A new criterion for determination of coal ash sintering temperature using the pressure-drop technique and the effect of ash mineralogy and geochemistry

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HIGHLIGHTS

- A new criterion for determining ash sintering temperature proposed and validated.
- The new criterion was independent of fuel types and experimental conditions.
- Ash specific area and pore volume decreased sharply at the on-set of sintering.
- The new criterion more adequately represents the ash sintering process.
- Effect of ash mineralogy and geochemistry on sintering systematically studied.

ARTICLE INFO

ABSTRACT

A new criterion for determining the ash sintering temperature measured using the pressure-drop sintering technique, based on the first-order and second-order derivatives of the pressure drop curves as a function of temperature, was proposed. The *new criterion* was evaluated against the one widely used in the literature (the *old criterion*) by examining the variations in the specific surface area, pore volume and pore size of the ash pellets being sintered as a function of sintering time and temperature for the ashes of three different coals of vastly different mineralogical and geochemical properties. The response of ash sintering temperature determined based on the two criteria to the experimental conditions, namely, the ash pellet compaction pressure and gas flow rate, was also investigated. The effect on ash sintering temperature of the base to acid (B/A) ratio ranging from 0.09 to 4.79 by blending the coals was also determined and evaluated. It was found that sintering temperature determined according to the new criterion was lower than that based on the old criterion. Consistent with the literature findings, the sintering temperature decreased with increasing the B/A ratio. The microstructural analysis confirmed that the ash sintering temperature defined using the new criterion was closer to the temperature of the onset of the sintering process than the old criterion. The ash sintering temperature based on the new criterion was independent of the ash pellet compaction pressure and gas flow rate, while the ash sintering temperature according to the old criterion was subject to the experimental conditions. This implies that the new criterion more accurately captures the onset temperature when the ash sintering occurs and provides an improved means to determine the ash sintering temperature using the pressure-drop technique.

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1. Introduction

Ash sintering is a key early step in the processes of ash fouling and slagging in coal-fired utility boilers. The ash particles initially deposit on the surfaces in the furnace by means of condensation, fume deposition, chemical reactions, diffusion, thermophoresis and inertial impaction [1–4]. The initial ash deposit increases the heat transfer resistance between the flame or hot flue gas and the heat transfer surfaces, resulting in an increase in the outer surface temperature of the ash deposit [5–10]. As the deposit surface temperature further increases to the ash sintering temperature, these particles become softened and fused together through bonding or welding of the particles [5,7]. The ash deposit further develops as sintering proceeds and mineralogical phases change,

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progressively going through the formation of powdery deposit, light molten deposit, semi-molten deposit, and highly molten deposit in different heat transfer sections in furnaces [4,5,11–14]. The presence of these ash deposits in the furnace reduces the heat transfer coefficient, affects the operation stability, and sometime leads to unplanned plant outages [4,10,15]. Therefore, a good knowledge of the ash sintering process and mechanisms is important and essential for efficient and effective management and resolution of ash related operational issues in utility boilers [1,9].

Ash sintering temperature is the temperature at which the ash particles in a deposit begin sintering, characterised by softening and increased contact of the ash particles [9,16,17]. The ash sintering temperature may be determined using different methods based on the changes in thermal conductivity, strength and viscosity of the ash as well as the changes of its physical dimensions [17–20]. Various experimental techniques, such as thermal conductivity analysis (TCA), thermo-mechanical analysis (TMA), heating microscopy, compression strength (CS) and pressure-drop technique have been reported in the literature [17,20,21]. Among the various experimental techniques, the pressure-drop technique stands out due to many advantages such as its simplicity, high sensitivity to dimension changes and ability to simulate real atmosphere, and high accuracy [17,22].

The pressure-drop technique measures the pressure drop across an ash pellet, through which a gas passes at a constant flow rate, while the temperature of the ash pellet is increased at a slow but constant heating rate. The ash sintering temperature is defined as the temperature when the pressure drop across the pellet reaches the maximum and starts to decrease [17,22–24]. However, this definition, referred to as the *old criterion* in the present work, seems loose with a degree of ambiguity and its validity is questionable as it has been shown that the ash sintering has already occurred prior to the pressure drop reaches the maximum.

This work was aimed to develop an appropriate criterion for determining the ash sintering temperature using the pressure-drop technique. The *new criterion* was based on the first-order and second-order derivatives of the pressure drop curves as a function of temperature. The ash sintering temperature was defined as the temperature at which an abrupt change in the rate of pressure drop versus temperature occurred. The feasibility and accuracy of the new criterion was validated via investigating the microstructural properties of the ash sintered at various temperatures and different times and evaluated against the old criterion to study the effect of experimental conditions including compaction pressure during the ash pellet preparation and the gas flow rate on the ash sintering temperature measurement. The new criterion was then applied to the sintering temperature measurements of the ashes of three coals of vastly different mineralogical and geochemical properties and their blends, with the base to acid (B/A) ratios ranging from 0.09 to 4.79. It was anticipated that the outcomes of this study would provide an alternative approach to determining the ash sintering temperature in a more accurate yet simple manner.

2. Experimental

2.1. Materials

An Australian bituminous coal (AB), a Chinese lignite (CL), and an Indonesian lignite (IL) with vastly different mineralogical and geochemical properties were chosen in this study. The as-received coal samples were grinded and sieved to particles less than 200 μm in size. Coal blends between AB and CL, AB and IL, and IL and CL, respectively, were prepared with fixed blending ratios of 8:2, 6:4, 5:5, 4:6, and 2:8 by dry mass. The corresponding ash samples were prepared according to Australian Standard 1038.3, by heating a sample in air in an electric furnace from room temperature to 773 K within 30 min, holding there for 30 min and then further heating to 1088 K and remaining there for 2 h. The residue was recovered as the corresponding ash sample for further analysis and sintering temperature measurement. The proximate analysis of the parent coal samples and their ash chemistry determined using XRF are shown in Table 1. The ash chemistry of the blends was calculated based on the blending ratio and is given in Table 2. The base to acid ratios, $B/A = (Na_2O + MgO + CaO + Fe_2O_3 + K_2O)/(SiO_2 + Al_2O_3 + TiO_2)$ of all samples were also calculated. The B/A ratio is an important index in evaluating ash sintering and fusion propensities [1,4].

2.2. Pressure-drop sintering device

A pressure-drop sintering device, similar to that first introduced by Al-Otoom et al. [17], was used to measure the ash sintering temperature, as schematically shown in Fig. 1. An ash sample was firstly compacted into a pellet in-situ in a mullite tube (5 mm in ID) using a device, also as schematically shown in Fig. 1, composed of a lever to exert a pressure on the ash pellet and a holder to support the mullite tube. Two copper rods with 5 mm in diameter were inserted into the tube to hold the ash pellet in a desired position at the centre of the mullite tube. At the end of the lever, a weight was hanged so that the ash pellet could be compacted. By changing the mass of the weight, ash pellets of different compaction pressures were produced. The compaction pressure P was calculated according to $P = L_2mg/AL_1$, where A is the cross-section area of the mullite tube, m the mass of the weight, and L_2 and L_1 are the lengths of the two arms of the lever as shown in Fig. 1. Typically, about 0.4 g ash was compacted into each pellet and the compaction pressures ranged from 3.75 MPa to 30 MPa in the current experimentation.

In order to evaluate the pressure-drop technique, the mullite tube containing the ash pellet was placed in a horizontal furnace and heated from room temperature at a rate of 6.7 K min^{-1} in

Table 1
Proximate analysis of coal samples and their ash chemical composition.

Coal samples	Proximate analysis (wt% as received)			
	M	A	VM	FC
AB	1.2	9.7	34.0	55.1
CL	17.1	2.8	30.6	49.5
IL	10.4	7.5	43.8	38.3

Ash samples	Ash composition (wt%)										
	SiO$_2$	Al$_2$O$_3$	CaO	Fe$_2$O$_3$	K$_2$O	MgO	Na$_2$O	SO$_3$	P$_2$O$_5$	TiO$_2$	B/A ratio
AB	64.9	24.1	0.38	5.24	1.46	0.69	0.67	0.22	0.065	1.44	0.09
CL	5.42	6.39	40.7	3.06	0.55	7.62	6.08	26.9	0.048	0.30	4.79
IL	35.0	32.0	12.7	3.70	0.18	5.77	0.94	4.24	1.16	2.42	0.34