Pressure and Field Strength Considerations on the Plasma Centrifuge for Isotope Separation

by
D. L. Lessor

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THE PLASMA CENTRIFUGE FOR ISOTOPE SEPARATION

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ABSTRACT

The plasma centrifuge is shown to give an isotope separation ratio α approximately equal to the gamma power of the rotationally induced pressure ratio, where gamma is isotope mass difference divided by mean particle mass. This assumes an ideal gas model. An analytical solution for the velocity profile is found for viscous incompressible conducting fluid with radial electric current and axial magnetic field in a cylindrical annulus. The separation ratio is estimated as the $\Delta m/m$ power of the calculated pressure ratio. The velocity is found to scale with the product of magnetic field times electric current per unit length. Inserting electrical current, electrical potential, and magnetic fields from a first cut bench top centrifuge at Battelle-Columbus shows low ionization but also low velocity due to viscous drag.

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INTRODUCTION

The plasma centrifuge has been proposed as an isotope separation device. The plasma centrifuge device which we shall discuss here is one in which crossed electric and magnetic fields in a partially or fully ionized plasma drive the rotation of that plasma. The rotation velocity is not limited by mechanical stress limits that restrict mechanical centrifuges, but plasma centrifuge performance is limited by a new family of constraints. Many extravagant and nonsensical claims appear in the literature for the plasma centrifuge, most of which can be attributed to disregard of reasonable physical limitations. Other workers have taken note of the problems associated with bremsstrahlung^{1,2,3} and thermal power losses and with the pressure constraints.⁴

This report will discuss two analyzable considerations in plasma centrifuge operation:

- (1) pressure relations
- (2) viscous boundary layer effects and their imposed field strength requirements

In addition, temperature and heating considerations will be discussed. The formalism developed in this report lends itself to an investigation of plasma heating effects, but funding limitations prohibit further study in the present project.

Special attention will be paid to and experimental numbers will be drawn from experiments performed at Battelle-Columbus under ERDA sponsorship with a first pass design rotating plasma device built by Battelle. In particular, experiments with neon at a fill pressure of 0.120 and 0.700 torr at current levels of 600 ma and field strength 410 and 450 gauss will be used to deduce certain parameters, especially conductivity.

PRESSURE RELATIONS

The equilibrium density of a gaseous species in a gravitational field has the form

$$n(z) = n(0) \exp(-mg z/kT). \quad (1)$$

A transcription to a rotating gas configuration is generated by the replacements

$$g \longrightarrow -\frac{v_\phi^2}{r} \quad (2)$$

$$gz = \int g dz \longrightarrow \int -\frac{v_\phi^2}{r} dr \quad (3)$$

where the rotational acceleration $-v_\phi^2/r$ plays the role of a pseudo-gravitational field. The equilibrium distribution in a uniform temperature rotating gas is accordingly

$$n(r_1) = n(r_0) \exp\left(+\frac{m}{kT} \int_{r_0}^{r_1} \frac{v_\phi^2}{r} dr\right). \quad (4)$$

Here tangential velocity v_ϕ is assumed to be the only velocity component. If multiple species are present in a rotating configuration we have at equilibrium

$$\frac{n_i(r_1)/n_i(r_0)}{n_j(r_1)/n_j(r_0)} = \exp\left(\frac{m_i - m_j}{kT} \int_{r_0}^{r_1} \frac{v_\phi^2}{r} dr\right). \quad (5)$$

If r_0 is the position where concentrations are those of the feedstock and r_1 is the location where the desired enriched species i is taken off, Equation 5 gives the maximum separation ratio α . The corresponding ratio of pressures between the two locations with species which differ only a little in mass is obviously

$$p(r_1)/p(r_0) \approx \exp\left(\frac{\bar{m}}{kT} \int_{r_0}^{r_1} \frac{v_\phi^2}{r} dr\right) \quad (6)$$

Here $\bar{m}$ is the average molecular mass. Equations 5 and 6 give us

$$\alpha = (p(r_1)/p(r_0)) \frac{\Delta m}{\bar{m}} \quad (7)$$

Thus the separation ratio for neon isotopes ($\bar{m} = 20.18$, $\Delta m = 2$.) varies as the one tenth power of the rotationally generated pressure ratio, while for metallic uranium vapor ($\bar{m} = 238$., $\Delta m = 3$.), the separation ratio varies as approximately the one-eightieth power of the pressure ratio. A pressure ratio of 10^6 in uranium vapor would give a maximum separation ratio of 1.19. This separation ratio of 1.19 could be obtained in neon with a pressure ratio of 5.8.

Equation 7 shows that high pressure ratios from rotation are needed to give high separation. A separation ratio of 1.02 in neon would require a 1.22 pressure ratio, while a separation ratio of 1.02 in uranium requires a pressure ratio of 4.8. An upper limit on pressure is imposed by the requirement that the medium remain gaseous.

VISCOUS BOUNDARY LAYER EFFECTS AND FIELD STRENGTH REQUIREMENTS

Boundary drag must be overcome to produce the high rotational speeds required for isotope separation. We shall here use an incompressible fluid model with viscous forces to solve for the velocity and hence the pressure profile. The pseudo-gravitational field integral

$$\int_{r_0}^{r_1} \frac{v_\phi^2}{r} dr \quad (8)$$

is a main contributor to the separation effect. In our incompressible fluid model, the pressure will be found to obey

$$\frac{\partial p}{\partial r} = \rho \frac{v_\phi^2}{r} \quad (9)$$

Since density affects velocity only weakly, the value of the v_ϕ^2/r integral (Expression 8) will be similar in this incompressible fluid model to that obtained in a gaslike model. We can estimate the achievable separation ratio from*

$$\alpha \approx (p(r_1)/p(r_0))^{(\Delta m/\bar{m})} \quad (10)$$

which requires for its validity

$$\frac{\rho}{p} \int_{r_0}^{r_1} \frac{v_\phi^2}{r} dr \ll 1. \quad (11)$$

We will use an incompressible fluid model to investigate viscous drag effects, then use Relation 10 to estimate the separation ratio.

The model we will consider is that of a radial electric field and an axial magnetic field applied to incompressible conducting fluid between coaxial cylinders. The fluid obeys the momentum equation

$$\rho \underline{V} \cdot \nabla \underline{V} = -\nabla P + \underline{J} \times \underline{B}/c - \eta \nabla \times (\nabla \times \underline{V}) \quad (12)$$

where ρ is the mass density, $\underline{V}$ is velocity, P is pressure, $\underline{J}$ is electrical current density, $\underline{B}$ is magnetic field strength, c is velocity of light, and η is fluid viscosity. We have assumed cgs Gaussian units. The current density $\underline{J}$ we take as

$$\underline{J} = \sigma (\underline{E} + \underline{V} \times \underline{B}/c) \quad (13)$$

* The separation ratio α used in the literature is the ratio of desired to undesired concentration at the enriched outlet divided by (desired/undesired) ratio at inlet. We will use here the higher number $\tilde{\alpha}$ defined as the highest desired/undesired concentration ratio in the device divided by the lowest desired/undesired concentration ratio.

with uniform conductivity σ . Electric field strength is $\underline{E} = E(r)\hat{r}$.

Taking

$$\underline{V} = V_\phi(r)\hat{\phi} \quad (14)$$

$$\underline{B} = B_z \hat{z} \quad (15)$$

$$p = p(r) \quad (16)$$

gives us from Equations 12 and 13

$$\begin{aligned} -\rho V_\phi^2/r \hat{r} = & -\frac{\partial p}{\partial r} \hat{r} - \frac{\sigma}{c} (E_r + V_\phi B_z/c) B_z \hat{\phi} \\ & + \eta \hat{\phi} \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial(rV_\phi)}{\partial r} \right). \end{aligned} \quad (17)$$

Thus we have

$$\frac{\partial p}{\partial r} = \rho \frac{V_\phi^2}{r} \quad (18)$$

$$\frac{\sigma}{c} (E_r + V_\phi B_z/c) B_z = \eta \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial(rV_\phi)}{\partial r} \right). \quad (19)$$

At this point two models were developed with different assumptions about E_r and J_r . Both models assume B_z uniform. Model 2 is preferred, but the two models give essentially the same results for Hartmann numbers much less than unity. Model 2 preserves total radial current per unit length for all cylinders coaxial with and lying between the two bounding ones. Model 1, by contrast, assumes electric field between the two cylinders is that of a charge-free space.

$$\text{Model 1.} \quad E_r = \frac{V(r_1) - V(r_2)}{\ln(r_2/r_1)} \frac{1}{r} = \frac{A}{r} \quad (20)$$

$$\text{Model 2.} \quad J_r = \frac{I_\ell}{2\pi r} \quad (21)$$

In Equation 20, $V(r_1)$ and $V(r_2)$ are the electrical potentials at inner radius r_1 and outer radius r_2 , respectively. The I_ℓ in Equation 21 is total radial current per unit of cylinder length.

Both models admit analytic solutions. The imposed boundary conditions for both cases are zero velocity at the bounding cylinders:

$$\begin{aligned} V_\phi(r_1) &= 0 \\ V_\phi(r_2) &= 0. \end{aligned} \quad (22)$$

MODEL 1 - UNPERTURBED RADIAL FIELD

Model 1 has its solution

$$V_\phi(r) = \frac{McA}{r_1 B_z} \mathcal{V}_\phi(x) \quad (23)$$

where the dimensionless velocity $\mathcal{V}_\phi(x)$ is given by

$$\begin{aligned} \mathcal{V}_\phi(x) &= \left\{ I_1(x_1) K_1(x_2) - I_1(x_2) K_1(x_1) \right\}^{-1} \\ &\quad * \left[\left(\frac{K_1(x_2)}{x_1} - \frac{K_1(x_1)}{x_2} \right) I_1(x) \right. \\ &\quad \left. + \left(\frac{I_1(x_1)}{x_2} - \frac{I_1(x_2)}{x_1} \right) K_1(x) \right] - \frac{1}{x} \end{aligned} \quad (24)$$

where

$$\begin{aligned} x &= M \frac{r}{r_1} \\ M &= \left(\frac{\sigma B_z^2 r_1^2}{\eta c^2} \right)^{1/2} = \text{Hartmann number} \end{aligned} \quad (25)$$

and x_1 and x_2 are the values of x at the inner and outer radii, respectively.

The solution to Model 1 (Equations 23, 24, and 25) is obviously the sum of the "free flow" velocity or $\underline{E} \times \underline{B}$ drift velocity and its viscous drag modification, where the "free flow" velocity is

$$\begin{aligned} v_{\phi}^{\text{free}} &= -c \frac{E_r}{B_z} \\ &= -\frac{McA}{r_1 B_z} \frac{1}{x}. \end{aligned} \quad (26)$$

Plots of velocity vs radius as calculated with Model 1 appear in Figure 1 with three values of Hartmann number M

$$M = \begin{cases} 0.1 \\ 1.0 \\ 10 \end{cases} \quad (27)$$

and with

$$\begin{aligned} r_1 &= 5 \text{ cm} \quad (\text{inner radius}) \\ r_2 &= 15 \text{ cm} \quad (\text{outer radius}) \\ V(r_1) &= -100 \text{ statvolts} = -30 \text{ kilovolts} \\ &\quad (\text{potential at inner electrode}) \\ V(r_2) &= 0 \quad (\text{potential at outer electrode}) \\ B_z &= 1 \times 10^4 \text{ gauss.} \end{aligned} \quad (28)$$

Since only M is varied in the sequence of three runs in Figure 1, one should consider it as varying σ/η (conductivity/viscosity). It is evident from Figure 1 that boundary drag keeps velocities low if $M \ll 1$. For $M \gg 1$ (like $M = 10$ in Figure 1), the velocity profile is dominated by cE_r/B_z except near boundaries. The curve for $M = 1$ does not lie between that for $M = 10$ and $M = 0.1$, but that is because of the M^{-1} dependence in the quantity plotted, namely $V_{\phi}/(McA/r_1 B_z)$ with V_{ϕ} the velocity. As M grows larger than unity, the linear velocity remains at cE_r/B_z except near boundaries.

FIGURE 1. Velocity Profiles as a Function of Hartmann Number M .
(Model 1 - Unperturbed Electric Field Calculation)

MODEL 2 - CONSERVED RADIAL CURRENT PER UNIT LENGTH

Taking the radial current density in the annulus from Equation 21 in Equations 12 and 13 or 17 and 13 gives us a velocity profile

$$V_{\phi}(r) = \frac{W}{u} \left\{ \frac{1}{u_2^2 - 1} [u_2^2 \ln u_2 - (u_2^2 - 1)/2] (u_2^2 - u^2) + u^2 \ln u - u_2^2 \ln u_2 - u^2/2 + u_2^2/2 \right\} \quad (29)$$

where

$$u = r/r_1 = \text{radius/inner radius}$$

$$u_2 = r_2/r_1 = \text{outer radius/inner radius}$$

$$W = \frac{I_{\ell}}{2\pi} \frac{B_z r_1}{2\eta c} \quad (30)$$

$$I_{\ell} = \text{current per unit of cylinder length}$$

$$\eta = \text{fluid viscosity}$$

$$\ln = \text{natural logarithm function}$$

From the relation

$$J_r = \sigma(E_r + V_{\phi} B_z/c) \quad (31)$$

we can obtain the radial electric field E_r as

$$E_r = \frac{I_{\ell}}{2\pi\sigma r} - V_{\phi} B_z/c \quad (32)$$

with V_{ϕ} given by Equation 29. We can find the difference in electrical potential between electrodes from

$$\begin{aligned} V(r_1) - V(r_2) &= \int_{r_1}^{r_2} E_r(r) dr \\ &= \frac{I_{\ell}}{2\pi\sigma} \ln u_2 + W r_1 [(u_2^2 - 1)/4 - (u_2 \ln u_2)^2 / (u_2^2 - 1)] \end{aligned} \quad (33)$$

(34)

with the notation given by Equation 30.

Equation 34 allows us to deduce plasma conductivity σ from measured current, electrical potential difference, and B_z . We must, of course, know an effective viscosity η .

APPLICATION OF THE VELOCITY PROFILE SOLUTION (MODEL 2) TO THE BATTELLE-COLUMBUS PLASMA CENTRIFUGE

The Battelle-Columbus plasma centrifuge does not exactly fit the cylindrical geometry assumptions of our solvable analytic model. Nevertheless, we can make a crude representation if we conjecture that the radial current flow occurs through 10 cm of cylindrical length. This gives a current/length I_ℓ of

$$\begin{aligned} I_\ell &= 0.6 \text{ amperes/10 cm} \\ &= 1.799 \times 10^8 \text{ (esu/sec) / cm.} \end{aligned} \quad (35)$$

We take for the geometry, field, and thermodynamic description

$$\begin{aligned} r_1 &= 5. \text{ cm} \\ r_2 &= 15. \text{ cm} \\ V(r_1) &= 3.3356 \text{ statvolts} = 1000 \text{ volts} \\ V(r_2) &= 0. \\ B_z &= 410 \text{ gauss} \\ T &= \begin{cases} 573^\circ\text{K} = 300^\circ\text{C} \\ 473^\circ\text{K} = 200^\circ\text{C} \end{cases} \end{aligned} \quad (36)$$

The temperature is used to scale the viscosity, which was taken as either air viscosity at 40°C (313°K) with $T^{1/2}$ scaling

$$\eta(T) = \eta_{\text{air}} (T = 313^\circ\text{K}) (T/313)^{1/2} \quad (37)$$

or neon viscosity at 200°C (473°K) with similar scaling.

We also use the temperature to set an appropriate density for separation ratio estimates:

$$\frac{p(r)}{p(r_1)} = 1 + \frac{\rho}{p(r_1)} \int_{r_1}^r \frac{v_\phi^2}{r} dr \quad (38)$$

$$\approx 1 + \frac{\bar{A}}{N_0 kT} \int_{r_1}^r \frac{v_\phi^2}{r} dr \quad (39)$$

Here $\bar{A}$ is average atomic mass and N_0 is Avogadro's number.

The temperature value used is essentially a guess. Experimental evidence suggests that the degree of ionization is small, since the conductivity deduced from the experimental values using Equation 34 tends to be reduced by a factor 10^{-4} from that of a fully ionized plasma at temperature $T = 573^\circ\text{K}$. This suggests that the material in the chamber is partially ionized gas with a modest heating (to 200°C or 300°C) from inlet conditions. The low velocities calculated can not be blamed on excessive viscosity, since reduction of neon temperature to 100°C would produce only a 30% increase in velocity.

The velocity profile calculated appears in Figure 2. It is evident that the velocities calculated are too small to effect a significant isotope separation. The calculated separation ratios $\tilde{\alpha}$ (see footnote *), pressure ratios, and maximum velocities calculated for $^{20}\text{Ne} - ^{22}\text{Ne}$ separation are:

$\tilde{\alpha} = 1.000082$	}	$\eta = 257 \text{ micropoise, } T = 573^\circ\text{K} = 300^\circ\text{C}$ (scaled air viscosity)
$p(r_2)/p(r_1) = 1.00083$		
$v_{\phi \text{ max}} = 1830 \text{ cm/sec}$		
$\tilde{\alpha} = 1.000037$	}	$\eta = 425 \text{ micropoise, } T = 473^\circ\text{K} = 200^\circ\text{C}$ (neon viscosity)
$p(r_2)/p(r_1) = 1.00037$		
$v_{\phi \text{ max}} = 1110 \text{ cm/sec}$

FIGURE 2. Velocity in "Best Estimate" Representation of Battelle-Columbus Neon Plasma Centrifuge Experiment (Model 2 - Conserved Radial Current Model)

CONCLUSIONS

While large uncertainties exist in the input, there seems to be very little uncertainty in the conclusion: The Battelle-Columbus plasma centrifuge probably was exhibiting little isotope separation, even from neon. The information gained from the experiment will be used later to infer the needed currents and fields.

One high uncertainty number in the input was the current per unit of cylinder length. In the input for the Battelle-Columbus neon experiment mockup, the measured current (600 milliamps) was assumed to be distributed through 10 centimeters of axial length in a radial outward charge flow pattern. The actual inner electrode geometry was not even cylindrical. The radial current could have been distributed in as little as one centimeter of axial length. This tenfold increase in current per unit length with preservation of other parameters would give $\tilde{\alpha} = 1.0036$, $p(r_2)/p(r_1) = 1.037$, and $V_{\phi \text{ max}} = 1.1 \times 10^4$ cm/sec in neon. This separation would still require extreme precision mass spectrometry to detect. It is not clear whether high rotational speeds in a small disc shaped region embedded in more slowly rotating fluid would actually give this separation. It is possible that the experimental electrode configuration produces less drag than would occur with the cylinders used in the analysis.

The viscosities were almost certainly no lower than those which we used, and they could be considerably higher. Hence we were probably taking an optimistic value.

In spite of the underpowered, under-fielded condition of this first working device, the calculations do give the encouraging result that velocities of the order 10 to 20 meters per second should have been obtained.

Accepting the failure of the present experimental configuration to give isotope separation, it is appropriate to ask what is needed. Equations 29 and 30 show that for fixed geometry, the linear velocity scales with

$$W = \frac{I_{\ell}}{2\pi} \frac{B_z r_1}{2\eta c} .$$

Thus either current per unit length I_ℓ or field strength B_z must be increased to give separation. In our most realistic mockup of the Battelle-Columbus experiments, we had

$$W = 2305 \text{ cm/sec.}$$

A demonstration scaleup calculation was performed as follows:

<u>Parameter</u>	<u>BCL Experiment Mockup</u>	<u>Scaleup</u>
Current/length I_ℓ	$1.799 \times 10^8 (\text{esu/sec})/\text{cm}$ = 0.06 amps/cm	$1.799 \times 10^9 (\text{esu/sec})/\text{cm}$ = 0.6 amps/cm
Magnetic field B_z	410 gauss	4024 gauss
Viscosity η	425 micropoise	preserved
Inner radius r_1	5 cm	preserved
Potential difference	3.336 statvolts=1000 volts	33.76 statvolts=10000 volts

This scaleup in current and field gives us for the velocity parameter

$$W = 2.26 \times 10^5 \text{ cm/sec}$$

and for operating results in neon

$$\tilde{\alpha} = 1.16$$

$$p(r_2)/p(r_1) = 4.57$$

$$V_{\phi \text{ max}} = 1.09 \times 10^5 \text{ cm/sec.}$$

The velocity profile in the scaled up representation appears in Figure 3. We note that at these pressure ratios the constant density approximation and separation ratio prescription (Equation 7) is introducing substantial error, but the calculated results still show the trends and the order of the performance. The weakness of this current and field scaleup calculation, of course, is that the viscosity was maintained constant, while in fact viscosity and conductivity would probably have changed considerably.

Assuming (unrealistically) preservation of plasma conductivity in the scaleup, the scaled up Hartmann number is still only 0.1.

FIGURE 3. Velocity in Representation of Battelle-Columbus Neon Plasma Centrifuge Experiment Scaled Up in Current and Magnetic Field.

The ionization and temperature would probably be much higher than in our "realistic" mockup of the Battelle-Columbus experiment. The velocity expression (Equations 29 and 30) could be inserted into the viscous energy dissipation per unit volume expression as a first pass at modeling these heating effects. At higher temperatures, bremsstrahlung and recombination radiation should probably be taken into account. The viscous heat generation is a self-stimulating process in gases in that a temperature rise increases the viscosity which further increases the heat generation.

The separation ratio (Equation 5) can be written as

$$\alpha = \exp \left((\Delta m / \bar{m}) \int_{r_0}^{r_1} \frac{\mathcal{E}_k}{kT} \frac{dr}{r} \right)$$

where $\mathcal{E}_k = \bar{m} v_\phi^2 / 2$ is the directed rotational kinetic energy per particle. This shows that increasing the directed rotational energy is of no avail for separation if the thermal energy kT goes up proportionately. Hence heating not only increases drag but also reduces separation.

While a scaleup in fields and currents should be performed, the ionization, temperature increase, and viscosity increase should be considered when predicting results.

It is encouraging to note from equations 29 and 30 that the velocity can be scaled up by increasing the magnetic field rather than the current. This may allow achievement of higher velocities without much higher temperatures and higher level of ionization, provided the character of the discharge does not change drastically.

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