



Full Length Article

Establishing a novel and yet simple methodology based on the use of modified inclined plane (M-IP) for high-temperature slag viscosity measurement

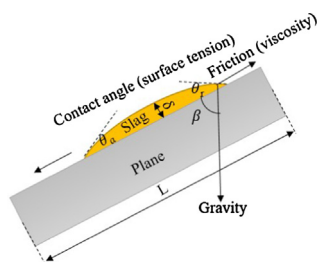
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GRAPHICAL ABSTRACT



(b) Schematic of slag falling film model

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ABSTRACT

In this study, a simple and yet novel methodology based on the use of modified inclined plane (M-IP) has been established and validated to determine the high-temperature slag viscosity. Seven synthetic standard ash samples have been tested on the inclined corundum plane, under the conditions of reducing environment of 1% CO in nitrogen, 1100 °C–1400 °C, 25°–90° and different duration time of 10–40 min. The slag mass was varied from 100 mg to 400 mg. A multiple linear regression fitting was conducted to establish an empirical equation to predict slag viscosity (η) based on the slag travel length per unit mass (L') and the inclination angle of the plane ($\cos\beta$). As has been fully validated, the new method is simple and requires a maximum of 200 mg ash for the slagging test. By measuring only two temperature points, an Arrhenius equation can be established to predict the travel length at any of the intermediate temperatures. Both the inclination angle and the reciprocal of slag viscosity affect the slag travel length in an intertwined manner, by following a linear relationship between the algorithm of slag travel length per unit mass, $\cos\beta$ and the logarithm of slag viscosity, as per the equation of $\ln\mu = 3.282281\cos\beta - 1.882827\ln L' + 7.397108$. The large correlation coefficient value and the normal quantile plot supported the high reliability of this equation. However, this empirical equation is limited to an upper temperature of 1400 °C and a maximum viscosity of 17.9 Pa·s. Any larger viscosity would only be measured qualitatively, whilst it is sufficient for a comparison with the critical viscosity 25 Pa·s from the perspective of a quick screening of solid fuel for entrained-flow gasifier or cyclone furnace.

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Nomenclature

A_A	pre-exponential factor for Arrhenius equation [$\text{g cm}^{-2} \text{atm}^{-1} \text{s}^{-1}$]
E_A	activation energy for Arrhenius equation [kJ mol^{-1}]
L	length of the plane [mm]
ρ	bulk density [g cm^{-3}]
g	gravity constant [–]
β	inclination angle [°]
v_z	velocity in z direction [m s^{-1}]

τ_{xz}	molecular stress tensor component on surface [N]
θ_a	advancing angle [°]
θ_r	receding angle [°]
μ	dynamic viscosity [Pa s]
η	viscosity [Pa s]
δ	thickness of slag film [mm]
n	flow behaviour index [–]
R	gas constant [–]
L'	slag travel length per unit mass [mm g^{-1}]
K	consistency index [–]

1. Introduction

Slag viscosity has implications in glass production, geophysical phenomena, metallurgical processes, fly ash vitrification, combustion and gasification. The viscosity determines the performance of slagging, which minimises the volume and drain of the ash from the high temperature process [1]. The formation of slag critically affects the heat transfer and the stability of the combustion and gasification processes [2]. The viscosity of a slag and its change with temperature are vital as they will determine the extent of motion taking place at the interface and affect the successful operation of high-temperature systems including gasifier, cyclone furnace and metallurgy furnace [3].

Viscosity is the ability to resist the movement of one layer of molecules over another when a stress is applied. It is a measurement of the internal friction of a fluid, which significantly depends upon structure, physical properties and temperature. For a coal slag sample, its viscosity is normally dominated by its silicate structure [4]. An acidic slag with a large quantity of polymerised silicate ions is highly viscous, whereas a basic slag with small de-polymerised silicates is much more like a fluid [4]. To date, a wide range of techniques has been developed for the viscosity measurement, as summarised in Table 1 [3–6]. The capillary method is normally used in a Shiraiishi Viscometer, detecting the parallel plate sample, height and time, and covers a large detecting range from 100 to 10^{11} Pa s [5]. However, it is restricted to the highly viscous fluids and impractical at high temperatures ($> 1500^\circ\text{C}$). The falling body viscometer determines the viscosity by measuring the time for a slag bob to drag through a measured distance. The measurement range varies from 3 to $100,000 \text{ Pa s}$ [4,5]. Its limitation is that it requires a long ($> 200 \text{ mm}$) and uniform high temperature zone, and accurate operations. The oscillating viscometer measures the logarithm decrement of amplitude of twisting. It is normally applicable for low viscosity fluids ($< 0.1 \text{ Pa s}$), and requires melt density to determine the viscosity according to the Roscoe Equation [5,6]. The rotating cylinder viscometer covers a viscosity range from 0.01 to 100 Pa s , which is a desirable range for most coal slags. Therefore, it has been widely used for measuring the viscosity of coal slags [3]. However, due to the difficulty in torque measurement, it requires very accurate vertical alignment and skilled operators. The uncertainty in the measurements for many slags is normally higher than $\pm 20\%$, due to the changes on slag composition during the measurement and the systematic errors from the equipment [6]. The particle precipitation and solidification in the slag also affect the accuracy of the results significantly.

The difficulty and high cost of viscosity measurement for slags has led to the establishment of a large number of empirical models based on

the slag chemical composition. Table 2 summarises the most common models for slag prediction [7–14]. The Urbain Model is one of the most widely used slag viscosity models, which is based on the $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ system. The slag constituents are classified into three categories, glass formers, modifiers and amphoteric [7]. Kondratiev and Jak modified the Urbain viscosity model to include the multi-component slags [8]. The four-component system $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-CaO-“FeO”}$ slag is used to describe the viscosity behaviour over the whole composition range instead of $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ system in Urbain Model. The Ribound model was initially developed to estimate the viscosity of mould powders in the $\text{SiO}_2\text{-CaO-Al}_2\text{O}_3\text{-CaF}_2\text{-Na}_2\text{O}$ system [9]. It has been extended to estimate the viscosity for other slags. However, it fails to differentiate between the various cations [9]. Mills and Sridhar have developed the National Physical laboratory (NPL) model [10]. It relates the viscosity of slag to the structure through optical basicity correcting [10,11]. However, it is only applicable for standard glasses and is inaccurate for slags. The Lida model is based on the Arrhenius type of equation, where the network structure of a slag is taken into account by using the basicity index [12,13]. However, it is implausible to apply the Lida model to systems when there is no experimental data for an accurate calibration. The high accuracy claimed by this model only comes from its calibration with experimental data for each slag [6]. The KTH model is based on the Eyring equation rather than the Arrhenius equation [14]. It takes into account the Gibbs energy of activation for viscosity. The model is commercially available in “THERMOSLAG” software [3,15]. However, the presence of net-forming and non-net-forming oxides in the slag, and the complicated interaction between cations and anions make the prediction using this model problematic.

There is a well-defined need for a simplified test to measure the viscosities for quality assurance of supplies on a routine basis. Mills investigated a simple test for the slag viscosity measurement by using an inclined plane [16]. An ash sample was first melted into slag at high temperatures (1200°C – 1400°C). Subsequently, the resultant molten slag was carefully poured onto an inclined plane to flow down. The inclined angle is only restricted to 9° and 23° and the viscosity range is restricted in the range of 1.5 – 6 Pa s with an error of $\pm 15\%$. Moreover, the prior melting makes this measurement risky and uncertain in operation. Any cooling during the transferring could affect the accuracy of the measurement.

This paper aims to modify the inclined plane methodology to create a fast and simple high-temperature methodology for slag viscosity measurement, namely modified inclined plane (M-IP) method. Its novelty includes, 1) a prior melting is not necessary, 2) a small amount of ash sample up to 200 mg is sufficient, 3) the methodology is

Table 1
Summary of the existing viscosity measurement methods [3–6].

Methods	Range. (Pa s)	Specification	Limitation	Ref
Capillary	10^2 – 10^{11}	Rotating plate-torque, Parallel plate-sample height-time	Unpractical for high temperature	[5]
Falling body	3 – 10^5	Time for bob to fall/drag through measured distance	Long and uniform hot zone required	[4,5]
Oscillating	10^{-4} – 0.1	Measures log decrement of amplitude of twisting	Applicable for low viscosity de-polymerised slag	[5,6]
Rotating cylinder	0.1 – 100	Measuring the torque when rotating the bob or crucible	Accurate alignment and experienced operation required	[3]

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