Petrochemistry of Coal Ash Slags. 2. Correlation of Viscosity with Composition and Petrographic Class

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The Grand Forks Energy Research Center (GFERC) of the Energy Research and Development Administration has reactivated a fixed-bed slagging coal gasification pilot plant which was formerly operated by the Bureau of Mines. Design of the gasifier, the Bureau of Mines test results, and preliminary results from the ERDA program have been documented (1-4).

A detailed study of the slagging operation is one aspect of the current GFERC pilot plant program. The objective of this study is to develop accurate knowledge of the flow and heat transfer behavior of the slag, both to improve operation of the GFERC plant and to suggest design approaches for future generation gasifiers. One of the important parameters in this work is the slag viscosity.

The experimental determination of slag viscosity as a function of temperature is a difficult procedure. Consequently, many efforts have been made to develop an approach to calculate this relationship. The equations generally proposed incorporate one or more terms which are calculated from the slag composition.

The equation

$$\log_{10}\eta = \frac{10^7 M}{(T-150)^2} + C \qquad [1]$$

has been suggested in several publications (5-7) for calculating viscosity as a function of temperature. In this equation, T is expressed in degrees Centigrade, and η in poises. M and C are terms calculated from the slag composition, being functions of SiO_2, Al_2O_3, Fe_2O_3, and CaO content. Various equations have been proposed for calculating C and M. These equations differ slightly in the values of the coefficients of the composition terms. The work done by Watt and Fereday (6) is based on British coals, while that reported by the Institute of Gas Technology (7) is based on synthetic melts.

Attempts were made to use equation [1] for the calculation of viscosities of some lignite ash slags for which experimental viscosity data was available at GFERC. Both the Watt-Fereday method (5,6) and the modified equations suggested by Bomkamp (7) were used. A test temperature was selected from the center of the temperature range over which viscosity data was available at GFERC (8). Some of the results are given in Table 1.

TABLE 1. Calculated Values of Lignite Slag Viscosities.A/

Lignite Slag	Temperature	Method 1B/	Method 2C/	Expt'l Value
Baukol-Noonan	1175°	197	11,600	42
Indianhead	1260°	21	2,276	60
Velva	1385°	<1	1	350

A/ Sources and compositions of the coal ash slags are given in the appendix.

B/ Watt-Fereday Method. C/ Modified Watt-Fereday Method.

Since the results shown in Table 1 are clearly unsatisfactory, the development of additional modifications to equation [1] was undertaken. Since the GFERC gasification program will test a variety of Western lignite and subbituminous coals, it was desired to develop an equation applicable to the widest possible range of slag compositions. Viscosity-temperature data were available for slags having the range of compositions shown below.

TABLE 2. Range of Slag Compositions Used in GFERC Study

Component	Range, Pct	Component	Range, Pct
SiO_2	15-49	MgO	1-10
Al_2O_3	9-27	Na_2O	.3-12
Fe_2O_3	7-23	K_2O	.1-4
CaO	3-43		

Equation [1] was rewritten as

$$Y = MX + C$$

where $X = 10^7/(T-150)^2$ and $Y = \log_{10}\eta$. The experimental data were then used to compute values of M and C for each slag, using a standard linear regression computer program. The results are given in Table 3.

TABLE 3. Values of C and M Computed by Linear Regression

SlagA/	C	M
Baukol-Noonan	-1.2180	.3069
Bentinck	- .8604	.5851
Cronton-19B/	-1.2194	.5288
Cronton-27C/	- .9997	.5849
Dickinson	-4.1015	.5945
Disco	- .5266	.4240
Disco-FluxD/	- .8429	.2948
Indianhead	-4.0781	.7264
Thoresby	- .7840	.4892
Velva	-7.2934	1.4996

A/ Source and composition data is given in the appendix.
B/ 19 pct ash coal. C/ 27 pct ash coal.
D/ 3 lb. blast furnace slag added per lb. of ash.

The computed values of C and M were used as input data for a multiple linear regression analysis for the development of equations relating C and M to slag composition. Repeated computer trials failed to produce a satisfactory fit of the data. As a result, attention was then focused on performing regression analyses for slags only of a single petrographic class. (In this paper petrographic classifications and terminology refer to igneous rock petrography, rather than to coal petrography.)

The test slags were divided into two groups on the basis of similarity of composition: Baukol-Noonan, Disco-Flux, and Indianhead in the first group; and Bentinck, Cronton-19, Cronton-27, Disco, and Thoresby in the second. Detailed petrographic analyses were done for Indianhead and Thoresby slags, the compositions of which are given in the appendix. The petrographic classification was done by the C.I.P.W. method (9), following the procedure outlined by Johannsen (10). This procedure is a taxonomic method for comparing chemical analyses from a petrological aspect. The analytical data is recalculated in terms of a set of standard mineral molecules. Indianhead slag was found to be pyroxene normative and Thoresby to be feldspar normative.

Correlation coefficients were calculated between each of the major slag components and the values of C and M, for both classes of slag. The calculations were done using a standard linear correlation computer program. This work was done so that the results would serve as a guide to which slag components might best be used in a multiple regression analysis for developing equations to calculate C and M. The computed values of the correlation coefficients are given in Table 4.

TABLE 4. Linear Correlation Coefficients Between Slag Composition and Computed Values of C and M.

Component	Pyroxene-normative Slags		Feldspar-normative Slags	
	C	M	C	M
SiO_2	-.369	.444	.681	.094
Al_2O_3	.554	-.485	-.573	.570
Fe_2O_3	-.996	.999	-.019	-.512
CaO	.360	-.283	.168	.255
MgO	.209	-.129	-.495	.200
Na_2O	-.140	.059	.030	.140
K_2O	-.589	.521	-.760	.940

Multiple linear regression analysis of the feldspar normative group developed the following equations:

$$C = -4.5413 - .2158\ (K_2O) + .0883\ (SiO_2) + .0091\ (Al_2O_3) \quad [3]$$

$$M = 0.3676 + .0783\ (K_2O) - .0043\ (Al_2O_3) \quad [4]$$

In these equations the concentration terms use the actual weight percent values determined from the chemical analysis.

The viscosity-temperature relationship for Cronton-19 slag was calculated by substituting equations [3] and [4] into equation [1]. The appropriate analytical data for this slag are 3.5 pct K_2O, 43.6 pct SiO_2, and 24.6 pct Al_2O_3. Figure 1 shows the experimental (11) and calculated viscosity curves.

Although only limited data are available for the pyroxene normative slags, a regression analysis was done to fit C and M values to Fe_2O_3 content because of the high correlation between these parameters. Equations [5] and [6] resulted.

$$C = 0.8143\ (Fe_2O_3) - 4.8749 \qquad [5]$$

$$M = 0.1135\ (Fe_2O_3) - .5219 \qquad [6]$$

The viscosity-temperature curve for Indianhead slag (Fe_2O_3 = 11.0 pct) calculated from equations [5], [6], and [1], is given in Figure 2.

These results demonstrate that this approach produces improved results for the specific slags studied thus far. It is suggested that classification of slags by a petrographic procedure may be more useful than other methods for the production of viscosity effects.

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APPENDIX

Composition and Source Data for Slags Used in this Study

Slag:	Baukol-Noonan	Bentinck	Cronton-19	Cronton-27	Dickinson	Disco	Disco & Flux	Indian-head	Thorseby	Velva
Source:	North Dakota	British	British	British	North Dakota	Pennsyl-vania	A/	North Dakota	British	North Dakota
Rank:	Lignite	Bituminous	Bituminous	Bituminous	Lignite	Bituminous		Lignite	Bituminous	Lignite
Slag Analysis, wt. %	B/	C/	C/	C/	B/	B/	B/	B/	C/	B/
SiO_2	33.0	48.9	43.6	47.7	21.8	48.0	39.8	39.5	46.7	14.7
Al_2O_3	13.5	23.2	24.6	27.1	9.1	23.0	15.6	13.6	23.4	11.1
Fe_2O_3	7.3	6.6	17.4	11.8	23.1	18.5	7.2	11.0	6.9	6.7
CaO	14.5	10.5	3.5	2.7	18.4	3.3	27.2	17.9	8.4	43.3
MgO	4.4	1.6	2.3	1.9	7.2	1.0	6.6	5.3	2.9	10.1
Na_2O	12.1	1.7	0.8	0.5	0.6	0.3	0.4	6.6	2.4	4.4
K_2O	1.0	3.5	3.4	4.2	0.1	1.9	0.5	1.0	3.0	0.3

A/ Disco ash fluxed with 3 lb. blast furnace slag per lb. of ash.
B/ GFERC data.
C/ Data of Hoy, Roberts & Wilkins (11).

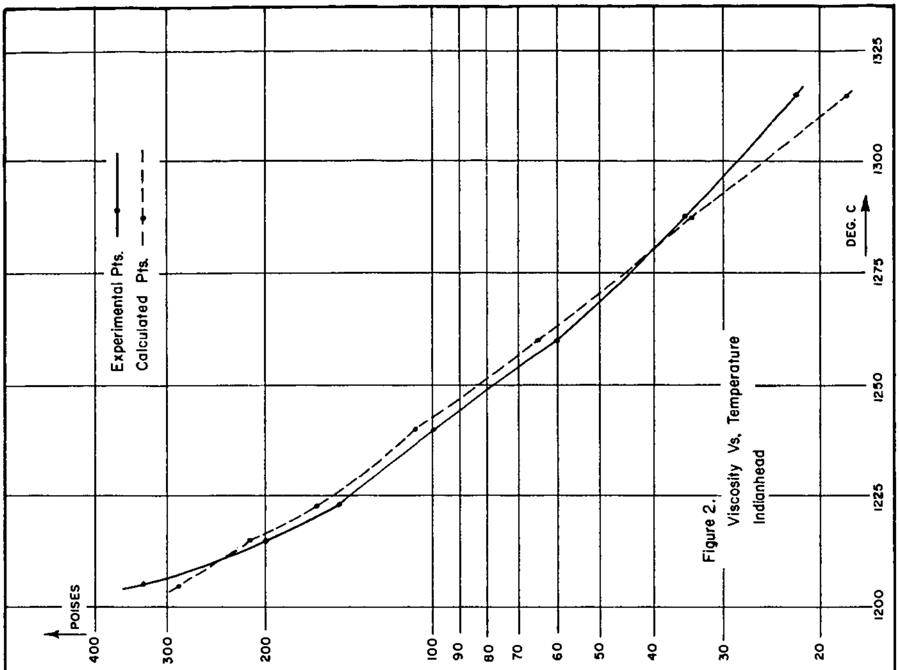

Figure 2. Viscosity Vs. Temperature Indianhead

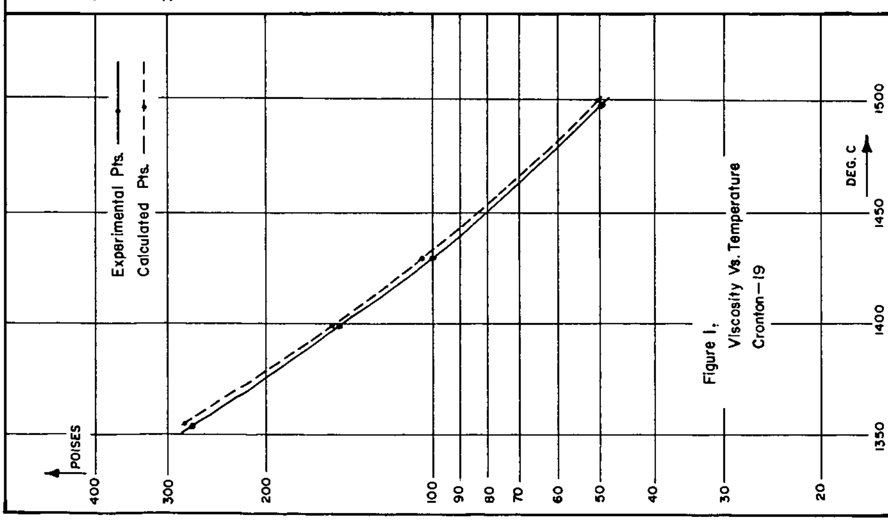

Figure 1. Viscosity Vs. Temperature Cronton—19