



Relationship between proximate analysis parameters and combustion behaviour of high ash Indian coal

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Abstract This work presents the analysis of combustion characteristics of high ash Indian coal (28%–40%) collected from different mines of Singaurali coalfield, India. All the coal samples were characterized by proximate and gross calorific value analysis. Combustion performance of the coals were characterised using thermo-gravimetric analysis to identify the burning profile of individual coals. Various combustion kinetic parameters such as ignition temperature, peak temperature and burnout temperature, ignition index and burnout index, combustion performance index plus rate and intensity index of combustion process, activation energy were determined to analyse the combustion behaviour of coal. Further all these combustion properties were compared with the volatile matter, ash, fixed carbon and fuel ratio of each coal. Theoretical analysis shows that with increase in ash content, combustion performance initially increases and later descends. Further, coal with $(25 \pm 1.75)\%$ volatile matter, 20%–35% ash and fuel ratio 1.4–1.5 were found to be optimum for coal combustion.

Keywords TGA–DTG · Proximate analysis · Combustion kinetics · Activation energy · Burning profile

1 Introduction

Coal utilities are currently the major source of electricity in India. Share of coal fired power is usually in the range of 60%–65% (Ministry of Power 2020; Department of Industry 2020). Though the share of solar and wind power has increased over the last two decades, coal would continue to dominate the electricity sector in India in next few decades. It is important that existing coal utilities are operated at low generation cost and in an environmentally friendly manner. Major drawback of coal utilities are their pollution due to uncontrolled combustion of coal. In India utilities usually get coal from multiple sources and coal is priced essentially on the basis of gross calorific value

(GCV). During combustion, GCV contributes only to the maximum possible heat release, though heat release rate is mostly controlled by coal proximate parameters i.e. ash, volatile matter, moisture and fixed carbon (Behera et al. 2018; Mazumdar 2000). Due to variations in these parameters varying burning characteristics of coal like ignition temperature, rate of coal burning and heat release could be different for each coal (Liu et al. 2015). Coal from different sources, having different hydrocarbons as part of combustibles have different internal energy, bond structure and finally different reactivity with oxygen/air. Therefore, overall rate of combustion for each coal might be different. When these types of mixed coal are fed to the boiler, individual coal burns with different residence time and hence different heat release rates. Such factors are not always considered in India during linkage, which is being mostly guided by the logistics associated with production, rail transport and pricing of coal (Nandi and Bhattacharya 2019). As a result, most of the power plants using multiple sources of coal end up with unburned carbon either in fly

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ash or in bottom ash as well as carbon monoxide release in flue gas.

Among different types of characterizations available for coal, proximate analysis is the easiest and can be carried out at plant level with minimum infrastructure. Other characterizations such as ultimate analysis, petrographic analysis, ash composition analysis etc. are necessary to get insights into coal characteristics and combustion process. However, these analysis are time consuming and need considerable infrastructure and trained manpower for analysis. Therefore, prediction of combustion behaviour based on easily carried out proximate analysis makes sense to utilities. Hence it is necessary to investigate the effects of various coal property parameters on combustion behaviour of coal. Considerable literature existing on coal combustion is focused on low ash (< 10%) content coal (Chen et al. 2015). In contrast, Indian utilities burn coal having very high ash content, typically 30%–40% and sometimes up to 50% (Zhang et al. 2013a, b). Combustion behaviour of these high ash coals could be different from that of low ash coal. Limited work however appears to have been carried out on combustion of high ash coal and its dependency on proximate analysis parameters of coal.

Present investigation has been carried out to examine the effects of coal proximate analysis parameters on the combustion behaviour of coal. Four different types of coal collected from four different sources were analysed for their proximate analysis, GCV and combustion behaviour analysis by TGA. Further, different combustion performance characteristic parameters were estimated and correlated with the proximate analysis parameters.

2 Theory

Thermo-gravimetric analysis (TGA) is carried out in a thermogravimetric analyser to determine the non-isothermal combustion of coal to evaluate various kinetic parameters of coal combustion. The standard experimental procedure for thermo-gravimetric analyser has been followed in this study. Various characteristic combustion parameters under oxy-fuel conditions including ignition temperature T_i (°C), peak temperature T_p (°C) and burnout temperature T_f (°C) are used to evaluate combustion behaviour on the same burnoff procedure or operating conditions (Bach and Skreiberg 2016; Ken et al. 2018). These parameters can be directly determined from TG-DTG curves. Ignition temperature (T_i) is defined as the temperature at which a fuel shows weight loss of 1 wt% per minute signifying the initiation of combustion process. Peak temperature (T_p) is the temperature where the rate of weight loss is maximum and burnout temperature (T_f) corresponds to where the weight becomes constant at the

completion of burning and the DTG profile reaches a 1 wt% per minute combustion rate at the tail-end of the profile. Lower burnout rate and higher burnout temperature T_f represent unfavourable burnout performance. $T_{1/2}$ is the temperature at which 50% burnoff occurs. However, based on the TGA–DTG data, ignition index (D_i , weight % per min³) and burnout index (D_f , weight % per min⁴) are often used to evaluate combustion performance of fuels on the same burn-off procedure or operating conditions. D_i represent the ignition performance of fuels, which reflects how difficult or easy and how fast and slow the fuel gets ignited. D_f represents the burnout performance of fuels, which mainly depends on how fast the char residue burns (Parthasarathy et al. 2013). Ignition index (D_i) and burnout index (D_f) are calculated as (Parthasarathy et al. 2013; Liu et al. 2012; Aich et al. 2019a).

$$D_i = \frac{DTG_{\max}}{t_p t_i} \quad (1)$$

$$D_f = \frac{DTG_{\max}}{\Delta t_{1/2} t_p t_i} \quad (2)$$

where DTG_{\max} (wt% per min) is the maximum combustion rate corresponding to T_p , t_p is the corresponding time of DTG_{\max} , t_i is the ignition time, the time taken by the sample for initial ignition after moisture removal, $\Delta t_{1/2}$ is the corresponding time where 50% burn-off (weight, ash free basis) occurs (Parthasarathy et al. 2013). $DTG/DTG_{\max} = 0.5$, t_f (min) is the burnout time, after which solid residues are left in the form of ash. Higher ignition index (D_i) with lower t_p and lower temperature weight loss is the desirable condition for the coal to burn easily. Theoretically, higher value of ignition index infers the fuel to be enriched with higher volatile matter content which is easily ignitable. Alternatively, low D_i infers that fuel is difficult to ignite. Burnout index represents combustion reactivity of coal. Higher index values signify faster reactions between coal and air/oxygen and therefore, higher energy release rate and better combustion rate. D_f can be expressed straight by centralized degree of the combustion region of char residues in DTG curve (Parthasarathy et al. 2013). Based on the TGA–DTG analysis, two comprehensive index—parameters namely comprehensive combustibility index (S , wt% per min² °C³) and rate and intensity index of combustion process (H_f , °C) can be estimated by Eqs. (3–4) (Parthasarathy et al. 2013; Liu et al. 2012; Aich et al. 2019a).

$$S = \frac{DTG_{\max} DTG_{\text{mean}}}{T_i 2 T_f} \quad (3)$$

$$H_f = T_p \ln \left(\frac{\Delta t_{1/2}}{DTG_{\max}} \right) 10^{-3} \quad (4)$$

where, DTG_{mean} is the mean combustion rate. The comprehensive combustibility index (S) reflects the ignition,

combustion and burnout properties of a fuel. Higher values of performance index reflects better combustion performance of a fuel represented by higher value of performance index S and a smaller value of rate intensity index H_f . Rate and intensity index H_f describes the rate and the intensity of the combustion process. Further, activation energy for different coal was estimated using the Coats-Redfern method using data obtained from TG analysis as $\ln \frac{-\ln(1-x)}{T^2}$ vs. $1/T$ from the Eq. (5) as given below (Behera et al. 2018; Ken et al. 2018)

$$\ln\left(\frac{-\ln(1-x)}{T^2}\right) = \ln\left(\frac{AR}{HE} \left[1 - \left(\frac{2RT}{E}\right)\right]\right) - \frac{E}{RT} \quad (5)$$

where x is the fraction of coal sample burned at time t , n is order of combustion reaction, H is heating rate in $^{\circ}\text{C}/\text{min}$, E is the activation energy of coal (kJ/mol), A is the frequency factor (min^{-1}), T is the temperature (K) and R is the universal gas constant (8.314 J/(K·mol)).

3 Experimental

A total sixteen coal samples, four each from four coal sources of Singrauli coal field were collected. Some of the seams are known to have variable characteristics, particularly in terms of grindability and ash content. Maturity of the coal seam being more or less same types of hydrocarbons present and GCV are broadly similar (Misra and Singh, 1990). Mining methods, out of seam dilution and post mining handling also contribute to variability in the characteristics of Run-of mine (ROM) coal. All the four sources are located in close proximity and are linked to same utilities, dominant linkage being for any three. Collected representative ROM coal samples were named as A1, A2, A3, A4 (for mine A), D1, D2, D3, D4 (for mine D), J1, J2, J3, J4 (for mine J), N1, N2, N3, N4 (for mine N). After stage by stage crushing and sampling followed by grinding and sampling, coal samples of less than 212 μm size (passing through 72 mesh screen) were prepared by following the standard coal sample preparation methods. Sampling at all stages of sample preparation were carried out using coning and quartering method as per BIS guideline (IS 436: Part 1: Sec 1: 1964). Characterization of all the samples were carried out by proximate analysis (ash, volatile matter, moisture and fixed carbon) as per ASTM D3173 guidelines, GCV determination using bomb calorimeter (Model: AC 350; Make: Leco, USA) and free swelling index (ASTM D720). Combustion characteristics studies were carried out using Thermo Gravimetric Analyser (Model: STA 449 F3 Jupiter; Make: NETZSCH, Germany) by heating the coal in presence of oxygen (rate 60 ml/min) at heating rate of 10 $^{\circ}\text{C}/\text{min}$.

4 Results and discussion

4.1 Characterization of coal samples

Table 1 shows the variation in proximate analysis for the coal sources A, D, J and N. These variations in case of A result in overall GCV variation of 4039 to 4582 kcal/kg. Similar variations are also observed for other coal samples D, J and N. Overall variations across all the coal samples were $(32.6 \pm 8.6)\%$ for ash, $(25 \pm 1.75)\%$ for volatile matter, $(32 \pm 5.3)\%$ for fixed carbon, $(10.7 \pm 2.5)\%$ for moisture. Corresponding overall GCV variation was calculated as 4036 ± 538 kcal/kg. All the coal samples were tested with free swelling index ≤ 0.5 .

4.2 Combustion studies by TGA–DTG

Results obtained from combustion studies from TGA–DTG analysis are shown in Fig. 1a–d. These experiments were carried out by heating the individual coal samples from room temperature to 700 $^{\circ}\text{C}$ in the presence of oxygen with a heating rate of 10 $^{\circ}\text{C}$ per minute. TGA results for coal A, (Fig. 1a) indicate about 10%–12% weight loss below 110 $^{\circ}\text{C}$ due to the removal of moisture in the coal. The results are in line with moisture content of the coal as reported in Table 1. In the temperature range of 150–250 $^{\circ}\text{C}$, weight gain of approximately 2%–3% are observed for all the samples due to adsorption of oxygen gas (O_2) in porous structure of the coal, generated due to moisture removal during the temperature range of below 150 $^{\circ}\text{C}$ (Zhou et al. 2016; Behera et al. 2018, 2020). After 300 $^{\circ}\text{C}$, rapid weight loss is observed indicating the initiation of combustion process. The ignition temperature corresponding to 1% weight loss in DTG graph gets varied between 296 and 305 $^{\circ}\text{C}$ for coal A (Table 2). Variation in the ignition temperature for coal samples from the same source (A1–A4) was due to variations in volatile matter, ash content etc., as reported in literature (Filho and Milioli 2008). Similar results were also observed for other coal samples (D, J and N). Rapid weight loss is observed in the temperature range of 375–400 $^{\circ}\text{C}$, signifying the peak combustion rate due to the burning of fixed carbon of coal (Behera et al. 2020). Corresponding peak temperatures for different coals are found to vary from 396 to 415 $^{\circ}\text{C}$ for coal A, 424 to 428 $^{\circ}\text{C}$ for coal D, 401 to 418 $^{\circ}\text{C}$ for coal J and 387 to 420 $^{\circ}\text{C}$ for coal N. Compared to coal A, D and N, higher peak temperature for coal J can be attributed to its higher ash content. After 450 $^{\circ}\text{C}$ in TGA graph, weight loss becomes negligible and coal shows constant weight indicating the completion of combustion process and generation of residue ash. Corresponding burnout temperatures

Table 1 Quality parameters of samples on equilibrated basis (40 °C, 60% RH)

| Sample | Ash (%) | Moisture (%) | Volatile matter (%) | Fixed Carbon (%) | GCV (kcal/kg) | Fuel ratio |
|------------|------------|--------------|---------------------|------------------|---------------|-------------|
| A1 | 25.2 | 12.5 | 28.4 | 33.8 | 4582 | 1.19 |
| A2 | 31.5 | 9.85 | 26.8 | 31.7 | 4153 | 1.18 |
| A3 | 32.6 | 10.2 | 24.9 | 32.2 | 4040 | 1.29 |
| A4 | 36.1 | 10 | 26.5 | 27.3 | 4268 | 1.03 |
| Variations | 31 ± 5 | 11.2 ± 1.35 | 26.7 ± 1.72 | 30.5 ± 3.25 | 4311 ± 271 | 1.16 ± 0.13 |
| D1 | 30 | 8.7 | 27.9 | 33.6 | 4616 | 1.20 |
| D2 | 30.5 | 8.8 | 27.4 | 33.1 | 4450 | 1.20 |
| D3 | 34.8 | 10.1 | 23.6 | 31.4 | 4191 | 1.33 |
| D4 | 41.9 | 9.1 | 20.6 | 28.4 | 4237 | 1.38 |
| Variations | 36 ± 6 | 9.4 ± 0.7 | 24.2 ± 3.6 | 31 ± 2.6 | 4403 ± 213 | 1.29 ± 0.1 |
| J1 | 34.4 | 9.1 | 26 | 30.5 | 4122 | 1.17 |
| J2 | 35.8 | 10.3 | 25.8 | 28 | 4010 | 1.08 |
| J3 | 46.8 | 6.2 | 24 | 22.9 | 3376 | 0.95 |
| J4 | 48.1 | 9.1 | 20.4 | 22.3 | 2874 | 1.09 |
| Variations | 41.2 ± 6.8 | 8.2 ± 2 | 23.2 ± 2.8 | 26.4 ± 4.1 | 3498 ± 624 | 1.06 ± 0.11 |
| N1 | 19.4 | 14.4 | 27.5 | 38.6 | 4887 | 1.40 |
| N2 | 21.9 | 12.7 | 26.1 | 39.2 | 4927 | 1.50 |
| N3 | 24.4 | 12.1 | 26.1 | 37.2 | 4727 | 1.42 |
| N4 | 27.6 | 13.9 | 24.3 | 34.2 | 4221 | 1.40 |
| Variations | 24 ± 4.1 | 13.2 ± 1.1 | 26 ± 1.6 | 37 ± 3 | 4574 ± 353 | 1.45 ± 0.05 |

vary 467–478 °C for A, 484–488 °C for D, 469–484 °C for J and 476–484 °C for coal N.

From DTG curves shown in Fig. 1a–d, clear variation in burning characteristics of 16 samples are observed. From Table 2 it can be inferred that characteristic burning temperatures T_i , T_p and T_f are different for all the coals, even for coal collected from the same source. For coal A overall variation for T_i are 350 ± 5 °C. Similar variations are also observed for the coals D, J, N and for other characteristic temperatures, T_p and T_f . This variation in characteristics temperatures can be attributed to the variations of volatile matter, fixed carbon and ash content in coal. Since volatile matter helps in ignition of coal, lower T_i for A and D can be justified by larger volatile content in samples A, D compared to samples J, N, and further in subsamples A1, A2, D1, D2 compared to A3, A4, D3, D4. During non-isothermal heating, more volatile matter gets released from coal, which easily starts burning and helps in burning of the sample at lower temperature (Zhang et al. 2013a, b). Overall variations of temperature T_p for coal A, D, J and N are 406 ± 10 °C, 426 ± 2 °C, 410 ± 9 °C, 404 ± 17 °C, respectively. Corresponding peak rates of combustion (DTG_{max}) are 14.15 ± 5.4 , 7.40 ± 0.82 , 11.15 ± 5.53 , 16 ± 6.55 wt%/min for coal A, D, J and N, respectively. Higher values of DTG_{max} for coal A, D can be attributed to the presence of presence of higher quantities of volatile

matters in the coal sample (Behera et al. 2020; Aich et al. 2019a). Presence of single peaks in coal D (sample D1, D2, D3, D4) in DTG curve indicates stage by stage smooth burning of coal by elimination of water, release of hydrocarbons and loss of higher molecular weight hydrocarbon (Zhang et al. 2013a, b; Aich et al. 2019a). Presence of multiple peaks (double peaks here) in other coal (A, J, N) signifies stage by stage burning of coal due to release of hydrocarbons in different stages during combustion. This type of stage by stage combustion can possibly be due to the presence of hydrocarbons with wide molecular structure difference. Wide differences in molecular structure in coal is possibly because of the lack of homogeneity in ROM coal sample. Burnout temperature (T_f) for sample A, D, J, N gets varied between 473 ± 6 °C, 486 ± 2 °C, 477 ± 8 °C, 480 ± 4 °C, respectively. Higher burn-out temperature for J and N compared to A and D indicates that coal J and N burn comparatively at a lower rate and takes longer time for complete combustion. Higher is the burn-out temperature, higher is the resistance to O_2 reaction and lower is the heat release rate which might lead to residual un-burnt carbon, if burnt at lower temperature.

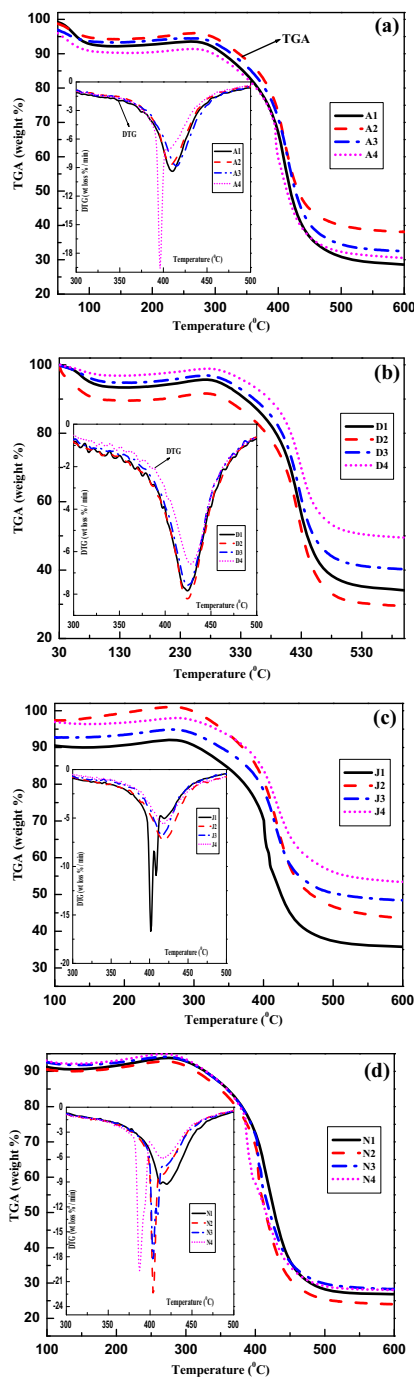


Fig. 1 TG-DTG curve of different coal sample **a** A1–A4, **b** D1–D4, **c** J1–J4, **d** N1–N4, at constant heating rate of 10 °C/min

4.3 Analysis of characteristic parameters of combustion

Extent of combustion rate was further estimated by the analysis of different combustion parameters, ignition time (t_i), peak time (t_p), burnout time (t_f), $\Delta t_{1/2}$, ignition index (D_i) and burnout index (D_f) and are shown in Table 3. Burnout time t_f for all the 16 samples lies in the range of 43

Table 2 Burning temperatures and combustion rate of different coal (A, D, J, N)

| Sample | T_i (°C) | T_p (°C) | T_f (°C) | DTG_{max} (wt%/min) |
|------------|--------------|--------------|-------------|-----------------------|
| A1 | 296 | 411 | 477 | − 9.39 |
| A2 | 304 | 415 | 478 | − 8.82 |
| A3 | 305 | 408 | 471 | − 8.71 |
| A4 | 298 | 396 | 467 | − 19.60 |
| Variations | 301 ± 5 | 406 ± 10 | 473 ± 6 | 14.15 ± 5.4 |
| D1 | 313 | 424 | 488 | − 7.84 |
| D2 | 310 | 424 | 486 | − 8.21 |
| D3 | 317 | 424 | 484 | − 7.59 |
| D4 | 333 | 428 | 484 | − 6.58 |
| Variations | 322 ± 12 | 426 ± 2 | 486 ± 2 | 7.40 ± 0.82 |
| J1 | 307 | 419 | 484 | − 7.40 |
| J2 | 319 | 416 | 472 | − 6.77 |
| J3 | 306 | 401 | 469 | − 16.69 |
| J4 | 343 | 418 | 484 | − 5.62 |
| Variations | 325 ± 19 | 410 ± 9 | 477 ± 8 | 11.15 ± 5.53 |
| N1 | 312 | 420 | 484 | − 9.25 |
| N2 | 305 | 404 | 477 | − 22.35 |
| N3 | 310 | 403 | 479 | − 18.24 |
| N4 | 306 | 387 | 476 | − 19.68 |
| Variations | 309 ± 4 | 404 ± 17 | 480 ± 4 | 16 ± 6.55 |

to 45 min that can be considered quite close to the complete burning time of thermal coal as indicated by many literature (Behera et al. 2018, 2020; Aich et al. 2019b). However there is variation in burning time t_f of 44 ± 0.5 , 45.04 ± 0.2 , 44.11 ± 0.74 , 44.46 ± 0.4 min, within the coal samples for sources A, D, J and N, respectively. This infers that some coal takes longer time for complete combustion. Longer time for complete combustion is ascribed to the presence of low volatile content and lower gas transport (CO_2/O_2) rate during combustion in coal that takes longer time for complete burning as has already been discussed in Sect. 4.2. It is observed that, $\Delta t_{1/2}$ values of all the 16 samples occur in a span of 35–36 min. Table 3 also shows equivalent ignition index (D_i) for 12 samples in the range of 4 to 7 wt%/min⁴ except sample A2 (20.75 wt%/min⁴), J2 (16.87 wt%/min⁴), N1 (18.10 wt%/min⁴), N2 (22.49 wt%/min⁴) and N4 (20.69 wt%/min⁴). Higher value of D_i indicates that coal burnt smoothly. For samples with lower D_i (4–7 wt%/min⁴) appears to signify increasingly greater difficulty in burning. For burnout index D_f it is observed that all values lie in the range of 1 to 3 wt%/min⁴ which are higher compared to literature reported values of above 4 wt%/min⁴ (Behera et al. 2018, 2020), inferring difficulty in combustion.

Table 3 Characteristic combustion parameters of different coal (A, D, J and N)

| Samples | t_i (min) | t_p (min) | t_f (min) | $\Delta t_{1/2}$ (min) | D_i ($\times 10^{-3}$ wt%/min ³) | D_f (wt%/min ⁴) |
|------------|------------------|------------------|------------------|------------------------|---|-------------------------------|
| A1 | 26.08 | 37.55 | 44.17 | 35.46 | - 9.59 | - 1.59 |
| A2 | 26.84 | 37.93 | 44.24 | 35.49 | - 8.67 | - 1.48 |
| A3 | 26.92 | 37.2 | 43.54 | 35.45 | - 8.70 | - 1.51 |
| A4 | 26.23 | 36.02 | 43.15 | 35.72 | - 20.75 | - 3.53 |
| Variations | 27 \pm 0.42 | 37 \pm 1 | 44 \pm 0.5 | 36 \pm 0.63 | 14.71 \pm 6.04 | 2.5 \pm 1.02 |
| D1 | 27.77 | 38.85 | 45.26 | 36.36 | - 7.26 | - 1.22 |
| D2 | 27.43 | 38.82 | 45.04 | 36.33 | - 7.71 | - 1.29 |
| D3 | 28.14 | 38.82 | 44.85 | 36.33 | - 6.95 | - 1.20 |
| D4 | 29.73 | 39.22 | 44.83 | 36.52 | - 5.64 | - 1.02 |
| Variations | 29 \pm 1.15 | 39.02 \pm 0.2 | 45.04 \pm 0.2 | 36.42 \pm 0.1 | 6.67 \pm 1.03 | 1.15 \pm 0.13 |
| J1 | 27.18 | 38.35 | 44.86 | 35.76 | - 7.10 | - 1.20 |
| J2 | 28.36 | 38.04 | 43.66 | 35.9 | - 6.27 | - 1.13 |
| J3 | 27.06 | 36.55 | 43.37 | 36.94 | - 16.87 | - 2.85 |
| J4 | 30.76 | 38.24 | 44.85 | 35.8 | - 4.77 | - 0.91 |
| Variations | 29.91 \pm 1.85 | 37.45 \pm 0.9 | 44.11 \pm 0.74 | 36.35 \pm 0.59 | 10.82 \pm 6.05 | 1.88 \pm 0.97 |
| N1 | 27.65 | 38.43 | 44.86 | 25.45 | - 8.711 | - 2.110 |
| N2 | 26.97 | 36.84 | 44.17 | 36.75 | - 22.496 | - 3.738 |
| N3 | 27.44 | 36.72 | 44.34 | 37.5 | - 18.105 | - 2.988 |
| N4 | 27.06 | 35.15 | 44.06 | 34.85 | - 20.695 | - 3.647 |
| Variations | 27.31 \pm 0.34 | 36.79 \pm 1.64 | 44.46 \pm 0.4 | 31.47 \pm 6.02 | 15.6 \pm 6.89 | 2.92 \pm 0.81 |

4.4 Analysis of comprehensive indices

From TGA–DTG data reported in Fig. 1, comprehensive indices H_f and S_f were estimated using Eq. (3) and (4) and the results are summarised in Table 4. It can be observed from Table 4 that, S_f for all the 16 coal samples lie in the range of 0.62×10^{-7} – 5.03×10^{-7} wt%²/(min² °C³). Most of the S_f values fall in the range of 1–2 wt%²/(min² °C³). However, coal A3, N3 and N4 show S_f values of 4.39, 5.03 and 4.23 wt%²/(min² °C³), respectively and this are higher for the remaining coal. It signifies that these coals have better combustion performance compared to other coal. Similar trend is also observed for combustibles like fixed carbon, volatile matter, versus non-combustibles such as ash, and ratio of (VM + FC)/A for the 16 coal samples. Coal A2, N2 and N4 possess very low H_f values of 1.19, 1.16 and 1.14 that is a clear indication of better combustion performance (Qi et al. 2017). The results obtained are in line with literature (Aich et al. 2019a; Liu et al. 2015), according to which a fuel having the maximum S_f value and the minimum H_f value shows better combustion performance since both the indices S_f and H_f are directly and inversely related to maximum combustion rate (DTG_{max}), respectively (Eq. (3) and (4)). Among the 16 samples maximum S_f and minimum H_f have been recorded for A3, N2 and N4.

4.5 Analysis of activation energy

Analysis of activation energy (E) for different coal were carried out using Coats-Redfern method and values are presented in Table 5. From Table 5 it is observed that, for all the sixteen samples E varied from 55.02 to 86.24 kJ/mol. For coal D4 and J4, calculated values of E are 86.24 kJ/mol and 85.52 kJ/mol which are significantly higher compared to other coal. This signifies better combustion performance for these coals as they contain lower ash values and high volatile matter content. On the other hand coal A1–A4, D1–D3, J1–J2 and N1–N4 coal shows lower E values in the range of 55.02–71.78 kJ/mol. Such variations may be correlated with the ash content of corresponding coal. For low ash coal, E values are lower compared to high ash coal (D4, J4). Such variation infers that, mineral matters present in coal prevents coal to get burnt easily. Hence for better combustion characteristics coal should always have lower ash content.

4.6 Weight gain analysis

During pre-ignition stage of combustion, certain physico-chemical phenomena such as adsorption of oxygen in porous coal structure (weight gain), release of highly volatile compounds from coal surface occurs (Zhou et al.

Table 4 Analysis of comprehensive indices and (VM + FC)/A

| Samples | $S_f (\times 10^{-7} \text{ wt}\%^2 / \text{min}^2 \text{ }^\circ \text{C}^3)$ | $H_f (\text{ }^\circ \text{C})$ | (VM + FC)/A |
|------------|--|---------------------------------|-----------------|
| A1 | 2.18 | 1.53 | 1.49 |
| A2 | 1.73 | 1.57 | 1.75 |
| A3 | 1.63 | 1.55 | 1.85 |
| A4 | 4.39 | 1.19 | 2.46 |
| Variations | 3.01 ± 2.76 | 1.38 ± 0.19 | 1.97 ± 0.48 |
| D1 | 1.45 | 1.66 | 2.04 |
| D2 | 1.63 | 1.65 | 1.98 |
| D3 | 1.23 | 1.68 | 1.57 |
| D4 | 0.79 | 1.76 | 1.17 |
| Variations | 1.21 ± 0.42 | 1.70 ± 0.05 | 1.60 ± 0.43 |
| J1 | 1.28 | 1.64 | 1.50 |
| J2 | 0.95 | 1.69 | 1.00 |
| J3 | 3.23 | 1.27 | 1.64 |
| J4 | 0.62 | 1.77 | 0.88 |
| Variations | 1.92 ± 1.30 | 1.52 ± 0.25 | 1.26 ± 0.38 |
| N1 | 1.9 | 1.44 | 3.40 |
| N2 | 5.03 | 1.16 | 2.98 |
| N3 | 3.84 | 1.25 | 2.59 |
| N4 | 4.23 | 1.14 | 2.11 |
| Variations | 3.46 ± 1.56 | 1.29 ± 0.15 | 2.75 ± 0.64 |

Table 5 Activation energy of different coal (A, D, J and N)

| Coal | E (kJ/mol) | Coal | E (kJ/mol) | Coal | E (kJ/mol) | Coal | E (kJ/mol) |
|------------|------------------|------|-------------------|------|-------------------|------|------------------|
| A1 | 56.85 | D1 | 61.52 | J1 | 57.45 | N1 | 67.79 |
| A2 | 62.08 | D2 | 55.02 | J2 | 64.07 | N2 | 65.45 |
| A3 | 67.10 | D3 | 69.30 | J3 | 73.70 | N3 | 68.53 |
| A4 | 56.07 | D4 | 86.24 | J4 | 85.52 | N4 | 71.78 |
| Variations | 61.59 ± 5.51 | | 70.63 ± 15.61 | | 71.48 ± 14.04 | | 68.61 ± 3.17 |

2016; Behera et al. 2018, 2020). As a result variation of weight in TG graph is observed during pre-ignition stages (Fig. 1). Analysis of net increase in weight and time duration of weight gain and also temperature increase during pre-ignition stage indicate the positive reactivity of coal towards combustion. Small weight gain across shorter time followed by ignition represents high reactivity of coal (Liu et al. 2015). Large weight gain across longer time and higher ignition temperature represent lower reactivity. Weight variation was estimated from TGA data as shown in Fig. 1. Table 6 summarizes the variation in weight percentage during pre-ignition stages of combustion for 16 samples. Coal A, shows an average lower weight gain (1.41 wt%) and lower time duration of 10.16 min, ($\Delta t = t_{\text{peak}} - t_{\text{start}}$) across a temperature range of 101.34 °C ($\Delta T = T_{\text{peak}} - T_{\text{start}}$) compared to coal D (2.16 wt%,

10.61 min, 106.33 °C), coal J (2.43 wt%, 12.37 min, 123.25 °C) and coal N (2.96 wt%, 11.67 min, 116.46 °C) during pre-ignition stages of combustion. That signifies sample A1, A2, A3, A4 to be more reactive than samples of D, J and N.

4.7 Effect of ash content on combustion parameters

Amount and compositions of mineral matter present in coal play an important role in combustion process and affect the various combustion characteristic parameters. Figure 2a–e shows the effect of ash percentage on various combustion performance parameter's DTG_{max} , D_i , D_f , S_f , H_f for all 16 coal samples. It can be observed from Fig. 2a–d that with increase in ash content the combustion performance parameters (DTG_{max} , D_i , D_f , S_f , H_f) initially increase and

Table 6 Weight gains and characteristic temperatures of coal

| Samples | wt% | t_{start} (min) | t_{peak} (min) | Δt (min) | T_{start} (°C) | T_{peak} (°C) | ΔT (°C) |
|------------|-----------------|--------------------------|-------------------------|------------------|-------------------------|------------------------|-----------------|
| A1 | 1.25 | 13.94 | 22.83 | 8.89 | 176 | 264 | 89 |
| A2 | 1.22 | 12.01 | 22.24 | 10.23 | 157 | 258 | 102 |
| A3 | 1.8 | 12.41 | 23.62 | 11.21 | 160 | 272 | 112 |
| A4 | 1.38 | 12.17 | 22.48 | 10.31 | 158 | 261 | 103 |
| Variations | 1.51 ± 0.29 | 13 ± 0.96 | 22.93 ± 0.69 | 10.05 ± 1.16 | 166 ± 9.45 | 265 ± 6.91 | 100 ± 11.49 |
| D1 | 2.36 | 12.67 | 23.87 | 11.02 | 163 | 275 | 112 |
| D2 | 2.09 | 14.74 | 23.73 | 8.99 | 183 | 273 | 90 |
| D3 | 2.23 | 12.53 | 23.54 | 11.01 | 161 | 272 | 110 |
| D4 | 1.96 | 12.41 | 23.82 | 11.41 | 160 | 274 | 114 |
| Variations | 2.16 ± 0.2 | 13.57 ± 1.16 | 23.70 ± 0.16 | 10.2 ± 1.21 | 172 ± 12 | 273 ± 1.64 | 102 ± 12 |
| J1 | 3.73 | 7.9 | 23.78 | 15.88 | 116 | 274 | 158 |
| J2 | 2.14 | 12.46 | 23.76 | 11.3 | 160 | 274 | 113 |
| J3 | 2.19 | 12.46 | 23.46 | 11 | 161 | 271 | 110 |
| J4 | 1.66 | 12.96 | 24.26 | 11.3 | 166 | 279 | 113 |
| Variations | 2.69 ± 1.03 | 10.43 ± 2.53 | 23.86 ± 0.4 | 13.44 ± 2.44 | 141 ± 25 | 275 ± 4 | 134 ± 24 |
| N1 | 3.55 | 11.42 | 24.05 | 12.63 | 151 | 277 | 126 |
| N2 | 3.01 | 11.87 | 23.67 | 11.8 | 155 | 273 | 118 |
| N3 | 2.39 | 13.14 | 23.73 | 10.59 | 168 | 273 | 106 |
| N4 | 2.92 | 11.43 | 23.66 | 12.23 | 151 | 273 | 122 |
| Variations | 2.97 | 12.28 ± 0.86 | 24 ± 0.19 | 11.61 ± 1.02 | 159 ± 8.39 | 275 ± 1.95 | 116 ± 10 |

later decrease. Optimum most combustion performance is observed at 21% ash content for coal A. Overall it is observed that for very low ash content, performance is of average quality and with increase in ash content performance improves and for very high ash content, deteriorates. This is attributed to the fact that as coal consists of carbonaceous material as well as mineral matters. Presence of large quantities of hydrocarbons (very less quantity of ash), make the coal structure almost homogenous. As a result overall transport of O_2/CO_2 gets slows down, rate of combustion reaction slows down (low rate of heat release). With increase in mineral matter in coal, overall heterogeneity in coal structure increases. Also mineral matters (inorganic oxides like: CaO, SiO_2 , Al_2O_3 , Fe_2O_3 etc.) increases overall heat transport in entire coal (Behera et al. 2018, 2020; Aich et al. 2019b). As a result, entire carbonaceous matters reach their ignition temperature early and hence combustion becomes faster compare to very low ash coal. However, for high ash coal, presence of higher amounts of mineral matter and lower mass of carbonaceous material result makes combustion process slower due to absence of sufficient quantities of combustibles in coal (Behera et al. 2018). Different values of parameters for same/similar ash percentage (e.g. A3, D2) were possibly due to change in the compositions of mineral matter as well as carbonaceous material of coal of different sources/sub-

sources. The overall comparison among four different sources of coal shows coal N has better combustion performance and coal D has poor combustion performance. These phenomena can be further explained by the fact that, increase in thickness of ash layer in coal results in significant reduction in volatile combustion and char oxidation rates with a resultant decrease in coal burning rates. Opposite phenomena is observed for performance index (H_f) which decreases initially with ash content and later increases as shown in Fig. 2e. Decrease in H_f actually shows better combustion performance which is in line with other parameters.

4.8 Effect of volatile matter on combustion parameters

Figure 3a–e shows the effects of volatile matter content on various combustion performance parameters DTG_{max} , D_i , D_f , S_f , H_f for all 16 coal samples. It can be observed from Fig. 3a–d that with increase in volatile matter content the combustion performance parameters (DTG_{max} , D_i , D_f , S_f) initially increase and later decrease. Optimum performance is observed for all the performance parameters (DTG_{max} , D_i , D_f , S_f) at volatile matter contents of 26% to 28% for coal samples of same sources. Overall it is observed that with increase in volatile matter percentage performance

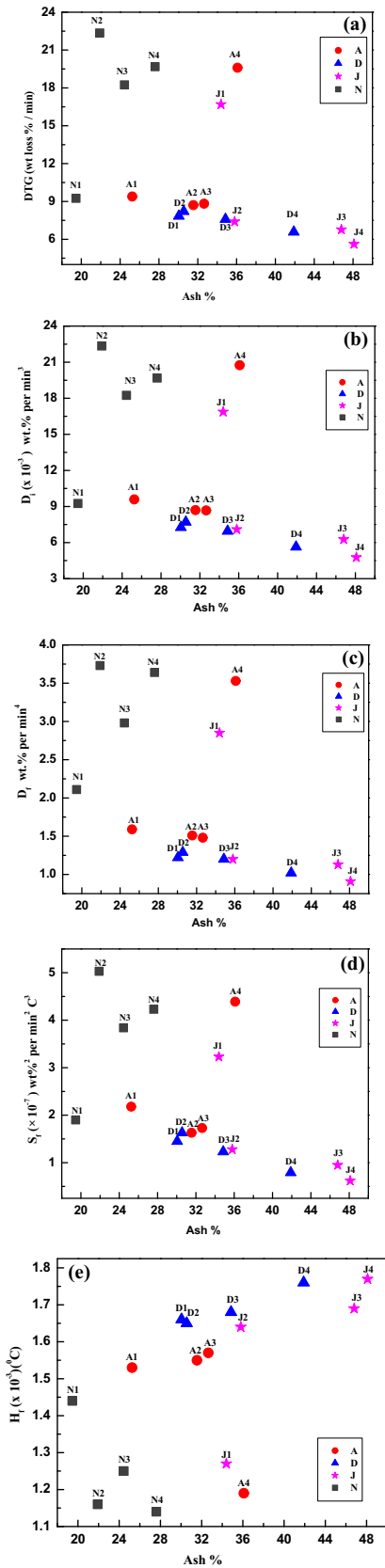


Fig. 2 Variation of combustion parameters: **a** DTG_{max}, **b** D_i, **c** D_f, **d** S_f, **e** H_f with ash content

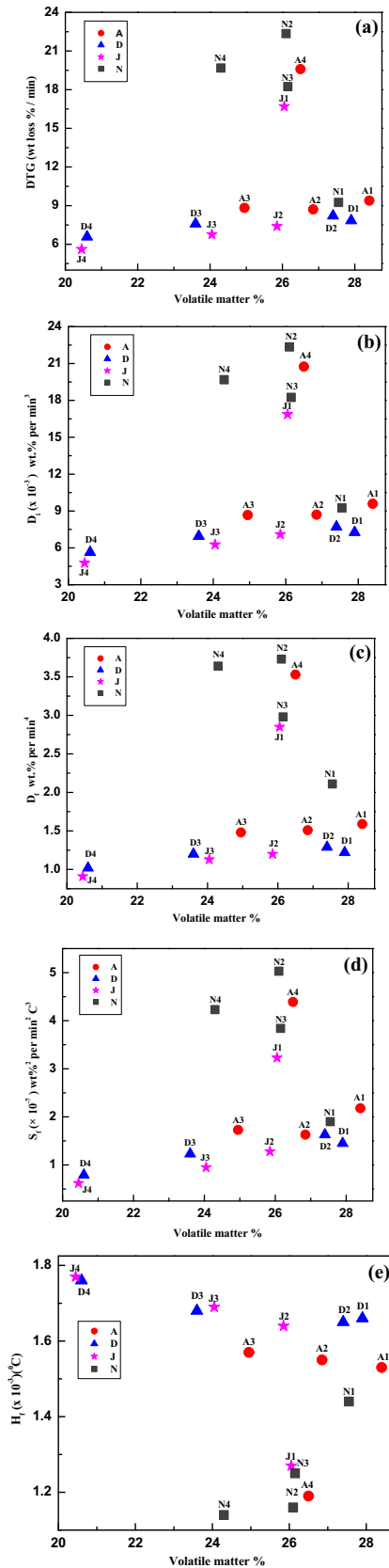


Fig. 3 Variation of combustion parameters: **a** DTG_{max}, **b** D_i, **c** D_f, **d** S_f, **e** H_f with volatile matter % for all the coal

improves and reaches maximum values at 26%. Performance deteriorates with further increase in volatile matter content except for coal N where performance is almost stabilized. Hence optimum volatile matter for combustion may be considered at 26%. This phenomena can be justified by the fact that with increase in volatile matter coal ignition characteristics improve. However for very high volatile matter content combustion performance deteriorates due to increase in flue gas volume produced by volatile matter (Liu et al. 2015). Opposite phenomena is observed for performance index (H_f) which decreases initially with volatile matter content and later increases as shown in Fig. 3e. Decrease in H_f actually indicates better combustion performance which is in line with other parameters. In this case too optimum performance is observed for volatile matter content of 26% to 28%. Overall comparisons among four different sources of coal shows coal N has better combustion performance and coal D has poor combustion performance which is in line with observation in previous Sect. 4.7. Further it can be observed from the graph that samples A1, D1, D3, J3 lying outside the considerable range of better combustion zone have inferior performance characteristics owing to less porous structure in coal due to uneven distribution of carbonaceous material contributes to the deterioration of the combustion performance.

4.9 Effect of fixed carbon content on combustion parameters

Fixed carbon is an important constituent of coal necessary for stable combustion process. From Figs. 4a–e, it can be observed that except coal A, with increase in fixed carbon content combustion performance initially improves and later stabilizes. For coal J and D, with increase in fixed carbon content from 22% to 34%, performance improves. For A with increase from 27% to 34%, performance drops. However, for N overall performance parameters (DTG_{max} , D_i , D_f , S_f , H_f) improves with increase in fixed carbon. From Fig. 4a–e, minimum fixed carbon content considered for good combustion performances lies between 28% and 39%. It is observed that coal J has poor combustion performance and N has better combustion performance compared to all other sources. Samples A2, D3, A3, D1, D2, in spite of high fixed carbon content do not show better performance. This is ascribed to low heating value and higher presence of mineral matter which affect the oxidation process of coal.

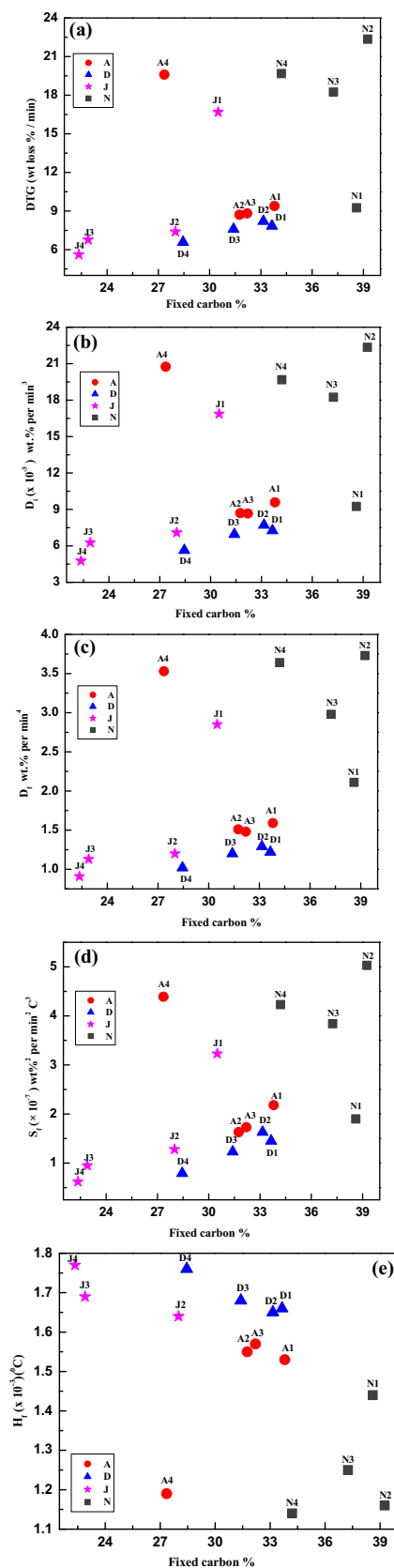


Fig. 4 Variation of combustion parameters: **a** DTG_{max} , **b** D_i , **c** D_f , **d** S_f , **e** H_f with fixed carbon content for all the coal

4.10 Effect of fuel ratio on combustion parameters (DTG_{max} , D_i , D_f , S_f , H_f)

Fuel ratio is an important parameter expressed as fixed carbon to volatile matter ratio of coal and represents the quality of coal. While increase in volatile matter helps in ignition behaviour of coal, higher fixed carbon helps in smooth burning of coal (Aich et al. 2019a; Liu et al. 2015). Lower values of fuel ratio leads to high ignition behaviour and might lead to spontaneous ignition of coal during stockpiling. Higher fuel ratio causes difficulty in coal ignition but leads to stable combustion process. From Figs. 5a–e, it can be observed that with increase in fuel ratio from 0.9 to 1.5, combustion performance improves. However, there is no particular optimum ranges of fuel ratio to deliver best performance. For coal A and D, with increase in fuel ratio from 1.11 to 1.4, performance decreases. For J and N, overall performance is improved with increase in fuel ratio. For coal A, best performance is obtained at fuel ratio of 1.15. On the other hand, for coal D, J, and N best performance is observed for fuel ratio 1.05, 1.2 and 1.5. Among all the coal sources studied that coal N has better combustion performance compared to all other sources. Such performance may be correlated to ash content of individual coal, as coal N have lower ash ($(24 \pm 4.1)\%$) compared to coal A ($(31 \pm 5)\%$ ash) and coal D ($(36 \pm 6)\%$ ash). This inferred that, for optimum combustion performance coal should have 20%–35% ash along with fuel ratio around 1.4–1.5.

5 Conclusions

In this work combustion behaviour of sixteen different coal samples obtained from four different closely located mines have been analysed using non-isothermal TGA. All the coals were characterized by proximate analysis, GCV and FSI. Proximate analysis shows that coal collected from same mines may have $(30 \pm 6)\%$ variation in ash content which results in GCV variations of 4000 ± 500 kcal/kg. Further, detailed analysis of various combustion parameters like ignition temperature, peak temperature and burnout temperature with variation of 300 ± 20 °C, 400 ± 20 °C and 480 ± 20 °C get varied with variation in coal properties. Coals with volatile matter content in the range of $(26 \pm 1.75)\%$ are found to give better combustion performance among the selected coals. Similarly, coal with fuel ratio 1.16 ± 0.15 , ash content $(25 \pm 5)\%$, and fixed carbon

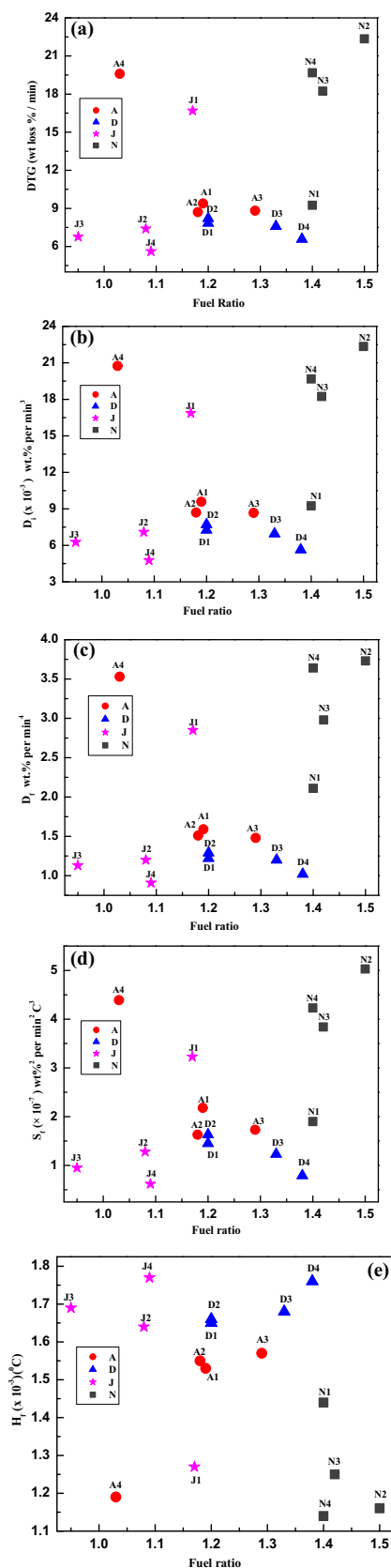


Fig. 5 Variation of combustion parameters: **a** DTG_{max} , **b** D_i , **c** D_f , **d** S_f , **e** H_f with fuel ratio for all the coal

(33 ± 3)% were also found to provide favourable combustion performance. Activation energy was found to get varied from 55.02 to 86.24 kJ/mol with change in ash content from 21.9% to 48.9%. Significant outcome of observations reported in present work are related to variations in ash, volatile matter, fixed carbon, fuel ratio of coal on its combustion performance along with pathways to selection of coal for optimum combustion performances. During procurement/selection of coal for thermal utilities, GCV is given top priorities compare to ash, volatile matter, fixed carbon or fuel ratio. However, present study infers that, ash, volatile matter, fixed carbon, Fuel ratio needs to be considered during selection of coal thermal utilities to get best combustion performances. Based on the experimental results and theoretical analysis, it may be concluded that for optimum combustion performance coal should have 20%–35% ash along with fuel ratio around 1.4–1.5.

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Availability of data and materials All the data has already included in manuscript.

Compliance with ethical standard

Conflict of interest There is no such interest applicable in this manuscript.

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