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Contributed Paper

# Combustion of Moist Coal Briquettes

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## ABSTRACT

In the present study, the effects of moisture in coal briquettes on mechanical strength, ignition time, and combustion characteristics of cylindrical, honey-comb cross-sectional coal briquettes were investigated. Each coal briquette was ~1.0 kg, ~10 cm diameter, ~10-12 cm high, with sixteen ~1 cm diameter axial holes. The moisture contents in the coal briquettes were in the range of 10-30 wt%. The mechanical strength of the coal briquettes was examined as a compressive strength by a compression machine in both vertical and horizontal directions. The ignition time was investigated using a muffle furnace at the temperatures of 700, 800, and 900 $^{o}$C. For the combustion tests, the already ignited coal briquettes, with an initial temperature of 800 $^{o}$C, were placed in a Thai traditional cooking stove. During each combustion test, mass loss history and the temperature of the coal briquette surface were monitored. It was found that the compressive strengths in the vertical and horizontal directions were in the ranges of 360.8-1,052.0 and 37.6-70.0 kN/m$^2$, respectively. When moisture content in the coal briquettes increased, their compressive strength decreased. Ignition times for the temperatures of 700, 800, and 900 $^{o}$C ranged from 14-37, 8-16, and 5-10 minutes, respectively. The ignition time decreased as the ignition temperature increased. On the contrary, the ignition time increased with moisture content. A decrease in mass of the coal briquettes with higher moisture contents was slower than that with lower moisture contents. The combustion of the coal briquettes was found to be first order for all moisture contents. The rate constants ($k$) were 0.0402, 0.0439, and, 0.0508 min$^{-1}$ for the coal briquettes with moisture contents of 10, 20, and 30 wt%, respectively.

**Keywords:** Coal briquette, moisture, combustion, mechanical strength, kinetics.

## 1. INTRODUCTION

In the past 15-20 years, coal has been extensively utilised as an alternative source of energy to petroleum products [1]. This is due mainly to the fact that coal is inexpensive and available domestically [2]. It is reported that amount of proven reserves of coal is as large as 2,870 million tonnes, which is ~700 million tonnes of crude oil equivalent (toe) [1]. Additionally, the amount of coal used in the form of coal briquette has been increasing steadily from 885,000 toe in 2001 (2545 B.E.) to 1,099,000 toe in 2005 (2548 B.E.), which is accounted for ~1.7-2.2% of the total energy consumption in Thailand [1].

Problematically, however, due to the tropical climate, coal and coal briquettes in Thailand (mainly lignite and sub-bituminous) usually contains a high amount of moisture, especially when kept or stored for a considerable period of time. It is reported that the moisture content of lignite and sub-bituminous coal can be as high as 40-50 wt% [3]. Burning highly moist coal or fuels leads to a decrease in combustion efficiency. This is due mainly to the fact that when the flue gas contains a high amount of water vapour, the temperature of the flue gas is lowered, thus leading a thermal loss [3-4]. In order for coal or fuels to be burned efficiently, the moisture content of the fuels should not exceed 20-30 wt% [4]. Moreover, moisture may affect the physical and combustion characteristics of coal and coal briquettes. Surprisingly, only a few works regarding the combustion of coal briquettes with a considerable amount of moisture have been found recently [3, 5-6]. Hence, it is the principal purpose of the present study to investigate the effect of moisture on mechanical strength and combustion characteristics of moist coal briquettes.

## 2. MATERIALS AND METHODS

Coal briquettes used in the present study were obtained from the coal briquette production project of the Mae-Moh power plant of the Electricity Generation Authority of Thailand (EGAT). The coal briquettes were in cylindrical shape, with a honey-comb cross section. Each coal briquette was ~1.0 kg, ~10 cm diameter, ~10-12 cm high, with sixteen ~1 cm diameter axial holes. The proximate analysis and heating value of the coal briquettes is shown in Table 1.

**Table 1.** Proximate analysis and heating value of coal briquettes.

| Type of analysis | Air-dried basis | Dry basis |
|---|---|---|
| Proximate analysis (wt%) | | |
| • Moisture | 2.5 | – |
| • Ash | 35.0 | 35.9 |
| • Volatile matter | 23.0 | 23.6 |
| • Fixed carbon (by difference) | 39.5 | 40.5 |
| Heating value (MJ/kg) | 14.7 | 15.1 |

The experiments were divided into 3 main parts: 1) the determination of the mechanical strength of moist coal briquettes with moisture contents ranging from 10-30 wt%; 2) the determination of ignition times of the coal briquettes with different moisture contents and ignition temperatures; and 3) an investigation of combustion characteristics of the coal briquettes with various moisture contents, particularly on the kinetic point of view.

Mechanical strength of the coal briquettes was determined as a compressive strength using a compression machine. Before each test run, a pre-determined amount of water was carefully poured onto a coal briquette sample, in order to make the moisture contents in the coal briquette to be within 10-30 wt% (it should be noted that the time period of pouring water into the coal briquette was brief, and its effect on the variation of coal briquettes' moisture contents was found to be negligible). The resulting coal briquette with a desirable amount of moisture was placed on the ELE CBR-Test 50, Model EL24-9610/01 compression machine. A load applied onto the coal briquette was increased steadily until the coal briquette was cracked, and the compressive strength was calculated by dividing the amount of force that caused the coal briquette to crack with the corresponding cross-sectional area.

To study the effect of moisture on the ignition time of the coal briquettes, a coal briquette, with a moisture content ranging from 10-30 wt%, was brought into a muffle furnace, at a temperature of 700, 800, or 900 °C. An observation was made periodically until the flame on the top surface of the coal briquette sample was detected. The time interval between the moment of initially placing the coal briquette into the furnace and that when the flame was observed was recorded. This time interval is essentially the ignition time.

In order to investigate the combustion characteristics of moist coal briquettes, a series of combustion test runs were carried out in a Thai traditional cooking stove at the ignited coal briquette temperature of 800 °C. In each test run, a coal briquette, with an initial moisture content of 10-30 wt%, was placed in the cooking stove, and a small fan was used to provide air for the combustion of the coal briquette through a window of the stove. Mass of the coal briquette was continuously monitored. The temperature of the coal briquette surface was also recorded periodically. The data obtained from the combustion tests were then analysed for the combustion rate, order of reaction, and rate constant.

## 3. Results and Discussion

The compressive strengths of the coal briquettes with different moisture contents, ranging from 10-30 wt%, were shown in Table 2. The average compressive strengths, in vertical and horizontal directions, ranged from 360.8-1,052.0 and 37.0-70.0 kN/m$^2$, respectively. It was evident that the mechanical strength decreased as the moisture content increased. When comparing with the results from a previous study [7], in which the average compressive strength in the vertical direction of the dry coal briquettes was approximately 1,864.5 kN/m$^2$, it was found that the compressive strengths of the moist coal briquettes decreased by 43.6%, 66.8%, and 80.6% for the samples with the moisture contents of 10, 20, and 30 wt%, respectively.

**Table 2.** Compressive strengths in vertical and horizontal directions of coal briquettes with various moisture contents.

| Moisture content (wt%) | Compressive strength (kN/m$^2$) | |
|---|---|---|
| | Vertical direction | Horizontal direction |
| **10** | 1,052.0 | 70.0 |
| **20** | 618.5 | 48.0 |
| **30** | 360.8 | 37.0 |

The ignition times of the coal briquettes at different moisture contents, ranging from 10-30 wt%, and ignition temperatures of 700-900 °C, were illustrated in Figure 1. The ignition times were in the range of 15-35, 9-15, and 5-10 minutes for the ignition temperatures of 700, 800, and 900 °C, respectively. The ignition time increased with moisture content, but decreased as the ignition temperature increased. Since the heat capacity or specific heat of water (*i.e.* moisture) is relatively high, the temperatures of moist coal briquettes are kept at relatively low (as low as ~150-200 °C [8]). Such relatively low temperatures are not high enough to drive off volatile matter. Thus, the ignition of the coal briquette is delayed until moisture is completely or nearly driven off from the coal briquette. With an increase in ignition temperature, the amount of heat required to drive off moisture increased, thus lowering the drying time, which leads to the speed-up of the time to drive off the volatile matter from the coal briquette until its concentration in the atmosphere is high enough to be ignited.

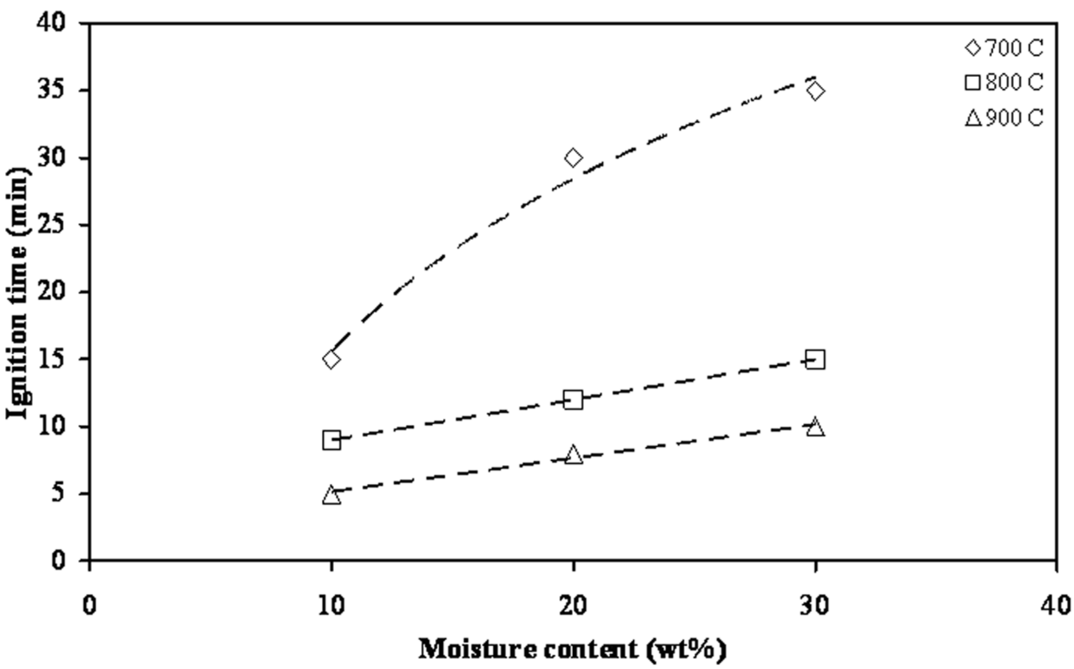


**Figure 1.** Ignition times of the coal briquettes with moisture contents of 10-30 wt% and ignition temperatures of 700-900 °C.

Mass-loss histories of the coal briquettes, with moisture contents of 10-30 wt%, were shown in Figure 2. For comparison, the result of burning a dry coal briquette, obtained from a previous study [9], was also included in Figure 2. Evidently, the coal briquettes with lower moisture contents displayed the higher rate of mass-decreasing (*i.e.* steeper slope, particularly during the initial combustion period). This was justified when translating the mass-loss histories to the combustion rates, as shown in Figure 3.

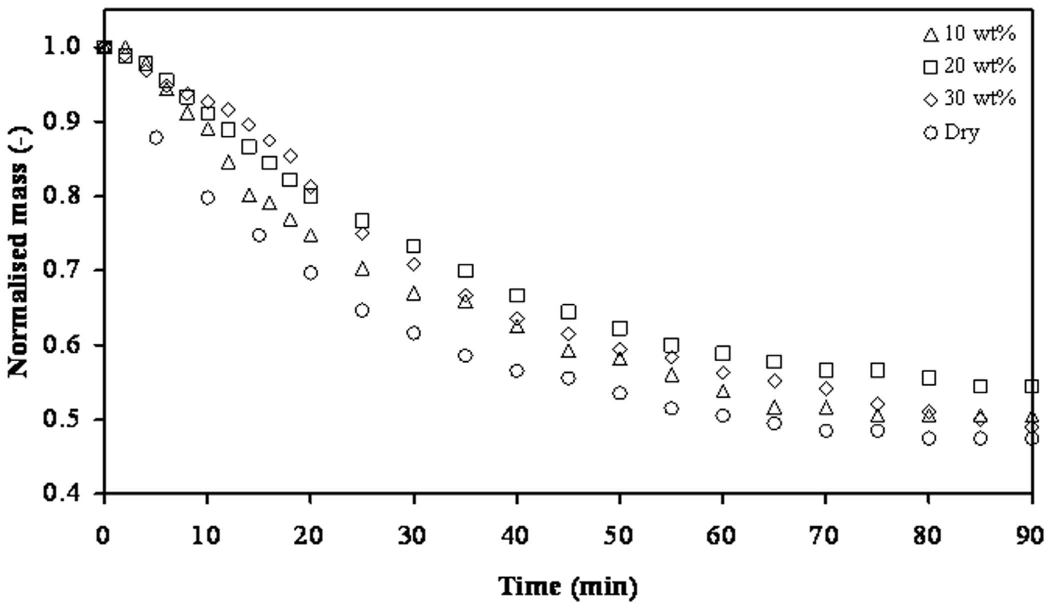


**Figure 2.** Mass-loss histories of the coal briquettes with moisture contents of 10-30 wt%, compared with that of the dry coal briquette (from Ref. [9]).

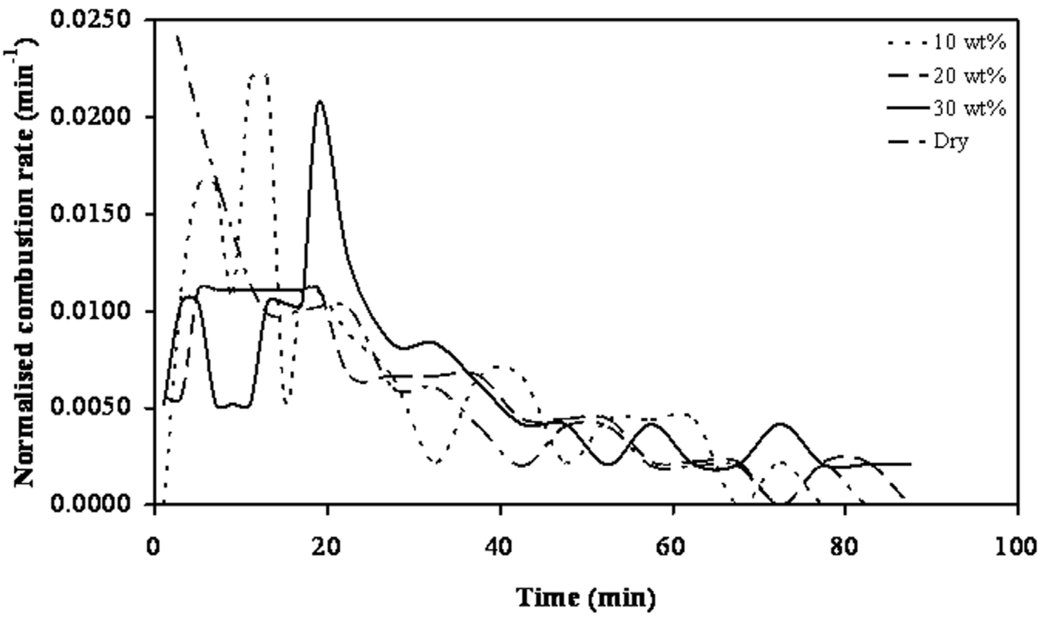


**Figure 3.** Combustion rates of the coal briquettes with moisture contents of 10-30 wt%, compared with that of the dry coal briquette (from Ref. [9]).

It was also found, from Figure 3, that the combustion rate of the dry coal briquette started to drop rapidly soon after it was placed on the stove, indicating that there was no delay of the combustion. The combustion rate of moist coal briquettes, on the contrary, reached their highest rate after the samples were placed on the stove for ~5-10 minutes for the coal briquettes with moisture contents of 10 and 20 wt%, and for ~20 minutes for the coal briquette with 30 wt% moisture content. This indicates that the delay of combustion resulting from the presence of water (or moisture) in the coal briquettes is significant.

In order to analyse the order of reaction of the moist coal briquette combustion, an integral technique was employed. Firstly, the combustion rate ($-r_A$ or $-\frac{dm_A}{dt}$) was written as a function of a remaining mass of a coal briquette sample ($m_A$), as illustrated in Eq.(1)

$$-r_A = -\frac{dm_A}{dt} = km_A^n \quad (1)$$

where $k$ is a rate constant and $n$ is a reaction order.

By performing a series of mathematical manipulations, for first (1st) order (*i.e.* $n = 1$) and second (2nd) order (*i.e.* $n = 2$), the following equations (Eqs. (2) and (3)) were obtained [10]:

for 1st order:

$$-\ln\left(\frac{m_A - m_{Ae}}{m_{Ao} - m_{Ae}}\right) = kt \quad (2)$$

for 2nd order:

$$\left(\frac{1}{m_A - m_{Ae}}\right) - \left(\frac{1}{m_{Ao} - m_{Ae}}\right) = kt \quad (3)$$

where $m_{A_o}$ and $m_{A_e}$ are the initial and final mass of the coal briquette, respectively.

A plot of Eqs. (2) and (3) for the coal

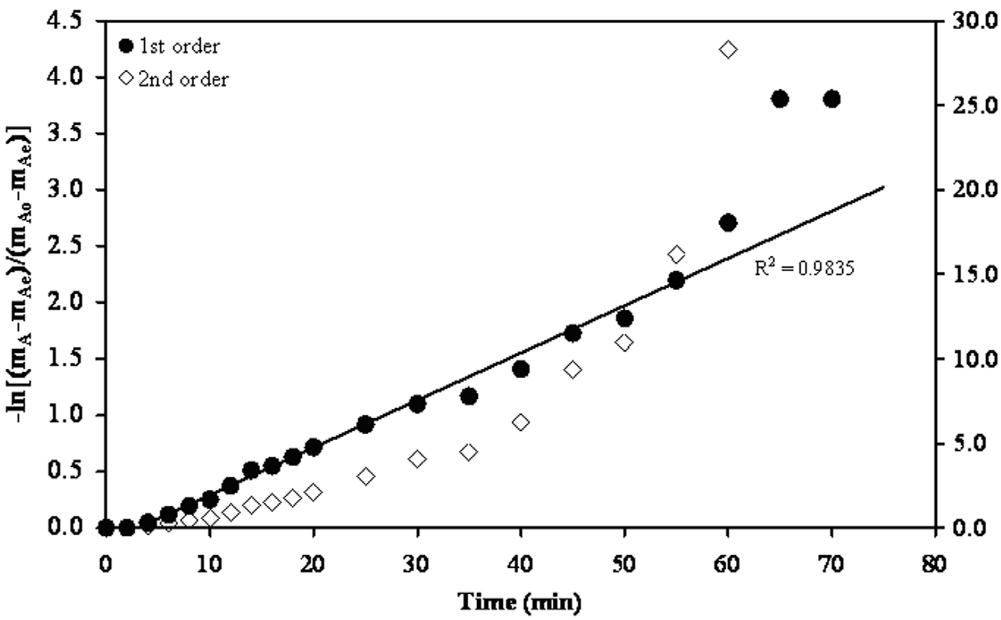


**Figure 4.** Determination of order of reaction of the combustion of the coal briquette with a moisture content of 10 wt%.

briquette containing 10 wt% of moisture was illustrated in Figure 4. In principle, the order of reaction for the coal briquette with 10 wt% moisture content was similar to those with other moisture contents. From Figure 4, it was obvious that the combustion of the coal briquettes was 1$^{st}$ order rather than 2$^{nd}$ order. The plot for the 1$^{st}$-order scheme was found to be more linear than that for the 2$^{nd}$-order one. These results agreed with those in previous studies [7, 9].

The slope of Eq. (2) or the 1$^{st}$ order equation is a rate constant (*k*). The *k* values of the coal briquette combustion at different moisture contents were summarised in Table 3. It indicated that an increase in moisture content caused the rate constant to decrease. This confirmed that the combustion of the coal briquettes was delayed when water was present in the sample.

**Table 3.** Rate constants (*k*) of the combustion of the coal briquettes with moisture contents of 10-30 wt%.

| **Moisture content (wt%)** | 10 | 20 | 30 |
|---|---|---|---|
| ***k*** **(min$^{-1}$)** | 0.0508 | 0.0439 | 0.0402 |

Time-resolved temperatures of the surface of the coal briquettes with different moisture contents (10-30 wt%) were shown in Figure 5. It should be noted that the surface temperature of the coal briquette with a moisture content of 30 wt% reached its peak slower than those with lower moisture contents. This is in accordance with the combustion-rate results illustrated in Figure 3.

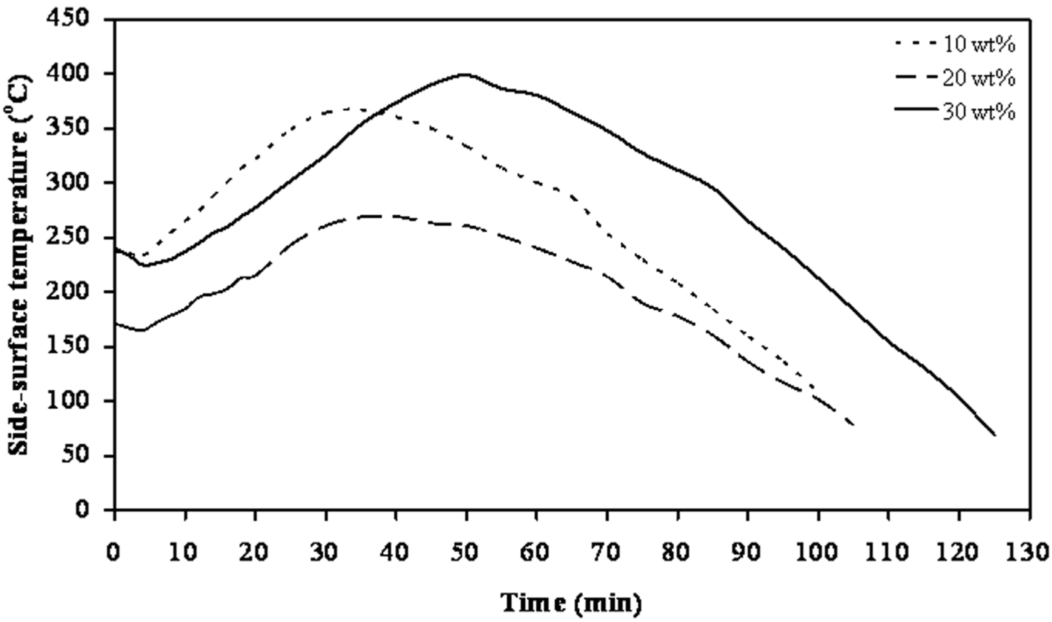


**Figure 5.** Time-resolved temperatures of the surface of the coal briquettes with moisture contents of 10-30 wt%.

## 4. Conclusions

1) The compressive strengths of the moist coal briquettes in the vertical and horizontal directions were 360.8-1,052.0 and 37.0-70.0 kN/m$^2$, respectively. An increase in moisture content resulted in a decrease in compressive strength.

2) The ignition time of the coal briquettes increased with moisture content, but decreased as the ignition temperature increased.

3) The combustion of the moist coal briquettes in the present study were found to be 1$^{st}$ order for all moisture contents (10-30 wt%).

4) The combustion rate, as well as the rate constant, of the coal briquettes was found to decrease as moisture content increased. The rate constants for the combustion of the coal briquettes with moisture contents of 10, 20, and 30 wt% were 0.0508, 0.0439, 0.0402 s$^{-1}$, respectively.

## Acknowledgement

The Mae-Moh power plant of the Electricity Generation of Thailand (EGAT) is thanked for providing coal briquettes used in the present study.

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