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Experimental and Numerical Investigations of Underground Coal Gasification (UCG) Using Half-teardrop Shape Cavity

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ABSTRACT

In this work, the process of Underground Coal Gasification (UCG) was studied experimentally and numerically. The typical cavity of UCG was a half-teardrop shape. The coal samples were collected from Mae Moh coal mine, Thailand. The coal type is mainly lignite. To generate the gasification process, the coal sample was heated in the half-teardrop cavity by injecting partial oxidant, which is air, according to the Equivalent Ratio (ER) of 0.1, 0.2, 0.3, 0.5, and 0.7. The properties of the product gas were measured using a syngas analyser. CFD technique, ANSYS (Fluent), was used to simulate flow characteristics and gasification process in the cavity. The experimental results show that the low heating value (LHV) of syngas peaks at 0.92 MJ/m3 when ER = 0.1, and LHV decreases monotonically as ER increases. The CFD results show that the area of high temperature in the UCG cavity is larger when the ER was greater.

1. Introduction

The demand for electricity generation is rapidly increasing in order to empower nations all over the world using coal as energy source [1]. The reasons are: coal generates the most stable electricity [2] and is the cheapest when compared to other energy sources [3]; coal is abundant and relatively simple in mining, transportation, and processing when compared to natural gas and oil; coal resource base is well-understood as a fuel of necessity, encompassing "energy security" in many less developed economies [4]; availability of technology and skilled labour-force; existing massive infrastructural infrastructure [5].

Nevertheless, there is a worldwide competition to decrease coal consumption for generating electricity, as conventional coal-fired power plants transmit higher levels of greenhouse gases (GHGs)

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such as carbon dioxide (CO_2) and pollutants such as sulfur dioxide (SO_2), nitrous oxide (NO_X), and particulates. However, according to the World Coal Association (WCA), coal remains the world's largest source of electricity, with a projected 22 percent share of global electricity in 2040. For developing countries, the figure is even higher; for example, coal will generate 39 percent of power generation in South East Asia at that time [3]. As a result, switching coal into a less polluting or cleaner fuel could be the only viable solution.

Another method of clean coal technology is underground coal gasification (UCG), which is carried out in situ in coal seams by burning the coal under controlled conditions. A traditional underground coal gasification plant is made up of two wells dug from the ground to coal seams. Several chemical reaction processes occur when underground coal gasification is converted into gaseous products. The combustion zone is located near the injection well, and the temperature ranges between 1,000 and 1,300 ^oC. The gasification zone overlaps in the same zone, and the temperature ranges between 800-1,300 ^oC. The drying zone occurred around the dry coal seam, and the temperature ranged between 100 and 200 ^oC [4].

A complex physicochemical process is carried out by an underground coal gasifier. Combustion (partial oxidation), reducing reactions leading to gasification, and pyrolysis-drying (destructive distillation) occur concurrently in a coal cavity as shown in Figure.1. Dewatering, cracking, absorption, and contraction of coal with high water content are the main physical changes. [7-9]. Drilling injection and production wells from the surface to the target coal seam are required. To facilitate a syngas flow path within the coal seam, a permeable channel is created between those wells [3] (Figure 1).

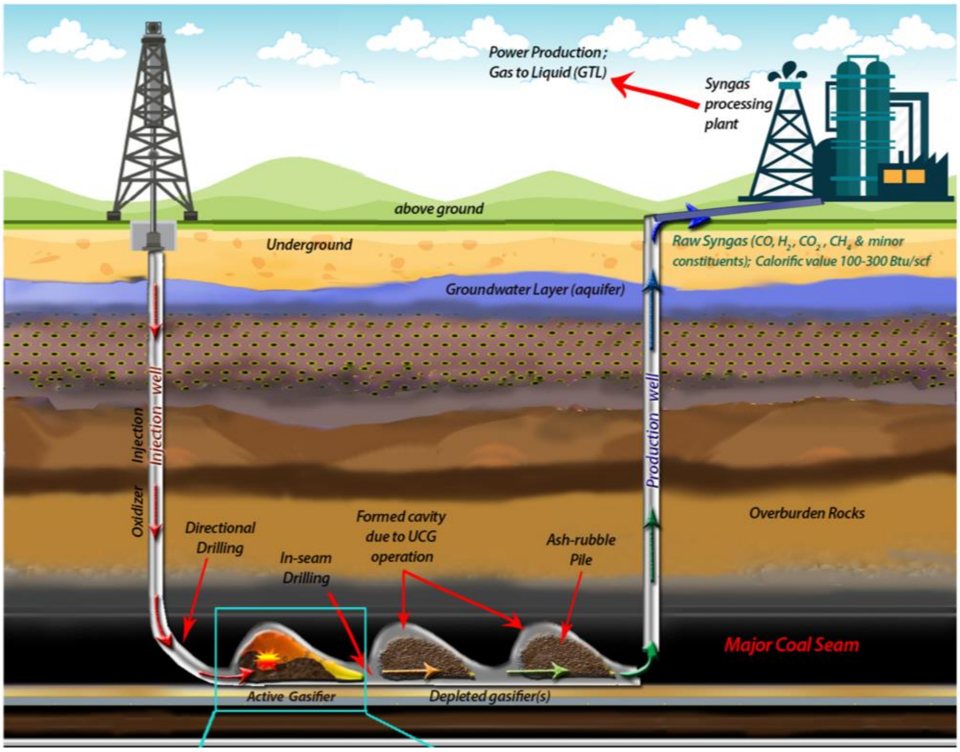


Fig. 1. Typical Underground Coal Gasification (UCG) [6]

Several research works have been conducted to investigate the effect of equivalence ratio (ER) on gasification performance. Most of those tests were carried out in conventional surface gasifiers. Fixed-bed, fluidized beds, and entrained flow gasifiers are three classical types of surface gasifiers [10].

Biswas *et al.,* [6] simulated flow and gasification characteristics in UCG cavity applying half-teardrop shape. The results show that streamlines of hot gas flow out from rubble zone circulating in the cavity and vent at the outlet. Daggupati *et al.,* [11] used compartment modelling to characterize the flow of a UCG cavity, which grows three-dimensionally in a nonlinear manner as gasification progresses. They discovered that the flow field primarily determines the cavity shape, which is a function of various parameters (e.g., inlet position and orientation), temperature distribution, and coal properties (e.g., thermal conductivity). The flow at Thulin UCG experiments was modelled by Debelle, *et al.,* [12]. The hydrodynamics of the flow profile inside the underground reactor was calculated, and the results showed that the flow conditions inside the underground reactor changed little during the series of reverse combustion tests.

Previous gasification works studying on equivalence ratio (ER) mostly relates to surface gasification. The subsurface gasification (i.e., UCG), however, is rare. Varying equivalence ratio (ER) would influence on combustion zone in the UCG cavity which needs to be understood. In this work, equivalence ratio (ER) effect on gasification characteristics in a UCG cavity was studied experimentally and numerically.

2. Experiment

2.1 Materials

The coal used for the experiment was took from Mae Moh coal mine, Thailand. The type of the coal is mainly lignite. The specific data for the elemental compositions and proximate analysis are analysed using a thermogravimetric analyser (TGA8000, Perkin Elmer, USA). The coal properties are shown in Table 1.

Before experimenting, the coal was coarsely crushed by a jaw crusher. The size of the crushed coal is about 5–10 cm. Then, the coals were grinded with a fine crusher, which would reduce the coal size to be 0.5-3.0 cm. The coal powders were sieved using fine filter. The coal powders were in the range of 0.5-0.6 mm. This coal powder would be used as sample in the experimental study.

Table 1
Proximate and ultimate analysis of coal used in the present study

Proximate analysis	% wt.
Moisture (As received basis)	13.17
Fixed carbon (As received basis)	33.07
Volatile (As received basis)	42.00
Ash (As received basis)	11.77
Ultimate analysis	% wt.
Carbon (C) (As received basis)	48.65
Hydrogen (H) (As received basis)	4.17
Oxygen (O) (As received basis)	31.51
Nitrogen (N) (As received basis)	1.50
Sulfur (S) (As received basis)	3.29
Low Heating Value (L.H.V) (kcal/kg) (As received basis)	3939.72

2.2 Experimental Apparatus

The UCG cavity model is shown in Figure 2, and the experimental apparatus is shown in Figure 3 and 4. The apparatus consisted of a UCG cavity block having 200 mm in width 170 mm in high and 700 mm in length, an air supplier system for injecting gasification agent, a LPG torch for heating coal sample and a gas analyzer unit for analyzing syngas properties. The UCG cavity block was made of refractory concrete which was separated in two parts. The upper part is for creating UCG cavity, and the lower part is for the cavity base. To create the upper part, a form was cut to be haft tear drop shape and was sucked in molten refractory concrete. After the refractory concrete drying to be solid, the form was removed remaining the cavity having haft tear drop shape.

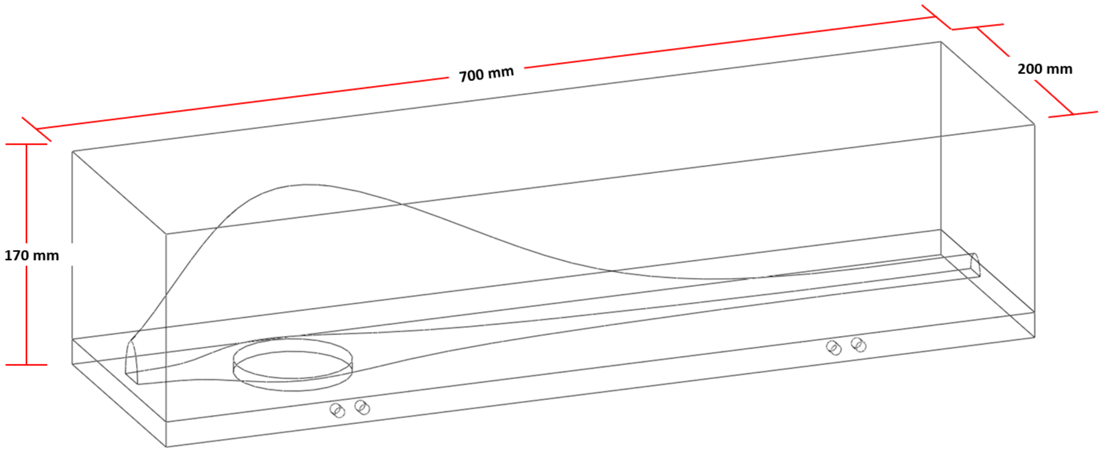


Fig. 2. Dimension of a UCG cavity

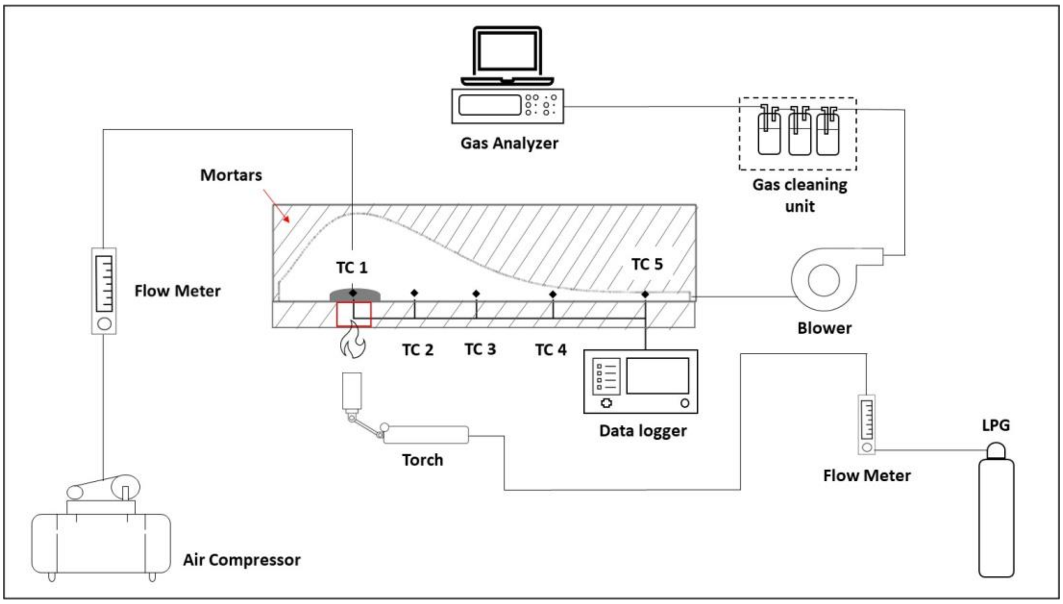


Fig. 3. The diagram of the experimental apparatus

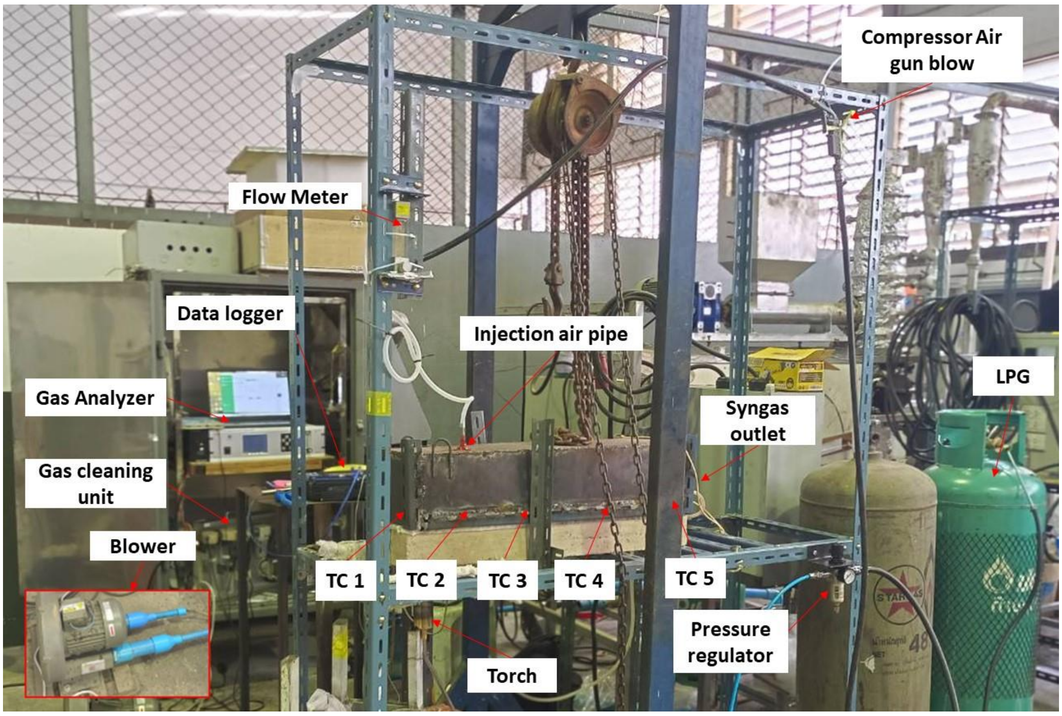


Fig. 4. The photo of the experimental apparatus

A vertical hole was drilled through the upper surface of the upper block for injecting the gasification agent. The air flows through the coal sample for generating syngas and vents out at the tail of the UCG cavity. Five horizontal holes were drilled, and type-K thermocouples were inserted in the holes for measuring temperature. Each thermocouple point (TC1, TC2, TC3, TC4, TC5) has a hole distance of 5 cm as shown in Figure 3. A high-temperature insulator (KAOWOOL, ASK-7912-H 8P Blanket 1,400 ^oC) was covered the block to reduce heat losses.

2.3 Experimental Procedure

In the experiment, the coal samples were weighted according to equivalence ratio (ER) as shown in Table 2. After the upper block lifting, the coal sample was placed on the lower block at the metal plate. Then, the upper block was placed on the lower block. To prevent gas leakage, the gasket was placed between the upper and the lower blocks.

In the first stage, the coal sample was placed on was heated using an LPG torch. The heating process took one hour. The gasification agent, in this work using air, was supplied into the vertical hole at 0.8 lpm. The coal sample was weighed according to equivalent ratio (ER) as shown in Table 2. In the second process, the heating system was turned off. The air still supplied for one hour. The gasification process was still running from partial combustion of the coal sample to generate heat source. Finally, in the third stage, the air supply was turned off, letting the process cooling down. During the experiment, the syngas was sucked by a blower and flowed through a gas cleaning unit. Then, the syngas was analysed using syngas analyser as shown in Figure 3 and 4.

Table 2
Experimental parameter

ER	Air Flow (lpm)	Amount of Coal (g)
0.1	0.8	91.8
0.2	0.8	46.2
0.3	0.8	30.6
0.5	0.8	18
0.7	0.8	13.2

3. CFD Simulations
3.1 Simulation Model and Boundary Conditions

Figure 5 depicts the 3-D model of the underground coal gasification (UCG) cavity using ANSYS-Fluent. The geometry of the domain was a half-teardrop shape, which has 90 mm in a maximum width, 132 mm in a maximum height, and 680 mm in a maximum length. The half-teardrop shape of UCG cavity has been reported in several previous works [6, 11, 12]. A vertical pipe with a diameter of 5 mm was located at the center of the domain for injecting gasification agents, here using air.

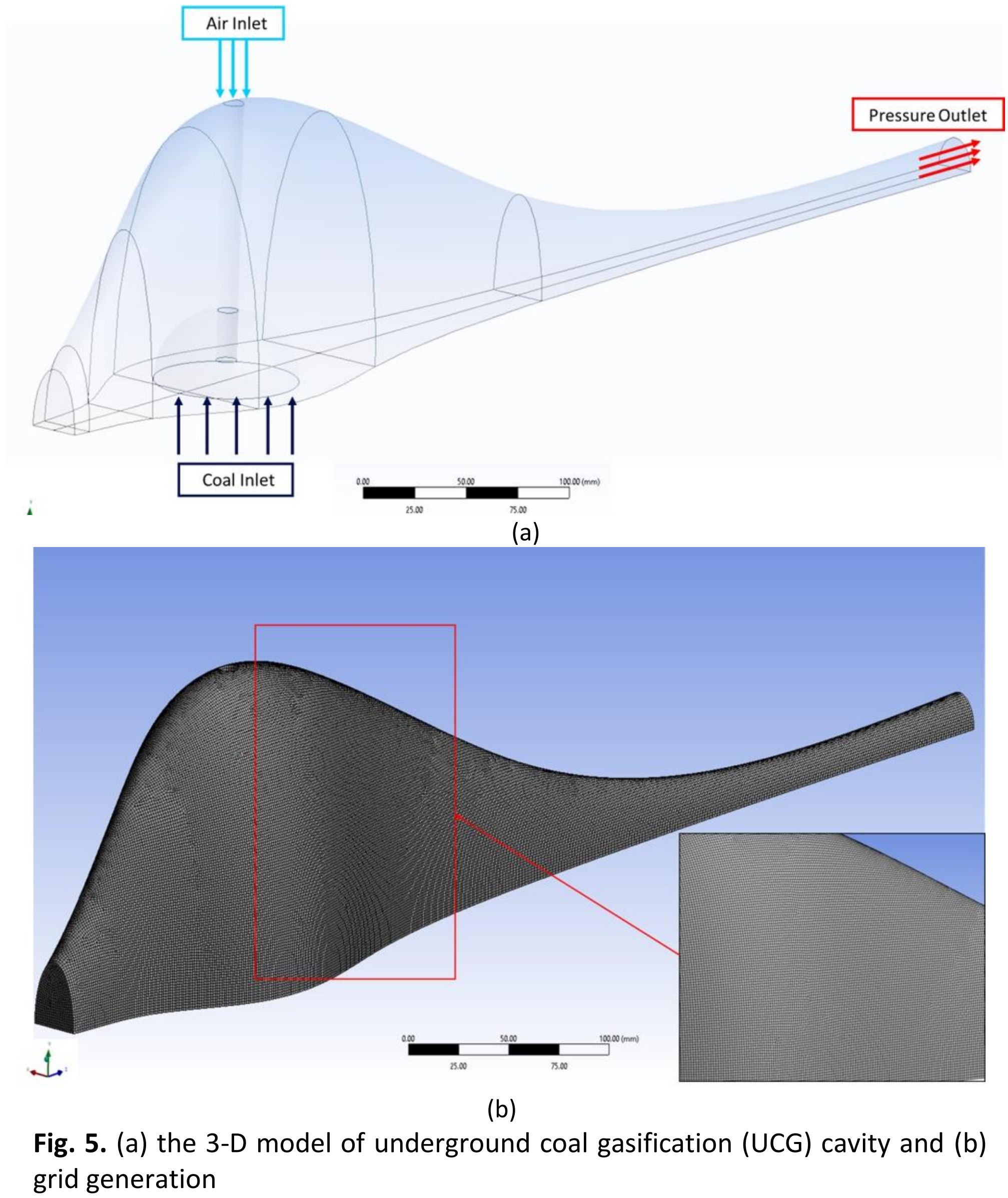


Fig. 5. (a) the 3-D model of underground coal gasification (UCG) cavity and (b) grid generation

Due to the falling of coal from the top surface of the cavity during gasification processing, a rubble pile was created to be a part of the accumulated fallen coal and remaining ash. This rubble-ash pile was dome shape, having a diameter of 55 mm, and was located at the bottom of the domain. The rubble pile was defined as a porous medium with a porosity of 50% [13]. The outlet for syngas was located at the tail of the domain.

3.2 Grid Generation

Figure 5(b) shows the grid generated from a numerical simulation of the underground coal gasification. The generated grids were refined at several locations. Due to the greatest velocity gradient at the ash-rubble pile (which is perched on the reactor's surface), the finest mesh was produced there. The grid-dependent test was varied in the element number of 0.1–0.8 million elements. It was found that the saturated elements which were not changing the results significantly were 0.67 million elements. Then, these element numbers were selected to apply to all CFD runs.

3.3 Calculation Method

The Navier-Stokes equations and Reynolds averaged continuity were used to address the issue after the computing procedure, within the boundaries that were specified. The K-epsilon turbulence model [14, 15] was used to resolve the numerical internal flow simulations. It was utilized for internal flow simulations with a low-cost computation method that could be performed with high forecast accuracy. The Discrete Ordinate (DO) model was utilized to calculate combustion. It was utilized in the radiation model part. The species transport model was performed based on the proximate and ultimate analysis of the coal sample as previously shown in Table 1.

SIMPLE algorithm with an upwind scheme was applied. Turbulent kinetic energy, turbulent dissipation rate, and discrete ordinates were all calculated using the first-order upwind scheme. The calculated pressure, velocity, and temperature were from the second-order upwind scheme. The convergent results were considered when the residuals was less than 1×10^{-4}.

4. Results and Discussion

4.1 Gasification Characteristics

Figure 6 shows the temperature contours on a plain at the center of the UCG cavity from the CFD work. The maximum temperature is detected up to 3,100 C, which can be attributed to the fact that there is no heat loss in simulation method. The area of high temperature is larger when the equivalence ratio (ER) was greater. This means that more air supplying as compared to the fuel (greater ER) would accelerate combustion sub-process of gasification reaction. It should be noted that the gasification is partial oxidation reaction. The acceleration of combustion sub-process in gasification is unsuitable to generate high heating values of syngas.

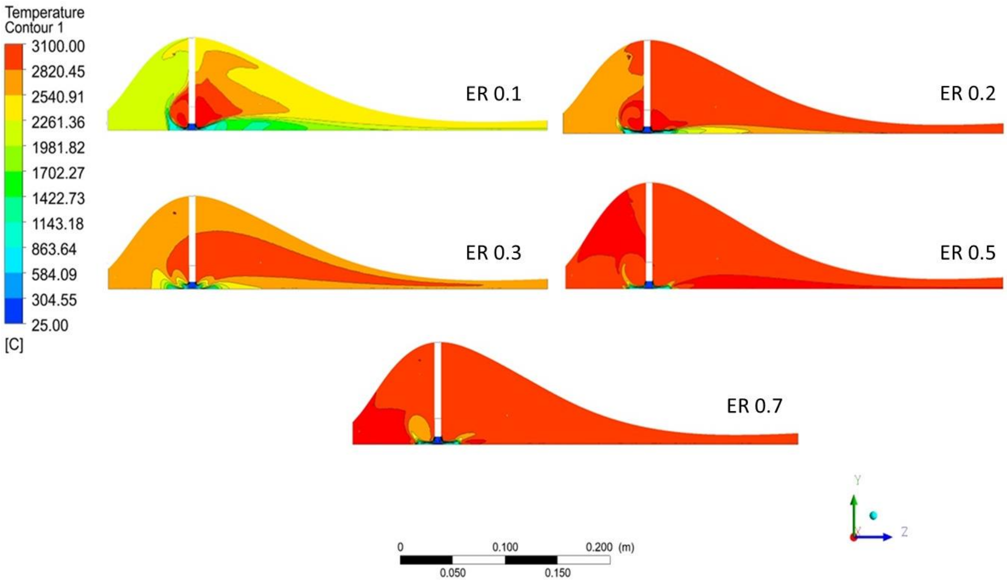
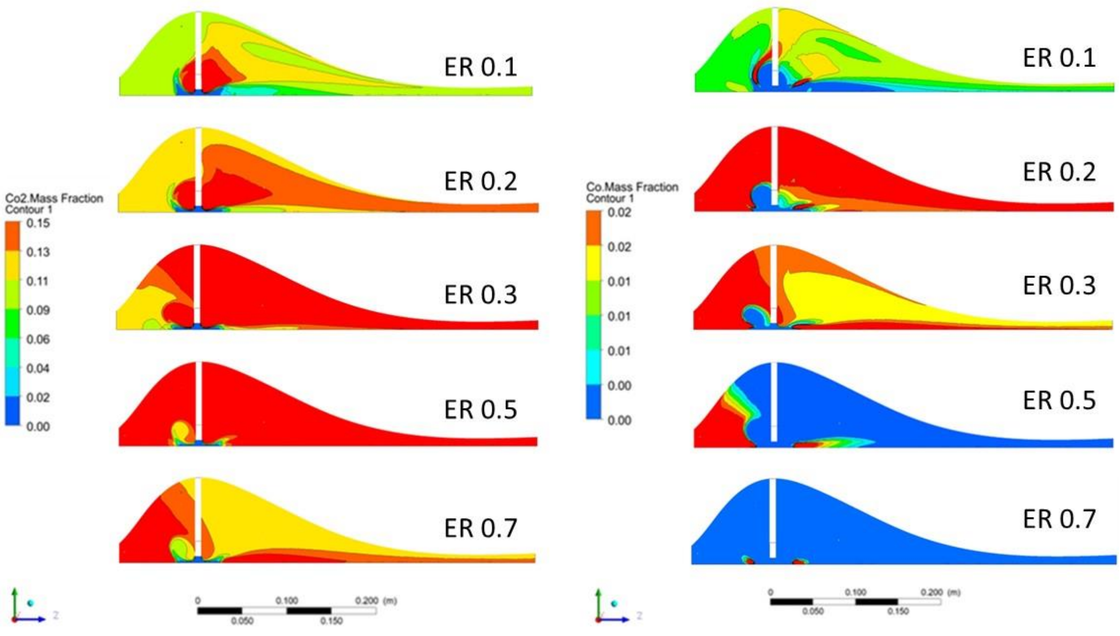


Fig. 6. the temperature contours on the plain at the center of the UCG cavity (CFD results)

Figure 7 show the CO_2 and CO contours on the plain at the center of the UCG cavity from the CFD work. The CO_2 is a product of complete combustion while the CO is a product of incomplete combustion (Gasification). The area of high CO took place at ER=0.2 When the condition is near complete combustion (ER=0.7), the area of high CO become the smallest.



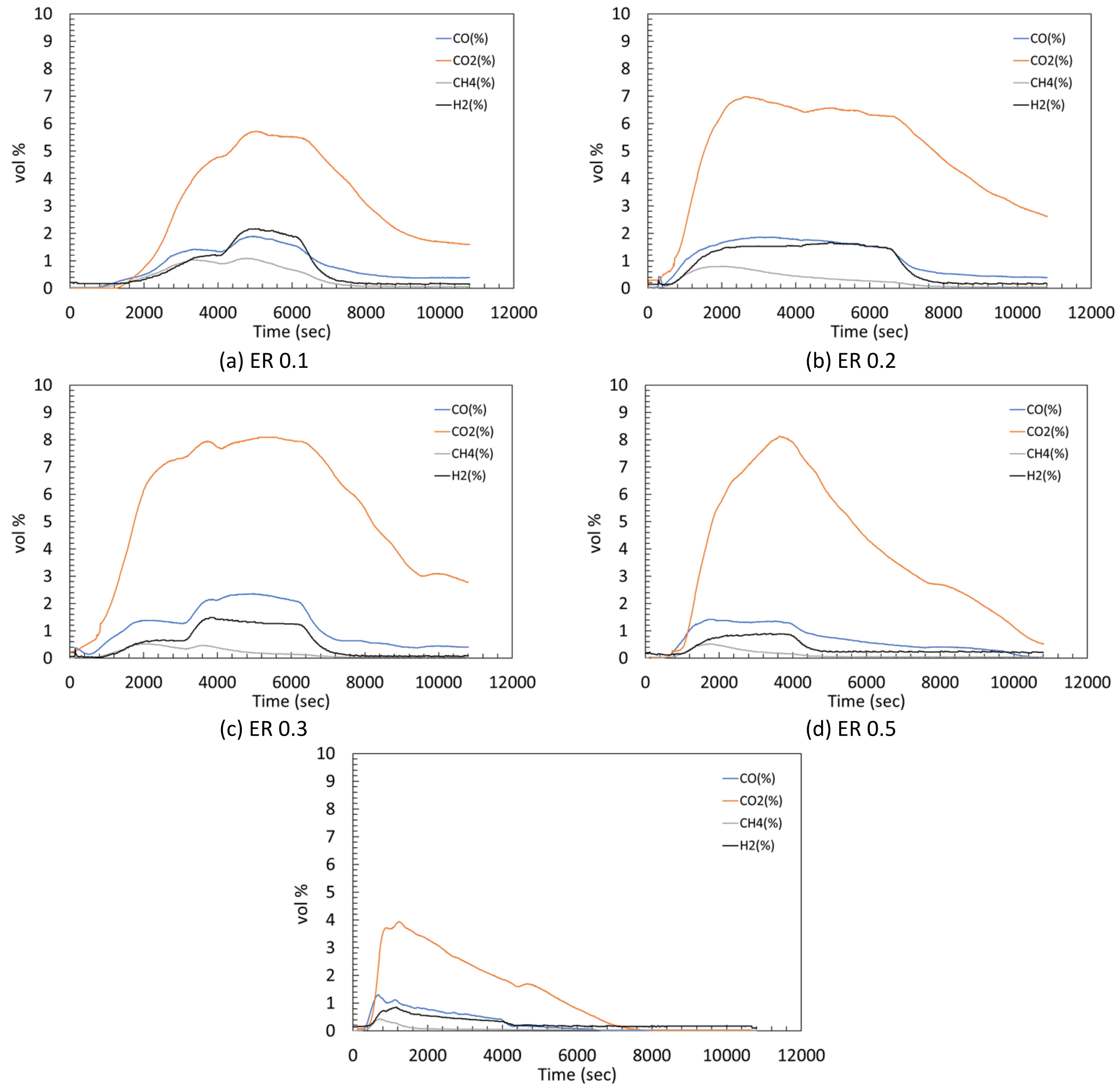
(a) CO_2 (b) CO

Fig. 7. the CO_2 and CO contours on the plain at the center of the UCG cavity (CFD results)

4.2 Gas Composition

Gas compositions of syngas by volume varying with time from experimental results are shown in Figure 8. This shows the variations of gas compositions for running over 3 hours. In the first stage, the coal sample was heated. The gas composition started to rise up due to decomposition of solid matter from the thermal reaction. The gas composition continues high in second stage. At this stage, however, the heating system was turned off. This continuous high gas composition is from self-reaction of gasification process having combustion sub-reaction for generating thermal source. The gas composition decreased in the third stage when the gasification agent was stopped to supply.

In this experiment, the concentration of CO_2 was higher than the other combustible gas as CO, CH_4 and H_2 in all equivalence ratio (ER). Considering combustible gas, the concentration of CO is higher than that of CH_4 and H_2. It is exception in short period (4,100 – 6,100 sec) of ER=1 which the concentration of H_2 is higher than that of CO and CH_4. Noted that the rest of gas composition without showing in these results is N_2 which was about 60-80% by volume. The high volume of N_2 is from using air (about 79% in air) as gasification agent.



(a) ER 0.1

(b) ER 0.2

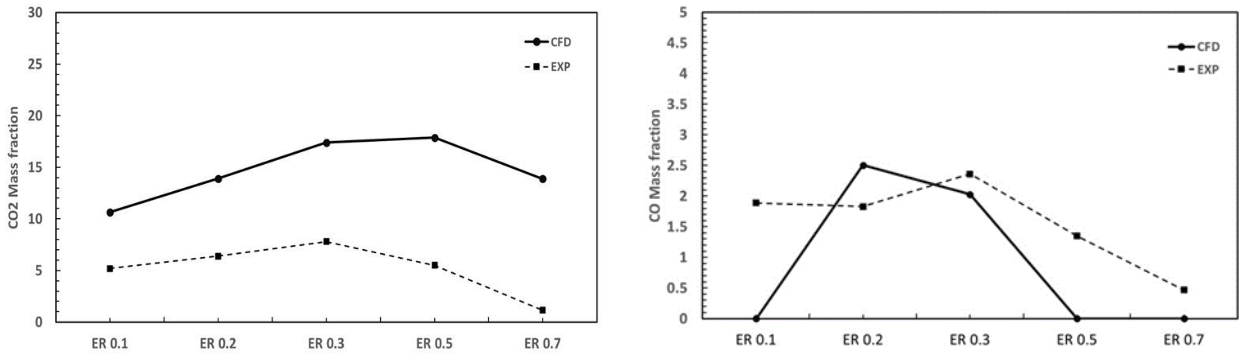
(c) ER 0.3

(d) ER 0.5

(e) ER 0.7

Fig. 8. Gas compositions of syngas by volume varying with time (Experimental results)

CO_2 and CO mass fraction of syngas from CFD and experimental results are shown in Figure 9. The experimental results were measured using syngas analyser while the CFD results were detected at the outlet of the cavity. Both CFD and experimental results show similar trend that the high mass fraction took place in ER=0.3-0.5 for CO_2 and ER=0.2-0.3 of CO. However, the discrepancy between CFD and experimental results of CO_2 looks large difference. This is from the limitation of CFD work which predict only partial combustion without gasification reaction.



(a) CO_2 (b) CO

Fig. 9. Percentage of CO_2 and CO in syngas (CFD and Experimental results)

4.3 Gas Calorific Value

The low heating value (LHV) of syngas was measured by the Gas analyzer varying with time from experimental results are shown in Figure 10. The peak of LHV took place when the run was over 2,100 sec for ER=0.1-0.3 and was before 2,100 sec for ER=0.5-0.7. This show that high supply of gasification agent (ER=0.5-0.7) can accelerate gasification process to take place in beginning of the run. The peak of LHV (which taking from Figure 10) is shown in Figure 11. The peak of LHV decreased monotonically when the ER increased. The highest peak of LHV took place at ER=0.1.

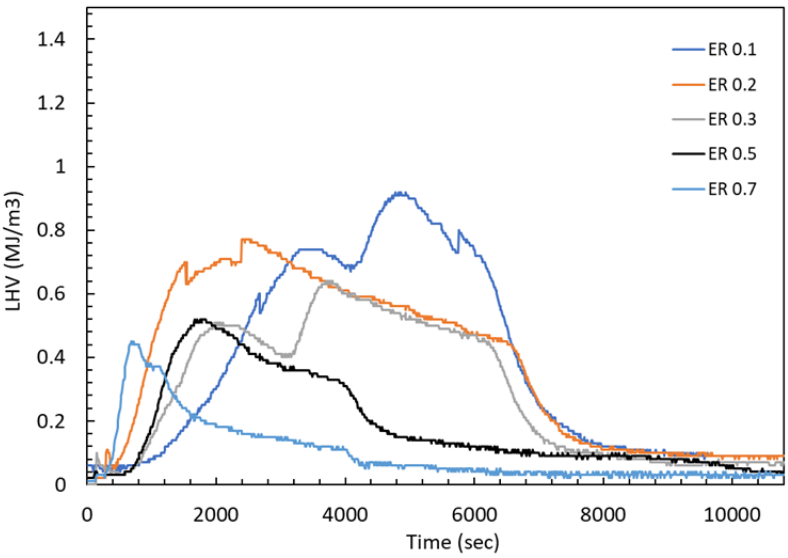


Fig. 10. Low heating value (LHV) of syngas varying with time (Experimental results)

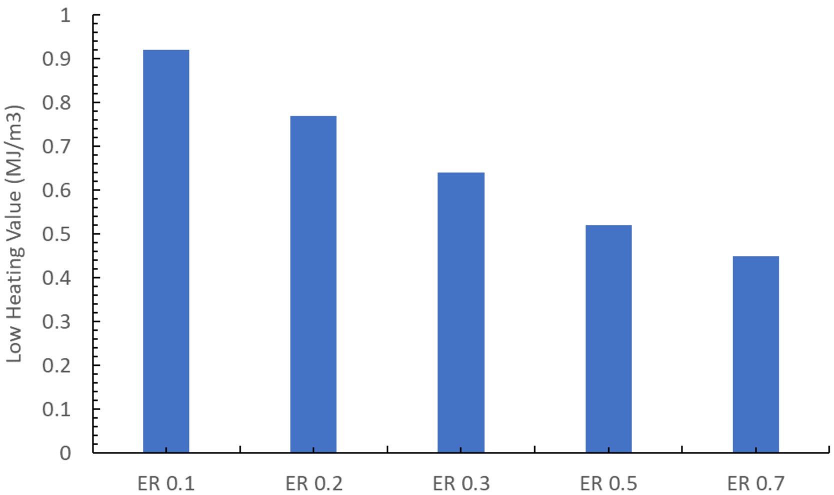


Fig. 11. Peak of Low heating value (LHV) of syngas varying with equivalence ratio (ER) (Experimental results)

5. Conclusion

In this work, the coal from Thailand, was tested under cavity imitating underground coal gasification (UCG) experimentally and numerically. The results can be concluded as follow

i. The CFD results show that the area of high temperature in the UCG cavity was larger when the equivalence ratio (ER) was greater. The area of high CO_2 and low CO were also larger when the equivalence ratio (ER) was smaller.
ii. Considering combustible gas, the concentration of CO was higher than that of CH_4 and H_2. It was exception in short period (4,100 – 6,100 sec) of ER=0.1 which the concentration of H_2 was higher than that of CO and CH_4.
iii. The peak of LHV decreased when the equivalence ratio (ER) increased. The highest peak of LHV took place at ER=0.1.

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