Steady Plane Poiseuille Flow of Viscous Incompressible Fluid Between two Porous Parallel Plates in Magnetic Field

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ABSTRACT
In this paper we have investigated the steady plane poiseuille flow of viscous incompressible fluid between two porous parallel plates in magnetic field. We have studied the velocity, average velocity, shearing stress, skin frictions, the volumetric flow, drag coefficients and stream lines.

Formulation of Problem
Let us consider two infinite porous plates AB & CD separated by a distance 2h. The fluid enters in y-direction. The velocity component along x-axis is a function of y only. The motion of incompressible fluid is in two dimension and is steady then

\[ u = u(y), \quad w = 0 \quad \text{and} \quad \frac{\partial}{\partial t} = 0 \]
The equation of continuity for incompressible fluid
\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]

Put \( w = 0 \),
\[ \frac{\partial u}{\partial x} = 0 \quad \text{&} \quad \frac{\partial v}{\partial y} = 0 \]

\( v \) is independent of \( y \) but motion along \( y \)-axis. So we can say \( v \) is constant

Velocity i.e. \( v = v_0 \) or The fluid enters the flow region through one plate at the same constant velocity \( v_0 \)

Also Navier-Stoke's equations for incompressible fluid in the absence of body force when flow is steady
\[ v_0 \frac{du}{dy} = -\frac{1}{\rho} \frac{dp}{dx} + v \frac{d^2u}{dy^2} + \frac{\sigma B_0^2 \nu u}{\mu} \quad \text{..... (1)} \]
\[ -\frac{1}{\rho} \frac{dp}{dy} = 0 \quad \text{...... (2)} \]

**Solution of the problem**

Equation (2) Shows that the pressure does not depend on \( y \) hence \( p \) is a function of \( x \) only and so (1) reduces to
\[ \frac{dp}{dx} = \rho \left[ v \frac{d^2u}{dy^2} - v_0 \frac{du}{dy} + \frac{\sigma B_0^2 \nu u}{\mu} \right] \]
\[ \Rightarrow \frac{d^2u}{dy^2} - \frac{v_0}{v} \frac{du}{dy} + \frac{\sigma B_0^2 \nu u}{\mu} = -\frac{P}{\mu} \]

\[ \Rightarrow \left( D^2 - \frac{v_0}{v} D + \frac{\sigma B_0^2 \nu}{\mu} \right) u = -\frac{P}{\mu} \]

\[ A.E \left( m^2 - \frac{v_0}{v} m + \frac{\sigma B_0^2 \nu}{\mu} \right) = 0 \]
\[ \Rightarrow \quad m = \frac{v_0}{v} \pm \frac{1}{2} \sqrt{\left( \frac{v_0}{v} \right)^2 - \frac{4 \sigma B_0^2 \nu}{\mu}} \quad = \frac{v_0}{2v} \pm \frac{1}{2} \sqrt{\left( \frac{v_0}{2v} \right)^2 - \frac{\sigma B_0^2 \nu}{\mu}} \]

\[ C.F. = e^{\frac{v_0}{2v} y} \left[ c_1 \cosh Ay + c_2 \sinh Ay \right] \quad P.I. = -\frac{P}{\sigma B_0^2} \]

here \( A = \sqrt{\left( \frac{v_0}{2v} \right)^2 - \frac{\sigma B_0^2 \nu}{\mu}} \quad \text{and} \quad B = \frac{\sigma B_0^2 \nu}{\mu} \)

\[ u(y) = e^{\frac{v_0}{2v} y} \left[ c_1 \cosh Ay + c_2 \sinh Ay \right] - \frac{P}{B \mu} \]

using boundary conditions:
\[ u = 0 \text{ at } y = -h \text{ and } u = U \text{ at } y = h \]
\[ e^{-\frac{v_0}{2v} h} \left[ c_1 \cosh Ah - c_2 \sinh Ah \right] - \frac{P}{B \mu} = 0 \quad \text{..... (3)} \]
\[ U = e^{\frac{v_0}{2v} h} \left[ c_1 \cosh Ah + c_2 \sinh Ah \right] - \frac{P}{B \mu} \quad \text{..... (4)} \]

or \[ \frac{P}{B \mu} e^{\frac{v_0}{2v} h} = c_1 \cosh Ah - c_2 \sinh Ah \]
\[ \left( U + \frac{P}{B \mu} \right) e^{-\frac{v_0}{2v} h} = c_1 \cosh Ah + c_2 \sinh Ah \]
\[ c_1 = \frac{1}{2Cosh Ah} \left[ \left( U + \frac{P}{B\mu} \right) e^{-\frac{\nu_0 h}{2\nu}} + \frac{P}{B\mu} e^{\frac{\nu_0 h}{2\nu}} \right] \]

\[ c_2 = \frac{1}{2Sinh Ah} \left[ \left( U + \frac{P}{B\mu} \right) e^{-\frac{\nu_0 h}{2\nu}} - \frac{P}{B\mu} e^{\frac{\nu_0 h}{2\nu}} \right] \]

\[ u(y) = \frac{e^{\frac{\nu_0 y}{2\nu}} Cosh Ay}{2Cosh Ah} \left\{ \left( U + \frac{P}{B\mu} \right) e^{-\frac{\nu_0 h}{2\nu}} + \frac{P}{B\mu} e^{\frac{\nu_0 h}{2\nu}} \right\} \]

\[ + \frac{e^{\frac{\nu_0 y}{2\nu}} Sinh Ay}{2Sinh Ah} \left\{ \left( U + \frac{P}{B\mu} \right) e^{-\frac{\nu_0 h}{2\nu}} - \frac{P}{B\mu} e^{\frac{\nu_0 h}{2\nu}} \right\} - \frac{P}{B\mu} \]

\[ u(y) = \left( U + \frac{P}{B\mu} \right) e^{\frac{\nu_0 y}{2\nu}(y-h)} \frac{Sinh A(y+h)}{2Sinh Ah \ Cosh Ah} - \frac{P}{B\mu} \]

\[ u(y) = \frac{1}{Sinh 2Ah} \left[ \left( U + \frac{P}{B\mu} \right) e^{\frac{\nu_0 y}{2\nu}(y-h)} \frac{SinhA(y+h)}{2Sinh Ah \ Cosh Ah} - \frac{P}{B\mu} \right] \]

Plane Poiseuille flow : In this case both plates are at rest so \( U = 0 \)

\[ u(y) = \frac{1}{Sinh 2Ah} \left[ \left( \frac{P}{B\mu} \right) e^{\frac{\nu_0 y}{2\nu}(y-h)} \frac{SinhA(y+h)}{2Sinh Ah \ Cosh Ah} - \frac{P}{B\mu} \right] \]

\[ \therefore u(y) = \frac{P}{B\mu \ Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Sinh A(y+h) + \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Cosh A(y+h) \right\} \]

\[ - \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Sinh A(y-h) - \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Cosh A(y-h) \]

\[ \sigma_{xy} = \frac{\mu \frac{du}{dy}}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \frac{Sinh A(y+h)}{2Sinh 2Ah} + A \left( Cosh 2Ah - e^{\frac{\nu_0 y}{2\nu}} \right) \right\} \]

\[ - \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \frac{Sinh A(y-h)}{2Sinh 2Ah} - A \left( e^{\frac{\nu_0 y}{2\nu}} - Cosh 2Ah \right) \]

\[ + \frac{PA}{B Sinh 2Ah} \left\{ e^{\frac{\nu_0 y}{2\nu}(y-h)} Cosh A(y+h) - e^{\frac{\nu_0 y}{2\nu}(y-h)} Cosh A(y-h) \right\} \]

\[ \sigma_{xy} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Sinh 2Ah + ACosh 2Ah - e^{\frac{\nu_0 y}{2\nu}} \right\} \]

\[ \sigma_{xy} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} Sinh 2Ah - ACosh 2Ah + e^{\frac{\nu_0 y}{2\nu}} \right\} \]

Shearing stress at any point

Skin friction at lower & upper plates

\[ \left( \sigma_{xy} \right)_{y=h} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \right\} \]

\[ \left( \sigma_{xy} \right)_{y=-h} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \right\} \]

\[ \left( \sigma_{xy} \right)_{y=-h} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \right\} \]

\[ \left( \sigma_{xy} \right)_{y=-h} = \frac{P}{B Sinh 2Ah} \left\{ \frac{\nu_0 e^{\frac{\nu_0 y}{2\nu}(y-h)}}{2\nu} \right\} \]
The average velocity distribution in poiseuille flow:

\[
\begin{align*}
\bar{u} &= \frac{1}{2h} \int_{-h}^{h} u(y) \, dy \\
&= \frac{P}{2B \mu h \sinh 2Ah} \int_{-h}^{h} \left[ e^{2B(y-h)} \sinh A(y + h) - e^{2B(y-h)} \sinh A(y - h) - \sinh 2Ah \right] \, dy
\end{align*}
\]

Now Let

\[
I_1 = \int_{-h}^{h} e^{2B(y-h)} \sinh A(y + h) \, dy
\]

\[
I_2 = \int_{-h}^{h} \left( e^{2B(y-h)} + e^{-2B(y-h)} \right) \, dy
\]

\[
I_3 = \int_{-h}^{h} \sinh 2Ah \, dy = 2h \sinh 2Ah
\]

\begin{align*}
\therefore \bar{u} &= \frac{P}{2B \mu \sinh 2Ah} \left[ I_1 - I_2 - I_3 \right] \\
&= \frac{P}{2B^2 \mu h \sinh 2Ah} \left[ \frac{v_0}{2v} \sinh 2Ah - A \cosh 2Ah + A e^{-v_0h} - \frac{v_0}{2v} \sinh 2Ah - A \cosh 2Ah + A e^{-v_0h} - 2hB \sinh 2Ah \right]
\end{align*}

The volumetric flow \( Q = 2h \bar{u} \)

\[
Q = \frac{2P}{B^2 \mu h \sinh 2Ah} \left[ A \left( \cosh \frac{v_0}{v}h - \cosh 2Ah \right) - Bh \sinh 2Ah \right] \quad \text{...... (11)}
\]

The Drug coefficients: \( C_f \) & \( C_f' \) at \( y = h \) & \( y = -h \)

\[
C_f = \frac{1}{2} \frac{(\sigma_{xy})_{y=h}}{\rho \bar{u}^2} \left[ \frac{v_0}{2v} \sinh 2Ah + A \cosh 2Ah - \frac{v_0}{2v}h \right] \left[ A \left( \cosh \frac{v_0}{v}h - \cosh 2Ah \right) - Bh \sinh 2Ah \right] \quad \text{...... (12)}
\]
\[ C_f = \left( \sigma_{xy} \right)_{y=-h} = \frac{2B^2 \mu^2 h^2 \sinh 2Ah}{\frac{1}{2} \rho(u_{av})^2} \left[ \frac{v_0}{2\nu} \sin 2Ah - A \cosh 2Ah + Ae^{\frac{v_0}{2\nu}h} \right] \]

\[ \frac{v_0}{2\nu} \cosh 2Ah - \frac{v_0}{2\nu} h - \cosh 2Ah \]

\[ ......(13) \]

The streamline in the plane poiseuille flow:

\[ \frac{P}{B \mu \sinh 2Ah} \left\{ e^{2B(y-h)} \sinh A(y) - e^{2B(y+h)} \sinh A(y-h) - 2Ah \right\} = \frac{dy}{v} = \frac{dz}{w} \]

Taking first two

\[ v_0 B\mu \sinh 2Ah \]

\[ x - \int \left\{ e^{2B(y-h)} \sinh A(y+h) - e^{2B(y+h)} \sinh A(y-h) - 2Ah \right\} dy = C_1 \]

\[ \text{Let } I_1 = \int e^{2B(y-h)} \sinh A(y+h) dy \]

\[ I_1 = \frac{1}{2} \left[ \frac{v_0}{2\nu} + A(y+h) - \frac{v_0}{2\nu} A(y+h) \right] \]

\[ = e^{2B(y-h)} \left( \frac{v_0}{2\nu} - A \right) e^{A(y+h)} - \frac{v_0}{2\nu} e^{-A(y+h)} \]

\[ \text{Since } \left( \frac{v_0}{2\nu} \right)^2 - A^2 = B \]

\[ = e^{2B(y-h)} \left( \frac{v_0}{2\nu} \sinh A(y+h) - A \cosh A(y+h) \right) \]

\[ I_2 = \int e^{2B(y-h)} \sinh A(y-h) dy = e^{2B(y-h)} \left( \frac{v_0}{2\nu} \sinh A(y-h) - A \cosh A(y-h) \right) \]

\[ I_3 = \int \sinh 2Ah \cdot dy = y \cdot \sinh 2Ah \]

\[ \therefore \text{ First streamline.} \]

\[ v_0 B\mu \sinh 2Ah \]

\[ x - \{ I_1 - I_2 - I_3 \} = C_1 \]

\[ \Rightarrow \frac{v_0}{2\nu} \left\{ \frac{v_0}{2\nu} \sinh A(y+h) - A \cosh A(y+h) \right\} \]

\[ + \frac{v_0}{2\nu} \left\{ \frac{v_0}{2\nu} \sinh A(y-h) - A \cosh A(y-h) \right\} + y \sinh 2Ah = C_1 \]

\[ ......(14) \]

Second streamline

\[ z = c_2 ......(15) \]

Clearly the curl \[ \vec{q} \neq 0 \]

\[ \therefore \text{ the fluid is Rotational} \]

Table for velocity: when \( y & A \) are vary and other are fixed

\[ \begin{array}{c}
\text{let} & K = 9, \quad \mu = 0.5, \quad \frac{v_0}{2\nu} = 6, \quad h = 0.5, \quad \sqrt{\left( \frac{v_0}{2\nu} \right)^2 - \frac{\sigma B_0^2}{\mu}} = A \quad \text{where} \quad \frac{\sigma B_0^2}{\mu} = B
\end{array} \]
Let $K = 9$, $\mu = .5$, $\frac{V_0}{2V} = 6$, $h = .5$, and $\sqrt{\frac{V_0}{2V}} - \frac{\sigma B_0^2}{\mu} = A$ where $\frac{\sigma B_0^2}{\mu} = B$.

Table 1

<table>
<thead>
<tr>
<th>y</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
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<tbody>
<tr>
<td>1</td>
<td>4.08</td>
<td>6.09</td>
<td>8.43</td>
<td>10.31</td>
<td>9.44</td>
<td>0</td>
<td>-31.67</td>
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<tr>
<td>2</td>
<td>3.11</td>
<td>4.5</td>
<td>6.07</td>
<td>7.29</td>
<td>6.6</td>
<td>0</td>
<td>-22.26</td>
</tr>
<tr>
<td>3</td>
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<td>3.03</td>
<td>3.93</td>
<td>4.59</td>
<td>4.09</td>
<td>0</td>
<td>-13.92</td>
</tr>
<tr>
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<td>2.43</td>
<td>0</td>
<td>-8.41</td>
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<tr>
<td>5</td>
<td>1.05</td>
<td>1.31</td>
<td>1.56</td>
<td>1.69</td>
<td>1.45</td>
<td>0</td>
<td>-5.178</td>
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Table 2

<table>
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<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
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<tbody>
<tr>
<td>1</td>
<td>8.83</td>
<td>11.18</td>
<td>11.62</td>
<td>5.44</td>
<td>-18.66</td>
<td>-86.39</td>
<td>-254.45</td>
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<tr>
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<td>7.695</td>
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<td>-60.3</td>
<td>-180.09</td>
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<tr>
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<tr>
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<td>.107</td>
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<td>-13.24</td>
<td>-44</td>
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</table>
Case 2: when  \( \frac{1}{K} > \frac{\sigma B_0^2}{\mu} \) let  \( \frac{1}{K} = 35 \) i.e \( A = 1 \) and  \( B = \frac{\sigma B_0^2}{\mu} = 20 \) i.e \( A = 4 \)

<table>
<thead>
<tr>
<th>y</th>
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<th>.1</th>
<th>.2</th>
<th>.3</th>
<th>.4</th>
<th>.5</th>
<th>.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>u(y)</td>
<td>4.08</td>
<td>6.09</td>
<td>8.43</td>
<td>10.31</td>
<td>9.44</td>
<td>0</td>
<td>-31.67</td>
</tr>
</tbody>
</table>

Table for skin friction:

\( \frac{1}{K} > \frac{\sigma B_0^2}{\mu} \) let  \( \frac{1}{K} = 35 \) i.e \( A = 1 \) and  \( B = \frac{\sigma B_0^2}{\mu} = 20 \) i.e \( A = 4 \)

<table>
<thead>
<tr>
<th>y</th>
<th>0</th>
<th>.1</th>
<th>.2</th>
<th>.3</th>
<th>.4</th>
<th>.5</th>
<th>.6</th>
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<tbody>
<tr>
<td>( \sigma_{xy} )</td>
<td>8.83</td>
<td>11.18</td>
<td>11.62</td>
<td>5.44</td>
<td>-18.66</td>
<td>-86.39</td>
<td>-254.46</td>
</tr>
</tbody>
</table>

Table for velocity:

\( \frac{1}{K} > \frac{\sigma B_0^2}{\mu} \) let  \( \frac{1}{K} = 11 \) i.e \( A = 5 \) and  \( B = \frac{\sigma B_0^2}{\mu} = 32 \) i.e \( A = 2 \)

Case 3: when  \( \frac{1}{K} > \frac{\sigma B_0^2}{\mu} \) let  \( \frac{1}{K} = 35 \) i.e \( A = 1 \) and  \( B = \frac{\sigma B_0^2}{\mu} = 20 \) i.e \( A = 4 \)
Table for skin friction:

\[ \frac{1}{K} < \frac{\sigma B_0^2}{\mu} \quad \text{let} \quad \frac{1}{K} = 11 \ \text{i.e} \ A = 5 \quad \text{and} \quad B = \frac{\sigma B_0^2}{\mu} = 32 \ \text{i.e} \ A = 2 \]

<table>
<thead>
<tr>
<th>y</th>
<th>0</th>
<th>.1</th>
<th>.2</th>
<th>.3</th>
<th>.4</th>
<th>.5</th>
<th>.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>u(y)</td>
<td>1.05</td>
<td>1.31</td>
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<td>1.45</td>
<td>0</td>
<td>-5.178</td>
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</tbody>
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Table 6

<table>
<thead>
<tr>
<th>y</th>
<th>0</th>
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<th>.2</th>
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<td>u(y)</td>
<td>3.11</td>
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<td>6.6</td>
<td>0</td>
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</tr>
</tbody>
</table>

**Conclusion and Discussion**

In this paper, we have investigated the velocity by the graph of Table 1 of equation (5) between velocity and distance in magnetic field. It is clear that the velocity increases in the interval \(0 \leq y \leq .3\), the velocity decreases in the interval \(.4 \leq y \leq .5\) for all values of \(A\) and velocity is negative at \(y = .6\) for all values of \(A\). Clearly \(y = .5\) is a stagnation point since velocity is zero at \(y = .5\) for all \(A\). The value of velocity decreases correspondingly for all values of \(y\) when \(A\) increases from 1 to 5.

Again from the table-2 it is clear that the skin friction decreases with positive sign correspondingly in the interval \(0 \leq y \leq .3\) when \(A\) is increases from 1 to 5 and decreases with negative sign correspondingly in the interval \(.4 \leq y \leq .6\) when \(A\) increases from 1 to 5.
Again it is clear from the table-3 the values of velocity in porous medium at \( \frac{1}{K} = 35 \) is greater than the corresponding values of velocity in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 20 \) in the interval \( 0 \leq y \leq 0.4 \), velocity is zero in both mediums at \( y = 0.5 \) and velocity (negatively) in porous medium is greater than the velocity in magnetic field at \( y = 0.6 \).

Again it is clear from the table-5 the values of velocity in porous medium at \( \frac{1}{K} = 11 \) is less than the corresponding values of velocity in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 32 \) in the interval \( 0 \leq y \leq 0.4 \), velocity is zero in both mediums at \( y = 0.5 \) and velocity (negatively) in porous medium is less than the velocity in magnetic field at \( y = 0.6 \).

Again from table-4 the values (positively) of skin friction in porous medium at \( \frac{1}{K} = 35 \) is greater than the corresponding values of skin friction in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 20 \) in the interval \( 0 \leq y \leq 0.3 \) and the values (negatively) of skin friction in porous medium at \( \frac{1}{K} = 35 \) is greater than the corresponding values (negative) of skin friction in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 20 \) in the interval \( 0.4 \leq y \leq 0.6 \).

Again from table-6 the values (positively) of skin friction in porous medium at \( \frac{1}{K} = 11 \) is less than the corresponding values of skin friction in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 32 \) in the interval \( 0 \leq y \leq 0.3 \) and the values (negatively) of skin friction in porous medium at \( \frac{1}{K} = 11 \) is less than the corresponding values (negatively) of skin friction in magnetic field at \( \frac{\sigma B_0^2}{\mu} = 32 \) in the interval \( 0.4 \leq y \leq 0.6 \). Also we have investigated the shear stress, volumetric flow and drag coefficients and stream lines given by the equation (7), (9), (11), (12), (13) (14) and (15) respectively.

References