COMPUTER PROGRAM FOR THE CALCULATION OF MULTICOMPONENT
CONVECTIVE DIFFUSION DEPOSITION RATES FROM CHEMICALLY
FROZEN BOUNDARY LAYER THEORY

Süleyman A. Gökoğlu
Analex Corporation
Cleveland, Ohio

and

Bor-Kuan Chen and Daniel E. Rosner
Yale University
New Haven, Connecticut

January 1984

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS3-23293 and Grant NAG3-201
Computer program for the calculation of multicomponent convective diffusion deposition rates from chemically frozen boundary layer theory

TLSP: Final Report

AUTH: A/GOEKOGLU, S. A.; B/CHEN, B. K.; C/ROSNER, D. E.

CORP: Analex Corp., Cleveland, Ohio.; Yale Univ., New Haven, Conn.

AVAIL: NTIS SAP: HC A03/MF A01

Washington Prepared in cooperation with Yale Univ., New Haven, Conn.

MAJS: /COMPUTER PROGRAMS/*THERMODYNAMIC PROPERTIES/*TRANSPORT PROPERTIES/*VAPOR DEPOSITION

MINS: /BOUNDARY LAYERS/ HEAT TRANSFER/ HOT CORROSION/ MASS TRANSFER/ PREDICTION ANALYSIS TECHNIQUES/ USER MANUALS (COMPUTER PROGRAMS)

ABA: Author

ABS: The computer program based on multicomponent chemically frozen boundary layer (CFBL) theory for calculating vapor and/or small particle deposition rates is documented. A specific application to perimter-averaged Na2SO4 deposition rate calculations on a cylindrical collector is demonstrated. The manual includes a typical program input and output for users.
COMPUTER PROGRAM FOR THE CALCULATION OF MULTICOMPONENT
CONVECTIVE DIFFUSION DEPOSITION RATES FROM CHEMICALLY
FROZEN BOUNDARY LAYER THEORY†

Süleyman A. Gökoğlu*

Analex Corporation
Cleveland, Ohio 44135

and

Bor-Kuan Chen** and Daniel E. Rosner***

Yale University
Chemical Engineering Department
New Haven, Connecticut 06520

SUMMARY

The computer program developed based on multicomponent chemically frozen boundary layer (CFBL) theory for calculating vapor and/or small particle deposition rates is documented. A specific application to perimeter-averaged Na$_2$SO$_4$ deposition rate calculations on a cylindrical collector is demonstrated. The manual includes a typical program input and output for users.

I. INTRODUCTION

A wide variety of different engineering fields—including chemical coating of metals, solid state electronics device fabrication, filtration, aircraft icing, corrosion and fouling of gas turbine blades, heat exchangers, etc.—deal with vapor and particle capture, either to exploit or to suppress it, depending on the context. A comprehensive but tractable convective diffusion deposition rate theory has been developed at Yale University based on the assumption of a multicomponent "chemically frozen" boundary layer (CFBL) as outlined in Rosner et al. [1]. The theory which makes full use of available transport coefficient and property information is not only applicable under conditions of multicomponent vapor transport (e.g., CVD applications), but it is also intrinsically capable of simultaneously dealing with particle transport provided the particles are small enough to be considered heavy molecules. The purpose of this manual is to document a simple but useful computer code based on CFBL

†Supported by NASA Lewis Research Center Contract NAS3-23293 (Analex Corp.) and Grant NAG3-201 (Yale Univ.).
*Research scientist.
***Professor of Chemical Engineering, Director, High Temperature Chemical Reaction Engineering Laboratory.

N85-27164#
theory for calculating alkali sulfate deposition rates. We hope that the
manual will prevent further misapplications of CFBL theory as has been en-
countered in the literature [2]. Detailed description of this program, with
specific application to perimeter-averaged Na₂SO₄ deposition rate calculations
on a cylindrical collector is given below. Typical program input and output
is included with explanations. The manual contains the program listing in
Appendix C.

SYMBOLS

\( B_T \) thermophoretic parameter, equation (35)
\( C \) nozzle discharge coefficient
\( C_{mh} \) coefficient defining relative sensitivity of mass transfer and heat
transfer to variable properties, equation (37)
\( c_p \) heat capacity per unit mass at constant pressure
\( c_v \) heat capacity per unit mass at constant volume
\( D \) Fick diffusion coefficient
d collector (target) diameter
dj nozzle jet diameter
F function
f fuel to air mass flow rate ratio
I mainstream turbulence intensity
K coefficients of curve-fit in equation (11)
k Boltzmann constant
L mainstream turbulence length scale
Le Lewis number (ratio of Fick to thermal diffusivity)
M molecular weight
\( \bar{M} \) average molecular weight of the mixture
\( \dot{m} \) deposition mass flux
\( \text{Nu} \) Nusselt number
\( \text{Nu}_p \) Perimeter-averaged Nusselt number
P pressure
Pr Prandtl number (ratio of kinematic viscosity to thermal diffusivity)
R universal gas constant
Re Reynolds number
S spin parameter, equation (33)
s defined by equation (31)
Sc Schmidt number (ratio of kinetic viscosity to Fick diffusivity)
T absolute temperature
U velocity
\( v \) sonic velocity
\( W_a \) air mass flow rate
X mole fraction

Greek Symbols:
\( \alpha \) thermal diffusion factor
\( \alpha_{r,\infty} \) thermal diffusion factor at infinite temperature
\( \alpha_{r,1} \) coefficient of T⁻¹ in power series expansion of \( \alpha_T \)
\( \epsilon \) Lennard-Jones molecular interaction energy (well-depth) parameter
\( \gamma \) specific heat ratio, \( c_p/c_v \)
\( \lambda \) thermal conductivity
\( \mu \) viscosity
\( \nu \) number of Na atoms in species 1
\[ \dot{m}_{Na_2SO_4} = \frac{1}{2} \cdot \frac{M_{Na_2SO_4}}{M} \cdot F(\text{turb}) \cdot \frac{\rho_\infty}{d} \cdot \sum_1 \left\{ \nu_1 \cdot D_{1,\infty} \cdot \frac{\bar{N}_{u,m,1}}{D_{1,\infty}} \cdot F_1(\text{Soret}) ight. \\
\left. \quad \cdot \left[ (X_{1,\infty} - X_{1,W}) - X_{1,W} \cdot \frac{D_{1,1}}{F_1(\text{Soret})} \cdot \left( \frac{\text{Le}_{1,W}}{\text{Le}_{1,\infty}} \right)^{0.6} \cdot \frac{c_{p,\infty}}{c_{p,W}} \cdot \frac{1}{c_{m,h,1}} \right] \right\} \]

The multicomponent nature of the problem is reflected by the appearance of summations which include each Na carrier species \( i \). The present program...
considers four different possible Na carriers: Na, NaOH, Na\textsubscript{2}SO\textsubscript{4} and NaCl. Note the implicit assumption (checked below via the element flux ratio constraint) that once Na arrives at the surface of the collector by any of Na carriers, there is always enough sulfur available (e.g., supplied to the system by fuel) to form Na\textsubscript{2}SO\textsubscript{4}.

The mole fraction of each Na carrier species in the free stream and at the collector surface ($X_{1,\infty}$ and $X_{1,w}$) is supplied to the program by the user. The theory leads to simple algebraic flux relations for each species since it assumes that there is thermo-chemical equilibrium at stations "\infty" and "w", although the boundary layer itself is chemically frozen. In the applications to Na\textsubscript{2}SO\textsubscript{4} deposition experiments at NASA LeRC, the Chemical Equilibrium Code (CEC) developed at NASA LeRC [4] is used to obtain the equilibrium compositions after combustion at specified temperatures and pressures. However, the CFBL code is by no means restricted to coupling with CEC, and the user may provide $X_{1,\infty}$ and $X_{1,w}$ values by any other means available.

Conditions prevailing at station "w" require the imposition of one additional constraint other than vapor/condensate equilibrium [1,5]. Because Na\textsubscript{2}SO\textsubscript{4} is being deposited, the molar fluxes of Na and S must stand in the ratio 2:1 at the prevailing vapor compositions. The element mass fractions of the inorganic constituents characterizing the free stream are dictated by the experimental conditions; however, the situation at station "w" is more complicated because transport across the boundary layer contributes to element "segregation." Therefore, the element mass fractions at the surface of the collector generally will not be the same as those in the free stream [5]. Hence, the CFBL program also calculates the total S molar flux to the surface with the same formulation given in equation (1). The dominant S carriers to the surface are chosen to be SO\textsubscript{2}, SO\textsubscript{3}, and H\textsubscript{2}S. Therefore, the user has to provide $X_{1,\infty}$ and $X_{1,w}$ values for SO\textsubscript{2}, SO\textsubscript{3}, and H\textsubscript{2}S as inputs to the program. For any particular set of $X_{1,\infty}$ and $X_{1,w}$ values, obtained from equilibrium calculations and input to the CFBL program, the output gives the calculated Na to S molar flux ratio. In order to satisfy both the thermodynamic (chemical equilibrium) and the transport (molar flux ratio) constraints, the user has to iterate on $X_{1,w}$ values obtained from equilibrium calculations with clever choices of element mass fractions. Finally, the properly chosen element mass fractions will give the proper equilibrium compositions of Na and S carriers at station "w" which in turn will satisfy the 2:1 Na to S molar flux ratio constraint. Experience with the CFBL program indicates that in cases where the system contains excess S, the predicted Na\textsubscript{2}SO\textsubscript{4} deposition rates are practically insensitive to the fulfillment of the transport requirement except close to the dew point temperature.\footnote{For the discussion of the fact that "dew-point" is not a pure thermodynamic quantity, the reader is referred to references [5] and [6].}

Modification of the CFBL program for application to the multicomponent chemical vapor deposition of condensates other than Na\textsubscript{2}SO\textsubscript{4} is conceptually straightforward. It requires the proper choice of dominant carrier species and provision of relevant thermodynamic and transport parameters to the program. Generalized versions of the present CFBL code are being developed and applied to Na\textsubscript{2}SO\textsubscript{4} + K\textsubscript{2}SO\textsubscript{4} and Na\textsubscript{2}SO\textsubscript{4} + K\textsubscript{2}SO\textsubscript{4} + Li\textsubscript{2}SO\textsubscript{4} solution condensate deposition situations used at Yale University [5] and NASA LeRC.
III. EVALUATION OF THERMODYNAMIC AND TRANSPORT PROPERTIES

Description of the property calculations given below assumes that the following information is supplied to the program by the user as input for a typical configuration given in figure 1:

- \( d_j \) jet exit diameter, cm
- \( d \) diameter of cylindrical collector (target), cm
- \( f \) fuel to air mass flow rate ratio
- \( P_j \) jet exit (ambient) pressure, atm
- \( P_0 \) stagnation pressure, atm
- \( T_0 \) stagnation temperature, K
- \( T_W \) collector surface (wall) temperature, K
- \( W_a \) air mass flow rate, g/sec

Note that we are assuming a circular jet and a cylindrical collector. For other geometries proper characteristic dimensions must be supplied to calculate the jet exit area, the Reynolds number and mass transfer Nusselt number.

The combustion is assumed to be complete and dominated by the reaction:

\[
\text{CH}_2 + 3/2 \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}
\]

(2)

Hence, starting with air of initial composition: 79.05 mole percent \( N_2 \) and 20.95 mole percent \( O_2 \), we estimate the composition of combustion product gases by:

\[
X_{N_2} = \frac{0.7905}{1 + 1.0331f}
\]

(3)

\[
X_{O_2} = \frac{0.2095 - 3.0993f}{1 + 1.0331f}
\]

(4)

\[
X_{\text{CO}_2} = X_{\text{H}_2\text{O}} = \frac{2.0662f}{1 + 1.0331f}
\]

(5)

All other species present in the combustion product gas stream are assumed to be of trace amounts and are neglected in the property calculations.

A. Calculation of \( \overline{M}, \gamma, T_j \) and \( U_j \)

Average molecular weight of the combustion gases is obtained from:

\[
\overline{M} = X_{N_2}M_{N_2} + X_{O_2}M_{O_2} + X_{\text{CO}_2}M_{\text{CO}_2} + X_{\text{H}_2\text{O}}M_{\text{H}_2\text{O}}
\]

(6)

where \( X \) is the mole fraction of each indicated species.

The ratio of heat capacity at constant pressure to heat capacity at constant volume of the mixture is calculated by:
\[
Y = \frac{c_{p,\text{mix}}}{c_{v,\text{mix}}} = \frac{c_{p,\text{mix}}}{c_{p,\text{mix}} - (R/M)} 
\]  

where \( R \) is the universal gas constant (1.9872 cal/mole - K), and the calculation of \( c_{p,\text{mix}} \) is described below. Assuming an isentropic jet, the temperature and the velocity at the jet exit plane is given by:

\[
T_J = T_0 \left( \frac{P_J}{P_0} \right)^{(\gamma-1)/\gamma} 
\]

and

\[
U_J = \frac{RT_J}{P_J M} \cdot \frac{W_d (1 + f)}{(\frac{d_j^2}{4}) \cdot C} 
\]

where \( R \) is the universal gas constant (82.057 atm-cm^3/mole-K), and \( C \) is the discharge coefficient of the jet nozzle to be supplied by the user. The discharge coefficient depends on the geometric shape of the nozzle and the Reynolds number based on the nozzle diameter. If no information is available for the nozzle discharge coefficient, then the program automatically assigns unity as the value of \( C \). Note that the velocity calculated from equation (9) based on the total mass flow rate and the effective area of the nozzle exit should agree with the velocity which can be calculated also from the prevailing Mach number based on the isentropic jet assumption as:

\[
U_J = c_s \cdot \left[ \left( \frac{T_0}{T_J} - 1 \right)^{\frac{2}{\gamma - 1}} \right]^{1/2} 
\]

where \( c_s \) is the sonic speed in the gas mixture at \( T_0 \). In equation (9) it is assumed that the mixture obeys the ideal gas law, so that the density of the mixture is simply:

\[
\rho_J = \frac{P_J M}{RT_J} 
\]

B. Calculation of \( c_p, \lambda, \mu, \text{ and } D_1 \)

The dimensionless heat capacity of each dominant species is computed from a curve fit:

\[
\left( \frac{c_{p,1} M_1}{R} \right) = K_{5,1} T^4 + K_{4,1} T^3 + K_{3,1} T^2 + K_{2,1} T + K_{1,1} 
\]

where \( R \) is the universal gas constant (1.9872 cal/mole - K). Two different sets of constants, \( K \), are used for \( T \geq 1000 \) K and \( T < 1000 \) K for a better fit.
Viscosity, $\mu_1$, and thermal conductivity, $\lambda_1$, of dominant species are calculated using Chapman-Enskog theory:

$$\mu_1 = 2.6693 \times 10^{-5} \frac{\sqrt{M_1 T}}{\sigma_1^2 \Omega_{\mu_1}} \text{ (g/cm-sec)}$$  \hspace{1cm} (12)

$$\lambda_1 = \frac{R}{M_1} \left[ \frac{15}{4} + 1.32 \left( \frac{c_{D,1} M_1}{R} - \frac{5}{2} \right) \right] \mu_1 \text{ (cal/cm-sec-K)}$$  \hspace{1cm} (13)

where $\sigma_1$ is the Lennard-Jones molecular size parameter of the species and $\Omega_{\mu_1}$ is the collision integral for viscosity which is a function of the dimensionless temperature $kT/\epsilon_1$ where $k$ is the Boltzmann constant and $\epsilon_1$ the Lennard-Jones molecular interaction energy (well-depth) parameter for species 1.

The binary Fick diffusion coefficient of trace species $k$ in each of dominant species $i$ is also calculated from Chapman-Enskog theory:

$$D_{kj} = 0.0018583 \frac{V^3}{\sigma_k^2 \Omega_{D,k1}} \text{ (cm}^2/\text{sec)}$$  \hspace{1cm} (14)

where

$$\sigma_{k1} = \frac{1}{2} \cdot (\sigma_k + \sigma_1)$$  \hspace{1cm} (15)

and $\Omega_{D,k1}$ is the collision integral for diffusion coefficient which (just like $\Omega_{\mu_1}$) is also a function of $kT/\epsilon_{k1}$ where:

$$\frac{\epsilon_{k1}}{k} = \sqrt{\frac{\epsilon_k \epsilon_1}{k}}$$  \hspace{1cm} (16)

The dimensionless thermal diffusion factor for trace species $i$ is conveniently expressed below after a curve-fit to calculations based on Chapman-Enskog theory.

$$\alpha_{T,1} = \alpha_{T,\omega,1} + \frac{\alpha_{T,-1,1}}{T}$$  \hspace{1cm} (17)

The resulting least-squares constants, $\alpha_{T,\omega,1}$ and $\alpha_{T,-1,1}$ for a number of species are given in reference [7].

It should be noted that unless experimentally determined, the uncertainties involved in the estimation of $\sigma$ and $\epsilon/k$ are directly reflected in $\mu$, $\lambda$, $\omega$, and $\alpha_T$ values [6]. Therefore the accuracy of prediction of the CFBL program is limited by the accuracy of such transport parameters.
C. Calculation of Mixture Properties

Specific heat of the gas mixture is simply given by:

\[ c_{p,mix} = \sum X_i c_{p,i} \quad (18) \]

where \( X_i \) is the mole fraction of species \( i \). Viscosity and thermal conductivity of the mixture are calculated from similar formulae:

\[ \mu_{mix} = \sum \frac{X_i \mu_i}{\sum_k X_k \Phi_{ki}} \quad (19) \]

\[ \lambda_{mix} = \sum \frac{X_i \lambda_i}{\sum_k X_k \Phi_{ki}} \quad (20) \]

where \( \Phi_{ki} \) are the Wilke-Wassiljewa coefficients given by:

\[ \Phi_{ki} = \frac{1}{\sqrt{8}} \cdot \left( 1 + \frac{M_i}{M_k} \right)^{-1/2} \cdot \left[ 1 + \left( \frac{\mu_i}{\mu_k} \right)^{1/2} \left( \frac{M_k}{M_i} \right)^{1/4} \right]^2 \quad (21) \]

The diffusion coefficient of species \( i \) in the mixture is calculated from:

\[ D_{i,mix} = \left( \sum_k \frac{X_k}{D_{i,k}} \right)^{-1} \quad (22) \]

The reader is referred to reference [9] for the details of thermodynamic and transport property calculations.

IV. DIMENSIONLESS NUMBERS

The dimensionless numbers given below are evaluated either at station "\( \infty \)" or "\( W \)" depending on relevance. The static temperature at station "\( \infty \)", \( T_\infty \), is assumed to be equal to \( T_j \), calculated in Section III.A. The collector surface temperature (or a representative average temperature if the collector is not isothermal) and the ambient pressure, \( P_\infty (= P_j) \), are supplied as inputs by the user.
\[ Pr = \frac{c_{p,\text{mix}} u_{\text{mix}}}{\lambda_{\text{mix}}} \]  
(23)

\[ Sc_1 = \frac{u_{\text{mix}}}{\rho D_{1,\text{mix}}} \]  
(24)

\[ Le_1 = \frac{Pr}{Sc_1} = \frac{D_{1,\text{mix}}}{[\frac{\lambda_{\text{mix}}}{(\rho c_{p,\text{mix}})}]} \]  
(25)

\[ Re = \frac{\rho U d}{u_{\text{mix}}} \]  
(26)

Calculation of the Reynolds number requires knowledge of \( U_\infty \). Although \( U_j \) is obtained in Section III.A, \( U_\infty \) is not necessarily the same as \( U_j \) depending on the jet velocity profile and the jet divergence angle. For jet diameters larger than the collector diameter (usually) the case), one needs the centerline velocity at station "\( \infty \)" for the proper calculation of \( Re \). However, \( U_j \) calculated in Section III.A. is the average velocity at station "\( j \)". Therefore, two corrections are needed; first, to correct average \( U_j \) to centerline \( U_j \), \( F(\text{shape}) \), and second, to correct centerline \( U_j \) to centerline \( U_\infty \), \( F(\text{div}) \). These corrections take into account the boundary layer effects and the flow area variation from station "\( j \)" to station "\( \infty \)" depending on jet divergence angle. Hence:

\[ U_\infty = U_j \cdot F(\text{shape}) \cdot F(\text{div}) \]  
(27)

where \( F(\text{shape}) \) and \( F(\text{div}) \) are defined as:

\[ F(\text{shape}) \equiv \left( \frac{U_{CL}}{U_{av,j}} \right) \]  
(28)

\[ F(\text{div}) \equiv \frac{U_{CL,\infty}}{U_{CL,j}} \]  
(29)

\( F(\text{shape}) \) and \( F(\text{div}) \) are optional inputs to the program. If no information is available, the program automatically assigns unity for both. Based on available data for fully developed turbulent flow in smooth circular ducts, a suggested estimate for \( F(\text{shape}) \) is:

\[ F(\text{shape}) \equiv \frac{(s + 1)(2s + 1)}{2s^2} \]  
(30)

where
The mass transfer Nusselt number correlations depend, among other things, on the geometry of the collector used. In the NASA LeRC experiment [3], a cylindrical collector was used. The example program listing given at the end of this manual also assumes a cylindrical collector. By making the replacement \( \Pr \rightarrow \Sc \), the perimeter averaged mass transfer coefficient, \( \Nu_{m,1} \), becomes based on the heat transfer correlations recommended for stationary infinitely long cylinders [10]. The additional effects of variable properties and Mach number are approximated by incorporating a post-multiplier term based on the recommendations of references [11] and [12].

\[
\Nu_{m,1} = (0.40 \Re^{1/2} + 0.06 \Re^{2/3}) \left( \Sc^{0.4} \right) \left( \frac{T_w}{T_0} \right)^{0.04}\]  

(32)

It should be noted that if a different collector geometry is used and/or the surface roughness of the collector can have an appreciable effect on mass transfer, the equation (32) may not be applicable, and the user has to modify the program to supply the best available corresponding mass transfer Nusselt number correlation from the literature.

In many experiments, uniformity of collector surface temperature is obtained by collector rotation and this requires additional modifications of the formulation given by equation (1). In the NASA LeRC deposition experiments the rotational speeds of the smooth collectors used have been neglected based on reference [13], which suggests that if one defines a "spin" parameter

\[
S = \frac{\omega d}{2U_{\infty}}
\]  

(33)

where \( \omega \) is the angular speed of the target, then equation (1) (or eq. (32)) should be corrected by the multiplier

\[
F(\text{spin}) = (1 + 2S^2)^{0.315}
\]  

(34)

V. THERMAL (SORET) DIFFUSION EFFECT, \( F(\text{SORET}) \)

Inclusion of thermal (Soret) diffusion in the mass transfer calculations introduces a nondimensional thermophoretic parameter, \( [14] \), which can be expressed as:

\[
B_{T,1} = -\alpha_{T,1,w} \cdot (Le_{1,w})^{0.4} \cdot \left( \frac{T_0 - T_w}{T_w} \right)
\]  

(35)

The effects of thermal (Soret) diffusion ("thermophoresis" for small particles) is thoroughly discussed and correlated in references [7, 14-17] for both vapor and small particle mass transfer. For the current applications of the CFBL program to NASA LeRC deposition experiments, the emphasis has been on vapor
deposition. Therefore, the "sink" effect of thermal diffusion is justifiably neglected, and only the "suction" effect is considered, i.e.:

\[ F_1 (\text{Soret}) = F_1 (\text{suction}) = \frac{-B_{T,1}}{1 - \exp(B_{T,1})} \]  

(36)

For small particle mass transfer applications where inertial effects are not important, the user should modify the program to include the "thermophoretic sink" effect as described in references [14] and [16]. For such applications a method for estimating small particle transport properties \(D_i, \alpha_{T,i}, \text{etc.}\) is given in reference [17].

In the program the user also has the option of completely "turning off," if so desired, the thermal diffusion effect from inclusion in the calculations by specifying the input variable "FSORET" as "false". In this simple way we can demonstrate the relative importance of thermal diffusion mass transport in any multicomponent CVD situation.

It is known that variable properties across the boundary layer affect mass transfer rates in a somewhat different manner than they do the better known heat transfer rates. In case of thermal diffusion, this effect is in addition to the one already incorporated in the perimeter-averaged Nusselt number (eq. (32)). Certainly, the effect will be different depending on the temperature dependence of the transport properties of the species in question and the characteristics of the mass transfer boundary layer. Therefore, it is convenient to introduce a new dimensionless parameter, \(C_{m\text{h},i}\), defined as:

\[ C_{m\text{h},i} \equiv \left( \frac{\text{Nu}_{m}/\text{Nu}_{m,cp}}{E} \right) \]  

(37)

Simple engineering correlations to predict the effect of variable properties on mass transfer (the numerator in eq. (37)) and on heat transfer (the denominator in eq. (37)) are given in reference [12]. However, if the space reserved for \(C_{m\text{h},i}\) in the input data is left blank, the program automatically assigns a value of unity for each \(C_{m\text{h},i}\).

VI. MAINSTREAM TURBULENCE EFFECT, \(F (\text{turb})\)

It is known that mainstream turbulence, apart from turbulence within the boundary layer, influences the transport rates to surfaces [18-19]. Although there is considerable quantitative disagreement among various researchers, the CFBL program uses the correlation given in reference [20] based on perimeter-averaged heat transfer measurements for cylinders in cross flow. If one has knowledge of free stream turbulence intensity, \(I_t\), and axial macroscale of turbulence, \(L_t\), then the correlation at a particular \(Re\) for a cylinder of diameter \(d\) is given in the separable form:

\[ F (\text{turb}) = 1 + fct_1(I_t,Re) \cdot fct_2(L_t/d) \]  

(38)

where \(fct_1\) and \(fct_2\) are presented in graphical form in reference [20]. The CFBL program uses the following curve fits for \(fct_1\) and \(fct_2\).
\[
\begin{align*}
\text{fct}_1(I_tRe) & = \begin{cases} 
12.375 \left[ 1 - \left( 1 - \frac{I_tRe}{10^4} \right)^3/2 \right] & \text{if } I_tRe \leq 10^4 \\
9.0 + 3.375 \times 10^{-4} \cdot I_tRe & \text{if } I_tRe > 10^4
\end{cases} \\
\text{fct}_2(L_t/d) & = \begin{cases} 
0.124 \times 10^{-3} \left[ (L_t/d) - 11.0 \right]^2 + 2.0 \times 10^{-3} & \text{if } L_t/d > 2 \\
-4.0 \times 10^{-3} \left[ (L_t/d) - 1.75 \right]^2 + 12.25 \times 10^{-3} & \text{if } L_t/d \leq 2
\end{cases}
\end{align*}
\]

\( F(turb) \) probably also depends on \( Sc_i \), but the information is not yet sufficient in the literature to incorporate it into the present formalism. The user has three options in using the \( F(turb) \) factor:

1. If one chooses not to use the \( F(turb) \) factor, then leave the variable "TURB" blank in input data, in which case the program automatically assigns the value of unity for \( F(turb) \).
2. If the particular \( F(turb) \) to be used by the program is known, then that value should be read in as input for the variable "TURB", but leave the variables "TURIN" and "TURL" blank.
3. If one has knowledge of \( I_t \) and \( L_t \) and chooses to use the correlation supplied by the program based on equations (38) to (40), then input data for "TURB" is dummy, but "TURIN" (percent \( I_t = I_t/100 \)) and "TURL" input values must be read in.

VII. ROUTINES

The names and functions of the subroutines used in the program are given below:

- **MAIN** calculates the deposition rate based on equation (1)
- **PARAM** provides \( \epsilon/\kappa \), \( \sigma \), and molecular weight of dominant species in the gas mixture
- **CAESL** provides the dimensionless heat capacity of dominant species in the gas mixture from a curve fit
- **CALMIX** calculates \( C_{p,m} \) in cal/g-K
- **COEDIF** calculates \( D_{k1} \) of trace species \( k \) in 1
- **COLINT** evaluates \( \Omega_{\mu} \) and \( \Omega_{\sigma} \) from a curve fit to the already supplied \( kT/\epsilon \) versus \( \Omega_{\mu} \) and \( \Omega_{\sigma} \) data [8]. Also calculates \( \mu_1 \) and \( \lambda_1 \) for dominant species
- **MIXPRO** calculates \( \mu_{mix} \) and \( \lambda_{mix} \)
- **NUM** calculates \( N_{m1} \)
- **TURBL** calculates \( F(Soret) \)
VIII. DESCRIPTION OF PROGRAM INPUT

The input data to the CFBL program is read in three different stages. The first stage reads in one card which contains the following information according to the format specified.

```
READ(5,1) IRUN, ITYPE, F, WA, TW, TO, PO, PJ, DC, WOBS, FSORET
1 FORMAT(212, 8F9.0, 3X, L1)
```

- **IRUN** The user can use this variable for his own purposes (e.g., to keep track of which experiment, which run, etc.).
- **ITYPE** The user can use this variable for his own purposes (e.g., to keep track of the type of salt fed to the combustor, etc.).
- **F** Fuel to air mass flow rate ratio
- **WA** Air flow rate, g/sec
- **TW** Collector (target) surface temperature, K. Give an average temperature if the collector surface is not isothermal.
- **TO** Stagnation temperature, K
- **PO** Stagnation pressure, atm
- **PJ** Jet exit (ambient) pressure, atm
- **DC** Discharge coefficient of jet nozzle. Optional input. Leave blank if no information is available. See Section III.A.
- **WOBS** Experimentally observed deposition rate. Used in calculating the percent error in the prediction, mg/hr.
- **FSORET** Logical variable. Specify as 'T' if thermal diffusion is desired to be included in the calculations, or as 'F' if otherwise.

The second stage reads in one card which contains the following information according to the format specified:

```
READ(5,998) DIAW, LW, DJ, TURB, TURIN, TURL, SHAPE, DIV
998 FORMAT(8F10.0)
```

- **DIAW** Diameter of the cylindrical target, cm
- **LW** Length (height) of the cylindrical target, cm
- **DJ** Diameter of circular jet nozzle exit plane, cm
- **TURB** Turbulence enhancement factor, F (turb). Optional input.
  (a) Leave blank if no consideration is required.
  (b) Give your own estimate if information is available, but then leave "TURIN" and "TURL" blank.
- **TURIN** Percent mainstream turbulence intensity (It/100). Optional input.
  (a) Leave blank if no consideration is required.
  (b) Leave blank if you supply your own "TURB".
  (c) Give your estimate if program consideration is desired, but then specify "TURL", too.
- **TURL** Axial macroscale of mainstream turbulence, cm. Optional input.
  (a) Leave blank if no consideration is required.
  (b) Leave blank if you supply your own "TURB".
  (c) Give your own estimate if program consideration is desired, but then specify "TURIN", too.
- **SHAPE** F (shape). Optional input. Leave blank if no information is available. See Section IV.
- **DIV** F (div). Optional input. Leave blank if no information is available. See Section IV.
The third stage reads in seven cards, one for each species. The order is given by:

1 = NaOH  
2 = Na  
3 = Na\(_2\)SO\(_4\)  
4 = SO\(_2\)  
5 = SO\(_3\)  
6 = NaCl  
7 = H\(_2\)S

Note that this input is specific to Na\(_2\)SO\(_4\) deposition only, and must be modified for other salts and/or salt solutions accordingly. Each card contains the following information according to the format specified.

READ(5,2) XW(I), XJ(I), CMH(I) 
2 FORMAT(2E15.4, F10.0)

XW(I) Equilibrium mole fraction of species 1 at station "w" 
XJ(I) Equilibrium mole fraction of species 1 at station "j" or equivalently at station "w" 
CMH(I) Ratio of effect of variable properties on mass transfer to heat transfer. Optional input. See Section V.

A typical input data set is given in Appendix A.

IX. DESCRIPTION OF PROGRAM OUTPUT

The program output contains all the information read into the program as input. Description of the additional variables printed out is given below:

D(I) Diffusion coefficient of species 1 in gas mixture, \(D_{1,\text{mix}}\), in cm\(^2\)/sec  
NU(I) Mass transfer Nusselt number of species 1, \(N_{\text{num}}\)  
SC(I) Schmidt number of species 1, \(Sc_1\), at station \(\infty\)  
TAU(I) Thermophoretic parameter of species 1, \(BT_1\)  
F(SORET)(I) \(F_1(\text{Soret})\) of species 1  
M(I) Equivalent Na\(_2\)SO\(_4\) deposition rate of species 1 mass transfer rate in mg/hr  
YNAJ Total Na mole fraction in flame  
YNAW Total Na mole fraction at station "w"  
YSJ Total S mole fraction in flame  
YSW Total S mole fraction at station "w"  
AM Average molecular weight of gas mixture (neglects trace species)  
TURB \(F(\text{turb})\)  
RE Reynolds number at station "\(\infty\)"  
SUM Total Na mass flux to the surface in g/cm\(^2\)-sec  
SMS Total S mass flux to the surface in g/cm\(^2\)-sec  
RATIO Na to S molar flux ratio at the surface  
ERROR Percent error between experimentally observed and predicted Na\(_2\)SO\(_4\) deposition rates  
GM \(\gamma = \frac{C_D\text{mix}}{C_v}\)  
PR Prandtl number at station "\(\infty\)"
X(I)  Mole fraction of dominant species in flame
TJ   Jet exit static temperature, T_j = T_\infty, K
RHOJ Density of gas mixture at station "j" or equivalently "\infty" in g/cm^3
UJ   Jet exit velocity, U_j, in cm/sec
E1AMIX \mu_{mix} at station "\infty" in g/cm-sec
LAMIX \lambda_{mix} at station "\infty" in cal/cm-sec-K
CMIX c_{p,mix} at station "\infty" in cal/g-sec

A typical output data set is given in Appendix B.
<table>
<thead>
<tr>
<th>F</th>
<th>WA</th>
<th>TW</th>
<th>TO</th>
<th>PO</th>
<th>PJ</th>
<th>DC</th>
<th>WOBS</th>
<th>FSORET</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>2</td>
<td>0.0481</td>
<td>20.0214</td>
<td>900.0</td>
<td>18.55</td>
<td>5.1</td>
<td>1.068</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>DIAW</td>
<td>LW</td>
<td>DJ</td>
<td>TURB</td>
<td>TURIN</td>
<td>TURL</td>
<td>SHAPE</td>
<td>DIV</td>
</tr>
<tr>
<td>1.905</td>
<td>1.2649</td>
<td>2.54</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>XW(I)</td>
<td>6.9810E-14</td>
<td>6.3810E-06</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1280E-20</td>
<td>8.2740E-07</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.6060E-12</td>
<td>2.6170E-13</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.0742E-06</td>
<td>2.4994E-05</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3345E-05</td>
<td>4.8236E-08</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.9210E-31</td>
<td>1.1600E-14</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CFBL THEORY FOR SODIUM SULFATE DEPOSITION RATE

ALL GAS PROPERTIES PERTAIN TO TJ,PJ

IRUN =19
IITYPE = 2
F = 0.048100
TW (K) = 900.000
TO (K) = 1855.500
PO (ATM) = 1.066000
PJ (ATM) = 1.000000
DC = 1.000000
WQBS (MG/HR) = 27.0000
FSORET =T
WA (G/SEC) = 20.02139
DIAH (CM) = 1.905000
LH (CM) = 1.26490
DJ (CM) = 2.54000
TURIN = 0.0000 PERCENT
SHAPE = 0.0000
DIV = 0.0000
I=1=NAOH , I=2=NA , I=3=NA2SO4 , I=6=NaCl

<table>
<thead>
<tr>
<th>I</th>
<th>DCI</th>
<th>NUI(I)</th>
<th>SCl(I)</th>
<th>X(J,I)</th>
<th>X(J,W)</th>
<th>IAU(I)</th>
<th>F(SORET),I</th>
<th>M(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.299050E 01</td>
<td>0.78633E 02</td>
<td>0.10820E 01</td>
<td>0.63810E-05</td>
<td>0.69810E-13</td>
<td>0.73561E-01</td>
<td>1.03738</td>
<td>0.10364E 02</td>
</tr>
<tr>
<td>2</td>
<td>0.37618E 01</td>
<td>0.71538E 02</td>
<td>0.17666E 01</td>
<td>0.63170E-12</td>
<td>0.56200E 00</td>
<td>-0.25133E-01</td>
<td>0.98848</td>
<td>0.14756E 01</td>
</tr>
<tr>
<td>3</td>
<td>0.16316E 01</td>
<td>0.95670E 02</td>
<td>0.69410E 00</td>
<td>0.82790E-06</td>
<td>0.31280E-19</td>
<td>-0.23133E-01</td>
<td>0.91398</td>
<td>-0.64711E-05</td>
</tr>
<tr>
<td>6</td>
<td>0.25178E 01</td>
<td>0.84255E 02</td>
<td>0.12051E 01</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.15291E 00</td>
<td>1.07840</td>
<td>0.00000</td>
</tr>
</tbody>
</table>

APPENDIX B

YNAJ 0.720840E-05 0.728181E-11 0.250422E-04 0.214192E-04

AM = 28.81070
TURB = 1.00000
RE = 12913.625
SUM (G/CM2/SEC) = 0.14063E-06
SMS (G/CM2/SEC) = 0.26371E-06
RATIO = 0.7437
PREDICTED NA2SO4 DEPOSITION RATE (MG/HR) = 11.83948
ERROR (%) = -56.1501
GM = 1.26601
PR = 0.689647
XCM2) = 0.733079
XH2O) = 0.037563
XH20) = 0.094679
XC(O2) = 0.094679
TJ (K) = 1859.6157

RHOC(G/CM*3) UIJ(CM/S) ETAMIX(POISE) LAMIX(CAL/CM/K/S) CMIX(CAL/G/S)
0.188806E-03 0.219344E 05 0.610923E-03 0.290277E-03 0.327682E 00
**APPENDIX C**

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADT</td>
<td>TEMPORARY STORAGE VALUE FOR KT/E</td>
</tr>
<tr>
<td>AII, AJJ</td>
<td>TEMPORARY STORAGE VALUE FOR DATOS(3, I)</td>
</tr>
<tr>
<td>AJ</td>
<td>AREA OF JET NOZZLE (CM×2)</td>
</tr>
<tr>
<td>ALFA(79)</td>
<td>KT/E AS INPUT PERMANENT DATA</td>
</tr>
<tr>
<td>ALPH(A1)</td>
<td>THERMAL DIFFUSION COEFFICIENT FOR TRACE SPECIES I</td>
</tr>
<tr>
<td>AM</td>
<td>MEAN MOLEC. WEIGHT OF GAS MIXTURE (NEGLECTS TRACE SPECIES)</td>
</tr>
<tr>
<td>AMPMIX</td>
<td>THERMAL DIFFUSIVITY OF MIXTURE AT STATION J</td>
</tr>
<tr>
<td>APMW</td>
<td>THERMAL DIFFUSIVITY OF MIXTURE AT STATION W</td>
</tr>
<tr>
<td>AN</td>
<td>AREA OF THE COLLECTOR (TARGET), (CM×2)</td>
</tr>
<tr>
<td>CMIX</td>
<td>CMIX INTERMEDIATE</td>
</tr>
<tr>
<td>CJ</td>
<td>DIMENSIONLESS HEAT CAPACITY</td>
</tr>
<tr>
<td>CHIX</td>
<td>MIXTURE HEAT CAPACITY AT STATION J (CAL/(G×K))</td>
</tr>
<tr>
<td>CHI(I)</td>
<td>RATIO OF EFFECT OF VARIABLE PROP. ON MASS TO HEAT TRANS.</td>
</tr>
<tr>
<td>COEF1</td>
<td>COEFFICIENTS FOR COMPUTING HEAT CAPACITY (1000K&lt;T&lt;5000K)</td>
</tr>
<tr>
<td>COEF2</td>
<td>COEFFICIENTS FOR COMPUTING HEAT CAPACITY (5000K&lt;T&lt;1000K)</td>
</tr>
<tr>
<td>CONDT</td>
<td>THERMAL CONDUCTIVITY (TEMPORARY), (CAL/(CM×SEC×K))</td>
</tr>
<tr>
<td>CP</td>
<td>MIXTURE HEAT CAPACITY AT STATION W (CAL/(G×K))</td>
</tr>
<tr>
<td>DATOS(1, I)</td>
<td>E/K FOR SPECIES I</td>
</tr>
<tr>
<td>DATOS(2, I)</td>
<td>SIGMA FOR SPECIES I (COLLISION DIAMETER PARAMETER)</td>
</tr>
<tr>
<td>DATOS(3, I)</td>
<td>MOLECULAR WEIGHT OF SPECIES I</td>
</tr>
<tr>
<td>DEN</td>
<td>DENOMINATOR</td>
</tr>
<tr>
<td>DIAW</td>
<td>DIAMETER OF THE CYLINDRICAL COLLECTOR (CM)</td>
</tr>
<tr>
<td>DIFF</td>
<td>TEMPORARY STORAGE FOR BINARY DIFF. COEF. (CM×SEC)</td>
</tr>
<tr>
<td>DIV</td>
<td>DIVERGENCE FACTOR FOR NOZZLE JET DEFINED AS THE RATIO</td>
</tr>
<tr>
<td>DIVC</td>
<td>CENTERLINE VELOCITY AT COLLECTOR LOCATION TO</td>
</tr>
<tr>
<td>DIVN</td>
<td>CENTERLINE VELOCITY AT JET EXIT. DEPENDS ON THE JET</td>
</tr>
<tr>
<td>DIVT</td>
<td>DIVERGENCE ANGLE. OPTIONAL INPUT, LEAVE BLANK IF NO</td>
</tr>
<tr>
<td>DJ</td>
<td>DIAMETER OF JET NOZZLE EXIT PLANE (CM)</td>
</tr>
<tr>
<td>DN</td>
<td>DIFF. COEF. OF TRACE SPECIES AT STATION W (CM×SEC)</td>
</tr>
<tr>
<td>E/K</td>
<td>RATIO OF MOLECULAR INTERACTION ENERGY PARAMETER</td>
</tr>
<tr>
<td>EPS0VK</td>
<td>DATOS(1, I) = E/K</td>
</tr>
<tr>
<td>ET</td>
<td>(LENNARD-JONES) TO BOLTZMANN CONSTANT (K)</td>
</tr>
<tr>
<td>EOKI, E0KJ</td>
<td>TEMPORARY STORAGE FOR DATOS(1, I) = E/K</td>
</tr>
<tr>
<td>E0VXJ</td>
<td>E/K, SQUARE ROOT OF E0K1×E0KJ</td>
</tr>
<tr>
<td>EPS0VK</td>
<td>DATOS(1, I) = E/K</td>
</tr>
</tbody>
</table>
ERN = DIFFERENCE BETWEEN PREDICTED AND OBSERVED DEP. RATES
ERROR = PERCENT ERROR BETWEEN PREDICTED AND OBSERVED DEP. RATE
ET = EXPONENTIAL(-TAU), SORET INTERMEDIATE
ETA = MIXTURE VISCOSITY AT STATION W (G/(CM*SEC))
ETAMJ = TEMPORARY VALUE FOR MIXTURE VISCOSITY (G/(CM*SEC))
ETAMIX = MIXTURE VISCOSITY AT STATION J (G/(CM*SEC))
F = FUEL TO AIR RATIO (BY MASS)
FSORET = LOGICAL VALUE PLACED INTO THE INPUT DATA FILE. IF IT IS
SET TO 'T' THEN THE SORET EFFECT WILL BE INCLUDED. IF IT IS
SET TO 'F' THEN THE SORET EFFECT WILL BE EXCLUDED.
GM = GAMMA
GMR = (GAMMA-1.)/GAMMA
G = MASSILJEWA-WILKE FACTOR
ITYPE = NOT USED BY PROGRAM. OPTIONAL FOR USER PURPOSES.
IRUN = NOT USED BY PROGRAM. OPTIONAL FOR USER PURPOSES.
LAMDA = MIXTURE THERMAL CONDUCTIVITY AT STATION W (CAL/(CM*SEC*K))
LAMP = TEMPORARY THERMAL CONDUCTIVITY (CAL/(CM*SEC*K))
LAMIX = MIXTURE THERMAL CONDUCTIVITY AT STATION J (CAL/(CM*SEC*K))
LEJ = LEWIS NUMBER FOR TRACE SPECIES AT STATION J
LOD = RATIO OF MAINSTREAM TURBULENCE LENGTH SCALE TO COLLECTOR DIAM.
LW = LENGTH OF THE CYLINDRICAL COLLECTOR (CM)
LEW = LEWIS NUMBER FOR TRACE SPECIES AT STATION W
M = DATOS3(1)=MOLECULAR WEIGHT OF SPECIES I
M(I) = EQUIVALENT NA2SO4 DEPOSITION RATE OF TRACE SPECIES MASS
NU = NUSSELT NUMBER FOR MASS TRANSFER
QEDT, OVDT = COLLISION INTEGRALS
QED(79) = COLLISION INTEGRAL FOR MASS DIFFUSIVITY
QIE (79) = COLLISION INTEGRAL FOR VISCOSITY OR THERMAL CONDUCTIVITY
PHI = F(TURB) INTERMEDIATE RELATED TO TURBULENCE INTENSITY
PJ = JET EXIT PLANE PRESSURE (ATM)
PO = STAGNATION PRESSURE (ATM)
PR = PRANDTL NUMBER AT STATION J
PROV = INTERMEDIATE IN CALCULATION OF ETAMIX
PSI = F(TURB) INTERMEDIATE RELATED TO TURBULENCE LENGTH SCALE
R = GAS CONSTANT=1.9872 CAL/(GMOLE*K)
RATIO = SODIUM TO SULFUR MOLAR FLUX RATIO
RE = REYNOLDS NUMBER AT COLLECTOR LOCATION
REJ = REYNOLDS NUMBER AT OUTLET OF JET
RHOJ = DENSITY OF MIXTURE AT JET OUTLET
RHOW = DENSITY OF MIXTURE AT WALL
SC = SCHMIDT NUMBER FOR TRACE SPECIES AT STATION J
SHAPE = SHAPE FACTOR (CENTERLINE VELOCITY)/(AVERAGE VELOCITY)
S = Optional input. Leave blank if no information available.
SIGMA = MOLECULAR SIZE PARAMETER (LENNARD-JONES)
SIGI, SIGJ = TEMPORARY STORAGE FOR DATOS(2,I)=SIGMA
SIGK, SIGL = TEMPORARY STORAGE FOR DATOS(2,I)=SIGMA
SIG = SIGMA VALUE FOR SPECIES I
SM(I) = MASS FLUX OF TRACE SPECIES I (G/CM**2/SEC)
SS = TOTAL SODIUM MASS FLUX TO THE SURFACE (G/CM**2/SEC)
SUM = TOTAL SODIUM MASS FLUX TO THE SURFACE (G/CM**2/SEC)
T = TEMPERATURE (K)
TAU = SORET SUCTION PARAMETER FOR SPECIES I
TO = STAGNATION TEMPERATURE (K)
THERM = THERMAL DIFFUSION FACTOR FOR SPECIES I
TJ = JET (STATIC) TEMPERATURE (K)
TURB = TURBULENCE ENHANCEMENT FACTOR. OPTIONAL INPUT.
A) LEAVE BLANK IF NO CONSIDERATION REQUIRED.
B) GIVE YOUR OWN ESTIMATE IF INFORMATION AVAILABLE, BUT
C) GIVE YOUR ESTIMATE IF PROGRAM CONSIDERATION DESIRED,
TURIN = PERCENT MAINSTREAM INTENSITY. OPTIONAL INPUT.
A) LEAVE BLANK IF NO CONSIDERATION REQUIRED.
B) LEAVE BLANK IF YOU SUPPLY YOUR OWN 'TURB'.
C) GIVE YOUR ESTIMATE IF PROGRAM CONSIDERATION DESIRED,
TURL = MAINSTREAM LENGTH SCALE (MACRO), CM. OPTIONAL INPUT.
A) LEAVE BLANK IF NO CONSIDERATION REQUIRED.
B) LEAVE BLANK IF YOU SUPPLY YOUR OWN 'TURB'.
C) GIVE YOUR ESTIMATE IF PROGRAM CONSIDERATION DESIRED,
TW = WALL TEMPERATURE (K)
UJ = JET EXIT VELOCITY
VISC(I) = VISCOSITY OF SPECIES (G/(CM*SEC))
VI = NUMBER OF SODIUM ATOMS IN TRACE SPECIES I
WA = AIR FLOW RATE (G/SEC)
WJ = TEMPORARY STORAGE VALUES FOR DATOS(3,I)
WRED = PREDICTED NA2504 DEPOSITION RATE (MG/HR)
WBS = EXPERIMENTALLY OBSERVED NA2504 DEPOSITION RATE (MG/HR)
X(I) = MOLE FRACTION OF SPECIES I IN FLAME
XI = TURB=RE/100, F(TURB) INTERMEDIATE
XH(I) = MOLE FRACTION OF SPECIES I AT WALL
X(4) = MOLE FRACTION OF DOMINANT SPECIES IN MIXTURE
YMAJ = TOTAL SODIUM MOLE FRACTION IN FLAME
YMAN = TOTAL SODIUM MOLE FRACTION AT STATION W
YSJ = TOTAL SULFUR MOLE FRACTION IN FLAME
YSW = TOTAL SULFUR MOLE FRACTION AT STATION W
0016300 C SODIUM VERSION OF CHEMICALLY FROZEN BOUNDARY LAYER THEORY
0016400 C USED FOR SODIUM SULFATE DEPOSITION RATE CALCULATIONS
0016500 C
0016600 C MAIN PROGRAM
0016700 C
0016800 C REAL LAMIX,LAMDA,LEW,LEJ,NU,LW
0016900 C REAL M(7)
0017000 C DIMENSION V(7),XW(7),XJ(7),SM(7),ALPHA(7),CMH(7)
0017100 C COMMON/V/A/DATE(3,5)
0017200 C LOGICAL FSORET
0017300 C COMMON FSORET
0017400 C COMMON/GFR/X(4)
0017500 C DATA V/ 1.0 , 1.0 , 2.0 , 0.0 , 0.0 , 1.0 , 0.0 /
0017600 C
0017700 C WRITE(6,490)
0017800 C 490 FORMAT(10X,'CFBL THEORY FOR SODIUM SULFATE DEPOSITION RATE',/)
0017900 C WRITE(6,900)
0018000 C 900 FORMAT(10X,'ALL GAS PROPERTIES PERTAIN TO TJ,PJ',/)
0018100 C
0018200 C**********************************************************************************************
0018300 C**********************************************************************************************
0018400 C PAY SPECIAL ATTENTION TO THE FORMAT OF THE INPUT PARAMETERS
0018500 C SEE 'VARIABLE NAME LIST' ABOVE FOR DESCRIPTION OF VARIABLES
0018600 C**********************************************************************************************
0018700 C**********************************************************************************************
0018800 C DOMINANT SPECIES IN THE MIXTURE
0018900 C 1=NITROGEN , 2=OXYGEN , 3=WATER , 4=CARBON DIOXIDE
0019000 C
0019100 C TRACE SPECIES IN THE MIXTURE
0019200 C 1=NAOH , 2=NA , 3=NA2SO4 , 4=SO2 , 5=SO3 , 6=NACL , 7=H2S
0019300 C
0019400 C
0019500 C INPUT : I
0019600 C
0019700 C READ(5,1)IRUN,ITYPE,F,WA,TW,T0,PO,PJ,DC,W3BS,FSORET
0019800 1 FORMAT(2I2,8F9.0,3X,L1)
0019900 C INPUT : 2
0020000 C
0020100 C READ(5,998) DIAW,LW,DJ,TURB,TURIN,TURL,SHAPE,DIV
0020200 C 998 FORMAT(8F10.0)
0020300 C
0020400 C INPUT : 3
0020500 C
0020600 C DO 502 I=1,7
0020700 C 502 CONTINUE
0020800 C
0020900 C READ(5,2) XW(I),XJ(I),CMH(I)
0021000 2 FORMAT(2E15.4,F10.0)
0021100 C
0021200 C OUTPUT OF INPUT PARAMETERS
0021300 C
0021400 C WRITE(6,978) IRUN,ITYPE,F,TW,T0,PO,PJ,DC,W3BS,FSORET
0021500 978 FORMAT(10X,'IRUN =',I2,/',10X,'ITYPE =',I2,/',10X,'F =', 21
C CALCULATE JET EXIT TEMPERATURE

AM = DATOS(3,1)*X(1) + DATOS(3,2)*X(2) + DATOS(3,3)*X(3) + DATOS(3,4)*X(4)

C COMPUTE THE AVERAGE MOLECULAR WEIGHT OF MIXTURE

C (NEGLCT THE TRACE SPECIES)

C MOLE FRACTIONS OF DOMINANT SPECIES AFTER COMBUSTION

C CALCULATE JET EXIT TEMPERATURE, (K), AND VELOCITY, (CM/SEC)

C CALL CALMIX(TO, AM, CMIX)

C DEFINE VELOCITY

GM = F05/AM
0027100 AJ=3.14159*DJ*(DJ/6).
0027200 TJ=T0*(PJ/P0)*KMR
0027300 IF(DC.EQ.0.00) DC=1.00
0027300 UJ=((2.057*TI)/(PJ*AM))*(W*AM(1+F))/(AJ*DC)
0027400 C
0027500 C CALCULATE MIXTURE PROPERTIES AT STATIONS J AND W
0027600 C
0027700 rhoj=pi*am/tj/8.2.057
0027800 rhoj=pi*am/tw/8.2.057
0027900 CALL CALMIX(tj,am,cmix)
0028000 CALL CALMIX(tw,am,cp)
0028100 CALL MIXPRO(tj,etamix,lamix)
0028200 CALL MIXPRO(tw,eta,lambda)
0028300 APHIX=LAMIX/C MIX/RHOJ
0028400 APHIW=EW/CP/RHOW
0028500 PR=CMIX*ETAMIX/LAMIX
0028600 C
0028700 C CALCULATE REYNOLDS NUMBER
0028800 C
0028900 IF(SHAPE.EQ.0.0) SHAPE=1.0
0029000 IF(DIV.EQ.0.0) DIV=1.0
0029100 REJ=RHORJ*UJ*DIAM/ETAMIX
0029200 RE=REJ*SHAPE*DIV
0029300 C
0029400 C GIVE VALUES OF E/K, SIGMA AND MOLEC. WEIGHT FOR TRACE SPECIES I
0029500 C
0029600 DO 10 I=1,7
0029700 25 IF(I.GT.1) GO TO 5
0029800 DATOS(1,5)=1962.0
0029900 DATOS(2,5)=3.804
0030000 DATOS(3,5)=39.9971
0030100 GO TO 11
0030200 5 IF(I.GT.2) GO TO 6
0030300 DATOS(1,5)=1375.
0030400 DATOS(2,5)=3.567
0030500 DATOS(3,5)=22.98977
0030600 GO TO 11
0030700 6 IF(I.GT.3) GO TO 7
0030800 DATOS(1,5)=2221.
0030900 DATOS(2,5)=5.00
0031000 DATOS(3,5)=142.0371
0031100 GO TO 11
0031200 7 IF(I.GT.4) GO TO 8
0031300 DATOS(1,5)=335.4
0031400 DATOS(2,5)=4.112
0031500 DATOS(3,5)=64.0588
0031600 GO TO 11
0031700 8 IF(I.GT.5) GO TO 9
0031800 DATOS(1,5)=431.4
0031900 DATOS(2,5)=6.207
0032000 DATOS(3,5)=80.0582
0032100 GO TO 11
0032200 9 IF(I.GT.6) GO TO 12
0032300 DATOS(1,5)=1989.
C DIFFUSION COEFFICIENT OF TRACE SPECIES AT STATIONS J AND W

C LEWIS NUMBER OF TRACE SPECIES AT STATIONS J AND W

C SCHMIDT NUMBER OF TRACE SPECIES AT STATION J

C MASS TRANS. NUSSELT NO. (PERIMETER-AVERAGED, CYLINDRICAL COLLECTOR)

C CALCULATE NA2SO4 DEPOSITION RATE CONTRIBUTED FROM SPECIES I

C PRINT INTERIM OUTPUT

C IF(CMH(I).EQ.0.0) CMH(I)=1.0

C IF(V(I).EQ.0.0) GO TO 10

C IF(V(I).EQ.0.0) GO TO 100

C GO TO 100

C GO TO 546
003780  546 WRITE(6,550) I,DA,NU,SC,XJ(I),XW(I),TAU,THERM,M(I)
003790  550 FORMAT(1X,11,6E15.5,F15.5,2E15.5,/
003800          10 CONTINUE
003810 C   COMPUTE TOTAL SODIUM(NA) AND SULFUR(S) MASS FLUX
003820 C   SUM=J(NA), SMS=J(S)
003830 C   SUM=SM(1)*22.98977/39.9971+SM(2)*1.0+SM(3)*2.*22.98977
003840 C   /*142.0371*6*22.98977/58.4428
003850 C   SMS=SM(3)*32.06/142.0371+SM(4)*32.06/64.0588+SM(5)*
003860          *32.06/80.0582+SM(7)*32.06/34.0758
003870 C   COMPUTE SODIUM TO SULFUR MOLAR FLUX RATIO
003880 C   RATIO=SUM/SMS*32.06/22.98977
003890 C   COMPUTE TOTAL NA AND S MOLE FRACTIONS AT STATIONS J AND W
003900 C   YNAJ=XJ(1)+XJ(2)+(XJ(3)+XJ(4)+XJ(5)+XJ(6)
003910 C   YNAW=XW(1)+XW(2)+XW(3)+XW(4)+XW(6)
003920 C   YSJ=XJ(3)+XJ(4)+XJ(5)+XJ(7)
003930 C   YSW=XW(3)+XW(4)+XW(5)+XW(7)
003940 C   WRITE(6,211)
003950 C   211 FORMAT(/,18,'YNAJ',T24,'YNAW',T40,'YSJ',T57,'YSW')
003960 C   WRITE(6,212)YNAJ,YNAW,YSJ,YSW
003970 C   212 FORMAT(F4.16,1/
003980 C   CALCULATE NA2SO4 DEPOSITION RATE (MG/HR)
003990 C   WPR ED=M(1)+M(2)+M(3)+M(6)
004000 C   COMPUTE PERCENT ERROR BETWEEN M(PRED) AND M(OBS)
004010 C   ERR=WPR ED-WOBS
004020 C   ERROR=ERR/WOBS*100.
004030 C   PRINT RESULTS
004040 C   WRITE(6,4)AM,TURB,RE,SUM,SMS,RATIO,WPR ED,ERROR,GM,PR,X(1),X(2),X(3),-
004050 C   X(X(4),T)
004060 C   4 FORMAT(/,10X,'AM =',F10.5,/,10X,'TURB =',F10.5,/,10X,'RE =',F10.3,/-
004070 C   10X,'SUM (G/Cm**2/SEC) =',E13.5,/,10X,'SMS (G/Cm**2/SEC) =',E13.5,/-
004080 C   10X,'RATIO =',F10.4,/,10X,= -
004090 C   X'PREDICTED NA2SO4 DEPOSITION RATE (MG/HR) =',F10.5,/,10X,= -
004100 C   X'ERROR (%) =',F10.4,/,10X,= PR =',F10.6,/,10X,= -
004110 C   X'X(H2) =',F10.6,/,10X,=X(02) =',F10.6,/,10X,=X(H20) =',F10.6,/,10X,= -
004120 C   X'X(CO2) =',F10.6,/,10X,=TJ (K) =',F10.4,/-
004130 C   WRITE(6,950)
004140 C   950 FORMAT(/,T5,'RHOJ(G/CM**3)',T21,'UJ(CM/S)',T37,'ETAMIX(POISE) -
004150 C   C',T52,'LAMIX(CAL/CM/K/S)',T73,'CHIX(CAL/G/S)')
004160 C   WRITE(6,951)RHOJ,UJ,ETAMIX,LAMIX,CMIX
004170 C   951 FORMAT(4E16.6,4X,E16.6,1/
004180 C   STOP
004190 C
SUBROUTINE PARAM (J, EPSOVK, SIG2, M)

SUBROUTINE PARAM GIVES THE VALUES OF E/K, SIGMA AND MOLECULAR WEIGHT

REAL M
COMMON/VA/DATOS(3,5)
EPSOVK=DATOS(1, J)
SIG2=DATOS(2, J)
M=DATOS(3, J)
RETURN
END

SUBROUTINE CALESL(J, T, CJ)

THIS SUBROUTINE CALCULATES DIMENSIONLESS HEAT CAPACITY FROM A CURVE FIT VALID FOR 300K < T < 1000K AND 1000K < T < 5000K

DIMENSION COEF(5,4), COEF2(5,4)

DATA COEF1 / 0.28532899E+01, 0.16022128E-02, -0.62936893E-06, -
0.11441022E-09, -0.78057465E-14,
0.36122139E+01, 0.74853166E-03, -0.19820647E-06,
0.33749005E-10, -0.23907374E-14,
0.26340654E+01, 0.31121899E-02, -0.90278449E-06,
0.12673054E-09, -0.09164732E-14,
0.44608041E+01, 0.30981719E-02, -0.12392571E-05,
0.22741325E-09, -0.15525954E-13/

DATA COEF2 / 0.37044177E+01, 0.16218753E-02, 0.28670392E-05,
0.12028885E-08, 0.13954677E-13,
0.37637135E+01, 0.30233634E-02, 0.99429751E-05,
0.98189101E-08, 0.33031825E-11,
0.41675564E+01, 0.18106868E-02, 0.59450878E-05,
0.48670871E-08, 0.15284144E-11,
0.24007797E+01, 0.87350957E-02, -0.66070878E-05,
0.20021861E-08, 0.63274039E-15/

IF(T.GT.1000) GO TO 10

CJ=COEF2(5,J)*T**4+COEF2(4,J)*T**3+COEF2(3,J)*T**2+COEF2(2,J)*T

**+COEF2(1,J)

GO TO 20

10 CJ=COEF1(5,J)*T**4+COEF1(4,J)*T**3+COEF1(3,J)*T**2+COEF1(2,J)*T

**+COEF1(1,J)

RETURN
END

SUBROUTINE CALMIX(T, AM, CMIX)

SUBROUTINE CALMIX PROVIDES MIXTURE HEAT CAPACITY IN CAL/(G*K)
```
0043600 COMMON/GFR/X(4)
0043700 C=0.
0043800 DO 8 J=1,4
0043900 CALL CAESL(J,T,CJ)
004400  C=C+X(J)*1.9872
0044100 8 CONTINUE
0044200 CMIX=C/AM
0044300 RETURN
0044400 END
0044500 C
0044600 C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
0044700 C
0044800 C SUBROUTINE COLINT(I1,J1,T,OM,T1,OMT,OMT1)
0044900 C
004500 C THIS SUBROUTINE GIVES COLLISION INTEGRALS, VISCOSITY AND THERMAL
0045100 C CONDUCTIVITY OF SPECIES USING CHAPMAN-ENSKOG THEORY
0045200 C
0045300 C REAL M
0045400 DIMENSION OME(79), ALPA(79), OMED(79)
0045500 0.300, 0.350, 0.400, 0.450, 0.500, 0.550, 0.600, 
0045600 0.650, 0.700, 0.750, 0.800, 0.850, 0.900, 0.950, 
0045700 1.000, 1.050, 1.100, 1.150, 1.200, 1.250, 1.300, 
0045800 1.350, 1.400, 1.450, 1.500, 1.550, 1.600, 1.650, 
0045900 1.700, 1.750, 1.800, 1.850, 1.900, 1.950, 2.000, 
004600 2.100, 2.200, 2.300, 2.400, 2.500, 2.600, 2.700, 
0046100 2.800, 2.900, 3.000, 3.100, 3.200, 3.300, 3.400, 
0046200 3.500, 3.600, 3.700, 3.800, 3.900, 4.000, 4.100, 
0046300 4.200, 4.300, 4.400, 4.500, 4.600, 4.700, 4.800, 
0046400 4.900, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00, 
0046500 20.00, 30.00, 40.00, 50.00, 60.00, 70.00, 80.00, 
0046600 90.00, 100.0/ 
0046700 DATA OME/ 2.7850, 2.6280, 2.4920, 2.3680, 2.2570, 2.1560, 
0046800 2.0650, 1.9820, 1.9080, 1.8410, 1.7800, 1.7250, 
0046900 1.6750, 1.6290, 1.5870, 1.5490, 1.5140, 1.4820, 
004700 1.4520, 1.4260, 1.3990, 1.3750, 1.3530, 1.3330, 
0047100 1.3140, 1.2960, 1.2790, 1.2640, 1.2480, 1.2340, 
0047200 1.2210, 1.2090, 1.1970, 1.1860, 1.1750, 1.1560, 
0047300 1.1380, 1.1220, 1.1070, 1.0930, 1.0810, 1.0690, 
0047400 1.0580, 1.0480, 1.0390, 1.0300, 1.0220, 1.0140, 
0047500 1.0070, 0.9999, 0.9932, 0.9870, 0.9811, 0.9755, 
0047600 0.9700, 0.9649, 0.9600, 0.9563, 0.9507, 0.9464, 
0047700 0.9422, 0.9382, 0.9343, 0.9305, 0.9269, 0.8963, 
0047800 0.8727, 0.8538, 0.8379, 0.8242, 0.7432, 0.7005, 
0047900 0.6718, 0.6504, 0.6335, 0.6194, 0.6076, 0.5973, 
004800 0.5882/ 
0048100 DATA OME/ 2.6620, 2.4760, 2.3180, 2.1840, 2.0660, 1.9660, 
0048200 1.8770, 1.7980, 1.7290, 1.6670, 1.6120, 1.5620, 
0048300 1.5170, 1.4760, 1.4390, 1.4060, 1.3750, 1.3460, 
0048400 1.3200, 1.2960, 1.2730, 1.2530, 1.2330, 1.2150, 
0048500 1.1980, 1.1820, 1.1670, 1.1530, 1.1400, 1.1280, 
0048600 1.1160, 1.1050, 1.0940, 1.0840, 1.0750, 1.0570, 
0048700 1.0410, 1.0260, 1.0120, 0.9996, 0.9878, 0.9770, 
0048800 0.9672, 0.9576, 0.9490, 0.9406, 0.9328, 0.9256, 
0048900 0.9186, 0.9120, 0.9058, 0.8998, 0.8942, 0.8888, 
```
* 0.8836, 0.8788, 0.8740, 0.8694, 0.8652, 0.8610, -
0.8568, 0.8530, 0.8492, 0.8456, 0.8422, 0.8124, -
0.7896, 0.7712, 0.7556, 0.7424, 0.6640, 0.6232, -
0.5960, 0.5756, 0.5596, 0.5464, 0.5352, 0.5256, -
0.5170/

005400

IF(JJ.EQ.0)GO TO 67
005410 CAL PARAM(JJ,EOKI,SIgL,AAJ)
005420 CALL PARAM(JJ,EOKI,SIgL,AAJ)
005430 M=(AAJ+AJJ)/2.
005440 SIGZ=(SIGL+SIGK)/2.
005450 EOVKIJ=SQR(EOKJ*EOKI)
005460 ADT=T/EOVKIJ
005470 GO TO 68
005480 CALL PARAM(JJ,EPSOVK,SIgL,M)
005490 ADT=T/EPSOVK
005500 67 J=3
005510 IF(ADT-ALPA(J))112,111,110
005520 110 J=J+1
005530 IF(J.LE.79)GO TO 69
005540 GO TO 204
005550 111 OVDT=OME(J)
005560 OME=OME(J)
005570 GO TO 200
005580 112 B=(ADT-ALPA(J-1))/(ALPA(J)-ALPA(J-1))
005590 OVDT=B*(B+1.)*OME(J-2)/2.+(1.-B*2.)*OME(J-1)+B*(B+1.)*OMED(J)/2.
005600 OME=B*(B+1.)*OME(J-2)/2.+(1.-B*2.)*OME(J-1)+B*(B+1.)*OMED(J)/2.
005610 *
005620 GO TO 200
005630 204 OVDT=0.5882*((ADT/100.)*(-0.17))
005640 OME=0.5170*((ADT/100.)*(-0.15))
005650 ETA=26.693/SQRT(MT)/(SIGL*2.*OVDT)*1.E-06
005660 CALL CALES(I1,T,CR)
005670 CONDT=(1.9872/M)*(15./4.+.32*(CR-5./2.))*ETA
005680 RETURN
005690 END

005700 C
005710 C SUBROUTINE MIXPRO(T,ETAMIX, LAMIX)
005720 C THIS SUBROUTINE PROVIDES MIXTURE VISCOSITY AND THERMAL CONDUCTIVITY
005730 C
005740 C

005750 C

005760 C
005770 C
005780 C
005790 C
005800 C

005810 C

005820 C

005830 C

005840 C

005850 C

005860 C

005870 C

005880 C

005890 C

005900 C

005910 C

005920 C

005930 C

005940 C

005950 C

005960 C

005970 C

005980 C
DO 18 I=1,4
PROV=0.
DO 28 J=1,4
G=1./((2.*SQRT((I.+DATOS(I,3))/DATOS(I,3,3)))*(-0.5))*((1.
+SQRT(VISC(I)/VISC(J))*SQRT(DATOS(I,3,3)/DATOS(I,3,1))))**2
PROV=PROV+G*X(J)
28 CONTINUE
END

SUBROUTINE COEDIF(T,P,I,J,D)
CALL COLINT(I,J,T,OVDT,ETA,COND,OMEDT)
CALL PARAM(I,EPSONK,SIK,WI)
CALL PARAM(J,EPSONK,SIJ,WJ)
SIG=1./2.*(SIK+SIJ)
D=0.001583*SQRT((T*3.)*(1./WI+1./WJ))/(P*OMEDT*(SIK**2))
RETURN
END

SUBROUTINE DIF(T,P,DA)
DEN=0.0
DO 101 J=1,4
K=5
CALL COEDIF(T,P,K,J,DIF)
DEN=DEN+X(J)/DIF
101 CONTINUE
DA=1./DEN
RETURN
END

SUBROUTINE TMDF(I,TW,TO,LEW,ALPHA,TAU,THERM)
SUBROUTINE TMDF CALCULATES THERMAL DIFFUSION EFFECT, F(SORET),
LABELLED AS 'THERM'. IF FSORET IS FALSE, THERM=1.0.
LOGICAL FSORET
COMMON FSORET
REAL LEW
DIMENSION ALPHA(7)
IF(FSORET) GO TO 10
IF(FSORET) GO TO 10
THERM=1.0
TAU=0.0
GO TO 20
TAU=ALPHA(I)*LEW*0.4*(TO-TW)/TW
ET=EXP(-TAU)
THERM=TAU/(1.-ET)
20 RETURN
END

SUBROUTINE HUM(TW,TO,RE,SC,NU)
C
C SUBROUTINE HUM CALCULATES PERIMETER AVERAGED NUSSLETT NUMBER
C INCLUDING EFFECTS OF MACH NUMBER AND VARIABLE PROPERTIES
C
REAL NU
NU=(0.40*SQRT(RE)+0.06*RE*(2./3.))*(SC*0.4)*
1*(TO/TW)**(-0.06)
RETURN
END

SUBROUTINE NUM(TW,TO,RE,SC,NU)
C
C SUBROUTINE NUM CALCULATES PERIMETER AVERAGED NUSSLETT NUMBER
C INCLUDING EFFECTS OF MACH NUMBER AND VARIABLE PROPERTIES
C
REAL NU
NU=(0.40*SQRT(RE)+0.06*RE*(2./3.))*(SC*0.4)*
1*(TO/TW)**(-0.06)
RETURN
END

SUBROUTINE TURBL(RE,TURB,TURIN,TURLDIAW)
C
C SUBROUTINE TURBL CALCULATES EFFECT OF MAINSTREAM TURBULENCE
C
REAL LOB
IF(TURIN.NE.0.0) GO TO 5
IF(TURIN.EQ.0.0) GO TO 10
GO TO 30
LORD=TURLDIAW
5 TURB=I.0
GO TO 30
TURB=I.0
GO TO 30
TURB=I.0
GO TO 30
END

C
C END OF PROGRAM

30
REFERENCES


Figure 1. - Station nomenclature.
**Computer Program for the Calculation of Multicomponent Convective Diffusion Deposition Rates from Chemically Frozen Boundary Layer Theory**

Süleyman A. Gökoğlu, Bor-Kuan Chen* and Daniel E. Rosner

Analex Corporation and Yale University
21000 Brookpark Rd. Chemical Engineering Dept.
Cleveland, Ohio New Haven, Connecticut
44135 06520

National Aeronautics and Space Administration
Washington, D.C. 20546

The computer program developed based on multicomponent chemically frozen boundary layer (CFBL) theory for calculating vapor and/or small particle deposition rates is documented. A specific application to perimeter-averaged Na₂SO₄ deposition rate calculations on a cylindrical collector is demonstrated. The manual includes a typical program input and output for users.

**Abstract**

Deposition; CVD; Corrosion; Heat and mass transfer; Boundary layer; Computer program

Unclassified - unlimited

Deposition; CVD; Corrosion; Heat and mass transfer; Boundary layer; Computer program

Unclassified