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FLOW AND THERMAL EFFECTS IN CONTINUOUS FLOW ELECTROPHORESIS

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ABSTRACT

In continuous flow electrophoresis the axial flow structure changes from a fully developed rectilinear form to one characterized by meandering as power levels are increased. The origin of this meandering is postulated to lie in a hydrodynamic instability driven by axial (and possibly lateral) temperature gradients. Experiments done at MSFC show a noteworthy agreement with the theory.

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INTRODUCTION

In one application of continuous flow electrophoresis the objective is the *fractionation* of biological cell populations rather than separation. The problems encountered with cells arise from the fact that the mobility differences are very small and so large electric fields are required. In the chamber a buffer fluid is inserted at the top and the sample (which consists of a suspension of the biological cells in the buffer solution) enters just below the buffer inlet. As fluid moves through the chamber in a more or less laminar flow an electric field is applied across the flow. The purpose of the electric field is to move the particles laterally at a rate proportional to their mobility. Then, at the bottom of the chamber, a set of collection tubes picks up the various fractions. This technique has been highly developed for many purposes but relatively unsuccessful for the fractionation of cell populations.

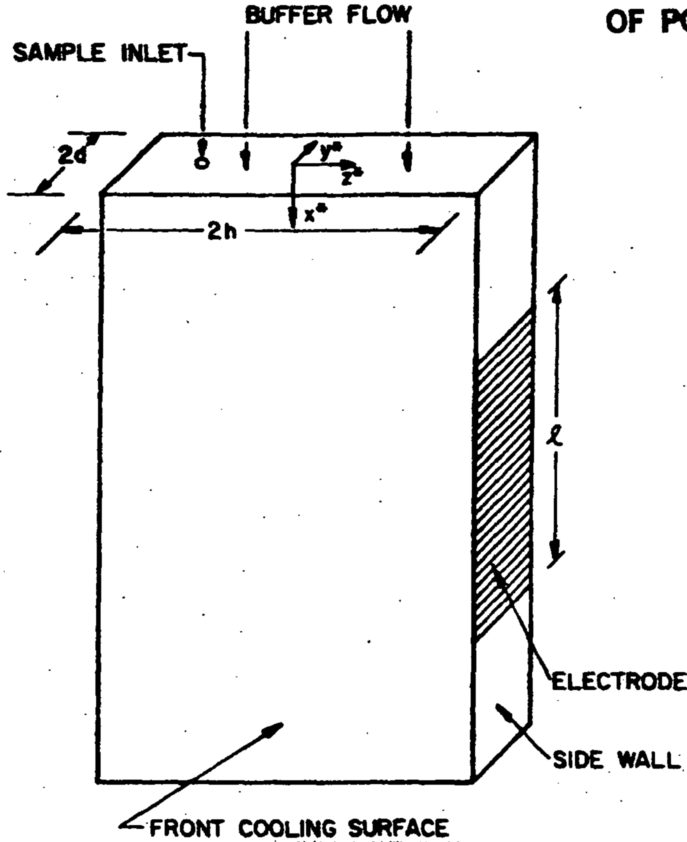

Figure 1. Chamber Schematic

In the conventional device, one has the familiar parabolic velocity profile along with a similar temperature profile because of the applied electric field and the associated Joule heating. To restrict the temperature rise the thickness of the chamber is kept small with cooling on the front and rear faces. Difficulties arise from a phenomenon known as electro-osmosis. In the chamber cross-section the applied electric field acts on the diffuse charge along the front and rear surface to induce flow. Since the chamber is closed by electrode membranes at either end, there is a return flow down the center of the chamber. This flow deforms the sample cross-section and stretches it out into a crescent shape. The longer the sample stays in the device, the higher the electric field, and the larger the sample diameter compared to the chamber thickness, the more electro-osmosis works to thwart matters. Thus, when the fractions are collected at the bottom of the chamber, the fractionation is poorer than it might have been. To overcome this the chamber can be made thicker to decrease the electro-osmotic shear across the sample cross-section. This works up to a point but produces some severe scale-up problems.

Changing from the narrow gap device (~1.5 mm) to a wider one (~5 mm) increases the temperature rise by an order of magnitude. Thus a small increase of 2-3°C in the narrow gap device is raised to a value that is almost unsatisfactory from the standpoint of biological viability. More importantly, since the Grashof number is changed by the fifth power of the thickness ratio because of the Joule heating, buoyancy effects become very important. This changes the structure of the flow dramatically and makes it possible for the flow to be hydrodynamically unstable. Experiments show that as the power is increased, the sample stream begins to twist and meander. Eventually the performance is completely unsatisfactory for any sort of fractionation process.

HYDRODYNAMIC INSTABILITY

The instability seems to depend upon the orientation of the chamber and at one point it was argued as to whether this is a really an instability or related to some other phenomena associated with the hydrodynamics or characteristics of the chamber. A first order stability analysis was carried out wherein there is an *axial* temperature gradient [1]. Such gradients could arise from uneven heating or cooling or from entrance effects. It turns out, according to the analysis, that fluids confined laterally but un-confined above and below are very sensitive to hydrodynamic instabilities. Whereas the critical Rayleigh number for fluids confined between two horizontal plates is 1700, the critical Rayleigh number is 6 if the plates are vertical and the walls isothermal. If the walls are perfectly insulated, which means that any disturbance is reflected back into the chamber, the critical Rayleigh number becomes inversely proportionalto the aspect ratio. For the chambers under study this ratio is 10^{-2} and so the critical Rayleigh number is much smaller. Thus the temperature gradient required to produce the instability is only a fraction of a degree per centimeter.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

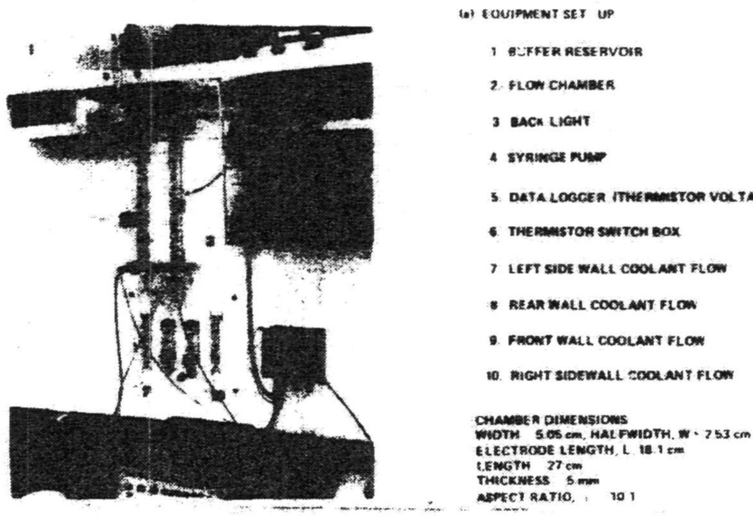

FIGURE 2. Experimental Apparatus

Experiments have been done at MSFC with the device shown schematically in Fig. 2. The dimensions of the chamber are 5 cm wide, 0.5 cm thick and 30 cm long. Neutrally buoyant colored particles are introduced through multiple ports at the top of the chamber and heating is produced by an alternating field which eliminates electro-osmosis. The flow is photographed and movable thermistors used to measure the temperature gradients in the fluid so as to determine whether the flow disturbances conform to the hydrodynamic instability suggested by the theory. The results of some of these experiments are in Figs. 3-6. The zero-power case shows rectilinear flow with no disturbances. Measuring temperature at all of the indicated positions gives the local Rayleigh number. As a power is applied, Fig. 4, one sees meandering of the sample streams. The buffer fluid is heated and cooled unevenly as it proceeds into the chamber and the buoyancy instability causes the redistribution shown. Temperature gradients measured internally turned out to be very close to the values predicted by the theory. Taking the velocity profile predicted by stability theory and superimposing this

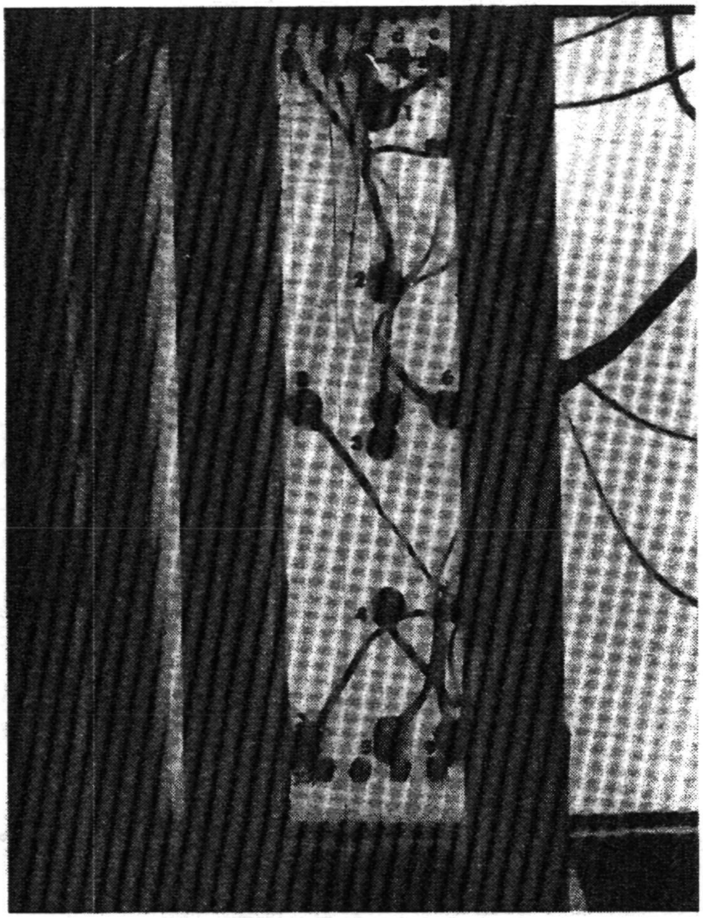

FIGURE 3. Flow at Zero Power Input

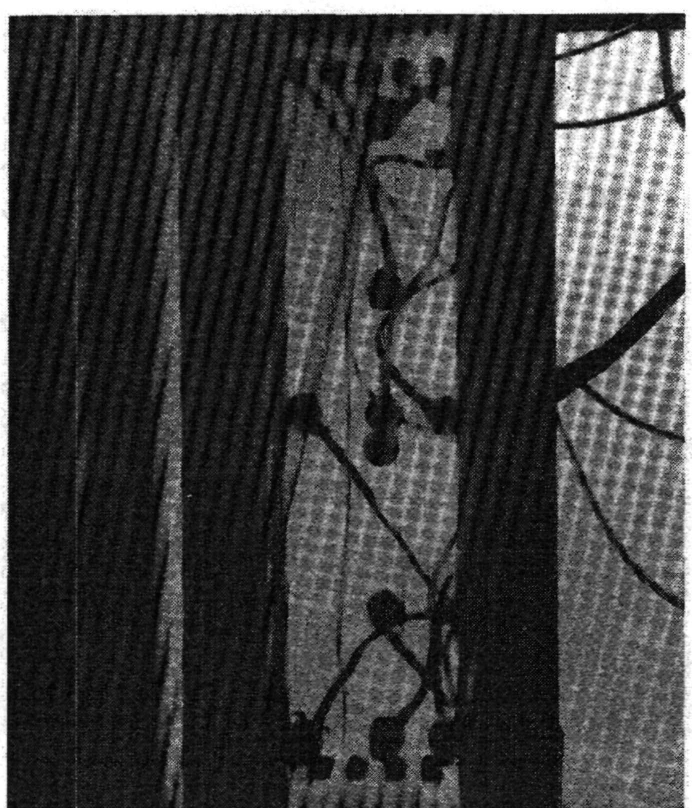

FIGURE 4. Flow at Power Input of 6.82 W.

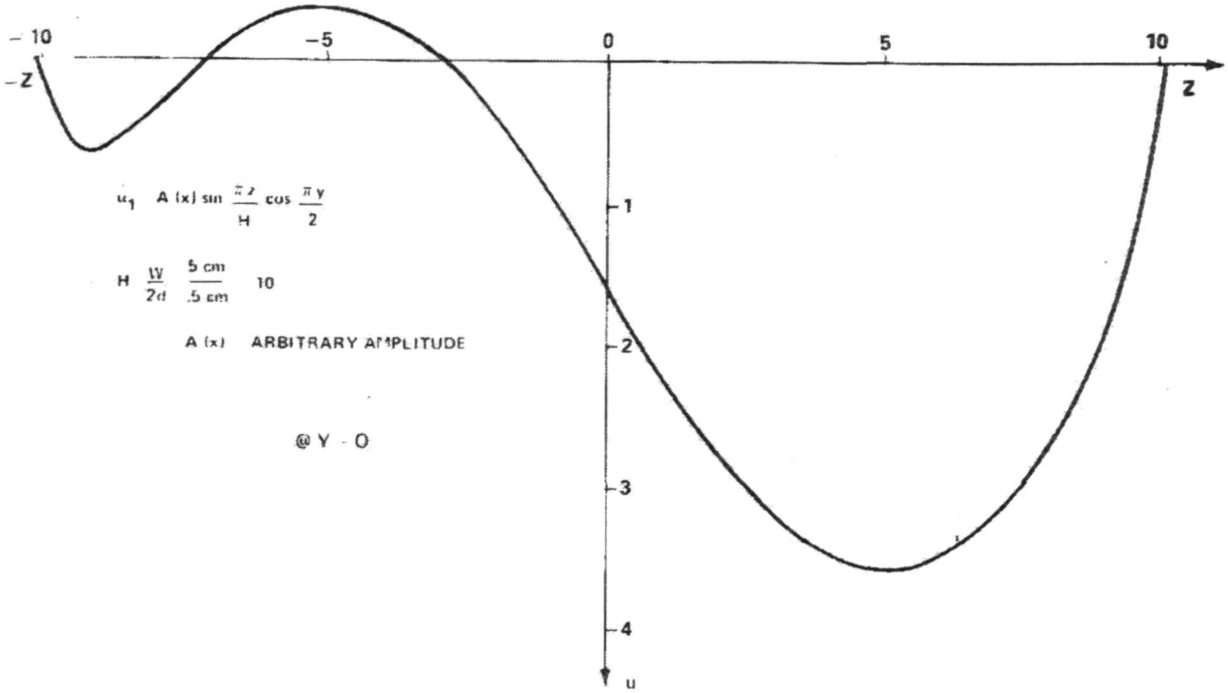

FIGURE 5. Superposition of antisymmetrical flow disturbance on the base flow.

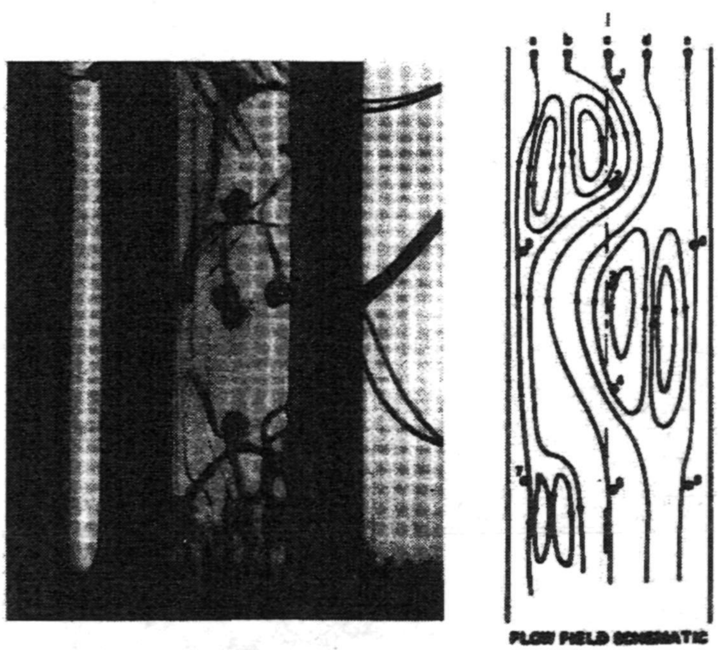

FIGURE 6. Flow at power input of 7.52 W.

on the steady rectilinear flow produces the profile shown in Fig. 5 which displays a structure similar to that shown in the previous photograph. If the power is turned up to an even higher level, to produce a temperature rise of 2-3 °C between the center of the chamber and the wall, patterns shown in Fig. 6 are obtained showing the further development of the flow. We now believe the cause of the meandering phenomenon is a hydrodynamic instability arising from axial temperature gradients that are present because of uneven heating and cooling of one sort or another. Presumably these gradients could be suppressed if the cooling jackets were designed carefully. On the other hand, a microgravity environment reduces the effect of buoyancy and also circumvents the problem.

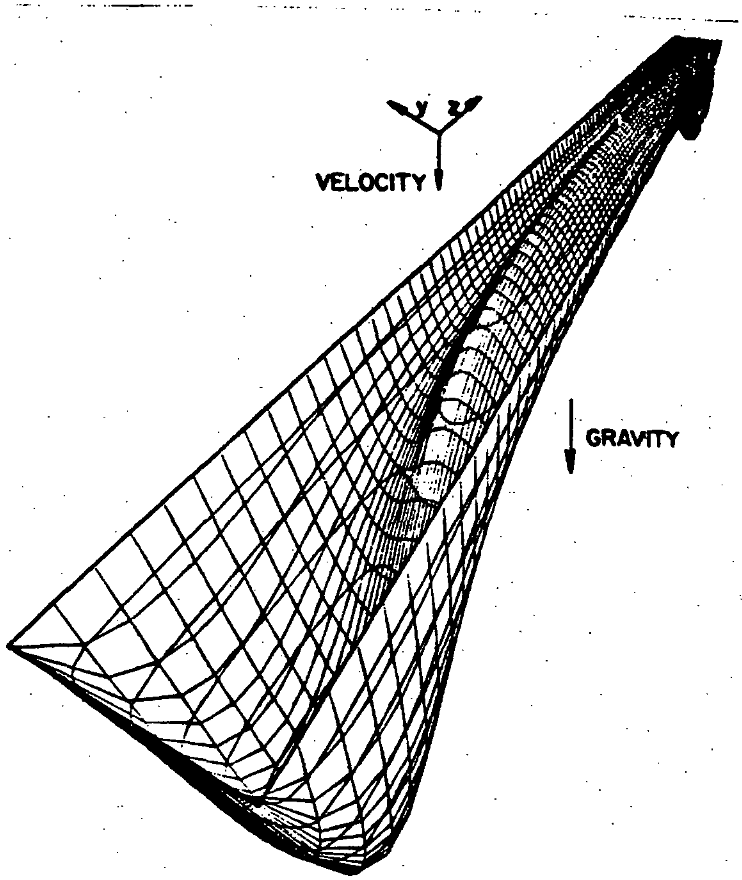

Figure 7. Axial Velocity Field at High Power Levels

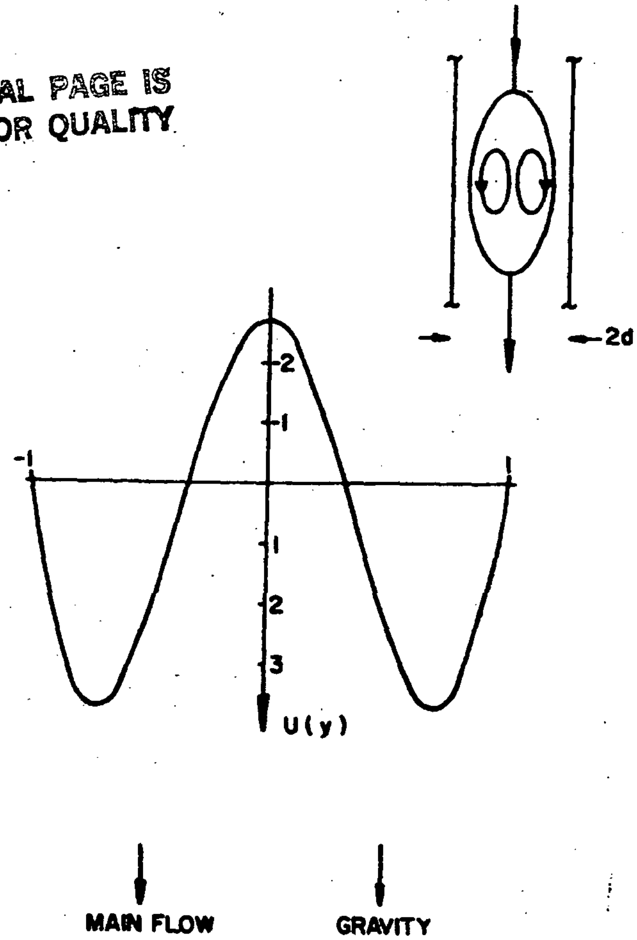

Figure 8. Axial Velocity Profile in Cross-section

Even if the heating problem is overcome the power increased without instability, the buoyancy forces still work against one. Figure 7 shows the velocity field in a cross-section of the chamber at power levels necessary to produce fractionation. Here there is so much Joule heating in the center that the buoyancy forces are large enough to cause a redistribution with downflow along the cold membranes on either side and upflow in the center. For a chamber of finite dimension, this means there is a recirculation. Figure 8 shows the same downflow configuration from the side showing clearly the large trapped eddy. Here any sample would move in and around this trapped eddy giving unsatisfactory results for any separation. In a micro-gravity environment, this recirculation would be absent.

We now understand enough about these instabilities to design an experiment to operate at low power levels in 1-g and at higher power in a micro-gravity environment which would enable us to verify the theory and the scaling laws.

REFERENCES

[1] D.A. Saville and S. Ostrach, Fluid Mechanics of Continuous Flow Electrophoresis, Final Report on contract NAS-8-31349 Code 361. Prepared for the George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama.