Slag/Seed Interaction in Coal-Fired MHD Generators

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An analytical investigation of slag/seed interaction phenomena in coal-fired MHD generators is presented. A two-dimensional boundary-layer model, including potassium seed mass transfer to the slag layer, was developed. Work on the chemistry of the seeded plasma/slag system performed in conjunction with the modeling approach is also discussed. The model is used to study slag/seed interaction effects on a 275 MW_{th} first-generation MHD power train. The simulations show that seed losses in the channel are small under normal operating conditions. The slag layer coating the walls, rather than the entrained droplets, is where most of the seed absorption takes place.

I. Introduction

A COAL-FIRED MHD open-cycle topping a conventional steam cycle can provide a way to achieve high efficiency in the production of electricity from the combustion of a fossil fuel. The combustion products of coal are rendered electrically conductive by seeding the flow with a readily ionizable material such as potassium.

As a result of combustion, mineral matter in coal is converted to molten slag. A portion of the slag is carried over from the combustor into the MHD channel and a liquid slag layer develops on the generator walls. The presence of the slag layer induces effects that can reduce the overall efficiency of the MHD plant. Slag (being mostly silica and alumina) combines with the potassium in the gas phase forming a chemical solution. Reduction of the seed (potassium and potassium compounds) concentration in the near-wall region leads to a decrease of the electron number density (and corresponding decrease in electrical conductivity), equivalent to an added voltage drop in the boundary layer. Because absorbed seed cannot be economically leached from the glass-like slag, the dissolved seed fraction is "lost" to the system (unavailable for reuse). Given the high cost of seed material, these losses should be minimized.[1]

The physicochemical mechanisms leading to the seed absorption by the slag and ensuing effects in the MHD generator are usually referred to as slag/seed interactions. Previous works in the field have been primarily concerned with the chemical aspects of the interaction. Research groups at Montana State University (MSU) and the National Bureau of Standards (NBS) embarked on projects aimed at measuring potassium partial pressures over MHD slags.[2-6]

Early attempts at quantifying the interaction effects predicted seed losses as high as 60%, raising concerns about the feasibility of operating slagging MHD ducts without almost complete slag rejection in the combustor.[7-9] These predictions contrasted with experimental evidence gathered at the University of Tennessee Space Institute (UTSI) facility, which suggested much lower seed loss rates.[7] The models used in those works were oversimplifications of the actual situation. Thermodynamic equilibrium was assumed and the slag phase was modeled as an ideal chemical solution. Mostinsky et al.[10] were the first to suggest that the seed absorption rate could not be predicted by means of equilibrium considerations and that transport mechanisms must be considered.

The first part of this paper presents an analytical model of slag/seed interaction phenomena in MHD channels. Two aspects of the interaction will be discussed: the chemistry of the slag solution including potassium and the transport phenomena controlling the rate of seed dissolution. The second part of the paper makes use of the model to predict slag/seed interaction effects in the channel of a 275 MW_{th} first-generation MHD power train.

II. Physicochemical Model of Slag/Seed Interactions

This section describes a model developed to study interaction effects in the MHD channel. The basic equations, a solution method, and the implicit assumptions behind it are summarized here. The complete modeling approach is described in greater detail in Ref. 11.

The chemical absorption of potassium by the slag layer is accompanied by physical processes that complicate the problem of calculating the amount of seed dissolved. Both phases (gaseous seeded plasma and liquid slag) are nonuniform systems. Velocity and temperature nonuniformities will develop in the flow, while the condensed slag will be mostly in the form of entrained droplets with a fraction depositing on the cold walls to form a slag layer (runoff).

To quantify the effect of slag-induced seed depletion, it is necessary to know the potassium concentration profile above the electrode wall. We can then calculate the boundary layer voltage drop, accounting for the reduced electron number density stemming from the potassium loss above the slag film. The model is schematically depicted in Fig. 1. A slag layer flows on the electrode walls and chemical equilibrium prevails at the interface (instead of throughout the system). Potassium must diffuse through a boundary layer before dissolving into the slag. The potassium concentration and temperature profiles, needed to calculate the voltage drop, are obtained as solutions to the two-dimensional boundary layer equations. Once the profiles are known, the integrated seed mass flux gives the total amount of potassium absorbed by the slag layer over the entire length of the channel.

Equations

Following the notation in general use, the boundary layer equations for a rectangular duct geometry can be written as follows.[12]

The continuity equation is

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \tag{1}$$

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where u and v are the time-averaged velocity components in the x and y directions, respectively. The momentum equation in the x direction is

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=-\frac{\mathrm{d}p}{\mathrm{d}x}+\frac{\partial}{\partial y}\left[\mu_{\mathrm{eff}}\frac{\partial u}{\partial y}\right]+(\boldsymbol{J}\times\boldsymbol{B})_x \tag{2}$$

where $(\boldsymbol{J}\times\boldsymbol{B})_x$ is the MHD body force per unit volume and μ_{eff} the effective (laminar plus turbulent) dynamic viscosity. The energy equation can be written as

$$\rho u\frac{\partial i^*}{\partial x}+\rho v\frac{\partial i^*}{\partial y}=\frac{\partial}{\partial y}\left[\left(\frac{k}{c}\right)_{\mathrm{eff}}\frac{\partial i^*}{\partial y}+\left(\mu_{\mathrm{eff}}-\left(\frac{k}{c}\right)_{\mathrm{eff}}\right)\frac{\partial}{\partial y}\left(\frac{u^2}{2}\right)\right]+S \tag{3}$$

where i^* is the stagnation enthalpy (thermal enthalpy plus kinetic energy) and $(k/c)_{\mathrm{eff}}$ the effective thermal diffusivity. The term S includes Joule heating in the plasma, radiation losses, and the work of the body force. The final equation is the diffusion equation for potassium atoms, which takes a form similar to the energy equation as

$$\rho u\frac{\partial m_{\mathrm{K}}}{\partial x}+\rho v\frac{\partial m_{\mathrm{K}}}{\partial y}=\frac{\partial}{\partial y}\left[\rho D_{\mathrm{K}}\frac{\partial m_{\mathrm{K}}}{\partial y}\right] \tag{4}$$

where m_{K} is the mass fraction and D_{K} the apparent binary diffusion coefficient of potassium species through the plasma. Since this equation is written for all potassium atoms regardless of chemical species in which they occur, no source term appears.

Before Eqs. (1-4) can be integrated, boundary conditions at the wall must be specified. The nonslip condition is used when solving for the velocity profile. For the energy equation, the temperature at the wall is specified along the channel. For the seed diffusion equation, neither a concentration nor a mass transfer can be specified a priori at the wall. The existence of chemical equilibrium for potassium is imposed at the slag/plasma interface. The boundary-layer equations were solved using a two-dimensional computer program STAN5[13] properly modified to allow for the specification of interfacial chemical equilibrium as wall condition.

Potassium Chemical Equilibrium at the Slag/Plasma Interface

A prerequisite for the solution of the boundary-layer equations is the determination of the interface equilibrium condition. That involves the solution of an entire problem in itself—calculation of the chemical composition of a two-phase system (seeded plasma and slag) in thermodynamic equilibrium. Of particular importance is the ability to predict the amount of potassium seed dissolved in the slag.

The approach taken in this work was to model the slag phase as a nonideal chemical solution composed of the basic oxides (SiO_2, Al_2O_3, CaO, and K_2O). The mathematical formalism of a nonideal condensed-phase was implemented in a computer code, called MQL, that can calculate the composition of a multiphase system when one or more of its phases are nonideal.[14]

Experimental thermochemical data are needed in order to model the nonideal solution. The basic form of the data is as potassium partial pressures and, as mentioned in the introduction, two sources are available—Montana State University[2-4] and the National Bureau of Standards.[5,6,8] It was observed that the measurements of partial pressures from these sources were in disagreement.[11,15] To gain confidence in the data being used, calculations were performed using the stoichiometric conditions corresponding to experiments in which the slag samples had been taken and analyzed for potassium content.[16] Excellent agreement between calculation and experiment was obtained when using the NBS data for coals from both the eastern and western United States.[17]

The chemical composition code can now be used to determine the equilibrium relation for potassium species at the

Table 1 Coal compositions, wt. %

Component	Western	Eastern
C	70	60
H	5	5
O	10	10
Moisture	5	5
Ash	10	20
Ash		
SiO_2	50	57
Al_2O_3	24	20
CaO	15	6
Fe_2O_3	6	15
MgO	5	2

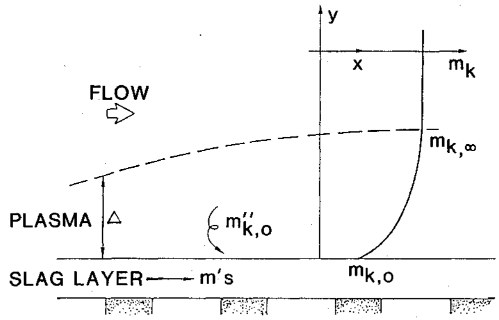


Fig. 1 Schematic of the problem. $\dot{m}_s'$ **= slag runoff, kg/m·s,** $m_{\mathrm{K},0}$ **= potassium mass fraction at the wall,** $m_{\mathrm{K},\infty}$ **= potassium mass fraction at the core,** $\dot{m}_{\mathrm{K},0}''$ **= potassium species mass transfer rate, kg/m²·s,** Δ **= concentration boundary-layer thickness, m, and** x,y **= coordinates, m.**

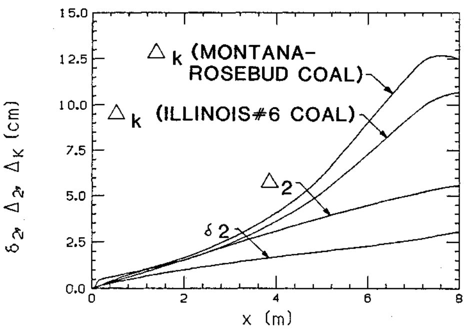


Fig. 2 Momentum δ_2**, enthalpy** Δ_2**, and potassium concentration** Δ_{K} **boundary-layer thickness (the latter for base cases with Montana-Rosebud and Illinois No. 6 coals).**

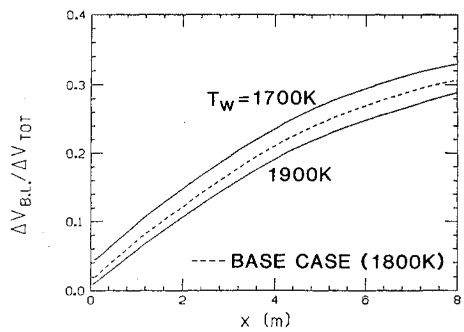


Fig. 3 Fraction of total voltage drop due to boundary layer, effect of wall temperature.

Table 2 Coefficients for Eq. (5)

Coefficient	Montana-Rosebud coal	Illinois No. 6 coal
a	629.3	9282
b	0.2428	0.1472
k	27,449	33,771
n	$0.55+0.5(\Phi-1)$	$0.55+0.5(\Phi-1)$
m	0.69 (for $\Phi<1$)	0.63 (for $\Phi<1$)
m	3.36 (for $\Phi>1$)	2.65 (for $\Phi>1$)
	Range	$0.8<p<10$ atm $1700<T<2300$ K $0.85<\Phi<1.15$ $1<r<1.7$ $0<m_{K20}<45\%$

slag/plasma interface. Such a relation is a thermodynamic property of the interface and does not depend on the relative amount of slag present in the system (corroborated by running the code considering different slag mass loadings). All calculations were performed for Montana-Rosebud (western) and Illinois No. 6 (eastern) coals. The compositions used in the runs are given in Table 1. Each type has been widely used in the MHD and coal technology literature as standard for western (high-calcium) and eastern (low-calcium) coal.

For each type of coal, parametric variations in pressure, temperature, oxygen enrichment, and stoichiometric ratio were considered. A curve-fitted equation was developed to correlate the interfacial gas-phase mass fraction of potassium and the K_2O mass fraction in the slag. The former reflects the total amount of potassium (in the form of various species) available in the gas phase (typically 1% under nonslagging conditions), while the latter corresponds to a common way of expressing the slag potassium content.

The correlation developed takes the form

$$m_{K,0}=a\left(\frac{r}{p}\right)^n\Phi^m\exp\left(-\frac{k}{T}\right)\exp\left(bm_{K_2O}\right) \tag{5}$$

where

a,b,m,n	= const
k	= const, K
$m_{K,0}$	= plasma potassium mass fraction
m_{K_2O}	= mass fraction of K_2O in slag, %
p	= pressure, atm
r	= degree of enrichment, vol% 0_2 in oxidant/21
T	= temperature, K
Φ	= (fuel air)/(fuel/air)$_{stoich}$

The numerical values of the coefficients in Eq. (5) for both types of coal and the ranges of applicability are given in Table 2. The expression developed fits the computational data with an average error of only 2% over the entire range and with a maximum deviation of 10%.

Assumptions of the Model

This section will briefly summarize the main hypotheses introduced when solving the system of boundary-layer equations. First, the validity of the interfacial equilibrium hypothesis was examined. It was shown that typical seed mass transfer rates are small enough for the assumption to hold.[17,18]

As noted in Fig. 1, it was assumed that only the slag layer absorbs potassium from the gas phase. The model does not include any interaction of the seed with the entrained droplets. This implies that the slag droplets deposit by diffusion on the walls without reaching chemical equilibrium with their surroundings. Chemical equilibration times were compared with deposition times and the hypothesis was found to be reasonable. Furthermore, the other limiting case was considered: that the droplets are in thermal and chemical equilibrium as they traverse the boundary layer (thermal equilibrium itself is a good approximation under most circumstances[11]). Calculations presented in the next section indicate that, even in the chemical equilibrium case, the slag droplets are not good potassium absorbers. Composition calculations showed that slag above 2000 K does not dissolve a significant amount of K_2O, meaning that droplets entrained in the flow will not absorb seed until they are very close to the wall. The practical implication is that even if all slag droplets reached chemical equilibrium with the gas phase, the main seed depletion mechanism involves its dissolution into the liquid slag layer in contact with the relatively cold walls.

Table 3 Summary of MHD power train specifications

Coal thermal input	275 MW_{th}
Oxidizer	Enriched air, 35% vol. O_2
Seed concentration	1% by mass K, as K_2CO_3
MHD channel	
Configuration	Faraday (diagonal wall)
Dimensions	8 m (length) 0.434×0.434m (inlet) 0.802×0.802m (exit)
Subsonic flow	Inlet Mach number: 0.885
Peak magnetic field	6T
Channel inlet pressure	3.3 atm
Channel exit pressure	1 atm
Inlet temperature	2660 K
Load parameter	0.652

The slag layer itself was assumed to have a uniform potassium content. This is equivalent to the limiting case of infinitely fast diffusion in the liquid phase. According to experimental results,[19] this is a reasonable assumption. It may not be valid at very low temperatures (very high viscosities). Slow diffusion in the liquid phase has the effect of an added resistance to the migration of potassium species from the gas phase to the molten slag. As a consequence, the present model gives "worst case" results.

The solution of the boundary-layer equations requires the specification of a turbulence closure in order to evaluate the effective transport properties. Since the problem corresponds to an internal flow, a constant eddy diffusivity was assumed.[13] Once the effective viscosity is known throughout the flow, the concepts of effective Prandtl and Schmidt numbers are used to evaluate the thermal and mass diffusivities. The turbulent Schmidt number was taken to be unity.

III. Modeling of a 275-MW_{th} First-Generation MHD Power Train

The model described in the previous section was used to study slag/seed interaction phenomena and their effects on a 275 MW_{th} MHD power train. The channel modeled corresponds to one of the conceptual designs considered in Ref. 20 (a subsonic channel designated design case D, pp. 2-98 and 2-104). The specifications of that channel are contained in Table 3.

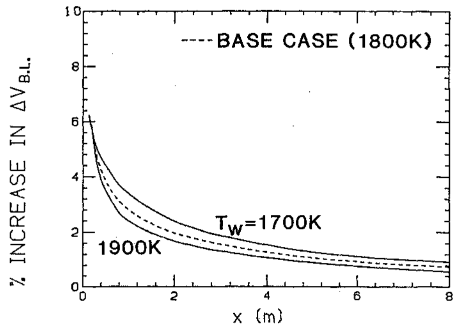
Parametric Studies

The objectives of the present study are not only to assess the importance of slag/seed interaction effects, but also to identify the physical variables that control the severity of these effects. Table 4 summarizes the parametric variations considered in the channel simulations.

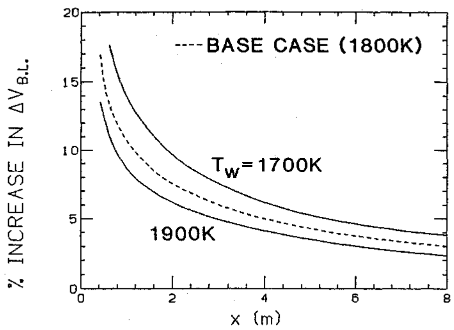
All calculations were performed for both western (Montana-Rosebud) and eastern (Illinois No. 6) slag. The former, having a higher calcium content exhibits less tendency to absorb potassium. For each coal type, the parametric studies were organized around a base case. The slag mass flow rate (kilogram per second per meter of channel

Table 4 Parameters in MHD channel simulation

Coal type	Montana-Rosebud, Illinois No. 6
Slag runoff	70% ash rejection, no ash rejection (base case), twice the runoff of base case
Slag layer temperature	1700, 1800 (base case), 1900 K
Equivalence ratio	0.9, 1.0 (base case), 1.1
Oxidizer	21, 30, 35% (base case)



a) Montana-Rosebud coal.



b) Illinois No. 6 coal.

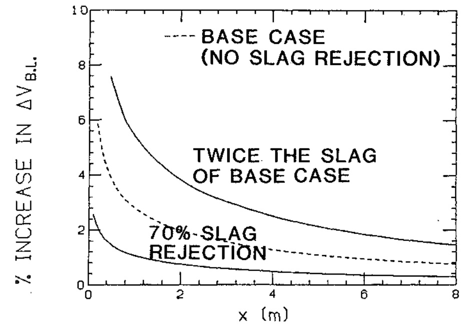
Fig. 4 Increase in boundary-layer voltage drop due to seed loss, effect of slag temperature.

perimeter) of the base case corresponds to a situation of no slag rejection in the combustor. The mass flow rate of the slag layer at the channel entrance (due to spilling from the combustor plenum into the channel) was taken to be 2% of the total amount of slag entering the combustor, with an additional 5% assumed to have deposited on the layer by the exit of the duct.[16] The total slag input to the combustor is 1 kg/s for the western coal case, and 2 kg/s for the eastern. In addition, 30% and twice the slag layer mass flow rate of the base case were considered. The latter could correspond to conditions of heavy spilling from the slag pool in the combustor, account for uncertainties in the deposition theory predictions, or asymmetry between top and bottom walls due to gravitational effects.

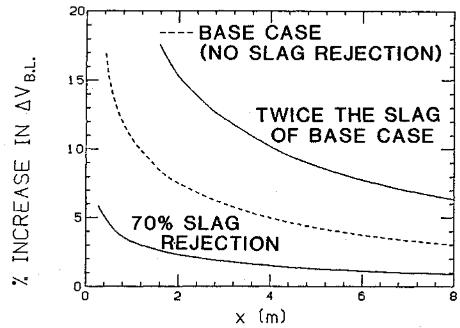
The slag layer temperature for the base case is 1800 K, with a ±100 K variation considered. The effect of stoichiometry was investigated, with the values of equivalence ratio and oxygen enrichment given in Table 4.

Results

Selected results from the channel simulation are now presented in graphical form. Figure 2 shows the momentum and enthalpy thicknesses[11,12] along the channel, as well as the potassium concentration thickness Δ_K defined in an analogous fashion. Δ_K is an indication of seed depletion in the gas phase, being the distance used to substitute the actual concentration profile by its equivalent two-layer model, an undepleted core region, and a layer of thickness Δ_K where the concentration is uniform and equal to the value at the wall.



a) Montana-Rosebud coal.



b) Illinois No. 6 coal.

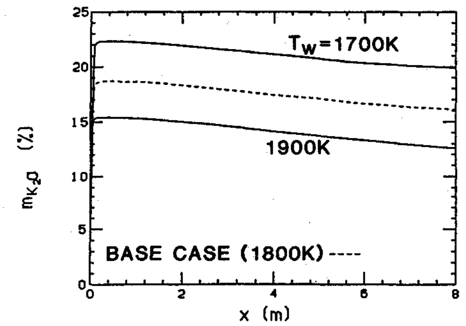
Fig. 5 Increase in boundary layer voltage drop due to seed loss, effect of slag runoff (slag layer mass flow rate).

The effect of slag/seed interaction on electrical performance can be best assessed through the boundary layer voltage drop. Figure 3 shows the percentage of total voltage drop confined within the boundary layer. In this work, the term voltage drop refers to the purely resistive loss due to the plasma electrical resistivity; no velocity gradient effects are included so as to better isolate the impact of seed depletion on electrical performance. The presence of the slag layer induces a depletion of seed near the electrodes, locally increasing the electrical resistivity. The resulting increase in boundary-layer voltage drop is shown in Figs. 4 and 5, where the parameters are the layer temperature and mass flow rate, respectively.

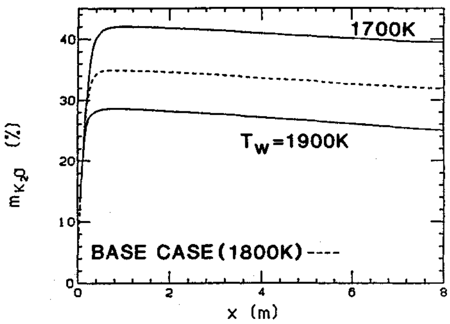
The slag K_2O content as the layer develops along the channel is calculated by simultaneously solving the mass diffusion equation and a potassium mass balance for the slag layer. Figure 6 shows that the layer starts forming and its potassium content rapidly increases, approaching thermodynamic equilibrium. The slight decrease along the channel is due to the drop in pressure as the gas flows down the MHD duct. Because of the interfacial equilibrium hypothesis, knowledge of the slag layer potassium content provides the gas-phase seed mass fraction at the interface [see Eq. (5)]; a typical plot is shown in Fig. 7. Note the sharp reduction from the core value of 1% by mass in the first section of the channel. The reduction in seed concentration at the electrode wall is significant for cases of heavy slagging.

All of the results shown thus far have been axial distributions of various physical parameters. Also of importance is the total, or integrated, mass of potassium seed dissolved in the slag layer as it leaves the channel. This quantity, expressed as a fraction of the total seed input, is shown in Figs. 8 and 9 as a function of layer temperature and runoff. Note that the seed loss is about 5% for the base case (no slag rejection) of eastern coal and under 5% for the western coal, even for cases of enhanced layer mass flow rate.

Finally, Fig. 10 shows potassium concentration profiles evolving along the channel. The profiles, obtained from the solution to the boundary-layer equations, start as a uniform



a) Montana-Rosebud coal.



b) Illinois No. 6 coal.

Fig. 6 Slag potassium mass fraction, effect of layer temperature.

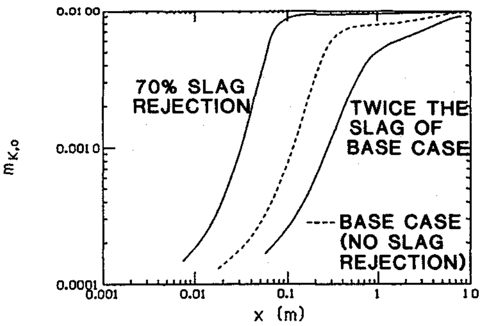


Fig. 7 Potassium mass concentration at the gas/slag interface, effect of slag runoff (slag layer mass flow rate), Illinois No. 6 coal.

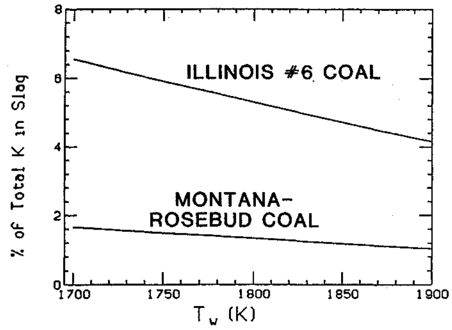


Fig. 8 Fraction of total potassium absorbed by the slag layer, effect of temperature.

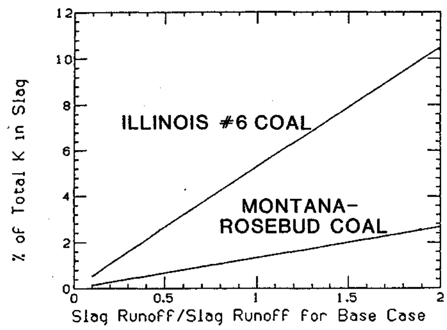


Fig. 9 Fraction of total potassium absorbed by the slag layer, effect of slag runoff (slag layer mass flow rate).

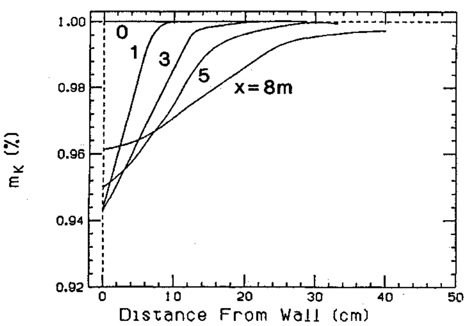


Fig. 10 Potassium concentration profiles, base case, Illinois No. 6 coal (parametric on x, distance along the channel).

distribution (1% by mass of potassium) at channel entrance and as the slag layer absorbs potassium they develop following a typical diffusional pattern.

No results showing the influence of stoichiometry are presented here. That influence is, in general, negligible. Only the amount of K_2O in the slag is slightly affected by the value of equivalence ratio.

The model was also used to investigate further consequences of the slag/seed interaction. All calculations described in this section assumed a constant slag layer temperature, irrespective of slag K_2O content. Actually, the layer will reach an equilibrium temperature depending on a balance between heat transfer and the viscosity (and thickness) of the layer. The slag viscosity is, in turn, a strong function of potassium content. It is an observed fact that the slag layer thickness and temperature change drastically when an MHD channel is changed from seeded to unseeded run conditions. Koester et al.[19] have pointed out the somewhat disconcerting fact that seemingly similar experimental arrangements can lead to opposite conclusions. Experiments conducted at Stanford showed an increase in slag layer temperature once potassium seed was added to the flow,[16] while similar experiments at AVCO led to the opposite effect.[21] No satisfactory explanation has been proposed to this paradox.[19] Data on the physical properties of potassium-seeded slags are rather scarce; however, detailed viscosity measurements on sodium-seeded slags have been made.[22] The viscosity exhibits a maximum for a sodium oxide/alumina ratio of unity. Since the layer temperature is related to its viscosity, it is possible then for the layer equilibrium temperature to increase or decrease, depending on the amount of potassium dissolved by the slag (a function of the mass transfer rate from the gas phase) and its alumina content. To test this hypothesis, the viscosity-temperature data[22] were implemented in the set of equations described in Sec. II. The base cases of eastern and western coals were run again, but now allowing for a variable slag temperature as the layer absorbs potassium and changes its viscosity. The results suggest the validity of the proposed mechanism; Fig. 11 shows the temperature variation of the slag layer after entering the channel at 1800 K. Given the different ash compositions and identical flow conditions, the slag layer temperature for Montana coal equilibrates above the initial temperature. For the Illinois coal, the temperature starts increasing as the slag absorbs potassium, until the ratio of K_2O to Al_2O_3 becomes unity. At that point, further absorption of seed induces a reduction in viscosity and

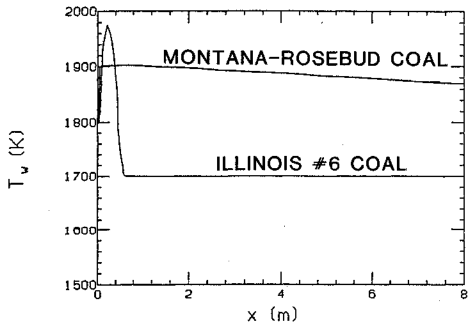


Fig. 11 Wall (slag layer) temperature for base cases including effect of slag potassium content.

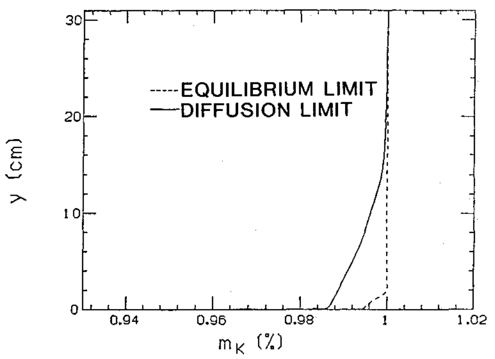


Fig. 12 Potassium concentration profile at $x=4$ m for Montana coal base case: comparison of diffusion (solid line) and equilibrium limits (dashed line).

temperature, leading to higher absorption rates of K_2O. The phenomenon obviously becomes unstable and the layer temperature decreases until equilibrated by some other mechanism (the minimum temperature was arbitrarily taken to be 1700 K).

As mentioned in Sec. II, one of the assumptions of the present model is that only the slag layer is absorbing seed from the gas phase. This is obviously a limiting case in which the entrained slag droplets do not reach chemical equilibrium with the gas phase, the rate limiting mechanism for seed absorption being gas-phase diffusion. The opposite limit was also studied, when the slag droplets are always in chemical equilibrium. In that case the slag potassium content is entirely determined by the local temperature and there is no need to solve the potassium species diffusion equation [Eq. (4)]. Gas-phase seed concentration profiles can be calculated using a potassium atom balance and the equilibrium composition code. Figure 12 shows a comparison of such an equilibrium profile (dashed line) with that obtained when diffusion toward the slag layer is taken into account. Note that in the latter case the seed depletion is more pronounced. In conclusion, even if the slag droplets reached chemical equilibrium as they traverse the boundary layer, they do not substantially absorb potassium. That is because the temperature does not decrease below 2000 K until the droplets are very near the wall (in the laminar sublayer).

IV. Summary and Conclusions

This paper has presented an analytical investigation of slag/seed interaction phenomena in coal-fired MHD generators. A review of the literature showed that certain aspects of the slag/seed interaction problem have not been adequately addressed before. In particular, no satisfactory model had been developed to predict the slag-induced seed loss in an MHD channel, or to assess the effect of boundary-layer seed depletion on voltage drops.

An approach based on the solution of the two-dimensional boundary-layer equations was developed. The potassium species diffusion equation was included in the system, using interfacial equilibrium as the wall condition. Chemical calculations, based on a nonideal solution model for the slag, were performed in support of this modeling approach. Good agreement between predicted slag compositions and experimental analyses was obtained when using thermochemical data from the National Bureau of Standards. The chemical calculations were extended to develop a generalized equilibrium equation for the slag/potassium-seeded plasma system.

The model was used to predict slag/seed interaction effects on a 275 MW_{th} first-generation MHD power train. Parametric studies were performed, showing that slag layer temperature and slag runoff are the most important parameters. Stoichiometry has almost no influence in the predicted effects.

With the exception of the channel entrance region, the effects of seed depletion on generator electrical behavior are small. The total seed loss was shown to be under 5% for Montana-Rosebud coal and about 5% for Illinois No. 6 coal and no ash rejection.

The slag layer (in contact with the cold walls) is the main mechanism for seed absorption. Slag droplets, at the higher gas temperatures, are not effective at dissolving potassium, even though they present a high surface/volume ratio. This observation has consequences in the design of MHD combustors; the key parameter is not the achievable slag rejection rate, but rather the fraction of slag that will reach the channel walls. Thus, avoiding slag overflow of the combustor is of particular importance and should be considered in addition to the slag rejection rate.

Acknowledgment

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