The monitoring and control of underground coal gasification in laboratory conditions

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Monitorovanie a riadenie podzemneho splyňovania uhlia v laboratórnych podmienkach

A number of coal gasification technologies are currently available or under various stages of development. One technology "Underground coal gasification (UCG)" is receiving renewed interest around the world. In this paper is provided the analysis of relevant processes during UCG. The laboratory equipment is described. Since experiments have long time response, partial automation has been realised. The structure of monitoring and control system is shown. Analysed are some results of measured data for oxidizing by air. Also, the influence of temperature on the structure of syngas is analysed. In light of the experimental results, potential performance of UCG in Slovak coal seam conditions is discussed.

***Key words**: clean technology, experimental equipment, structure of control system, gas composition.*

Introduction

Underground Coal Gasification (UCG) is an in situ technique to recover the fuel or feedstock value of coal that is not economically available through conventional recovery technologies. Although coal is the most plentiful fossil fuel, only a small fraction of the potential coal reserves can be economically accessed through shaft or strip mining. The remaining coal has no value - unless alternative recovery technologies, such as UCG, are developed.

The idea of UCG is not new. UCG was apparently first suggested by two German engineers, brothers Werner and Wilhelm Siemens, as early as in 1868. Independently of that, the Russian scientist Dmitry I. Mendeleyev had been developing a detailed design for operation concept of UCG (1880). An early patent was granted in 1909 to American A.G. Bets. A plan for the first real UCG experiment was announced by the English chemist Sir William Ramsey (1912). The gas composition depends on the coal geology as well as the process parameters. It can be produced using a variety of oxidants, including air and oxygen-rich gaseous blends (O_2/H_2O, CO_2/O_2 and so on). The UCG can be applied to coal in a wide range of geological conditions, with the following preferred parameter: coal seam thickness from 0.5 to 30 m, dip from 0° to 70°, depth from 30 to 800 m, calorific value from 8 to 30 $MJ.kg^{-1}$ (which includes low-quality lignite and bituminous coal). The basic process of UCG is shown in Fig. 1.

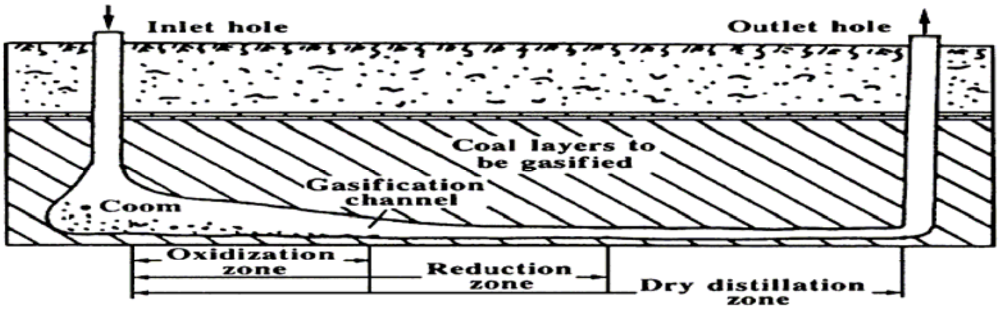

Fig. 1. Underground coal gasification in horizontal coal seam.

Consider a roughly horizontal coal seam sandwiched between underlying and overlying layers of rock. Two vertical wells are completed near the bottom of the coal seam A highly gas - permeable channel is created between these two wells, for next described processes. A mixture of steam, air, and oxygen is forced into the gas injection well. The partial combustion of coal in the gasifier cavity around the injection well creates heat that drives the endothermic gasification reactions between coal, oxygen and water. The product gas is a mixture principally of carbon dioxide, carbon monoxide, hydrogen, methane, steam

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and nitrogen if air is used. It also contains in smaller amounts ethane, propane and higher hydrocarbons, along with coal tars. (Dobbs, R.L., Krantz,W.B., 1990).

Products of gasification depend from particular coal seam.

Reasons for using UCG are decrease of energy costs, impossibility to mine coal for economic and ecologic aspects. In the world, the underground coal gasification is investigated in laboratories and in real coal seams. Table 1 shows basic data from UCG in USA und Spain. Presented are various properties of the coal seams and intake gasses. In Table 2 is shown the structure of syngas from Australia and USA (Blinderman, M. S. et al., 2002).

Tab. 1. Data for five experimental fields.

	Hanna I	Pricetown	PSC	RM I	El Tremedal
Country	USA				Spain
Year	1973	1979	1983	1987	1997
Coal density (kg/m^3)	1380	1360	1390	1390	1363
Fixed carbon (weighted %)	35.5	49.5	28	30.8	28.2
Volatile substances (weigh.%)	28.5	38.1	34	31.7	24.4
Ash (weighted %)	14.4	11	21	28.9	28.2
Humidity (weighted %)	21.6	1.4	17	8.6	19.1
Intake gas	H_2O/O_2	Air	H_2O/O_2	H_2O/O_2	H_2O/O_2
Pressure (kPa)	150	2100	430	500	5000

Tab. 2. Comparison of syngas structure.

Locality	Intake gas	CO	CO_2	H_2	CH_4	N_2	Caloric value (MJ/m^3)
Chincilla - Austrália	Air	7	19	22	8	43	6.6
Rocky Mountain I - USA	H_2O/O_2=2:1	12	37	40	9	2	9.5
Centralia LKB – 1 - USA	H_2O/O_2=3:1	24.1	27.1	40.9	3.9	2.2	9.2

On the basis of this analysis the following processes are highly probable during gasification.

Combustion of carbon	$C + O_2 \longrightarrow CO_2$
Partial oxidation	$C + 1/2\ O_2 \longrightarrow CO$
Oxidation CO	$CO + 1/2\ O_2 \longrightarrow CO_2$
Water gas shift	$CO + H_2O \longrightarrow CO_2 + H_2$
Methanation	$CO + 3H_2 \longrightarrow CH_4 + H_2O$
Hydrogenization	$C + 2H_2 \longrightarrow CH_4$
Boudouard’s reaction	$C + CO_2 \longrightarrow 2CO$
Reaction steam-carbon	$C + H_2O \longrightarrow CO + H_2$
Loosening of hydrogen	$2H$ (in coal) $\longrightarrow H_2$ (gas).

Laboratory equipment

The form of experimental vessel has been chosen to simulate the gasification of natural form coal seam (Kostúr, K., Kačúr, J., 2007). Of course, this plant is permanently being improved.

The base of this plant is steel generator (G) (Fig. 2). The tilting generator enables to simulate an inclination of coal seam. The compressor (K) forces air into a pressure vessel (TN). The pressure in vessel is controlled by programming logic controller (PLC) through solenoid (SV). The air can be concentrated by oxygen, water steam or dioxide of carbon by connection on input tube. The air or gas mixture is provided into generator by valves and tubes. This system of valves (V_i) and tubes will enable to simulate various arrangements of inlet holes and outlet holes. The pressure flow direction of gas is can be regulated in the generator by valves and flap valves. But this possibility is very limited. The syngas is exhausted by fan and it is combusted by a burner. The experimental plant has others measurement equipments as for example the flue gas analyzer, flow meters, the measurement of calorific value, etc.

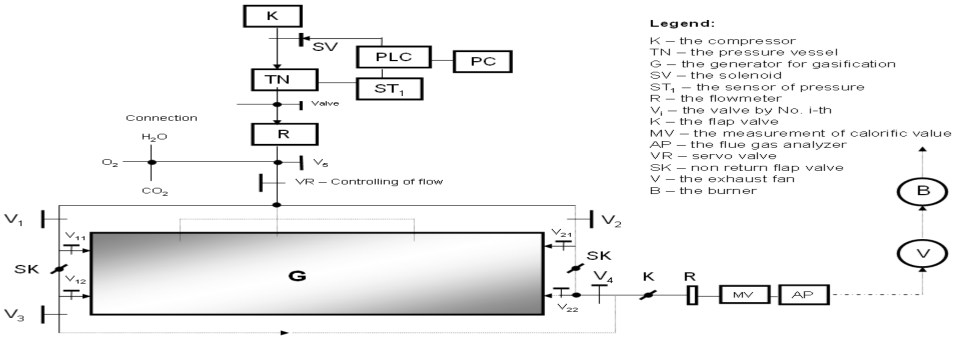

Fig. 2. Diagram of experimental plant.

The safety glass is located on the upper cover. Its aim is to observe the gasification process. Internal walls are covered by insulation.

The primary objective of this project is to obtain information for UCG under Slovak coal mining conditions. Figure 3 is basicallly the vessel component of coal gasification. Coal samples in the form of blocks can be sealed in the upper (Fig. 3a) or (and) lower part (Fig. 3b). The rock and coal are pressurised by vibration equipment. In all cases, the link (channel) must by made through coal. Fig. 3b shows the arrangement of sounds. This system of sounds consists of tubes and a number of valves. It enables to analyze processes along the vessel because valves are mounted on each sample tube in axial direction.

The system of sounds serves for monitoring:

- the pressure (static and dynamic),
- the gas content,

but it enables some gas agents to add into the process also. Addition of the gas agent is helpful for the control of gasification processes.

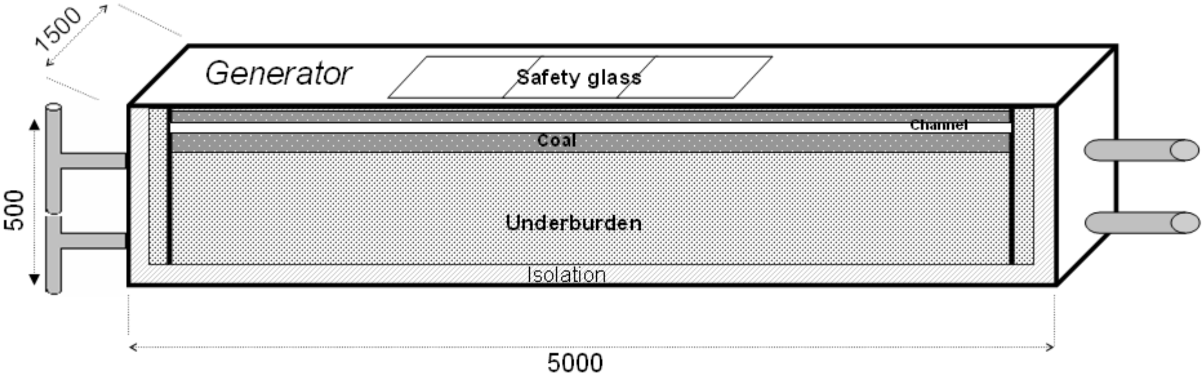

Fig. 3a. Coal gasification test vessel.

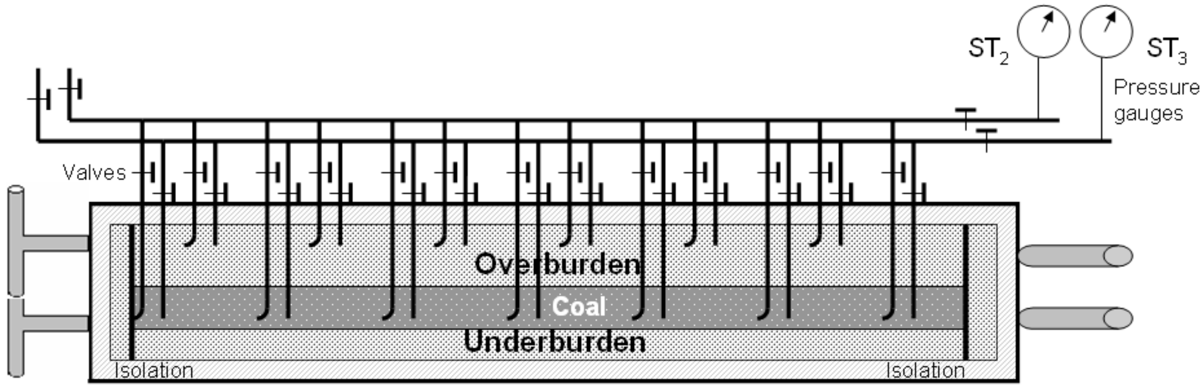

Fig. 3b. Coal gasification test vessel with sound system.

Correct temperatures are very important for gasification. Therefore, temperatures are measured in the channel, coal, and in the rock. In Fig. 4 is shown the arrangement of thermocouples. For experimental research, temperatures in channel and coal are sufficient. However, surface temperatures and temperatures in rock are necessary for mathematical model [3] which is developed within the framework of this project.

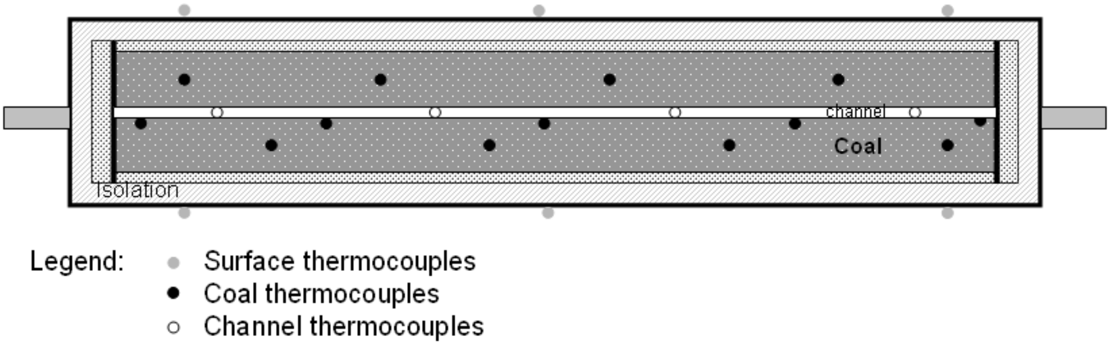

Fig. 4. Diagram of temperature measurement.

Monitoring and controlling system

The research of relevant processes of UCG required more information. This process is slow in laboratory conditions also. Therefore, the measurement was performed with the help of automation. The automation system can be divided into two parts:
- the monitoring system,
- the control system.

The hardware concept is based on connection between the PLC and PC through serial port.

The monitoring system provided data acquisition and data - preprocessing. The sampled - data system is based on programming logic controller (PLC) and special modules (multiplexers). The monitoring system provided the measurement with the following variables:
- temperatures in coal, channel, rock (34),
- surface temperatures (9),
- pressures in generator ,
- pressures of air, oxidizing agents, syngas,
- volume flows of air, oxidizing agents, syngas,
- the calorific value,
- the composition of syngas.

The structure of syngas is measured by the flue gas analyzer. This analyzer measures the content of CO, CO_2, O_2, H_2S, CH_4, NO, NOx. Selected data is shown on operating panel during experiment. All measured data is stored in computer (PC). Sample period can be changed during experiment also.

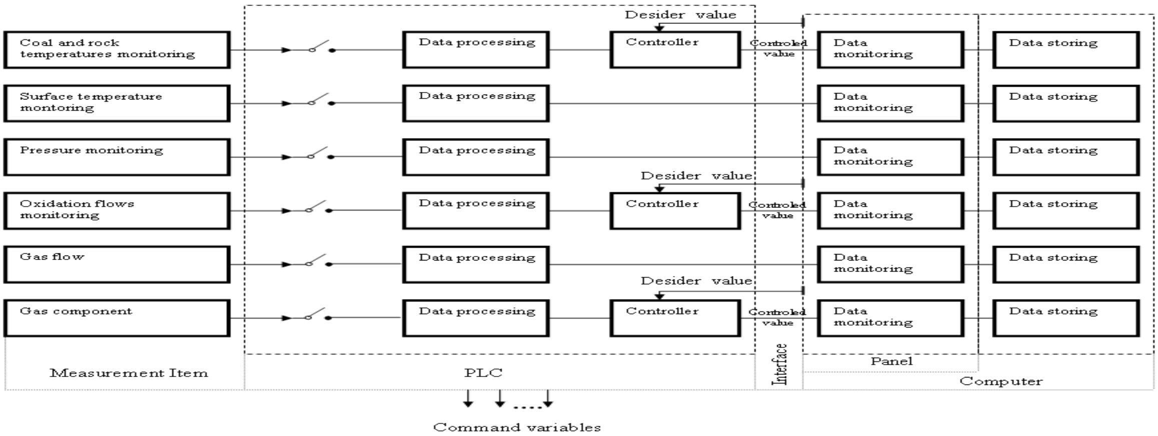

Fig. 5. The architecture of monitoring and controlling system.

The control system provided logical control (valves) and feedback control. Both functions are realized by PLC. Volume flows (air, addition oxidizing agents) are controlled by PI algorithms. Concentrations of CO and CO_2 are controlled by extreme control. The output pressure of syngas is provided by manual control. The temperature of syngas is controlled by PI controllers. Of course, all controllers are not active at the same time. The architecture of monitoring and controlling system is shown in Fig. 5.

Results and discussion

This equipment has been built for program research in the first half of year 2007.

In Tab. 3 are shown results from a technical analysis of the considered coal for our experiment.

Tab. 3. Technical and elementary analysis of the coal in mass %.

W_t^r	A^d	V^{daf}	C^{daf}	O^{daf}	H^{daf}	N^{daf}	Calorific value [MJ.kg^{-1}]
25,8	14,1	56,8	66,4	25,33	4,7	0,98	15,05

Where W_t^r is the capacity of water, A^d is the capacity of ash, W^{daf} is the capacity of volatile materials in combustibles, C^{daf}, O^{daf}, H^{daf}, N^{daf} are capacities of carbon, oxygen, hydrogen and nitrogen in combustibles.

Results from chemical analysis of the coal are shown in Tab. 4.

Tab. 4. Chemical analysis of the coal.

Elements and compounds	**Mass percent**
C	**27,66**
H	**3,43**
N	**0,51**
O	**18,30**
CaO	**1,47**
MgO	**0,94**
SiO_2	**31,70**
Al_2O_3	**9,49**
Fe_2O_3	**3,30**
Na_2O	**0,30**
P_2O_5	**0,06**
TiO_2	**0,31**
Total S	**1,37**

The original coal and rock was stored to the generator, which was inclined at 10° angle. The higly gas - permeable channel was created on lower level. The air was used as oxidizer. In the test reported here, the volume flow of air was from range 1.5 – 15 m^3.h^{-1}. The initial oxidant air flow rate was set to 3 m^3.h^{-1}. The power was gradually increased to full power over a period of 25 minutes. The temperature of the thermocouple near or on the ignited coal face was monitored. Ignition was detected frequently by an abrupt temperature rise to 550 – 700 °C in one or more of first rank thermocouples. The measured temperatures in approx. distance ¼ (T21) or ½ (T26) and ¾ (T30) of the generator length are shown in Fig. 6. The maximal temperature in coal was 800 °C. The maximal temperature measured by thermocouples in rock was below 100 °C.

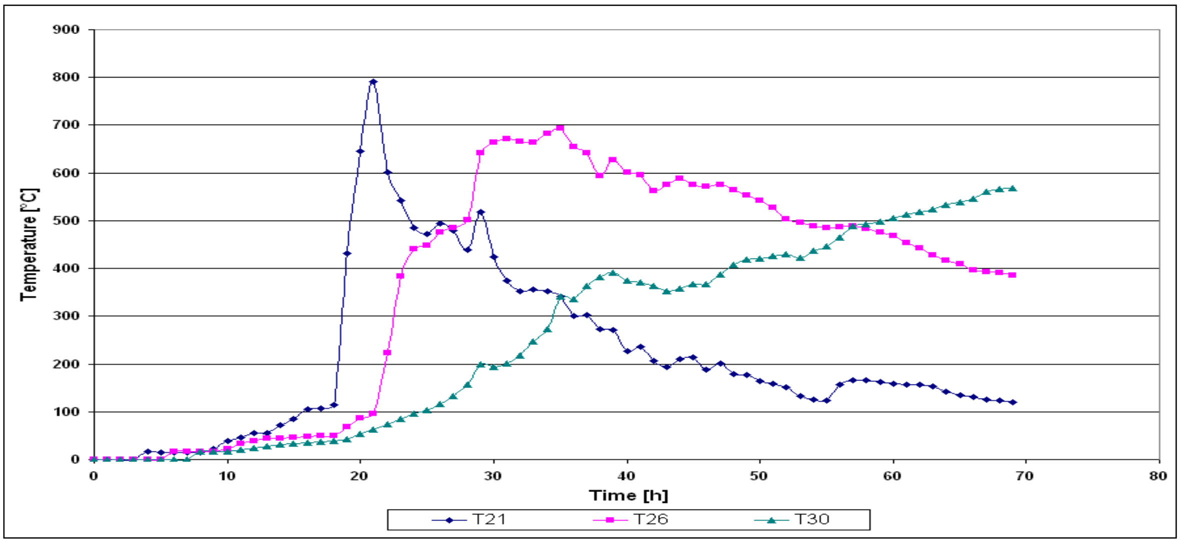

Fig. 6. Measured temperature of coal near gasification tunnel.

In Fig. 7 and 8 are shown concentrations of combustion products. From Fig. 7 we can see (8 hour) that if the controller brings down air flow rate (lowering O_2) then the concetration of CO_2 and CO rises. Again, this event was repeated from 55 to 60 hours of experiment. Fig. 8 shows the time response of concetration gases with higly calorific value (CH_4, H_2). The maximal concetration of methane was approx. 3,5 % and for hydrogen it was 1.2 %. This event was in time intervals 20-30 hours and 50-60 hours. In these intervals the concentration of CO_2 was high also (Fig. 7). It confirms the importance of oxidation zone. Maximal calorific value was 2.2 $MJ.m^{-3}$.

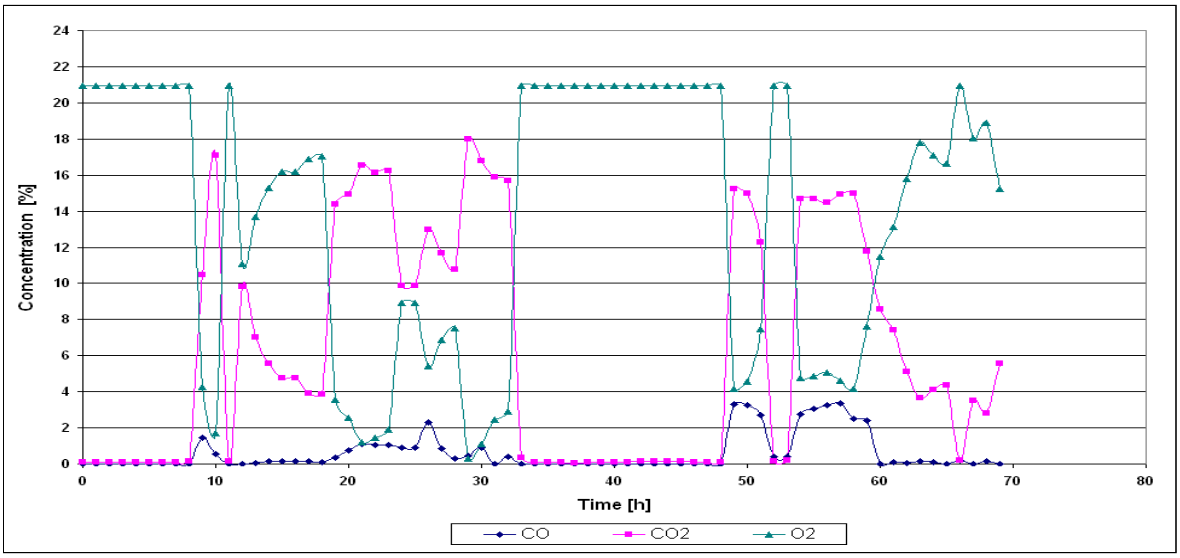

Fig. 7. Concentrations of CO, CO_2, O_2 during experiment.

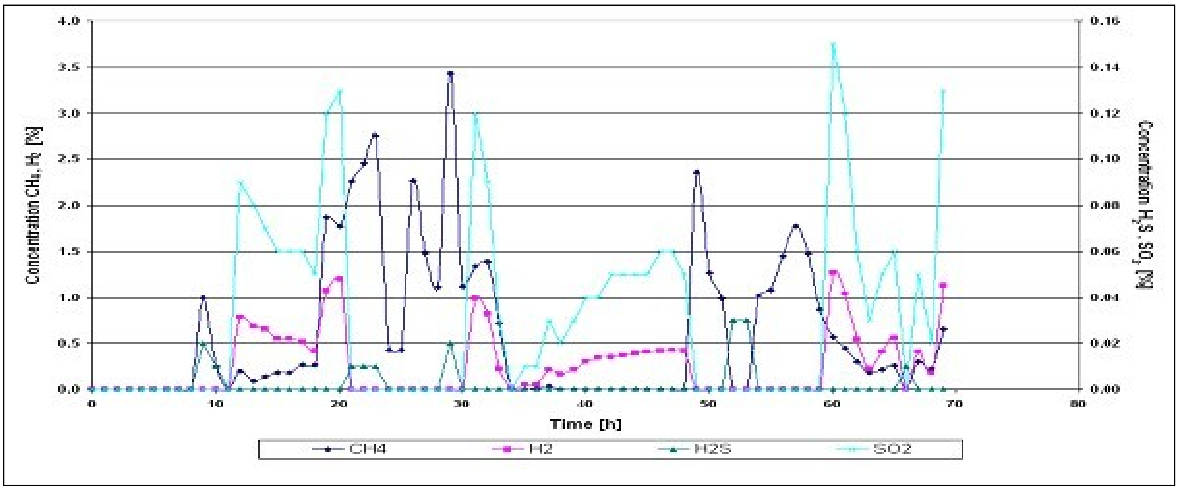

Fig. 8. Concentrations of CH_4, H_2, H_2S, SO_2 during experiment.

Conclusion

The objectives of the experimental program were established within constraints imposed by the research grant that supported this work. The first objective of the laboratory studies was to study the response of observed combustion front characteristics to changes in the process parameters. This was an empirical investigation of natural coal for the given range of conditions investigated.

The next objective will be to test scale – down laws for channel propagation. Previous modeling work indicated that the size of combustion channels created in coal could be changed by altering certain process parameters.

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References

Dobbs, R L, Krantz, W B.: Combustion Front Propagation in Underground Coal Gasification, *Final report. University of Colorado 80309-0424, pp. 405 (1990)*

Blinderman, M. S. et al.: The Chinchila IGCC Project: UCG and Environment, Gasification Technologies Conference, *San Francisco, USA, 2002*

Kostúr, K, Kačúr, J.: Design of experimental equipment for underground coal gasification, Proceedings of ICCC 07, TU BERG Košice, ISBN 978-80-8073-805-1, pp. 334-338 (2007)