Modified respiratory quotient to evaluate the environmental impact of Chinese coal combustion

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Abstract: Considering the effect of ash and moisture on CO_2 emission during combustion, a modified respiratory quotient (RQ_m) was employed to determine the CO_2 emission potential of anthracite, bituminous, lignite, and peat in China. It was found that the conventional RQ of different Chinese coals was almost the same (from 0.9 to 1), but RQ_m of coals varies significantly. The low-rank coals such as peat and lignite have significantly high RQ_m which can go up to 7. The high-rank coals such as anthracite and bituminous coals have RQ_m between 1 and 2. Higher RQ_m means more CO_2 emission since more energy is required to transport or process the low-rank coals. Moreover, correlations between O/C and H/C ratios of the coals and RQ_m were also analysed. It was found that low-rank coals such as lignite and peat have higher H/C and O/C ratios and their RQ_m are correspondingly higher. [Received: April 2, 2017; Accepted: July 1, 2017]

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1 Introduction

Coal is the most important source of energy in China. Due to the rapid economic growth in China, the dependence on this fossil fuel for power generation keeps growing. The combustion of coals, however, adds in a significant amount of carbon dioxide (CO_2, a major greenhouse gas contributing to global warming) to the atmosphere per unit of heat energy, more than does the combustion of other fossil fuels (DOE/EIA, 1993). Moreover, coal burning is a major source of atmospheric pollution, with particulates, SO_2 and NO_x. According to Energy Information Administration (EIA, 2014), the total CO_2 emission of China was around 8,106 million metric tons in 2012. CO_2 from the utilisation of coals contributed 80.3% (6,512 million metric tons) of total emissions (EIA, 2014). Moreover, the world's total coal consumption reached 165 quadrillion BTU in 2015, of which China's share was more than 50%. Also, China contributed 88% of the growth in world's coal consumption (EIA, 2017). The total CO_2 emission of China will keep increasing in the next decades. In China, power generation consumes about 80% of the coal production. Thus, improving energy conversion efficiency and reducing the pollution from coal combustion would be the first priority for Chinese authorities.

Different methods have been used to evaluate the CO_2 emission with regard to the rank of coals. Hong and Slatick (1994) used CO_2 emission factor which is defined as pounds of CO_2 per million BTU in terms of the energy content of coals to evaluate the emission of different types of coals. Annamalai (2013) and Thanapal et al. (2014) first applied the concept of respiratory quotient (RQ), a term used in the biological literature, to evaluate the rank of fossil and biomass fuels combustion based on CO_2 emissions. RQ is defined as the ratio of moles of CO_2 produced to moles of stoichiometric oxygen (O_2) consumed during oxidation reaction (e.g., oxidation of nutrients in the human body) (Thanapal, 2014). RQ enables the estimation of global warming potential (GWP) of different fuels, even new fuels such as torrefied biomass fuels for combustion applications. RQ of the new fuels can be compared to the conventional fossil fuels in order to determine the fuels' emission potential. Thanapal (2014) calculated RQ of various gaseous, liquid and solid fuels. RQ of raw biomass is equal to zero if biomass is considered as carbon neutral fuel. Lower RQ values mean less CO_2 emission to atmosphere and less GWP. In order to reduce CO_2 emission, more stringent regulations and laws such as carbon tax were levied by national governments and international organisations such as European Union's carbon tax (Annamalai, 2013; Jangam et al., 2011). Utilisations of new combustion technology and renewable energy are encouraged to reduce greenhouse gas emission. Thanapal et al. (2014) found 90:10 blends of coal (RQ of 0.92) and torrefied woody biomass (RQ of 0.82) could reduce the RQ value to 0.84.

By now, all the RQ values of the fuels were calculated on a dry and ash free basis. In reality, ash and moisture exist in all kinds of fuels, especially solid fuels and the weight percentages vary with fuel types. Lignite coal may contain a high amount of moisture (up to 60%) (Gordillo et al., 2009); animal waste such as dairy biomass and feedlot contain more than 15% ash (Annamalai et al., 1987). High percentages of moisture and ash in fuels lead to significantly low energy density and low furnace energy conversion efficiency. Meanwhile, it increases the emission of CO_2 in a unit of ton/GJ. The recent development of hydraulic fracture technology has dramatically increased the production of shale gas or natural gas, a large portion of which are used for power generation in the

USA. In 2015, natural gas overtook coal as the top source of USA's electric power generation. However, low-ranked coals are still the primary fuel for electricity power generation in China. Currently, the greenhouse gas release regulation is more stringent than ever. A more realistic method to define RQ and its influence on coal ranking are very important to estimate CO_2 emission potential. The definition of RQ from the empirical chemical formula (or ultimate analysis) and from exhaust gas analysis is not enough to estimate the CO_2 emission of coal combustion since low-ranked coals contain abundant ash and moisture, but RQ does not consider ash and moisture.

In this study, a modified respiratory quotient (RQ_m) which considers the contribution of the ash and moisture in combustion was proposed to estimate CO_2 emission potential for coals of different ranks such as anthracite, bituminous, lignite, etc. The correlation between fuel heating value and RQ_m was analysed and established. Moreover, the effect of O/C and H/C ratios on RQ_m was studied. RQ_m combines carbon content and heating values of fuels and is an explicit metric for comparison of GWP among fuels.

2 Definitions of RQ and RQ_m

2.1 Conventional RQ

The conventional RQ which was used to calculate basal metabolic rate in biology was recently applied to evaluate the CO_2 emission potential of four different types of fuels such as biomass fuels and transportation fuels (Annamalai, 2013; Thanapal, 2014). Since empirical chemical formulas of coals are in the form of C-H-N-O-S, the negligible N from air or fuel is assumed to be converted into NO during combustion and coal combustion is completed in a stoichiometric condition (Thanapal, 2014). According to the definition of RQ, it can be determined from the empirical chemical formula or the ultimate analysis of fuel as shown in equation (1) (Thanapal et al., 2014; Annamalai, 2013).

$$RQ = \frac{CO_2\ moles\ produced}{O_2\ moles\ produced} = \frac{1}{\left\{1 + \left(\frac{H}{4C}\right) - \left(\frac{O}{2C}\right) + \frac{S}{C}\right\}} \tag{1}$$

where *C*, *H*, *O* and *S* are the numbers of carbon, hydrogen, oxygen and sulphur atoms respectively. According to equation (1), Thanapal et al. (2014) calculated that RQ value is 0.5 for methane (gaseous fuel); 0.67 for methanol (liquid fuel); 0.92 and 0.93 for Wyoming coal and Texas lignite respectively. Based on this definition, hydrogen is considered as a clean fuel since the combustion product is H_2O with zero RQ value.

Instead of analysing fuel compositions, an alternative method to determine RQ for a fuel based on exhaust gas composition is proposed in equation (2) (Annamalai, 2013; Thanapal et al., 2014).

$$RQ = \frac{CO_2\ moles\ produced}{O_2\ moles\ produced} = \frac{X_{CO_2,e}\left(\frac{X_{N_2,i}}{1 - X_{O_2,e} - X_{CO_2,e}}\right) - X_{CO_2,i}}{1 - X_{O_2,e}\left(\frac{X_{N_2,i}}{1 - X_{O_2,e} - X_{CO_2,e}}\right)} \tag{2}$$

where X_{N_2}, X_{CO_2} and X_{O_2} are the mole fractions of N_2, CO_2 and O_2 which could be either on a dry or a wet basis and the subscripts *i* and *e* refer to inlet and exit of combustion chamber respectively.

2.2 Modified respiratory quotient

Different from gaseous fuel, the conventional RQ cannot make a distinction for solid fuel combustion since it is calculated based on a dry-and-ash-free basis. The RQ values are similar for different coals and it cannot differentiate the coals' CO_2 emission potential. For example, RQ of Wyoming coal and Texas lignite are 0.92 and 0.93, respectively (Thanapal, 2014). In reality, moisture and ash significantly lower the energy density of coals and hence, power plants need to consume more low-rank coals to maintain the same energy input, which results in extra CO_2 emission. The process and transportation of low energy density coals incurs more energy and financial costs (electrical power for grinding, fuel used for collection and transportation and energy for coal ash removal, etc.). Considering the CO_2 release from all these processes, the actual RQ value should be even higher. As a result, a RQ_m considering the energy density of coal was used to estimate CO_2 emission from coals of different ranks. In this study, a heating value factor (h_f) defined as the ratio of fuel higher heating value (HHV, as received) to that of natural gas was brought into the conventional RQ equation to describe solid fuel quality as shown in equation (3). Here, H_2O in the end product gases was assumed to be liquid water and latent heat was released to the environment. Thus, HHV was selected for calculation in equation (3). In this equation, the HHV of natural gas (main composition is CH_4) is used as a reference for coals of different grades since natural gas is a gaseous fuel and considered to be a more efficient and cleaner fuel to replace coal in power plants to reduce CO_2 emission. The modified RQ is defined as

$$RQ_m = \frac{CO_2 \text{ moles produced}}{O_2 \text{ moles produced}} = \frac{h_f}{\left\{1 + \left(\frac{H}{4C}\right) - \left(\frac{O}{2C}\right) + \frac{S}{C}\right\}} \tag{3}$$

where $h_f = \dfrac{HHV_{CH_4}}{HHV_{fuel(As\ received)}}$.

RQ_m based on exhaust gas composition of an unknown fuel is given as equation (4):

$$RQ_m = \frac{CO_2 \text{ moles produced}}{O_2 \text{ moles produced}} = h_f \frac{X_{CO_2,e}\left(\dfrac{X_{N_2,i}}{1 - X_{O_2,e} - X_{CO_2,e}}\right) - X_{CO_2,i}}{1 - X_{O_2,e}\left(\dfrac{X_{N_2,i}}{1 - X_{O_2,e} - X_{CO_2,e}}\right)}. \tag{4}$$

3 Fuel proximate and ultimate analysis

In this study, four ranks of coals including anthracite, bituminous, lignite and peat were selected for RQ analysis. Each rank of coal includes five samples obtained from different locations. Tables 1 to 4 give the proximate analysis, ultimate analysis and CO_2 emission potential of these 20 samples.

4 Results and discussions

4.1 Fuel properties

As shown from the ultimate analysis of coals in Table 1 to Table 4, anthracite and bituminous coals contain a large amount of carbon have the least impurities and higher energy density. However, lignite contains more than 30% ash and moisture and peat has more than 50% ash and moisture. High amounts of moisture and ash not only reduce the calorific value of coals and the thermal efficiency of power plants but also increase the system maintenance cost. Coals with high amounts of ash and moisture are less suitable for combustion. In addition, more energy is required to process these low-rank coals before combustion which increases of CO_2 emission. CO_2 emission of these four ranks of coals ranges from 0.075 to 0.095 tons/GJ on a dry and ash-free basis. Among these coals, anthracite has the highest CO_2 emission (around 0.095 tons/GJ on dry ash free basis).

4.2 HHV of coals per unit stoichiometric oxygen

The heating value of a fuel is defined as the amount of heat released when a unit mass or volume of fuel is burned at stoichiometric conditions. Boie empirical equation for estimating the HHV of fuels in the form of $C_CH_HN_NO_OS_S$ on dry and ash free basis is given in equation (5) (Annamalai et al., 1987):

$$HHV_{\text{daf},kJ/kmole} = 422270N_C + 117385N_H - 177440N_O + 87985N_N + 335510N_S \quad (5)$$

where N_C, N_H, N_O, N_N and N_S are the number of carbon, hydrogen, oxygen, nitrogen and sulphur atoms respectively in the fuel, which can be obtained from the fuel's ultimate analysis. Since coals contain a certain amount of moisture and ash, the HHV of coals would be lower on as-received basis. The HHV_{ad} is given in equation (6):

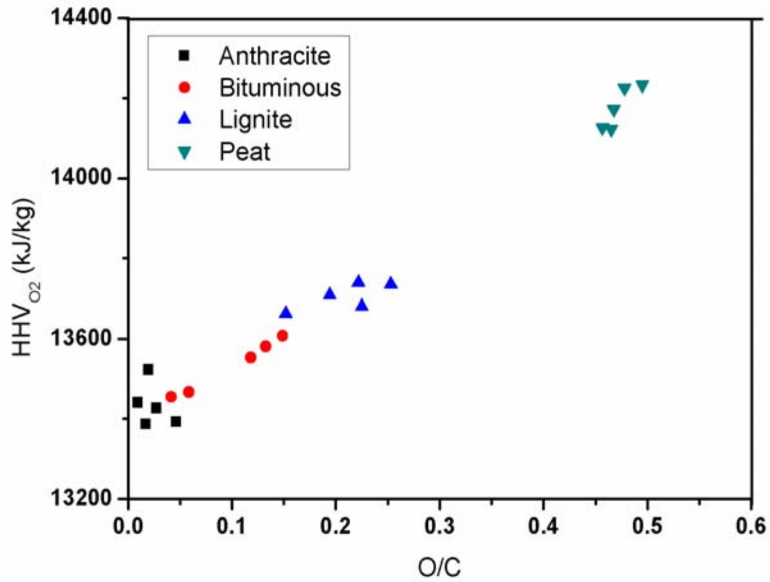
$$HHV_{ad} = HHV_{daf} / M_{C_CH_HN_NO_OS_S} \times (1 - Y_A - Y_M) \quad (6)$$

where $M_{C_CH_HN_NO_OS_S}$ is the molecular weight of fuel, Y_A and Y_M are the weight percentage of ash and moisture, respectively. To estimate the amount of heat produced from consumption of per unit mass oxygen during the combustion process, HHV_{O_2} is defined as equation (7) (Thanapal, 2014):

$$HHV_{O_2} = \frac{HHV_{ad}}{W_{O_2}} \quad (7)$$

where W_{O_2} is consumed oxygen weight (kg) per kg fuel. It is observed from Figure 1 that HHV_{O_2} is between 13,000 and 14,400 kJ/kg O_2 for different coals and it increases with the decrease of coal rank. The reason is that with the decrease of coal rank, O/C ratio increases and less O_2 is required to sustain the combustion to release the same amount of heat from coal.

Figure 1 Coal HHV_{O2} vs. O/C ratio (see online version for colours)



4.3 Coal RQ and RQ_m based on fuel ultimate analysis

According to equation (1) and equation (3), RQ and RQ_m of these 20 coals were calculated and are shown in Figure 2. It is found that RQ of methane is 0.5, which is lower than those of coals (0.85 to 1). Also, RQ values do not vary much from anthracite to peat and the values vary from 0.9 to 1. As a result, the GWP of these coals cannot be distinguished based on conventional RQ values. When ash and moisture were considered in the calculation, RQ_m values of these coals vary significantly. For example, RQ_m is around 1.5 for anthracite while it rises to 4 for lignite. Moreover, RQ_m also varies in a certain level for each class of coals, especially for lignite and peat due to the variation of ash and moisture mass percentages.

4.4 HHV_{ad} of coals vs. RQ_m

The HHV_{ad} of coals to RQ_m are given in Figure 3. It shows that the heating values of coals decrease with the increase of RQ_m. High-grade coals (e.g., low RQ_m) such as anthracite contain more fixed carbon, less ash and less moisture and thus, its energy density is high. For example, the heating value of anthracite coal with RQ_m of 1.5 is more than 30,000 kJ/kg. However, it is less than 15,000 kJ/kg for peat coal. As a result, coals with lower RQ_m are more environmentally friendly due to lower CO_2 emissions.

Table 1 Fuel properties of anthracite

Coal no.	*1*	*2*	*3*	*4*	*5*
Ref.	Sichuang (Zou et al., 2014)	Yangquan (Ouyang et al., 2014)	Neimenggu (Li et al.,2013)	Huaibei (Ge et al, 2015a)	Shanxi (Cheng et al., 2015)
Proximate analysis (%)					
Moisture	0.46	2.04	0.45	1.01	1.46
Ash	12.54	8.64	10.77	9.82	10.80
Volatile matter	10.80	7.58	11.49	8.82	7.95
Fixed carbon	76.71	81.74	77.29	80.35	79.79
Ultimate analysis (%)					
Carbon	89.91	92.27	90.80	90.67	91.02
Oxygen	5.59	2.10	3.32	1.11	2.40
Hydrogen	2.86	3.52	4.03	5.18	3.42
Nitrogen	1.05	1.33	1.44	1.56	1.25
Sulphur	0.60	0.79	0.41	1.48	0.8
Chemical formula	$CH_{0.382}O_{0.0466}N_{0.01}S_{0.0025}$	$CH_{0.4576}O_{0.0171}N_{0.0123}S_{0.0032}$	$CH_{0.5329}O_{0.0274}N_{0.0136}S_{0.0017}$	$CH_{0.6857}O_{0.0092}N_{0.0147}S_{0.0061}$	$CH_{0.451}O_{0.0198}N_{0.0118}S_{0.0037}$
HHV_{daf} (kJ/kmol)	460,556	475,111	481,718	504,484	473,937
HHV_{ad} (kJ/kg)	30,021	32,498	32,359	33,990	31,863
CO_2 (tons/GJ)	0.0943	0.0925	0.0908	0.0876	0.0926

Table 2 Fuel properties of bituminous

Coal no.	*6*	*7*	*8*	*9*	*10*
Ref.	Xuzhou (Ge et al., 2015a)	Datong (Yang et al., 2015)	Shenhua (Liu et al., 2014)	Shenhua (Ge et al., 2015b)	Shenmu (Li et al., 2016)
Proximate analysis (%)					
Moisture	1.53	9.21	11.5	6.01	4.53
Ash	14.33	11.47	10.7	4.76	8.82
Volatile matter	12.82	31.53	24.22	35.10	35.55
Fixed carbon	71.32	54.31	53.58	54.13	51.10
Ultimate analysis (%)					
Carbon	87.31	88.76	81.14	77.97	79.14
Oxygen	6.82	4.92	12.78	15.48	13.98
Hydrogen	4.02	4.32	4.65	4.82	4.73
Nitrogen	1.48	1.46	0.90	1.15	1.26
Sulphur	0.38	0.54	0.53	0.58	0.89
Chemical formula	$CH_{0.552}O_{0.0586}N_{0.0145}S_{0.0016}$	$CH_{0.5846}O_{0.0415}N_{0.0141}S_{0.0023}$	$CH_{0.6881}O_{0.1181}N_{0.0095}S_{0.0024}$	$CH_{0.7417}O_{0.1489}N_{0.0127}S_{0.0028}$	$CH_{0.7167}O_{0.133}N_{0.0136}S_{0.0042}$
HHV_{daf} (kJ/kmol)	478,501	485,530	483,743	484,974	485,504
HHV_{ad} (kJ/kg)	31,290	28,488	25,489	28,116	29,061
CO_2 (tons/GJ)	0.0904	0.0897	0.0876	0.0866	0.0870

Table 3 Fuel properties of lignite

Coal no.	*11*	*12*	*13*	*14*	*15*
Ref.	XiLinHaoTe (Guo et al., 2008)	Yuanbaoshan (Yang et al., 2015)	Dayan (Li et al., 2013)	Baiyinhua (Yang et al., 2015)	Shengli (Zhang et al., 2015)
Proximate analysis (%)					
Moisture	34.00	27.65	21.62	32.94	11.8
Ash	11.35	27.13	11.33	25.69	10.7
Volatile matter	46.77	45.35	31.95	54.89	42.3
Fixed carbon	7.88	24.71	35.10	19.81	35.2
Ultimate analysis (%)					
Carbon	71.34	68.52	76.92	72.26	69.81
Oxygen	21.39	23.10	15.56	18.70	20.65
Hydrogen	5.09	5.04	5.66	5.78	6.19
Nitrogen	0.35	1.08	1.67	1.64	1.16
Sulphur	1.83	2.26	0.18	1.62	2.19
Chemical formula	$CH_{0.8556}O_{0.2249}N_{0.0042}S_{0.0096}$	$CH_{0.8829}O_{0.2529}N_{0.0136}S_{0.0123}$	$CH_{0.884}O_{0.152}N_{0.0186}S_{0.0009}$	$CH_{0.9592}O_{0.1941}N_{0.0195}S_{0.0084}$	$CH_{1.0647}O_{0.221}N_{0.0143}S_{0.0118}$
HHV_{daf} (kJ/kmol)	486,399	486,363	501,010	504,950	513,099
HHV_{ad} (kJ/kg)	15,803	12,560	21,543	12,581	23,132
CO_2 (tons/GJ)	0.0843	0.0838	0.0838	0.0824	0.0806

Table 4 Fuel properties of peat

Coal no.	*16*	*17*	*18*	*19*	*20*
Ref.	Dehui Da Qingzu (Jiang, 1991)	Shuhuaxian (Jiang, 1991)	Shulanfate Farm (Jiang, 1991)	ShulanXiaochengzi (Jiang, 1991)	Yushu Chengfa (Jiang, 1991)
Proximate analysis (%)					
Moisture	30	30	30	30	30
Ash	26.58	11.62	32.64	34.03	40.24
Volatile matter	31.25	42.28	27.86	27.52	23.35
Fixed carbon	12.17	16.1	9.5	8.45	6.41
Ultimate analysis (%)					
Carbon	56.54	57.42	56.42	54.63	55.07
Oxygen	35.08	34.96	35.17	36.06	35.08
Hydrogen	4.28	4.74	5.25	5.50	5.91
Nitrogen	2.95	2.62	2.92	3.25	3.46
Sulphur	1.15	0.26	0.24	0.56	0.47
Chemical formula	$CH_{0.9092}O_{0.4653}N_{0.0447}S_{0.0076}$	$CH_{0.9916}O_{0.4567}N_{0.0391}S_{0.0017}$	$CH_{1.116}O_{0.468}N_{0.0443}S_{0.0016}$	$CH_{1.2092}O_{0.4950}N_{0.0510}S_{0.0038}$	$CH_{1.2886}O_{0.478}N_{0.0539}S_{0.0032}$
HHV_{daf} (kJ/kmol)	452,928	461,649	474,725	482,139	494,577
HHV_{ad} (kJ/kg)	9,266	12,895	8,339	7,895	6,755
CO_2 (tons/GJ)	0.0833	0.0818	0.0797	0.0782	0.0769

Figure 2 RQ and RQ_m of the four ranks of coals (see online version for colours)

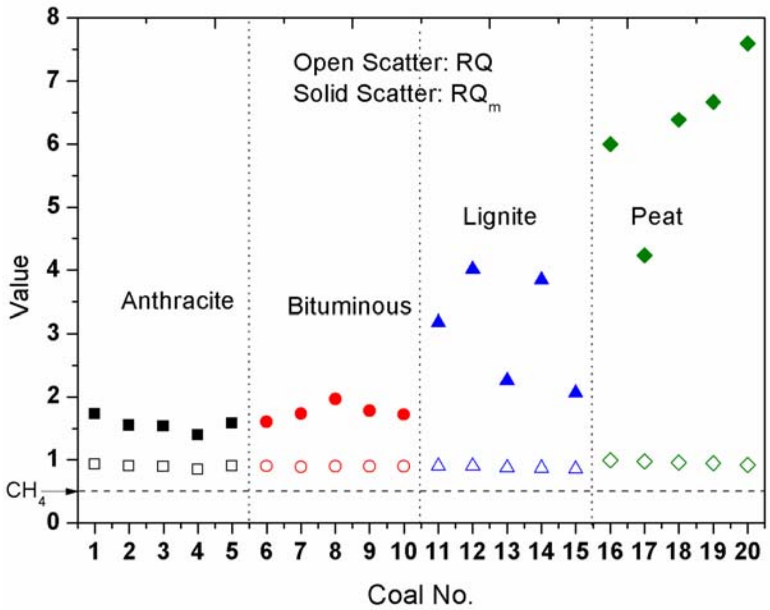
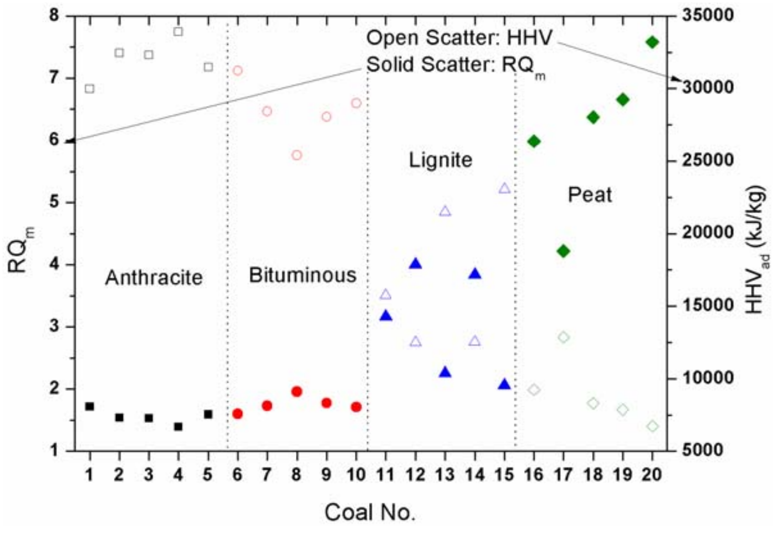


Figure 3 HHV_{ad} and RQ_m of the four ranks of coals (see online version for colours)



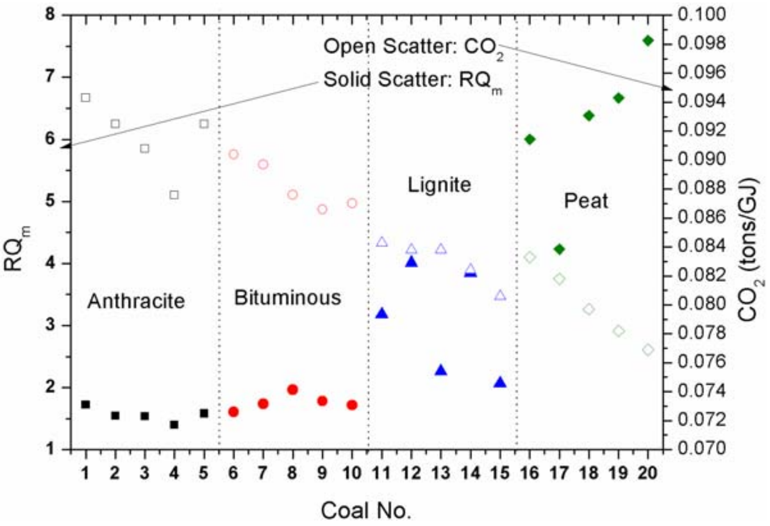
4.5 CO_2 emission

The global warming is attributed primarily to the increasing industrial CO_2 emissions into earth's atmosphere, especially CO_2 emission from coal combustion. Coals with high RQ_m tend to release more CO_2 than fuels with low RQ_m such as ethanol. The CO_2 emission in tons/GJ of energy input from the fuel was estimated based on chemical composition, as shown in equation (8) (Thanapal, 2014):

$$CO_2 \; in \; tons / GJ = \frac{1 \times 44 \times 1000}{\left\{ 422270 \times \left(1 + \frac{117385}{422270} \right) \times \left(\frac{H}{C} \right) - \left(\frac{117440}{422270} \right) \times \left(\frac{O}{C} \right) \right\}} \quad (8)$$

The relationship between CO_2 emission and RQ_m of these 20 coals is given in Figure 4. It shows that the CO_2 emissions of coal combustion decrease with the increase of RQ_m values, which means low quality fuels has less CO_2 emission from combustion of coal per unit mass.

Figure 4 CO_2 emissions and RQ_m of the four ranks of coals (see online version for colours)



However, this trend does not reflect the actual CO_2 emission of the coals since equation (8) does not take into account of the effect of moisture and ash on the combustion. High ash and moisture content of the coals not only decreases the heating values but also consumes more processing energy which results in more CO_2 emission. Thus, equation (8) was further developed to estimate CO_2 emission and the influence of processing low quality coals:

$$CO_2 \; in \; tons / GJ = h_f \frac{1 \times 44 \times 1000}{\left\{ 422270 \times \left(1 + \frac{117385}{422270} \right) \times \left(\frac{H}{C} \right) - \left(\frac{117440}{422270} \right) \times \left(\frac{O}{C} \right) \right\}} \quad (9)$$

where h_f is the heating value factor. Based on equation (9), a new correlation between CO_2 emission and RQ_m is shown in Figure 5. It is found that CO_2 emission is between 0.14 and 0.18 tons/GJ for anthracite and bituminous, while for low rank coals like lignite and peat CO_2 emission goes up to around 0.5 tons/GJ. If the low rank coals were upgraded to high energy density fuels at a low energy penalty, h_f would increase and CO_2 emission would decrease. Recently, different technologies including conventional evaporation drying methods and non-evaporation dewatering methods such as mechanical thermal expression (MTE) process and hydrothermal dewatering (HTD) process were developed to remove moisture and increase the heating value of coals. Moreover, coals can also be blended with biomass to be burned in furnaces to reduce CO_2 emission since biomass fuel is considered to be carbon neutral (Thanapal, 2014).

Figure 5 Modified CO_2 emissions and RQ_m of the four ranks of coals (see online version for colours)

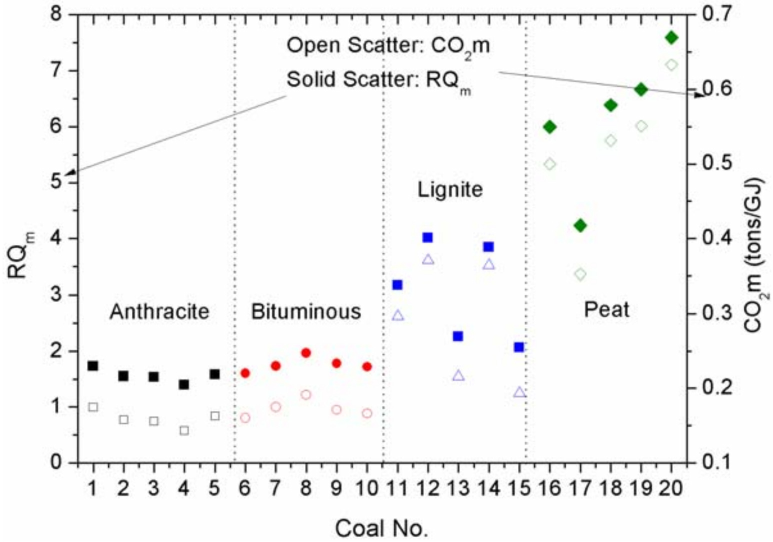
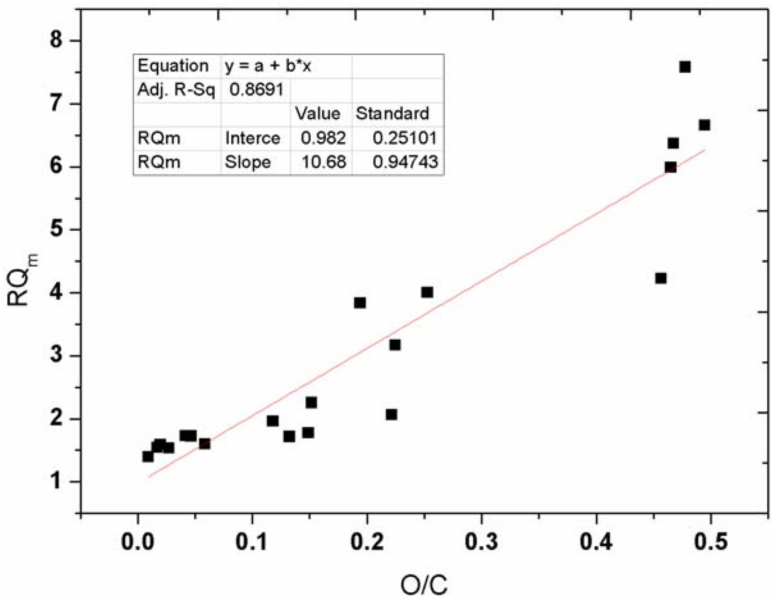


Figure 6 Variation of different coal RQ_m with O/C ratio (see online version for colours)



4.6 H/C and O/C ratios vs. RQ_m

Since solid fuels contain certain amount of moisture and ash which affect the C, H and O elements in the fuels, RQ_m shows strong correlation with H/C and O/C ratios. Thus, a linear relationship of RQ_m and O/C ratio (RQ_m = 10.68O/C + 0.98) is plotted in Figure 6. It can be seen from the equation that RQ_m increases with an increase of O/C ratio. The low-ranked coals like lignite contains high amount of oxygen. The oxidisation of the low ranked coals requires less oxygen and hence, results in increase of RQ_m value.

Figure 7 Variation of different coal RQ_m with H/C ratio (see online version for colours)

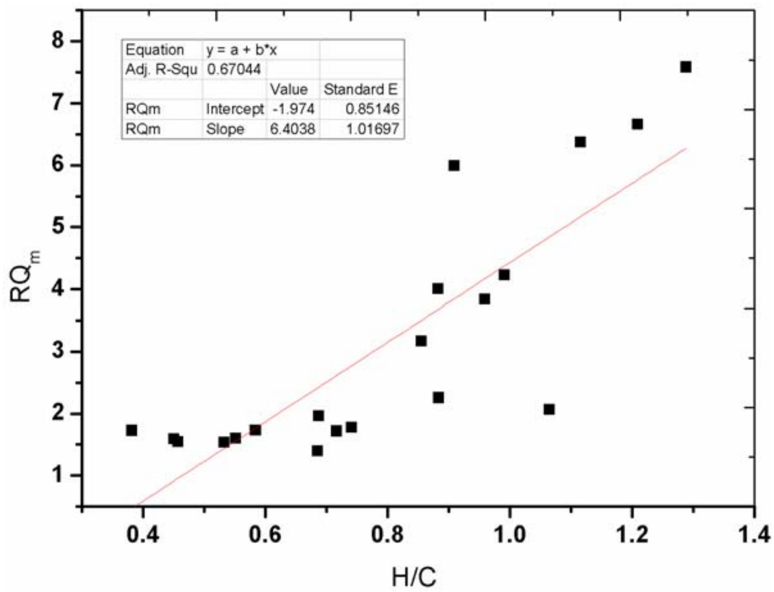


Figure 7 gives the relationship between H/C ratio and RQ_m (RQ_m = 6.40H/C – 1.97). Similar to O/C ratio, H/C ratio increases with the decrease of coal quality. Moreover, RQ_m increases with increase of H/C ratio. Both oxygen and hydrogen contents increases with lowering of grade and decrease of energy density (e.g., low h_f).

5 Zero RQ technology (zero emission)

If RQ_m is equal to zero, according to the definition of RQ_m, CO_2 emission from combustion should be zero which means the fuel has no GWP. Recently, various approaches for CO_2 capture were studied. These approaches can be grouped into three categories: pre-combustion, oxy-combustion, and post-combustion (Smith et al., 2013). The post-combustion measures are the most popular method. For the post-combustion technologies, chemical loop combustion (CLC) is considered to be 'zero emission' technologies. CO_2 is captured after combustion, which will be recycled and mixed with O_2 as coal gasification agent. Thus, no CO_2 is released to the atmosphere. These technologies reduce the CO_2 emission and eventually reduce RQ_m. However, CO_2 capture may cause considerable thermal efficiency penalties, typically varying from 6.5% to 15% (energy consumption for CO_2 compression is included) depending on the technology pathways (Kanniche et al., 2010). Since any kind of energy consumption will result in CO_2 emission, the actual RQ_m of the CO_2 capture would never be equal to 0. The RQ_m value for fuel production combined with CO_2 capture will be studied in the near future.

6 Conclusions

In this study, RQ, a dimensionless index used in calculations of basal metabolic rate in the biological field, is modified to evaluate coal combustion and CO_2 emission potential. The RQ_m, which considers the effect of ash and moisture content, is calculated to evaluate the CO_2 emission potential of 20 coals. The results are listed below:

1 Generally, higher RQ value means higher CO_2 emission during combustion. RQ of CH_4 is 0.5 and RQ of coals are between 0.9 and 1. The conventional RQ definition is based on dry and ash free basis hence it does not reflect the actual CO_2 emission of coals.

2 Considering the effect of moisture and ash, high rank coals such as anthracite and bituminous have lower RQ_m which ranges from 1 to 2, while RQ_m of peat is relatively high. It could go up to 7. Higher RQ_m (eg., low rank coal) means higher CO_2 emission potential.

3 Lignite and peat have higher O/C (> 0.15) and H/C ratios (> 0.85) than those of anthracite and bituminous. The heating values of the coals decrease with increase of O/C ratio. Similar to heating value, RQ_m also increase with increase of O/C and H/C ratios.

4 For zero emission technology, RQ_m is zero since CO_2 is captured after combustion. However, CO_2 capture may decrease thermal conversion efficiency significantly and lead to increase of RQ_m. As a result, actual RQ_m of hydrocarbon fuel combustion would not be zero. But with the advance of technologies, both CO_2 emissions and RQ_m of hydrocarbon fuel combustion would be very low.

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Nomenclature

Symbol	*Description*
CLC	Chemical loop combustion
CO_2	Carbon dioxide
h_f	Heating value factor
HHV	Higher heating value
daf	Dry and ash free basis
ad	As received basis
HTD	Hydrothermal dewatering
MTE	Mechanical thermal expression
RQ	Respiratory quotient
RQ_m	Modified respiratory quotient

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