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Review article

Models of coke quality prediction and the relationships to input variables: A review

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ABSTRACT

Within the coke making industry, the ability to accurately predict the quality of the coke produced from a variety of global coal basins is critical in both coal selection and blast furnace control. However, due to the complexity of the coke making process, the prediction of the resulting coke properties is a difficult task. This review analysed published models for the prediction of various measures of coke quality, with a particular emphasis on coke strength after reaction (CSR) and the related coke reactivity index (CRI). Focus was placed on the coal parameters selected as model inputs, and their reported behaviour with respect to the predicted coke quality. This review draws similar conclusions to previous analysis, namely there is a limited range of model applicability beyond the specific range of coals for which each model was derived. This conclusion is extended to suggest that the inconsistent utilisation of key attributes contributes to these limitations.

1. Introduction

1.1. Coal in the blast furnace

Coal is a critical part of the ironmaking process, as either coke or as an injectant. In the form of coke, it provides physical support for the ferrous materials (burden) in the blast furnace, as well as providing a source of heat and the reducing environment necessary for the production of iron [1–3]. Displacement of more expensive, non-renewable "prime" metallurgical coking coals by cheaper or renewable injectant sources, or lower quality coking coals is an emerging issue for coal producers, evidenced by the number of papers investigating the use of such alternate injectants or blend components [4–8]. For coal producers and coke manufacturers, understanding the relative performance of different coals in the coking and ironmaking processes is becoming more critical to the successful marketing and effective utilization of coals in a competitive market.

Of particular importance to blast furnace operators is the determination of the burden support function provided by coke, and its resulting degradation within the blast furnace, which impact the permeability of the burden materials, and hence the productivity and control of the furnace [1]. As blast furnaces grow in size and financial pressures on operators increase, it is paramount for coke producers to manufacture consistent, strong, cost competitive coke. Determination of what constitutes suitable blast furnace coke is difficult, and due to the harsh operating environment and working temperatures of more than 2200 °C in the raceway [1], direct measurement of coke performance within the blast furnace is virtually impossible.

1.2. Coke quality measures

A number of measures have been developed globally as a proxy for coke behaviour within the blast furnace. The earliest standard tests were for the examination of cold coke strength properties, termed the Micum, and Irsid tests [9], as well as ASTM tests for stability and hardness (currently standard D3402 [10], previously D294 [11]). More recently adopted were the coke strength after reaction (CSR) and the associated coke reactivity index (CRI) standard tests [12,13]. These tests were developed based on the observations of Nippon Steel Corporation in the late 1960's, and aim to measure indirectly coke behaviour in the blast furnace [14], where the coke is subjected to thermal, physical, and chemical effects [15,16]. This is replicated as the exposure of coke to CO_2 at 1100 °C for two hours (for full details, see [12,13]).

1.3. Prediction of coke quality

Coke quality tests are often expensive and time consuming and only provide information about the coke quality after it is produced. For

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these reasons, it is desirable to be able to predict coke quality from the information available about the parent coals. From the most recent review of coke quality prediction completed in 2002 [17], there was no singular model from which the properties of coke derived from coals of any global coal basin can be predicted with reasonable accuracy, with prediction abilities diminishing as coal blends increase in complexity. Since this time, a broader range of techniques have been developed within the experimental and data analytics domains, which have provided further insight into coal and coke behaviour.

1.4. Method of review

This review focusses on regression based coke quality prediction models for coke strength after reaction (CSR) and coke reactivity index (CRI). These parameters are selected due to their prevalence within recent literature and their importance for coal marketing.

The models discussed in this paper were collected between 30th March 2016 and 30th March 2017, with no bounds placed on the publication date of the model. Due to the nature of publications in the area, which includes conference papers that are not peer reviewed, not all publications are searchable using conventional databases. Therefore, any relevant papers, not found in the search, but referenced by these papers, were added to the review. Not all referenced articles were able to be collected due to restricted availability. Where professional translations were not available, papers not in English were translated using Google Translate [18].

The first part of this review discusses the founding models of coke quality prediction, that have had strong influence on the conscious and unconscious biases that later investigators have presented. The criticisms and modifications of these models are also discussed.

The second part of this review compares prediction models for each key attribute with respect to CSR and CRI, and discusses the fundamental basis for the observed data fits.

Finally, a comparison is made of models for other coke quality measures, including the ASTM Hardness and Stability, Micum, Irsid, and Japanese Drum Index values.

2. Early models of coke quality prediction

Since the 1930's, prediction of coke properties became of interest to investigators (e.g. [19]), and further advances in coal property measurement, particularly the improvement of microscopy based approaches allowed major steps forward in the prediction of coke behaviour. The identification of components within coal [20] and the definition of the maceral concept by Stopes in 1935 [17] formed the basis for many of the early contour plots for the prediction of coke properties. The following sections discuss the main early models applied in the literature and their application and descendant models.

2.1. Ammosov, Schapiro and Gray

The classification of macerals into "reactives" and "inerts" formed the basis of the models of Ammosov [21] and Schapiro and Gray [22,23]. Reactive materials were identified as those that softened upon heating and participated in the binding processes, whilst as the name suggests, inerts did not change size and shape on heating. Ammosov [21] and Schapiro and Gray [22,23] suggested that to obtain a coke of sufficient quality, there was an optimum ratio of reactive and inert material, as a function of nature of the reactive material.

2.1.1. Description of the model of Ammosov, 1957 and Schapiro and Gray, 1961, 1964

Ammosov et al. [21] suggested that the volatile matter of a coal is a poor indicator of rank, and that the plastometric methods for prediction of coke properties, such as those applied in the work of Brewer, Atkinson [19] were often misleading.

The models of both Ammosov et al. [21] and Schapiro et al. [23,22], considered that the relative concentration of the various maceral groups and the reflectance of the vitrinite group was a better indication of rank, and from this assertion, generated a graphical model. Fusible components were asserted to be vitrinite, liptinite, and 1/3 of the semifusinite, whilst the other macerals were considered to be inert. These inerts were termed by Ammosov et al. [21] the "leaning components", and the fusible components "caking" or "clinkering" components; terms still commonly applied in Eastern European literature. This notion was extended by Schapiro et al. [23,22], who utilised the terminology of reactive and inert components (representing the fusing and leaning components respectively), and described the "concrete model" of coke analogy. The concrete model compares the reactive phases of coke to the cement binder in concrete and the inert material in coke to the strengthening gravel components. Reactives and inert components were defined as materials that form the bonding agent within the reaction, and those that behave like aggregate, respectively. Both models described an optimum ratio infusibles as a function of rank, and related this behaviour to coke drum strength (Ammosov) or ASTM stability (Schapiro and Gray). Ammosov et al. [21] defined the leaning index and the coefficient of coking capacity, from which the drum strength was determined from a contour plot. The leaning index was the ratio of the infusible components present and the optimum proportion of these leaning components, whilst the coefficient of coking capacity related the coal rank to the proportion of infusible components at that rank. Schapiro et al. [23,22] redefined these terms as the Composition-Balance index and the rank (strength) index, determined from a larger data set than that used by Ammosov et al. [21].

2.1.2. Applications and modifications of the Ammosov model and the Schapiro and Gray model

The definitions of leaning components is extensively used throughout Eastern European literature and Russian coal characterisation [24–27]. Despite the prevalence of use of the leaning index within models, there is a lack of consistency reported on the effect. Bulanov et al. [25] report different coefficients for the leaning components for the CRI of two batteries. Leaning components were reported as having a detrimental influence on coke properties by Mizin et al. [26] and a positive influence by Bukharkina et al. [28]. It is noted, however, that the first of these models is based on a very limited CSR range (CSR = 45.8–52.7) and low number of data points (n = 16), whilst the second reports a relatively poor fit between measured and predicted values (r^2 = 0.38), which may account for this discrepancy. Alternatively, the caking components are implemented in models, with a positive effect on coke properties reported [29]. Intuitively from the logic of Ammosov and Schapiro and Gray, there is an optimum amount of leaning components. Above this amount increasing caking components will increase strength and below this amount increasing leaning components will increase strength.

Modifications to the definition of the coefficient of coking capacity, one of the terms developed by Ammosov to account for variation of coke quality with rank, were made by Stankevich and co-workers to account for oxidation (also linked to weathering – see Section 4.6.2 for a discussion on weathering) and coal rank, typically described as a parabolic relationship between fusible components and vitrinite reflectance. This modified coefficient had inconsistent relationships reported with coke quality, including parabolic and linear, and negative and positive relationships associated with an increase [29–31].

Artser, Vents [24] implement a similar concept to that of Ammosov et al. [21], defining an additional function for the optimal proportion of leaning components derived from Ammosov and co-workers' tabulated data, finding a parabolic relationship linked to vitrinite reflectance. Similarly, an equation for the coking coefficient of a blend is presented, which utilises vitrinite reflectance and the sum of the leaning components. A relationship is fitted to CRI including parabolic terms for leaning index and coking coefficient.