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THE RESEARCH OF UNDERGROUND COAL GASIFICATION IN LABORATORY CONDITIONS

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Abstract

A number of coal gasification technologies are currently available or under various stages of development. One technology "Underground coal gasification (UCG)" receiving renewed interest around the world. In this paper will be described a principles of underground coal gasification and a research of UCG in Slovak conditions. This research is organized in two lines. First way is based on mathematical modeling and second direction is experimental research. Mathematical model enables to solve a dynamic heat transfer in a rock and in a coal seem. By the internal source of heat are oxidation reactions and its combustion products are immediately reduced on a syngas. These complicated reactions with coal are mathematical solved on base of the thermodynamics. Mathematical model is developed to understand the complex phenomena of heat and mass transfer in combination with chemical reactions. Its aim is to simulate limits of concentrations production of gas. Finally, there are will be described experimental devices including control system and some experimental results.

Keywords: *clean coal technology; chemical essential; Gibbs´s energy; gas composition; experimental object*

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1. INTRODUCTION

Coal is our most abundant fossil fuel. While oil and natural gas account for 64 percent of the world's energy consumption, they total only 31 percent of the world's known fossil fuel reserves. Today, less than one sixth of the world's coal is economically exploited. In present time most coal is extracted by classical mining technology. In generally are well known disadvantages of classical mining (a big cost, a danger work, problems by ecology,…). Therefore, in world are permanently investigated other technologies, especially clean technology. These technologies, where belongs underground coal gasification too, may be defined as those technologies which improve the environmental acceptability of coal extraction, preparation and utilization [1].

The idea of UCG is not a new. Underground Coal Gasification was apparently first suggested by two engineers, brothers Werner and Wilhelm Siemens, as early as in 1868. Independently of that, the Russian scientist Dmitry I. Mendeleev had been developing a detailed design for, and operational concepts of UCG (1880). The first experimental work was led by William Ramsey in County Durham, United Kingdom in 1912 [1]. Intensive development work in the USSR during the 1930's led to the operation of industrial scale UCG in the 1950's at Krutova, Tula, Shakhty, Lenisk-Kuznets, Gorlovka and Lisichansk [2]. The research of UCG continued in European country in Belgium, France, Spain, Great Britain, and Czechoslovakia [3]. In the USA was more than 30 experiments conducted between 1972 and 1989 and in China was since the late 1980s, sixteen UCG trials have been carried out.

Over the last few years, the number of activities throughout the world focusing on UCG has rapidly increased. The Chinchilla project, operating from 1997 to 2003 in Queensland, Australia, demonstrated the first long-term UCG pilot in the Western world. That project has now advanced to the stage of raising capital for a coal gas-to-liquids pilot that will make ultra clean diesel and aviation fuel. In South Africa, the electricity supply company Eskom is developing UCG at the Majuba Coal Field and achieved ignition in 2007 [1].

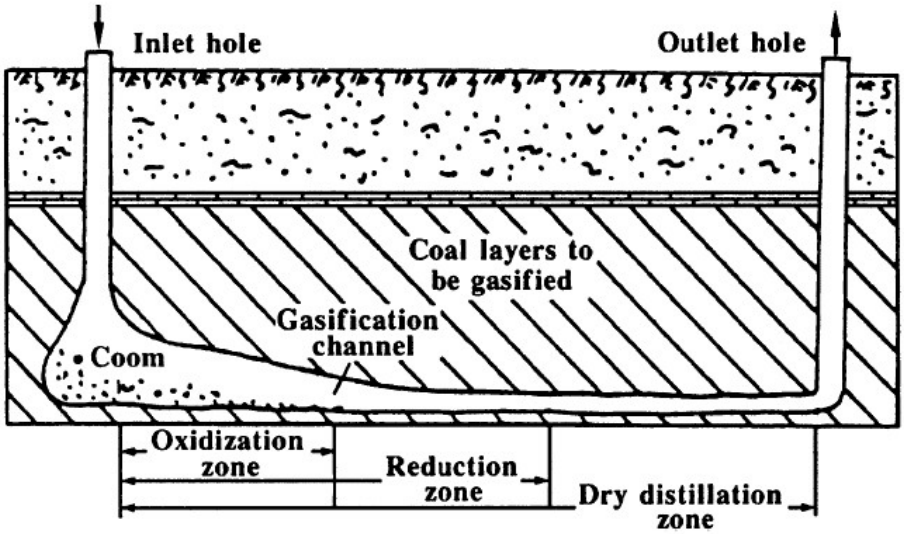

Figure 1. Underground coal gasification in horizontal coal seam.

Underground coal gasification is a mining method that utilizes injection and production wells drilled from the surface and linked together in the coal seam. Once linked, air and/or oxygen are injected. The coal is then ignited in a controlled manner to produce hot, combustible gases which are captured by the production wells (Fig.1). This process can be conducted below the water table as water flows into the gasification zone and is utilized in the formation of the gas, known as syngas. The syngas is brought to the surface and cleaned for power generation and liquid hydrocarbon formulation [1] UCG has the potential to exploit coal resources which are either uneconomic to work by conventional underground coal extraction, or inaccessible due to depth, geology or other mining and safety considerations [4].

Chemical is gasification a complex processes, where following reactions can be considered:

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

Each coal seam is very specific and for this reason before the real realization of UCG in situ is necessary to make geology exploration, to propose the suitable method of gasification and control system. Process control is very important for this technology because the generator is given by nature.

The research is made by 2 ways: experimental and mathematical modeling [5, 6].

2. Experimental

2.1.Materials

For experiments are used materials from Cígeľ mine. The mine Cígeľ belongs to Upper Nitra coal Basin. Coal is from seam b_1. The analysis of the coal is summarized in Table 1. By experiments is overlay clay from deposit used for creating underlay and overlay of coal in experimental plant.

Table 1. The analysis of the coal

Proximate analysis (%)		Elementary analysis	
moisture	22,25	C	37,11
volatile	60,39	H	3,2
ash	20,47	N	0,59
Heat value	13,74		

2.2 Experimental plant

The base of this plant is a steel generator (G) - see Figure 2 [7]. 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 is possible to concentrate by oxygen, water steam or dioxide of carbon by connection on input tube. The air or a gas mixture is provided into generator by valves and tubes. This system of valves (V_i) and tubes will enable to simulate various the arrangement of inlet holes and outlet holes. The pressure flow direction of gas is possible to regulate in 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. Experimental plant has others measurement equipments as for example the flue gas analyzer, flow meters, the measurement of calorific value, etc.

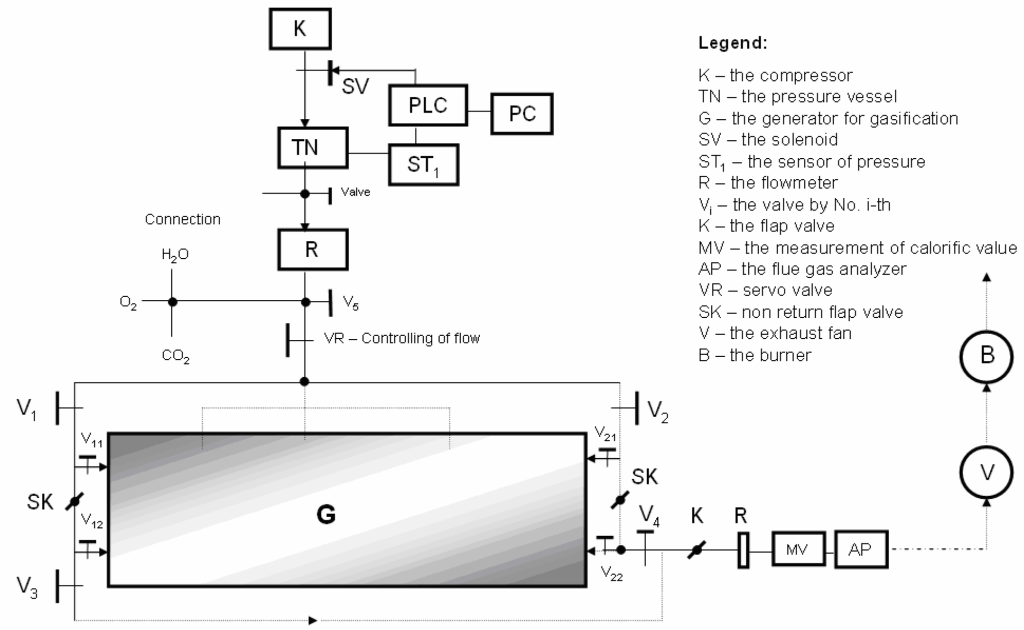

Figure 2. The scheme of experimental plant.

The safety glass is localized on upper cover. Its aim is to observe of the gasification procces. Internal walls are covered by isolation. The primary objectiv of this projekct is to obtain an information for UCG in conditions Slovak coal mining. Figure 3, is basicallly the vessel component of coal gasification. Coal samples in form blocks can be sealed upper (Figure 3 or (and) lower (Figure 4). Figure 4 shown the arrangement of sounds. This system of sounds consists of tubes and number valves. It enables to analyze processes along 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 process also. Addition of the gas agent is helped for control of gasificiation processes.

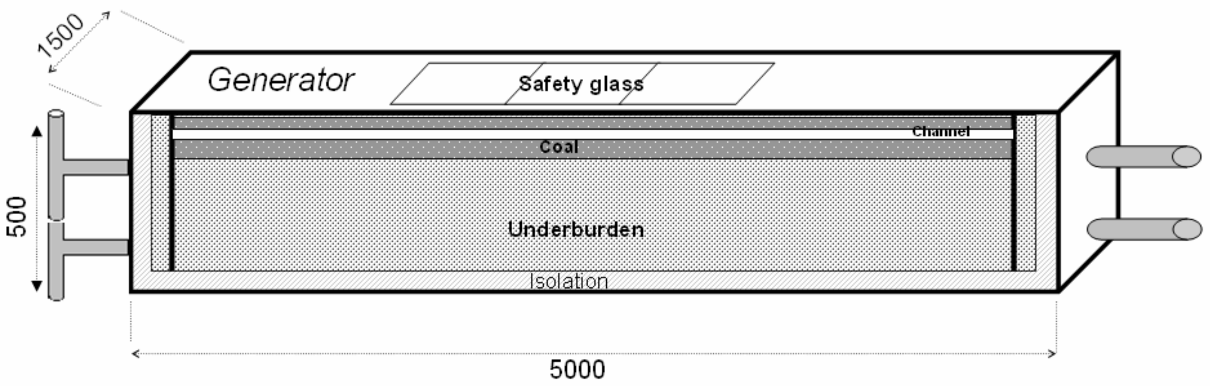

Figure 3. Coal gasification test vessel.

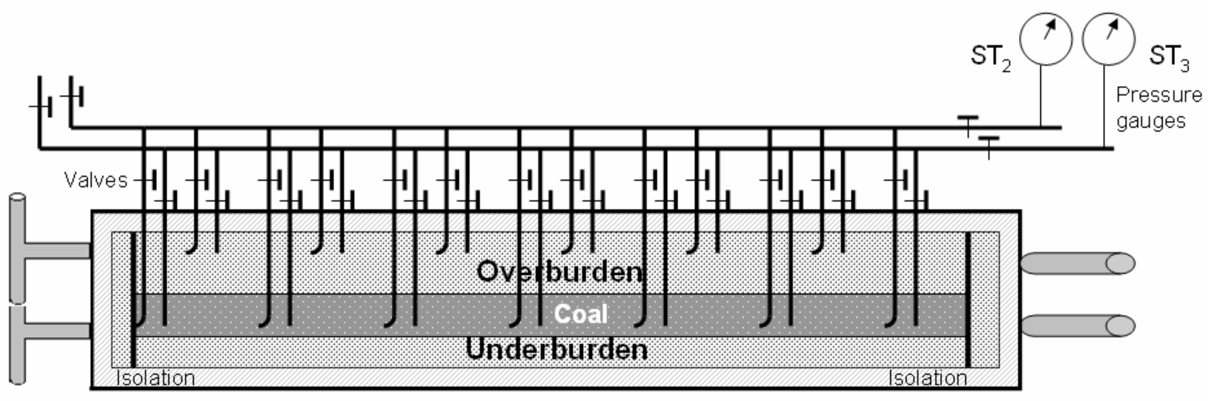

Figure 4. Coal gasification test vessel with sound system.

Correctly temperatures are very important for gasification. Therefore, temperatures are measured in a channel, a coal and in a rock. On Figure 5 is shown the arrangement of thermocouples. For experimental research, temperatures in channel and coal are sufficient. However, surface temperaures and temperatures in rock are necessary for mathematical model [6] which is developed in frame of this project.

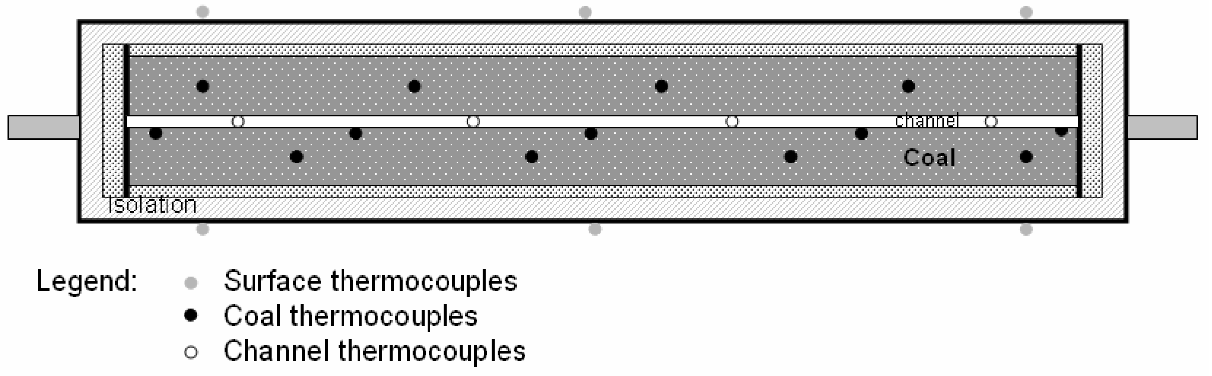

Figure 5. Scheme of temperature measurement.

2.3 Monitoring and controlling system

Research of relevant processes UCG has required more information. This process is slowly in laboratory conditions also. Therefore, the measurement has been solved by help of automation. The automation system is possible to divide on two parts:

- the monitoring system,
- the control system [8].

Hardware conception is based on connection between PLC and PC through serial port. Monitoring system has provided data acquisition and data - preprocessing. The sampled - data system is based on programming logic controller (PLC) and special modules (multiplexers). Monitoring system has provided the measurement following variables:

- temperatures in coal, channel, rock,
- surface temperatures,
- 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 CO, CO_2, O_2, H_2S, CH_4, NO, NOx. Selected data are shown on operating panel during experiment. All measured data are stored in computer (PC). Sample period is possible to change during experiment also. Control system has 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 extremely control. The output pressure of syngas is provided by manual control. The temperature of syngas is controlled by PI controllers.

This equipment has been built for program research in first half of 2007 year. The original coal and a rock was stored to the generator, which was inclined at 10° angle. The higly gas - permeable channel was created on down 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 at 25 minutes. The temperature of thermocouple near or on the ignited coal face was monitored. Frequently ignition was detected by an abrupt temperature rise to 550 - 700°C in one or more of first rank thermocouples. Measured temperatures in approx. distance ¼ (T21) or ½ (T26) and ¾ (T30) of the generator length are shown on Fig.6. The maximal temperure in coal was 800°C. The maximal temperature in rock was below 100°C.

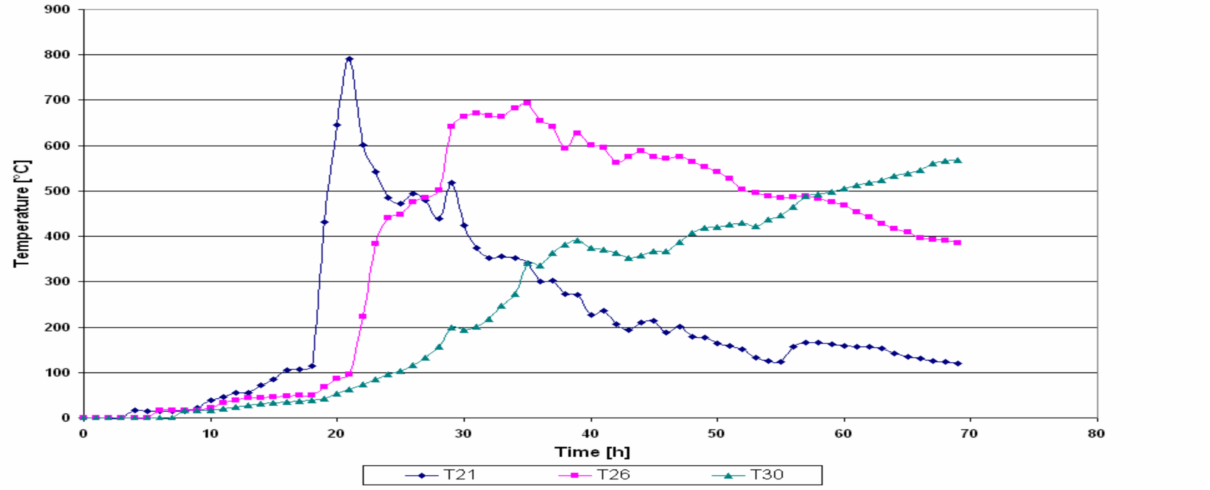

Figure 6. Measured temperature of coal nearly of gasification tunnel.

3. THERMODYNAMICS MODEL

Mathematical model is developed to understanding the complex phenomena of heat and mass transfer. By its aim is to simulate the composition of solid and a gas phase in gasification of the coal. In process of modelling are not considered mutual reactions by SiO_2, Al_2O_3, $CaCO_3$ because its capacity and heat is small.

The considered system is in equilibrium if total Gibson's energy will be minimum.

$$G = \sum_{j=1}^{N} n_j \mu_j \qquad (1)$$

$$\mu_j = \mu_j^o + RT\ln\left(\frac{n_j}{\sum\limits_{j=1}^{N} n_j}.\frac{p}{p^o}\right) \tag{2}$$

where

μ_j - is the standard Gibson's energy [kJ], R – is the universal gas constant, T – is the temperature [K], p – is the pressure in system [Pa], p^0 is the standard pressure [Pa].

$$\begin{aligned}
\mu_1^0 &\equiv \Delta G_{t_1}^0 = -8263 - 17{,}18.T.\ln(T) - 0{,}002135.T^2 + \frac{439500}{T} + 121{,}2914.T \\
\mu_2^0 &\equiv \Delta G_{t_2}^0 = -9689 - 30{,}0.T.\ln(T) - 0{,}002095.T^2 + \frac{84000}{T} + 203{,}1046.T \\
\mu_3^0 &\equiv \Delta G_{t_3}^0 = -8118 - 27{,}32.T.\ln(T) - 0{,}001635.T^2 + \frac{25000}{T} + 183{,}655.T \\
\mu_4^0 &\equiv \Delta G_{t_4}^0 = -119404 - 28{,}45.T.\ln(T) - 0{,}002055.T^2 + \frac{23000}{T} + 563{,}1203.T \\
\mu_5^0 &\equiv \Delta G_{t_5}^0 = -410193 - 44{,}2.T.\ln(T) - 0{,}004525.T^2 + \frac{427500}{T} + 1624{,}833.T \\
\mu_6^0 &\equiv \Delta G_{t_6}^0 = -286212 - 30{,}04.T.\ln(T) - 0{,}005365.T^2 + \frac{17000}{T} + 1133{,}374.T \\
\mu_7^0 &\equiv \Delta G_{t_7}^0 = -84719 - 23{,}67.T.\ln(T) - 0{,}023965.T^2 + \frac{96500}{T} + 425{,}1971.T \\
\mu_8^0 &\equiv \Delta G_{t_8}^0 = -8506 - 27{,}91.T.\ln(T) - 0{,}002135.T^2 + \frac{0}{T} + 188{,}1857.T
\end{aligned} \tag{3}$$

Very interesting results has been obtained by simulations for analysis of products structure. These products of gasification are called "syngas". Its structure is given in mass per cent. From Figs 7,8, we can see that the comparative differentiation of every points ranges from 0°C to 1000°C. In Fig. 7 is shown the structure of syngas if the oxidation will be provided by oxygen in coal only. There is maximal concentration of CO. From Fig. 7, we can see that carbon was consumed total in temperature 1000°C.

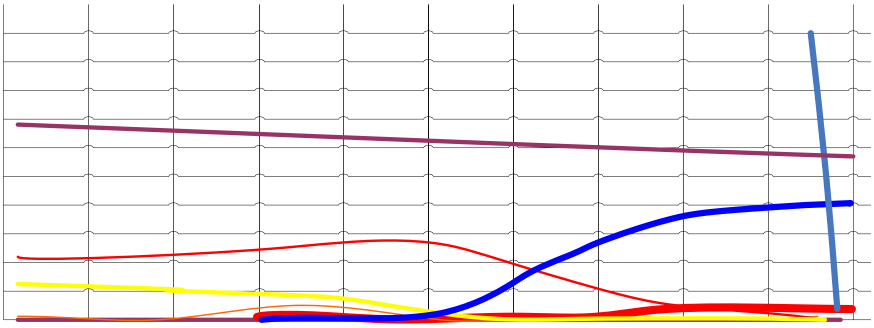

Figure 7. The structure of syngas for oxidation by oxygen

Finally, on Fig. 8 is shown a case if the oxidation will be provided by air. In simulation, the air was considered by stoichometric ratio. The concentration of required products (CO, CH_4, H_2,…) will be less than in case of oxidation by addition of oxygen. The reason of this fact is more of nitrogen which is transported into gasification by air.

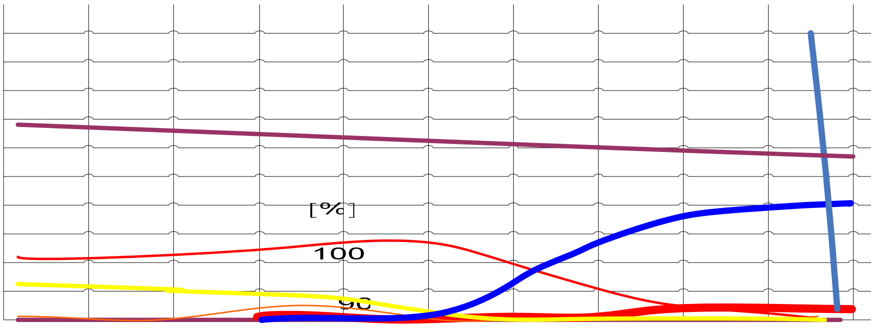

Figure 8. The structure of syngas for oxidation by air

4. CONCLUSIONS

This mathematical model has been developed capable of estimating the syngas structure of underground coal gasification reactors. Of course, results are obtained by using equilibrium constraints. Therefore, the agreement between simulation and real process will be more for higher temperatures. This modeling has also indicated that current model's performance predictions are generally more sensitive to process changes, such as temperature and then the type of oxidizing agent (oxygen, air). This model will be by part of total model which enables to observe heat losses.

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.

Both ways of research appear as suitable because they mutual supplement necessary the knowledge for control of UCG.

Acknowledgements

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