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Fluid Mechanics of Continuous Flow Electrophoresis

Final Report

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Prepared for George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812

Submitted by

Universities Space Research Association P.O. Box 1892 Houston, Texas

Savilla

D.A. Saville Principal Investigator Princeton University

S.Ostach (DAS)

S. Ostrach Co-Investigator Case-Western Reserve University

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April 1978

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ABSTRACT

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The following aspects of continuous flow electrophoresis were studied: flow and temperature fields, hydrodynamic stability, separation efficiency, and characteristics of vide-gap chambers (the SPAR apparatus). Simplified mathematical models were developed so as to furnish a basis for understanding the phenomena and comparison of different chambers and operating conditions. Studies of the hydrodynamic stability disclosed that a "wide-gap" chamber may be particularly sensitive to axial temperature variations which could be due to uneven heating or cooling. The mathematical model of the separation process includes effects due to the axial velocity, electroosmovic cross-flow and electrophoretic migration, all including the effects of temperature dependent properties.

INTRODUCTION

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Hydrodynamics plays varied roles in the continuous flow electrophoresis of small particles, in some situations the suspending fluid does little more than carry particles through the apparatus, in others the flow is so convoluted that electrophoretic separation is impossible. One of the complicating factors is the role of buoyancy forces which can destabilize the flow or establish an unfavorable, but steady laminar flow. To circumvent such problems it has been suggested that the apparatus be operated in a microgravity e vironment where, due to the reduced size of buoyancy forces, the chamber could be made larger and field strength increased. Then populations of large biological particles could be fractionated into narrow subpopulations on the basis of unique surface characteristics which are reflected in the electrophoretic mobility. Such an undertaking obviously requires careful evaluations of many types. The purpose of this investigation is to furnish a basis for understanding the hydrodynamic characteristics of the chamber and their effects on the separation process. Particular emphasis is placed on the role buoyancy plays in establishing the basic flow and affecting its stability.

Work began on this project in February of 1977 with the objective of assembling and evaluating current knowledge of the hydrodynamics of continuous flow electrophoresis. Four tasks were specified for the one year contract period:

- (1) Develop models to describe the flow and temperature fields;
- (2) Investigate the hydrodynamic stability of the flow field;
- (3) Develop a model to predict electrophoretic separation efficiency;
- (4) Review the SPAR apparatus and experiment.

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Work on these tasks is complete insofar as it is covered by this contract and results are described in this report. The studies begun here continue under a separate NASA contract with Princeton University. The main part of the report is divided into two parts: SUMMARIES AND CONCLUSIONS, and DESCRIPTION OF RESULTS, where more detailed information is set forth.

SUMMARIES AND CONCLUSIONS

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More detailed information on the various subjects is contained in the DESCRIPTION OF RESULTS sections, here we simply summarize and discuss conclusions.

Flow and Temperature Fields

The temperature field enters the problem because it alters the electrophoretic mobility of the particles and causes density contrasts which lead to buoyancy driven flows. The non-uniform temperature field itself derives from heat effects associated with the electric field and current. Although the field is three-dimensional, it is possible to simplify matters using perturbation methods. For present purposes we sought to establish the edge effects due to cooling through the side walls containing the electrodes (cf. Figure 1), the effects of temperature dependent conductivities for heat and electricity, and estimate time scales for thermal equilibration of the chamber.

The edge effects were found to be substantial in that they extend into the chamber for distances of 1-2 chamber thicknesses from each side. This alters the mobility of particles in these regions and has a dramatic effect on the flow through buoyancy effects. It was also found that the effects of temperature dependent conductivities were substantial, the calculated temperature rise being 70% larger for a wide-gap chamber (0.5 cm thick) than that calculated assuming constant properties. Although temperature relaxation times for the fluid are only 10-15 seconds for a narrow-gap chamber (0.15 cm) 2-3 minutes are required to establish the steady field in a widegap chamber.

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^{*} Representative dimensions, fluid properties, operating conditions, etc., are summarized on Table I, p. 72. A schematic diagram is on p. 7.

FIGURE 1.

Schematic representation of an electrophoresis chamber.

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For the flow field analytical solutions in two-dimensions were constructed to investigate ways buoyancy could alter the axial flow and to study edge effects. One-dimensional models were then developed to investigate the effects of temperature dependent transport properties on the axial flow and electroosmotic cross flow.

Several conclusions can be drawn from this part of the study.

(a) It is necessary to include effects of temperature on transport properties. Models which ignore this, or treat matters inconsistantly, can be qualitatively and quantitatively misleading, especially with wide-gap machines like the SPAR device. With narrow-gap machines operated with modest field strengths (cf. Table 1) the use of 'average' values is satisfactory since temperature variations are usually small.

(b) In wide-gap machines operating in a 1-g environment the steady-state axial velocity profile is unsatisfactory at modest field strengths insofar as electrophoretic separations are concerned. An earlier study by Ostrach (using a 'constant properties' one-dimensional model) identified a buoyancy-driven feature which made downflow operation unsatisfactory. Edge effects and alterations due to temperature depending properties accentuate the buoyancy feature making matters worse. Upflow, which was once suggested as a means of overcoming the difficulty, turns out to be only marginally better for the cases studied. In downflow the difficulty arises from a recirculating eddy in the center of the chamber; in upflow two eddys appear, attached to the front and rear cooling surfaces, and these restrict the area available for separation. A micro-gravity environment would suppress or eliminate secondary flows of this sort. Of course other means of eddy suppression ought not be ruled out.

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; \$ (c) Experiments at General Electric using the wide-gap SPAR apparatus disclosed a meandering sample flow pattern thought to be evidence of the structure noted in (b). Subsequent calculations made with the models developed here showed that the actual power levels were far lower than those required according to the theory and thus the meandering flow must be due to another process.

Hydrodynamic Stability

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In an attempt to ascertain the cause of the meandering observed in the Genera! Electric experiments the stability of several chamber configurations was examined. Attention focussed on buoyancy driven instabilities for obvious reasons and investigations of other sorts of instability, e.g., those due to viscosity stratification or electrokinetic effects, etc., were deferred. Three sorts of instability were investigated: the inception of cellular motion due to heat generation in a quiescent layer, roll cells in a buoyancy driven shear flow and the effect of an axial temperature gradient on a fully developed flow. Critical temperature differences for the quiescent layer or the shear flow are much larger than those present in the experiments. For the vertical chamber with axial flow a new two-dimensional instability was identified with an expecially low critical Rayleigh number. For conditions characteristic of the SPAR machine the critical axial gradient is (ca.) $0.5^{\circ}C/cm$.

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Further experimental work will be required to establish whether or not the flow 'meandering' is a manifestation of the instability predicted by the current theory. If it is, then a micro-gravity environment will provide a means of avoiding it. Other types of instability mechanisms should also be investigated, however, so as to provide a comprehensive picture.

Prediction of Electrophoretic Separator Performance

Using the flow and temperature fields described earlier, a mathematical model of continuous electrophoretic separation was developed. The model (in brief):

(a) Accept. as input data the dimensions of the chamber, operating conditions and flowrates, transport properties of the buffer, location and size of the sample injection tube, mobility distribution of the sample, zeta-potential of the wall coating, number and size of the sample outlet streams, etc.

(b) Predicts the mobility distribution in each of the sample withdrawal streams.

Calculations were carried out using computer programs which have been tested on "model systems". Further refinements will be made under the current NASA contract with Princeton.

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SPAR Electrophoresis Experiment

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Throughout the course of this investigation attention focussed on understanding the behavior of wide-gap machines and predicting their performance. We now have models of the flow and temperature fields and can estimate the electrophoretic separation characteristics of a given device.

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Although refinements will be necessary, the requisite 'first generation' models now exist for interpreting results from SPAR (or other) experiments. Furthermore, the effects of changes in process variables can be examined so as to optimize the separation.

Final Comments

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Work begun during this program is being .rried on under a joint program coordinated by Dr. R.S. Snyder of MSFC. These tasks include:

(a) Experimental studies (at MSFC) to ascertain the reason for flow meandering in wide-gap machines at 1-g. This will serve to prove or disprove the proposal that observed unsatisfactory operation is due to a buoyancy driven instability and assist in developing ways to circumvent the problem.

(.) Case-studies with the flow and separation models developed here to ascertain the ultimate (theoretical) capabilities of continuous flow devices.

(c) Theoretical work to extend the capabilities of the model, to develop an understanding of three-dimensional effects and finite sample concentration, and to investigate other hydrodynamic instabilities which could limit resolution. Establishing the limitations due to gravity and those arising from other phenome.

Frequent observations of particle agglomeration and 'clumping' phenomena with cells underscore the need for an investigation of effects due to particle concentration. Recent theoretical studies (Batchelor, 1972) suggest substantial changes in sedimentation velocity at particle concentrations of a few percent but none of the extant studies deal with electrokinetic effects present in electrophoresis.

(d) The development of experimental techniques to test the model using mixtures of well-characterized particles. This will include micro-gravity experiments where appropriate

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DESCRIPTION OF RESULTS

I. Flow and Temperature Fields

Introduction

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Inside a continuous flow electrophoresis chamber of the sort depicted on Figure 1 the temperature and velocity have a three-dimensional character. Cold buffer enters one end of the chamber and adjusts to the new geometry within a distance, x_e , which is given roughly by the formula (Schlichting, 1960)

$$x_{e} = 0.16 \text{ Re d.}$$
 (1)

Here d stands for the half-thickness and Re for the Reynolds number, $u_0 d/v_0$; u_{o} is the mean axial velocity and v_{o} the kinematic viscosity. Since the Reynolds number lies in the range 1-5, the entrance length is relatively short and here the velocity field can be modelled as being fully developed (viz. independent of x). As the buffer flow moves into the electrode region heat is added (volumetrically) through the action of the electric field and the associated current, so, to limit the temperature rise, the front and back walls are kept cold. For reasons that will be explained later (in the section on stability) the adjustment length for the temperature field can be substantial. Thus, in the electrode region the three-dimensional nature of the temperature field alters the structure of the velocity field through its effects on density and viscosity. Another contributory factor is the electroosmotic cross-flow caused by the action of the field on the thin layer of charge in the fluid adjacent to the lateral boundaries. Although this velocity is typically much smaller than the axial velocity, it has a major role in altering the electrophoretic separation processes. ORIGINAL PAGE IS

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The models developed here to describe the temperature and velocity fields take advantage of three facts:

- (i) The magnitude of the electro-osmotic velocity, w₀, is small compared to u₀.
- (ii) The axial variation of the temperature is slow.
- (iii) The effect of temperature on thermal conductivity and electrical conductivity is approximately linear over the temperature range of interest: 0° - 35°C.

These facts justify the use of perturbation methods to develop a description of the temperature and velocity fields. First, because of (i), the velocity field can be split into two parts, an axial flow field due to forced and natural convection with a superimposed electro-osmotic flow. Next, due to the slow variation of the transport properties with axial position, (ii), the velocity fields can be split into a fully-developed part (independent of x) with corrections added later to allow for axial structure. Finally, the simple linear variation, (iii), makes the description of the temperature field particularly simple.

Separate parts of the sequel are devoted to:

- A. Mathematical models for the structure of the temperature field
 - a. A two-dimensional model in which the effects of temperature on thermal conductivity are suppressed. This provides a means of evaluating edge-effects due to heat transfer near the side wall electrodes.
 - A one-dimensional model to evaluate effects of a temperature dependent thermal conductivity.
 - c. A transient heat conduction model to estimate thermal relaxation times.

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- B. Models for the structure of the axial velocity field
 - A two-dimensional, constant properties model provides a means of examining edge effects and buoyancy effects using the Boussinesq approximation.
 - b. A one-dimensional, variable properties model is the basis for evaluating thermal effects and is used in the separation model described in Part III.
- C. Models for the electro-osmotic cross-flow velocity
 - a. A one-dimensional, variable properties model provides a basis for evaluating thermal effects and is used in the separation model (Part III).

Temperature Field

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The equation for the conservation of thermal energy is

$$C_{p} u \frac{\partial T}{\partial x} = \nabla \cdot k \nabla T + \sigma_{o} E_{o}^{2}$$
(2)

The symbols are: C_p - volumetric heat capacity, k - thermal conductivity, σ - electrical conductivity, and E_o - the electric field strength. E_o is assumed to be a constant throughout the analysis. Both k and σ vary with temperature in a linear fashion (see Figure 2) and so we write

$$\sigma = \sigma_0 (1 + \sigma_1 \Theta) \tag{3}$$

$$k = k_0 (1 + k_1 \Theta) \tag{4}$$

where k_0 and σ_0 are reference values evaluated at the wall temperature and 0 stands for a dimensionless temperature, i.e.,

ORIGINAL PAGE IS OF POOR QUALITY FIGURE 2.

Thermal conductivity and electrical conductivity of the A-1 buffer.



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$$T = T_{U} + \Delta T \Theta$$
 (5)

The wall temperature is T_w and ΔT is a characteristic temperature difference. If we transform to dimensionless variables with u_0 as the characteristic velocity and d the characteristic length, then

Pe
$$u \frac{\partial \Theta}{\partial x} = \nabla \cdot [(1 + k_1 \Theta) \nabla \Theta] + 1 + \sigma_1 \Theta$$
 (6)

where $Pe = C_p u_o d/k_o$ and $\Delta T = \sigma_o E_o^2 d^2/k_o$.

Both k_1 and σ_1 are less than unity: k_1 is typically $O(10^{-2})$ while σ_1 is $O(10^{-1})$, and so it is convenient to represent the temperature by means of a perturbation series in k_1 , viz.

$$\Theta = \Theta^{(0)} + k_1 \Theta^{(1)} + k_1^2 \Theta^{(2)} + \dots$$
 (7)

Substituting into (6) we generate a sequence of equations for $\theta^{(0)}$, $\theta^{(1)}$, ...

Pe u
$$\frac{\partial \Theta^{(0)}}{\partial x} = \nabla^2 \Theta^{(0)} + \sigma_1 \Theta^{(0)} + 1$$
 (8)

Pe u
$$\frac{\partial \Theta^{(1)}}{\partial x} = \nabla^2 \Theta^{(1)} + \sigma_1 \Theta^{(1)} + \nabla \cdot (\Theta^{(0)} \nabla \Theta^{(0)})$$
 (9)

etc.

From equation (8) we deduce that in the thermal entrance region $\partial_{1}^{(0)}/\partial x$ is $O(Pe^{-1})$ and varies exponentially. Viscosity and density also depend on temperature so that a description of the temperature field to the order implied by equations (8) and (9) would entail an expansion for the axial velocity of the form

 $u = u^{(0)} + u^{(1)} + \dots$ (10)

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where $u^{(0)}$ is the constant properties solution, $u^{(1)}$ accounts for temperature variations, etc. This expansion would be used to furnish complete velocity fields for (8) and (9). Because of the complexity of the problem it has not been practical here to attempt a solution which includes axial variations. Instead we have suppressed the axial structure and developed a 'zero-order' approximation with which we can assess the orders-of-magnitude of the thermal effects. An investigation of the details of the axial structure of the temperature and velocity fields is part of the work being done now under another NASA contract.

Two-Dimensional, Constant Thermal Conductivity Model

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The major features of the fully developed temperature field can be found by solving equations (8) and (9), omitting the convective terms. The boundary conditions are:

- (i) isothermal side walls, 0 = 0, at $y = \pm 1$.
- (ii) heat transfer through the side walls at z = ±H modelled in terms of a heat transfer coefficient, h, i.e.,

$$- k \frac{\partial T}{\partial z} = h_0(T - T_B).$$

 ${\rm T}_{\rm B}$ stands for the coolant temperature. For the zero-order field we have, in dimensionless form:

$$0 = -\nabla^{2} \Theta^{(0)} + \sigma_{1} \Theta^{(0)} + 1$$

$$\Theta^{(0)} = 0, \quad y = \pm 1, \quad \frac{\partial \Theta^{(0)}}{\partial z} = -Bi \Theta^{(0)}, \quad z = \pm H$$
(11)

The Biot number, Bi, is h_0/k_0 ; H = h/d. For Bi = 0 the end walls are perfectly insulating and the temperature field is one-dimensional. For Bi + ∞ the end walls are isothermal with $\Theta^{(0)} = 0$. Fourier transforms were used to solve equation (11) and the solution is

$$\Theta^{(0)}(y,z) = \frac{2}{\pi} \sum_{1}^{\infty} [A_n \cosh \lambda_n z + B_n] \sin \frac{n\pi}{2} (1+y)$$
(12)

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$$A_{n} = \frac{Bi}{\lambda_{n}^{2}} \frac{(1+(-1)^{n})}{n} (\lambda_{n} \sinh \lambda_{n} H - Bi \cosh \lambda_{n} H)^{-1}$$

$$B_{n} = \frac{1-(-1)^{n}}{n\lambda_{n}^{2}}$$

$$\lambda_{n}^{2} = \frac{n^{2}\pi^{2}}{4} - \sigma_{1}$$

Figures 3-6 display representative features of the temperature fields for narrow-gap and wide-gap chambers. Figures 3 and 5 are perspective views, Figures 4 and 6 are sections. A noteworthy feature is that the effect of side walls, shown on Figures 4 and 6, persists for a distance of 2-3 half thicknesses into the chamber at each side. For the wide-gap chamber (0.5 cm wide) this distance is (roughly) 0.75 cm and for the narrow-gap chamber (0.15 cm wide), 0.45 cm. Thus, due to the effect of temperature, particles within these regions will have a different electrophoretic mobility from those in the interior. In addition, buoyancy effects will be accentuated.

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FIGURE 3.

Perspective view of the temperature field for the narrow-gap chamber operating at conditions listed on Table I (uniform thermal conductivity). Note: 2d = 0.15 cm, 2h = 5 cm. Eq. (12).

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FIGURE 4.

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Sections of the temperature field as shown in Figure 3.



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FIGURE 5.

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Perspective view of the temperature field for the wide-gap chamber operating at conditions listed on Table I (iniform thermal conductivity). Note: 2d = 0.5 cm, 2h = 5 cm. Eq. (12).



FIGURE 6.

Sections of the temperature field as shown in Figure 5.

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One-Dimensional, Variable Thermal Conductivity Model

A one-dimensional temperature field corresponds to a very wide chamber, $H \rightarrow \infty$, or one with insulated end walls at $z = \pm H$. The zero-order field is given by

$$e^{(0)}(y) = \frac{1}{\sigma_1} \left[\frac{\cos N_1 y}{\cos N_1} - 1 \right]$$
(13)

 $N_1^2 = \sigma_1$

and perturbations are found from solutions to

$$\frac{d^2 \Theta^{(1)}}{dy^2} + \sigma_1 \Theta^{(1)} = -\frac{1}{2} \frac{d^2}{dy^2} \left[\Theta^{(0)}\right]^2$$
(14)

Using Fourier transforms the solution is found to be

$$\Theta^{(1)}(y) = \frac{2}{\pi} \int_{1}^{\infty} \mathbf{f}_{s}(n) \sin\left[\frac{n\pi}{2}(1+y)\right]$$
(15)

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$$f_{s}(n) = -\frac{1}{2} \frac{n^{2}}{n^{2} - 4\sigma_{1}/\pi^{2}} S_{n}\{(\Theta^{(0)})^{2}\}$$

Sn{ $(\Theta^{(0)})^{2}$ } = sine transform of $(\Theta^{(0)}(y))^{2}$.

Temperature fields for narrow-gap and wide-gap chambers are shown on Figure 7, along with that for constant thermal and electrical conductivities. Figure 7 depicts matters in <u>dimensionless form</u> and it is seen that with the wide gap the temperature rise is 1.7 times that expected with constant properties at the conditions shown, for the A-1 buffer this is nearly 30°C.

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FIGURE 7.

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One-dimensional temperature field calculated so as to account for temperature dependent thermal conductivity and electrical conductivity, A - wide-gap, B - narrow-gap, C - constant properties (cf. Table I). Eqs. (13) and (15).

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With the narrow-gap, the temperature rise is so small, about 1.5°C, that variable-property effects are negligible. Here we also see (upon comparison with Figure 5) that the influence of variable thermal conductivity serves to alter the temperature rise. Accounting for the variable thermal conductivity lowers this maximum by about 2°C for the wide-gap chamber at the conditions shown.

One-Dimensional, Transient Response Model

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An estimate of the minimum time required to reach a steady thermal state can be made using a transient thermal model which ignores convection, since it tends to increase the equilibration time by adding colder fluid and withdrawing warm fluid from the region of interest. A rough estimate can be found from the characteristic relaxation time scale, d^2/α_0 . For the A-1 buffer $\alpha_0 = 1.39 \text{ cm}^2/\text{s}$ so that for a narrow-gap machine (d = 0.075 cm) the time scale is about 4 seconds; for the wide-gap machine the time-scale is 45 seconds. To attain a condition near the steady-state generally requires 2-3 'relaxation times', as shown on Figures 8 and 9. Data for the graphs were calculated using the solution to a transient heat conduction problem with heat generation, viz.

$$\frac{\partial \Theta}{\partial \tau} = \frac{\partial^2 \Theta}{\partial \mathbf{v}^2} + 1 + \sigma_1 \Theta$$
(16)

with $\Theta(\tau, -1) = 0$, $\Theta(0, y) = 0$. The solution given by Carslaw and Jaeger (1959) is

ORIGINAL PAGE IS OF POOR QUALITY FIGURE 8.

Transient temperature response for a narrow-gap chamber (one-dimensional, constant thermal conductivity) (cf. Table I). Eq. (17).

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FIGURE 9.

Transient temperature response for a wide-gap chamber (onedimensional, constant thermal conductivity) (cf. Table I). Eq. (17).

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$$\Theta = \frac{1}{\sigma_1} \left[\frac{\cos N_1 y}{\cos N_1} - 1 \right] + \frac{16}{\pi} \frac{\infty}{\sigma} (-1)^n \frac{\exp(\cdot)\cos[2n+1)\pi y/2]}{[4\sigma_1 - (2n+1)^2\pi^2][2n+1]}$$

$$(\cdot) = [-(2n+1)^2\pi^2 + \sigma_1]\tau$$

$$\tau = \alpha_0 t/4d^2, \quad y = y^*/d$$
(17)

Obviously a more refined estimate could be made by solving a two-dimensional with convection included, however, the characteristic time for equilibration would probably not change too much. Thus, in any experiment with wide-gap machine at least 2-3 minutes should be allowed for thermal equilibration.

Axial Velocity Field

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Equations to describe the axial velocity are derived from the Navier-Stokes equations using an expansion described earlier

$$u(y,z) = u^{(0)}(y,z) + u^{(1)}(y,z) + \dots$$
(10)

The effects of buoyancy on the two-dimensional flow field are described in the first part of this section. In the second, where the effects of the lateral boundaries at $z = \pm H$ are ignored, exact solutions are possible which account fully for the effects of temperature on viscosity and buoyancy.

Two-Dimensional, Constant Transport Properties Model

$$0 = -K + N_2 - N_3 \Theta^{(0)} + \nabla^2 u^{(0)}$$
(18)

where K is a constant (dimensionless) axial pressure gradient; $N_2 = gd^3/v_0^2$ Re and $N_3 = gd^3\beta\Delta T/v_0^2$ Re, Re = du_0/v_0 . The parameter N_3 describes the magnitude of the buoyancy effect while (-K + N₂) is a constant to be determined from the fact that the volumetric flowrate is independent of the temperature rise, since the velocity is scaled using the mean velocity, u_0 . Using Fourier Sine transforms we find

$$u^{(0)}(y,z) = \frac{2}{\pi} \sum_{0}^{\infty} g_{s}(n) \sin \frac{n\pi}{2} (1+y)$$
(19)

with

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 $g_{s}(n) = B_{n} \cosh \frac{n\pi}{2} z + C_{n} \cosh \lambda_{n} z + D_{n}$

The coefficients B_n , C_n , and D_n are found from the relations

$$B_{n} \cosh \frac{n\pi H}{2} + C_{n} \cosh \lambda_{n} H + D_{n} = 0$$

$$C_{n} = -\frac{N_{3}A_{n}}{\sigma_{1}}$$

$$D_{n} = -\frac{4}{n^{2}\pi^{2}} \left[\frac{K - N_{2}}{n} (1 - (-1)^{n}) + \frac{N_{3}}{n} \frac{(1 - (-1)^{n})}{\lambda_{n}^{2}} \right]$$
(20)

Finally $(-K + N_2)$ is found from the requirement that

$$\int_{-H}^{H} \int_{-H}^{1} u^{(0)}(y,z) dy dz = 4H$$
(21)

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FIGURE 10.

Axial velocity field for the narrow-gap chamber (cf. Table I). The velocity is almost indistinguishable from the fully developed parabola, $3(1 - y^2)/2$ except near the side walls at $z = \pm 33.3$. Eq. (19).

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FIGURE 11.

Perspective view of the axial velocity field for the wide-gap chamber (cf. Table I). Downflow at g = 980 cm/s^2 . Eq. (19).

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FIGURE 12.

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Central sections of the field shown on Figure 11. Note weak upflow in center and strong downflow along front and back cooling walls and near side walls at $z = \pm 10$.



FIGURE 13.

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Perspective view of the axial velocity field for the wide-gap chamber (cf. Table I). Upflow at $g = 980 \text{ cm/s}^2$. Eq. (19).

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FIGURE 14.

Central sections of the field shown on Figure 13. Note downflow along front and rear cooling walls and near the side walls at $z = \pm 10$.

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Results of representative calculations are shown on Figures 10-14 Figure 10 shows that buoyancy has relatively little effect on a narrow-gap chamber due to the excellent heat transfer. The maximum temperature rise for this case is about 1°C. End effects due to the no-slip condition at $z = \pm 4$ are similar to those encountered with the temperature field.

With the wide-gap chamber dramatic effects are present at unit gravity. Figure 11 is a perspective view, Figure 12 shows the velocity across two sections of the chamber with downflow. Here buoyancy causes regions of reversed flow throughout a large part of the central section. With a finite length chamber this implies that a large recirculating eddy would be present in the central section and the chamber would be difficult to use as an electrophoretic separation device. If the flow is reversed, the recirculating eddy splits apart and is attached to the side walls, as is shown on Figures 13 and 14. Since the recirculating regions are adjacent to the side walls, the central section allows more-or-less free passage of fluid and any sample. Of course, any sample that migrated into the eddy structures would be difficult to recover.

One-Dimensional Velocity Fields

Effects due to a temperature dependent viscosity and buoyancy can be investigated easily using a one-dimensional model and, in fact, exact solutions can be obtained. Since variations are confined to the y-direction we have

$$0 = K + N_2 \rho + \frac{d}{dy} \mu \frac{du}{cy}$$
(22)

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 $u(\pm 1) = 0$

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The solution is

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$$u(y) = -K \int \frac{y_1}{\mu} dy_1 + N_2 \int \frac{1}{\mu} \int \rho dy_1 dy_2$$
(23)

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with *I* determined from the fact that the velocity scale is the mean velocity. Thus

$$1 = -K \int \int \frac{y_1}{\mu} dy_1 dy + N_2 \int \int \frac{1}{\mu} \int \rho dy_1 dy_2 dy$$

$$0 = Y \qquad 0 = Y \qquad 0 \qquad (24)$$

Given expressions for the dimensionless viscosity, and density, both scaled on values evaluated at the wall, it is a straightforward task to evaluate the integrals. In the calculation a two-term expression was used for the temperature, viz.

$$\Theta = \Theta^{(0)} + k_1 \Theta^{(1)}$$
(7)

For purposes of comparison we can evaluate the velocity field for uniform viscosity and buoyancy. The temperature field is

$$\theta^{(0)}(y) = \frac{1}{\sigma_1} \left[\frac{\cos N_1 y}{\cos N_1} - 1 \right], \quad N_1^2 = \sigma_1$$
(13)

and the velocity works out to be

$$u^{(0)}(y) = \frac{3}{2} (1-y^2) - \frac{3N_3}{\sigma_1} \left[\frac{1}{\sigma_1} + \frac{1}{3} - \frac{1}{\sigma_1 N_1} \tan N_1 \right] (1-y^2) + \frac{N_3}{\sigma_1} \left[\frac{1}{\sigma_1} + \frac{1}{2} (1-y^2) - \frac{1}{\sigma_1} \frac{\cos N_1 y}{\cos N_1} \right]$$
(25)

For $\sigma_1 \neq 0$ we recover an earlier result due to Ostrach (1976),

$$u^{(0)}(y) = \frac{3}{2} (1-y^2) - \frac{N_3}{120} (1-y^2) (1-5y^2)$$
(26)

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It is important to note that the magnitude of the buoyancy effect as compared to forced convection is contained in the dimensionless group N_x , viz.

$$\frac{g_{\beta}}{v_{o}u_{o}} \frac{\sigma_{o}E_{o}^{2}d^{4}}{k_{o}}$$

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Here β represents an average coefficient of thermal expansion, - $\rho^{-1}(\partial \rho/\partial T)$. Thus, all other things being equal, going from a narrow-gap machine (2d = 0.15 cm) to a wide-gap machine (2d = 0.5 cm) alters the effect of gravity by a factor of $(10/3)^4$, roughly two orders-of-magnitude. It follows that whereas gravity forces play minor roles with narrow-gap machines the situation with wide-gap machines is quite the opposite.

For $|N_3| \ll 1$ the velocity differs very little from the familiar parabolic profile characteristic of forced convection. For $|N_3| \gg 1$ regions of reverse flow are present as illustrated on Figures 15 and 16. Qualitatively these profiles are similar to those derived from the two-dimensional model; quantitatively, however, they differ in the magnitude of the maximum velocity, which is higher here due to the effects of variable viscosity and buoyancy. Note regions of reversed flow in the center for dcwnflow and adjacent to side walls for upflow (see insets).

The recirculating eddy present in the downflow configuration at *these* operating conditions renders this configuration almost useless for electrophoretic separation. Even if the flow was steady, the sample stream would be deflected towards the wall where electro-osmotic effects would be strong. FIGURE 15.

One-dimensional velocity field calculated with allowance for variable viscosity and density (cf. Table I). Downflow, $g = 980 \text{ cm/s}^2$. Eq. (23).

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FIGURE 16.

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One-dimensional velocity "ield calculated with allowance for variable viscosity and density (cf. Table I). Upflow, $g = 980 \text{ cm/s}^2$. Eq. (23).

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In the upflow configuration the eddys attached to the walls take up nearly 80% of the cross section and severely reduce the region available for sample separation.

At the same time, however, it must be recognized that the calculations presented here do not exhaust the set of configurations and operating conditions. The recirculations, for example, can be changed by independent control of the pressure gradient. Lowering the field strength has a dramatic effect on the buoyancy, since the temperature rise is proportional to E_0^2 , but would necessitate an increase in the length of the chamber, etc. There are, therefore, a number of options which remain to be investigated, the calculations given here simply illustrate the hydrodynamic phenomena.

Electro-osmotic Cross-flow Velocity Field

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The presence of a thin layer of space charge adjacent to the boundaries in the y-z plane (cf. Figure 1) along with the transverse electric field causes a well-known electro-osmotic flow (Shaw, 1969). In a parallel plate system open to reservoirs at $z = \pm H$ where $H \gg 1$ the velocity profile would appear to be flat up to a very small distance from the wall (a few multiples) of the Debye thickness, κ^{-1}) where a rapid transition occurs to accommodate the no-slip condition. For most purposes the double-layer thickness, κ^{-1} is so small that we can approximate the velocity just outside this layer using one of the Smoluchowski equations,

$$w_{\rho} = -\varepsilon E_{\rho} \zeta / \mu \tag{27}$$

where w_0 is the velocity in the z-direction, ε , the dielectric constant, E_0 , the field strength and, ζ , the zeta-potential of the wall material in

-55-

contact with the solution in question. This apparent slip-velocity is of the order of a few microns per second for a potential gradient of one volt per centimeter. When the flow is constrained by walls at $z = \pm H$ the profile is forced to be (roughly) parabolic so as to accommodate the condition of no net flow across the y-z plane. Although this velocity is too slow to affect the axial flow substantially the cross-flow interferes with any electrophoretic separation by stretching the sample cross section. To provide an estimate of thermal effects and furnish a consistent representation of the velocity field for use in the separations model a simplified model is used. In this model end effects are omitted except insofar as the works force the flow to turn round as sketched in Figure 17. The electro-osmotic velocity can be calculated from solutions to

$$0 = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial y} \mu \frac{\partial w}{\partial y}$$
(28)

with $w = w_0$ at $y = \pm d$.

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The pressure gradient arises from the need to balance viscous forces outside the double-layer so as to produce a field with no net flow. If we scale the velocity using w_0 , and lengths using d, and write the viscosity as $\mu_0 \mu(\theta)$ to account for the thermal effects we obtain

$$0 = K_2 + \frac{d}{dy} \mu \frac{dw}{dy}$$
(29)

which can be integrated to

$$w = K_2 \int \frac{y_1}{\mu} \, dy_1 - 1$$
(30)

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The constant K_2 is found from the requirement that the net flow across any cross section in the x-y plane be zero.

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Although effects due to temperature dependent viscosity are relatively small and change the velocity only about 10% in the wide-gap chamber, these could be significant if one were modelling the separation of particles with small mobility differences.

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FIGURE 17.

Electro-osmotic crossflow velocity: A - plan view showing recirculation caused by end walls, B - velocity profile with constant viscosity, $(1 - 3y^2)/2$; C - velocity profile with wide-gap (cf. Table I).

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II. HYDRODYNAMIC STABILITY

Introduction

During the early s ges of development of the wide-gap machines large scale, irregular convective mixing was observed during experiments with dye tracers. One of the possible causes is the flow reversal caused by buoyancy (see Part I and Ostrach, 1976). At that time, the absence of quantitative data prevented a rest of this hypothesis. Later experiments at General Electric by H. Semon (1977) provided additional data and disclosed a persistent "wavering" of the sample stream at low power inputs; higher power levels caused irregular mixing. However, the power levels corresponded to maximum (centerline) temperatures only a few degrees higher than the wall (buffer) temperature, far below those which could produce the w-shaped profiles described in Part I. According to the analysis in Section I the dimensionless group $g_{\beta\sigma}E_0^2d^4/v_0k_0u_0$ must be $O(10^2)$ or more for buoyancy to alter the velocity profile significantly; in the General Electric experiments it was 0(1). Changes in the orientation of the flow relative to gravity. changed the allowable power levels somewhat but irregular flow persisted at voltage gradients necessary to give a significant electrophoretic separation. It was decided, therefore, to investigate the hydrodynamic stability of the flow.

Several sorts of phenomena are included under the general topic of hydrodynamic stability: the inception of motion in an otherwise quiescent system, the transition from one steady laminar flow to another and transition from laminar to turbulent flow. To establish orders-of-magnitude, theories for the stability of a horizontal layer and of a shear flow were reviewed. As a result it appears that neither of the buoyancy mechanisms involved in these

two situations would be able to destabilize the flow.

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Previous work on the stability of stratified fluid layers has centered on quiescent layers (cf. Chandrasekhar, 1961; Ostrach, 1964). This body of literature was combed to locate reports of special significance to the problem at hand which is distinguished by the combined processes of volumetric heat generation and fluid motion. Sparrow, Goldstein and Jonsson (1964) studied the buoyancy driven instability of a quiescent, horizontal layer bounded above and below by rigid walls and heated internally. Although a nonlinear profile does lower the critical temperature difference considerably, calculations based on parameter values for the wide-gap chamber showed that the critical difference is about 10°C which is well above the values reported by General Electric for the horizontal (or vertical) configuration with flow. Allowance for the effect of temperature on the rate of heat generation (which is not part of the Sparrow-Goldstein-Jonsson theory) may lower the critical temperature difference somewhat but an extension of this sort was not attempted, since it seemed best to understand the behavior of the vertical configuration which would be used in electrophoretic separation.

Vest and Arpaci (1969) studied the stability of natural convection in a vertical slot, where however, since the base flow is driven by an antisymmetric temperature, it is different from that in a continuous flow electrophoresis chamber. The stability with respect to roll waves, oriented perpendicular to the main flow was examined and a critical Grashof number of 7880 was found for this sort of instability. In the General Electric experiment the Grashof number based on the maximum centerline temperature is roughly 10 and, although the circumstances are quite dissimilar, it seems unlikely

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that the observed meandering derives from a shear instability of the sort studied by Vest and Arpaci.

If the meandering and subsequent large scale convection are the result of an instability, then it must be one where the critical Rayleigh number is small. One possibility is that the instability derives from small *axial* temperature gradients which result from uneven heating or cooling. In addition the thermal region near the entrance to the electrode section extends over a region of several chamber half-thicknesses. This gradient can be estimated from an earlier equation describing the balance between convection, conduction and generation,

Pe u(y)
$$\frac{\partial \Theta^{(0)}}{\partial x} = \frac{\partial^2 \Theta^{(0)}}{\partial y^2} + 1 + \sigma_1 \Theta^{(0)}$$
 (8)

for temperature-independent properties. This equation has solutions which decay exponentially with x and have the form

 $e^{-\lambda_n^2} x P e^{-1}$ $f_n(y)$

The mode which has the smallest eigenvalue, λ_n , fixes the relaxation distance, x_e . An estimate of the smallest eigenvalue can be found from the problem where the variable velocity u(y) is approximated by the (constant) average velocity. A more exact calculation would refine this estimate but would not change the order-of-magnitude. It is found that the distance over which the temperature adjusts to the ohmic heating is approximately (Pe)(d). For the wide-gap chamber operation at the conditions listed on Table I the Peclet number is about 50. Thus, since the temperature rise here is over 30 degrees, axial gradients at the inlet (and outlet) are of the order of 1°C/cm.

Stability of a Fully Developed Flow with an Axial Temperature Gradient

The presence of cold fluid above warmer fluid (in the region above the electrodes with the downflow configuration and in the electrode "outlet" region with upflow) is an unstable configuration. To study the stability of the velocity and temperature fields they were modelled with a fully developed axial flow in a rectangular channel. The basic temperature field consists of an axial gradient of magnitude denoted by A, with lateral variations due to the balance between heat generation and conduction through the walls, i.e.,

$$T = T_{y} + Ax + \Delta T \Theta(y, z)$$
(31)

If we scale lengths, velocities, etc., as before we obtain

$$\frac{\partial u}{\partial \tau} = -\frac{\partial p}{\partial x} + N_2 (1 - \beta \Delta T) - \frac{Ra}{Pr Re} x - \frac{Gr}{Re} \Theta + \nabla^2 u$$
(32)

$$\Pr \frac{\partial \Theta}{\partial \tau} + \frac{\operatorname{Ra} \operatorname{Re}}{\operatorname{Gr}} u = \nabla^2 \Theta + 1$$
(33)

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$Gr = g\beta\Delta T d^3/\nu_0^2$	Grashof number
$Ra = g\beta Ad^4 / v_0^{\alpha} o$	Rayleigh number
$Re = u_0 d/v_0$	Reynolds number
$Pr = v_0 / \alpha_0$	Prandtl number

with u = 0 = 0 cn boundaries at $y = \pm 1$, $z = \pm H$.

The mathematical problem is to identify conditions under which temperature and velocity fields other than the steady-state, symmetric forms exist. In particular we are interested in forms with an exponential time dependence, $e^{\omega t}$. The demarcation between stable and unstable flows is $\omega = 0$. Because of the linear structure of the equations we can show that the imaginary part of ω , $I_m(\omega)$, is zero so that the so-called "exchange of stabilities" principle is satisfied and any disturbance will grow exponentially. Thus, we simply look for conditions where $\omega = 0$. The problem is decomposed into the sum of the steady parts u,0 and perturbations \hat{u} and $\hat{\theta}$.

This problem is very similar to one solved earlier by Ostrach (1955). Here those results are extended to include two-dimensional effects and other disturbance planforms. In the early work the instability was identified through a degeneracy in a base flow, now we see that the disturbances are superimposed on a symmetric base flow.

For the disturbance flow, u, and temperature, 0, we have

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$$\nabla^{4}_{II}\hat{\mathbf{u}} = Ra \hat{\mathbf{u}}$$

$$\hat{\boldsymbol{\Theta}} = Ra^{-1}\nabla^{2}_{II}\mathbf{u}$$
(34)

where ∇_{II}^2 stands for the two-dimensional Laplace operator. $\hat{u} = \hat{0} = 0$ on the boundaries. One set of solutions will, of course, simply be multiples of the symmetric (with respect to the x-z and x-y planes) steady-state solutions. We are interested in anti-symmetric solutions, which represent no change in the volumetric flow rate through the y-z plane. In general, the solutions to these equations can be written

$$\hat{u} = u_1 + u_2$$
 (35)

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$$\nabla^2_{II} u_1 = \lambda^2 u_1 \tag{36}$$

$$\nabla^2_{II} u_2 = -\lambda^2 u_2$$

 $\lambda^4 = Ra$

The temperature is

$$\Theta = Ra^{-1/2}(u_1 - u_2), \qquad (37)$$

Solutions are

$$u_{1} = \sin qz(A_{1} \sinh \gamma_{1}y + B_{1}\cosh \gamma_{1}y)$$

$$+ \cos qz(A_{2} \sinh \gamma_{1}y + B_{2}\cosh \gamma_{2}y)$$

$$\gamma_{1}^{2} = q^{2} + \lambda^{2}$$

$$u_{2} = \sin qz(A_{3} \sinh \gamma_{2}y + B_{3} \cosh \gamma_{2}y)$$

$$+ \cos qz(A_{4} \sinh \gamma_{2}y + B_{4} \cosh \gamma_{2}y)$$

$$\gamma_{2}^{2} = q^{2} - \lambda^{2}$$
(38)

To satisfy the boundary conditions on the walls at $z = \pm H e_{\pm}$ ther

(i)
$$\sin qH = 0$$
, $A_2 = B_2 = A_4 = B_4 = 0$, $q = n\pi/H$; (39)

or

(ii)
$$\cos qH = 0$$
, $A_1 = B_1 = A_3 = B_3 = 0$, $q = \frac{2n-1}{2} \frac{\pi}{H}$. (40)

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The first condition, (i), corresponds to a disturbance that is anti-symmetric with respect to the x-y plane with upflow on one side and downflow on the

other. This form preserves the volumetric flow rate. The second condition, (ii), describes a flow with the requisite asymmetry if $B_2 = B_4 = 0$.

Next, with (i), either $B_1 = B_3 = 0$ so that $A_3 = 0$ and $\gamma_1 = \pm in\pi$ which gives

$$\lambda^{4} = n^{4} \pi^{4} (1 + H^{-2})^{2}$$
(41)

or $A_1 = A_3 = 0$ so that $B_3 = 0$ and $\gamma_1 = i(2n - 1)\pi/2$ which gives

$$\lambda^{4} = \pi^{4} \left[(2n - 1)^{2} / 4 + \eta^{2} / H^{2} \right]^{2}$$
(42)

With (ii), $A_4 = 0$ and $\gamma_2 = \pm in\pi$ so that

$$\lambda^{4} = \pi^{4} \left[n^{2} + (2n-1)^{2} / 4H^{2} \right]^{2}$$
(43)

The mode with the lowest critical Rayleigh number corresponds to the velocity field

$$u_1 = \sin \frac{\pi z}{H} \cos \frac{\pi v}{2} \tag{44}$$

with the critical Rayleigh number

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$$Ra_{c} = \frac{\pi^{4}}{16} \left(1 + H^{-2}\right)^{2}$$
(45)

For the wide-gap chamber with dimensions noted on Table I, $Ra_c = 6.58$ and with a narrow-gap, $Ra_c = 6.11$. Using data for water at 10°C the critical temperature gradient is 0.5°C/cm for the wide-gap and 53°C/cm for the narrow-gap chambers. These results agree *qualitatively* with experimental observation in that they disclose a great deal of sensitivity to axial

temperature gradients for the wide-gap machine. With a narrow-gap it would be rather difficult to achieve the axial gradie..ts large enough to excite the instability.

Although this explanation is consistent with experimental findings for a vertical configuration, questions still remain with regard to cilted or horizontal configurations. These cases have not been analyzed in detail but it is easy to show (mathematically) that buoyancy effects coupled with an axial gradient will destry the unidirectional character of the flow. At present, however, neither experimental data or quantitative theoretical results are sufficient to assess this matter fully.

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111. MODELING THE ELECTROPHORETIC SEFARATION IN CONTINUOUS FLOW ELECTROPHORESIS

Introduction

We turn now to the task of describing how a sample with a particular mobility distribution will be altered in its passage through a continuous flow electrophoresis chamber. To provide a first approximation we have chosen to base the model on one-dimensional approximations to the various flow and temperature fields and ignore, for the present, two-dimensional effects due to side walls at $z = \pm h$ (except insofar as they cause the electro-osmotic flow to recirculate). Consequently, the temperature and velocity fields and the particle mobility are functions of y alone. This procedure is accurate as long as $d/h \ll 1$ and regions near the side walls are ignored. The effect of the side walls requires much more extensive analysis and remains to be done.

The model for separation is based on the fact that the velocity of a particle of a given mobility can be written as a superposition of an axial velocity, u(y), and a transverse component made up of the electro osmotic flow velocity, w(y) and the particle velocity due to electrophoresis, $v_m(y)$. Thus for a particle of mobility, m, say, the velocity is

$$\hat{i}u(y) + \hat{k}[w(y) + v_m(y)]$$
 (46)

and particles which enter with the sample at y_0, z_0 will exit at $y = y_0$, $z = z_0 + L[w(y) + v_m(y)]/u(y)$. If we denote the mobility distribution as $N_m(x,y,z)$, to represent the number doi ity of particles with mobility, m, then

$$u(y) \frac{\partial N_m}{\partial x} + [w(y) + v_m(y)] \frac{\partial N_m}{\partial z} = 0$$
(47)

describes the fact that the particles are conserved. The number density at a point x,y,z, is, therefore,

$$N_{m}\{0,y,z - x[w(y) + v_{m}(y)]/u(y)\}$$

and the problem is simply one of "tracking".

To predict the mobility distributions at the exit from the separator we suppose that there are a number of collector tubes of area $(2d)(\Delta)$ at the outlet plane. The mobility distribution in a given collector is simply

$$\langle N_{m} \rangle_{i} = \frac{1}{\Delta} \int_{z_{i}}^{z_{i}+\Delta} \overline{N}_{m}(z) dz$$
 (48)

$$\overline{N}_{m}(z) = \frac{\int_{-d}^{d} N_{m}(L,y,z)u(y)dy}{\int_{-d}^{-d} u(y)dy}$$
(49)

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A computer program was written to implement this scheme; representative results are tabulated in Table II.

Outline of the Computation Method

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The computation of the mobility distribution in the collection streams proceeds as follows

Main Input Data are: Cnamber dime sions (2d and Zh) Electrode length (1) Number of collection streams Electric field strength Buffer flowrate Buffer temperature Constants in the linear equation for buffer electrical conductivity Constants in the linear equation for buffer thermal conductivity Buffer conductivities for heat and electricity at the wall temperature Coating mobility at 20°C Mobility di≤tribution of sample at 20°C Location and size of sample stream.

The program then evaluates the temperature field using Eqs. (7), (13) and (15) and calculates the local values of density and viscosity using analytical formulas supplied. (Other relations can be used if necessary.) Then the local axial and electro-osmotic velocities are calculated using the appropriate equations for temperature dependent properties cited in Part I, Eqs. (23) and (30). Finally, particles on the edge of the sample are tracked to the outlet, using mobilities which reflect the local temperature, and the mobility distribution for each collector calculated. Numerical output includes

Temperature field Axial velocity field Electro-osmotic velocity field Mobility distribution for each collector.

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Results of two representative calculations, one with a narrow-gap chamber, the other with a wide-gap, are shown on Table II. General conditions are as shown on Table I. The sample contained two types of particles in equal amounts. Although both configurations show complete separation the wide-gap configuration separates the sample into two widely spaced collectors; the narrow-gap chamber barely separates the two fractions and if either fraction contained a distribution of mobilities there would be overlap. It was not possible to operate the wide-gap chamber model at 1-g without the recirculating flows described in Part II - so gravity had to be suppressed in the calculation.

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These calculations are intended to be *illustrative* of the sorts of results that can be obtained using the models derived here. Much more extensive calculations are required to establish the differences in the separatory capabilities of various continuous flow devices.

TABLE I.

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Farameters used in numerical calculations

Fluid Properties (A-1 Buffer)

Buffer Temperature	10	°C
Density	1.0	g/cm ³
Viscosity	1.33×10^{-2}	g/cm-s
Thermal Conductivity	5.82×10^{-3}	watts/cm-°C
Electrical Conductivity	6.9×10^{-4}	$(ohm-cm)^{-1}$
Coefficient of Expansion	8.62×10^{-5}	(°C) ⁻¹
Thermal Conductivity Coefficient	2.58×10^{-3}	(°C) ⁻¹
Electrical Conductivity Coefficient	3.12×10^{-2}	(°C) ⁻¹

Chamber Parameters

		Narrow-Gap	Wide-Gap
Electric Field Strength,	v/cm	70	70
Gravitational Constant [*] ,	cm/s ²	980	980
Gap Distance (2d), cm		0.15	0.5
Width (2h), cm		5	5
Length, cm		16	10
Volumetric Flow, cm ³ /s		0.35	0.7
Average Velocity, cm/s		0.467	0.28
ΔT _r , °C		3.17	35.2
Re		2.63	5.26
N ₂	ORIGINAL PAGE IS	8.88×10^{2}	1.64×10^4
N ₃	OF POOR QUALITY	2.4×10^{-1}	4.98×10^{1}
k ₁		8.2×10^{-3}	9.1 \times 10 ⁻²
σ ₁		9.9×10^{-2}	1.1

* except where noted

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TABLE II

Red-Blood Cell Separation in Narrow-Gap and Wide Gap Machines

To demonstrate the use of the separation model two runs were made at conditions shown on Table I with samples made up of equal amounts of particles ('red-blood cells') with mobilities of 2.15 μ m-cm/v-s (m=1) and 4.15 μ m-cm/v-s (m=2)(at 20°C).

Other conditions were:

Coating mobility 2.15 µm-cm/v-s

Sample inlet size 0.05 cm

Number of collectors 100

Locations of Separated Particles

Narrow-Gap Chamber

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Chamber #	<u>1-13</u>	<u>14</u>	<u>15</u>	<u>16</u>	<u>17</u>	<u>18</u>	<u>19</u>	<u>20</u>	<u>21-100</u>
m = 1	0	.177	.590	.233	0	0	0	0	0
m = 2	0	0	0	0	.159	.477	.353	.021	0

Wide-Gap Chan	ber [*]								
Chamber #	<u>1-20</u>	<u>21</u>	<u>22</u>	23	24-29	<u>30</u>	<u>31</u>	<u>32</u>	<u>33-100</u>
m = 1	0	.043	.546	.411	0	0	0	IJ	0
m = 2	0	0	0	0	0	.282	.610	.108	0

* g = 0

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Dr. R.S. Snyder of MSFC, Dr. G.V.F. Seaman of the University of Oregon and Dr. R.N. Griffin of General Electric have each helped us to understand the many problems involved in the electrophoresis of small particles. Kurt Hebert of Princeton University did much of the computer programming. BIBLIOGRAPHY

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COMPUTER PROGRAMS

Four programs were written in FORTRAN IV:

- 2TEMP the two-dimensional temperature field, Eq. (12)
- VELO the two-dimensional velocity field, Eq. (19)
- TRANST the transient temperature field, Eq. (17)
- TEMP the separation model.

Listings of these are given on the following pages.

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C • CCRDUCIVIT C • DI -THE ASPECT BATIO UP THY CHANNEL C • W -THE ASPECT BATIO UP THY CHANNEL C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-T LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER -THE NIGHTS -THE SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS -THE WIBBER OF EQUALLY SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS - THE PARAMET (CARATER -THE SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS - THE PARAMET (CARATER -THE SPACED CONSTANT-Z LIBBS FROM (AM. C • NIGHTS - THE PARAMET (CARATER - THE SPACED CONSTANT-Z - THE PARAMET (AM. C • NIGHTS - THE PARAMET (CARATER - THE SPACED CONSTANT - THE PARAMET		C + SIGHA1	-PARAMETEE IN THE	SIPRESSION FOR THE ELEC	TEICAL
C = D1 - THE JICH BURGER C = U -THE ASPECT BATEO OF TRY CHANNEL C = NIGHAS - THE NUMBER OF TEAMS TO DI TAALN IN THE SLAIPS FOR THE VELOCITY C = NYPTS - THE NUMBER OF LQUALLY SPALED CONSTANT-Y LIMES FROM (AN- INCLUDING) Y=0 TO T=1 ALONG WHICH THE VELOCITY IS C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- INCLUDING) 2=0 F0 C+N ALONG WHICH THE VELOCITY IS C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- C = INCLUDING) 2=0 F0 C+N ALONG WHICH VELOCITY IS EVALUATE C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- C = INCLUDING) 2=0 F0 C+N ALONG WHICH VELOCITY IS EVALUATE C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- C = INCLUDING) 2=0 F0 C+N ALONG WHICH VELOCITY IS EVALUATE C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- C = INCLUDING) 2=0 F0 C+N ALONG WHICH VELOCITY IS EVALUATE C = NZETS - THE NUMBER OF TQUALLY SPALED CONSTANT-2 LIMES FROM (AN- C = INCLUDING) 2=0 F0 C+N ALONG WHICH VELOCITY IS EVALUATE C = NZETS - TAALO = ',L'O,J,Z','NZ = ',Z'O,J,Z', 'HJ = ',Z'O,J) DJ35 111 FCSNAT ('J', Z', 'ILA','N VLLOCITY') DJ36 112 FCSNAT ('J', Z', 'ILA','N VLLOCITY') DJ31 112 EACH (5110',J,Z', 'NT, 'ILX', 'NELOCITY') DJ31 112 EACH (5110',J,Z', 'N', 'ILX', 'N', 'N', 'N', 'N', 'N', 'N', 'N', '			CONDUCTIVITY		
C NIEWS -THE NUMBER OF TERMS TO DETARLE IN THE SLAFES FOR THE VELOCITY C NIEWS -THE NUMBER OF EQUALLY SPACED CONSTANT-Y LINES FROM (AN C TECLUDING) Y=0 TO Y=1 ALONG WHICH THE VELOCITY IS IECLUDING) Y=0 TO Y=1 ALONG WHICH THE VELOCITY IS FAULDATED C NEFTS -THE NUMBER OF EQUALLY SPACED CONSTANT-Z LINES FACA (AN C NIEWLODING) 2=0 TO Z=W ALONG WHICH THE VELOCITY IS EVALUATE C NIEWLODING) 2=0 TO Z=W ALONG WHICH TWILOUTY IS EVALUATE C NIEWLODING) 2=0 TO Z=W ALONG WHICH TWILOUTY IS EVALUATE C NIEWLODING) 2=0 TO Z=W ALONG WHICH TWILOUTY IS EVALUATE C NIEWLODING) 2=0 TO Z=W ALONG WHICH TWILOUTY IS EVALUATE C NIEWLODING (2007) 100 FORMI (10), 22 (2017) SEAL LAZECA, LANGBUZ, NZ, 32 100 FORMI (10), 2X, VIEWLOJ, 2X, VM Z=*, 210, 3, 3, 2X, Z=*, 210, 3, 2X, Z=*, 210, 3, 3, 2X, Z=*, 210, 3, 3, 3, 3, 2X, Z=*, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,			-THE STOL BURDEN	OF THE CHANNEL	
<pre>VELCCITY VELCCITY VELCCIT</pre>			-THE NUMPER OF TER	US TO SE TAKEN IN THE S	EALLS FOR THE
C • NYPTS -THE WUBBER OF EQUALLY SPACE CONSTANT-Y LIMES FROM (AM. INCLUDING) Y=0 TO Y=1 ALONG WHICH THE VELOCITY IS C • NZETS -THE NUBBER OF EQUALLY SPACED CONSTANT-Z LINES FROM (AM C • INCLUDING) Z=0 TO Z=V ALONG WHICH THE VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING) Z=0 TO Z=V ALONG WHICH VELOCITY IS EVALUATE C • INCLUDING (Z=0, 1, 1, 1, 1, 1, 1, 2, 1, 2, 2, 1, 2, 2, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,		C +	VELCCITY		
C • IECLUDING) Y=0 TO I=1 ALONG WHICH THE VELOCITY IS C • FVENDATE C • FVENDATE C • FVENDATE C • FVENDATE C • INLUDING) 2=0 IO D=W ALCNO WHICH THE VELOCITY IS FVALUATE C • C • C • C • C • C • C • C •		C + NYPTS	-THE NUMBER OF LOU	ALLY SPACED CONSTANT-Y	LINES PROM (AND
C * EVALUATE C * N2FTS -THE KURDER OF FUDPLLY SPALED CONSTANT-2 LINES FEGA (AM C * INCLUDING) 2*0 IO 2*W ALCHG WHICH VELOLITY IS EVALUATE C ************************************		C •	INCLUDING) Y=0 TC) Y=1 ALONG WHICH THE VE	LOCITY IS
C • R2FIS -THE NUMBER OF PUPELLY SPACED CONSTANT-2 LINES FROM (AM C • INCLUEING) 2=0 FO C-W ALONG WHICH VILOLITY IS EVALUATE C • • • • • • • • • • • • • • • • • • •		C •	EVALUATED		
C C C C C C C C C C C C C C C C C C C		C NZEIS	-THE NUMBER OF EQU	FALLY SPACED COBSTANT-2	TELES FAGA (AND TO TO THATUATE
C C C C C C C C C C C C C C			THEFORTHS) L=0 IC	12. W ALONG WHICH VELOCI	II IS LINDWILL
C C C C C C C C C C C C C C		C ***********	*********************	*****************	****
C 0001 11HINSIGN U(201,101),YY(101),CE(401) 57C2 5003 10D FCFMAT (101) 11D FCFMAT (101) 11D FCFMAT (''', 24,'SLUHA1 =',100,3,24,'BLOT 300, =',510,3,24, 'ASPECT FACIC =',210,3,24,'BLOT 300, =',510,3,24,'BS =',10,3) 11D FCFMAT ('),24,'SLUHA1 =',100,3,24,'BLOT 300, =',510,3,24,'BS =',10,3) 11D FCFMAT ('),24,'SLUHA1 =',100,3,24,'BLOT 300, =',510,3,24,'BS =',10,3) 11D FCFMAT ('),24,'SLUHA1 =',100,3,24,'BLOT 300, =',510,3,24,'BS =',15) 0006 12D FORMAT ('),24,'SLUHA1,21,4,'Y VLCCITY') 01CC6 14D FORMAT (2(24,'PE14.0)) 15D FCFMAT (510,3,315) 0101 16D FORMAT ('),24,'Y',11X,'Y VELCCITY') 0111 16AC (5,15), END=999) SIGMA1,3L,F.N2,N3,NTEEMS,N1 TS,NZPIS 0112 WILLE (6,110) SIGMA1,5L,M,N2,N3 0114 46I11 (6,111) SIGMA1,LL,M,N2,N3 0114 46I11 (6,111) SIGMA1,LL,M,N2,N3 0115 0117 FI=3,1415926 1717 FI=3,1415926 1717 FI=3,1415926 1717 FI=3,1415926 1717 1224 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0221 124+FI2/4. 0222 124+FI2/4. 025 13042-1. 026 13043+C. 027 14 14 14 14 14 14 14 14 14 14		c			
0001 CHENSIJU (201,1)1,YY(1)1,CT(2) BEAL LASECA,LAMBD2,K2,C3 100 PCPHAT (1H1) 110 FORMAT (''', 24,'SIGMA1 =',1'U.3,24,'EIOT 40. =',EIO.3,2X, 'ASPECT FACIG =',L'U.3,24,'N2 =',2'U.3,2X,'N2 F',L'U.3) 111 FORMAT ('),2X,'NTLHES =',IS,2X,'N2 F',L'U.3,2X,'N2 FT',L'U.3) 0006 120 FORMAT ('),9X,'Z',114,'X VLLOCITY') 0107 130 FORMAT ('') 0006 120 FORMAT (SF1^3,315) 100 PORMAT (SF1^3,315) 101 160 FORMAT (SF1^3,315) 101 160 PORMAT (SF1^3,315) 101 170 161 160 PORMAT (SF1^3,315) 101 160 PORMAT (SF1^3,315) 102 160 PORMAT (SF1^3,31		С			
G1C2 BEAL LASECALLAND2, RZ, B3 G003 100 PCPHAI (141) S104 110 POBHAI (141) S105 111 PCBHAI (101, 24, SIGHAI =*, 100, 3, 24, M2 =*, 210, 3, 21, M2 =*, 210, 3, 31, M2 =*, 210, M2	0001	PCISKIM13	U(201,101), XX(101), 22	((2) 1)	
0003 100 FORMAI ('', 24,'SIGMA1 =',1003,24,'EIOT 300, =',510.3,24,'ASPECT FMCIG =',1003,24,'ASPECT FMCIG =',1003,24,'ASPECT FMCIG =',1003,24,'ASPECT, FMCIG =',200,25,'ASPECT, FMCIG =',200,25,'ASPEC, FMCIG =',20	F3C2	BEAL LASE	DA,LAMBDZ,NZ,23		
3.34 11.1 FORMAT (1, 2, 2, 1, 2, 1, 2, 1, 2, 2, 1, 2, 2, 1, 10, 3, 22, 1, 10, 3, 12, 11, 10, 11, 10, 10, 11, 10, 10, 11, 10, 10	2003	110 FCFMA1 (1	пц) «1. эк.+станья ж. так.	3.22 PETOT NO. #1.710.	1.21.
<pre>3035 111 FCENAT (') ,2X,'WIEKHS =',I5,2X,'WIEFTS =',I5,2X,'WIEFTS =',I5) 0006 120 FORMAT ('),9A,'Z',114,'X VLLOCITY') 0006 130 FCENAT (''),9X,'Y',114,'X VLLOCITY') 0006 150 FCENAT ('',9X,'Y',11X,'Y VELOCITY') 010 160 PORMAT (2(2X,1PE14.0)) 151 CENAT ('',9X,'Y',11X,'Y VELOCITY') 011 EEAL (5,15),FND=999 SIGMA1,5I,*.N2,N3,NTEEMS,5: TS,N2FIS 0112 WELE (6,100) 0113 ARIT: (6,110) SIGMA1,EL,*,N2,N3 014 AETTE (6,111) VIENTS,NIPTS,N2FI: 015 DHIN=0. 0016 UNAX=0. 016 UNAX=0. 017 FI=3.1415926 712 FI=3.1415926 712 FI=4FIZ/4. 0220 FI4=FIZ/4. 0221 FIX=FI*#/2. 0222 WEIZ=FI*#/2. 0223 TPI=2./PI 022 WEIZ=FI*#/2. 0223 TPI=2./PI 024 SUM1=C. 025 SUM2=0. 0026 SUM3=C. 027 K=-1 C DITERTINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C</pre>	جەر ر ر	Y POSAKI (*	ASPELT SACIO = $1.110.3$	$2X_1 + X_2 = 1 \times 1 \times 3 \times 2X_1 + X_3$	= 1, <u>2</u> , 10, 3)
0006 120 FORMAT (*); 9x, *2*, 114, *Y VLLOCITY*) 007 130 FCEMAT (* ') 0006 140 FORMAT (2 (2X, 1PE14.0)) 0079 150 FCEMAT (* ') 010 160 FORMAT (2 (2X, 1PE14.0)) 010 160 FORMAT (* ') 010 160 FORMAT (* ') 011 BEAD (5, 15), FND=999) SIGNA1, SL, *. N2, N3, NTEEMS, N. TS, NZPIS 011 BEAD (5, 15), FND=999) SIGNA1, SL, *. N2, N3, NTEEMS, N. TS, NZPIS 011 BEAD (5, 10) 012 WELE (6, 111) NIEKTS, NIPTS, NZPI: 013 GENERATOR 014 FETE (6, 111) NIEKTS, NIPTS, NZPI: 015 DHIN=0. 016 UNAX=0. 017 FI=3,1415926 018 FIZ=FI*FI 019 FIZ=FI*FI 019 FIZ=FI*FI 021 FIN=PI4 022 WEI2=FI*W/2. 023 TPI=2./PI 024 SUM1=0. </td <td>2025</td> <td>111 PCRMAT (*</td> <td>) .2X. 'NTLEES =', 15, 2,</td> <td>, 'NY2TS =', 15, 2X, 'N2PIS</td> <td>; = ', 15)</td>	2025	111 PCRMAT (*) .2X. 'NTLEES =', 15, 2,	, 'NY2TS =', 15, 2X, 'N2PIS	; = ', 15)
0007 130 FCEMAT (' ') 0008 140 FORMAT (2(2X,1PE14.00)) 0019 150 FCEMAT ('',9X,'Y',11X,'Y VELOCITY') 010 160 *ORMAT ('',9X,'Y',11X,'Y VELOCITY') 011 EFAC (5,15),END=999) SIGMA1,61,#.N2,N3,NTELMS,AL'TS,NZFIS 011 BEAC (5,150,END=999) SIGMA1,61,#.N2,N3,NTELMS,AL'TS,NZFIS 011 BEAC (5,151) SIGMA1,61,#.N2,N3,NTELMS,AL'TS,NZFIS 011 BEAC (5,151) SIGMA1,61,#.N2,N3 011 BEAC (5,151) SIGMA1,61,#.N2,N3 011 BEAC (5,151) SIGMA1,61,#.N2,N3,NTELMS,AL'TS,NZFIS 011 BEAC (5,151) SIGMA1,61,#.N2,N3 011 BEAC (5,151) SIGMA1,61,#.N2,N3 011 BEAC (5,151) SIGMA1,61,#.N2,N3 011 BEAC (5,111) YIEMS,NYPTS,NZFIS 015 DHIN=0. 016 UNAFE0. 017 FI=3.1415926 018 FI2=FIFFI 019 EI2=FIFFI 019 EI2=FIFFI 020 EI3=FIFFI 021 EI3=FIFFI 022 WEI2=FIFFI 023 TPI=2./PI 024 SUM3=0. 025 SUM2=0.	0306	120 FORMAT (*	J', 94, 12', 114, 1X VLLOU	:ITY*)	
0000 140 PORMAT (2(2x,1Pt14.0)) 010 150 FCRMAT (5F1^.3,315) 0010 160 PORMAT ('0',9X,'Y',11X,'X VELOCITY') 011 BEAD (5,15),END=999) SIGMA1,SI,#.N2,N3,NTELMS,D.'TS,N2PIS 011 BEAD (5,15),END=999) SIGMA1,SI,#.N2,N3,NTELMS,D.'TS,N2PIS 011 ARIT: (6,110) SIGMA1,L1,#,N2,N3 011 ARIT: (6,111) NIEMYS,NYPTS,N2PI: 0115 DHIN=0. 0016 UMAX=0. 017 FI=3.1415926 018 FI2=FI*FI 019 FI24=FI2/4. 020 FI4=FI/4. 021 FIN=PI*M 0022 WFI2=FI*#/2. 023 TPI=2./PI 024 SUM1=C. 025 SUM2=0. 0026 SUM3=C. C C C C C C C C11EKMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	0007	130 FCEMAT (*	•)		
153 FCMAAT (5F1^.3,315) 0010 165 * 06MAAT ('u',9X,'Y',11X,'Y VELOCITY') 011 READ (5,15),END=999) SIGMA1,SI,#.N2,N3,NTELMS,N'TS,NZPIS 011 READ (5,15), SIGMA1,L1,#,N2,N3 011 NSI11 (6,11) SIGMA1,L1,#,N2,N3 013 NSI11 (6,11) NIEKYS,NIPTS,NZPI: 014 RET1E (6,111) NIEKYS,NIPTS,NZPI: 015 DHIN=0. 0016 UNAZ=0. 017 FI=3.1415926 018 FI2=FI*FI 019 EI24+FI2/4. 020 EI4+FI2/4. 021 FIN=PI*W 0022 WEI2=FI*W/2. 0023 TPI*2./PI 0024 SUM1=C. 0125 SUM2=0. 0026 SUM3=C. C DINEEAINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	6000	140 PORMAT (2	(2X, 1P=14.0))		
J011 READ (0,99,99, 11,91,91,91,91,91,91,91,91,91,91,91,91,9	-)-9 	150 FCRMAT (5	F1 ⁻ .3,315)	7 m # 1 \	
0.11 MRL: (0,100,000,000,000,000,000,000,000,000,0	1010	100 TURNAL (* DIAR (5 1	STADEGOGY CLART AT	HE NO SE NYPERS KIITS NO	210
0113 ABIL: (6,11)) SIGHA1,LI,H,N2,N3 0014 ABIL: (6,111) NTERPS,NEPI: 0015 DHIN=J. 0016 UNAI=0. 0017 FI=3.1415926 0018 FI2=51#FI 0019 BI2=51#FI 0019 EI4=FI/4. 0020 EI4=FI/4. 0021 FIN=PI## 0022 NEI2=FI*#/2. 0023 TPI=2./PI 0026 SUM1=C. 0026 SUM3=C. (027 K=-1 C DITERMINE THE LONSTANT, K, FRUB THE INTEGRATES VELOCITY.	0.)12		1201	······································	, = 1 0
JJ14 #ETE (6,111) NTERPENDETS, NEPIE 0J15 UNIN=J. 0U16 UNAX=0. JJ17 FI=3.1415926 UJ18 #EZEFIFFI JU19 EI24=FI2/4. JJ20 EI4=FI/4. OJ21 FIN=PI*N J022 NEI2=FI*N/2. OJ23 TPI=2./PI C SUM2=J. OO26 SUM3=C. C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	2213	3311: (6.	11)) SIGNAT, EL, N. N2, N.	ا	
0015 DHIN=J. 0016 UNAX=0. 0017 FI=3.1415926 0018 #12=FI+FI 0019 £124=F12/4. 0020 £14=F1/4. 0021 EIW=PI*W 0022 WEI2=FI*W/2. 0023 TPI=2./PI 0024 SUB1=C. 0026 SUM2=J. 0026 SUM3=C. CO27 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	0014	WEILE (6,	111) NIEKSS, NYPTS, NZPI	t ()	
0016 UMAX=0. 0017 FI=3.1415926 0018 FI2=FIFT 0019 FI2=FIFT 0019 FI2=FIFT 0019 FI2=FIFT 0020 FI4=FI74. 0021 FIN=PI*N 0022 NFI2=FI*N/2. 0023 TPI=2./PI 0024 SUB1=C. 0026 SUM2=0. 0026 SUM3=C. C027 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	0015	DHIN=J.			
0317/ FI=3.141592b 0318 FI2=FIFFI 0319 FI2+FI2/4. 0320 FI4=FI/4. 0321 FIN=PI*N 0022 NFI2=FI*N/2. 0323 TPI=2./PI 0324 SUB1=C. 0325 SUM2=3. 0026 SUM3=C. C027 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	0016	UMAX=0.	AA (
0015 PL2=21+E1 0019 F124=F12/4. 0020 F14=F1/4. 0021 F1W=P1*W 0022 WF12=F1*W/2. 0023 TP1=2./PI 0024 SUB1=C. 0026 SUM2=0. 0026 SUM3=C. CO27 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	2377	FI=3.1415	920		
0017 F14=F1/4. 0020 F14=F1/4. 0021 F1W=P1*W 0022 WEI2=F1*W/2. 0023 TPI=2./PI 0024 SUM1=0. 0025 SUM2=0. 0026 SUM3=0. 0027 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY.	3:119	ビンピージュービック たてつは エアウィ	4.		
0021 FIWEPI+W 0022 WEI2=FI+W/2. 0023 TPI=2./PI 0024 SUM1=C. 0026 SUM2=0. 0026 SUM3=C. 0027 K=-1 C C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	0020	F144-F12/	* •		
0022 WEI2=FI+W/2. 0023 TPI=2./PI 0024 SUM1=0. 0025 SUM2=0. 0026 SUM3=0. 0027 K=-1 C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C C	0321	PIN=PI*#			
0023 TPI=2./PI 0024 SUS1=C. 0026 SUN2=D. 0026 SUN3=C. 0027 K=-1 C C DETERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	0022	WEI2=EI*W	/2.		
C024 SUM1=C. JJ25 SUM2=J. 0026 SUM3=C. C027 K=-1 C C C DENEMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C C	0023	IPI=2./PI			
JJ25 SUN2=J. 0026 SUN3=C. C027 K=-1 C C DINERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	0024	SU51=C.			
C SUBJEC. CO27 K== 1 C C DIMERSINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	JJ25 002(SUN2=J.			
C C C DIMERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	0026	309J=C. V1			
C DITERMINE THE CONSTANT, K, FRUE THE INTEGRATED VELOCITY. C	(027	л=- I С			
ς		C DIREEMINE To	E CONSTANT, K. FRUE TI	HE INTEGRATED VELOCITY.	
		C			

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POETBAN IV C	3 LLVEL	21	HAIN	DATE = 76110	09/14/24	
0029		<=K+2				257
0110	1	LANBE 2=K +K +)	PI24-SIGRA1			U5 8
0031	l	LANECA=LANE)	D2*+u.5			5.9
0232		• N 2 = K • K				260
0033						0.51
0034		C 1 4 1 C 1 7 K				060
0.034			/XAED12)			0.53
1126		***************************************	(*************************************			00.
0000			() ()			
0037		5 I= (2 I+11KA) 5 - 74 - 54 ABB	n (-w)/FN4			003
3355		52451/1888U.				. 00
0033		53=((P1+F1)	ANH 1-FTANH2/LAMEDA)/	(LANSDAFFTABE2-BI))/FB2	/LANBD2	36
0040	:	5091=5001+5	1			C68
0341		S082≖S08∠+S	2			069
0042		3+5 Pi 5= c Pi 6	3			- 277
043	5 (CONTINUE				U7 1
0044		1=5081#32.,	/W/(PI**4)			072
0045	1	12=5092*32.	/#/(P1**4)			07
2346		3=3683#8./	SIGNA 1/PI/PI/W			- ä7i
1147		=K=(1.+1.2+A	1-N3+A2-N3+BI+A31/A1			07
ត រមុន		9717 16.11	7) FX			17.
2240	117	FCENAT (1 4	27 514 31			
	r 112	COURT F	,			
	C 793					170
	C 27A.	LAIS VELUL.	III AL EACH (Isc) PC.	NI IANEN.		073
	L.					U 13 1
0.050		(NYE1./(NYEI)	5-1.)			08
2751		CZ=d/(NZEIS	-1.,			. 3.
0052		Y = - C Y				- e :
J053	1	EK 1 = PK - N 2				181
0054	:	f1=8./PI2				08
3655	i	2=2.*N3*EI	/SIGHA1			101
0056		CC 30 I=1.N	YPTS			ີ່ປີອີ
0057		Y ÷ Y+DT				18
0154		/==(+(1)	+Y1 /2			6.8
1159		== 17				
3350		T 20 Ta	1 N7645			0.0
1.101			1 # M L F 1 3			
		2=4+6	2			0.9
1102		SUZEJ	•			63
0063		K=-1				09
u]64		20 1)	N=1,NILKNS			. J9:
0005		K=	к+2			09
0066		LA	HBD2=K+K+PI24-SIGHA1			29
2067		Lt	MEDA#LANDD2**0.5			5
0068		28	3=K**3			19
0069		FT.	ANS=TANE (LANDDAFR)			10
2070		C 1	= E1+ (K1+N3/LA86E2) /	283		1)
1071		C 1	#F2/K/LAMED2			15
2760		C2				1.1
0173		4 E	CIERRY (CHODDA'IIANA DI) CIERRY (7-L) /TOI			1.5
0170		1.6	0 1 - 1 - 16- #J / 181 20- 24 / 24 - 1 / 201			1 1
. 175		K.A.	12			4.5
3773		A d				1,
0010		r k	_ 4= LARDEA= (Z==)			1.'
5377		۲.	G5=-LAMEDA* (2+8)			10
0078		٨R	G6=-2. +LAdeca+W			•)*
3379		LF	(ARG1.LE190.) E1=			11
0060		17	(ARG1.GT1)). E1=	EXP (ABG1)		11
0081		1 🖛	/A302.18 +100.1 E2=	`		11

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FORTRAN IV C	IEVEL 21 MAIN	DA12 = 78110	34/14/24
0982) F (AP(2) (CT 10) (A F7558)	P (A=C2)	11
10002	TE (1023.151)) \ E i=).	(ARGI)	
	$\frac{1}{1} = \frac{1}{1} $	5/11-07)	
2004	TE (ADCU TE -1)0 / EU-)	r (## 33)	
0085	TE (ABG4+55+**100+) E4***	D / N T //)	11
0086	$\frac{11}{10} \left(2000 + 10000 + 10000 + 1000 + 1000 + 1000 + 1000 + 1000 + 1000 +$	r (x1) a4)	11
1087	1F (ARGD.LE (V).) ED-J.	0.43 × 05	11
0088	IF (ARGD.GIIUU.) ED-EL	P (AAGO)	
0039	IF (ABG0.LE()).) LO=).		14
0090	IF (ARG6.G1100.) 26=FI	2 (AKG6)	14
3341	E = (E1 + E2) / (1 + E3)		12
0392	A 1=C1+E		14
9923	≥2=C2=E		14
2394	A3=-C3+(E4+25)/(LAABDA+\	1=6)-pi#(1.+36))	1.
0095	24=-C1		12
<u>^</u>]}6	SU%=SUH+ (N1+A2+A3+A4) #SI	h (h + X)	14
2032	10 CONTINUE		12
0) 98	0(J,I)=-2.+SOM/PI		14
0099	IP (J(J,I).LE.UNIN) UMIN=U(J,I)		13
2100	IF (U(J,I).GL.UHAK) UHAX=U(J,I)		1.
J101	$2C \qquad ZZ (J) = Z$		1.3
0102	3) YY (I) = V		1,
	c c		1
	C PICE THE VEROCIT TITELD AS A SUBFACE	VIEWED IN PLESPECTIVE.	1.
	c	-	1.
3163	K=2+NYPTS		1
0104	CC 0 7 T=1. KY243		1
0105	a=K+1		1
3106	5 - 5 - F 7 ± 3 ± 1 7 = 7 5		1.
01.07			1.
0107			1,
2103		τ.	1.
1109		1)	1.
	U. LURINUL		
J111	NIZ=JIELD=1		
0112	NZ3=N42T5+3		
.113	K=Z=NIEIS		
J114	LU 62 1=7, NYPIL		1.
3115	$\mathbf{K} = \mathbf{K} - 1$		
J110	CO 62 J=1,#28		1
0117	62 U(WZFTS-J,K) = U(WZPTS+J,K)		1:
1118	NZ=2+BZPTS-1		1:
J T 19	by=2=BIPTS+1		1
0120	CQ 65 J=1, #Z		1
0121	DO 65 I=1, BYB		12
J122	05 U (J,NYPTS-I) = U (J,NYPTS+I)		15
J123	U(1,1) = 1.		1:
0124	U(N2, 1) = C.		15
3125	J (1,31)=0.		1:
0126	J(NZ,NY) = J.		11
J 127	2=-12-1		16
0118	CC 72 J=1,NZ		10
0 1 2 9	2=2+22		10
0130	7) 2∠ (J) =Z		10
0131	$\mathbf{Y} = -\mathbf{D}\mathbf{Y} - 1$.		16
0132	CC 8) I=1,NY		10
0133	1 = Y + C Y		1 r
2120			1

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FORTRAN IV	G LEVEL	21		HAIN	DATE = 76110	J9/14/24	
0135		WRITE	(0,12^)				1
0136		WRITE	(6,130)				1
0137		DC 47 3	1,1Z				1
0138	40	WRITE	(6,140)	22(I),U(I,MYPTS)			1
0139		8FI1E	(6, 160)	••••			1
0140		ASILF	(6,130)				1
3141		20 93 3	I=1,NY				
0142	9 u	AFITE	16.1401	YY(I),0(NZPTS,I)			
2143		UNIN=1.	.1÷UEIN				
0144		UMAX=1.	1+04AX				
3145		CALL FI	ERVUE(1	1,22,11,0,0+.5,3.,	3.,201,101,NZ,WY,0,10,0	, UHIN, JHAX,	
	,	(ు	.0.0.9.9.91.14.	VELOCITY FIELD")	• • •	
0 146	995	STCP			· · · · ·		
0147		END					

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FORLEAN I	V G LEVEL 21	MAIN	DATE = 78104	15/00/00
	C			
	C C ************	**************	********	
		PHINIC RUE AUTORID		
	C • INANSAL LITE C • THE ELECTROP C • PATA IS IIST C • SELF-EXP'.NA	HURESIS CHANNEL AS EC IN THE CUTEOT OP TOPY EXCEPT THE POL	THE FROM THE AND CENTRAL FUNCTIONS OF TIME. THE THE FROGRAM. ALL THE LOWING-	FF2JIRED INPUL FF2JIRED INPUL INIJI VAFIADILS
	C * C * NUNTAG - T C * CTAU - T	HE NUCLEB OF TIMES HE DIRLASSIONLESS TI	AF WAICH TESPERATURE IS ME TO WHICH TEMPERATURE	EVALUAISLE IS EVALUA'ED
	C * NT2PNS - T C * T C * T	HE NUMBER OF TERMS Emperature. For ta aker is controlled	TANEN PCP TAU = 0 IN TH J GBEATEM THAN ZERO, 16 By NUALES.	E SLAIFS FUR E budbet ur 15a
	(•			
	C			
	c			
0001	EIMLASICA CT TIMEASICA AV	'EMP (1001) 'TEMP (1001)		
2203	LINENSION T	1001)		
3004	LIMENSION TI	82 (1001)		
0005	EINENSIGN NU 171 FORMAT (7F1)	NDZE(TUUT)		
0007	102 FCR4AT (215,	(2 ± 10.3)		
9536	103 ECEMAT (181)		_
0009	104 208431 (*C*, 104 208431 (*C*, 104 208431 (*C*, 104 208431 (*C*, 104 208431 (*C*, 104 208431 (*C*,	*THEFMAI CONDUCTIVI SITY -*.19210-2.14. *CAL/C-G*/*0*.*2120	TY -', 19210,1X, 'WA115, '5/CC',2A,'5PLCIFIC HLA' TFIC CONDUCTIVITY -'. 19	/CM-C+,IX, I -+,1211012 x1v12,1X,
	X */UF X *AL	N-CN',22, 'FIELL Sia F DIFTH -',12310.3,	LNGIH - *, 12:1).2,1X, *V/ 1X,*C**,2A,*2JFE TLAP.	LN 1/101, 1, 12E 10. J
	x •C*)	1		
3313	1)5 FCHMAT (*0*, X 2X,*	*NUNTAJ =*,17,24,*N CTAU =*,19£10.2)	IELMS =',17,24,'SI32A1	=*,12210
J)]∡	100 ECREAT (* 5*)	OY' STCONTS. 17' WA	1.32+C*,8%,*CIL3.=C*}	
0 2 1 3	135 ECENAI (3 (24	(,12214.6))		
0014	3EAL (5, 101)	TUCUND, DENSIY, SPAT	,ELCOND, IO, LIPTH, TBUFF	
0016	888L (5,102) WRITE (6,103	UDIAU, NIEBPS, SIGN N	A F, CIAJ	
3317	WRIT: (6,1)4) THCCND, DINSTY, SPh	T, ELCOND, 23, DEPTH, TBUFF	
0018	#FITE (0,105) NUMTAD, NTERMJ, SIG	HAT, CTAU	
0020	CSN=CUSIFN1:	· J • 5		
J021	21=3.1415920)		
C 0 2 2	4= (1./CSK-1.)/SIGHA1		
6324		N 1/516881-1./516381 NMT16-11		
	C			
1025	C COMEUTE THE IIS	TE AND TEMPTEATORE S	CALES FROM THE DINENSIC	NEE INEUT FROLÀ
0025	TERSCIPLICE TIMSCIPLET - I	NE#EU#EJ#CEEIH#DEEIH Stwall ртнагьюстуасри	/180080 7/18008044_164	
••••	(17 Incont 41 104	
	C NUNDER SECURI	IS THE NUPBER OF TER	SS TAKEN IN THE SIRIES	FCA ILSFEAALUA.

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ORIGAN IV G	IEVEL	21	HAIP		DAIE =	78104		15	/00/50
	C PO	TAJ GREATE	P THAN ZERG. I	8052 18	AN NUNDER	1 EPMS	ALE :	inkza,	LARGALAL 337
	C 014	TERFLOW NAY	CCCUF.						350-
	C								15 9
9027		BC=NURTAU-1							L D C
JJ28		EC 4 J=1,30							vo 11
3329]=J+1							-12
0030		726=11-1) *CTAU						101
3931		NUSCES (1)≠.5*((16./IAU):	**.5-1.)					(o4)
0032		<u>NUNLER(1) = N</u>	TEFAS						005:
	C								566
0033		TAC=-ETAU							So 7
ŨŬ 34		CC 7 JTAU=1	, NUMTAU						Jud
0035		+GAT=GAL	CIAJ						ปรริ
0036		2¥SU‼ ≖0.							J 1 1
0037		LSU‼≠C.							J71
0038		H 1= 1+¥U¥	EER (JTAU)						.7:
CC39		CO 6 5=1	,81						ú73
0040		おキ ぎー 1							J7→
0041		18=2*	N+1						(75
01.12		182=7	8+75						J 7 +
3043		c & - E &	P ((- 182*EI*EI+4	+SIGNA1)	*140)				.77
0344		レ=(4。	*SIG:A1-1N2*PI*	PI) (IS	•				.70
0145		AVSUP	=AVSUE+LA/TA2/D	•					. 1 >
JU46	c	s usuf=	CSUN+EX* (-1.) **	x/E/IN					LJU
2347		AVTEME (J	1AU) = 5+ 32. /21/2.	L*AVEJE					101
0049		AVILAP (J	TAU) = TEUFF + TEPS	L*AVIIMP	(JTAU)				136
0349		CI E 82 (Ĵ 1	AJ1=A+10./PI*LS	30	•				しらい
0050	7	7 CILAP (JT	AU =TUUFF+TMFSC	L+CTE4E (J	TAU)				54
	C	•		-	•				L05
	C FI	LINT AND PLOI	(142000H DF1PS) THL IIS	2F3ATJ52	AS n E	U D C T I	lin i₽	Tlaza est .c7
0051			6)						600
3052		#5112 (6,10	7)						Jiè
0153		IAU=-ETAU	·						ن و ن
0354		EC 5 K=1,N0	TAU						1+1
0055		1AU=1AU+	DIAU						5.
J350		19=190+1	I ISCL						640
2257		TIBE(F)=	T						しうい
0058	9	5 #RITE (6.	108) TINE (8)	LEBB (K) .C	TEMP(K)				195
0059		SX=7.5		• • •	•••				50
0060		CALL EPIFS1	(TISE,CTESP,NOP	IAU,01,5X					583
		X	" (""FELAXATION	••)•,,,,,•,	**SECUNES	**) * , 1			しちし
		X	" ("" LEGRIES CE	NTIGALL	•)•,0)				1) # S
0061		CALL EFIFS2	(IIME, AVIINP, NU	11 AJ. (1)					1.
0062		CALL IFIPS3	(3.,5.,2." ("AV	58205111	,0)				101
0063		CALL LELESS	(37.5.2. 1110	EN128 11 1	101				1.2
		STCD			• •				
0064		3465							1.1.3

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CATE = 78104FORTRAN IN G LIVEL 21 MAIN 15/01/04 C --10 С * TEMP EVALUATES AS FUNCTIONS OF Y THE TEMPELATURE PROPILE AND X- AND С 3222 2- DIRECTION VELOCITY PROPILES FOR AN ELECTROPHORESIS CHIL VITA HEAT С . 1.14 CONFUCTION IN THE Y-DIRECTION. IT ALSO AGEELS PARTICLE SIPARATILE FUE JUL С ٠ . AN INFUT STREAM OF GIVEN SIZE, LOCATION AND MOBILITY DISIDEUTICH. Ĺ 1)0) - 720 * THERE ARE THE SUBFOUTINES- SIMPS, WHICH FERPORMS INTEGRATICS IN С SILLSCH'S FULE, AND TEME, WHICH COMPUTES THE TEMPERATURE FILLS. AMONG THE INPUT VARIABLES ARE--C . 1.540 С ٠ JUYU ¢ . 101 С . 111L . AVEL -NUMBER OF FOINTS AT WHICH THE VELOCITY 15 EVALUATED C ul∡ù NVIL PUST EE COD С .13% ¢ . NLOL -INE NUMBER OF COLLECICE UNIES 0140 C . AP.C. -THE NUBBER OF FOINTS IN EACH COLLECTOR .115.) ٠ -NPCOL BUST EE ODD ¢ 0160 . -THE NUMBER OF FOINTS TAKEN IN THE MOBILITY "IST. С N N ,17. ٠ -ASSAY DEPRESENTING MOBILILIES С F*CPL J15 С . -NUMBER OF TERMS TAKEN IN THE LAFINITE SERIES FOR the .1-NSUA с FINST UNDER TIMPEAATURE FLELD .21 -AREAT REPRESENTING THE MOLILLIES -AREAT REPRESENTING THE MOLILITY CONCENTRATIONS. C . ENCEL С . INCOL C لاد تار • С 1 - - U 1630 C 261 ٤ 0001 - 5I.4_XSICH - 1 (_ 331) , : LU (2001) , EAU (1001) , EAUUI (1001, , 31 (1001, , 51 (501) 1273 $\mathcal{A}^{1}2(5,1), B(5,1), *(5,1), YI(5,1), LI(5,1), LALA(5,1),$ L(3,0(1,-1), ZF(10,1), LF2(12,1), Aa(12,1), BY(12,1),._==) 4 à .270 ENEAF (1001) . 2300 ۸ λ FHCSI(54), FNSCLL(57), CMOLL(1101) . 1 . 1002 BEAL EUG 201 ريدوب C 3353 101 FCERAT (515) 1241 0005 0005 0006 102 FCEMA1 (4110.3) いいかい 103 FOR: AT (2810.3) 1.0) 104 FCFMA1 (3510.3) .370 0307 105 FORMAT (4210.3) 03-0 1)6 SCENAT (2110.3) 110 FCRMAT ('1', 'INTEGEE INPOT VABIAGLES') 5223 1391 0009)+)) 0010 3410 レオイレ 3311 ن د د ن))12 4.4 2423 X 1X, "WAITS/UN-C'/" ELECTIIC CONDUCTIVITY -", TPE10.2, . +0 N 1X, '/CHM-CM') 114 FORMAI ('0', '/'0', 147J 0013 . + . *LUPPEE PROPERTIES (TEMPERATURE VARYING, DIMENSION_163) *, X 34.0 115 "CEMAT ('C', 'IFIRE. COND.', 61, 'ILICT. CUND.') 2014 456

120 FORMAT (11+,2X, "MULILITY (MICRUNS-CM/VOLT-5)", 2X, "COLLECTOR", 2X,

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		FCBTRAN IV	G LEVEL 21	MAIN	EA12 = 78104	15/01/34
	ť		X	"ACEILITY ELNSITY")		35 7 3
		CC20	121 3034	A1 (* *, 18210.2,201, 18210.	. 2)	JSeJ
	(0021	122 FCRM	AT (')',' '/')','ELECTRIC	FIELD STALNG18 -1,110.2,	14,14/081,24
	•		X	,*BUFPER TEMPERATURE -*	,10.2,1X,'C',2X,'EUPFC&	PLCA LATE - Obud
			X	',E17.2,1X,'CC/S',/' ',	CATING BUELLINY -", ETD	-2,1%, J61J
	U		1	"EICACHS-CH/V-S")		
		3322	123 BORA	AT ("",24,"HUBILITY (HICS	(CHS-CH/VCL1-S) · 24, · 1051	
•	•	6 1 2 3	104 FOAM	AT (131.28 18 (CA) - 18.15	NIFRAURE (C)	25, 1, 87,
	•	6723	X X	14 (CE/S) + (CC/) (K) 12		uped
		0024	125 FC68	LAI (¹ ¹)		1.670
	•	0025	126 PCF.	AT (* *, 75.3, 3 (3X, 12E14.6)	.)	Dr. o û
		3026	127 PCR5	1AT (* *,9X,=14.4,11X,I5,3X	(,E14.4)	くちょう
		0.027	126 2CB.1	A1 ('0', 'FABIICLES CF FOSI	LTY, 1911J.2,2X,	
-	E.		Å	ICST FECK INTIAL PCS	$\sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{n} \sum_{i$	-/1u
		0028	129 2033	A] {' ',']! =',214.0,21,"2 17 /75)	[] = , , [] 4 . J , Z I , ' B = ' , E] 4 .	5) 6/27
	•	0030	131 2024	(AL (17) (AT (1510.3)		57) ⁺
	•	3630	132 7Ca#	AT († †. †GRAVITATIONAL FIL	110 STRINGTH = 1. E14.5.10*	1/3**21) 7
		3.32	133 7023	AT ('3', 'SAMPLE INLET IC.	CALICA AND SIZE / " ","COU	DALINALS Y JTC.
	(_	X	-', I4, 2X, E10.3, 2x, 'Z-'	,I4,2x,E10.3,2x,*5432LL	TRAIJS . U770
			X	,2X,E1).3)		ر د7.
		0033	134 FCFY	A1 ('0',2X,'Y',6X,'TEMELE,	1Jā±*,1∪%,*J*,15×,*₩*;	C7 3 3
-	C C	UJ34	135 rCan	121 (*1*)		, rat
		2 1 2 6	U			
	(2000	SIN. Sila	- (5 100) REE1, REUL,	(_)	، عرب الدوريين
	•	0037	JEAD	(5.103) ELCUNE.THEONE		
	•	2038	3 E A L	(5,104) "ILTH, CEE13, XLUNG	٠	6550
	C	0039	READ	(5,104) ¥1,21,8		1031
		C 0 4 0	3EA1	/ (5,105) EN,TEURF,CT1CAL,	LEJEE	(01)
		0041	READ) (5,131) GPAV		1501
	•	CC42	FIAD	(5,106) (1.05L(1),1NHCBL	(1) ,	
	ſ		C SVLDAR	TERPERATURE FIELD AS ARA	A. 1- JIVES LEAPLANTURE -	T NILIP PLANAS - USAD
2			C FECS i=	- IC Y=1.		93
			c			U 12 44 J
	C	2043	» C E =	=2+bVEI-1		5 - 5
		0044	NIE.	1E=2+NCE-1		L J ČU
	(3345	150	LE=ELCCND+EJ+EJ+DBFTH+DEP:	IH/THCONE/4.	U970
	L.	J046	[]=]			
		0048 2047	12-1	1 # #]		1.0.2
	(0349	LI-1 LENS	SIX=0.998233/(1().30421-	151 +T 1+ (3.53552-36) +12- (0	.7==-Jd)=is) 131J
		0050	CALL	L TIME (NTIME, NOUP, ESET, EKP	1,T)	1923
			C			1632
	(C EVALUAT	IT DENSITY AT EACH TEMPERAT	IURE POINT- ARBAY RHO	1040
			C			1,15)
	1	0001	0380)=]. 9782]3/EENSIY		1.6.
	-	0J52	TO 2	2 IF 1, NTERP TOUESATS, AT TAT / TS		+ // J 1
		0,054	1 - 1	1002271368627 <u>4</u> [4] 227480		1.14.3
	1	2255				11.3
	•	0355	3.40	$(1) = C_n dC / (1 (0. Co421-5) + F)$	I+ (8.5055±-0) *FT2- (0.79	-6) #F13) 111J
4		2257	2 CCN1	TINJT		114

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		THE IS INCOME AND A	● 28 ● 25 ▲ #11 J ↓ → 54 Y → # ↓ → ★ ▲	
	C LVALUATE VISCUS	ITI AT EVENT CITER	FERELBAIURE PULAIT ABEA	- 7 A J
0058	3=-1			
0059	ARG =TEUFF-2	0.		
0060	ARG= 3.00067/	(1.+C. JC82+ABG)		
0 26 1	AEG=-7.6039+	ABG		
0062	SUC=EXP (ARG)			
0063	301=3, 13937	,		
3064	CTRUEL=CTACE	14401/400		
0065	VISC= MUJ			
0066	EC 3 I=1.NCF	:		
0 26 7	J≖J+?			
0068	AKG=TSCALE*T	(J) +T30FF+20.		
0.369	ARG=3, 2))b7/	(1.+), J082#A5G)		
0070	AEG=-7-6135+	ARG		
0071	PND (I) = FYP (A	RG) / NO.)		
0072	3 CONTINUE			
6 3 7 3	SETTE (6.11)	n		
0074	ANTE 16.111	NVSL.NCCL.APCOL.W	1.8531	
0075	ARTTE 16.112		· • · · · · ·	
0176	#RITE (6,113	N VISC. ELNSTY, 19005	A.FICCND	
30 77	SRITE (6,114			
1078	-5175 (6.115			
3.79	55TT (6.116) TAP1 5501		
0010	22172 (6)110	A FREI FREU		
1.3.61				
0.162	3317 - (6, 119	9 6) ".T.D.T.H., ZT.C.N.G., D.T.P.T.H		
3083	LPT) 5 (6 12)		10.51	
CC54		$\frac{1}{2} = \frac{1}{2} = \frac{1}$		
0.385	ARTT - (6, 172			
1)46	HATTE (6.123			
0.047	2617F (6,121) (PACALITYARMANALI	1).T=1.96)	
• • • •	((1.022(1))1.00022(_ ; * _ · ; w u;	
	ē.			
	C CONFUTE DENSITY	TROFORD, AS AFFAV	PARAT REPARTMENDED AND	5. ThTT
	C Y=1 10 11-69 01	1413 D ASITV-SEVERA	TINE FGINT	
	C			
0048		2-1-1		
0089	FRHUI (1) #C.			
0090	N1=1			
0091	N 2= 3			
0292	EC 4 1=2.400	•		
0393		(N1)+4_+_B(:(N1+1)+.	JC (N21)/3.	
6094	N1=N2			
0095	2= 12+2			
0096	285CI/1)=	A+FRHCI (I-1)		
0097	4 CONTINE			
	(
	C COMPRESS VASNO T	NIEGRAL AS AFRAY RT	PRESENTING VERB INTERS	NELD 2. C. 1=4 .
	C EVERY UTHER UTS	SCCSITY PCINT (T	LVIRY FOURTH DIASIN-T	1122 - 1200 - 2 V .
	C FIFST EVALUATE	Y/FOU AS AFRAY ST.		
	C	-,		
0098	2 Y= 1. / (NT F- 1	(_)		
0099	S1(1)=C.			

(
	FCRTBAN I	V G LEVE	1 21	HAIN	1.41E = 76134	15/31/34
ſ						
٠	0101		X=2X+ ()	I-1)		165)
1	C 102		S1(I)*	1/230(1)		1703
•	0103		D LCATIAUE			1710
•	0104		UT(1)=0. N1=1			174J
C	0106		42=3			1743
•	0107		EC 6 1=2.1	NVFL.		1754
_	0 108)= E Y + (31(N1)+4.#51(N1+1)+51(A	2))/3.	176 J
ſ	3139		#1=#2	••••••		177
	0110		¥2=¥1+;	2		1765
1	0111		01(I)=	A+U1(I-1)		17-1
•	0112	_	6 CCNTIBUE			1703
		C C				
(WEDY OTHER !	UTSCOSTON DOTES. RIBSS	EVALUATE FERRITZENE AN	
•			VIAI VIBLE			1840 IA40
	0113	<u> </u>	51(1)=C.	· · · · · ·		1850
(2114		EC 7 1=2.	NCF		1002
	0115		S1 (I) =	PBHCI (I) /FBU (I)		1-70
	0116		7 CONTINUE			1001
C	6117		J2(1)≠C.			1523
	5115		81=1			1943
(0119		N 2= N 1+ 2			1,1,
•	5120		LC 8 1=2,	BVEL Clause and the state state of the	211.43	174.2
	1121		A=LI+() 51=57	51(31)+4.+51(11+1)+51(6	2}}/3.	1925 1947
(0123		# 1- #Z k/=%14	2		1
•	0124		J2(T)#	2 2+11 2 (T = 1)		1401
	0125		E CONTINCE			127
(.	•••••	c				1963
		Č L	FANGE UT AS	D U2 FFCH INTEGBALS TAK	Em Broz 2130 10 Y TO 14	21 - FURT AN ARL 1990 -
<u>د</u>		c v	FLOCITY EXP	BESSLUB- TAKEN FROM Y I	C 1.	ې کا او ایم
' _		C				- 1
•	C 126		1=1 11 JI	, AVEL		لانية با الانتقال
	0127		01(I)≠	U1(4V2L)-U1(L)		- 151
•	U128	, I	1 52(1)=	02(NA.T) -05(T)		2.4
				COUSTANT FR DV TRUTHDA	STRA FREELT & SLADD FAL	
			SE SETTING	EFSUIT FOUAL TO CAR.		
		č				2367
	6129		CY=1./(NV	EL-1.)		2053
¢.	0130		¥1=1	-		ر 10 ي
	0131		CALL STAF	S(DY,U1,N1,NVEL,A1)		_11)
	0132		CALL SIMP	S(DY,U2,K1,KVLL,A2)		21
•	0133		FNU=VISC/	LENSTY		يشأهم
	J 134		USCALL=28	UFF/WILTH/ELPIH		 15.
(0135			DIFINTULFIN/FAU/USCALL/	(4.)	2130
•	0130	c	rn− (− 1• *r	# 6 T F / J / # 1		
		č i	VALUATE THA	AL VELOCITY		_ 1
(č				_ 1(-)
-	\$137	-	USUM=).			
	0138		DC 9 I=1,	NVEL		د 21ء
۰.	2139		J (I) =-	FK+U1(I)+FN2+U2(I)		at a st
•	0 14 0	-	9 USUA=U	50#+0(I)		2.3.
-		Ç				4.4

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Frank 1. 5 4 41

	(
		FOBTRAN IV	G LE	VEL	21		MIAP	Call = 7	E104	15/31/24	•
	•		ç	CCME	UTT THE	ELECTROUS"	DTIC (Z-DIBECT	IICN) VILGLITY	• TBLS n	AD 147 YOLK 17 5 507774 - 1-	لا ساعات
	(Ċ	30 3	ILRILI U	JE INIEGAMI					1100 127 u
		0141		4	SCALE=C	THCBI * EC+. G	C 0 1				2292 1
	1	C142 0143			**************************************	A 1					-۳ لاتانا
	•	0144]#-1						1 5 4
		0145		1	C 12 I=	1,SVEL					224
-	C.	0 146]=]+2	-1 03010801	************				(و ف ــــــــــــــــــــــــــــــــــ
		0147		,	(1) 1303. = (1) 2	-PK2=01(I)-	1.				2:50
	ſ	3149		12		KSU#+W(I)					-34
			C				-		.		(7: 2
	1		ç	731:	NT TEATE NE DECO	ÈNTURE AND City Doints	U- AND N- VEL	CCITE FILLOS A	I MALUID	U. I COMEDECA	، عدست شاہ بنج دی
	· ·		c	16 1	TOL ALLC		•				2400
	_	0150	•	Į	C7=1./ (N	IVEL-1)					4+10
	ſ	0151		ī	WRITE (6	i,135)					2,
		J152			ARITE (6 Netre (6	134)					243. .443
	(0153		1	10 3) 1=	1.NVEL					
		0155			1=04+ (1-	-1)					2+53
		<u>^ 156</u>			J=1+(I-1) *4	· ·····				_+/u
	•	0157		ن ټ ک	RRITE (C DV=TVADS	5g 140) - Xg2 (J (2762)) • U (1) • M (1)				C ·
		J 159			ABITE (6	5,135)					2223
	t	2162			#FI1£ (6	5,124)					ا د د
		2161			ARITE (6	125					
	ť	0162			10 17 1ª 177±7	=					
	•	2164			J= 14	(1-1) +4					
		1105			U(I)=	U(I) #USCALE					
	C	J166			L (1) =	=# (I) = # SC AL 3 =# (): # T 3/ AT 5	******				ا جو ہو۔ ان چاہ ج
		3168		1:		$E_{0} = 126$	1(J),J(I),J(I)			
	ť	••••	c								26-53
			C.								LU1*
	f	0169 3173			J=∠₹₩¥21 20 14 14	= 1 . NVEI					2020
	,	2171			J=J-	1					21-40
		0172			CHOEL (J)	=CHOPL (NVEL	(+1~I)				2050
	(J173		. .	ü (J) 4	=0 (NVFL+1-I)					
		0174		14	₩ (J)* 	=#{}**=1=}) =#{}**=1=}					
	1	3176			CC 15 I	= 1, NVELN					L 1 14
		0177			CHOLL (N	VEL-1) =C%081	.(NVEL+I)				-1-1
	4	0178			U (NV)	<u> </u>	(+I)				-1:1
	Ľ	5179		15	1477)# 1477-7471	51-1)=» ("VLI 51-1	1)				
		3161			YC=LEFT	8/2.					_ 7→
	t	0182			Y=-1L-E	Y					
		0183			IC 16 I	= 1, NV					1111
	1	0184			(† I = 1 V = 1 V V	F I					12.
		J166		16	CONTINU	E					27-)
			c								• •

•

J

(,	FCBIBAN IV	G LEVEL 2	1	NTT	DATE = 70104	15/01/34
*		C SET T	HE 2-CCCEDIN	TE ARBAY AND THE	Z-DIRECTION STEP SIZE.	1810
Ć	1187	ас				2020
	0184	20	CCCI VINCCCI-	L		ں ڈی ∡
	0189	L L 1	-2001/(824,01-			2040
(0190	2 =1	- (82601-1)+80			2.50
	0191	8.7	FTSENVET			2 ~ 0
•	0192		ETS= (NZ-1)/24	•1		
•	0 19 3	2=-	23-12	•		
	3194	DC	190 I=1,NZ			2590
	J 195	2=:	Z+DZ			2900
C	C 196	190 22	(I) = 2			2413
		Ĺ				ک 2 کے بید بند (
		C RCUJE	THE CENTER A	NE AADIUS OF THE	SATE. JAIAA 10 THE N	FAREST MB. (14) 63643
C		C OF 31.	•			245
		C				2900 2950
1	0197	IY	I= (X1/CX+_5) +	NYFIS		2970
۲.	0198	12	1= (Z1/DZ+_5) +	NZPTS		2987
	0199	¥ 1:	= YY (_Y1)			, y ^o u
(9293	21	= 22 (121)			3163
•	3291	181	=a/E¥+.5			5010
	0232	5=	13 4 €1			آ ہےں ا
(# R 2	112 (6,133) 1	1,1,1,121,21,3		ن ر ب د
•						3.14)
			CH ACELLITY	TAKED IN THE SAM.	PLL DISTRIBUTION, DETER	ulaz idi exii - sis.
(C LUCALI	CAS OF FARTI	CLES ON THE SEGE	CF THE SADFLE STREAM.	ようた し
	3204	1=3	V 1-5 /5 V-1			3.73
	12:5	10 J	(1)-0/01-1 2)-0/01-1			Jue J
(0206	50	200 J#1.NVH	•		3,25
	22 07	•••	I=J+M			5 I U J
	0208		P= (A35 (R+E- (YY (I) - V1) + (VV ()).		
(•	0209		2.11N (J) =2 1-P	(-) ((/	11/// •••	نيم 1 س د تر ه
	2210	203 663	TINUE			313]
	0211	281	11 (6.120)			3143
•	P212	rc	3-C J=1.88			
	0213		-0 27C K=1,3	YN		3103
	1214		1=K+E			110.
1	0215		2F(K)=251	N (K) +XICNG* (W (I)	+ 20 + F # C 2 L (J) + C 4 C a L (L)) /	U(L) 41-1
	0216		1F(YY(L).	GT.YC.OR.YY (L) . LI	EID)	3200
		X	2P (K) =	999.		3210
•	0217		F= (AES (B+	R- (YY (L) -Y 1) + (YY	(L)-II))++.5	3220
	0218		2 F 2 (K)	=2F(K)+2_+P		3231
	6219		IF (ZF	(K) . L 2 H)		3240
-	1991	X	155 ST	TI (6,128) PACEL	(J),YT(L)	3250
	JZZ J	273	IF (ZF	2 (K) . GE. ZW)		3160
(C I	WRI	TE (6,122) FNCBL	(J),YY(I)	3273
-						- ۲ ـ ف
		C FINL 1	HE I-AVERAGE	L ACSILITY DISTRI	LEGTIONS AT BACH 2 POLS	L. (197
(3221					بالاد
•	0222		LO 210			2310
	0223			14410		341)
•	0224		6 - N - N - N 1 E / 7 7	11) GE 78 (K) AND	C7/T1 15 020/011	233-
•		¥	11 124	(4/*95*68 (N)*886 K)# 6886(51/1)*886	· ← ← (↓) + ↓ E + ← F ← (下))	3340
	0225	210	T # 122	() = INCODI(U) +0 (1 /.) .17 (F/K) /5 -	4) 19/11 09 - 85/255	1350
			15 (44	ミニノーション・シェ (ト) ・しだいム	64 (L) + GI+4FZ (S) }	L 12 E

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FCATBAN IV J	i level 21	XAIN	DA11 = 70104	15/01/34
	X	A ± (K) =).		. 7. 5
0220	CALL	SINFS (CY.AR. 1. WYH.D)		
0227	PNA	E(I)=D/USCALE/DEPTH		
C228	23C CONTINUE			24.36
	c			3-1
	C PINE THE AVERA	GE BCALLIFY DISTRIBUT	ION IN EACH SAMPLE CULI	ECTCR.
	c			343
0229	NEIV=NFCCI-	1		344
0230	EC 260 1=1.	NCCL		
0231		-1) +NCIV		346
3232	50.24	D K=1. APCLL		347
1213	1=	KAJINIT		i-le
1234	24 ° 5#	(K)=FAR(T)		340
0235	6 47 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6	PS/DZ. 28. 1. NFCC1 .C1		(n.)
		les (berent it he cortet		
0236	c	•		35.0
			DHTTCHE	202 263
		-CICB PUBLIAL PASIAL	DU11083+	
1137	L	7. 84051 (1) (C		104 365
237	ABITE (Dele	() FROEL (J) PIPC		355
V230	100 CUNINUE			350
J239	SJU CONTINUE			ا د ک
2240	YY SICE			
3241	ENE			355

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	FURTRAN I	V G LEV <i>e</i>	21	TEMP	CATE = 781)4	15/01/34
	0001		SUBACUTIN	E TEAP(NI.NS.FS.FKP.T)		
•		c				- i de
6		C 1 C 1	BE TEAL SULL ZIEC IS THE	ROUTINE EVALUATES THE I ZERC CEDEB FIELD- TONE	ENPERATURE FILLS I = 12 The FIRST JEDIE FILLS.	ERU + Fretiuns still The ibunt Gitatal
;		C 1	BE TEMPEBAT	USE AT NTEMP POINTS PRO-	N Y=0 TO Y=1	20-0
C		С				3653
	0302	_	DISENSICS	1(1)))		sie
1		C				a~70
•		5	CALCULATE	ZERU CPEEN PIELE		
	3303	L.	ET=3 14150	a 74		2020
1	0003		FI-J0141J: FK1=FC44//	0 5)		3/17
•	0.305		C#h3=CCS/	U . JJ E N 11		2712 2713
	0006		122122.42	N 1		17
(0307		EY=1.//NI	- 1)		1/
	0008		EC 2 J=1	. #I		3750
-	0009		¥=CY+ (J-1)		3760
E	0010		X= (1.+)	Y) *F1/2.		377
	0011		TLERC=	(CCS (PE1+Y) -CFN1) /CFH1/	FS	ني 7د .
		с				.7.
L		Ĺ	CALCULATE	FIRST CECEB PIELL		مان - نو
		c				1 -
	3012		Su3≖C.			ت ہے 7 ک
L	0013		FK3=4.	+FS/PI/PI		ل د د.و
	0014		50 J J.	1=1,NS		L + 3C
ŕ	0015		EWE	≠JI#PI/2.		1000
•	0110		FK I	= 279 (cpl)		J (5.0
	0017		FC P			2010
Ċ	0010		FL23	モルアフィーアガル アメリンパイト ノー・シアグラム クアメリル・シント	16 AEC	JC++ .
` #	1121		N-3.	A 1 (* C 1) / 46/2 C 14 3 N (PC2). A 1 4 5 8 1	/4•/FC2*FK //FNF/2•	ص · _ : ك
•	021			******** ******		
(0322		PC 24			0
•	0 3 2 3		P=S	IN (PC1) /2. /FC1+SIN (FC2)	12-1852	
	6024		E=-	2#2.#FI#FK1#C#N1	,,	ن در د د در مواه در
:	0025		NC=	1-(-1)**JI		
	0026		(=(2N1+C2N7+NC/JI		370)
	6327		FJI	S=JI+JI		
4	0028		130	N= (A+B+C) +FJIS/2./(FJIS	-EK3)	3703
	0029		ASU	B=ASUN*SIN (JI+X)	·	3990
~	0030		3 SUB	=SUE+ASUE		4663
L	0031		TONE=-	SUB/PS/ES/CPB1/CFB1		4013
	0032		10NI=1	LNE#2./FI		4
	0033		2 I (J)=1	ZEEC+FK2+ICNE		الا، بلُ بي مد
•	0034		RETURN			ا به ا
	0C35		EAC			4.5

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(
r	FORTRAN IV	G LZVEL 21	SIMPS	DATE = 70104	15/01/34	,
•	2301	SUELOUTINE	SIMPS (H, A, N1, N2, ABEA)		4.20L. [‡]	
		С			4070 _	
4		C TEL SIMPS SUBE	OUTINE USES STRESON'S	5 AULE TO INTEGRATE AN A	REAY 400)	
		C	_		4092	
	0002	REAL PICSUL			((1+	
E C	0003	C7.MENSION J	(1001)		4110	
	0004	ENCSUM=0.			+120	
_	1005	NICSU3=0.			41.50	
(C\$26	NI=(#2~#1)/	/2		4140	
	0007	J=N1-1	-		+15J	
	0008	EG 1 I=1.NJ	r		+16.)	
(0009	.1=.1+1			u17)	
-	a * 1 0	SET CIAN			416	
	2211	2 7 2 3 4 3	- HE 308+X (0)		4100	
(6212				413.	
•	0012	I EILSUGES	11203+V(n)		4200	
	0013	A 5 E A= H + (2.4	FENDSCH+4, #HIDSUH-A (N	1) + A (B2)) / Se	4410	
•	0014	5 ETURN			4220	
ť	0015	ENC.			4235	

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