EFFECT OF PRESSURE ON ASH FORMATION DURING PULVERISED COAL COMBUSTION AND GASIFICATION

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Abstract

In this paper, effects of the operating pressure on ash formation reported in the open literature have been reviewed. In particular, the recent significant advances achieved at the Cooperative Research Centre for Coal in Sustainable Development (CCSD) in Australia are highlighted. The operating pressure significantly influences the size and the chemistry of ash generated through its effects on the structure of chars generated. Previous work has shown that pressure has marked impacts on the volatile yield new work has shown that it also impacts particle swelling behaviour during devolatilisation and hence the resulting char structure and morphology. Char particles generated at elevated pressures have high porosity. These char particles experience more extensive fragmentation during the combustion and gasification, which leads to finer ash particles compared to that formed at low pressures. At high pressure, the char particles appear to burn faster. The char structure also determines the ash liberation for the different combustion stages. The PSD of ash is less sensitive to pressure during gasification process. Ongoing research in the CCSD is determining the chemistry of the char and ash generated in a Pressurised Entrained Flow Reactor (PEFR), and has developed a mechanistic model to predict char structure and hence ash properties.

Introduction

Advanced clean coal technologies, including pressurised fluidised bed combustion (PFBC) and integrated gasification combined cycle (IGCC) have attracted increasing technological and scientific interests over the last decades [1]. These technologies provide several advantages over the conventional coal firing processes, including an increase in coal throughput, a reduction in pollutant emission and an enhancement in the intensity of reactions [1,2]. The recent previous work on coal pyrolysis [3-9], coal swelling [10-14] and char reactivities [7,15-31], has revealed that the operating pressure has marked impacts on coal swelling during devolatilisation, and that char reactivity is enhanced at high pressure. However, ash formation at elevated pressures has not been well understood.

Studies of mineral matter transformation are motivated by the concerns with performance of the utility boilers [32,33], such as fouling and slagging. The ash formed during the gasification process has been found to have a major effect on IGCC system design and operation, slag formation and tapping, ash deposition in gas circuit, heat exchange passes and fly ash collection equipment [1]. Fundamental knowledge of ash formation at elevated pressures is therefore essential to the development of these technologies and to the improvement of the performance of the pressurised reactors.

General mechanism of ash formation has been summarized in the literature [33-35]. Many factors are known to control the chemistry of the final ash particles during pulverised coal combustion and gasification, including mineral content, mineral distribution among pulverized coal particles, coal particle size distribution, char structure and burnout mechanism, physical properties of the ash, char fragmentation [32]. It should be pointed out that strong association exists between ash formation and the char structure related behaviour [36,47], such as char fragmentation [32,37,38] and the coalescence of the included minerals [39]. Therefore, any factors that influence char structure may impact the ash formation and chemistry.

Significant advances in the understanding of effects of the operating pressure on the ash formation has been achieved through the projects undertaken at the Cooperative Research Centre for Coal in Sustainable Development (CCSD) of Australia. In particular, it has been found that the operating pressure significantly influences the ash formation mechanism through its effect on chemistry of chars formed during the devolatilisation. In this paper, the effects of the pressure on the devolatilisation behaviour of coal and the chemistry of the final ash have been summarised.

Effects of pressure on the deveolatilisation of coal

Impacts of the operating pressure on pyrolysis behaviour of coal have been extensively investigated[3-9], and documented [40-43]. In general, pressure significantly influences the volatile matter yields, coal particle swelling and the structure of the resulting char residues. This further influences the char reaction rate [36] and the ash formation mechanism [47].

Volatile matter yields

A pronounced reduction of the total weight loss and tar yields at elevated pressures and temperatures has been observed using wire mesh reactors or entrained flow reactors. The early investigations carried out using Pittsburgh bituminous coal [44] showed that the total volatile matter yield decreased with increasing the operating pressure, and the effect was more distinguishable at high temperature. Measurements on Pittsburgh No.8 coal by Suuberg et al [45] revealed that as pressure increases the total volatile matter and tar yields decreases whilst total gas production increases, as shown in Fig 1. The published data at various conditions regarding the pressure effect in the open literature have been summarised in Fig 2 [42].

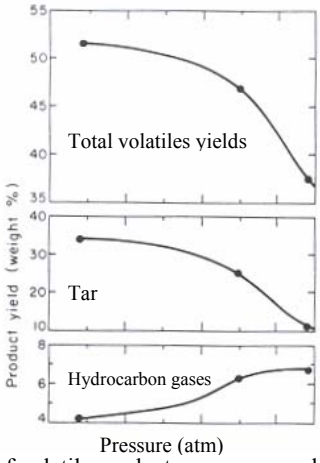


Figure 1. Yields of volatile products vs. pressure during pyrolysis of Pittsburgh No.8 coal at 1000°C [45]

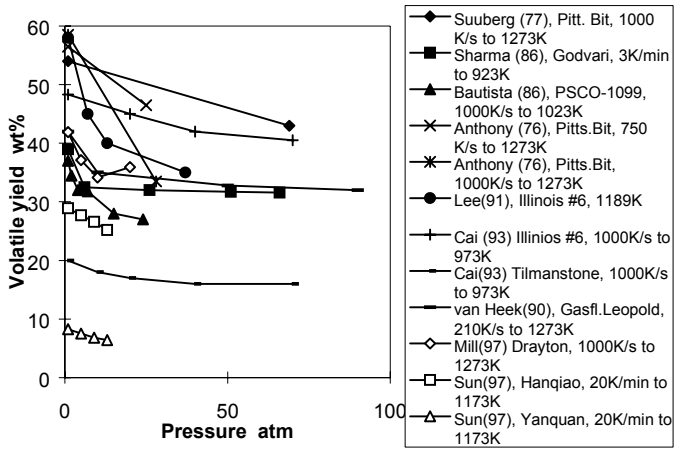


Figure 2. Volatile yields as a function of operating pressure [42].

It has been clear that pressure suppresses the formation and release of tar, shifts the molecular weight of tar to the lighter fraction. On the other hand, high pressure promotes secondary reactions, whence increases the total yield of hydrocarbon gases. Because tar is the predominant product of the volatiles, therefore the total volatile matter yields decrease significantly at high pressure [40].

Coal swelling

Swelling is an important phenomenon during the devolatilisation of bituminous coal, and has significant impacts on the coal combustion properties. The effect of pressure on coal swelling has been addressed and investigated in the recent decade [6,10,11,46,47]. Higher swelling has been observed using Australian bituminous coals at pressures 0.5 to 1.5 MPa [48], as shown in Figure 3.

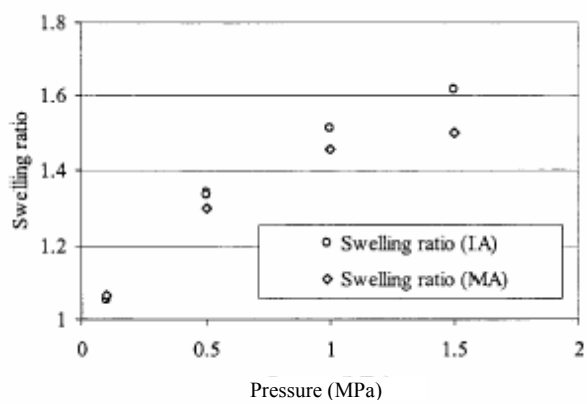


Figure 3. Experimental results of swelling ratio of char samples from Australian coal against pressures [48]

However, in general, the swelling ratio is not a monotonous function of the pressure [36]. Experimental data showed that there appeared an optimal pressure for the highest swelling ratio [6]. This has also been predicted using different models [6,46,49]. Figure 4 compares the experimental data and the model predicted results. The peak is most likely to appear at 0.5 to 1.5 MPa. That more gaseous volatiles are trapped inside the coal particle due to the elevated external pressure is the reason for the increase of the swelling. However, some other factors are obviously doing some work, such as viscous forces, extent of secondary reactions, surface tension, etc. The implication is that the changes in the swelling due to the high pressure are associated with the impact on the char structure. High swelling will lead to a high porosity of the resulting char, and will further influence the ash formation.

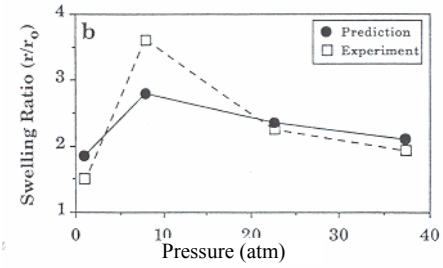
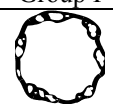


Figure 4. Experimental data and model predictions on swelling ratio of Illinous No.6 coal against pressures [6,46]

Char structure

Char structure formed during devolatilisation has been extensively studied over the last decades. In the recent work [50-53] by CRC for Black Coal Utilisation in Australia, char structures are classified into three groups based on the morphological characteristics of chars, as summarized in Table 1. The populations of the different groups of chars for a given coal are strongly influenced by operating conditions, including the ambient pressure of the system.

Table 1. Char classification system [50,51,52,53]

	Group I	Group II	Group III
Two-dimensional schematic representation			
Porosity, %	> 70 %	Variable, 40-70 %	< 40 %
Wall thickness, μm	< 5	> 5	> 5
Shape	Spherical-subspherical	Sub-spherical	Angular
Typical swelling ratio	>1.3	<1.0	<0.9

Influences of the ambient pressure on char structure have been investigated very recently, using Australian coals [47,54] and maceral concentration samples [50], as shown in Figure 5 and 6. Clear trends show that as the pressure increases the overall proportion of Group I char increases whilst that of Group II and III chars decreases. In particular, when pressure increases from 0.5 MPa to 1.5 MPa, the Group I chars increase from 38% to 72% for the sample containing high inertinite maceral. Chars with different structures tend to behave differently during the subsequent char combustion or gasification. Group I chars, due to the high porosity, can be more easily fragmented, leading to the formation of finer ash particles. Therefore, the changes in the population of the Group I chars have significant influence on the final ash chemistry [47].

An empirical equation [54] has been proposed to correlate char morphology to the ambient pressure and vitrinite content based on the work by Benfell et al [50], and has been applied in predicting ash formation [55,61]:

$$n_{GrpI}\,(\%)=0.6\times P_t+0.53\times vitr+37$$

Where n_{GrpI} is the number percentage of Group I char, P_t is the total pyrolysis pressure (atm), and vitr is the vitrinite content. A

similar correlation has been given based on investigations on the same maceral concentration samples to predict Group I char population at different pressures by Benfell et al [50].

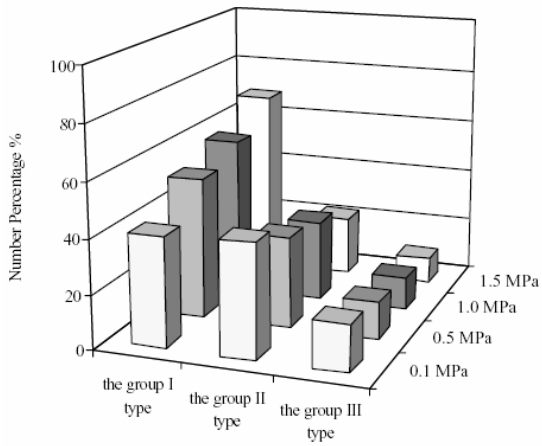


Figure 5. Char characteristic of coal A (an Australian bituminous coal) generated at different pressures [47]

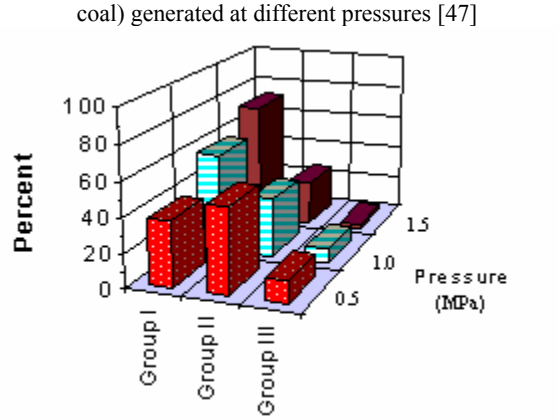


Figure 6. Percentages of Group I, II and III char for inertinite-concentration (prepared at 1300°C and indicated pressures [50])

A mechanistic char structure model has recently been developed based on bubble mechanisms [56]. The model has provided potential capacity of predicting pressure effect on swelling and char structure evolution from standard raw coal properties. An ongoing project in the CCSD, Australia, is looking at the char and ash characteristics collected in a Pressurised Entrained Flow Reactor (PEFR) at high pressures and temperatures [57].

Effect of pressure on char reactions

It has been known that char structure plays an important role in the char burnout. In general, in regime I, porous char particles (Group I) burn at a faster rate compared to the solid chars (Group III). In regime II, porous char burns at similar rate to the solid one. However, the porous char has experienced more extent of devolatilisation resulting in much high weight loss. The mass of carbon in the porous char is much less than that in the solid char. Therefore, the porous char will burn out at the earlier stage of the combustion [47]. Figure 7 shows predicted burning rates of Group I and III chars [36].

An important aspect in the char reaction is the fact that porous char particles are easily fragmented in combustion. The tendency of the fragmentation of the different chars has major impacts on the chemistry of the final ash particles (47). It has been observed that chars generated at elevated pressure have higher porosity, as shown in Figure 8. The increased porosity results in more chance of char fragmentation during the char combustion (35,47).

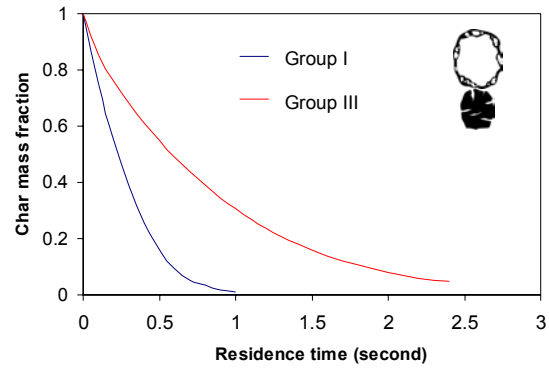


Figure 7. The predicted mass fraction of remaining char vs. residence time for Group I and Group III char particles [36].

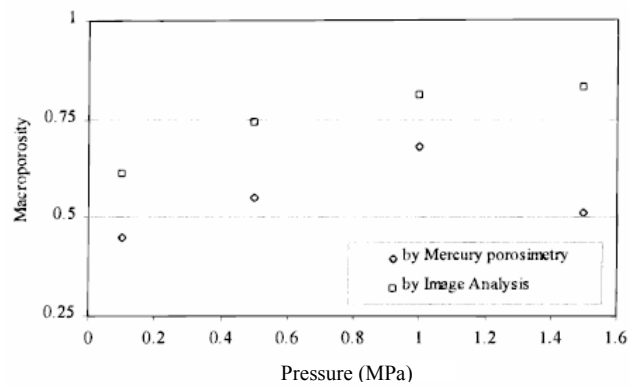


Figure 8. The predicted mass fraction of remaining char vs. residence time for Group I and Group III char particles [35,47].

The effect of pressure on the char reaction has been extensively studied in the past a few decades, and has been reviewed by Wall et al [36]. Table 2 summarises the data for the effect of pressure on char reactions provided in the open literature.

Table 2. Summary of pressure effects on various aspects of char reaction [Modified from 36]

Aspects	The effect of pressure	Ref.
Char combustion	Rate ↑ with increasing O_2 partial pressure at a fixed total pressure	[64,65]
Char combustion	Rate first ↑ then ↓ with increasing total pressure at a fixed O_2 mole fraction	[64,65]
Char temperature	↑ with increasing O_2 partial pressure at a fixed total pressure	[66]
Char gasification	Rate ↑ with increasing reactant gas pressure	[30,67, 68]
Char reactivity	↓ with increasing pyrolysis pressure	[10,15, 29,69]
Swelling	First ↑ then ↓ with increasing pyrolysis pressure	[11,14, 35]
Bulk diffusivity	↓ with increasing total pressure	[70]
Char porosity	↑ with increasing total pyrolysis	[35,47, 53]

Effect of pressure on ash formation

Very little data have been provided in the open literature in relation to ash formation at pressure. An increase in the system pressure results in a decrease in the vaporization of ash species [39,47,59,60]. However, the char fragmentation and the coalescence of included minerals in the char particle are the main mechanisms of ash formation during bituminous coal combustion [47]. Very recently, a number of Australian coals have been used in examining pressure effects on ash liberation [58]. Strong association has been found between the ash formation and the char structure, and the mechanism for ash formation from different char types has been proposed [47,58].

Ash liberation at high pressures

The characteristics of the liberated ash particles reflect the dominant ash formation mechanism at different burn-off levers (47). Figure 9 indicates that there was almost no change between the PSD of the liberated ash between burnoff levels of 54.3% and 35.5%. At the middle combustion stage where the burnout level is 70%, the percentage of liberated ash particles in the sample increased, and the PSD of liberated ash shows that char fragmentation was still the dominant mechanism for ash formation during combustion from 54.3% to 70.1% burnoff levels. However, the PSD shifts to a slightly larger size. The change in PSD of liberated ash implies that some coalescence of included mineral matter occurred at this burnoff level. At an 87.1% burnoff level the PSD for the liberated ash increased significantly compared to the 70.1% burnoff level. This suggests that included mineral matter experienced more significant coalescence during this stage. At the 95.6% burnoff level, the majority of the particles in the sample are presented as liberated ash (about 80%). The largest shift in the liberated ash PSD was observed indicating that the most significant extent of coalescence for included mineral matter occurred during this stage.

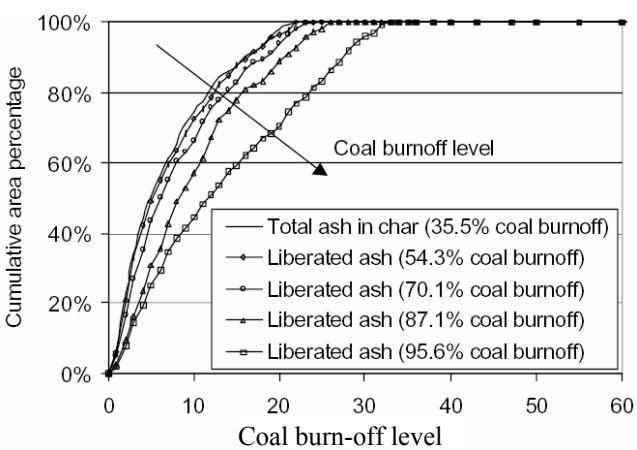


Figure 9. Characteristics of combustion solid residues (at 0.1 MPa) at different burn-off levels [47,58]

Combustion solid residues at different burn-off levels were also analysed under SEM [47,58]. Clear trends are presented in Figure 10 that the level of ash liberation increases with an increased level of burn-off. No apparent liberated ash particles were observed at a burn-off level of 35.5%. At a burn-off level of 54.3%, which corresponds to the early combustion stage, some free ash particles were observed. Significant char fragmentations were also observed at this burn-off level [36]. The number percentage of liberated ash particles increases from around 11% at 54.3% burn-off to 82% at 95.6% burn-off level.

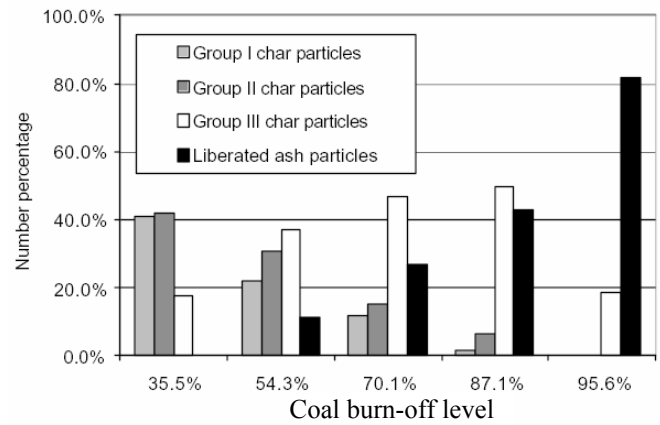


Figure 10. Characteristics of combustion solid residues (at 0.1 MPa) at different burn-off levels [47,58]

However, no experimental data are available to compare the pressure effects on the ash liberation at the same burn-off level. Although chars produced at high pressure have high porosity, whence are expected to experience more extensive fragmentation during combustion [47]. Other previous studies [62,63] have also shown that fragmentation is strongly associated with the porous char structures. Highly porous char tends to fragment frequently.

Chemistry of the high-pressure ash

Wu et al [35,47] have studied the chemistry of the ash produced during the combustion of Australian bituminous coals at four different pressures. The morphology of the ash particles examined using SEM is shown in Figure 11. The SEM images clearly show that as pressure increases from 0.1 MPa to 1.5 MPa considerably higher numbers of finer ash particles are formed.

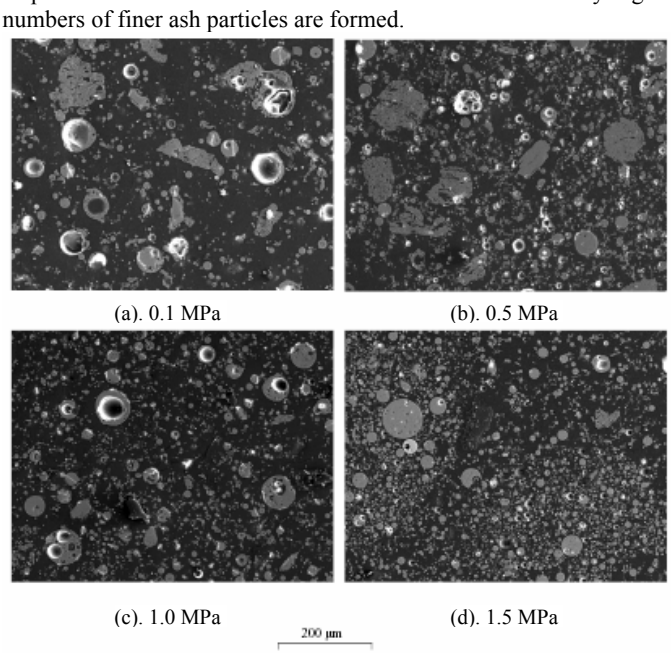


Figure 11. SEM image of ash particles of coal A collected at different pressures [35,47]

The results for ash particle size distribution (PSD) were measured for the same Australian coal, and are presented in Figure 12. When pressure increases from 0.1 MPa to 1.5 MPa, the PSD of the ash shifts to smaller particle sizes, indicating that the ash formed

at higher pressures has a much finer size. Sink/float analysis shows that over 70% of the mineral matter in coal is present as included species [36]. Figure 13 compared the results of PSD measurements of the ash for another two Australian coals, and the similar trends were observed. However, the PSD of the ash formed during gasification is expected to be less sensitive to the system pressure [47].

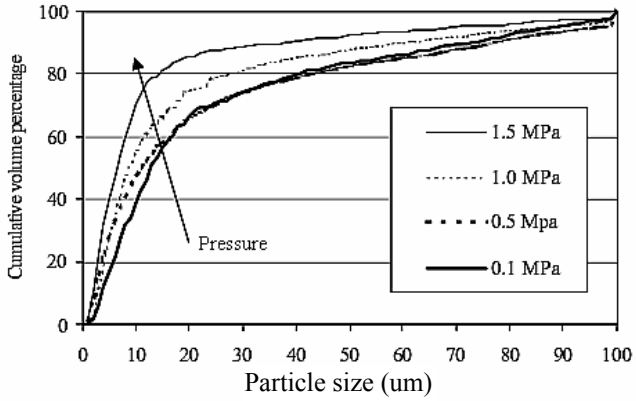


Figure 12. PSD of ash formed from combustion of coal A in air at pressures indicated [35,47].

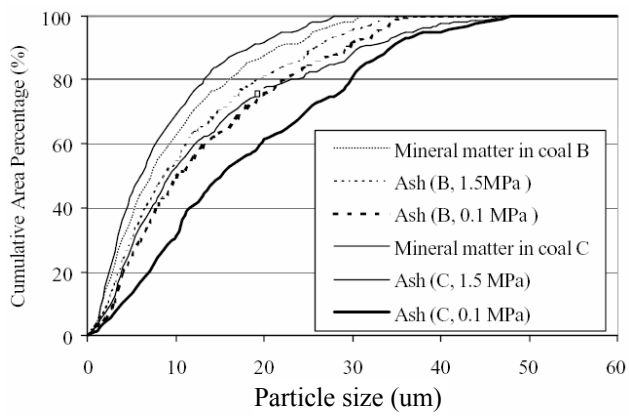


Figure 13. PSD of ash formed from combustion of coal B in air at a gas temperature of 1300 °C and the pressure indicated [47]

Char structure has been found to be a significant linkage between pressure and ash formation [36, 47], and the char fragmentation and the coalescence of the included minerals are dominant ash formation mechanism during the bituminous coal combustion [47]. At 1.5 MPa, the char sample contains mainly Group I particles with high porosity. However, at 0.1MPa, it is dominated by the Group II and III type particles with relatively low porosity. During combustion, Group I chars will undergo extensive fragmentation, reducing the coalescence of the included minerals, and therefore producing a large number of smaller ash particles. For Group III char particles, the chance for fragmentation is much less. There is a much higher probability of coalescence for the included minerals, resulting in the formation of ash particles with larger sizes during combustion. The ash formed from Group II particles will therefore be of a size between that of Group I and III derived ash particles.

Mechanism of ash formation at high pressure

A mechanism for the ash formation, as shown in Figure 14, has been proposed very recently by Wu et al [35, 47], where the char fragmentation and the coalescence of the included minerals play the dominant role. Based on this study a comprehensive ash formation model including this char structural mechanism has been recently presented to predict ash deposition [61].

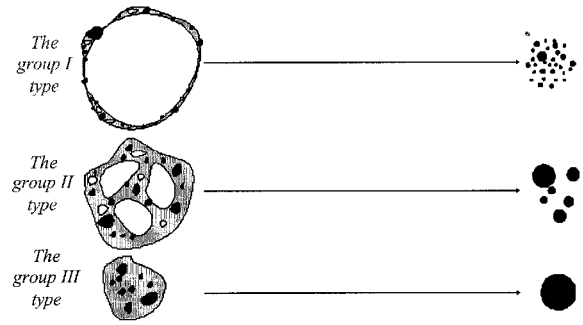


Figure 14. Proposed mechanisms for ash formation from different char types [35,47]

From Figure 14, Group I type char particles fragment extensively during the early and middle combustion stages and burn out early. The extent of coalescence for the included mineral particles in the Group I char is very low. Therefore, one Group I type char particle may produce a number of small ash particles, resulting in a small PSD for liberated ash. Group II type char particles fragment less compared to the Group I type char particles. Char fragmentation is still the dominant mechanism for ash formation but the included mineral particles undergo some coalescence. One Group II type char particle may produce several ash particles with a relatively larger size compared to the Group I type char particle, resulting in an increase in PSD of the liberated ash during the middle burnout stage. Group III type char particles exhibit low or no fragmentation. The included mineral particles undergo a large extent of coalescence. One Group III type particle may form only one or two ash particles of a larger size compared to Group I and II type char particles, resulting in a significant shift to larger size of the liberated ash PSD during the late combustion stage. At high pressures, larger amounts of highly porous char particles are generated. Therefore more finer ash particles are formed. This ash formation mechanism provides a mechanistic explanation for the observations under pressurised conditions.

Conclusions

Recent studies have demonstrated that the operating pressure has significant impacts on ash formation during pf combustion and gasification due to its relationship with char character. At elevated pressures, more swelling and higher porosity of chars are observed, and a maximum swelling seems to occur at an optimal pressure. Larger population of Group I chars are formed at higher pressure and finer ash particles tend to be generated due to the formation of more porous chars. The formation mechanism for the finer ash during combustion results from more significant fragmentation and less coalescence of included minerals within the porous chars.

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References

(1) Takematsu, T. and Maude, C., *Coal Gasification for IGCC Power Generation*, IEA Coal Research, Gemini House, London, 1991
(2) Harris, D. J. and Patterson, J. H*., Aust. Inst. of Energy J*., 13:22 (1995)
(3) Cai, H. Y., Guell, A. J., Dugwell, D. R. and Kandiyoti, R., *Fuel*, 72:321 (1993)
(4) Green, P. D., Patrick, J. W., Thomas, K. M. and Walker, A., *Fuel*, 64:1431 (1985)
(5) Griffin, T. P., Howard, J. B. and Peters, W. A., *Fuel*, 73:591 (1994)
(6) Lee, C. W., Jenkins, R. G. and Schobert, H. H., *Energy and Fuels*, 5:547 (1991)
(7) Megaritis, A., Messenbock, R. C., Chatzakis, I. N., Dugwell, D. R. and Kandiyoti, R., *Fuel*, 78:871 (1999)
(8) Mill, C. J., Harris, D. J. and Stubington, J. F., *8th Australian Coal Science Conference*, The Australian Institute of Energy, Sydney, Australia, p. 151 (1998)
(9) Sun, C. L., Xiong, Y. Q., Liu, Q. X. and Zhang, M. Y., *Fuel*, 76:79 (1997)
(10) Lee, C. W., Jenkins, R. G. and Schobert, H. H., *Energy and Fuels*, 6:40 (1992)
(11) Khan, M. R. and Jenkins, R. G., *Fuel*, 65:725 (1986)
(12) Khan, M. R. and Jenkins, R. G., *Int. Conf. Coal Sci*., IEA, p. 1336, 1983
(13) Khan, M. R. and Jenkins, R. G*., Fuel,* 65:1291 (1986)
(14) Lee, C. W., Scaroni, A. W. and Jenkins, R. G., *Fuel*, 70:957 (1991)
(15) Cai, H. Y., Guell, A. J., Chatzakis, I. N., Lim, J.-Y., Dugwell, D. R. and Kandiyoti, R., *Fuel*, 75:15 (1996)
(16) Croiset, E., Mallet, C., Rouan, J.-P. and Richard, J.-R., *26th Symposium (International) on Combustion* (1996), The Combustion Institute, p. 3095
(17) Essenhigh, R. H. and Mescher, A. M., *26th Symposium (International) on Combustion (1996)*, The Combustion Institute, p. 3085
(18) Messenbock, R. C., Dugwell, D. R. and Kandiyoti, R., *Fuel*, 78:781 (1999)
(19) Lin, S.-Y., Suzuki, Y., Hatano, H. and Tsuchiya, K., *Chemical Engineering Science*, 55:43 (2000)
(20) Richard, J.-R., Majthoub, M. A., Aho, M. J. and Pirkonen, P. M., *Fuel*, 73:485 (1994)
(21) Joutsenoja, T., Saastamoinen, J., Aho, M. and Hernberg, R., *Energy and Fuels*, 13:130 (1999)
(22) Turnbull, E., Kossakowski, E. R., Davidson, J. F., Hopes, R. B., Blackshaw, H. W., and Goodyer, P. T. Y., *Chem. Eng. Res. Des*., 62:1217 (1984)
(23) Monson, C. R. and Germane, G. J., *Energy and Fuels*, 7:928 (1993)
(24) Essenhigh, R. H. and Mescher, A. M., *Combustion and Flame,* 111:350 (1997)
(25) Li, S. and Xiao, X*., Fuel*, 72:1351 (1993)
(26) Megaritis, A., Zhuo, Y., Messenbock, R., R., D. D. and Kandiyoti, R., *Energy and Fuels*, 12:501 (1998)
(27) Sha, X. Z., Chen, Y. G., Cao, J., Yang, Y. M. and Ren, D. Q., *Fuel*, 69:293 (1990)
(28) Megaritis, A., Messenbock, R. C., Collot, A.-G., Zhuo, Y., Dugwell, D. R. and Kandiyoti, R., *Fuel*, 77:1411 (1998)
(29) Roberts, D. and Harris, D. J*., Energy and Fuels*, 14:483 (2000)
(30) Blackwood, J. D. and Ingeme, *A. J., Aust. J. Chem*., 1958 (11), pp.16
(31) Ranish, J. M. and Walker, P. L., *Carbon*, 31:135 (1993)
(32) Kang, S. G.; Sarofim, A. F.; Beer, J. M.. *24th Symposium (International) on Combustion Institute (1992)*, The Combustion Institute, pp. 1153
(33) Couch, G. Understanding Slagging and Fouling in PF Combustion; IEA Coal Research; London, 1994
(34) Helble, A. F.; Neville, M.; Sarofim, A. F.. *21st Symposium (International) on Combustion (1986);* The Combustion Institute; Pittsburgh, PA, pp 411-417
(35) Wu, H.; Bryant, G.; Wall, T.. *Energy & Fuel,* 14, pp745-750 (2000)
(36) Wall, T; Liu, G.; Wu, H.; Benfell, K.; Lucas, J.; Roberts, D.; Yu, J.; Harris, D.. *Australian Combustion and Flame Day (2002)*, Adelaide, Australia
(37) Baxter, L. L*., Combustion and Flame*, 90:174 (1992)
(38) Helble, J. J. and Sarofim, A. F., *Combustion and Flame*, 76:183 (1989)
(39) Raask, E., *Mineral impurities in coal combustion: behavior, problems and remedial measures*, Hemisphere Publishing Corporation (1985)
(40) Gavalas, G. R.. *Coal pyrolysis*,. Amsterdam; Elsevier Scientific Pub. Co. (1982)
(41) Howard, J.. *Chemistry of coal utilization : second supplementary volume*,. M. A. Elliott. New York, pp. 665- (1981)
(42) Shan, G.. *PhD Thesis.* In Dept. of Chemical Engineering. University of Newcastle. (2000)
(43) Wall, T. Liu, G. Wu H. Roberts, D. Benfell, K.; Lucas J.. *Progress in Energy and Combustion Science*;, 2002 (In press)
(44) Anthony, D. B.; Howard, J. B.; Hottel, H. C.; Meissner, H. P.. *15th Symposium (International) on Combustion Institute (1975)*, The Combustion Institute, Pittsburgh, pp. 1303
(45) Suuberg, E. M.. Sc.D Thesis, MIT (1977), USA
(46) Solomon, P. R.; Fletcher, T. H.. *25th Symposium (International) on combustion (1994)*, The Combustion Institute, pp. 463
(47) Wu, H., *PhD thesis*, The University of Newcastle, Australia (2000)
(48) Wu, H. Bryant, G.; Benfell, K.; Wall, T.. *Energy & Fuels*, 14. pp. 282-290 (2000)
(49) Oh, M. S.;Peters, W. A; Howard, J.B.. *AIChE J*., 35(5), pp.775-792 (1989)
(50) Benfell, K. E., *PhD thesis*, The University of Newcastle, Australia (2001)
(51) Bailey, J. G., Tate, A. G., Diessel, C. F. K. and Wall, T. F., *Fuel,* 69:225 (1990)
(52) Benfell, K. E. and Bailey, J. G., *8th Australian Coal Science Conference,* p. 157 (1998)
(53) Benfell, K. E., Liu, G.-S., Roberts, D., Harris, D. J., Lucas, J. A., Bailey, J. G. and Wall, T. F., *28th Symposium (International) on Combustion (2000)*, The Combustion Institute
(54) Liu, G. *PhD thesis*, In Chemical Engineering, The University of Newcastle, Australia (1999)
(55) Yan, L. *PhD thesis*, In Chemical Engineering, The University of Newcastle, Australia (2000)
(56) Yu, J.; Strezov, V.; Lucas, J.; Liu, G.; Wall, T.. *29th Symposium (International) on combustion (2002)*, The Combustion Institute, Japan (Accepted)
(57) Harris, D. et al. *CRC Report, CRC for Black Coal Utilization*, Newcastle, Australia (2000/2001)
(58) Wu, H.; Wall, T.; Liu, G.; Bryant, G.. *Energy & Fuels,* 13, pp. 1197-1202 (1999)
(59) Mojtahedi, W.; Backman, R.. *J. Inst. Energy.* 62, pp. 189-196 (1989)
(60) Wu, H.; Bryant, G.; Wall, T.. *Proceeding of the Adelaide International Workshop on Thermal Energy Engineering and the Environment,* Adelaide, Education Technology Unit, The University of Adelaide, pp. 525-534
(61) Yan, L.; Gupta, R.; Wall, T.. *Fuel,* 80, pp. 1333-1340 (2001)
(62) Baxter, L.L.. *Combustion and Flame,* 90:174 (1992)
(63) Helble, F. F.; Sarofim, A. F.. *Combustion and Flame;* 76:183 (1989)
(64) Monson, C.R.; Germane, G.J.; Blackham, A.J.; Smoot, L.D.. *Combustion and Flame*, 100:387 (1995)
(65) Laster, T.W.; Seeker, W. R.; Meerklin, J.. *18th Symposium (International) on combustion (1981)*, The Combustion Institute, pp.1257
(66) Saastamoinen, J.J.; Aho, M.J.; Hamalainen, J.P.. *Energy and Fuels*, 10:599(1996)
(67) Blackwook, J.D.; Ingeme, A.J.. . *J., Aust. J. Chem*., 13:194 (1960)
(68) Muhlen, H. J.; van Heek, K. H.; Juntgen, H,.. Fuel, 64:591 (1985)
(69) Robert, D.. *PhD thesis;* In Chemical Engineering, University of Newcastle (2000)
(70) Satterfield, C.N. *Mass transfer in heterogeneous catalysis*, MIT Press, 1970