Experimental investigation on the discharge structure in a noble gas MHD generator

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by

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Abstract

An experimental investigation of the discharge structure in a noble gas MHD plasma has been performed, employing streak photography and other optical diagnostics. The discharge appeared to be concentrated in streamers. It was observed that the streamer structure of the discharge is very pronounced at stagnation temperatures around 2000 K, where the conductivity of the plasma becomes critical. Moreover, the observations indicate the presence of friction forces which result in a velocity of the streamers being always close to the velocity of the gas flow. The observations suggest that streamers are generated by break down phenomena at the inlet of the generator and subsequently convected downstream the channel.

The structure of the discharge in the direction perpendicular to the electrode walls was analysed by taking streak pictures with the slit in this direction in order to obtain information about the angle of propagation of the streamers.
1. Introduction

It has been observed in studies of non-equilibrium plasmas in noble gas MHD generators that the d.c. electrical power output is considerably lower than the theoretical prediction based on the assumption of uniform plasma properties. In addition, fluctuations in the electric field and in the plasma properties have been observed. Moreover, this inhomogeneous behavior becomes more pronounced at lower stagnation temperatures, around 2000 K.

Many authors tried to explain the generator performance taking into account the influence of these inhomogeneities on Ohm's law. In that way a better agreement with the experimental values has been found [1,3].

By measuring the fluctuation in the electron density Hellebrekers et al [4] could explain a 50% reduction in the conductivity.

An other effect of the inhomogeneous distribution of the electric current is its influence on the relaxation phenomena at the inlet of the MHD channel. Experimental results show a relaxation length much larger than theoretically predicted by models using a more homogeneous current distribution [5,6].

Theoretical models taking into account the streamer structure seem to be more close to reality and will be a further step to a better description of the performance of the generator.

Up to now no satisfactory explanation for the physical nature of the streamers has been given. Linear or quasi-linear theories [7,9] about ionization instabilities cannot be applied to a fully developed structure like a streamer.

The existing non linear model of M. Mitchner and V. Zampaglione [10] essentially describes only a steady state situation in which the existence of streamers is assumed.

In the computer simulation of L. Lengyel [12] the effect of the gas flow has been neglected. Some experimental work on streamer structure has been published [11, 13, 14].

The purpose of the work reported here has been to provide in a more extensive set of experimental data where magnetic induction and stagnation temperature have been varied and where the streamer behavior has been studied in the core of the gas flow as well as close to the electrodes.
2. Experimental device and diagnostics

The experiments have been carried out with the shock-tunnel MHD generator described earlier [15]. The working medium employed is cesium seeded argon. The generator duct has been made of lexan. It diverges from $3.8 \times 12 \text{ cm}^2$ to $12 \times 12 \text{ cm}^2$ over a length of 80 cm. The electrode walls are parallel. The 32 stainless steel cylindrical electrode pairs with a diameter of 0.7 cm are half way buried in the walls. The pitch is 2.5 cm. An upstream nozzle provides in an inlet Mach number of 1.6.

An image converter camera was used in the streak operational mode. The camera was placed 4 m away from the generator using an optical system, but still a correction for the influence of the magnetic field had to be made for a proper interpretation of the pictures. Experiments were carried out with two different arrangements of the photographic equipment. In fig.1, the scheme of the photographic arrangement where the projection of the flow direction is perpendicular to the streak direction, is shown. The slit, parallel to the direction of the flow, has been placed in the region of the 15th electrode pair. The projected slit width was 10 mm and it covered 2.8 cm of the channel at H cm from the anode wall. The axis of the optical system was in the z-direction (along the magnetic field) and the enlargement was 2.07. Streak velocities of 1, 0.5 and 0.25 mm/μs were used. In fig.2, the scheme of photographic arrangement is shown where the projection of the direction of the flow on the film is parallel to the streak direction. The slit was taken perpendicular to the direction of the flow and placed in the center of the channel wall. The photomultiplier used in the image converter camera is an S-11 model, which is sensitive for the visible region of the light till to about 6000 Ǻ. Because of its spectral sensitivity, the photomultiplier is not able to detect the radiation of the two cesium resonance lines (8521 Ǻ and 8943 Ǻ). The detected light originates from free bound recombination and from non-resonance lines. It is therefore an indication of the properties of the electrons. Moreover, the plasma is optically thin for the detected radiations. Recombination radiation measurements have been done at 4102 Ǻ and 4897 Ǻ. The load current was measured at several electrodes. Pressure measurements were carried out at three locations of the channel. Using the measured values of pressure, currents and the magnetic induction, the gasdynamic behavior of the generator has been analyzed with a Varian 620f computer, directly connected with the facility.
3. Experimental results

Using the arrangement shown in fig.1, the slit was first placed in a central position. Experiments were performed for several values of the magnetic field B at high stagnation temperature ($T_s \approx 3750 \text{ K}$) and at low stagnation temperature ($T_s \approx 2000 \text{ K}$). The parameters of the runs belonging to this experiment are given in Tabs. 1, 2, and 3. In figs.3 and 4 streak pictures of typical runs are shown. Both at high and low stagnation temperature, a pronounced streamer behaviour of the plasma has been observed. From the streak pictures the velocity of the streamers is calculated according to

$$v = \frac{a \nu_s \tan \alpha}{(\sin \beta \tan \alpha + \cos \beta)}$$

(1)

where $\beta$ represents the rotation of the image caused by the magnetic field. In figs.7, 8 and 9 the streamer velocity, computed for several runs, is plotted versus the magnetic induction. Further the velocity $\nu_{gp}$ of the gas flow, as computed by the gas dynamical program, is shown. From the figures it can be concluded that the streamers have the same velocity as the gas flow. The straight lines indicate a constant streamer velocity over a segmentation length. The observed dimension of the streamer does not change too. All the observations lead to the indication that the streamers are frozen in the gas flow. Recombination radiation measurements have been done. In figs.5 and 6 typical signals of these measurements are shown. The signals are comparable with the streak pictures. The main frequencies deduced from both measurements are in first order agreement.

Both the streak pictures and the radiation measurements show clearly that at low stagnation temperature the plasma has a much more pronounced inhomogeneous structure than at high stagnation temperature. As can be seen from figs.5 and 6 the relative fluctuations level of the recombination radiation intensity is much larger for low stagnation temperature.

A clear dependence of the streamer structure on the magnetic field on the gasdynamic performance is shown in the figs.10 and 11. Here the $\mathbf{J} \times \mathbf{B}$ force and the $\mathbf{V}_p$ force acting on the plasma between the 14th and the 15th electrode pairs are compared. It can be seen that for high magnetic fields $15 \text{ el.p.}$ $\nu_{14 \text{ el.p.}}$ $\nu_{15 \text{ el.p.}}$ $\mathbf{J} \times \mathbf{B}$ is much larger than $(\Delta \mathbf{p})_{14 \text{ el.p.}}$, $15 \text{ el.p.}$
Since it follows from the streak pictures that also in these cases the streamers propagate with the gas velocity, it has to be concluded that there is a strong frictional interaction between the streamer and the gas flow.

A set of experiments has been performed using the arrangement in fig.1, where the distance of the slit to the anode wall has been changed. The slit was placed at 23.5 mm, 15 mm and 6 mm from the anode wall. Some characteristic pictures are shown in fig.12. All these runs are done at low stagnation temperature, $B = 3$ T and a load resistance $R_L = 1 \Omega$.

No significant variation of the velocity and of the dimension of the streamers have been registered when the position of the slit has been changed from $H = 33.5$ mm to $H = 23.5$ mm and to $H = 15$ mm. At 6 mm from the anode wall the behaviour of the discharge becomes more irregular. As can be seen from fig.12-a, the velocity of the streamer changes over the observed segmentation length. Also the dimension of the discharge changes.

With the arrangement of the streak photography shown in fig.2, it is possible to measure the angle between the $y$-direction and the direction of the streamer when it moves through the channel with the velocity $v$. The relation between $\delta$ and $\gamma$ is given by

$$\tan \delta = \frac{v \cos \delta}{a \nu_s} \left( \frac{1}{\tan \gamma} - \tan \beta \right)$$

In eq. (2) the correction due to the magnetic field influence (represented by $\beta$) has been taken into account.

The most important parameters of a number of runs, performed for this experiment, are given in Tab.4 and the corresponding streak pictures in fig.13.

In about all the pictures only straight strips can be identified, which means that a streamer keeps its inclination constant during its motion. Different streamers, however, show different inclinations. The angles of inclination are always in the same direction and the theory for which the current flows from the upstream edges of the anode to the downstream edges of the cathodes, is confirmed.

Using the arrangement with the slit in the $y$-direction a more irregular behaviour of the discharge has been registered, the strips on the streak photographs have not the regular shape shown by the pictures taken with the slit in the $x$-direction (compare for example figs.3 and 4).
4. Discussion and conclusions

The discharge in a nonequilibrium MHD-generator is characterized by a streamer structure which is more pronounced at low stagnation temperature (2000 K). At this temperature the conductivity of the plasma is critically dependent on the nonequilibrium ionization. The constant dimension of the streamers and the fact that the velocity is approximately equal to the gas flow, demonstrate that the streamers flow through the generator frozen in the bulk of the gas. Since the experiments considered situations with $J \times B$ forces well in excess of $\nabla p$ forces, it is concluded that strong frictional interaction keeps the streamers frozen in the gas flow.

The observations close to the electrode wall suggest, that a streamer, flowing through the generator with the gas, changes its connection with the segmented electrodes jumping from one electrode to the next one. Then, before disconnection the shape of the streamer becomes oblenged and its velocity decreases. Only in the proximity of the next electrode pair, or even when the new electrode pair is reached, the change of connection is performed.

Earlier studies on discharges tranverse to an argon flow show, under comparable fluid dynamic conditions, a similar behaviour [16-18]. By putting the slit perpendicular to the direction of the flow the angle between the streamer and the y-direction has been measured.

It is expected that the observed streamers originate from break down processes in the inlet region of the generator, where-after they propagate through the channel convective with the gas flow.

5. Summary

The structure of the discharge in a noble gas MHD-generator has been investigated by means of an image converter streak camera under several conditions in the generator. A streamer structure has always been observed. The streamers have been seen to flow with a velocity close to the velocity of the gas even at high magnetic fields. This demonstrates a strong frictional interaction between the streamers and the gas flow. At low stagnation temperature a more pronounced streamer behaviour was observed.

The discharge has also been examined near to the anode wall.
6. Acknowledgement

This work was supported by the Laboratorio di Magnetofluidodinamica dell'Università di Bologna with funds of the NPI and the CNR. It was a part of the research program of the Group Direct Energy Conversion of the Eindhoven University of Technology. The authors wish to express their thanks to mr. A. W. M. van Iersel, mr. H. F. Koolmees and mr. J. P. Verhagen for their assistance in the operation of the facility, in the other diagnostics and in the data reduction.
References


<table>
<thead>
<tr>
<th>Run</th>
<th>B (T)</th>
<th>T_s (K)</th>
<th>V_{GP} (m/s)</th>
<th>V (m/s)</th>
<th>\frac{V - V_{GP}}{V}</th>
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<td>3658</td>
<td>1099</td>
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<td>1219</td>
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<td>1206</td>
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<td>3747</td>
<td>1447</td>
<td>1470</td>
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<td>1474</td>
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Table 1. Runs at high stagnation temperature; 
R_L = 2 \, \Omega, \, H = 33.5 \, \text{mm}

<table>
<thead>
<tr>
<th>Run</th>
<th>B (T)</th>
<th>T_s (K)</th>
<th>V_{GP} (m/s)</th>
<th>V (m/s)</th>
<th>\frac{V - V_{GP}}{V}</th>
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<tr>
<td>1962</td>
<td>3.22</td>
<td>1986</td>
<td>777</td>
<td>871</td>
<td>0.108</td>
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<td>1961</td>
<td>2.42</td>
<td>1999</td>
<td>990</td>
<td>1063</td>
<td>0.069</td>
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<tr>
<td>1963</td>
<td>1.95</td>
<td>1986</td>
<td>1096</td>
<td>1051</td>
<td>- 0.049</td>
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</table>

Table 2. Runs at low stagnation temperature; 
R_L = 1 \, \Omega, \, H = 33.5 \, \text{mm}
<table>
<thead>
<tr>
<th>Run</th>
<th>B(T)</th>
<th>T_s(K)</th>
<th>( \nu_{GP}(\text{m/s}) )</th>
<th>( \nu(\text{m/s}) )</th>
<th>( \frac{\nu - \nu_{GP}}{\nu} )</th>
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<tr>
<td>1964</td>
<td>3.20</td>
<td>1960</td>
<td>991</td>
<td>1077</td>
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<td>1978</td>
<td>3.12</td>
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<td>949</td>
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<td>1013</td>
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<td>973</td>
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<td>1973</td>
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<td>1135</td>
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Table 3. Runs at low stagnation temperature,
\( R_L = 2 \Omega, H = 33.5 \text{ mm} \)

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<tr>
<th>Run</th>
<th>B(T)</th>
<th>T_s(K)</th>
<th>( \nu(\text{m/s}) )</th>
<th>( \delta )</th>
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<tr>
<td>1994</td>
<td>2.60</td>
<td>3872</td>
<td>1195</td>
<td>( 0^\circ &lt; \delta &lt; 32^\circ )</td>
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<tr>
<td>1996</td>
<td>1.66</td>
<td>3836</td>
<td>1197</td>
<td>( 10^\circ &lt; \delta &lt; 40^\circ )</td>
</tr>
<tr>
<td>1998</td>
<td>3.12</td>
<td>1999</td>
<td>890</td>
<td>( 0^\circ &lt; \delta &lt; 28^\circ )</td>
</tr>
<tr>
<td>1999</td>
<td>2.17</td>
<td>1973</td>
<td>1091</td>
<td>( 20^\circ &lt; \delta &lt; 40^\circ )</td>
</tr>
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Table 4. Runs for the angle investigation; for the runs 1994 and 1996 \( R_L = 2 \Omega \); for the runs 1998 and 1999 \( R_L = 1 \Omega \)
Scheme of the streak photography arrangement where the protection of the direction of the streamer velocity on the film is perpendicular to the streak velocity. $V_g$ is the velocity of the gas flow, $\dot{v}$ is the velocity of the streamer, $V_s$ is the streak velocity, $a$ is the enlargement of the optical system, $H$ is the distance of the slit from the anode wall, and $\alpha$ is the angle between the strip left on the streak picture by the streamer and the direction of streak velocity.
Fig. 2. Scheme of streak photography arrangement where the projection of the direction of the streamer velocity on the film is parallel to the streak velocity. \( V \) is the velocity of the streamer, \( V_s \) is the streak velocity, \( \delta \) is the angle between the streamer and the \( y \)-direction and \( \theta \) is the angle between the strip left on the film by the streamer and the direction of the streak velocity.
Fig. 3 Streak pictures at high stagnation temperature.

Fig. 4 Streak pictures at low stagnation temperature.

a) Run 1935; b) Run 1938; c) Run 1962;

\[ \begin{align*} 
\text{d) Run 1961; e) Run 1963.} 
\end{align*} \]
Fig. 5 Radiation recombination signals for run 1976 and for run 1960.
Fig. 6 Radiation recombination signals for run 1961 and run 1963.
Fig. 7. Experimental results for the runs at high stagnation temperature and $R_L = 2 \Omega$.

- velocity of the streamers from the streak pictures
- velocity of the flow computed by the gas dynamic program

Fig. 8. Experimental results for the runs at low stagnation temperature and $R_L = 1 \Omega$.

- velocity of the streamers from the streak pictures
- velocity of the flow computed by the gas dynamical program
velocity of the streamers from the streak pictures.

velocity of the flow computed by the gas dynamical program

Fig. 9. Experimental results for the runs at low stagnation temperature and $R_0 = 2 \Omega$.

Fig. 10. Comparison between gradient of pressure and $\nabla \times \mathbf{B}$ forces in the runs at low $T_s$. 
Fig. 11. Comparison between gradient of pressure and $\vec{J} \times \vec{B}$ forces in the runs at high $T_s$. 
**Fig. 12**
Streak pictures at different distances from the conducting wall.

a) Run 1974, $H = 6 \text{ mm}$,

b) Run 1968, $H = 15 \text{ mm}$,

c) Run 1967, $H = 23.5 \text{ mm}$.

**Fig. 13**
Streak pictures for the angle investigation.

a) Run 1994,

b) Run 1996,

c) Run 1998,

d) Run 1999.