	408
5	12.8-16.0	73	92	6	172	123	51	17	266	124	65	17	309	104	47	10	239	73	13	5	196	149	14	0	408
6	16.0-19.2	69	103	7	164	98	79	18	262	137	70	16	291	106	42	11	241	70	16	5	195	132	55	1	269
7	19.2-22.4	67	104	7	165	80	58	15	190	91	73	15	221	107	54	11	229	92	35	6	266	95	68	1	236
8	22.4-25.6	53	97	6	129	83	59	16	185	91	72	17	219	104	54	13	229	104	44	7	301	94	60	1	244
9	25.6-28.8	49	103	6	127	89	62	14	177	97	75	16	211	98	69	13	220	90	40	7	263	94	61	1	244
10	28.8-32.0	42	83	5	98	82	67	16	178	98	79	18	205	97	67	13	223	106	44	8	299	95	61	1	243
11	32.0-35.2	40	82	5	101	77	71	18	178	96	80	19	205	106	60	12	222	101	51	8	297	93	65	1	241
12	35.2-38.4	40	82	5	101	77	73	16	175	74	90	16	164	101	72	13	215	104	46	8	299	92	64	1	243
13	38.4-41.6	41	85	5	98	78	76	19	170	85	74	16	167	89	66	12	175	101	48	8	301	93	66	1	239
14	41.6-44.8	40	87	6	95	71	69	14	132	85	70	17	171	86	62	16	179	89	44	7	260	80	59	1	203
15	44.8-48.0	28	69	4	70	76	64	13	133	66	67	15	138	85	64	11	183	87	47	7	259	79	61	1	202
16	48.0-51.2	19	46	3	46	61	81	15	128	47	68	16	155	91	47	13	192	76	37	6	223	69	51	1	165
17	51.2-54.4	18	48	3	45	49	65	13	101	48	49	13	118	71	57	11	147	76	40	6	221	68	52	1	165
18	54.4-57.6	19	47	3	45	48	60	14	106	44	37	9	82	45	30	6	91	76	41	6	220	65	45	1	175
19	57.6-60.8	18	48	3	45	41	47	10	73	29	26	6	54	43	36	6	86	76	43	6	218	53	40	1	135
23	A = Total [cm^3] t = 60.8 min	870	1743	110	2474	1595	1311	310	3753	1714	1171	283	4202	1835	1156	223	4098	1575	649	112	4805	1901	963	17	5345

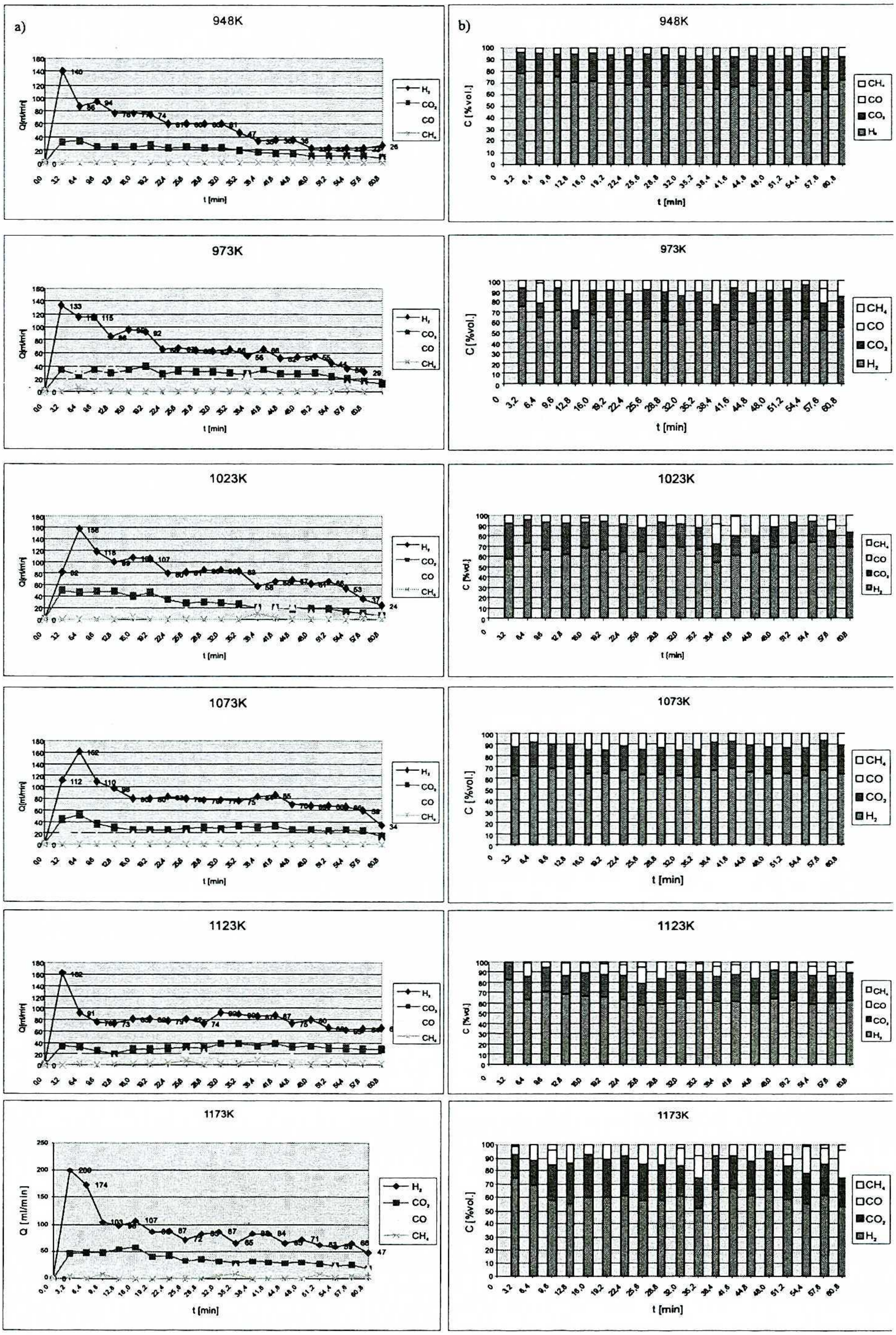

Fig. 5. (a) The main gaseous products flows and (b) percentage composition of the gaseous products mixture in a steam gasification process of Piast coal mine samples with CaO (layered) at the temperature range of 948–1173K

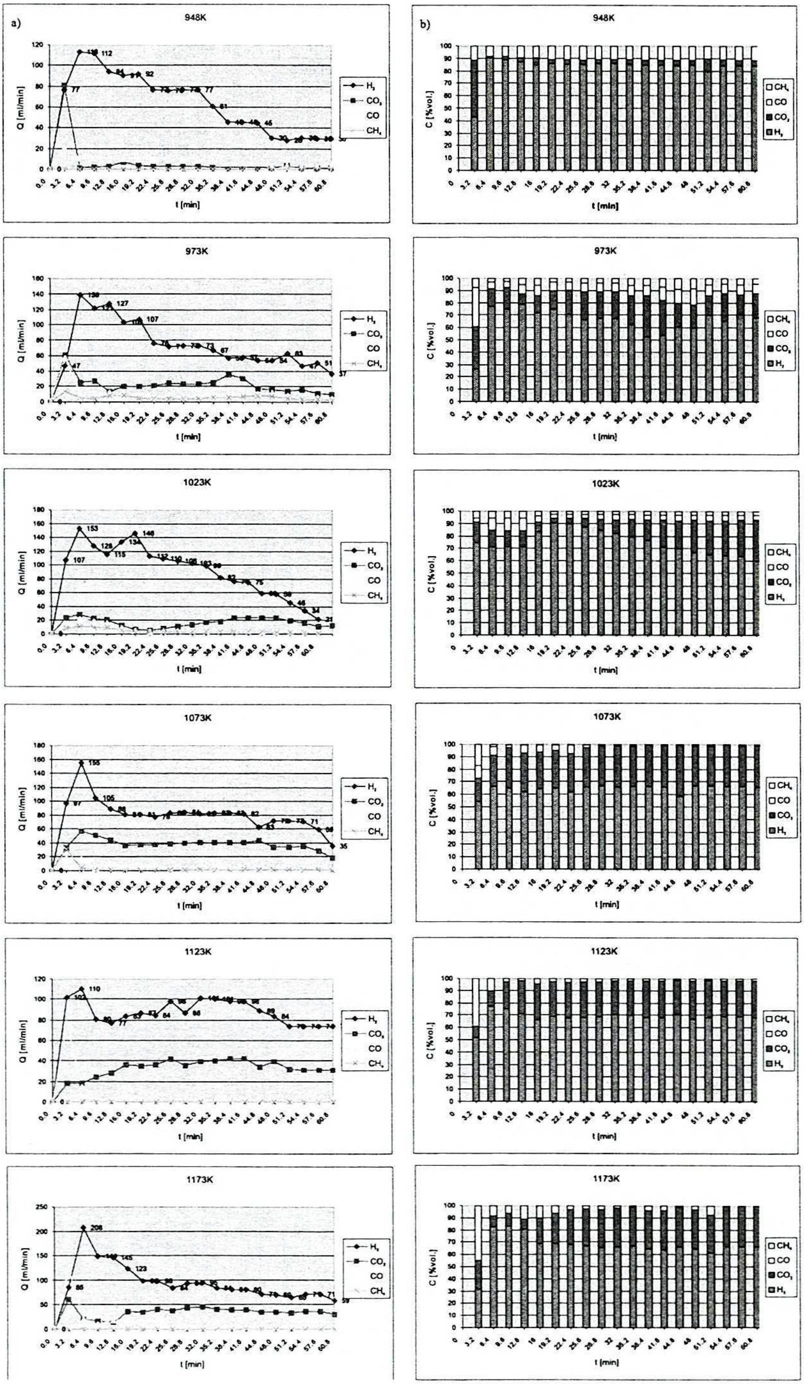

Fig. 6. (a) The main gaseous products flows and (b) percentage composition of the gaseous products mixture in a steam gasification process of Piast coal mine samples with CaO (mixed) at the temperature range of 948–1173K

The highest amount of hydrogen produced in tests with CaO layered (5442 cm^3) was observed at 1173K, while the highest hydrogen percentage content in the gaseous products mixture (70%) at 948K. In the case of CaO mixed with coal, the highest volume of hydrogen was 5857 cm^3 at 1173K and the highest hydrogen content in the outlet gas was 81% at 948K.

The process of CO_2 capture by the absorption on CaO was effective in the case of CaO mixed with a coal sample at a relatively low temperature (948K) (Fig. 7). At higher temperatures a reaction resulting in CO_2 concentration increase in the product gas mixture was observed. In tests with CaO layered on a coal sample CO_2 absorption was not observed possibly due to CaO agglomeration effect.

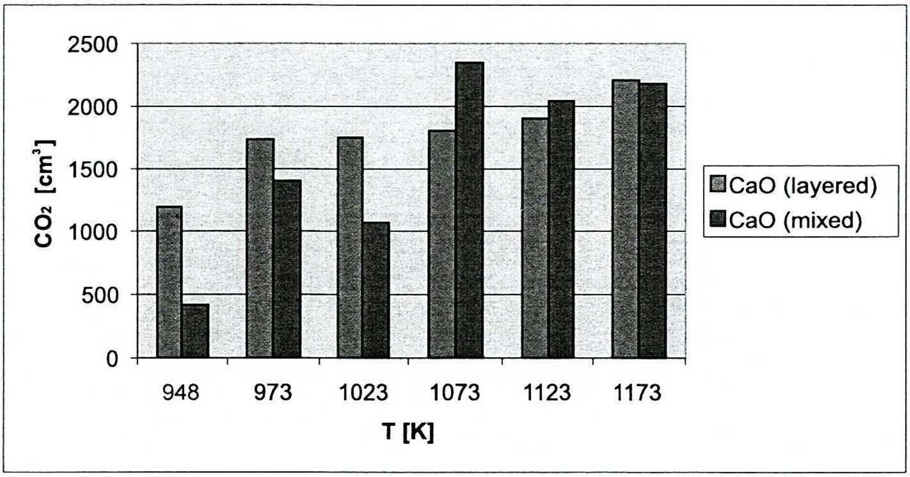

Fig. 7. Amount of CO_2 in gaseous product mixture generated in one-hour test duration

CONCLUSIONS

The hydrogen yield increased with the temperature in each of the three test series (that is I – steam gasification, II – steam gasification with CaO layered and III – steam gasification with CaO mixed) and reached the maximum of 72% of the theoretically achievable at 1173K with CaO mixed with a coal sample.

The removal of CO_2 from the outlet gas stream in the process of CaO carbonation resulted in a significant hydrogen content increase in the products mixture at 948K (70% and 81% for series II and III in comparison with 48% in series I) and in hydrogen yield increase in the outlet gas when comparing results at corresponding temperatures in the three series.

According to the expectations, mixing coal sample with CaO before gasification resulted in hydrogen yield increase as well as in percentage content in product mixture in comparison with CaO layered.

In the calcinations process (not discussed in the paper) $CaCO_3$ may be decomposed to produce pure stream of CO_2 ready for sequestration and CaO recycled to the process.

Based on the thermodynamic analysis of the gasification process and a literature review, a conclusion may be drawn that the temperature is one of the most important

Table 3. The amounts of gaseous products generated in steam gasification process of Piast coal mine samples with CaO (layered) at the temperature range of 948–1173K

		948K				973K				1023K				1073K				1123K				1173K			
		CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]	CO_2 [cm^3]	CO [cm^3]	CH_4 [cm^3]	H_2 [cm^3]
No	t [min]																								
1	0-3.2	100	23	0	449	106	39	0	427	160	34	0	264	142	71	0	358	112	0	0	517	150	57	9	641
2	3.2-6.4	105	18	0	277	81	106	16	369	149	31	0	506	164	59	0	519	100	62	3	292	154	91	0	555
3	6.4-9.6	80	20	0	300	111	35	0	369	156	37	0	379	113	50	0	351	81	18	0	244	152	64	24	331
4	9.6-12.8	82	17	0	243	93	147	0	274	155	42	0	317	99	45	0	313	64	39	5	234	174	83	0	314
5	12.8-16.0	81	16	0	245	109	42	0	305	130	25	11	348	86	57	0	257	91	39	5	265	185	44	0	343
6	16.0-19.2	85	21	0	237	124	39	0	294	145	27	0	342	86	58	0	256	88	44	7	261	131	51	0	275
7	19.2-22.4	75	16	0	195	87	44	0	212	108	36	0	256	86	47	0	267	94	41	13	252	139	38	0	280
8	22.4-25.6	79	15	0	191	100	29	0	214	90	51	0	259	91	55	0	254	100	70	24	263	110	60	0	231
9	25.6-28.8	76	17	0	192	97	38	0	208	98	28	0	274	96	53	0	251	97	68	0	235	120	72	0	264
10	28.8-32.0	71	18	0	196	94	51	0	197	88	38	0	274	92	60	0	248	123	37	3	294	104	61	14	278
11	32.0-35.2	63	15	0	150	92	39	0	211	85	48	0	267	103	56	0	241	124	35	8	289	91	70	31	208
12	35.2-38.4	50	11	0	110	85	80	0	178	61	64	32	185	99	33	0	268	112	45	23	277	101	34	0	265
13	38.4-41.6	44	12	0	115	107	24	0	211	65	63	5	211	99	27	0	273	123	41	14	280	98	33	0	269
14	41.6-44.8	45	11	0	115	83	36	0	166	58	69	0	215	83	35	0	225	101	60	0	239	91	43	0	209
15	44.8-48.0	33	8	0	73	86	27	0	173	58	31	0	196	81	42	0	220	111	33	0	256	98	16	0	228
16	48.0-51.2	33	8	0	73	89	21	0	176	55	21	0	210	80	44	0	219	99	29	4	212	88	30	25	200
17	51.2-54.4	34	9	0	72	75	11	0	142	45	13	0	170	85	45	0	212	94	33	14	201	79	71	4	188
18	54.4-57.6	32	9	0	73	64	32	16	116	29	16	8	118	77	19	0	190	93	30	15	206	80	43	10	211
19	57.6-60.8	23	9	0	83	50	27	0	94	17	19	0	78	43	18	0	110	92	35	4	212	61	60	12	152
23	A = Total [cm^3] t = 60.8 min	1193	272	0	3389	1735	866	32	4336	1751	691	57	4870	1806	875	0	5032	1898	759	142	5027	2207	1019	130	5442

Table 4. The amounts of gaseous products generated in steam gasification process of Piast coal mine samples with CaO (mixed) at the temperature range of 948–1173K

		948K				973K				1023K				1073K				1123K				1173K			
		CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]	CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]	CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]	CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]	CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]	CO2 [ml]	CO [ml]	CH4 [ml]	H2 [ml]
No	t [min]																								
1	0-3.2	260	66	0	245	196	181	43	151	75	15	25	342	106	57	97	311	58	245	0	325	196	387	0	273
2	3.2-6.4	5	33	0	361	81	31	18	443	92	69	37	488	181	55	12	495	59	46	0	352	68	67	0	665
3	6.4-9.6	8	34	0	358	88	26	12	388	72	57	34	409	164	11	3	337	77	8	0	257	56	38	0	478
4	9.6-12.8	9	33	0	300	41	40	25	408	64	50	31	369	143	27	4	283	90	6	0	246	46	61	0	464
5	12.8-16.0	21	32	0	290	64	38	25	330	39	29	18	428	116	21	4	259	116	17	0	267	118	59	0	394
6	16.0-19.2	12	36	0	295	66	31	15	344	20	16	12	466	119	17	3	260	112	10	0	277	112	30	0	315
7	19.2-22.4	10	31	0	245	67	22	11	243	18	12	10	360	121	27	3	248	116	13	0	270	131	14	0	312
8	22.4-25.6	10	33	0	243	78	23	14	228	27	13	10	350	126	7	3	264	133	11	0	313	121	11	0	268
9	25.6-28.8	9	31	0	245	74	24	12	233	37	14	11	338	128	1	4	268	114	10	0	276	142	15	0	300
10	28.8-32.0	9	31	0	246	73	24	12	233	44	16	11	329	133	1	3	263	126	8	0	323	146	8	0	303
11	32.0-35.2	8	25	0	195	80	29	19	215	56	15	11	318	131	1	3	265	128	8	0	322	130	2	0	267
12	35.2-38.4	7	20	0	145	114	29	19	181	57	13	11	262	131	1	3	266	137	7	0	313	126	15	0	258
13	38.4-41.6	6	20	0	145	99	37	24	184	75	13	10	245	132	1	3	264	137	8	0	312	129	14	0	257
14	41.6-44.8	7	19	0	145	55	32	26	173	77	15	11	240	138	0	3	202	110	5	0	284	113	2	0	227
15	44.8-48.0	5	13	0	97	53	38	24	171	75	11	9	191	110	1	3	229	125	6	0	268	111	10	0	222
16	48.0-51.2	12	12	0	91	45	26	15	200	78	12	9	187	109	1	3	230	102	5	0	235	107	26	0	209
17	51.2-54.4	5	12	0	96	51	17	10	151	63	10	8	147	112	1	3	228	101	6	0	236	115	0	0	228
18	54.4-57.6	6	13	0	96	37	19	11	162	50	6	6	109	93	0	2	190	100	6	1	237	116	0	0	227
19	57.6-60.8	5	13	0	96	33	13	8	117	38	4	4	68	57	0	2	113	100	7	1	235	96	0	0	190
23	A = Total [cm^3] t=60.8 min	415	505	0	3934	1395	679	343	4552	1060	388	275	5646	2349	228	160	4975	2040	432	4	5349	2181	760	0	5857

process parameters. There is an optimal temperature range in which a maximum of the gaseous product is produced. The temperature has also a great impact on the endothermic reaction of coal gasification and on WGS reaction.

An effective CO_2 capture was observed at relatively low temperatures in tests with CaO mixed with a coal sample.

Thermodynamic analysis of the process of coal gasification to hydrogen-rich gas with CO_2 absorption and the results of the experiments carried out show that finding the 'compromise' temperature for gasification and carbonation is of crucial importance in terms of process optimization.

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BADANIA LABORATORYJNE PRODUKCJI WODORU NA DRODZE ZGAZOWANIA WĘGLA Z JEDNOCZESNĄ REDUKCJĄ EMISJI CO_2 Z ZASTOSOWANIEM SORBENTU WAPNIOWEGO

Wodór postrzegany jest jako konkurencyjny ekonomicznie, przyjazny środowisku nośnik energii. W pracy przedstawiono wyniki badań laboratoryjnych procesu zgazowania polskiego węgla kamiennego ukierunkowanego na produkcję gazu bogatego w wodór, z jednoczesnym wychwytywaniem CO_2 z otrzymanego gazu syntezowego na drodze absorpcji z zastosowaniem CaO. Badany węgiel pochodził z pokładów KWK Piast uważanej za jedną z potencjalnych dostawców węgla dla zgazowania przemysłowego, ze względu na zasoby, jakość, cenę i reaktywność surowca. Testy prowadzono w reaktorze ze złożem stałym w zakresie temperatur 948–1173K w trzech seriach: z dodatkiem CaO w układzie warstwowym (II), z dodatkiem CaO wymieszanym z próbką węgla (III) oraz bez dodatku CaO (I). Zastosowanie CaO wpłynęło na zwiększenie produkcji oraz zawartości procentowej wodoru w mieszaninie gazowych produktów reakcji w porównaniu z wynikami serii I. Zgodnie

z oczekiwaniami lepsze wyniki w zakresie ilości produkowanego wodoru oraz jego zawartości procentowej uzyskano w przypadku wymieszania CaO z próbką węgla niż w układzie warstwowym. Efektywna absorpcja CO_2 zaobserwowana została w przypadku testów prowadzonych z zastosowaniem CaO zmieszanego z węglem w stosunkowo niskich temperaturach. W wyższych temperaturach zaobserwowano zwiększenie stężenia CO_2 w powstającym gazie.