

ANALYSIS OF A CONTINUOUS FLOW PARALLEL PLATE THERMAL DIFFUSION CLOUD CHAMBER*

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Abstract – In order to make reliable measurements of water droplet growth in a thermal diffusion cloud chamber, it is essential to have a detailed picture of all transient behavior and edge effects associated with the temperature and diffusion fields within the chamber. In the application of a continuous flow chamber where test nuclei are injected into a carrier air stream, additional care must be taken to account for the transition from turbulent to laminar flow of the carrier air. Here we present an analysis of the transient behavior and edge effects within a continuous flow parallel plate thermal diffusion cloud chamber including: (a) the transition to the steady state of the temperature field, (b) the transition to the steady state of the water vapor density field, (c) the evolution of the boundary layer along the edge of the chamber and (d) the development of the laminar parabolic flow profile from an initial "plug flow" state at the inlet to the chamber.

1. INTRODUCTION

Thermal diffusion chambers, originally designed by Langsdorf (1936) for the study of cosmic rays, have proved to be useful devices for experimental studies of cloud condensation nuclei (CCN). They provide a convenient method for producing a wide range of saturation ratios and for simulating the environmental conditions expected for cloud and fog formation. An account of the evolution and applications of thermal diffusion chambers is given by Saxena *et al.* (1970). The continuous flow chamber to be discussed here is a modification of an instrument developed for the study of the activation supersaturation of CCN by Saxena and Kassner (1970) and Saxena and Fukuta (1974). The modifications were made to facilitate the observation of nucleation and droplet growth on naturally occurring atmospheric nuclei and on respirable mineral particulates. The development of a new control technology for the latter is a long-range goal of the project. Since the size of a particulate strongly influences the most effective collection or removal technique, with small particles being generally more difficult, expensive and more energy intensive to control, increasing the effective size of the particulates should simplify removing them from the environment. Such an increase in size may be brought about through the nucleation of a water droplet on the particulate and its subsequent growth by condensation. The results of these droplet growth-rate measurements will be reported separately.

We observe, in agreement with many others (Fitzgerald, 1970; Saxena *et al.*, 1970; Saxena and Fowler, 1973; Elliott, 1971), that wall effects and transient conditions may limit the utility of thermal diffusion chambers. The apparent complications of the continuous flow variable thermal gradient system we have chosen are more than compensated for in its experimental simplicity; experiments for different saturation ratios can be performed without the time delays associated with the thermal relaxation of the mathematically simpler (uniform temperature gradient) systems. Here we will discuss four problems as they relate to the operation of the continuous flow chamber; specifically (1) thermal conduction, (2) the diffusion of water vapor, (3) turbulence in the development of laminar flow and (4) transient behavior of the conduction and diffusion processes.

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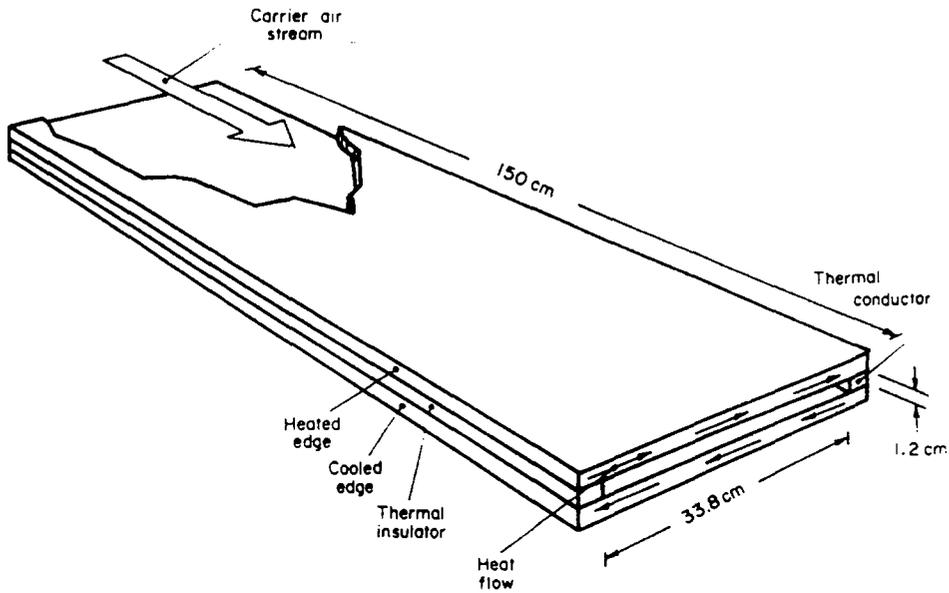


Fig. 1. A schematic diagram of the diffusion cell in a continuous flow parallel plate thermal diffusion cloud chamber.

Figure 1 provides an operational description of our continuous flow thermal diffusion chamber. The internal dimensions of the chamber are 1.2 by 33.8 by 150 cm. The carrier air and aerosol flow is directed along the 150 cm length. As shown in Fig. 1, heat is added along one edge of the top plate and is removed along the corresponding edge of the bottom plate. These edges are separated by a strip of thermal insulator. The opposite edges are separated by a strip of thermal conductor. This arrangement produces a nearly uniform temperature gradient along the thermal circuit formed by the plates and a varying gradient across the gap between the plates. The inside surfaces of the plates are covered with canvas which is wetted frequently, producing a saturated condition along the internal boundaries. Edge effects in the diffusion process are expected along the length of the chamber at either side. Conduction and diffusion transients, and turbulence will occur at the entrance to the chamber.

2. THERMAL CONDUCTION

Mathematically, the equations describing the thermal conduction and water vapor diffusion are identical (*Methods of Theoretical Physics* (1953) Morse and Feshbach, Vol. 1, p. 173).

$$D\nabla^2\rho = \frac{\partial\rho}{\partial t} \quad (\text{diffusion}), \quad K\nabla^2T = \frac{\partial T}{\partial t} \quad (\text{conduction})$$

with ρ = density of diffusing matter, T = temperature, D = diffusivity, K = thermal diffusivity.

The values used here for D and K were taken from the Smithsonian Meteorological Tables (List, 1951); D and K depend on temperature and at 20°C, $D = 0.257 \text{ cm}^2/\text{sec}$, $K = 0.215 \text{ cm}^2/\text{sec}$; D is inversely proportional to pressure.

The design of the thermal diffusion chamber imposes particularly simple boundary conditions for the solution of the conduction equation; the walls introduce no edge effects because the thermal gradient along either vertical wall (insulator or conductor) exactly matches the gradient in the immediately adjacent differential element of air. Mathematically the walls represent "image" planes or boundaries. Of course the thermal current density in the two materials differs by the ratio of the product of the conductivity and the temperature gradient. From Fourier's Law of heat conduction, the thermal current density is given by:

$$\vec{j} = -K\nabla T.$$

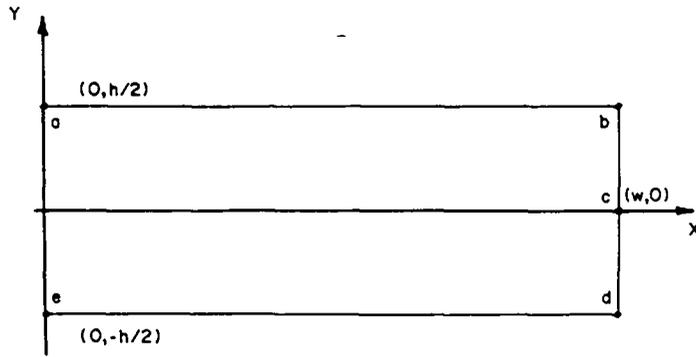


Fig. 2. An outline of the diffusion cell cross-section is superimposed on the coordinate system used in the solution of the steady state thermal conduction problem. Point *a* corresponds to the heated junction, point *b* the cooled junction; line *b-c-d* is treated as an isothermal boundary. The coordinate origin is shifted to point *e* for the solution of the steady state diffusion equation and the transient analysis.

It is possible to model the actual temperature field within the chamber very well with linear boundary conditions that admit a particularly simple solution in closed form. While the choice of coordinate origin is arbitrary (see Fig. 2), it is also convenient to introduce a shift in the temperature zero which results in a homogeneous boundary condition along the edge *b-c-d*. The formal statement of the problem for our model is:

- (a) $T(x, y, z) = T(x, y)$ (no longitudinal dependence),
- (b) $T(0, h/2) = T_{hot}$ (point *a*, Fig. 2),
 $T(0, -h/2) = T_{cold}$ (point *e*, Fig. 2),
 $T(w, y) = T_{mid} = \frac{T_{hot} + T_{cold}}{2}$ (no gradient along side *b-c-d*, Fig. 2),
- (c) $T(x, y) \rightarrow T(x, y) - T_{mid}$ (shift temperature origin),
 $T(w, y) = 0$,
 $T(x, h/2) = \frac{\Delta}{2w}(w - x)$,
 $T(x, -h/2) = \frac{\Delta}{2w}(x - w)$,
 $T(0, y) = \frac{\Delta}{h}y$

with $\frac{\Delta}{2} = T_{hot} - T_{mid} = T_{mid} - T_{cold}$,

- (d) $\nabla^2 T(x, y) = 0$ (steady state Laplace's equation).

The solution of Laplace's equation for the temperature is simple for the assumed boundary conditions. Set $T(x, y) = T_x(x)T_y(y)$, then

$$\frac{1}{T_x} \frac{d^2 T_x}{dx^2} + \frac{1}{T_y} \frac{d^2 T_y}{dy^2} = 0,$$

$$\frac{1}{T_x} \frac{d^2 T_x}{dx^2} = -\frac{1}{T_y} \frac{d^2 T_y}{dy^2} = k$$

and

$$k = 0 \Rightarrow T_x = a + bx,$$

$$T_y = c + dy.$$

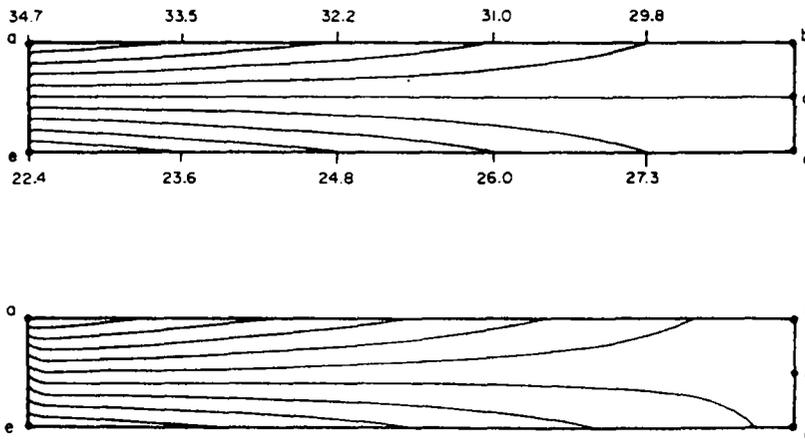


Fig. 3. (a) Isotherms from the steady state solution of the thermal conduction problem within the diffusion cell corresponding to $T_{\text{hot}} = 34.7^{\circ}\text{C}$ (point a) and $T_{\text{cold}} = 22.3^{\circ}\text{C}$ (point e). (b) Lines of constant water vapor density from the steady state solution of the diffusion problem within the diffusion cell corresponding to the boundary conditions given in Fig. 3a. (dimensions - 33.8 : 1.2 cm).

Returning to the boundary conditions, which are linear in x and y , $k = 0$ is the only allowed value for the separation constant k . Therefore,

$$T = T_x T_y = (a + bx)(c + dy).$$

Applying the boundary conditions first along $y = 0$, then $x = 0$ and finally for $y = h/2$. we conclude

$$T(x, y) = \frac{\Delta}{h} y \left(1 - \frac{x}{w} \right),$$

which can be shown to satisfy Laplace's equation as well as the boundary conditions. Figure 3a shows a set of isotherms resulting from a solution to this problem corresponding to $T_{\text{hot}} = 34.7^{\circ}\text{C}$ and $T_{\text{cold}} = 22.3^{\circ}\text{C}$.

3. WATER VAPOR DIFFUSION

The assumption made regarding the temperature boundary conditions taken together with the mode of operation of the chamber completely determines the vapor density boundary conditions which the solution to the steady-state diffusion equation must satisfy; in two dimensions

$$\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} = 0,$$

where $\rho(x, y)$ is the density of water vapor. The chamber was designed to be operated with the top and bottom surfaces ($y = \pm h/2$) (see Fig. 2) saturated. These conditions are achieved by covering those surfaces with canvas which is wetted frequently. From Fick's Law for diffusion, the vapor current density is given by

$$\vec{j} = -D\nabla\rho$$

and is responsible for maintaining the saturated boundary conditions on the side walls ($x = 0, w$). Since the temperatures are known everywhere along the boundaries, integration of the Clausius-Clapeyron equation yields the vapor pressure along the boundaries:

$$P = P_0 \exp \left[\frac{L}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right].$$

Assuming that the water vapor may be treated as an ideal gas, we obtain the density:

$$\rho(x, y) = \frac{\rho_0 \exp\left[\frac{L}{R}\left(\frac{1}{T_0} - \frac{1}{T(x, y)}\right)\right]}{T(x, y)/T_0} \quad (\text{along the boundaries}), \quad (1)$$

where T_0 is an arbitrary temperature and ρ_0 the corresponding saturation vapor density.

The formal statement of the water vapor diffusion problem becomes

- (a) $\rho(x, y, z) = \rho(x, y)$ (no longitudinal dependence),
 (b) $\nabla^2 \rho(x, y) = 0$ (steady state Laplace's equation),
 (c) along the boundaries

$$\rho(x, y) = \frac{\rho_0 \exp\left[\frac{L}{R}\left(\frac{1}{T_0} - \frac{1}{T(x, y)}\right)\right]}{T(x, y)/T_0},$$

$$T(x, y) = \frac{\Delta}{h} y \left(1 - \frac{x}{w}\right).$$

There are several methods for solving Laplace's equation subject to such complicated though analytic boundary conditions. Here we present the Green's function approach.

In the Green's function method the "point source" equation (*Mathematical Physics* (1968) Butkov Chap. 12).

$$\nabla^2 G(r, r_0) = \delta(r - r_0) \quad (2)$$

partially defines the Green's function. The complete specification comes, as usual, from the imposition of boundary conditions on $G(r, r_0)$ which may be chosen for convenience. Since the steady-state diffusion equation is homogeneous, applying Green's theorem to the differential equations for $\rho(r)$ and $G(r, r_0)$ results in

$$\rho(r) = \oiint \{[\nabla' G(r', r)]\rho(r') - G(r', r)\nabla'\rho(r')\} \cdot d\mathbf{S}',$$

where the surface integral is over the area defined by the boundaries of interest and ∇' implies differentiation with respect to the primed field variables. In the two dimensional case we obtain:

$$\rho(x, y) = \oint \left\{ \frac{\partial G(r', r)}{\partial n'} \rho(r') - G(r', r) \frac{\partial \rho(r')}{\partial n'} \right\} dl', \quad (3)$$

$$\frac{\partial G}{\partial n'} = \nabla G \cdot \hat{n}',$$

$\hat{n}' =$ outward pointing unit vector normal to the boundary.

Now, in choosing the additional conditions which $G(r', r)$ must satisfy, it becomes clear that the desirable choice is to pick the $G(r', r)$ which vanishes on the boundary. Then equation (3) becomes

$$\rho(x, y) = \oint \frac{\partial G(r', r)}{\partial n'} \rho(r') dl'$$

and the integral is performed counter clockwise around the perimeter of the chamber. For the sake of simplicity in form, the choice for the range of the independent variables x and y is now taken as $0 \leq x \leq w$, $0 \leq y \leq h$. This choice is different from that in the heat conduction problem of part 1; the symmetry of the temperature distribution is not present in the case of diffusion. The Green's function may be expanded in terms of the eigenfunctions of the

Laplacian operator which vanish along $x = 0$ and w , $y = 0$ and h .

$$G(x, x', y, y') = \frac{2}{\sqrt{wh}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \sin \frac{m\pi x}{w} \sin \frac{n\pi y}{h}$$

Substituting this into equation (2) results in

$$A_{mn} = -\frac{2}{\sqrt{wh}} \frac{\sin \frac{m\pi x'}{w} \sin \frac{n\pi y'}{h}}{\left(\frac{m^2\pi^2}{w^2} + \frac{n^2\pi^2}{h^2}\right)}$$

which yields the "boundary condition" Green's function.

The Green's function method may yield a particularly simple or convenient form for the solution. In the case at hand, an examination of the readily available transform tables did not reveal an entry for the boundary conditions of interest here. We include the method, although we choose to use an iterative numerical technique, because of its general applicability and because for other boundary conditions it can considerably simplify the solution. A less revealing but simpler appearing solution for this problem can be obtained using the method of finite sine transforms (*Operational Mathematics* (1972), Churchill, Chap. 11).

The solution shown in Fig. 3b was obtained using a numerical relaxation or iteration technique based on an interesting property of the Laplacian; the Laplacian of a function can be regarded (to fourth order) as a measure of the variation of that function at a point from its average value in the neighborhood of the point (*Fundamentals of Mathematical Physics* (1967) Kraut, Chap. 7). In the case that

$$\nabla^2 \rho(x, y) = 0,$$

then

$$\rho(x, y) = \frac{1}{4}[\rho(x + \delta, y) + \rho(x - \delta, y) + \rho(x, y + \delta) + \rho(x, y - \delta)].$$

Only the values of $\rho(x, y)$ on the boundaries are required to begin the iteration but convergence can be enhanced by initializing the array with a simple estimate of the results. Figure 3b shows the loss of symmetry for diffusion and the extent of the "edge" effects. In Figure 4, the maximum in the saturation ratio

$$S(x, y) = \frac{\rho(x, y)}{\rho_{\text{sat}}(T(x, y))}$$

can be seen to occur near $y = 0.45 h$, slightly below the midplane, and is larger than the value usually taken for this parallel plate geometry (Saxena and Fukuta, 1974):

$$S_{\text{max}} = \frac{\rho_{\text{sat}}(y = h) + \rho_{\text{sat}}(y = 0)}{2\rho_{\text{sat}}(T_{\text{mid}})}$$

where ρ_{sat} is the saturation vapor density and $\rho_{\text{sat}}(T_{\text{mid}})$ is to be evaluated for the temperature at the midplane.

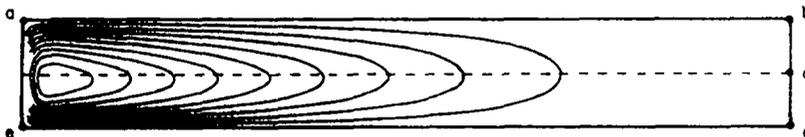


Fig. 4. Lines of constant saturation ratio obtained from the steady state solutions to the diffusion and conduction equations within the diffusion cell corresponding to the conditions in Fig. 3.

4. TRANSIENT BEHAVIOR AT SPECTROMETER ENTRANCE

In order to estimate the "end effect" due to the time required to bring a parcel of air to its (dynamic) equilibrium saturation, we solve a simple one-dimensional, time-dependent diffusion problem with appropriate boundary conditions. The coordinate system is the same as used for the steady-state diffusion problem; i.e. $0 \leq x \leq w, 0 \leq y \leq h$. The time-dependent diffusion equation is

$$\frac{\partial^2 \rho(y, t)}{\partial y^2} = \frac{1}{D} \frac{\partial \rho(y, t)}{\partial t}.$$

The approach to equilibrium is modeled by requiring:

- (a) $\rho(y, t = 0) = \rho_i$ (input sample is of uniform vapor density),
- (b) $\rho(h, t) = \rho_i$ (saturated boundary condition at temperature T_{top}),
- (c) $\rho(0, t) = \rho_b$ (saturated boundary condition at temperature T_{bot}).

In order to establish homogeneous boundary conditions at $y = 0$ and $y = h$, we introduce a change in the dependent variable

$$\rho'(y, t) = \rho(y, t) - \left[\rho_b + \frac{(\rho_i - \rho_b)}{h} y \right]$$

which satisfies the boundary conditions

$$(d) \rho'(y, 0) = \rho_i - \rho_b - \frac{(\rho_i - \rho_b)}{h} y$$

$$(e) \rho'(h, t) = 0,$$

$$(f) \rho'(0, t) = 0.$$

Now, separation of variables yields

$$\frac{1}{R(y)} \frac{d^2 R(y)}{dy^2} = \frac{1}{DT(t)} \frac{dT(t)}{dt} = -q^2,$$

with

$$\rho'(y, t) = R(y)T(t).$$

The negative separation constant is necessary to insure the appropriate time dependence; then applying boundary conditions (e) and (f) yields the time dependent solution to the diffusion equation:

$$\begin{aligned} \rho(y, t) &= \rho'(y, t) + \rho_b + \frac{(\rho_i - \rho_b)}{h} y \\ &= \rho_b + \frac{(\rho_i - \rho_b)}{h} y + \sum_1^{\infty} A_n \sin \frac{n\pi y}{h} \exp(-Dn^2\pi^2 t/h^2). \end{aligned}$$

Imposing the initial condition on this solution determines A_n . Thus,

$$\begin{aligned} \rho(y, t) &= \rho_b + \frac{(\rho_i - \rho_b)}{h} y + \sum_1^{\infty} \frac{2}{m\pi} [\rho_i(-1)^m - \rho_b] \sin \frac{m\pi y}{h} \exp(-Dm^2\pi^2 t/h^2) \\ &+ \sum_0^{\infty} \frac{4\rho_i}{(2m+1)\pi} \sin \frac{(2m+1)\pi y}{h} \exp(-D(2m+1)^2\pi^2 t/h^2). \end{aligned}$$

The transient behavior of the heat conduction process can now be obtained by inspection since the differential equation and the boundary conditions can be made equivalent to those

for the water vapor diffusion process. The temperature field satisfies (in one dimension):

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{K} \frac{\partial T(x,t)}{\partial t}.$$

If the sample air is introduced into the chamber at a temperature T_i between two isothermal boundaries at temperatures T_i and T_b the boundary conditions become

(g) $T(y, t = 0) = T_i$,

(h) $T(h, t) = T_i$,

(i) $T(0, t) = T_b$.

Introducing a change in variables as in the diffusion problem such that

$$T'(y, t) = T(y, t) - \left[T_b + \frac{(T_i - T_b)}{h} y \right],$$

the boundary conditions become

(j) $T'(y, t) = T_i - T_b + \frac{(T_i - T_b)}{h} y$,

(k) $T'(h, t) = 0$,

(l) $T'(0, t) = 0$

and the time dependent solution for the temperature field can be taken from equation (4):

$$T(y, t) = T_b + \frac{(T_i - T_b)}{h} y + \sum_1^{\infty} \frac{2}{m\pi} [T_i(-1)^m - T_b] \sin \frac{m\pi y}{h} \exp(-Km^2\pi^2 t/h^2) \\ + \sum_0^{\infty} \frac{4T_i}{(2m+1)\pi} \sin \frac{(2m+1)\pi y}{h} \exp[-K(2m+1)^2\pi^2 t/h^2].$$

In either case, diffusion or conduction, the transients or "end effects" in a continuous flow chamber are determined by the exponentials in the series part of the solution.

Requiring t to be greater than the larger of $3(h^2/\pi^2 D)$ and $3(h^2/\pi^2 K)$ guarantees that the largest term in each series will vary less than 5% from the steady state value and the remainder of the terms will differ negligibly from it. At 30°C, $D = 0.27 \text{ cm}^2/\text{sec}$ and $K = 0.23 \text{ cm}^2/\text{sec}$, and, therefore, it is the conduction process that limits the approach to the steady state. In practice, the approach to the steady state requires less than three "conduction time constants". Explicit evaluation of the solution provides a better criterion (see Fitzgerald, 1970; Saxena *et al.*, 1970); we have found that for our geometry, variations from the steady state conditions are reduced to 5% after 1.0 sec. For the sake of completeness we note that the Laplace transform method yields solutions that are in a convenient form for the examination of the transients for small times.

Now we consider the transient behavior of the fluid flow near the inlet to the cloud chamber. The filtered, humidified air which becomes the carrier for the test aerosols enters the chamber through a diffuser at some uniform speed v_0 . This initial velocity is taken to be constant over the entrance cross-section of the chamber; this state is turbulent and transient in nature and will approach, in the steady state, laminar flow. Across the vertical dimension (1.2 cm) the velocity profile will become parabolic and boundary layers will develop at both sides of the chamber (along its full length). The importance of the development of laminar flow is made clear by considering that for an input velocity of v_0 , the laminar flow results in velocities which vary from 0 to $1.5 v_0$ across the height of the chamber.

We model the fluid flow within the chamber as follows.

- (a) Because of the 28 : 1 aspect ratio of the chamber, the development of laminar flow is described by the flow between infinite parallel plates.
- (b) The "width" (33.8 cm) edge effects are estimated by the flow along a single flat plate.
- (c) Coupling between the velocity, vapor and temperature fields is neglected.

An estimate of the effect in (b) is obtained from Blasius' solution of the flat boundary layer (Schlichting, *Boundary Layer Theory* (1955) Chap, 7). We take the displacement thickness, δ^* , defined by Schlichting as an estimate of the extent of the edge effect.

$$\delta^* = 1.73 \sqrt{\frac{\nu L}{v_0}},$$

$\nu = \mu/\rho =$ kinematic viscosity,

$L =$ length of surface along which boundary layer is developing and

$v_0 =$ velocity of flow far from the boundary.

In this application ($L = 150$ cm, $v_0 \lesssim 40$ cm/sec) the boundary layer extends less than 2 cm from either wall in the worst case – at the chamber outlet.

As mentioned previously, the flow of the carrier air as it enters the chamber may be regarded as “plug flow”; the velocity v_0 is constant over the cross-section (perpendicular to the flow) of the chamber. The boundary layer effects have just been shown to be negligibly small across the width (33.8 cm). Across the height the initial velocity profile will evolve into a parabolic laminar flow (Schlichting, 1955, Chap. 5), given by

$$v(y) = \frac{6v_0}{h^2} y(h - y), \quad 0 < y < h.$$

The estimation of the development length, a characteristic length for fluid flow beyond which laminar flow may be assumed to exist, for flow between two parallel plates requires a numerical or approximation solution to the Navier–Stokes equation. Schlichting (1955, Chap. 9) has applied an approximation technique to the solution of this problem. First, the boundary layer growth is expanded in terms of the downstream distance. Second, the deviation from the asymptotic parabolic flow profile is expanded in terms of the upstream distance. The matching of the two expansions determines the parameters of the approximation method. Figure 5 is based on the calculation by Schlichting and shows clearly the evolution of the laminar parabolic flow from the initial plug flow. The parameter describing the development state is:

$$\alpha = \frac{4\nu x}{h^2 v_0},$$

where $\nu =$ kinematic viscosity, $v_0 =$ initial (input) velocity, $h =$ plate separation (height of chamber), $x =$ distance over which the flow has been evolving.

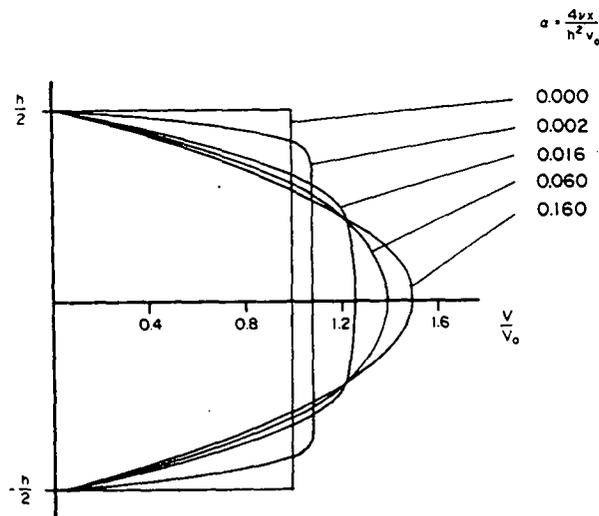


Fig. 5. The evolution of the carrier air velocity profile from plug flow ($\alpha = 0$) to laminar flow ($\alpha = 0.16$) with $\alpha = 4\nu x/h^2 v_0$ as the parameter.

As can be seen from Fig. 5, when $\alpha \simeq 0.16$ the flow may be regarded as fully developed and, therefore, the development length is given by

$$l_D = x = \frac{(0.16)h^2v_0}{4\nu}$$

For velocities less than 40 cm/sec and a plate separation of 1.2 cm,

$$l_D < 20 \text{ cm}$$

and the parabolic velocity profile can be considered to be fully developed beyond the first 20 cm of the diffusion chamber.

5. CONCLUSIONS

In summary we can see that the transients in the conduction and diffusion processes, and, consequently, the saturation ratio will have become negligible after 1.0 second for the geometry of this chamber. For carrier air velocities of 40 cm/sec or less these transients will extend less than 40 cm into the chamber. For initial velocities of less than 40 cm/sec and for the dimensions of this cloud chamber, laminar parabolic flow will be established after approximately 20 cm. The edge effects due to the boundary layer extend less than 2 cm into the chamber from either side. There are no edge effects in the steady state temperature field (see Fig. 3a). Finally, the iso-vapor density contours in Fig. 3b indicate that the "fringing" of the diffusion currents extends less than 2 cm into the chamber on the high saturation side. On the low saturation side the choice is more subjective; we make no measurements closer than about 6.5 cm.

We conclude that it is straightforward to avoid all edge or wall effects and virtually eliminate all perturbations due to them in a continuous flow diffusion chamber. If care is taken to maintain the velocity of the carrier air below the threshold determined by the geometry of the chamber, errors due to transients at the inlet to the chamber may be minimized. Our analysis indicates that the equilibration of the carrier air will always be limited by its thermal relaxation, but this limit may be partially removed by careful choice of its initial temperature or by the use of a separate set of parallel thermal conditioning plates.

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