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A 2-D ANALYSIS OF EVAPORATION IN LAMINAR FLOW (U)

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO. 1093

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Abstract

This report documents a two-dimensional, finite element study of the evaporation of a liquid on a flat surface into a laminar air stream for three geometries: a hemispherical drop on a flat plate; a hemispherical drop between parallel plates; a smear on a flat plate. The problems are made dimensionless and the flux from the liquid is determined in a parametric analysis with a range of values of the resulting independent variables. A comparison is made with some experimental data and an example of the use of the results is given.

Résumé

Ce rapport documente une étude bi-dimensionnelle utilisant un modèle d'élément défini de l'évaporation d'un liquide sur une surface plane dans un passage d'air laminaire sur trois configurations: Une goutte hémisphérique sur une surface plane; Une goutte hémisphérique entre deux surfaces parallèles; Une tache sur une surface plane. Les problèmes sont faits sans dimensions et la fluctuation provenant du liquide est calculée dans une analyse paramétrique ayant une échelle de valeurs pour les variables indépendantes résultantes. Une comparaison est faite avec certaines données expérimentales et un exemple de l'usage des résultats numériques est donnée.

Executive Summary

Evaporation of liquids from fabrics is of interest in a number of areas of research such as the study of thermoregulation by evaporation of sweat from the body, the study of heat and moisture transport from clothing and the study of the performance of protective clothing when challenged by drops of chemical agent.

In order to adequately predict the evaporative heat flux or the performance of protective clothing for a variety of conditions, a knowledge of the evaporation rate of liquids from the clothing should be known. This information can be obtained from a number of sources, most of which are complimentary rather than competing techniques. Field tests are useful since they closely approximate actual applications, however, the large number of variables involved may complicate the study to the point where the results are too specific to extrapolate to other cases or the effects cannot be attributed to individual causes. Laboratory tests can be more easily controlled than field tests and parameters may be varied to examine the effects of different variables but there remains the problem of extending the laboratory data to field conditions. Numerical analysis can be a source of detailed data which can be substantiated by both laboratory and field data. Numerical analyses can provide detailed information on individual aspects of a problem which may not be measurable in physical experiments. It can also be used to more confidently extend laboratory data to field conditions. Thus, numerical modelling provides the investigator with a complimentary tool for understanding the physics and physical relationships involved in a problem.

This paper reports a parametric study of the transport characteristics from surfaces into a laminar fluid flow by means of a two-dimensional, finite element analysis for three simple geometric configurations. The configurations which were investigated are evaporation of a drop between two parallel plates, the evaporation of a drop from a flat plate and evaporation from a smear on a flat plate. Although the analysis was kept as general as possible, these geometries were selected as they are encountered in the study of protection from hazardous chemicals. The case of a drop between two parallel plates is similar to an experimental apparatus employed to measure the vapour penetration of a chemical agent drop on a repellent, chemically-protective fabric. The flat plate geometry is similar to the parallel plate geometry, however, it is more representative of a drop on a repellent, chemically-protective garment. The smear on a flat plate geometry corresponds to the situation of a drop on a chemically-protective fabric that permits spreading of the liquid into the fabric. The equations governing these problems are made dimensionless, that is without units, to make the results more generally applicable to other, similar problems.

A parametric study using dimensionless variables is shown to provide a concise presentation of the results which can then be used to supply information on particular problems with little additional work. Using dimensionless variables, both in physical experiments and numerical analyses, allows the investigator additional flexibility since the equations of heat transfer and mass transfer have similar form. This technique also minimizes the number of independent variables required to characterize the problem.

The results presented in this report can be used to predict evaporation rates from drops (or heat fluxes from cylinders) for three similar geometries. The results for the specific example of a drop of mustard between parallel plates compare very favourably with measured values from drops in experimental test cells, although the comparison is limited to one set of experimental results. Although limited, the good agreement lends confidence to the validity of the numerical results and to the use of the results to make predictions for cases difficult to obtain in the laboratory. Extension of the comparison to include field data under similar conditions remains to be done and so no conclusion can be made in this area based on the results of this study.

An analysis of this type would also be of use to designers of a test apparatus for measuring agent penetration into protective fabrics. By selecting the desired air speed and drop size, calculations can be made of the appropriate dimensionless variables. The theoretical results can then be used as guidelines for establishing parameters of the apparatus such as channel height and drop position so that the apparatus itself does not influence the outcome of the experiment.

It should be stressed that the two-dimensional study presented here is only an approximation to the actual, three dimensional physical problem and therefore the results must be used with some caution, preferably with experimental corroboration. The comparison of a flow over a cylinder to that over a sphere, which can be found in most elementary fluid mechanics and heat transfer texts, further illustrates the caveats which must be observed when approximating a three-dimensional problem with a two-dimensional model. More powerful computers would allow the analysis to be extended into three dimensions which should make the results more representative of the physical problem and which could be used to explore more interesting geometries.

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1.0 Introduction

Evaporation of liquids from fabrics is of interest in a number of areas of research such as the study of thermoregulation by evaporation of sweat from the body, the study of heat and moisture transport from clothing and the study of the performance of protective clothing when challenged by drops of chemical agent.

In order to adequately predict the evaporative heat flux or the performance of protective clothing for a variety of conditions, a knowledge of the evaporation rate of liquids from the clothing should be known. This information can be obtained from a number of sources, most of which are complimentary rather than competing techniques. Field tests are useful since they closely approximate actual applications, however, the large number of variables involved may complicate the study to the point where the results are too specific to extrapolate to other cases or the effects cannot be attributed to individual causes. Laboratory tests can be more easily controlled than field tests and parameters may be varied to examine the effects of different variables but there remains the problem of extending the laboratory data to field conditions. Numerical analysis can be a source of detailed data which can be substantiated by both laboratory and field data. Numerical analyses can provide detailed information on individual aspects of a problem which may not be measurable in physical experiments. It can also be used to more confidently extend laboratory data to field conditions. Thus, numerical modelling provides the investigator with a complimentary tool for understanding the physics and physical relationships involved in a problem.

This paper reports a parametric study of the transport characteristics from surfaces into a laminar fluid flow by means of a two-dimensional, finite element analysis for three simple geometric configurations. The configurations which were investigated are evaporation of a drop between two parallel plates, the evaporation of a drop from a flat plate and evaporation from a smear on a flat plate. Although the analysis was kept as general as possible, these geometries were selected as they are encountered in the study of protection from hazardous chemicals. The case of a drop between two parallel plates is similar to an experimental apparatus employed to measure the vapour penetration of a chemical agent drop on a repellent, chemically-protective fabric. The flat plate geometry is similar to the parallel plate geometry, however, it is more representative of a drop on a repellent, chemically-protective garment. The smear on a flat plate geometry corresponds to the situation of a drop on a chemically-protective fabric that permits spreading of the liquid into the fabric. The equations governing these problems are made dimensionless, that is without units, to make the results more generally applicable to other, similar problems.

2.0 Theory

2.1 Background

The equations governing the conservation of mass, momentum, energy and chemical species for an incompressible, laminar flow can be written as [Currie 1974, Rohsenow 1961]:

$$\nabla u = 0 \qquad (1)$$

$$\rho u \cdot \nabla u = -\nabla p + \mu \nabla^2 u \qquad (2)$$

$$\rho c_p u \cdot \nabla t = k \nabla^2 t \qquad (3)$$

$$u \cdot \nabla c_a = D \nabla^2 c_a \qquad (4)$$

Buoyancy effects have been neglected and the mass concentration of the chemical species is assumed to be sufficiently small that it does not significantly affect the fluid properties. Definition of the terms in the equations can be found in the glossary. These equations can be non-dimensionalized through the introduction of appropriate geometric and fluid property constants relevant to the problem. These constants typically include: a length scale such as a boundary length or channel width; a velocity scale such as the mean inlet velocity; a temperature scale such as the difference between the inlet fluid temperature and a hot wall temperature; and a chemical species mass concentration scale such as the difference between the chemical species concentration of the inlet fluid and a source on another boundary. These constants in addition to physical properties of the fluid such as viscosity, thermal conductivity and mass diffusivity can be used to group a large number of variables into a much smaller number of non-dimensional variables which characterize the flow. This greatly simplifies a parametric study of a given problem. Proper non-dimensionalization of the governing equations also gives the investigator an indication of which terms are significant in the analysis once numerical values are assigned to the various constants and fluid properties.

In dimensionless form, the equations may be written as:

$$\nabla \cdot U = 0 \qquad (5)$$

$$U \cdot \nabla U = -\nabla P + \frac{1}{Re} \nabla^2 U \qquad (6)$$

$$U \cdot \nabla \mathrm{T} = \frac{1}{RePr} \nabla^2 \mathrm{T} \qquad (7)$$

$$U \cdot \nabla C = \frac{1}{ReSc} \nabla^2 C \tag{8}$$

Note the similarity between the energy transport equation and the mass transport equation. By simply changing the non-dimensional quantity from RePr to ReSc, results from a heat transfer experiment (either numerical or physical) can be used to describe mass transfer in the same geometry. This can be useful as heat transfer experiments are frequently easier to perform than mass transport experiments and yet will provide essentially equivalent information.

The non-dimensional heat or mass transfer, Q, from a surface can be converted back into a dimensional quantity, q, through the following equations:

$$q = \frac{k \Delta T}{L} Q \tag{9}$$

or

$$q = \frac{D \Delta C_a}{L} Q \tag{10}$$

respectively.

The boundary conditions required to complete the mathematical statement of a problem are the specification of velocity, temperature and chemical species along all of the domain boundaries or a combination of these primitive quantities along some of the domain boundaries and specification of fluxes along the remaining boundaries. In a non-dimensional analysis, appropriate dimensionless boundary conditions must be supplied.

This study will only consider a laminar, isothermal, mass transport problems using equations 5, 6, 8 and 10 with terminology consistent with mass transport problems. The results are, as noted before, equally applicable to heat transfer problems of similar geometries without a chemical contaminant present. It should be noted that, when considering a heat transfer problem, radiant heat transfer must also be considered as a boundary condition if the flowing fluid is a gas.

2.2 Problem Description

The three geometries studied are shown in Figure 2.2.1 with an accompanying description of the boundary conditions and the associated non-dimensionalization parameters used for each analysis.

Figure 2.2.1a shows a drop at some position downstream of the leading edge of a flat plate. Variables of importance in this problem are the drop radius, r, the boundary layer thickness at the drop, δ, the mean flow

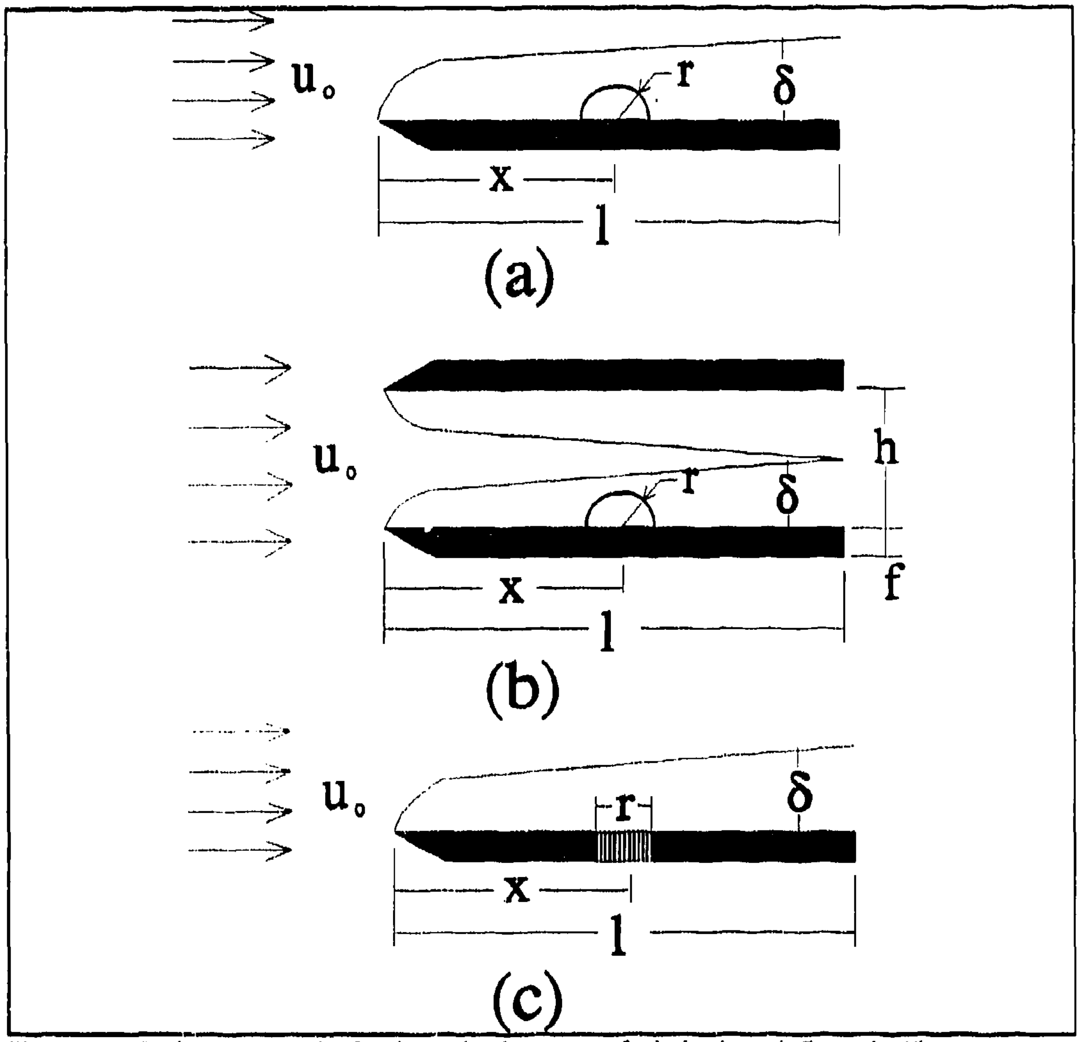

Figure 2.2.1 Problem geometries for the study of mass transfer in laminar air flows: (a) Flow over a drop on a flat plate; (b) Flow over a drop between parallel plates; (c) Flow over a smear on a flat plate.

velocity, u_0, the diffusivity of the drop species in the fluid, D, the fluid viscosity, μ, and the fluid density, ρ. The boundary layer thickness is a function of the distance along the plate, x, and so the boundary layer thickness at the drop may be replaced by the distance from the leading edge of the plate to the drop. All of these parameters can be combined into three dimensionless groups which can be used to characterize the flow:

the dimensionless drop position,	$X = x/r$	(11)
the flow Reynolds Number,	$Re = \rho u_0 r/\mu$	(12)
the flow Schmidt Number,	$Sc = \mu/\rho D$	(13)

Figure 2.2.1b shows a similar problem where the drop is now between two parallel plates. This introduces an additional parameter to the previous list, the distance between the plates, h, which can be non-dimensionalized by the drop radius:

the dimensionless plate separation,	$H = h/r$	(14)

Also, the boundary layer growth is now limited to one-half the distance between the two plates except in the vicinity of the drop which disturbs the flow. If the drop is within the fully developed portion of the flow (where the boundary layer extends to the middle of the plates), the results should not change as the drop position along the plates is increased. Thus, the drop position along the plate is only important in the initial, developing region of the flow.

Figure 2.2.1c shows a somewhat simpler problem, that of a smear on a flat plate. Now, the flow is not disturbed by the size of the "drop" although the evaporation rate (per unit area) will depend somewhat on the smear radius. In this problem, the plate length is the more relevant length scale and the problem parameters are:

the dimensionless smear position,	$X = x/\ell$	(15)
the dimensionless smear size,	$R = r/\ell$	(16)
the flow Reynolds Number,	$Re = \rho u_0 \ell/\mu$	(17)
the flow Schmidt Number,	$Sc = \mu/\rho D$	(18)

The Schmidt Number is an indicator of the relative importance of the diffusivity of momentum to the chemical diffusivity in the flow, similar to the Prandtl number in heat transfer problems. In this study, three Schmidt numbers were used: 0.6, 0.7 and 2.5. The first two Schmidt Numbers produce virtually the same results and can be considered equivalent for most purposes. These Schmidt Numbers are representative of the diffusion of water vapour in air (0.6) and the diffusion of mustard vapour in air (2.5). A Schmidt Number of 0.7 produces results equivalent to those obtained from a heat transfer analysis into the air stream with the same geometry (that is with a Prandtl Number of 0.7).

Although the emphasis of this study is on the evaporation of a liquid into the adjacent laminar air-stream, the diffusion of the liquid contaminant from the drop through the fabric upon which it rests is also of interest. A limited investigation of this is presented here using a constant value of the mass diffusivity through the fabric. In this case, the fabric thickness, f, is the principle variable.

With the above transformation, the problem is to quantify the non-dimensional mass flux, Q, in terms of the relevant non-dimensional quantities:

$Q = f^n(X, Re, Sc)$,	for a drop on a plate;	(19)
$Q = f^n(X, H, Re, Sc)$,	for a drop between parallel plates;	(20)
$Q = f^n(X, R, Re, Sc)$,	for a smear on a plate;	(21)
$Q = f^n(F)$,	for diffusion through a fabric.	(22)

This is accomplished by holding all but one independent variable in the above relationships constant and examining the effect of changing the remaining variable on the flux. Each independent variable is examined over a range which includes practical limits so that the results can be interpolated to yield information on specific configurations.

2.3 Solution Technique

Unfortunately, no general solution exists for equations 5 through 8 so that it is necessary to make use of an approximation technique to obtain an estimate of the solution. The technique used in this study was that of finite elements, implemented through commercial software called Fidap [Engleman 1991].

In the finite element technique, the problem domain is divided into many smaller domains or finite elements. The governing equations are then approximated over each of these finite elements. The solution at the various nodes within these elements is obtained by specifying the form of the distribution of the independent variables over the elements, re-assembling the elements into a global matrix and then solving the resulting simultaneous nonlinear, algebraic equations. In this study, nine-node quadrilateral elements were used.

Two different geometries were considered for the solid fabric surface below the liquid contaminant. In the two problems involving a drop (Figure 2.3.1a), it was assumed that the drop rested on a liquid repellent but vapour permeable surface. Thus, diffusion of the vapour through the lower boundary was included in the analysis. In the remaining problem, it was assumed that the boundary was not repellent but instead promoted spreading of the liquid resulting in a smear. In this problem, diffusion within the porous surface was not modeled for simplicity (Figure 3.2.1b). It should be noted that lateral diffusion in the fabric would probably be present in an actual application.

Because of the non-linear nature of the governing equations, the solution is found using an iterative procedure. Typically, the iterative procedure involved between two to six steps of successive substitution followed by as many as forty steps of Quasi-Newton iterations. Acceleration factors between 0.5 and 0.9 were used for problems in which convergence was difficult. Streamwise Upwinding, a technique frequently used to promote stability of the numerical analysis was not used in the solution. Convergence was assumed when each of the following criteria were met: the norm of the relative change of the solution vector, $|U_i - U_{i-1}|/|U_i|$, was less than 0.001; the norm of the relative change of the residual vector, $|R_i|/|R_0|$ was less than 0.001; the maximum norm of the residue, $|U_i-U_0|$, was less than approximately 0.05.

3.0 Results and Discussion

3.1 Drop on a Plate

Figure 3.1.1 shows a typical result for the flow field streamlines and mass concentration contours for transport from a drop on a flat plate in a laminar flow field. Most of the evaporated mass remains close to the

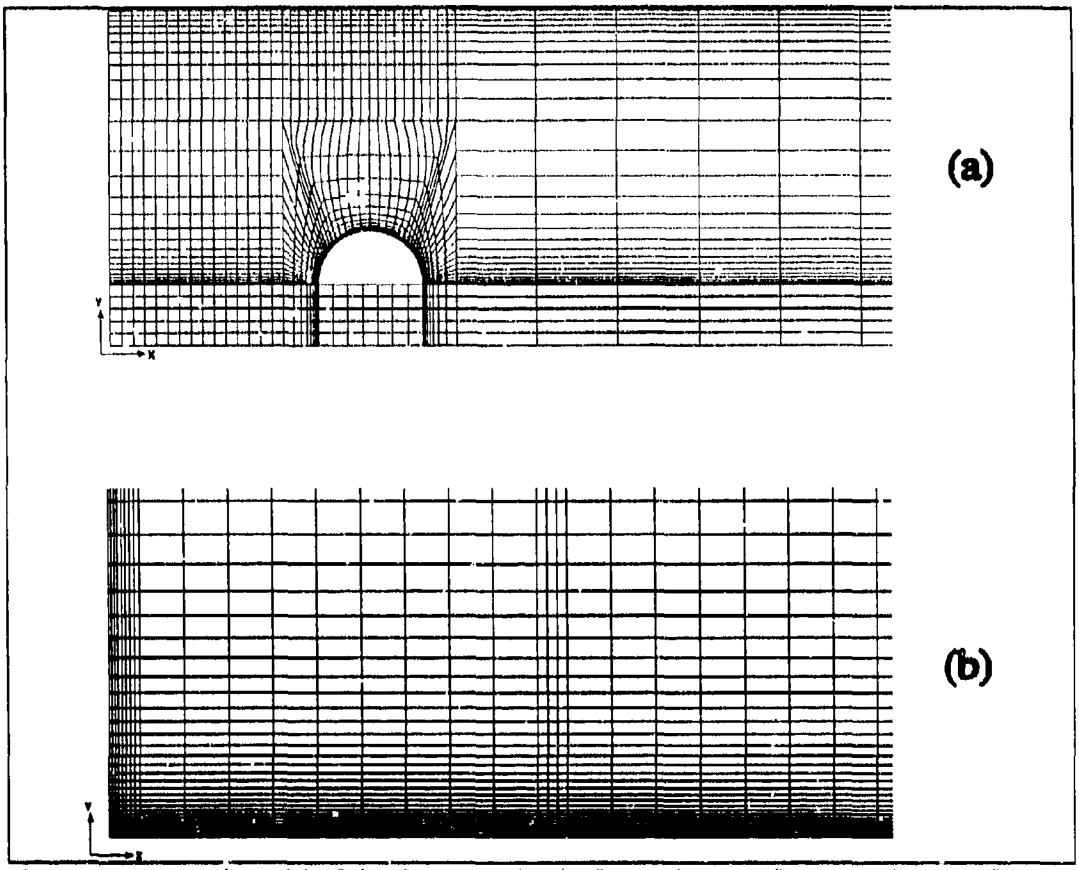

Figure 2.3.1 Sections of the finite element meshes for flow analyses: (a) flow over a drop on a flat plate and a drop between parallel plates; (b) flow over a smear on a flat plate.

plate; little is transported far into the flow which is typical of laminar transport flows. The vapour from the drop can also be seen to spread laterally through the fabric for approximately four drop radii downstream and three drop radii upstream of the drop edges.

Figure 3.1.2 shows the resulting mass flux into the air-stream as a function of position along the plate for two Schmidt Numbers at a selected drop Reynolds Number of 30. The flux decreases with increasing distance from the leading edge of the plate, or as the boundary layer thickness increases. The shape of the curve suggests an asymptotic decrease with increasing distance. For a drop Reynolds Number of 30, little change in the flux occurs beyond L=50. The position along the plate after which the flux remains effectively constant will probably increase somewhat with an increasing drop Reynolds Number, although this is speculation as this study did not examine this point.

Figure 3.1.3 shows the mass flux from the drop into the air-stream as a function of the drop Reynolds Number at two positions along the plate and for two Schmidt Numbers. As the drop Reynolds Number increases, the mass flux also increases although the changes are diminishing as the drop Reynolds Number

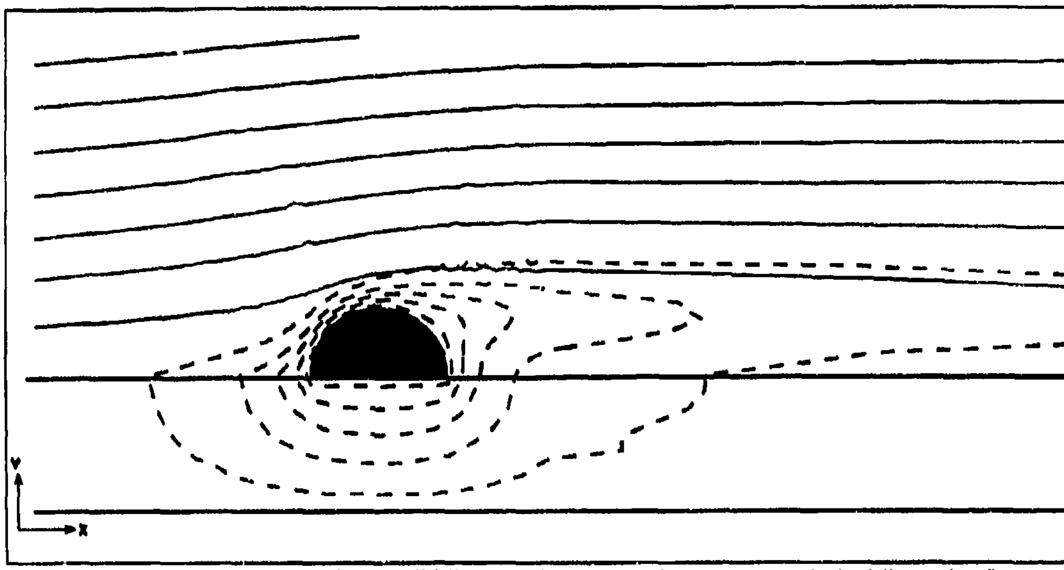

Figure 3.1.1 Typical streamlines (solid lines) and concentration contours (dashed lines) for flow over a drop (solid hemisphere) on a flat plate.

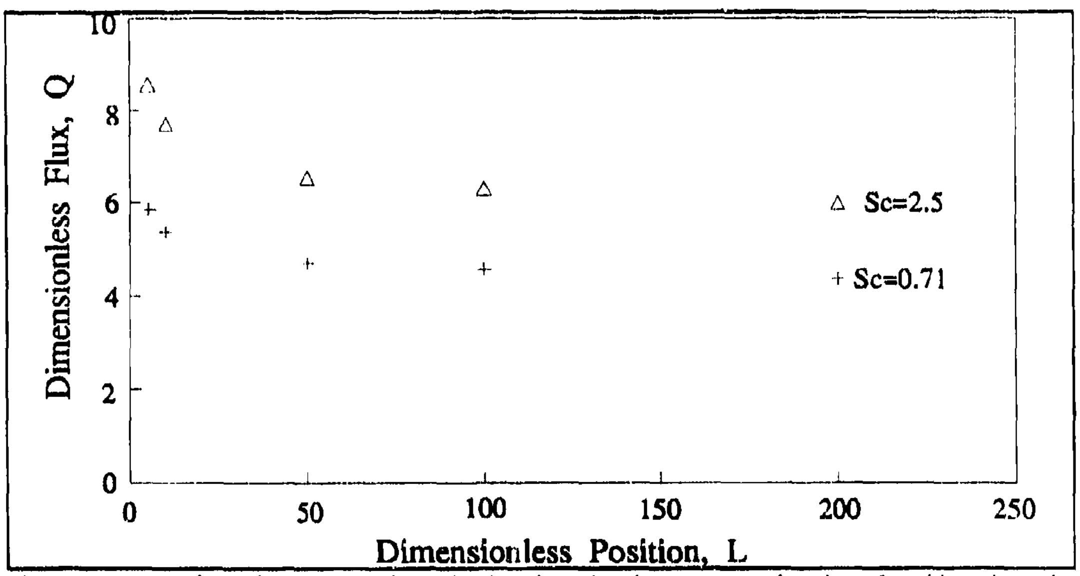

Figure 3.1.2 Flux from the upper surface of a drop into the airstream as a function of position along the plate for two different Schmidt Numbers and a drop Reynolds Number of 30.

increases. The flux will likely increase abruptly and substantially, however, when the flow becomes turbulent as the rate of convective mass transport increases significantly with the onset of turbulence.

It should be noted that an increasing drop Reynolds Number can result either from an increasing drop size or an increasing flow velocity and that the dimensional mass flux is inversely proportional to the drop size

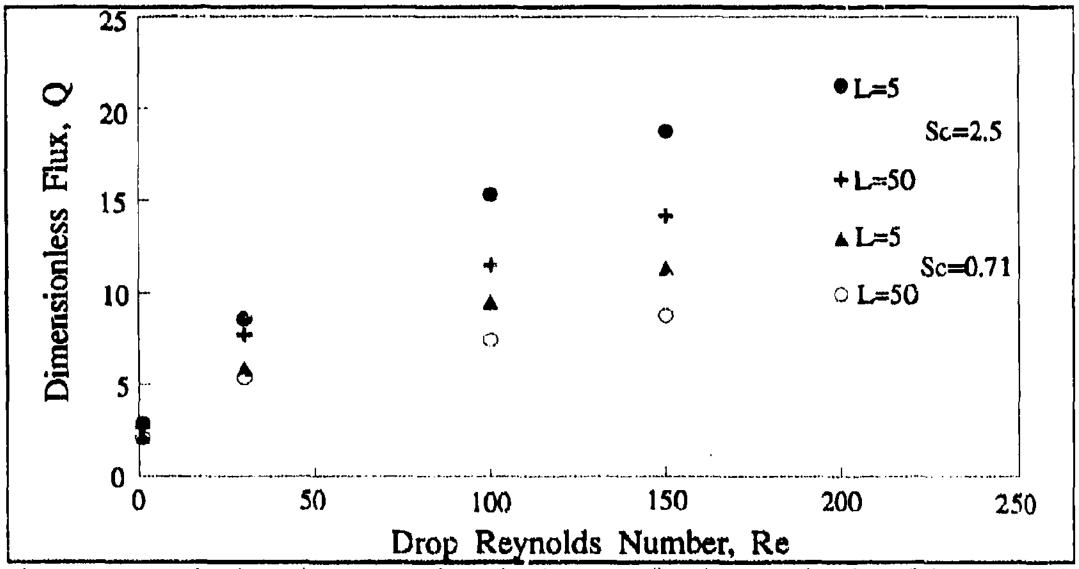

Figure 3.1.3 Flux from the upper surface of a drop on a flat plate as a function of drop Reynolds Number for two positions along the plate and two Schmidt Numbers.

for this problem:

$$q = Q\,(D\,\Delta c_u/r) \qquad (23)$$

Thus, even though the non-dimensional flux may increase with an increasing drop Reynolds Number, the dimensional mass flux may be quite different depending on whether the larger Reynolds Number change is due to increasing drop size or increasing flow velocity.

The cases with the large Schmidt Number have the greater non-dimensional mass flux and again the mass flux is greater closer to the leading edge of the plate where the boundary layer is thinner. At first glance this is somewhat surprising as the Schmidt Number is inversely proportional to the chemical diffusivity, however, on inspection, the dependence of the non-dimensional flux is not linearly proportional to the Schmidt Number and when actual mass fluxes are calculated, using equation 23, the chemical species with the greater diffusivity does indeed have the greater flux.

As expected, the mass flux downwards (through the fabric) showed no dependence on the position along the plate. As only one value of the non-dimensional plate thickness was used in this portion of the investigation, no general conclusions can be drawn. It is expected that the downwards flux for this geometry will be virtually identical to that for a drop in a channel which is discussed in the next section.

3.2 Drop In A Channel

Figure 3.2.1 shows typical streamlines and concentration contours for flow over a drop between parallel plates. Notice that there is some horizontal diffusion from the bottom of the drop within the lower plate which then diffuses upwards into the airstream both in front of and behind the drop.

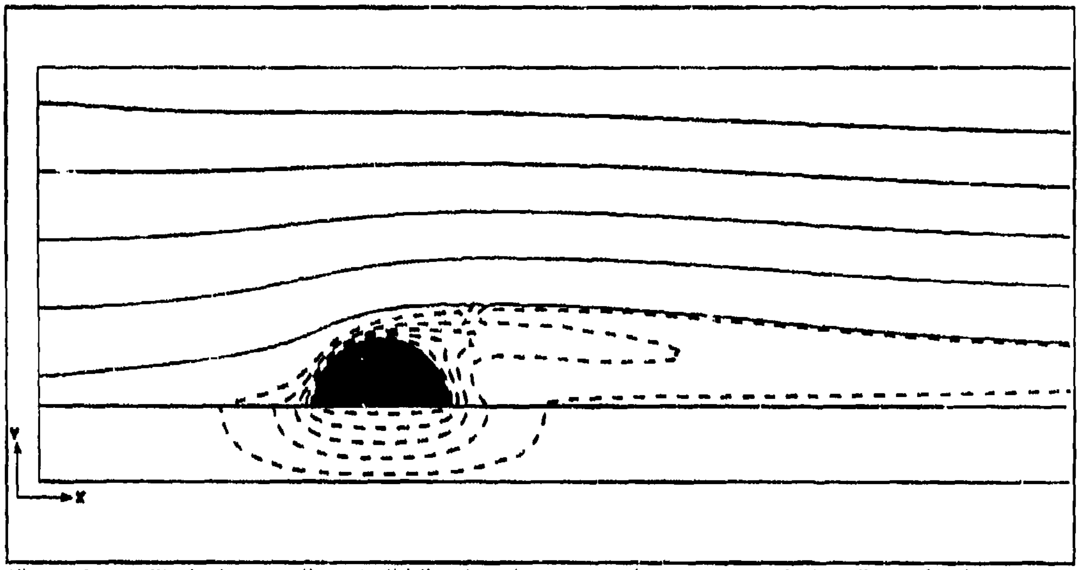

Figure 3.2.1 Typical streamlines (solid lines) and concentration contours (dashed lines) for flow over a drop (solid hemisphere) in a channel.

The vertical flux showed only a slight dependence on the position along the plates (Figure 3.2.2) with the flux being marginally greater near the leading edge of the channel. The results indicate that if the non-dimensional distance, L/r, from the leading edge of the channel is greater than approximately 10, no significant dependence on position will be observed for drop Reynolds Numbers less than 30.

Only a very slight dependence of the vertical flux on the channel height was found (Figure 3.2.4). As the drop height approaches that of the channel height, the flow becomes disturbed by the drop, especially in a two-dimensional analysis, and the flux increases accordingly. The results indicate that if the height of the channel is greater than 10 to 15 times that of the drop size, then the channel height will have a negligible influence on the vertical flux from the drop.

The vertical flux increases with an increasing drop Reynolds Number. Figure 3.2.3 shows this dependence at two positions along the plate, 5 and 50.

Figure 3.2.5 shows the downwards mass flux due to diffusion through the porous (fabric) wall as a function of the wall thickness. As one would expect, all flow parameters (Re, H/r, L/r) other than the wall thickness have no effect on the downward flux which is shown in Figure 3.2.5 where all data fall on a single

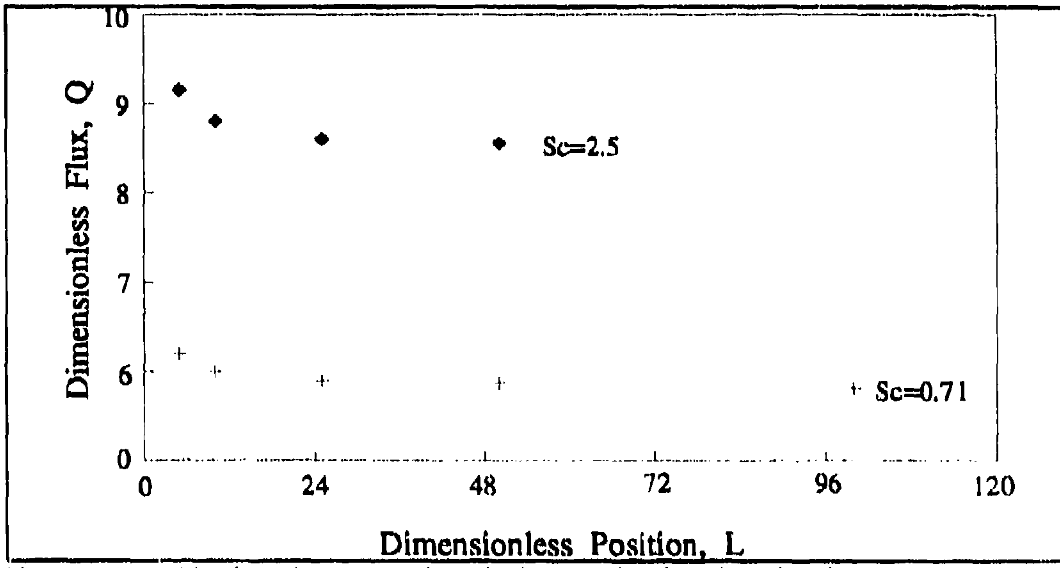

Figure 3.2.2 Flux from the upper surface of a drop as a function of position along the channel for two Schmidt Numbers. The Drop Reynolds Number was 30 and the channel height was 5.

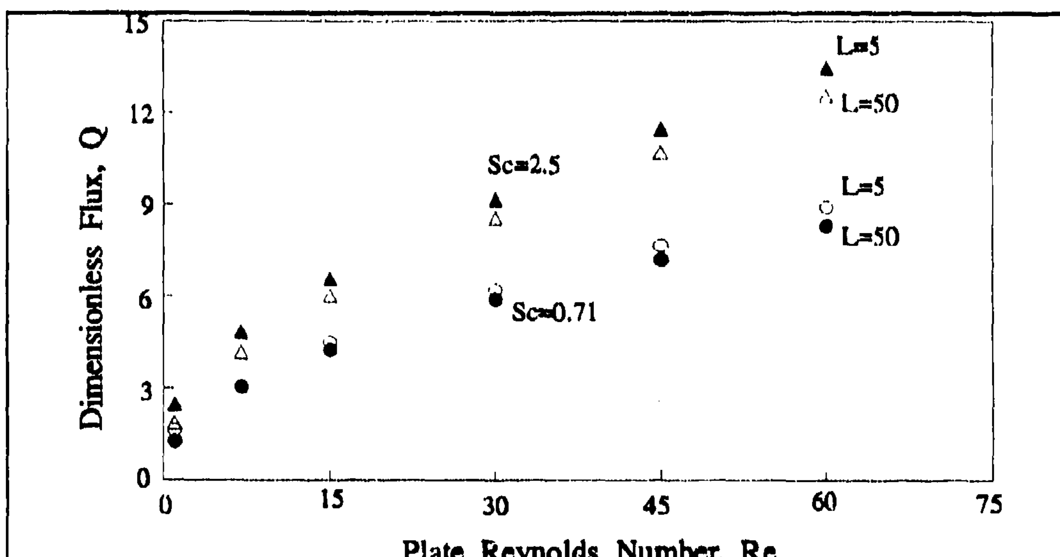

Figure 3.2.3 Flux from the upper surface of a drop in a channel as a function of drop Reynolds Number for two Schmidt Numbers and two positions along the channel. The channel height was 5.

curve. This also implies that the downwards flux from a drop on a flat plate, described in the previous section, should be identical to the downwards flux in a channel for the same wall thickness and concentration difference.

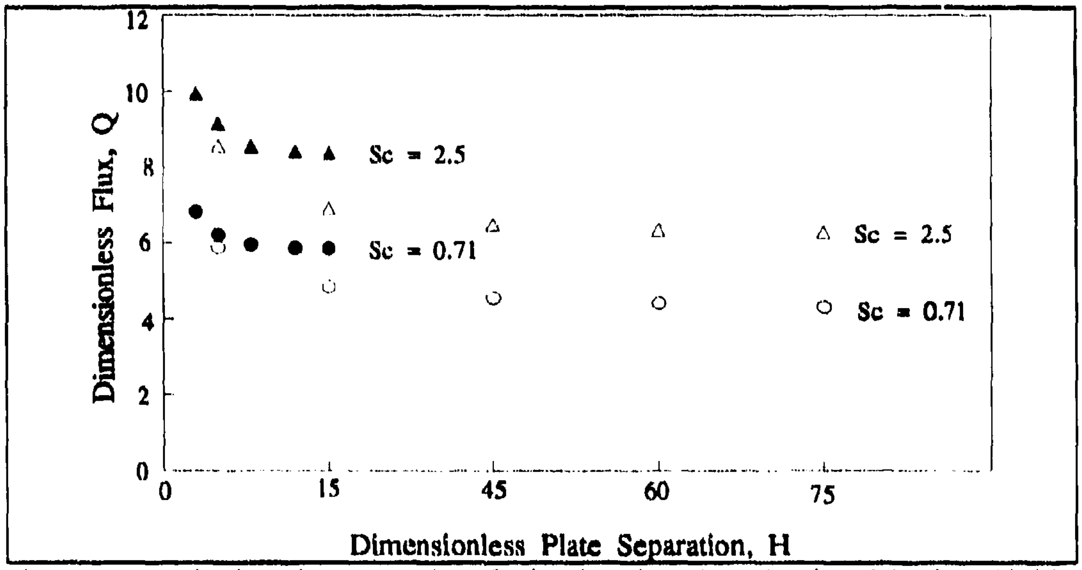

Figure 3.2.4 Flux from the upper surface of a drop in a channel as a function of the channel height. Two Schmidt numbers and two positions are shown. The drop Reynolds Number was 30.

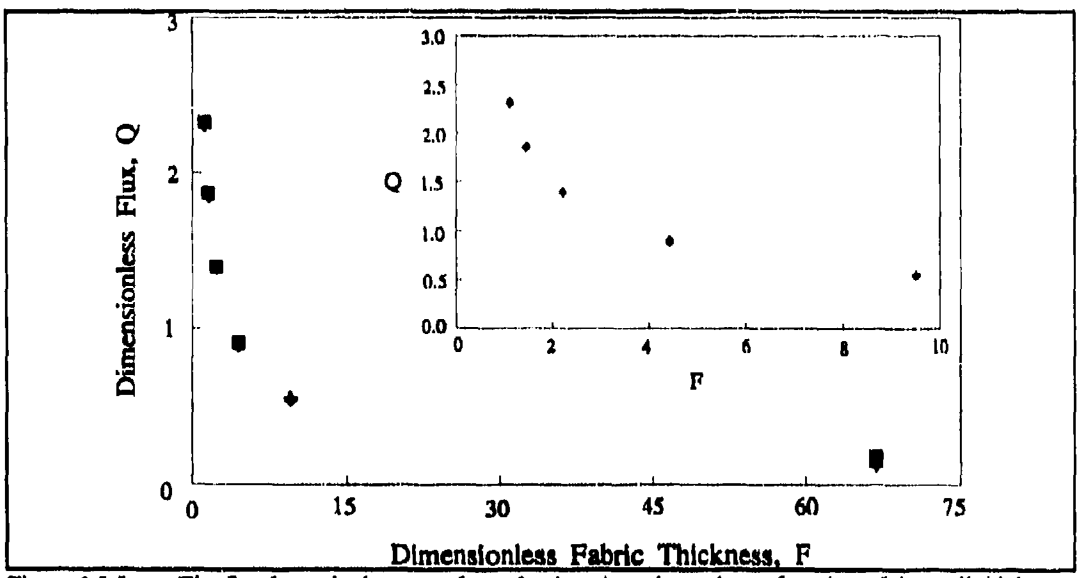

Figure 3.2.5 The flux from the lower surface of a drop in a channel as a function of the wall thickness. The insert gives the results in greater detail for thin walls.

As the wall thickness increases, the flux decreases due to the decreasing concentration gradient across the wall. The results suggest that as the wall thickness decreases to zero, the mass flux becomes very large if not infinite and as the wall thickness increases, the flux tends to zero. The greatest change in the downwards mass flux occurs in the wall thickness range of zero to fifteen. For wall thicknesses greater than fifteen, a substantial increase in the wall thickness is required in order to noticeably reduce the mass flux.

3.3 Smear On A Flat Plate

Figure 3.3.1 shows a typical set of streamlines and concentration contours for the flow over a smear on a flat plate. As diffusion within the plate was not modeled in this problem, there is no mass flux into the fluid before the start of the drop. Based on the results of the previous section, one would expect some diffusion and mass flux from the wall into the fluid to occur both before and after the contaminated region.

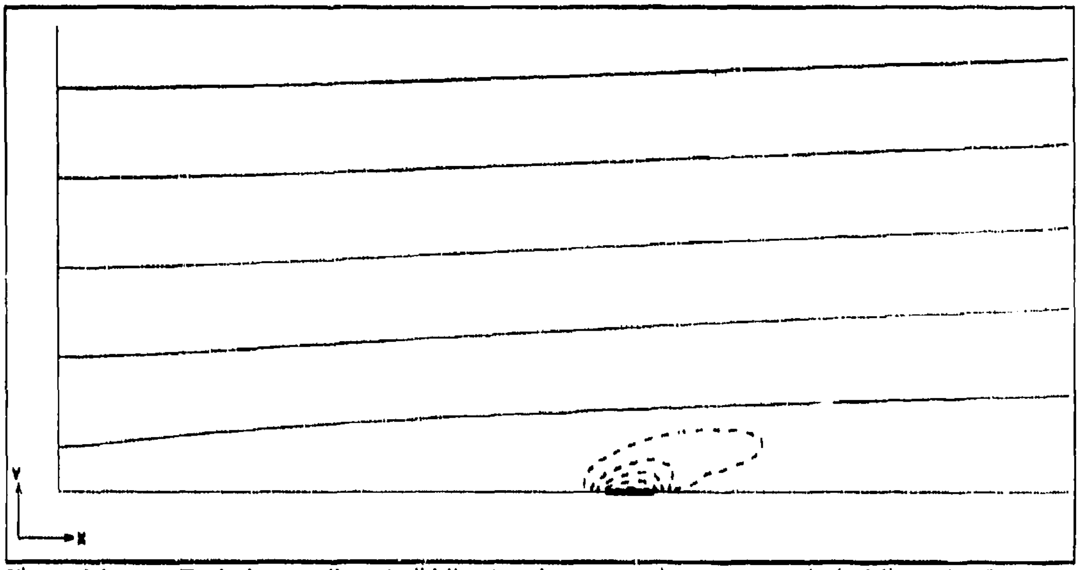

Figure 3.3.1 Typical streamlines (solid lines) and concentration contours (dashed lines) for flow over a smear (thick solid line) on a flat plate.

The vertical mass flux from the smear was found to vary with position along the plate (Figures 3.3.2 and 3.3.3), although, most of the differences occur within the first quarter of the plate length. The variation is most pronounced at the lower Reynolds Numbers as the boundary layer increases in thickness more rapidly in these cases and the convective mass transport is much less intense.

The vertical mass flux varies considerably with an increasing drop Reynolds Number, especially beyond the first quarter of the plate length where the boundary layer thickness is changing as the inverse square-root of the plate Reynolds Number. These variations are primarily a result of changes in the fluid velocity.

3.4 Use of Results

In order to demonstrate how the results of dimensionless studies may be used, an example is presented for each of the geometries analyzed above. It is assumed that a 1 microlitre drop of liquid mustard (HD) having a diffusivity, D, of 6×10^{-6} m^2/s is placed at a position, ℓ, 2.5 cm from the leading edge of a 5 cm long plate. The drop is exposed to a mean air speed, u, of 0.5 m/s and the air temperature is 30°C. For the flow between

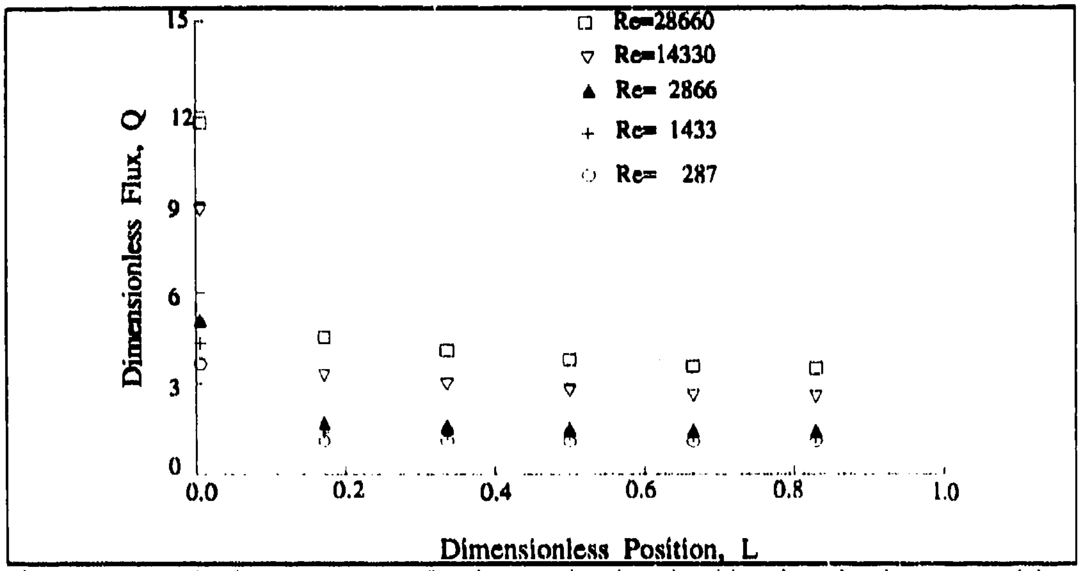

Figure 3.3.2 Flux from a smear on a flat plate as a function of position along the plate at several drop Reynolds Numbers. The Schmidt Number was 0.6.

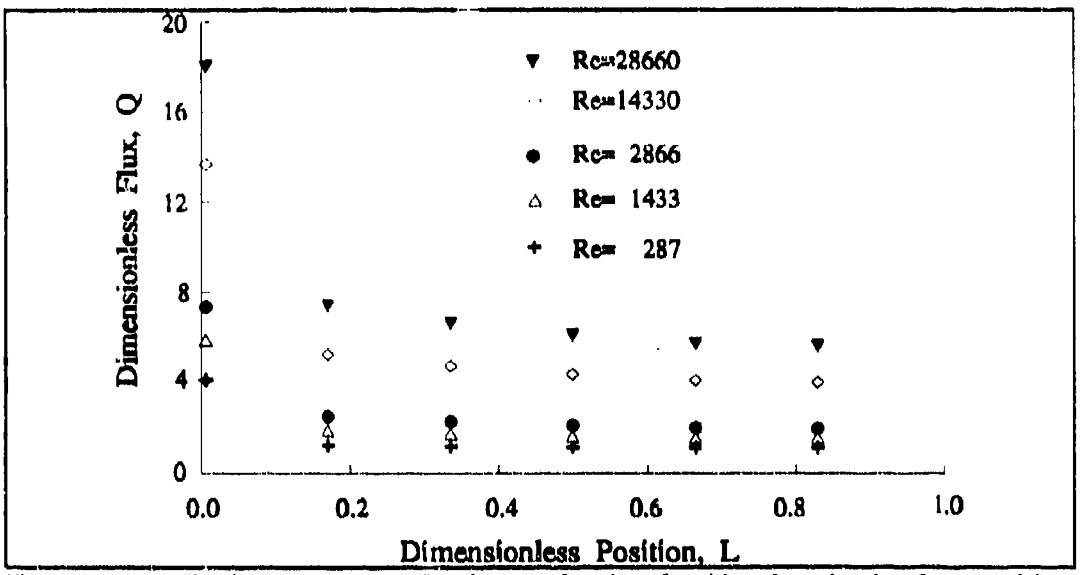

Figure 3.3.3 Flux from a smear on a flat plate as a function of position along the plate for several drop Reynolds Numbers. The Schmidt Number was 2.5.

parallel plates geometry, the plate separation, h, is 0.5 cm. For the case of a smear on a flat plate, the fabric is assumed to be 0.5 mm thick and the volume of fabric through which the drop spreads is half-filled with fabric threads. The volatility of the liquid is assumed to be approximately 1.2 g/m^3 and the inlet air is assumed to have a zero concentration of the mustard vapour.

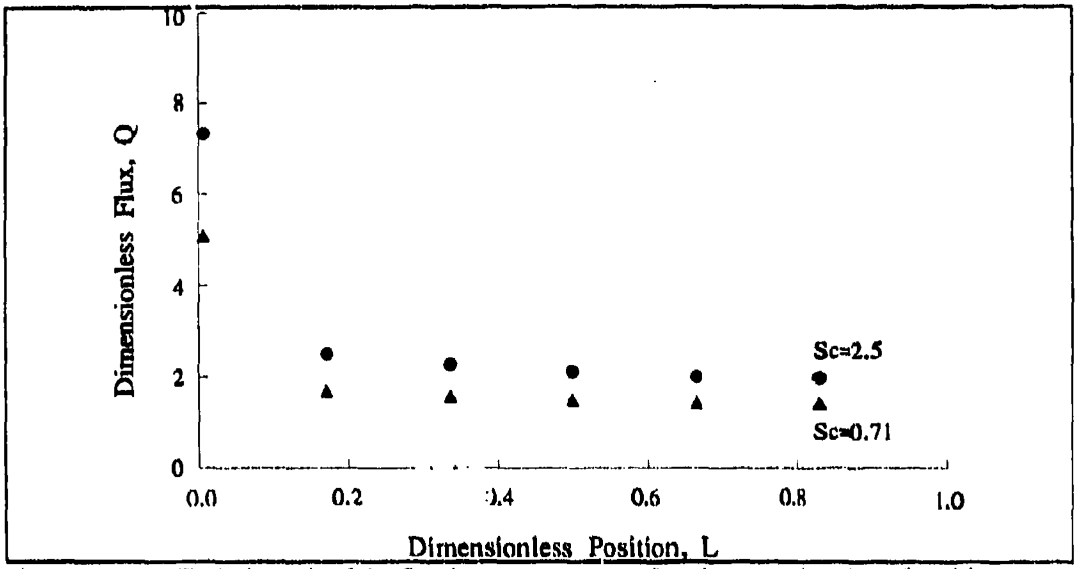

Figure 3.3.4 Typical trends of the flux from a smear on a flat plate as a function of position at two Schmidt Numbers. The Drop Reynolds Number was 2866.

Non-dimensionalizing the physical parameters for a drop on a flat plate yields the following:

$$r=\left(\frac{3(10^{-9}m^3)}{2\pi}\right)^{1/3}=7.8x10^{-4}m \qquad (24)$$

$$Sc=\frac{1.8x10^{-5}kg/m\cdot s}{(1.3kg/m^3)(6x10^{-6}m^2/s)}=2.3\approx2.5 \qquad (25)$$

$$Re=\frac{(1.3kg/m^3)(0.5m/s)(7.8x10^{-4}m)}{1.8x10^{-5}kg/m\cdot s}=28 \qquad (26)$$

$$L=\frac{2.5x10^{-2}m}{7.8x10^{-4}m}=32 \qquad (27)$$

From figure 3.1.4, the dimensionless flux into the airstream from the upper surface of the drop is found to be approximately 8.5. This can be converted back into a dimensional flux:

$$q = 8.5\frac{(6x10^{-6}m/s)(1.2-0g/m^3)}{7.8x10^{-4}m} = 0.078g/m^2s \tag{28}$$

which, when multiplied by the upper surface area of the drop gives an absolute flux of $3x10^{-7}$ g/s.

For the same drop between parallel plates, most of the above dimensionless variables can be used along with the dimensionless plate separation:

$$H = \frac{0.5x10^{-2}m}{7.8x10^{-4}m} = 6 \tag{29}$$

From Figure 3.2.3, the dimensionless flux is found to be approximately 9. This is equivalent to a dimensional flux of 0.083 g/m^2s or an absolute flux of $3.2x10^{-7}$ g/s. This is similar to that found for the flux from a drop on a flat plate which is to be expected as H, the ratio of the channel height to the drop height, is large.

If the liquid soaks into the fabric, the resulting smear radius is:

$$r = (\frac{2(10^{-9}m^3)}{(0.5x10^{-3}m)\pi})^{1/2} = 1.1x10^{-3}m \tag{30}$$

The plate Reynolds Number is:

$$Re = \frac{(1.3kg/m^3)(0.5m/s)(0.05m)}{1.8x10^{-5}kg/m \cdot s} = 1800 \tag{31}$$

The dimensionless position is H=0.5. From Figure 3.3.3, the dimensionless flux is found to be approximately 2 which can be converted into dimensional form as:

$$q = 2\frac{(6x10^{-6}m^2/s)(1.2-0g/m^3)}{0.05m} = 0.0003g/m^2s \tag{32}$$

The spread of the drop on and through the fabric depends a great deal on the fabric material and on the construction both of the fabric itself (its weave) and of the individual yarns of the fabric [Crow 1989]. If extrapolation from experimental data [Crow 1989] to smaller drop volumes is valid, a 1 μl drop should spread between $1x10^{-6}$ and $4x10^{-6}$ m^2 which yields a very small absolute flux of 10^{-9} g/s. If the smear spreads along the yarns of the fabric instead of just filling the voids between the yarns, the area of the drop could be a good deal larger and the resulting flux more substantial, however, the smear would have to increase its area two orders of magnitude to be comparable to the evaporation from the drops.

3.5 Comparison of Numerical and Experimental Results

Measurements of the evaporation of mustard (HD) drops have been made in a standard Penetration Test Cell [Pagotto, 1991]. Five, one-microlitre drops were distributed over a treated fabric and exposed to an air flow velocity of approximately 0.44 m/s at 30°C. Due to the repellent treatment on the fabric, the drops remained approximately hemispherical. These conditions are similar to the example conditions for flow over a drop between parallel plates discussed in the previous section.

Air contaminated with vapour leaving the cell was sampled by a gas chromatograph and then run through a bubble extractor. The instantaneous concentration of vapour in the air was measured once every minute. From this, an average, instantaneous evaporation rate was calculated. As a check on the accuracy, these instantaneous evaporation rates were time integrated to determine the total mass evaporated from the drops. This result was then compared to the total measured by the bubble extractor and the results where found to be in agreement to within 5%. Since the bubble extractor measures only the cumulative total mass of vapour leaving the cell, it does not directly corroborate the instantaneous evaporation rate, however, it does lend credence to the results.

After an initial period during which the apparatus came up to temperature, the average, instantaneous evaporation rate per drop seemed to achieve a relatively constant 2.7×10^{-7} g/s. This rate continued until approximately 80% of total liquid had evaporated after which the evaporation rate decreased steadily.

The measured evaporation rate (2.7×10^{-7} g/s) compares quite favourably to the predicted rate found in the previous section (2.4×10^{-7} g/s) which was approximately 12% less than the measured value.

4.0 Conclusion

A parametric study using dimensionless variables is shown to provide a concise presentation of the results which can then be used to supply information on particular problems with little additional work. Using dimensionless variables, both in physical experiments and numerical analyses, allows the investigator additional flexibility since the equations of heat transfer and mass transfer have similar form. This technique also minimizes the number of independent variables required to characterize the problem.

The results presented in this report can be used to predict evaporation rates from drops (or heat fluxes from cylinders) for three similar geometries. The results for the specific example of a drop of mustard between parallel plates compare very favourably with measured values from drops in experimental test cells, although the comparison is limited to one set of experimental results. Although limited, the good agreement lends confidence to the validity of the numerical results and to the use of the results to make predictions for cases difficult to obtain in the laboratory. Extension of the comparison to include field data under similar conditions remains to be done and so no conclusion can be made in this area based on the results of this study.

An analysis of this type would also be of use to designers of a test apparatus for measuring agent penetration into protective fabrics. By selecting the desired air speed and drop size, calculations can be made of the appropriate dimensionless variables. The theoretical results can then be used as guidelines for establishing parameters of the apparatus such as channel height and drop position so that the apparatus itself does not influence the outcome of the experiment.

It should be stressed that the two-dimensional study presented here is only an approximation to the actual, three dimensional physical problem and therefore the results must be used with some caution, preferably with experimental corroboration. The comparison of a flow over a cylinder to that over a sphere, which can be found in most elementary fluid mechanics and heat transfer texts, further illustrates the caveats which must be observed when approximating a three-dimensional problem with a two-dimensional model. More powerful computers would allow the analysis to be extended into three dimensions which should make the results more representative of the physical problem and which could be used to explore more interesting geometries.

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Glossary

c_a	chemical concentration
C_a	dimensionless chemical concentration, $c_a/\Delta c_a$
Δc_a	constant chemical concentration difference
c_p	heat capacity
D	thermal diffusivity
f	fabric thickness
F	dimensionless fabric thickness, f/L
h	plate separation
H	dimensionless plate separation, h/r
k	thermal conductivity
ℓ	plate length
L	generic length scale or dimensionless plate length
p	fluid pressure
P	dimensionless fluid pressure, $p/(\frac{1}{2}\rho u_o^2)$
Pr	Prandtl Number, $\mu c_p/k$
q	heat or mass flux
Q	dimensionless heat $(qL/k\Delta t)$ or mass $(qL/D\Delta c_a)$ flux
r	drop radius
R	dimensionless drop radius, r/L
Re	Reynolds Number, $\rho u_o L/\mu$
Sc	Schmidt Number, $\mu/\rho D$
t	temperature
T	dimensionless temperature, $t/\Delta t$
Δt	constant temperature difference
u	velocity vector
U	dimensionless velocity vector, u/u_o
u_o	reference speed
x	distance from the leading edge of a plate
X	dimensionless distance from the leading edge of a plate, X/L
δ	boundary layer thickness
ρ	fluid density
μ	fluid viscosity
∇	gradient operator
∇^2	Laplacian operator

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

Department of National Defence
Defence Research Establishment Ottawa
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2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable)

UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

A 2-D Analysis of Evaporation in Laminar Flow(U)

4. AUTHORS (Last name, first name, middle initial)

CAIN, Brad

5. DATE OF PUBLICATION (month and year of publication of document)

November 1991

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

23

6b. NO. OF REFS (total cited in document)

5

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Report

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

051LC

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DREO REPORT 1093

10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

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This report documents a two-dimensional, finite element study of the evaporation of a liquid on a flat surface into a laminar air stream for three geometries: a hemispherical drop on a flat plate; a hemispherical drop between parallel plates; a smear on a flat plate. The problems are made dimensionless and the flux from the liquid is determined in a parametric analysis with a range of values of the resulting independent variables. A comparison is made with some experimental data and an example of the use of the results is given.

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Protection
Transport
Evaporation
Diffusion
Laminar
Plate
Smear