Delta J. Sci. 17(3) 1993, 1-21

STEADY COUETTE FLOW OF A RAREFIED GAS CONSISTING OF CHARGED PARTICLES INSIDE POROUS WALLS WITH ARBITRARY REFLECTION COEFFICIENT

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ABSTRACT

Plane steady couette flow problem of rarefied gas law at Mach number is studied in the presence of constant magnetic field and porosity. The reflection coefficient of the upper and lower walls are considered different. The B.G.K. kinetic model has been solved using the moment method with two sided distribution function. The dependence of flow velocity, slip velocity, shear stress and coefficient of viscosity on reflection coefficient is obtained.We shell neglect electric fields arising from the distribution of charged particles and induced magnetic fields.

INTRODUCTION

The flow between two parallel infinite plates or concentric cylinders in relative tangential motion is called couette flow problem. Actually, one of the motives for studying the couette flow is the usefulness in studying boundary layer; it is sufficiently similar and considerably easier to solve. In the last few years, many investigators have been succeeded in obtaining approximate solutions for the plane couette flow of natural rarefied gas, which is suitable for any knudsen number.

The theory of interaction between gases and solid surfaces is far from being in final stage. Many authors such as (Shidlovskiy 1967),(Kogan 1969), (Chapman & Cowling 1970), (Khidr, 1970), (Cercignani 1975), (Hady 1976), (Johnson 1982), (Mahmoud 1985) made successful demonstrations of the gas flow using Boltzmann kinetic equation, specially in the study of Couette compressible flow between two solid parallel walls. Various models have been suggested, but the simplest of them takes the gas-surface interaction in the form of a tangential accommodation coefficient with respect to momentum. Different efforts were done for imposing the conditions at the boundaries, however they were not enough in describing a variety of phenomena that demand further predictions.

In the works of (Hady 1976), Mahmoud (1985) and Abourabia (1988) the equations of transfer were used to describe the problem of Couette flow in rarefied gases with perosity, they open a large area of study to follow this effect.

2. SETTING UP THE PROBLEM

In this paper steady Couette compressible flow between two parallel plates of the gas consists of charged particles moving under constant magnetic field whose components are (o, o, B_0) and with porosity is discussed. We consider also that the reflection coefficients of the upper and lower walls are different.

For simplicity it will be assumed that the flow is gentle i.e the Mach number sufficiently small such that

$M^2 << 1 \quad , \quad M = \sqrt{\alpha_o} U,$

where $\alpha_o = (2RT)^{-1}$, T is the constant temperature at the walls, $U/2$ $(-U/2)$ is the velocity of the upper (lower) wall in the x-direction, d is the distance between the walls and $y=d/2(-d/2)$ is the equation of the upper (lower wall). As well known one of the important factors to investigate the effect of porosity is the gas flows out from the lower and upper walls with velocities $V_1=aU$ and $V_2=b\,U$, $a<0$, $b>0$.

The relevant Boltzmann equation governing the present problem is

$$C_y \frac{\partial f}{\partial y} + \frac{e}{m} \left(B_o C_y \frac{\partial f}{\partial C_x} - B_o C_x \frac{\partial f}{\partial C_y} \right) = I(f) \qquad (1)$$

where I(f) is the usual Boltzmann collision operator. Because shear is assumed to be weak, it is reasonable to linearize the number density distribution function f about the zero-shear maxwellian:

$$f_o = n(\alpha_o/\pi)^{3/2} \exp\{-\alpha_o C^2\} \qquad (2)$$

where n is the constant density number.

To obtain an approximate kinetic-theory solution to eq. (1) one may use the B.G.K equation with which a a molecule tends to relax to local equilibrium after a single collision. Thus

$$C_y\frac{\partial f}{\partial y}+\frac{e}{m}(B_oC_y\frac{\partial f}{\partial C_x}-B_oC_x\frac{\partial f}{\partial C_Y})=I(f)\to\frac{\sqrt{2RT}}{L}(f_o-f) \tag{3}$$

i.e. the processes of transfer of molecular quantities depend appreciably on the mean free path L.

Eq. (3) is nonlinear integrodifferential equation, there are many method for solving it. During the paper we look for a solution of eq. (3) by the approximation method of (Liu & lees 1961). The method starts by replacing the exact distribution function by a two stream Maxwellian. Then we use the moments method to solve eq. (3).

Multiplying both sides of equation (3) by $\Phi_I(\vec{C})$ and integrating over all values of $\vec{C}$ we get for $\Phi_I(\vec{C})$

$$\frac{d}{dy}(\overline{C_y\Phi_I})-\frac{eB_o}{m}(\overline{C_y\frac{\partial\Phi_I}{\partial C_x}})+\frac{eB_o}{m}(C_x\frac{\partial\Phi_I}{\partial C_y})$$
$$=\frac{\sqrt{2RT}}{L}\int\Phi_I(f_0-f)\,d\vec{C} \tag{4}$$

where, for any function of velocity $Q_j(\vec{C})$ we have

$$\overline{Q_j}=\int_{-\infty}^{\infty}\int_{-\infty}^{0}\int_{-\infty}^{\infty}Q_jf^-dC_xdC_ydC_z+\int_{-\infty}^{\infty}\int_{0}^{\infty}\int_{-\infty}^{\infty}Q_jf^+dC_xdC_ydC_z$$

and $f^{\pm}$ is chosen to be:

$$\left.\begin{aligned}f^-&=n(\alpha_o/\pi)^{3/2}(1+V_1C_y/RT)\exp-\alpha_o[(C_x-V_{x1})^2+C_y^2+C_z^2]:C_y<0\\ f^+&=n(\alpha_o/\pi)^{3/2}(1+V_2C_y/RT)\exp-\alpha_o[(C_x-V_{x2})^2+C_y^2+C_z^2]:C_y>0\end{aligned}\right\} \tag{5}$$

Here V_{x1}, V_{x2} are y-dependent parameters determined by the requirement that f satisfies a suitable number of (lower order) moment of the governing equations.

In this paper, we are going to predict the flow velocity function, shear stress and coefficient of viscosity.

3. THE BOUNDARY CONDITIONS

The boundary conditions on each V_{x1} and V_{x2} are obtained from the assumption that a fraction θ_1 of molecules is re-emitted with a Maxwellian distribution, $(1-\theta_1)$ is reflected specularly from the lower plate, that a fraction θ_2 of molecules is re-emitted with a Maxwellian distribution, and $(1-\theta_2)$ is reflected specularly from the upper plate. Using functions (4), it is desired to integrate two equations of the form,

$$f^{\pm}=(1-\theta_{1,2})f^{\mp}+\theta_{1,2}f_{S_{1,2}}$$

with respect to C_x, where

$$f_{S_{1,2}}=n(\alpha_o/\pi)^{3/2}[1+V_{1,2}C_y/RT]\exp\{-\alpha_o[(C_x\pm U/2)^2+C_y^2+C_z^2]\}$$

Hence we obtain at the lower wall in nondimensional form

$$V_{x1}(-1/2)=(1-\theta_2)SV_{x2}(1/2)-\theta_1/2 \qquad (6)$$

and at the upper wall

$$V_{x2}(1/2)=(1-\theta_1)S^{-1}V_{x1}(-1/2)+\theta_2/2 \qquad (7)$$

where y and both $V_{x1,2}, V_{1,2}$ are nondimensionalized with respect to d and U respectively.

The suction factor S is equal to

$S=(1/2+\gamma b/\pi)(1/2-\gamma a/\pi)^{-1}$

where $\gamma=\frac{U}{2}\sqrt{\frac{2\pi}{RT}}$ is the same order of Mach number.

The solution of the system of equations (6),(7) are obtained in terms of the arbitrary coefficients θ_1,θ_2 and S as follows;

$$V_{x1}(-1/2)=[\theta_2(1-\theta_2)S-\theta_1][2(\theta_1+\theta_2-\theta_1\theta_2)]^{-1} \quad (8)$$

$$V_{x2}(1/2)=[\theta_2 S-(1-\theta_1)\theta_1][2S(\theta_1+\theta_2-\theta_1\theta_2)]^{-1} \quad (9)$$

4. THE CHARACTERISTICS OF THE FLOW

In this section the determination of V_{x1} and V_{x2} are obtained by putting

$\phi_1=C_x$, $\phi_2=C_xC_y$ in eq. (4)

when $\phi_1=C_x$ eq. (4) becomes in the following nondimensional form

$$\frac{d}{dy}[(V_{x2}-V_{x1})+\gamma(aV_{x1}-bV_{x2})]=\gamma\beta(a-b) \quad (10)$$

when $\phi_i=C_xC_y$, eq. (4) becomes in the nondimensional form

$$\frac{d}{dy}[1/2(V_{x2}+V_{x1})-\frac{\gamma}{\pi}(aV_{x1}+bV_{x2})]+$$

$$+\frac{\beta\gamma^2}{\pi}(V_{x1}^2+V_{x2}^2)\frac{-2\beta\gamma^3}{\pi^2}(aV_{x1}^2+bV_{x2}^2)+\frac{\gamma\beta}{\pi}(a+b)$$

$$=-\delta[(V_{x2}-V_{x1})+\gamma(aV_{x1}-bV_{x2})] \quad (11)$$

where $\beta=\frac{eB_o d}{mU}$ is a constant related to magnetic field, and $\delta=\frac{d}{L\sqrt{\pi}}$ is the degree of rarefaction.

We shall solve eq.s (10) and (11) by using the method of small parameter. Considering γ sufficiently small such that $\gamma^2<<1$, we seek the solution in the form

$$V_{xi}=V_{xi}^{(o)}+\gamma V_{xi}^{(1)}$$

On substituting these values in eq.s(10), (11) and equating the terms free of γ on both sides of these equations, we get two equations by solving it simultaneously using the boundary conditions, we obtain:

$$V_{x1}^{(o)}=-\delta C_1 y+C_3-\frac{C_1}{2} \quad , \tag{12}$$

$$V_{x2}^{(o)}=-\delta C_1 y+C_3+\frac{C_1}{2} \quad , \tag{13}$$

where

$$C_1=\frac{(\theta_1^2+\theta_2^2)}{8(1-\delta)(\theta_1+\theta_2-\theta_1\theta_2)} \quad , \tag{14}$$

$$C_3=\frac{(\theta_2-\theta_1)(1-\theta_1-\theta_2)}{16(\theta_1+\theta_2-\theta_1\theta_2)} \tag{15}$$

Then equating the coefficients of γ on both sides we have ;

$$V_{x1}^{(1)}=-\frac{\delta}{2}(a-b)\beta y^2-[\frac{(a+b)}{\pi}(\beta+\delta C_1)+\delta C_2+(\delta C_1+\beta)\frac{(a-b)}{2}]y$$

$$+[\frac{2(a+b)+\pi(a-b)}{2\pi}]C_3-[\frac{2(a-b)+\pi(a+b)}{4\pi}]C_1+C_4-\frac{1}{2}C_2 \qquad (16)$$

$$V_{x2}^{(1)}=-\frac{\delta}{2}(a-b)\beta y^2+[\frac{(a-b)}{2}(\delta C_1+\beta)-\frac{(a+b)}{\pi}(\beta+\delta C_1)-\delta C_2]y$$

$$+[\frac{2(a+b)-\pi(a-b)}{2\pi}]C_3+[\frac{\pi(a+b)-2(a-b)}{4\pi}C_1+C_4+\frac{1}{2}C_2 \qquad (17)$$

where

$$C_4=\{(a-b)(\theta_1-\theta_1^2+\theta_2^2)]\}[8\pi(\theta_1+\theta_2-\theta_1\theta_2)]^{-1}-[\frac{(a+b)}{\pi}]C_3$$

$$+[\beta(a-b)(\delta-2)/8]+[(a-b)(2-\pi\delta)/4\pi]C_1 \qquad (18)$$

and

$$C_2=\{(a-b)(2\theta_2-\theta_1-\theta_2^2+\theta_1^2)\}[4\pi(1-\delta)(\theta_1+\theta_2-\theta_1\theta_2)]^{-1}$$

$$+[\beta(a+b)/\pi(\delta-1)]+[(a+b)(2\delta+\pi)/2\pi(\delta-1)]C_1$$

$$-[(a-b)/(\delta-1)]C_3 \qquad (19)$$

5. DISCUSSION OF THE RESULTS

From the above results we get the macroscopic velocity V` of the flow form:

$$V=\frac{(\pi+2\gamma a)}{2\pi}(-\delta C_1 y+C_3-\frac{1}{2}C_1)+\frac{(\pi+2\gamma b)}{2\pi}(-\delta C_1 y+C_3+\frac{1}{2}C_1)+$$

$$+\frac{\gamma}{2}[-\delta(a-b)\beta y^2+(\delta C_1+\beta)(a-b)y-2\delta C_2 y+\frac{2(a+b)}{\pi}C_3$$

$$-\frac{(a-b)}{\pi}C_1+2C_4] \qquad (20)$$

The normal velocity of the flow is

$$V_y=\frac{1}{2}(a+b) \qquad (21)$$

Delta J. Sci. 17 (3) 1993
Mahmoud, M. A.

The shear stress P_{xy} is in the form:

$$P_{xy}=\frac{1}{4}(a-b)C_1+\frac{\gamma(a+b)}{2\pi}\{-\delta C_1(a-b)y+(a-b)C_3-\frac{C_1}{2}(a+b)\}$$

$$+\frac{(a-b)}{4}\gamma[(\delta C_1+\beta)(a-b)y-(a-b)C_3+\frac{(a+b)}{2}C_1+C_2] \quad (22)$$

and the coefficient of viscosity is in the form:

$$\mu=\{\frac{(a-b)}{4}C_1+\frac{\gamma(a+b)}{2\pi}[-\delta C_1(a-b)y+(a-b)C_3-\frac{C_1}{2}(a+b)]$$

$$+\frac{(a-b)\gamma}{4}[(\delta C_1+\beta)(a-b)y-(a-b)C_3+\frac{(a+b)}{2}C_1+C_2]\}/$$

$$/\{\frac{-\delta C_1}{2\pi}(\pi+2\gamma a)-\frac{\delta C_1}{2\pi}(\pi+2\gamma b)+\frac{\gamma}{2}[-2\delta\beta(a-b)y$$

$$+(\delta C_1+\beta)(a-b)-2\delta C_2]\} \quad (23)$$

The situation studied here is a matter of proper condition that are imposed at the boundaries. We shall discuss the dependence of the flow velocity function, shear and coefficient of viscosity on the normal velocity, degree of rarefaction, magnetic field and reflection coefficient. We have the following cases;

(i) For non porous plates, for arbitrary degree of rarefaction δ , the nondimensionless velocity and shear stress are given by:

$$V=-\delta C_1 y+C_3$$

$$P_{xy}=0$$

(ii) For porous plates and free molecular flow $K_n\to\infty$ (when the collision may be meglected $\delta=0$) the dimensionless slip velocity and shear stress are given by:

$$V_s=1/2-\acute{V}(1/2)$$

$$=\frac{1}{2}-\frac{(\theta_2-\theta_1)(2-\theta_1-\theta_2)}{4(\theta_1+\theta_2-\theta_1\theta_2)}+\frac{\gamma(a-b)(\theta_1^2+\theta_2^2)}{4\pi(\theta_1+\theta_2-\theta_1\theta_2)}-\frac{\gamma(a+b)(8\theta_2-4\theta_1-5\theta_2^2+\theta_1^2)}{4\pi(\theta_1+\theta_2-\theta_1\theta_2)},$$

$$P_{xy}=[\frac{1}{4}(a-b)-\frac{(a-b)^2}{4\pi}\gamma+\frac{(a^2-b^2)}{8}\gamma]\frac{(\theta_1^2+\theta_2^2)}{2(\theta_1+\theta_2-\theta_1\theta_2)}$$

$$+[\frac{\gamma(a^2-b^2)}{2\pi}-\frac{(a-b)^2\gamma}{4}]\frac{(\theta_2-\theta_1)(2-\theta_1-\theta_2)}{4(\theta_1+\theta_2-\theta_1\theta_2)}+\frac{\beta(a-b)^2}{4}\gamma y$$

$$+\frac{(a-b)\gamma}{4}[\frac{(a+b)(\theta_1-\theta_2-\theta_1^2+\theta_2^2)}{\pi(\theta_1+\theta_2-\theta_{1_2})}+\frac{\beta(a+b)}{\pi}-\frac{(a+b)(\theta_1^2+\theta_2^2)}{2(\theta_1+\theta_2-\theta_1\theta_2)}+\frac{(a-b)(\theta_2-\theta_1)(2-\theta_1-\theta_2)}{4(\theta_1+\theta_2-\theta_1\theta_1\theta_2)}]$$

(iii) For porous plates, continuous gas, $K_n\to 0$ (when $\delta\to\infty$) and in the absence of magnetic field the non-dimensional slip velocity and shear stress are given by:

$$V_s=\frac{1}{2}-\acute{V}(\frac{1}{2})=\frac{1}{2}-\frac{\gamma(a+b)(\theta_1+\theta_2-\theta_1^2-\theta_2^2)}{\pi(\theta_1+\theta_2-\theta_1\theta_2)}-\frac{(\theta_2-\theta_1)(2-\theta_1-\theta_2)}{4(\theta_1+\theta_2-\theta_1\theta_2)}$$

$$P_{xy}=\gamma[\frac{(a^2-b^2)}{2\pi}-\frac{(a-b)^2}{4}]\frac{(\theta_2-\theta_1)(2-\theta_1-\theta_2)}{4(\theta_1+\theta_2-\theta_1\theta_2)}.$$

(iv) For porous plates and for any δ, the slip velocity at the upper plate is given by:

$$V_S=\frac{1}{2}+\frac{(\pi+2\gamma a)}{4\pi}(\delta C_1+C_1-2C_3)-\frac{(\pi+2\gamma b)}{4\pi}(-\delta C_1+C_1+2C_3)+$$
$$+\frac{\gamma\delta\beta}{8}(a-b)-\frac{\gamma}{4}(\delta C_1+\beta)(a-b)+\frac{\gamma\delta}{2}C_2-\frac{\gamma(a-b)}{\pi}C_3$$
$$+\frac{\gamma(a-b)}{2\pi}C_1-\gamma C_4 \qquad (24)$$

(v) In the absence of porosity and magnetic field we have two limiting cases arise:

(1) The very dilute gas $K_n\to\infty(\delta\to 0)$ eq. (20) gives $V'(y)=V_0$. where V_0 is an arbitrary constant.

(2)The very dense gas, the continuous gas, $K_n\to 0(\delta\to\infty)$ gives from eq. (20) $V'(y)=y+V_0$.

This shows that the flow velocity is linear. The cases(1),(2) agree respectively with the Zeroth-approximation-the knudsen collissionless gas-and the first approximation- the Navier stokes equations of the hydrodynamic equations for hard sphere model in a continuous gas derived erom the Boltzmann equation.

6.CONCLUSIONS

The values of velocity, shear stress and slip velocity are calculated from formula (20),(22) and (24) when the parameters take the following values and for different value of θ_1,θ_2. The results are given in Figures (1-9), these results gives:

1. (i) If the reflection coefficient is the same

$\theta_1=\theta_2=\theta$, the slip velocity at the upper plate $V_s(\frac{1}{2})$ increases as θ increases for any degree of rarefaction δ, and it increases with the increase of δ for any constant θ, as it may be shown in Fig.(1)

(ii) From Fig.(2) we see that the slip velocity increases as the difference between the reflection coefficient of the two plates $(\theta=\theta_1-\theta_2)$ increases for any constant δ, and it increases with the increase with the increase of δ for any constant θ.

(iii) The slip velocity increases as the increase of the ratio a/b for constant δ and θ, and it increases with the increase of δ for constant a/b and θ, as it may be shown in Fig.(3).

2. (i) If the reflection coefficient is the same $(\theta_1=\theta_2=\theta)$, the magnitude of shear stress P_{xy} increases as θ increases for any constant y, and it decreases as y increases for any constant θ [see Fig. 4].

(ii) From Fig.(5), we see that the magnitude of shear stress increases as the increase of δ for constant y and θ, and it decreases with the increase of y from the lower plate for constant δ and θ.

(iii) The magnitude of shear stress P_{xy} decreases as the increase of the ratio a/b for constant y and θ, and it decreases with the increase of y for constant a/b and θ, as it may be shown in Fig. (6).

3.(i) If the reflection coefficient is the same ($\theta_1=\theta_2=\theta$), the magnitude of the flow velocity V' increases with the increase of θ for constant y, and it decreases with the increase of y from the lower plate for constant θ, as it may be shown in Fig.(7).

(ii) From Fig. [8], we see that the magnitude of flow velocity increases as δ increases for any constant y and it decreases as y increases for any constant δ and θ.

(iii) The magnitude of flow velocity decreases as the increase of y for constant a/b and it increases with the increase of a/b for constant y and θ, see Fig.(9).

FIGURG CAPTIONS:

Fig. (1)-The relation between the slip velocity V_S and the degree of rarefaction δ for the same values of θ_1, θ_2, and β (constant related to the magnetic field)=0.001.

Fig. (2)-The relation between the slip velocity V_S and the degree of rarefaction δ for different values of θ_1, θ_2 (reflection Coefficients) and β=0.001.

Fig. (3)-The relation between the slip velocity V_S and δ for different values of a/b (ratio of suction), β=0.001 and θ_1=θ_2=0.8°

Fig. (4)-The relation between the shear stress P_{xy} and the distance y for the same values of θ_1, θ_2, δ=0.4 and β=0.001.

Fig. (5)- The relation between the shear stress P_{xy} and the distance y for different values of δ, β=0.001 and θ_1=θ_2=0.5.

Fig. (6)- The relation between the shear stress P_{xy} and the distance y for different values of a/b, δ=0.5, β=0.001 and θ_1=θ_2=0.5.

Fig. (7)- The relation between the flow velocity V' and distance y for the same values θ_1, θ_2, β=0.001 and δ=0.5

Fig. (8)- The relation between the flow velocity V' and the distance y for different values of δ, β=0.001 and θ_1=θ_2=0.5.

Fig. (9)- The relation between the flow velocity V' and the distance y for different values of a/b, β=0.001, δ=0.5 and θ_1=θ_2=0.5.

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Delta J. Sci. 17 (3) 1993

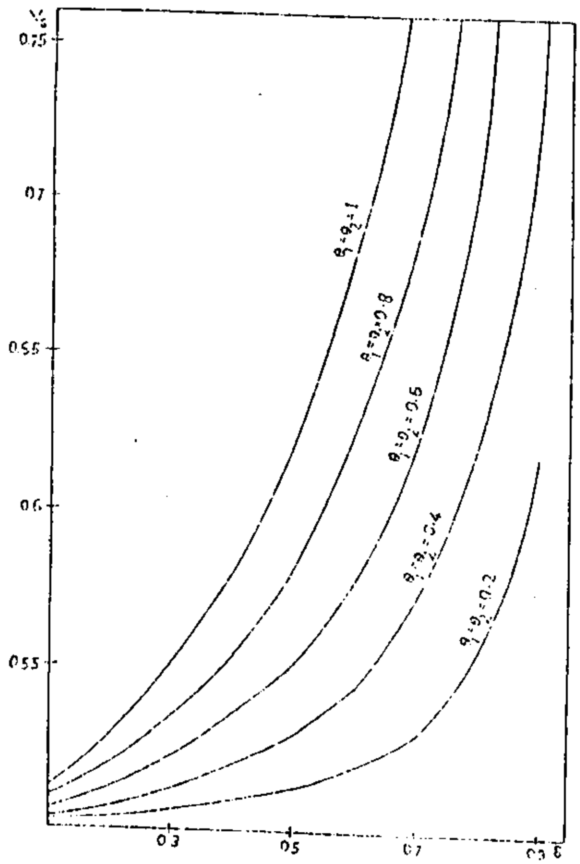
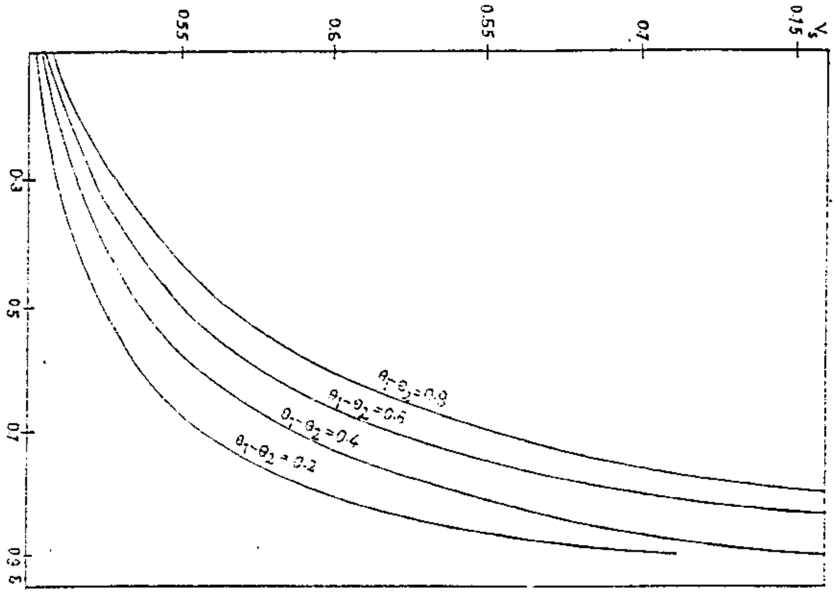


Fig (I)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0.5
0.7
0.9
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$\theta_1-\theta_2=0.4$
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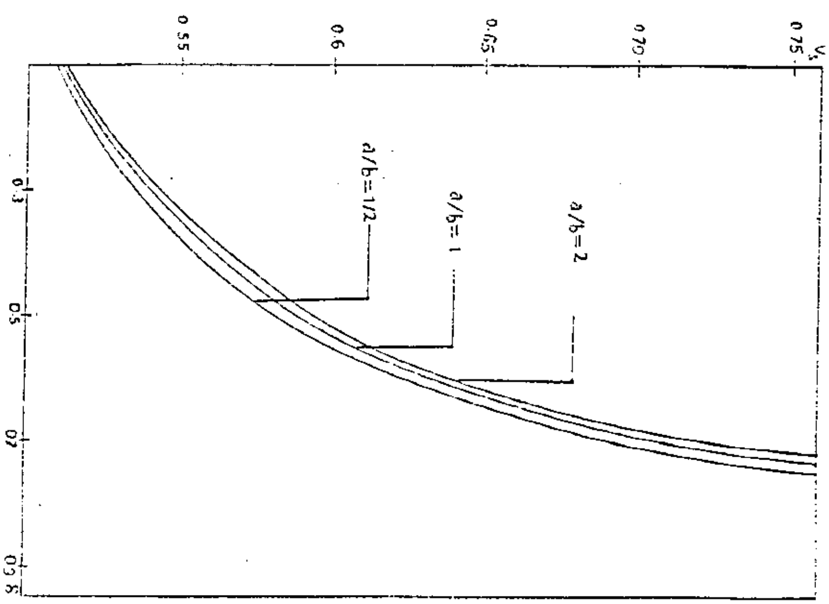
Fig(2)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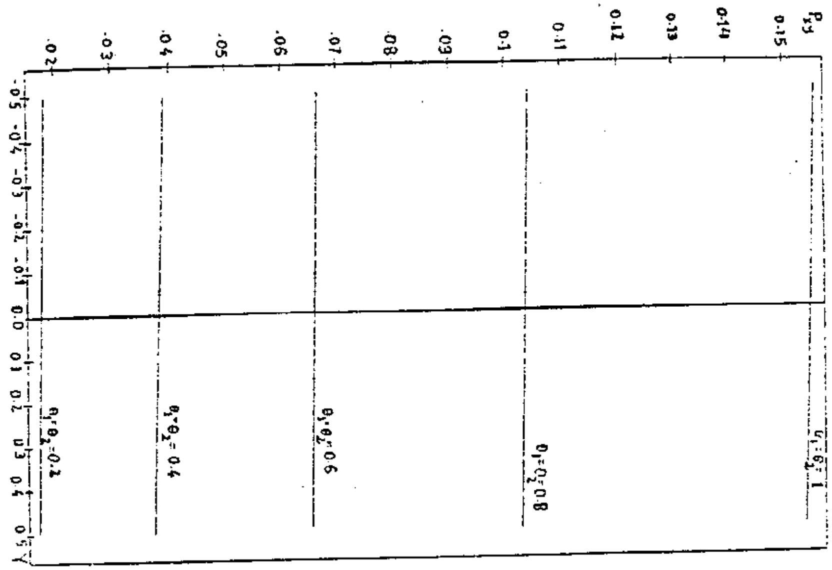
a/b=2

Fig(3)


P_{xy}
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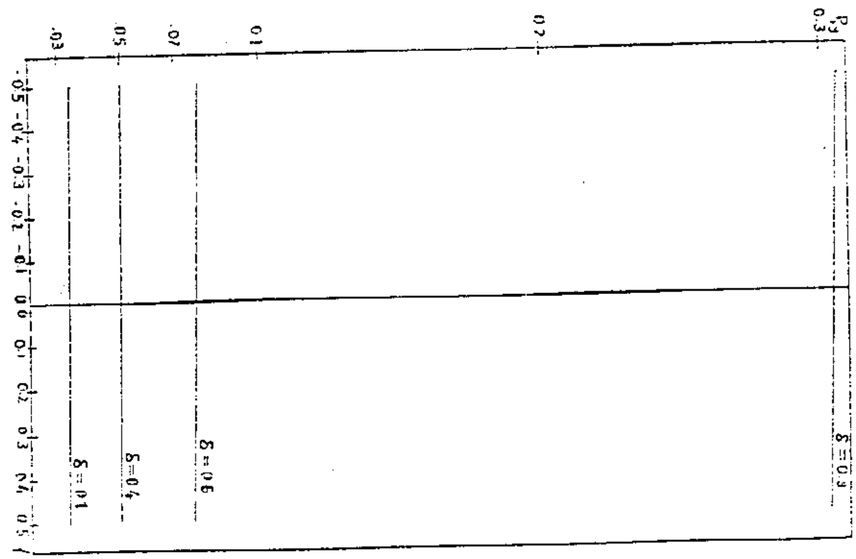
$\theta_1=\theta_2=0.4$
$\theta_1=\theta_2=0.6$
$\theta_1=\theta_2=0.8$
$\theta_1=\theta_2=1$

Fig(4)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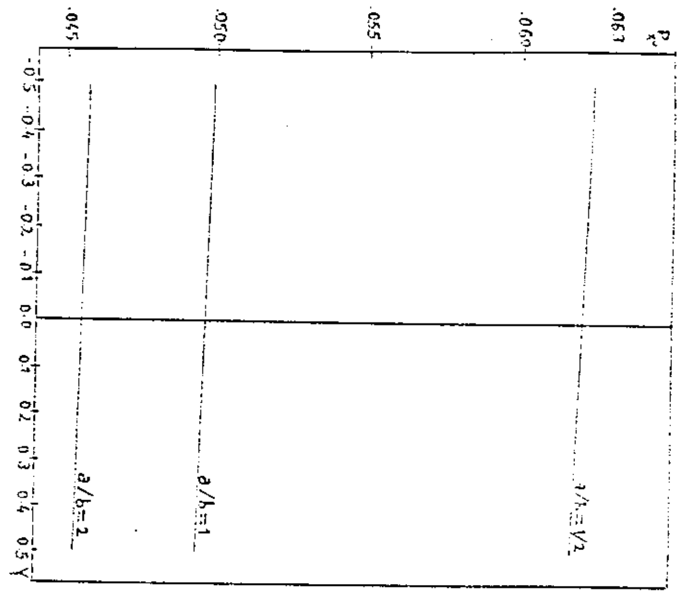
$\delta=0.9$

Fig(5)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.055
.060
.063
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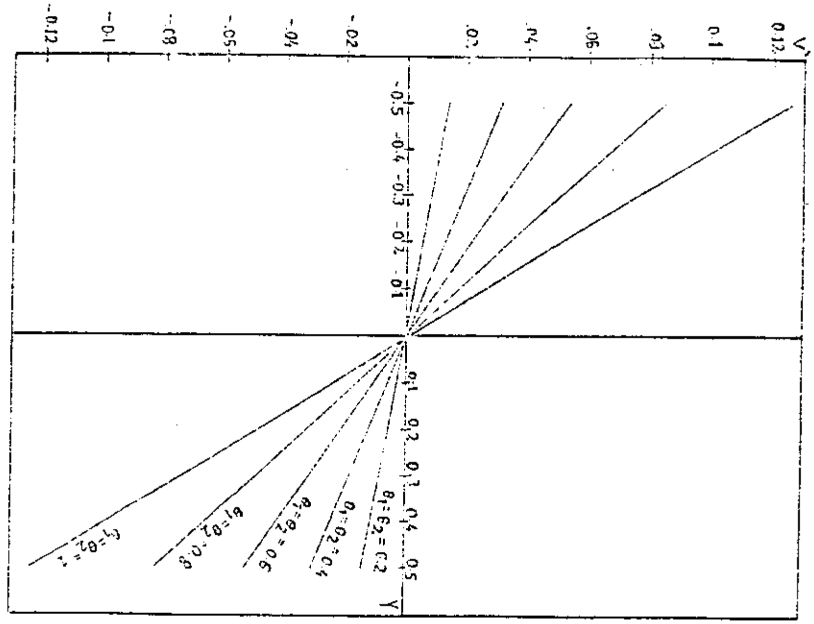
a/b=1
a/b=1/2

Fig.(6)


V
Y
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-0.1
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-.06
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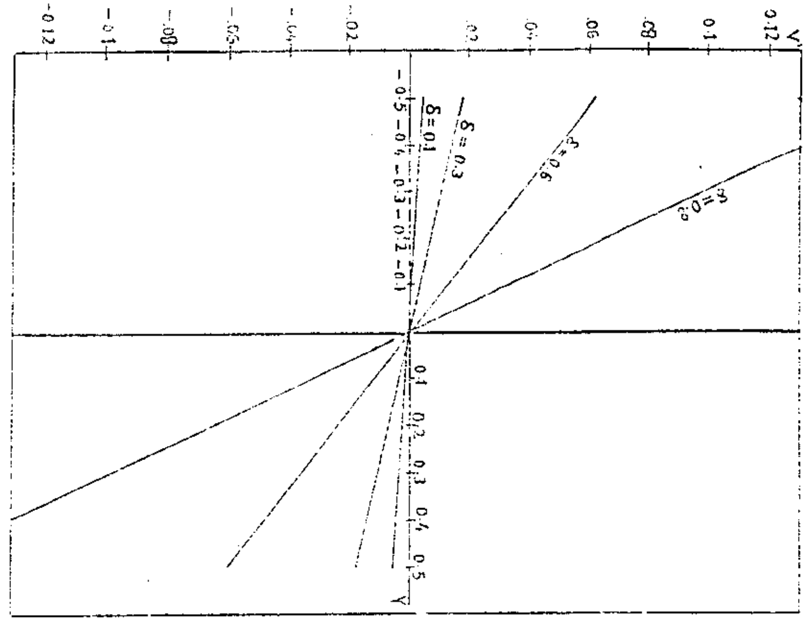
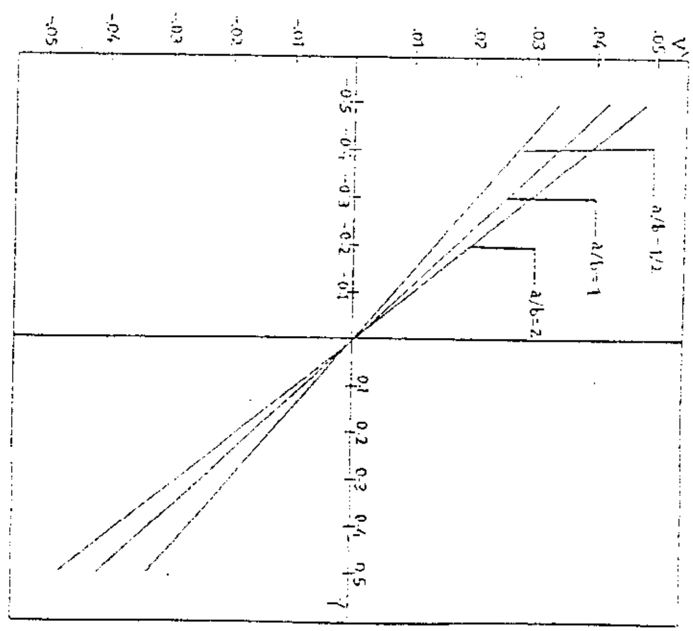
.06
.08
0.1
0.12

Fig(7)

Delta J. Sci. 17 (3) 1993



Fig(8)



Fig(9)

انسياب كوبت المنتظم لغاز مخلخل مكون من جسيمات مشحونةبين لوحين مساميين مع وجود معامل انعكاس اختيارى

محمود عبد العاطى محمود
كلية العلوم ببنها - جامعة الزقازيق
قسم الرياضيات

فى هذا البحث تم دراسة مسألة انسياب كوبت المنتظم لغاز مخلخل عند عدد منخفض لمساخ فى وجود مجال مغناطيسى ثابت ووجود مسامية فى اللوحين. مع اعتبار أن معاملى الانعكاس فى كل من اللوحين العلوى والسفلى مختلفين. وقد تم حل معادلة كرووك للحركة باستخدام طريقة العزوم مع وجود دالتى التوزيع الجانبية. وقد حصلنا على سرعة انسياب المائع والسرعة الانزلاقية وقوة القص وأيضا معامل الانزلاق كدالة فى معامل الانعكاس.

وهنا يجب ملاحظة أننا أهملنا المجال الكهربائى الناشئ من توزيع الجسيمات المشحونة وأيضا المجال الكهربائى الناشئ من تأثير المجال المغناطيسى.