HEAT TRANSFER INCLUDING RADIATION AND SLAG PARTICLES EVOLUTION IN MHD CHANNEL-I

MASTER

by

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HEAT TRANSFER INCLUDING RADIATION AND
SLAG PARTICLES EVOLUTION IN MHD CHANNEL-I*Kwan H. Im and R. K. Ahluwalia
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Accurate estimates of convective and radiative heat transfer in the magnetohydrodynamic channel are provided. Calculations performed for a base load-size channel indicate that heat transfer by gas radiation almost equals that by convection for smooth walls, and amounts to 70% as much as the convective heat transfer for rough walls. Carbon dioxide, water vapor, and potassium atoms are the principal participating gases. The evolution of slag particles by homogeneous nucleation and condensation is also investigated. The particle-size spectrum so computed is later utilized to analyze the radiation enhancement by slag particles in the MHD diffuser. The impact of the slag particle spectrum on the selection of a workable and design of an efficient seed collection system is discussed.

Nomenclature

A	cross-sectional area
B, E, J	magnetic field, electric field and current density
h, u, v	enthalpy and flow velocities
$I_{b\gamma}, I_{w\gamma}$	black body intensity and its value at wall temperature
J	nucleation rate
Kn, Kn_v	Knudson number of gas and vapor
k	Boltzmann constant
$m_c, \hat{v}$	mass and volume of a condensable molecule
N, N_0	total number density and its value at channel inlet
n	distribution function
p, p_v	pressure of gas and vapor
$\dot{q}_c, \dot{q}_{rs}$	convective and radiative flux at wall
$\dot{q}_r$	radiation flux
$\dot{r}$	growth rate
r, $\bar{r}$	particle radius and average size
R, R_v	gas constants for combustion products and slag vapor
T, T_s	gas and particle temperatures
$\langle u \rangle$	average velocity
W	channel width
x, y, z	Cartesian coordinates
δ	boundary layer thickness
ρ, ρ_g, ρ_v	density of gas, liquid slag and slag vapor
τ_{xy}, τ_s	shear stress and its value at wall
τ, τ_0	optical thickness and its value at wall
μ_{eff}	effective viscosity
μ	cosine of cone angle
γ	ratio of specific heats
κ, κ_v	spectral absorption coefficient
λ	wavelength
ϵ_w	wall emissivity
σ_w	surface tension
σ_e	electrical conductivity

I. Introduction

An accurate knowledge of heat transfer in MHD channels is required for proper selection of material for channel walls, for designing a wall cooling system, and for optimal integration of MHD topping cycle with the steam bottoming plant. In almost all of the studies performed to date, contribution of radiation to heat transfer has been omitted in calculations of electrodynamics and the flow field in MHD channels. This omission is probably justifiable for small experimental channels where the optical beam length is small enough to make the gas radiation a second-order effect. For large base load-size channels, it may be anticipated that the heat transfer by convection will exceed that by radiation at the front end of the channel, where the boundary layer is thin. As the flow proceeds downstream and the boundary layer grows, convective heat flux drops off rapidly. The radiative flux diminishes less rapidly, because the increase in beam length, resulting from channel divergence, will partly compensate for the drop in temperature. Thus, it is conjectured that, at the back end of the channel, the heat flux by radiation may be as high as, or even higher than that by convection. Although the total heat flux will decrease along the length of the channel, a significant heat transfer occurs at the back end, where the surface area for convection and volume for radiation are highest. An approximate analysis of Ref. 1 bears out the validity of this conjecture. The present study was undertaken to furnish accurate estimates of the total heat transfer rate (including radiation) in MHD channels.

In order to calculate simultaneously the heat transfer by both convection and radiation, the quasi-three-dimensional model of Ref. 2 is extended in Part A to include a term for gradient of radiant heat flux and an explicit term for radiative heat transfer to the sidewalls of the channel in the energy equation. The radiation terms are calculated by solving the radiation transport and gas dynamic equations concurrently. The principal gases contributing to radiation are water vapor and carbon dioxide, formed by combustion of fuel, and potassium atoms, formed as a result of seeding the combustion products with aqueous potassium carbonate. The sample calculations performed herein for a representative base load-size channel confirm that the heat transfer by radiation is as high as that by convection when the channel walls are smooth; when the walls are rough, nearly 70% as much heat is transferred by radiation as by convection.

From the coal-fired MHD combustors, whether linear-can or swirl-flow type, the vaporized ash and at least some of the unvaporized ash particles will flow into the MHD channel. As the gas cools down in the MHD channel from the combined effects of power extraction and heat loss, the slag vapor retention capability of the gas decreases. At some point, the supersaturation ratio attains the

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critical value at which homogeneous nucleation of slag vapor ensues. Homogeneous nucleation is a kinetic process resulting from the collisions of monomers, some of which collision may lead to cohesion, forming n-mers; the activation energy to be overcome for cohesion to occur is the surface tension energy. Paralleling the homogeneous nucleation process of slag vapor removal is the direct condensation (heterogeneous nucleation) of vapor on the surface of the slag particles already present. The final size and number density distribution of slag particles evolve as the homogeneous and heterogeneous nucleation mechanisms compete to strip the gas of slag vapor; the former mechanism forms new particles, whereas, the latter tends to restrict the population growth by condensing vapor on the particles.

An analysis has been conducted, in Part B, to determine the slag particle spectrum evolving in the MHD channel. The spectrum information is used in a following study (see Ref. 3) to quantify the enhancement of radiative heat transfer by slag particles in the MHD diffuser. There are several reasons for the demand for accurate information about the spectrum of particle sizes. For example, it is possible that the slag particles may act as a strong electron sink, by providing sites for electron-ion recombination with attendant loss in electrical conductivity of the plasma. This possibility is strongest at the back end of the channel, exactly where it is difficult and crucial to maintain high electrical conductivity. Also, for environmental, as well as economic reasons, the seed injected in the combustor to provide free electrons must ultimately be recovered from the gas exiting the diffuser. The slag particle spectrum information is basic to the selection of a workable and efficient design for a seed recovery system. This aspect of the problem is more fully discussed elsewhere in the paper.

II. Part A. Convective and Radiative Transfer in MHD Channel

In formulating a flow field model, the approach advocated in Ref. 2 has been followed. The model is constructed by partially integrating the gas dynamic equations in the sidewall direction. This procedure leads to a set of quasi-three-dimensional equations, in which the displacement effects caused by the sidewall boundary layers enter through the boundary layer quantities characterizing the flux deficit: displacement thickness in the continuity equation, momentum thickness in the momentum equation, and enthalpy thickness in the total energy equation. Explicit terms also appear to account for friction and heat transfer on the sidewalls. This procedure presents the advantage of having to solve the one-dimensional (radiation exchange in the axial direction is negligible) radiation transport equation, yet the procedure is globally exact.

Governing Equations

The gas dynamic equations given below differ from those of Ref. 2 because of the inclusion of radiation terms in the energy equation.

$$\frac{\partial}{\partial x} [\rho u (W - 2\delta_{1s})] + \frac{\partial}{\partial y} [\rho v (W - 2\delta_{1s})] = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial}{\partial x} [\rho u u (W - 2\delta_{2s})] + \frac{\partial}{\partial y} [\rho u v (W - 2\delta_{2s})] \\ = -W \frac{\partial p}{\partial x} + W \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial u}{\partial y}) - 2\tau_s + \int_0^W J_y B_z dz \end{aligned} \quad (2)$$

$$W \frac{\partial p}{\partial y} = - \int_0^W J_x B_z dz \quad (3)$$

$$\begin{aligned} \frac{\partial}{\partial x} [\rho u (h + \frac{1}{2} u^2) (W - 2\delta_{3s})] + \frac{\partial}{\partial y} [\rho v (h + \frac{1}{2} u^2) \\ (W - 2\delta_{3s})] = W \frac{\partial}{\partial y} (k_{eff} \frac{\partial h}{\partial y}) + W \frac{\partial \dot{q}_r}{\partial y} + W \frac{\partial}{\partial y} (u \tau_{xy}) \\ - 2(\dot{q}_c + \dot{q}_{rs}) + \int_0^W (J_x E_x + J_y E_y) dz \end{aligned} \quad (4)$$

Where the subscript s denotes sidewall direction, and δ_1 , δ_2 , δ_3 are, in order, displacement momentum, and enthalpy thicknesses, defined for convenience as,

$$\delta_{1s} = \int_0^{\delta_s} (1 - \frac{\rho u}{\rho_c u_c}) dz \quad (5)$$

$$\delta_{2s} = \int_0^{\delta_s} (1 - \frac{\rho u^2}{\rho_c u_c^2}) dz \quad (6)$$

$$\delta_{3s} = \int_0^{\delta_s} [1 - \frac{\rho u (h + \frac{1}{2} u^2)}{\rho_c u_c (h_c + \frac{1}{2} u_c^2)}] dz \quad (7)$$

The gradient of the radiant heat flux is given by the following integral.

$$\frac{\partial \dot{q}_r}{\partial y} = 4\pi \int_0^\infty \kappa_v (I_{bv} - \frac{G_v}{4\pi}) dv \quad (8)$$

where G_v is the incident radiation defined as

$$G_v(y) = 2\pi \int_{-1}^1 I_v(y, \mu) d\mu \quad (9)$$

and I_v , the spectral radiation intensity, is a solution of the one-dimensional transport equation:

$$\mu \frac{dI_v}{dy} + \kappa_v I_v = \kappa_v I_{bv} \quad (10)$$

To expedite the numerical solution, a symmetry about the channel centerline ($y = 0$) is assumed. This assumption is neither crucial nor overly restrictive. Being singular at $\mu = 0$, Eq. (10) is decomposed into two regions $\mu > 0$ and $\mu < 0$. The solutions in the two regions are:

$$I_v^+(\tau, \mu) = I_v^+(0, \mu) e^{-\tau/\mu} + e^{-\tau/\mu} \int_0^\tau e^{\xi/\mu} I_{bv} d\xi \quad \mu > 0 \quad (11)$$

and

$$I_v^-(\tau, -\mu) = I_v^-(0, -\mu) e^{\tau/\mu} + e^{\tau/\mu} \int_0^\tau e^{-\xi/\mu} I_{bv} d\xi \quad \mu > 0 \quad (12)$$

Applying the two boundary conditions,

$$I_v^+(0, \mu) = I_v^-(0, -\mu) \quad \mu > 0 \quad (13)$$

$$I_v^-(\tau_0, -\mu) = \epsilon_w I_{wv} + (1 - \epsilon_w) I_v^+(\tau_0, \mu) \quad \mu > 0 \quad (14)$$

(specularly reflecting wall)

 $I_v^+(0, \mu)$ can be determined as,

$$I_v^+(0, \mu) = \left\{ \epsilon_w I_{wv} - \int_0^{\tau_0} d\xi \left[\exp\left(-\frac{\tau_0 - \xi}{\mu}\right) - (1 - \epsilon_w) \exp\left(-\frac{\xi - \tau_0}{\mu}\right) \right] I_{bv} \right\} / \left[\exp\left(-\frac{\tau_0}{\mu}\right) - (1 - \epsilon_w) \exp\left(-\frac{\tau_0}{\mu}\right) \right] \quad (15)$$

In terms of I^+ and I^- , the incident radiation is:

$$G_v = \int_0^1 [I_v^-(\tau, -\mu) + I_v^+(\tau, \mu)] d\mu \quad (16)$$

With the help of the above equation, the gradient of the radiant heat flux can be determined from Eq. (8). Although wall heat flux can be calculated by integrating the gradient, it is obtained more easily from the following equation:

$$\dot{q}_{rs} = \int_0^\infty d\nu \int_0^1 [I_v^+(\tau_0, \mu) - I_v^-(\tau_0, \mu)] \mu d\mu \quad (17)$$

This completes the solution.

Turbulence Model

The mixing length type turbulence model developed by Ahluwalia and Doss² for flow and heat transfer on smooth as well as rough surfaces is employed in the present work. This model incorporates the effects of compressibility, pressure gradient, and viscous damping on the momentum and enthalpy mixing lengths. The turbulence model has been validated by comparing its predictions of skin friction and heat transfer with the experimental measurements reported in the literature.

Electrical Model

Strictly speaking, the electrical field, E , and the current density, J , must be obtained by solving the Maxwell equations. The solution is slow and lengthy and provides greater details of electrical fields than can be realistically used in the overall channel performance computations. A simpler recourse is to invoke an "infinitely-fine electrode segmentation" assumption. Under this assumption, $E_x(x)$, $J_y(x)$, $E_y(x, y)$, and $J_x(x, y)$ can be determined from the Ohm's law; Maxwell equations are obeyed in a global sense only. For a Faraday configuration, the following electrical solution can be derived:

$$J_y = \frac{\langle u \rangle B (\langle K \rangle - 1)}{\frac{1 + \beta^2}{\sigma_e} - \frac{\langle \beta \rangle^2}{\langle \sigma_e \rangle^2}}$$

$$E_x = \frac{\langle \beta \rangle}{\langle \sigma_e \rangle} J_y$$

$$E_y = uB - \beta E_x + \frac{1 + \beta^2}{\sigma_e} J_y$$

and

$$J_x = \sigma_e E_x - \beta J_y$$

where $\langle K \rangle$ is the average load factor ($\epsilon \langle E \rangle / \langle u \rangle B$) and $\langle \rangle$ denotes a quantity averaged in the electrode wall direction.

Radiation Properties

Carbon dioxide, water vapor, and potassium atoms are considered to be the principal participating gases. The spectral absorption coefficients for carbon dioxide and water vapor are evaluated from the exponential wide-band model⁴. For atomic potassium, effective absorption is assumed to occur in the range $7465 < \lambda (A^\circ) < 8199$. The following correlations, presented in Ref. (5), are used to calculate the absorption coefficients ($\kappa, 1/cm$) of atomic potassium in this range as a function of the potassium number density ($N_k, \#K/m^3$). Near the two resonant doublets, the broadening is assumed to be of Lorentzian form in the present calculations.

$$\frac{\kappa_{\lambda}}{N_k} = 2 \times 10^{-18} \left(\frac{100}{\lambda - 7699} \right), \quad 7710 < \lambda < 8199 \text{ \AA} \text{ (data)}$$

$$\frac{\kappa_{\lambda}}{N_k} = \frac{6 \times 10^{-15}}{(\lambda - 7655)^2 + 100}, \quad 7665 < \lambda < 7710 \text{ \AA} \text{ (assumed)}$$

$$\frac{\kappa_{\lambda}}{N_k} = \frac{1.24 \times 10^{-15}}{(\lambda - 7665)^2 + 206.9}, \quad 7640 < \lambda < 7665 \text{ \AA} \text{ (assumed)}$$

$$\frac{\kappa_{\lambda}}{N_k} = 8.0 \times 10^{-18} \left(\frac{30}{7665 - \lambda} \right)^{1.2}, \quad 7564 < \lambda < 7640 \text{ \AA} \text{ (data)}$$

$$\frac{\kappa_{\lambda}}{N_k} = 8.0 \times 10^{-18} \left(\frac{200}{7665 - \lambda} \right)^{1.5}, \quad 7640 < \lambda < 7465 \text{ \AA} \text{ (data)}$$

Numerical Solution

The gas dynamic equations, Eqs. (1) - (4), are transformed into Von Mises space and finite-differenced by an implicit procedure with nonlinear terms locally linearized. The algebraic equations in the resulting tridiagonal set are easily inverted. The radiation terms in the energy equation are treated as source terms and evaluated for a temperature distribution prevailing at the preceding step. For accurate spectral integration, the integration domain (200-15000 cm^{-1}) is divided into 7 bands. Integration over these bands is carried out by adopting a 16-point Gaussian quadrature scheme. Spectral integration is a slow and tedious process and the computing cost would be prohibitive if the radiation source terms were evaluated at each marching step. Fortunately, those terms vary rather slowly along the axial direction and, therefore, need not be updated at each station. Some numerical experimentation was conducted, to determine how infrequently the radiation terms can be updated without incurring a noticeable loss in accuracy. On the basis of this experimentation, radiation terms were calculated once every 50 cm. Similarly, the radiation terms are not evaluated at every grid point either; they are calculated at all near-wall grid points and at every fifth point away from the wall. For a wider applicability, it is not Eqs. (11, 12 and 15) that are computer programmed, but a more general solution to the one-dimensional transport equation that includes the possibility of scattering by particles, if present.

Despite the many simplifications and programming tricks, a typical execution time for a channel 20 m long is 15-20 CPU minutes on the IBM 370/195 or IBM 3033. However, no specific attempts were made to optimize the structure or the organization of the computer program.

Results and Discussion

Thermodynamic properties corresponding to combustion of coal with 5% moisture content in oxygen-activated air preheated to 967 K are used in all calculations. It is assumed that 1.0% potassium, in the form of an aqueous solution of K_2CO_3 , is introduced into the combustor. Thermodynamic data are obtained by assuming the gas to be in local chemical equilibrium⁶, and the required thermodynamic variables: gas density, temperature, sonic velocity, electrical conductivity, and Hall parameter, are curve-fitted by fourth-order polynomials as functions of pressure and enthalpy. The gas temperature at channel inlet is taken as 2750 K.

Thermodynamic data showed that, in the pressure and temperature range of 4 to 1 atm and 2750 to 2400 K, the mole fraction of CO_2 varied from 0.196 to 0.224, of H_2O from 0.113 to 0.121, and of K from 0.0039 to 0.0042. On the basis of these data, it was decided to take mole fractions of CO_2 , H_2O , and K as 0.20, 0.12, and 0.004, in that order, for the gas radiation calculations.

The channel is assumed to be 20 m in length, 1 m x 1 m at inlet, and 2 m x 2 m at exit. The mass flow rate is taken as 350 kg/s, and the average load factor (Faraday configuration) equal to 0.75. Though not necessarily optimal, these conditions are thought to be representative of base load operation. A wall temperature of 1800 K -- typical of slag-coated walls -- is assumed. It is also assumed that the magnetic field builds up from 4 to 6 tesla over the first 75 cm of channel and drops from 6 to 3 tesla over the last 17 m.

Convective and Radiative Heat Transfer

Results of sample calculations for the channel with smooth walls and with moderately rough walls (roughness = 3 mm) are shown in Figs. 1 and 2.

Fig. 1 Heat Flux Characteristics of Channel

Fig. 2 Heat Transfer Characteristics of Channel

Figure 1 shows that, for the channel with smooth walls, convective heat flux exceeds its radiative counterpart for the first 8 m, and then the reverse occurs. The total heat transfer by the two modes, however, is approximately equal (see Fig. 2). For rough walls, the convective heat flux is higher than the radiative heat flux for the larger portion of the channel, the crossover occurring at 19 m. As compared to the smooth wall case, Fig. 2 shows an enhancement in convective heat transfer of 35%, from 65 to 88 MW, with roughening of walls; the radiative heat transfer decreases slightly from 64 to 61 MW.

It is noted in Fig. 1 that the convective heat flux decreases much more rapidly along the flow direction than does the radiative heat flux. The decrease in convection is associated primarily with the thickening of boundary layer. As to radiation, the heat flux should decrease because of general lowering of the temperature. This decrease is somewhat negated by the increase in optical thickness arising from channel divergence.

There are five active bands in CO_2 , band centers being at 15, 10.4, 9.4, 4.3, and 2.7 μm . The four active bands for H_2O have band centers at 5.3, 2.7, 1.87 and 1.38 μm . Potassium is active at a shorter wavelength around 0.78 μm . From Wien's displacement law, it can be inferred that black body intensity has a peak at 1.0 μm for a temperature of 2750 K, at 1.1 μm for 2600 K gas temperature, and at 1.2 μm for 2400 K gas temperature. This means that a substantial contribution to radiative flux in the present problem comes from K and from the 1.38 μm H_2O band. It is estimated that half the radiative flux is from potassium atoms.

Channel Performance

For the base load channel, radiation was found to have an insignificant effect on channel power output. The effect of wall roughness on boundary layer voltage is more prominent; for rough walls, the voltage drop is 1165 V, compared with 724 V for the channel with smooth walls. The channel produces 285 MW of electrical power and the enthalpy extraction rate is 17 percent.

Gas radiation has a first-order effect on the boundary layer characteristics. For the channel with smooth walls, blockage at the channel exit increased from 7.2% to 10.9% when gas radiation was taken into consideration. The blockage information is required in computing the diffuser recovery coefficient. With rough walls and gas radiation considered, the blockage at the channel exit increases by more than 50%, to 17.6%.

Radiation, being a sizeable portion of the total heat transfer, has a significant effect on gas temperature. It is worth mentioning that the two volumic cooling mechanisms, MHD power extraction and radiation heat transfer, are comparable in magnitudes. The average power density for the rough wall channel is 5.72 MW/m^3 , and the combined magnitude of divergence of radiation heat flux and radiative heat transfer to the sidewall varies from 3 MW/m^3 at channel entrance to 0.5 MW/m^3 at channel exit. Results indicate that, for the channel with smooth walls, omission of radiation would result in the overprediction of the average temperature at channel exit by more than 65 degrees. With radiation accounted for, the average temperature at channel exit is 2366 K. It drops to 2322 K with roughening of channel walls. The axial profiles of average temperature and pressure are plotted in Fig. 3.

Fig. 3 Channel Operating Conditions

These profiles will be used in the second part of the paper to study the evolution and growth of liquid droplets in the MHD channel.

III. Part B. Evolution of Slag Particles

As mentioned earlier, in coal-fired MHD plants, slag will enter the channel in both liquid and condensed phases. As the gas temperature drops and supersaturation ratio rises, parallel processes of homogeneous nucleation and heterogeneous nucleation are initiated. Under this condition, the alteration in the spectral distribution function of slag particles $[n(r, x)]$ is governed by the following cross-sectionally averaged spray equation.⁷

$$\frac{1}{A} \frac{\partial}{\partial x} (n(x, r) A \langle u \rangle) + \frac{\partial}{\partial r} (\dot{r}(r, x) n) = J\delta(r - r^*(x)) \quad (18)$$

As a result of the condensation and nucleation processes, the change in slag vapor density is determined by the following cross-sectionally averaged conservation equation.

$$\frac{1}{A} \frac{d}{dx} (\rho_v A \langle u \rangle) = -4\pi \rho_l \int_0^\infty \dot{r} r^2 n(x, r) dr - \frac{4\pi}{3} r^{*3} \rho_l J \quad (19)$$

The population spectrum of slag particles contains particles as small as $7 \text{ \AA}$, the size of newly-formed nucleated particles, and as large as $10 \text{ \mu m}$, the size of slag droplets brought into the channel from the combustor. As a comparison, a typical mean-free path of the MHD plasma is on the order of a micrometer. Therefore, droplet-gas interaction (heterogeneous nucleation) encompasses the free-molecular to the continuum regime. For this situation, the following expression for growth rate ($\dot{r}$) can be derived.⁷

$$\dot{r} = \frac{12}{5} \frac{K n_v p_{\text{sat}}(T) f(K n_v)}{\rho_l \sqrt{2\pi R_v T}} \left[S - \left(\frac{T}{T_s} \right)^{1/2} \frac{p_{\text{sat}}(T_s)}{p_{\text{sat}}(T)} \exp\left(\frac{\phi}{kT_s}\right) \right] \quad (20)$$

where

$$T_s = T \left\{ 1 + f(K n_v) p_{\text{sat}}(T) L (S - \exp(\phi/kT)) \right\} \quad (21)$$

$$\left[\frac{25}{8} p T g(K n) \sqrt{R_v T} + p_{\text{sat}}(T) L f(K n_v) \exp(\phi/kT) \left(\frac{L}{R_v T} - \frac{\phi}{kT} - \frac{1}{2} \right) \right]$$

The functions, $f(K n_v)$ and $g(K n)$, are defined as,

$$f(K n_v) = \frac{K n_v + 1}{1 + \frac{15}{2} K n_v (K n_v + 1)} \quad (22)$$

and

$$g(K n) = \frac{K n + 1}{1 + 15 \left(\frac{\gamma - 1}{\gamma + 1} \right) K n (K n + 1)} \quad (23)$$

The supersaturation ratio, S , is defined as,

$$S = \frac{p_v(T)}{p_{\text{sat}}(T)} \quad (24)$$

In the above equations, ϕ is the work required to form a spherical droplet from the same volume of the bulk liquid, and is expressed⁷ as,

$$\phi = \frac{2\sigma m_c}{\rho_l r} \quad (25)$$

The expression for the homogeneous nucleation rate is

$$J = \left(\frac{2}{\pi} \right)^{1/2} \left(\frac{p_v}{kT} \right)^2 \hat{v} \left(\frac{\sigma}{m_c} \right)^{1/2} \exp \left(-\frac{4\pi}{3} r^{*2} \sigma / kT \right) \quad (26)$$

The critical radius, r^* , which is the radius of the particle as it is first formed, is given by the Gibbs-Thompson relationship,

$$r^* = \frac{2 \sigma \hat{v}}{kT \ln S} \quad (27)$$

Numerical Solution

Our numerical procedure is geared toward solving for the distribution function itself. The first step of the analysis is to divide the large size range of the particles in up to 79 cells. Direct finite-differencing of the spray equation encounters a particularly severe difficulty because the homogeneous nucleation term is multiplied by the delta function. The nucleation rate of Eq. (26) has a moderately large activation energy with an inflection point at a supersaturation ratio of ~ 1.8 -2.4. For the problem at hand, the nucleation rate changes by approximately 12 orders of magnitude near this point. Another source of difficulty is that, before nucleation takes place and after nucleation has subsided, the growth rate ($\dot{r}$) is negative for small particles and positive for large

particles. This produces a numerical instability.

The difficulty of handling particles of broad size range, from 7 Å to 10 μm, is alleviated by employing a logarithmic transformation in r . Since cell sizes are preassigned, $r = r^*$ may not entirely correspond to any particular cell size. In such a case, the nucleation source term of Eq. (18) is distributed between the two cells adjacent to $r = r^*$. Within the cell in which nucleation occurs, the delta function is approximated as reciprocal of the cell size. For numerical accuracy, in the r^* size range, small cell sizes, typically less than 2 Å, are maintained.

When a precipitous change in nucleation rate occurs, the step size (Δx) is carefully controlled, to minimize numerical error. An estimate of numerical error is maintained in the form of total number density. The true number density at any step can be readily computed by integrating Eq. (18).

$$(N A \langle u \rangle)_{x+\Delta x} = (N A \langle u \rangle)_x + (J A)_{x+\Delta x} \Delta x \quad (28)$$

The difference between $NA \langle u \rangle$ determined from Eq. (28) and that calculated from the distribution function

$$A \langle u \rangle = \int_0^\infty n(x, r) dr$$

is the error estimate. At each marching step, the error propagation is arrested by renormalizing the distribution function in the ratio of the quantity, $NA \langle u \rangle$, as calculated from Eq. (28) and as calculated from the distribution function itself.

The difficulty posed by wave splitting, i.e., $\hat{r}$ changing sign with r , is resolved by adopting a modification that is equivalent to upwinding for parabolic partial differential equations. This modification is employed in calculating

$$\frac{\partial}{\partial r} (\hat{r} n) \quad \text{whenever } \hat{r} \text{ changes sign across the}$$

faces of a cell.

With the major numerical problems circumvented, the two-step Lax-Wendroff⁹ procedure yields a satisfactory solution of the spray equation, Eq. (18).

Results and Discussion

Before discussing the results, we will investigate the chemistry of slag vaporization in the combustor. This will help in identifying reasonable initial conditions for Eqs. (18) and (19).

Slag Vaporization in Combustor

For the combustion conditions of Part A, the constitutions of major slag components are listed in Table I as weight fractions of the total fuel and oxidizer. In this listing, some of the chemically similar components, e.g., CaO and MgO,

Table I. Slag Vaporization in Combustor

Specie	Weight Fraction at Combustor Inlet	Equilibrium Percentage Vaporized
SiO ₂	0.011326	84.8
Al ₂ O ₃	0.005161	0.0
CaO	0.003433	52.5
K ₂ O	0.000163	100.0
Fe ₂ O ₃	0.001822	100.0

K₂O and Na₂O, have been grouped together. At the high combustor temperature, 2750 K in this case, some of the slag components vaporize, and chemically react with other gaseous species. Most of SiO₂ vaporizes to SiO, with some SiO_{2g} appearing at the higher temperature. When SiO_g and SiO_{2g} condense, they re-form SiO_{2s}. At typical MHD combustion conditions, only a negligibly small fraction of Al₂O₃ vaporizes, but it does melt at ~2300 K. The vaporization of CaO leads to the formation of Ca(OH)₂, which, under conditions favorable for condensation, re-forms CaO. In an MHD environment, K₂O vaporizes almost completely, and the resulting potassium reinforces the potassium injected into the combustor in the form of aqueous K₂CO₃. This potassium is unlikely to condense in either the channel or the diffuser, or even in the radiant boiler. Fe₂O₃ vaporizes in the combustor and is present in the gas phase as Fe and FeO in almost equal proportions. When lower temperature are encountered in the channel, Fe and FeO may react with the other gaseous species to form Fe(OH)₂. Under proper conditions, all Fe, FeO and Fe(OH)₂ condense as FeO₂.

The equilibrium composition of slag constituents corresponding to the channel inlet condition of Part A, has been computed, and is listed in Table I. The actual fraction of slag vaporized is less than the equilibrium value, and depends upon the combustor flow configuration. For the linear-type can combustor, the fraction vaporized will be close to the equilibrium value. With no apparent attempt to reject slag, a weight fraction of 0.00859 liquid droplets and 0.01336 slag vapor will enter the channel. Point 4 of Fig. 4 corresponds to this situation.

The use of flow swirling in combustors has been advocated as a means of controlling slag carryover into the channel and of providing a compact efficient combustor design. In a swirl-flow combustor, coal particles will segregate in the cold wall region, so that the amount of slag vaporizing will be much smaller than the equilibrium value. Points 1, 2, and 3 denote situations in which only 10, 25, and 50% of the maximum slag vapor that can vaporize (the equilibrium value) does so. The vaporized slag flows into the channel. Simultaneously, depending upon the swirl number, some slag

Fig. 4 Combustor Characteristics Regarding Ash Carryover

liquid droplets will also enter the channel. Quite clearly, the higher the swirl number, the smaller the slag vaporization rate and the smaller the fraction of the unvaporized liquid droplets that flow with the slag vapor into the channel. On the basis of this consideration, two hypothetical slag carryover characteristic curves for swirling combustors have been constructed. On the low condensed phase carryover curve of Fig. 4, points 1, 2, and 3 denote situations in which 2, 5, and 10% of the unvaporized slag travels into the channel in the form of liquid droplets. Similarly, points 1, 2, and 3 of the high condensed phase carryover curve refer to situations in which 5, 10 and 30% of the unvaporized slag finds its way into the combustor. For easy comprehension, the total ash carryover, the more conventional terminology, to which these points refer is indicated. These operating curves will be used to study the effect of ash carryover on the population spectrum of slag particles existing at the exit of the channel.

Evolution of Slag Particles

To clarify how homogeneous and heterogeneous nucleation processes combine and compete with each other to determine the population spectrum, we will trace the evolution history of slag particles for approximately 50% ash carryover condition of point H3 in Fig. 4. All the calculations will be performed for the axial pressure and average temperature distributions of Fig. 3. It is considered that the liquid droplets initially entering the channel are distributed according to the Nukiyama-Tamasawa equation:

$$n(o, r) = 130.2 \frac{N_o}{r} \left(\frac{r}{r_o} \right)^4 \exp \left(-5 \frac{r}{r_o} \right) \quad (29)$$

For the 50% carryover case, which may approximate the behavior of a low-swirl combustor, it is assumed that the original average size of liquid droplets is 2 μm . From the discussion of the previous section and the data of Table 1, it can be deduced that SiO is the major constituent of slag vapor;

more than 70% of slag vapor is composed of SiO. Therefore, for the purpose of calculating slag nucleation, the slag vapor is considered to consist entirely of SiO. This is an excellent approximation, because the next major components, Fe and FeO, have condensation characteristics very similar to that of SiO. For the channel operating environment of Part A, the saturation vapor pressure of SiO is:

$$\log p_{\text{sat}} (\text{atm}) = 12.5946 - 3.85 \times 10^4 / T \quad (30)$$

Some other data used in the computations are: surface tensions (σ) = 0.32 N/m, liquid density (ρ_L) = 2500 kg/m³, and heat of vaporization (L) = 4.85×10^6 J/kg.

With the initial conditions and the specification of relevant physical properties, the numerical solution can be obtained. Figure 5 depicts the

Fig. 5 Particle Size and Population History

initial distribution of liquid droplets, the distribution at an intermediate location, and the final distribution at channel exit. In the front end of the channel ($x < 3.5$ m), the gas temperature is high and the supersaturation ratio is slightly less than unity (see Fig. 6). In this region, liquid droplets vaporize, causing the average size of particles to decrease, as shown in Fig. 7. Between $x = 3.5$ m and $x = 7.8$ m, the gas becomes supersaturated with slag vapor. However, the supersaturation ratio is not high enough to initiate any significant nucleation of new particles. In this region, the slag particles initially carried into the channel grow in size; this growth process is shown in Fig. 7. For $x > 7.8$ m, the total number density of slag particles, expressed as $\#/\text{cm}^3$, decreases because of the diverging geometry

Fig. 6 Dependence of Nucleation Rate on Supersaturation Ratio

Fig. 7 Particle Formation and Growth

of the channel.

Around $x = 7.5$ m, nucleation of new particles begins. Figure 6 shows nucleation to occur between $x = 7.5$ m and $x = 11$ m. Because of the exponential dependence of nucleation rate on supersaturation ratio and a moderately large activation energy, the nucleation rate increases steeply when the supersaturation ratio exceeds a critical value -- 1.75 for the 50% carryover case. The nucleation rate increases by ten orders of magnitude between $x = 7.5$ m and $x = 11$ m, as the supersaturation ratio rises from 1.75 to 2.51 because of the drop in gas temperature and the logarithmic relationship of saturation pressure to gas temperature. At

$x = 11$ m, nucleation has stripped the gas of slag vapor, so much so that despite decreasing gas temperature, the supersaturation ratio begins to drop and the nucleation rate follows suit.

Figure 5 shows emergence of a characteristic bimodal distribution at $x = 8.3$ m. The bigger particles are the ones brought into the channel from the combustor. The smaller particles with maximum population density at about $0.02 \mu\text{m}$ have originated from homogeneous nucleation. The peak of the distribution function for larger particles has dropped because of the area expansion effect; the distribution function has shifted to the right as a result of particle growth. The point, $x = 8.3$ m, lies in the early period of the homogeneous nucleation regime.

Figure 7 shows a manyfold drop in particle size in the homogeneous nucleation regime, from more than $2 \mu\text{m}$ to less than $0.02 \mu\text{m}$, as a consequence of the appearance of submicrometer-sized nucleated particles. The region, $11 \text{ m} < x < 12 \text{ m}$, is the growth regime. Paralleling the homogeneous nucleation process of depleting slag vapor, is the homogeneous nucleation mechanism. As new particles are formed, more surface area is available for vapor condensation (heterogeneous nucleation), and the particle growth rate accelerates. This acceleration causes further drop in the supersaturation ratio and, because of exponential dependence of J on S , homogeneous nucleation vanishes precipitously at $x = 11$ m. The rapid reduction in supersaturation ratio between $x = 11$ m and $x = 12$ m and the slow reduction beyond $x = 12$ m are attributed entirely to the heterogeneous nucleation process. Particles quickly increase in size, to $0.1 \mu\text{m}$ at $x = 12$ m from less than $0.02 \mu\text{m}$ at $x = 10$ m. As to the total number density, a four-order increase is observed in the homogeneous nucleation regime, and a slight drop is seen beyond $x = 11$ m, because of area expansion effect.

Finally, attention is drawn to the size cut-off phenomenon of Fig. 5. In the slag vaporization regime ($x < 3.5$ m), the gas is superheated, and particles of all sizes vaporize with smaller-size particles evaporating faster than the larger particles. In the early growth regime, $3.5 \text{ m} < x < 8$ m, smaller particles continue to disappear by growing in size. In the nucleation regime, $8 \text{ m} < x < 11$ m, submicrometer-size particles are formed while the already-present particles continue to grow. In this regime, the fresh nucleated particles represent the smallest-size particles of the spectrum. The particles smaller in size than r^* have already disappeared by either vaporizing in the vaporization regime ($x < 3.5$ m) or growing in size in the early growth regime ($3.5 \text{ m} < x < 8$ m). This leads to the size cut-off phenomenon evidenced by the shape of the distribution function at $x = 8.3$ m. Next, in the predominantly growth regime, $x > 11$ m, bigger particles grow while the smaller particles either evaporate or grow to large size. This explains the size cut-off of the final distribution function, as well as its shifting to the right. At $x = 20$ m, the slag vapors have almost vanished.

Effect of Slag Carryover

As explained in the last section, a characteristic bi-modal particle size spectrum develops as a result of keen competition between the homogeneous nucleation and the heterogeneous nucleation processes. Since the homogeneous nucleation process increases the particle population, whereas the heterogeneous nucleation tends to restrict the population, the particle size spectrum depends intimately upon the parameters that govern the two nucleation rates, i.e., channel operating conditions, namely, axial variation of pressure and temperature, ash carryover rate, and liquid droplet-to-slag vapor ratio at channel inlet. It is desirable to acquire information pertaining to particle size spectrum for three primary reasons. First, it is important to maintain a sufficiently high electrical conductivity in the channel, especially at the downstream end, where gas temperature is low. This is of serious concern, because MHD power extraction is a volumetric process and, because of diverging geometry, the volume per unit length is maximum at the back end of the channel. There is a possibility that the nucleated slag particles can act as sites for free electro-ion recombination, with attendant loss of electrical conductivity. Second, slag particles play a dominant role in promoting radiative heat transfer in the diffuser. Third, this information is required for properly designing a slag screen to remove slag particles from the hot gas stream.

As touched upon earlier, point 1 of Fig. 4 is representative of a high-swirl combustor, point 2 of an intermediate-swirl combustor, point 3 of a low-swirl combustor, and point 4 of a linear can-type combustor. A characteristic of the swirling-flow combustor is that the larger slag particles are likely to be rejected and that the smaller particles entrained by the flow will enter the channel. In the computations relative to Fig. 8,

the average size of particles exiting the swirl combustor and entering the channel was assigned a value of $2 \mu\text{m}^{10}$. For the can-type combustor, because all the unvaporized slag particles enter the channel, it was deemed appropriate to assign a higher value, $3 \mu\text{m}$, to the average initial size. In Fig. 8, the computed particle size spectra for the ash carryover rates of Fig. 4 are recorded.

Figure 8 shows that a larger total number density and, hence, smaller average particle size is associated with a smaller slag carryover rate. For the same vapor carryover rate, higher condensed phase entrainment leads to lower number density and larger average particle size. For comparison, for the 100% ash carryover case, the number density and average particle size are $1.9 \times 10^7/\text{cm}^3$ and $0.2 \mu\text{m}$, which changes to $1.4 \times 10^9/\text{cm}^3$ and $0.02 \mu\text{m}$ when the ash carryover rate is reduced to 8%. The discussion given in the previous section applies equally well to all cases considered, and the location and length of various regimes identified earlier are given in Table 2.

Fig. 8 Effect of Ash Carryover on Particles Spectrum

Table 2 Nucleation and Growth Regimes

Point in Fig. 4	Evaporation Regime	Initial Growth Regime	Homogeneous Nucleation Regime	Rapid Growth Regime	Slow Growth Regime
H1	$x < 10.0$	$10.0 < x < 13.2$	$13.2 < x < 15.4$	$15.4 < x < 18.0$	$x > 18.0$
H2	$x < 6.6$	$6.6 < x < 10.2$	$10.2 < x < 12.1$	$12.1 < x < 12.2$	$x > 12.2$
H3	$x < 3.5$	$3.5 < x < 7.8$	$7.8 < x < 11.2$	$11.2 < x < 11.9$	$x > 11.9$
L1	$x < 11.0$	$11.0 < x < 14.5$	$14.5 < x < 17.3$	$17.3 < x < 19.2$	$x > 19.2$
L2	$x < 7.5$	$7.5 < x < 10.6$	$10.6 < x < 12.6$	$12.6 < x < 16.0$	$x > 16.0$
L3	$x < 4.2$	$4.2 < x < 8.0$	$8.0 < x < 9.8$	$9.8 < x < 11.0$	$x > 11.0$
4	-	$0 < x < 5.4$	$5.4 < x < 7.0$	$7.0 < x < 7.5$	$x > 7.5$

IV. Conclusions and Impacts of Results

1. Heat Transfer in Channel

A quasi three-dimensional model has been formulated and solved numerically to study the electro-dynamics, as well as flow and heat transfer in MHD channels. The contribution of gas radiation is incorporated into the analysis. In the temperature range of interest, water vapor, carbon dioxide, and potassium atoms are the principal participating gases. The results of the analysis indicate that, in the front end of the base load-size channel, where the boundary layer is thin, heat flux by convection exceeds that by radiation. The difference between the heat flux by the two modes diminishes as the flow proceeds downstream, and the radiation may exceed convection at the back end of the channel. For smooth walls, the total heat transfer by the two modes are equal, 65 MW each. With the channel walls roughened to 3 mm, the convective heat transfer registers a 35% enhancement (from 65 to 88 MW); the radiative heat transfer decreases slightly from 64 to 61 MW.

For the channel studied, radiation is found to have an insignificant effect on the electrical power generated by the channel. However, gas radiation has a first-order effect on channel gas-dynamics. For smooth walls, if the contribution of gas radiation is omitted, blockage at channel exit is 7.2% and the average temperature 2431 K. With radiation accounted for, the blockage increases to 10.2%, and the average temperature drops to 2366 K. It is emphasized that the blockage is one of the important parameters that determine the diffuser recovery coefficient.¹¹ Evolution of slag particles in the channel also depends intimately on the average temperature level.

2. Slag Particles Spectrum

The problem of homogeneous nucleation and droplet growth of the slag vapor carried into the channel from the combustor has also been analyzed. The numerical problems associated with solving the spray equation are described and the method of eradicating them delineated. The equilibrium vaporization chemistry of coal slag is outlined. A reasonable combustor characteristic curve for non-equilibrium slag vaporization vs condensed-phase carryover rate into the channel is developed. On the basis of this curve, the slag particles spectrum is studied as a function of the ash carry-

over rate. It is found that the average particle size increases from 0.02 to 0.20 μm and the total number density decreases from 1.4×10^9 to 1.9×10^7 particles/cm³ as the ash carryover is raised to 100% from 8%.

3. After-Gas Treatment

For environmental, as well as economic reasons, the seed injected in the combustor must be recovered from the hot gas exiting the diffuser. Just as the slag particles were formed in the channel by homogeneous nucleation and grew in size by slag vapor condensation, so can the seed particles (from potassium atoms) at much lower temperature (less than 1600 K) in the steam superheater. An additional complexity, however, arises from the presence of the slag particles in the steam superheater. Consequently, whether the seed vapor (potassium atoms) will undergo homogeneous nucleation or simply condense on the already-present slag particles will depend on the gas cooling rate in the superheater and the slag particle spectrum. If the gas cooling rate is sufficiently low or the slag particles surface area sufficiently large, the seed vapor will preferentially condense directly on the slag particles. If so, the particle spectrum of Fig. 5, for example, will essentially remain unchanged, although the entire spectrum will shift slightly to the right. The spectrum of Fig. 5, which is also typical of other spectra, has already revealed that more than 99% of particles are smaller than 1 μm in size. Typically, cyclones are incapable of separating particles from gas that are smaller than 10 μm ¹² and, hence, cyclones are of marginal utility for seed recovery in MHD systems.

The particles smaller than 1 μm or larger than 5 μm deposit efficiently on the cooled tube banks of the steam superheater. The mechanism responsible for deposition of small particles is thermophoresis¹³ -- a temperature gradient-induced force. The particles larger than 5 μm deviate from the flow stream lines near the tube surface and are deposited by direct impingement.¹³ The intermediate-size particles, $1 < (\mu\text{m}) < 5$, follow the flow turbulence and are harder to deposit on cooled tube banks. Their removal will require either a baghouse or an electrostatic precipitator. The actual sizing of these equipments will depend on the kind of spectrum information presented in Fig. 5. More complete details of the seed recovery aspect of the problem are found in Ref. 8.

4. Heat Transfer in Diffuser

In a follow-up study (see Ref. 3), the particle spectra whose number density and average particle size are graphed in Fig. 8 have been employed to estimate heat transfer rate in MHD diffusers. The study reveals that the slag particles play a dominant role in promoting radiative heat transfer in the diffuser. For the 100% ash carryover case, Ref. 3 calculates the radiative heat transfer in the diffuser to be 79 MW as opposed to 44 MW for the 8% carryover case. Comparison, heat transfer by convection is 25 MW. Reference 3 discusses and elaborates the impact of the enhancement in heat transfer by radiation in the channel and diffuser on the overall system design.

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