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Laminar axisymmetric multicomponent buoyant plumes in a thermally stratified medium

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Abstract—This paper presents the results of a numerical study of laminar axisymmetric plumes that emanate from a source of combined buoyancy due to simultaneous heat and mass diffusion. The ambient is considered to be stably stratified through a linear temperature increase with height. Boundary layer and Boussinesq approximations are incorporated in the governing equations of mass, momentum, energy and species conservation. These equations are solved using an explicit finite-difference numerical scheme. Velocity, temperature and concentration fields are obtained for a range of Pr and Sc. The basic physical mechanisms that underlie these flows are described. The results indicate a complex interaction between buoyancy ratio, thermal stratification, and Prandtl and Schmidt numbers.

INTRODUCTION

FREE BOUNDARY flows, such as plumes and jets, are important in many applications, for example, buoyant sources in enclosures, heat and material rejection to enclosed spaces, and effluent discharges into water bodies and atmosphere. There are many analytical, experimental and numerical studies concerning plumes originating from a thermal source alone [1], but there are few studies concerned with a source that contains an additional buoyant mechanism (like mass diffusion). Mollendorf and Gebhart [2] presented a similarity solution for plumes with combined buoyancy. It was shown that similarity exists for power-law and exponential centreline variation of temperature and concentration.

In natural convection flows, the ambient is often stratified, with lighter fluid overlaying denser fluid. This density variation may be due to a temperature distribution, or variation of the concentrations of one or more diffusing species, or both. Since temperature as well as the concentration of species contribute to density, stability requires that the net density should decrease with height in a gravity field, irrespective of the individual contributions of temperature and concentration. Wirtz and Chiu [3] presented a theoretical and experimental study (for $Pr < 1$) for laminar thermal plume rise in a thermally stratified environment. Hubbell and Gebhart [4] considered the flows from a heated horizontal cylinder in a concentration stratified environment.

In the present work, we consider laminar axisymmetric plumes that emanate from a source of constant temperature and concentration of a single diffusing species. In the ambient, we assume that the density is stably stratified with temperature variation alone, and that the concentration is constant. For a fluid whose density decreases with temperature, stable stratification corresponds to an increase in temperature with height.

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ANALYSIS

Consider a point source of temperature t_0 and concentration c_0 of diffusing species (Fig. 1). The ambient is stable and thermally stratified, with temperature linearly increasing with height. Linear ambient stratification is considered, since it is often encountered in practice [5, 6]. The concentration in the ambient is constant. The coordinate system and boundary conditions are shown in Fig. 1. We consider flows that occur vertically upwards. This requires that the net buoyant force acts upwards. At the source, the temperature (t_0) is greater than that of the ambient ($t_{\infty,0}$). As the flow proceeds downstream, the centreline temperature decays while the ambient temperature increases. The combined effect is that the thermal buoyancy decreases rapidly in the flow downstream. If the ambient is highly stratified, i.e. if the temperature in the ambient exceeds the centreline temperature at a particular x location (Fig. 1), the thermal buoyancy further downstream is negative. In that case, for the flow to proceed upwards, the buoyancy due to concentration difference should be higher than thermal buoyancy and act vertically upwards.

Boundary layer analyses are known to be valid for plume flows originating from both point and line sources [1, 2, 7]. The governing equations for laminar axisymmetric flows resulting from the combined buoyancy effects of thermal and mass diffusion can be written as

$$\frac{\partial}{\partial x}(yu)+\frac{\partial}{\partial y}(yv)=0 \qquad (1)$$

NOMENCLATURE

B	buoyancy ratio
c	concentration of the diffusing species
C	non-dimensional concentration
D	diffusion coefficient
g	gravitational acceleration
p	pressure
Pr	Prandtl number
S	thermal stratification parameter
Sc	Schmidt number
t	temperature
T	non-dimensional temperature
u, v	velocity components in axial and radial direction, respectively
U, V	non-dimensional velocity components
x, y	axial and radial space coordinates, respectively
X, Y	non-dimensional space coordinates.

Greek symbols

α	thermal diffusivity
β	coefficient of thermal expansion
β^*	concentration expansion coefficient
ν	kinematic viscosity
ρ	density
τ	time
τ^*	non-dimensional time.

Subscripts

0	location indicating the source
∞	location indicating far away from the plume axis
$\infty, 0$	location indicating far away from the source at $x = 0$.

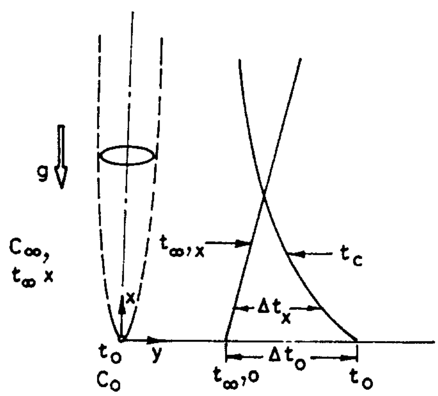

FIG. 1. Sketch showing plume geometry, temperature boundary conditions and coordinates.

$$\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\nu}{y}\frac{\partial}{\partial y}\left(y\frac{\partial u}{\partial y}\right)+g\beta(t-t_{\infty,x})-g\beta^*(c-c_\infty) \quad (2)$$

$$\frac{\partial t}{\partial \tau}+u\frac{\partial t}{\partial x}+v\frac{\partial t}{\partial y}=\frac{\alpha}{y}\frac{\partial}{\partial y}\left(y\frac{\partial t}{\partial y}\right) \quad (3)$$

$$\frac{\partial c}{\partial \tau}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=D\frac{1}{y}\frac{\partial}{\partial y}\left(y\frac{\partial c}{\partial y}\right). \quad (4)$$

In the above formulation Boussinesq approximations are incorporated and the species concentration levels are assumed to be small. The volumetric coefficient of expansion with concentration, β^*, is defined as $(1/\rho)(\partial\rho/\partial c)_{t,p}$ [8], while the thermal expansion coefficient is defined as $(-1/\rho)(\partial\rho/\partial t)_{c,p}$. Hence the two buoyant forces aid each other when the quantities $(t_0-t_{\infty,x})$ and (c_0-c_∞) have opposite signs.

The following variables are defined to make the equations dimensionless:

$$X = x\left(\frac{g\beta\Delta t_0}{\nu^2}\right)^{1/3}, \quad Y = y\left(\frac{g\beta\Delta t_0}{\nu^2}\right)^{1/3}$$

$$\tau^* = \frac{\tau}{\nu^{1/3}}(g\beta\Delta t_0)^{2/3}, \quad U = \frac{u}{(\nu g\beta\Delta t_0)^{1/3}}$$

$$V = \frac{v}{(\nu g\beta\Delta t_0)^{1/3}}, \quad T = \frac{t-t_{\infty,x}}{t_0-t_{\infty,0}}$$

and

$$C = \frac{c-c_\infty}{c_0-c_\infty}. \quad (5)$$

In the above definitions, t_0 is the temperature and c_0 the concentration at the source, and $\Delta t_0 = (t_0 - t_{\infty,0})$.

The non-dimensional conservation equations are then obtained as

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{V}{Y}=0 \quad (6)$$

$$\frac{\partial U}{\partial \tau^*}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\frac{1}{Y}\frac{\partial U}{\partial Y}+\frac{\partial^2 U}{\partial Y^2}+T-BC \quad (7)$$

$$\frac{\partial T}{\partial \tau^*}+U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}+SU=\frac{1}{Pr}\left(\frac{1}{Y}\frac{\partial T}{\partial Y}+\frac{\partial^2 T}{\partial Y^2}\right) \quad (8)$$

$$\frac{\partial C}{\partial \tau^*}+U\frac{\partial C}{\partial X}+V\frac{\partial C}{\partial Y}=\frac{1}{Sc}\left(\frac{1}{Y}\frac{\partial C}{\partial Y}+\frac{\partial^2 C}{\partial Y^2}\right) \quad (9)$$

where $B = \beta^*(c_0-c_\infty)/\beta(t_0-t_{\infty,0})$ is defined as the buoyancy ratio and

$$S = \frac{1}{\Delta t_0}\frac{\mathrm{d}t_{\infty,x}}{\mathrm{d}X}$$

is the thermal stratification parameter. It is observed from the non-dimensional momentum equation (7), and from the definition of B, that the two buoyant mechanisms aid each other when $B < 0$, and oppose each other when $B > 0$.

The following non-dimensional boundary and initial conditions are prescribed:

$$\begin{aligned}
&\tau^* > 0 \\
&X > 0,\ \frac{\partial U}{\partial Y} = \frac{\partial T}{\partial Y} = \frac{\partial C}{\partial Y} = V = 0 \quad \text{for } Y = 0 \\
&U = T = C = 0 \quad \text{for } Y \to \infty \\
&X = 0,\ \ T = C = 1.0 \quad \text{for } Y = 0 \\
&T = C = U = 0 \quad \text{for } Y > 0 \\
&\tau^* = 0 \\
&U = V = T = C = 0 \quad \text{for all } X \text{ and } Y.
\end{aligned} \tag{10}$$

The centreline quantities of U, T and C along the axis of the plume have to be obtained as a part of the solution. $Y = 0$ refers to the centreline position, and for this, certain quantities in the governing equations (6)–(9) become indeterminate. Hence, separate equations are obtained for the centreline by making use of L'Hospital's rule and the boundary conditions. The non-dimensional centreline equations can then be written as

$$\frac{\partial U}{\partial \tau^*} + U\frac{\partial U}{\partial X} = 2\frac{\partial^2 U}{\partial Y^2} + T - BC \tag{7a}$$

$$\frac{\partial T}{\partial \tau^*} + U\frac{\partial T}{\partial X} + SU = \frac{1}{Pr}\left(2\frac{\partial^2 T}{\partial Y^2}\right) \tag{8a}$$

$$\frac{\partial C}{\partial \tau^*} + U\frac{\partial C}{\partial X} = \frac{1}{Sc}\left(2\frac{\partial^2 C}{\partial Y^2}\right). \tag{9a}$$

NUMERICAL PROCEDURE

The energy and the species conservation equations (equations (8) and (9)) are coupled through the momentum equation (7). Hence the set of four equations (6)–(9) is to be solved simultaneously. We have used an explicit finite-difference scheme. The unsteady governing equations are written in finite-difference form and marched one time-step forward. The converged solution represents the steady state.

We have employed upwind-differencing for convective terms and central-differencing for diffusion terms. Since the cell Reynolds number, R_c, defined as $|U|X/(1/Pr)$ or $(1/Sc)$ was higher than 2, upwind-differencing was required for stability [9].

An explicit scheme has restrictions on the time-step due to stability considerations. These are discussed in detail by Roache [9]. We varied the grid size between 10×10 and 50×50. For a grid size finer than 30×30, numerical values changed only in the fourth decimal place. We have chosen a grid size of 40×40 for the results presented. This ensures that the error is less than 0.5%.

The convergence criteria employed is of the form $|\theta_{ij}^{n+1} - \theta_{ij}^{n}|_{max} \leq \varepsilon$, where n refers to time level, and i and j to space. θ is any variable under consideration like U or T. The value of ε was chosen to be 10^{-4}.

An arbitrary initial velocity field was chosen. We varied this to check that it had no influence on the converged solution.

RESULTS AND DISCUSSION

We have employed the same numerical scheme as the one used by Himasekhar and Jaluria [6]. They compared the results with an earlier study [2] with $S = 0$ and in our case, $B = 0$. The agreement was found to be good, and we have verified this.

We will first present results for the case where the Prandtl and Schmidt numbers are equal. In Fig. 2, the effect of ambient thermal stratification on velocity profiles in aiding flow is indicated. $S = 0$ refers to constant temperature in the ambient. When thermal stratification is high the thermal buoyancy driving the flow is less. Hence the velocity levels fall. In Fig. 3, we present the effect of stable ambient thermal stratification on temperature profiles. If stratification is not present in the ambient, the temperature and concentration profiles will be identical for $Pr = Sc$. As expected, a stable ambient thermal stratification affects the thermal and concentration boundary layers in different ways. In Fig. 3, it is observed that the values of non-dimensional temperature are negative within the boundary layer at $X = 200$ for $S = 0.0005$. In a buoyant plume, the centreline temperature decays in the flow direction, while the ambient temperature increases because of a stable thermal stratification. If the ambient thermal stratification is strong, at a particular downstream X location the core temperature of the plume equals the ambient temperature (Fig. 1), and further downstream the core temperature is less than that of the ambient. In the latter region, the

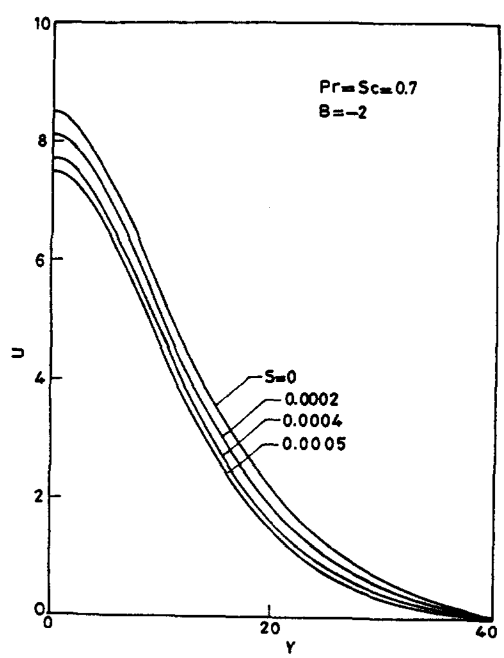

FIG. 2. Velocity profiles in aiding flow at $X = 200$.

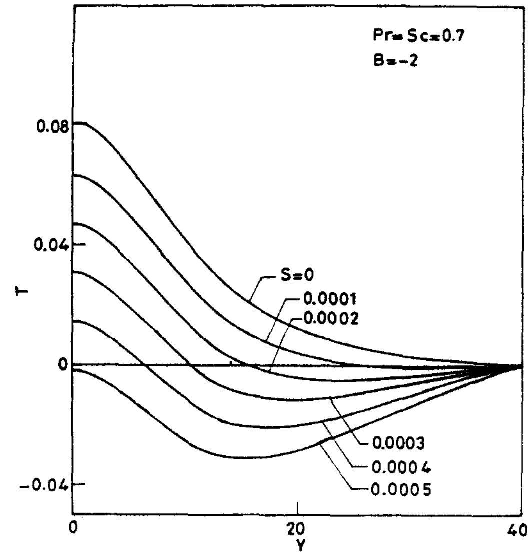

FIG. 3. Temperature profiles in aiding flow at $X = 200$.

non-dimensional temperature starts with a negative value at the core, dips further and reaches zero at the edge of the boundary layer.

At the origin of the plume the buoyancy due to mass diffusion outweighs the thermal buoyancy by a factor of 2 (since $B = -2$). As the flow progresses in the X direction the thermal buoyancy decays very rapidly because the temperature in the ambient increases with height. We have observed that at $X = 200$ the temperature profile is negative for $S = 0.0005$, but the flow is still upwards as can be seen from the velocity profile for the same stratification level in Fig. 2. This is because of the presence of a strong upward buoyant force due to mass diffusion. If mass transfer is not present, at the X location where the temperature of the core of the plume equals that of the ambient the plume will spread horizontally. The buoyancy due to mass diffusion offsets the negative thermal buoyancy and sustains the boundary layer flow upwards. This phenomenon is also observed in double diffusive free convection flows adjacent to vertical surfaces in a thermally stratified medium [8].

For values of $S < 0.0005$, the thermal buoyancy is positive at $X = 200$, but negative values of temperature are still observed in the 'wings' of the profile. This occurrence is called a 'temperature defect' in the flow and its physical nature is discussed in detail by Angirasa and Srinivasan [8].

In many problems of practical importance it is of interest to know the variation of centreline velocity with height. In a stratified medium, this information determines the height to which the plume will rise. In Fig. 4, the variation of the non-dimensional core velocity is plotted as it varies along the non-dimensional axis X. We make a note here that the boundary layer analysis is inaccurate at the source. There is a sharp acceleration of flow near the source for all values of S. For $S = 0$, the flow accelerates further,

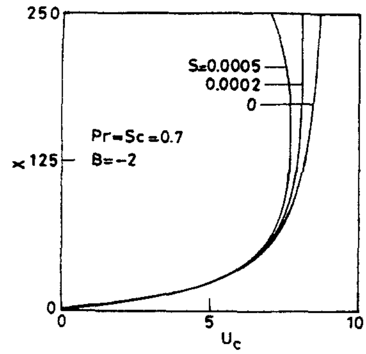

FIG. 4. Axial variation of centreline velocity.

but slowly. This is due to the presence and slow decay of the thermal buoyancy. When the value of S is 0.0002, the core velocity attains a constant value at a shorter distance. For $S = 0.0005$, the flow shows a trend of deceleration after $X = 200$. For still higher values of S, the negative thermal buoyancy is strong and results in horizontal spreading. Thus, the centreline velocity decelerates faster. This flow situation is not a boundary layer and cannot be studied with the present analysis.

So far we have considered thermal buoyancy and its effect on flow. In Fig. 5, we present the effect of thermal stratification on concentration profiles. Since thermal stratification reduces thermal buoyancy with a resultant decrease in velocities, local concentration levels increase. This makes mass diffusion more dominant, and hence the concentration boundary layer thickness. We have also observed similar trends in flows adjacent to vertical surfaces [8]. In the case of plumes, this effect is not as pronounced as it is for flows adjacent to surfaces, as can readily be seen from Fig. 5. The centreline decay is not influenced by thermal stratification.

We will now proceed to the more complex cases of multicomponent buoyant plumes where the Schmidt and Prandtl numbers are not equal. We will also consider both aiding and opposing buoyancies, besides various levels of thermal stratification in the ambient.

Figure 6 represents U velocity profiles of the bound-

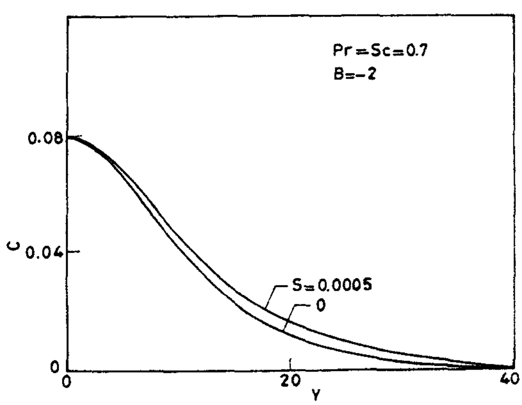

FIG. 5. Concentration profiles in aiding flow at $X = 200$.

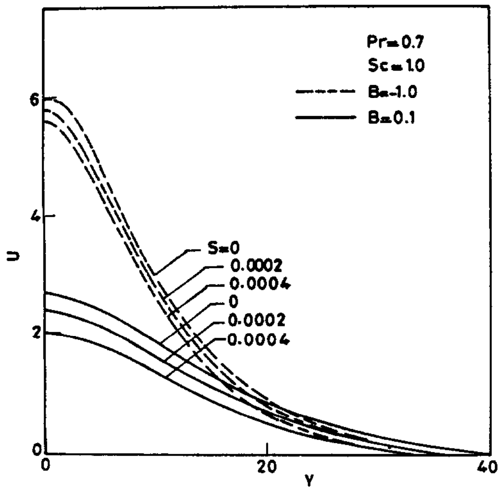

FIG. 6. Velocity profiles in aiding and opposing flows at $X = 100$.

ary layers for aiding and opposing flows, and for various values of S. We have observed that thermal stratification decreases the magnitude of the U component of velocity. Opposing buoyancies further reduce the magnitude of velocities and spread the boundary layers. When stratification and opposing buoyancies are simultaneously present, the reduction in flow velocities is significant. This is due to the suppression of convection and the dominance of diffusion, which also increases the boundary layer thickness. In Fig. 7, temperature profiles are presented for the same parameters. We clearly see that for opposing buoyancies, the thermal boundary layer is much thicker, and with increasing ambient stratification the thickness increases further. For the same stratification level, the thickness for opposing buoyancies is twice that of aiding flows. Another important aspect of opposing flows is that they do not exhibit a significant temperature defect. By comparing Figs. 3 and 7, we find that a reduction in buoyancy ratio also

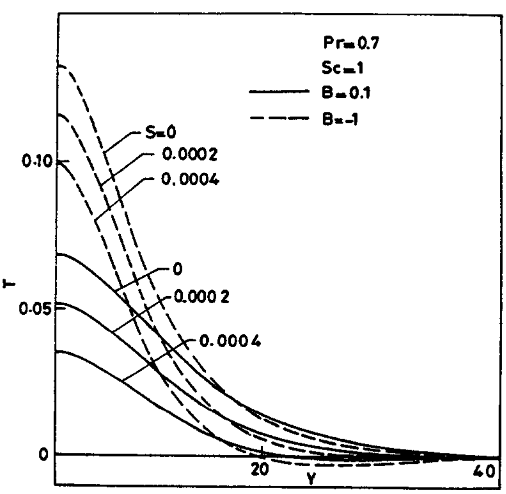

FIG. 7. Temperature profiles in aiding and opposing flows at $X = 100$.

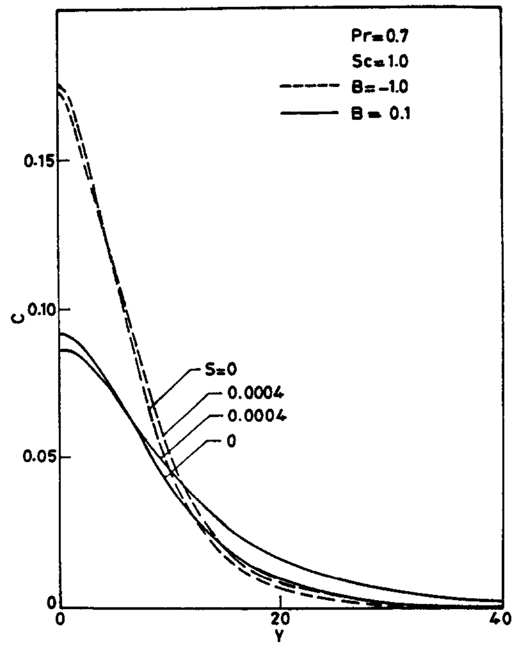

FIG. 8. Concentration profiles in aiding and opposing flows at $X = 100$.

affects the temperature defect. We also observe that for opposing flows, the temperature levels fall steeply in the core region, and for the same S, they are comparatively further away from the ambient. This gives us another important finding that when the buoyancies oppose each other strongly, i.e. for higher positive values of B, boundary layer approximations are not valid.

In Fig. 8, the effect of ambient stratification on the diffusion of species is discussed for aiding and opposing buoyancies. At a given height of the plume, the concentration level for aiding flow is higher than that of opposing flow. In aiding flow, convection is higher. Hence, the species are more readily carried away than in the case of opposing flow. We also note that away from the core of the plume, concentration levels for opposing flows are higher. In this case, diffusion plays a dominant role. We observe that ambient stratification reduces the concentration at the core and increases it away from the core. Thermal stratification suppresses convection due to reduced buoyancy. Hence the species are not carried away in the core but are radially dispersed. Consequently, there is an increase in the concentration in the 'wings'.

EFFECT OF SCHMIDT NUMBER ON THERMAL STRATIFICATION

We will now discuss some important features of the effect of Schmidt number on the plume behaviour in the presence of thermal stratification. In Figs. 9 and 10 velocity profiles are given for the range of Sc that is of practical interest. We find in Fig. 10 that velocity profiles do not vary with Sc at high values of Sc. Also,

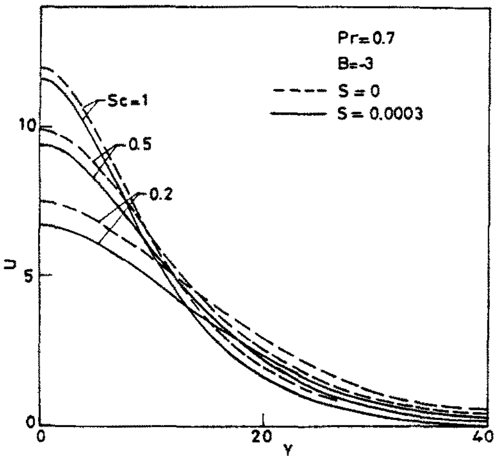

FIG. 9. Velocity profiles in aiding flow at $X = 200$ for various values of Schmidt number.

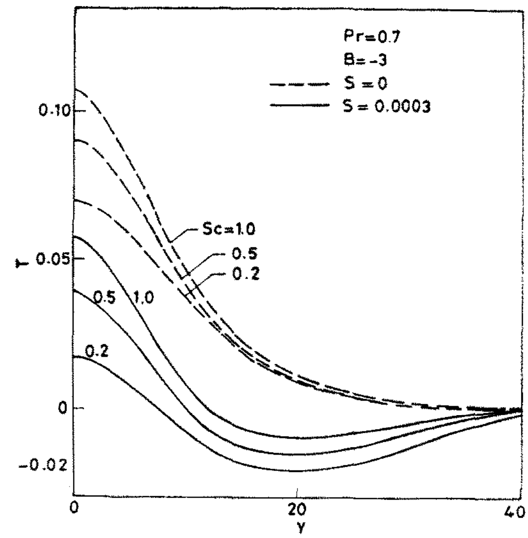

FIG. 11. Temperature profiles in aiding flow at $X = 200$ for various values of Schmidt number.

the profiles are steeper. For high Schmidt number flows, species diffusion is small and hence is confined to the core. Therefore the velocity profiles are influenced more by the thermal stratification than by the value of Sc. For lower values of Sc, species diffusion is higher, hence the velocity profiles are significantly affected by the value of Sc. Increasing values of Sc reduce the plume thickness and increase the steepness of the profile. Thermal stratification, by contrast, makes the profiles flatter and increases the plume thickness. These arguments can be readily discerned from Fig. 9. The effect of Sc on temperature profiles is presented in Figs. 11 and 12. We have previously discussed the presence of significant negative temperatures as a consequence of ambient thermal stratification (also see ref. [8]). It is interesting to note that for the lower Sc range, an increase in Sc significantly offsets the 'temperature defect' in the flow. We have noted (Fig. 9) that with increasing Sc, velocities in the region away from the core are reduced. Hence less colder fluid will come up to a warmer ambient. This causes the drop in temperature defect. We also observe that in the absence of thermal stratification, the effect of Sc is felt more at the core of the plume than at its outer regions. For the Sc range of 400–600, the value of Sc has no influence on the temperature profile, but thermal stratification has a profound effect (Fig. 12). For $S = 0.0003$, the thickness of the thermal boundary layer is double that for the unstratified case.

We therefore see a complex interaction between buoyancy ratio, thermal stratification and Schmidt number. These are all additional factors to be considered for the stability of these flows.

CONCLUSIONS

The present numerical study of laminar multicomponent buoyant plumes in a thermally stratified medium brings forth the following salient features.

(1) Boundary layer type of plume flow is possible

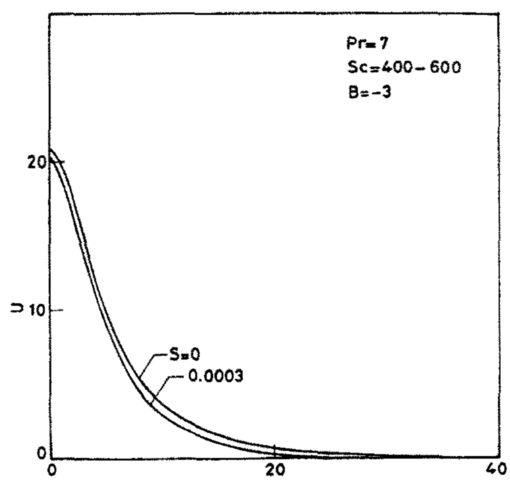

FIG. 10. Velocity profiles in aiding flow at $X = 200$.

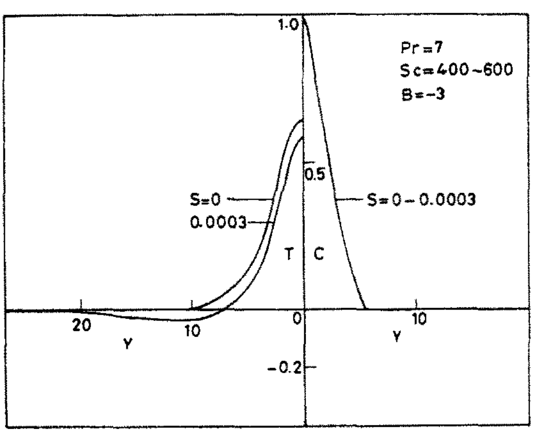

FIG. 12. Temperature and concentration profiles in aiding flow at $X = 200$.

even in a highly stratified medium with negative thermal buoyancy, provided the buoyancy due to mass diffusion is sufficiently high.

(2) Ambient thermal stratification reduces the plume velocities and the height to which the plume can rise.

(3) Temperature defects in the regions away from the core, which are observed in all thermal buoyant convection flows in thermally stratified media, are highly significant in multicomponent buoyant convection.

(4) In plumes with opposing buoyancies, thermal stratification destabilizes the boundary layer flow.

(5) Higher values of the Schmidt number increase the core velocities and decrease the velocities in the 'wings', while thermal stratification does quite the opposite.

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PANACHES FLOTTANTS LAMINAIRES AXISYMETRIQUES DANS UN MILIEU THERMIQUEMENT STRATIFIE

Résumé—On présente les résultats d'une étude numérique des panaches axisymétriques laminaires qui émanent d'une source de flottement du à une diffusion de chaleur et de masse. L'ambiance est considérée stable, stratifiée par un accroissement linéaire de température en fonction de la hauteur. Les approximations de la couche limite et de Boussinesq sont introduites dans les équations de bilan de masse, de quantité de mouvement, d'énergie et d'espèces. Ces équations sont résolues en utilisant un schéma numérique explicite aux différences finies. Des champs de vitesse, de température et de concentration sont obtenus dans un domaine de *Pr* et *Sc*. Les mécanismes physiques de base qui gouvernent ces écoulements sont décrits. Les résultats indiquent une interaction complète entre le rapport de flottement, la stratification thermique, les nombres de Prandtl et de Schmidt.

LAMINARE ACHSENSYMMETRISCHE AUFTRIEBSFAHNEN AUS MEHREREN KOMPONENTEN IN EINEM THERMISCH GESCHICHTETEN MEDIUM

Zusammenfassung—In dieser Arbeit werden die Ergebnisse einer numerischen Untersuchung von laminaren achsensymmetrischen Auftriebsfahnen vorgestellt, die aufgrund simultaner Wärme- und Stoffdiffusion entstehen. Die Umgebung wird als stabil geschichtet betrachtet, mit einem linearen Temperaturanstieg mit der Höhe. In den grundlegenden Erhaltungsgleichungen für Stoff, Impuls, Energie und Konzentration sind die Grenzschicht- und die Boussinesq-Näherungen eingeführt. Diese Gleichungen werden mit einem numerischen expliziten Finite-Differenzen-Verfahren gelöst. Dabei ergeben sich in einem bestimmten Bereich von *Pr*- und *Sc*-Zahl die Geschwindigkeits-, Temperatur- und Konzentrationsverteilungen. Die zugrundeliegenden physikalischen Mechanismen werden beschrieben. Die Ergebnisse zeigen eine kommplizierte Wechselwirkung zwischen dem Auftriebsverhältnis der Temperaturschichtung und der Prandtl- und Schmidt-Zahl.

ЛАМИНАРНЫЕ ОСЕСИММЕТРИЧНЫЕ МНОГОКОМПОНЕНТНЫЕ СВОБОДНОКОНВЕКТИВНЫЕ СТРУИ В СРЕДЕ С ТЕПЛОВОЙ СТРАТИФИКАЦИЕЙ

Аннотация—Приводятся результаты численного исследования ламинарных осесимметричных струй, истекающих из источника под действием совместного тепло- и массообмена. Предполагается, что с линейным ростом температуры по мере увеличения высоты возникает устойчивая стратификация окружающей среды. С использованием приближения пограничного слоя и Буссинеска получены определяющие уравнения сохранения массы, импульса, энергии и отдельных компонент смеси. Эти уравнения решаются численно при помощи явной конечно-разностной схемы. Найдены поля скоростей, температур и концентраций в зависимости от значений *Pr* и *Sc*. Описываются физические механизмы, лежащие в основе данных течений. Полученные результаты указывают на сложное взаимодействие между следующими параметрами: отношением подъемных сил, тепловой стратификацией, а также числами Прандтля и Шмидта.