Laboratory research project on High Voltage Travelling Arc «Jacob's Ladder»

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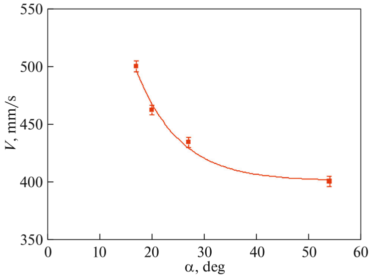
To be discussed

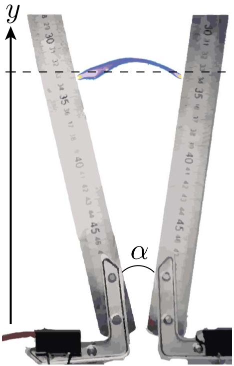
Beginings of a research

Jacob's ladder is the phenomena of an high voltage electic arc moving up between two electrodes.

The same idea of moving plasma is used in chemistry, aeronautics and weldment.

Articles we have started with





K. I. Almazova et al. 2020 Plasma Vol. 90, No. 7, pp. 1076–1079

Jindong Huo, JoAnne Ronzello et al. AIP Advances 10, 085324 (2020)

Fluid plasma description

The formulas that are used to describe arc bulk plasma are taken from following work

M.Lisnyak Plasma Physics. Université Orléans, 2018. tel-01808258

Assuming quasi neutrality of the plasma, one obtains the Navier-Stokes equation for the whole gas:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \rho \boldsymbol{v} \otimes \boldsymbol{v} = -\nabla p - \nabla \hat{\pi} + \boldsymbol{j} \times \boldsymbol{B}, \tag{1}$$

where p is the total plasma pressure and $\hat{\pi}$ is the viscous tensor.

Energy conservation

In terms of *Landau-Lifshitz. Theoretical physics. «Hydrodynamics»* concervation of energy of the plasma can be written as:

$$pC_p\left(\frac{\partial T}{\partial t}+\boldsymbol{v}\cdot\nabla T\right)=-\nabla\cdot\boldsymbol{q}+Q_{\mathrm{JH}}-Q_{\mathrm{rad}}, \tag{2}$$

where q, the energy flux, is presented with following formula:

$$\boldsymbol{q}=-\lambda\nabla T-\left(\frac{5}{2}+k_T\right)\frac{k_BT}{e}\boldsymbol{j}.$$

Laws of flows

The continuity equation of the whole plasma can be obtained from the species mass conservation

$$\frac{\partial p}{\partial t} + \nabla \cdot p\boldsymbol{v} = 0. \tag{3}$$

The simplified Ohm's law shows that arc current:

$$\boldsymbol{j} = \sigma \boldsymbol{E} + \frac{eD_e^T}{m_e T} \nabla T, \tag{4}$$

where D_e^T is the thermal diffusion coefficient.

Charge conservation and Maxwell

Due to the formula for charge density $\rho_e = e(Zn_i - n_e)$ the charge conversation might be written as:

$$\nabla \cdot \boldsymbol{j} = 0 \qquad \rightsquigarrow \qquad \nabla \cdot \boldsymbol{j}. \tag{5}$$

And useful Maxwell's equations:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} \qquad\qquad \nabla \times \boldsymbol{A} = \boldsymbol{B}, \tag{6}$$

where A is vector potential.

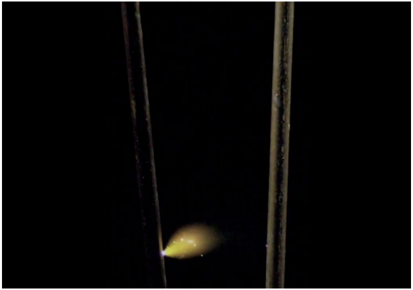
Qualitative Description

$I \neq 0$

1. An air breakdown;
2. A plasma arc forming;

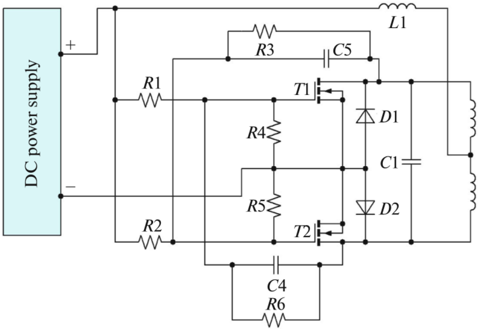
$I = 0$

3. The arc fading;
4. A higher breakdown.



link: «Jacob's Ladder in slow motion»

Choosing high a voltage circuit



ZVC-driver that is used in Almazova's article

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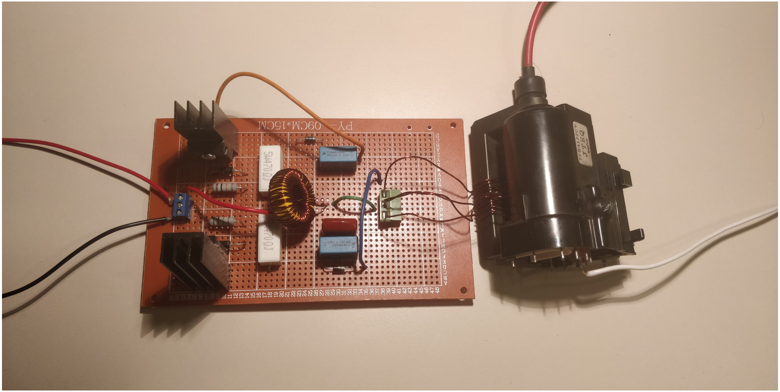
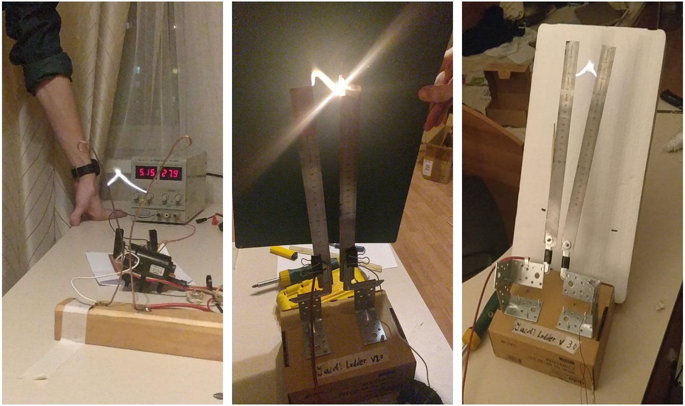
The circuit was soldered



Circuit is connected to a transformator from an old TV

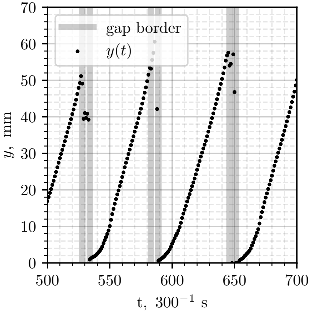
Evolution of experimental setup

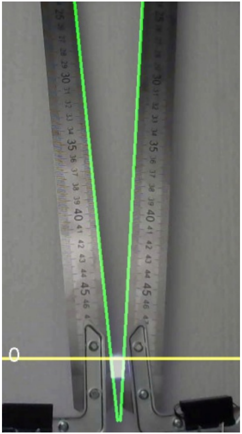


All versions in a row: v1 – first attempt; v2 – supports opening; v3 – supports rotation.

Computer vision implementation

$$Oy \in \text{ plane of electrodes,}$$
$$\beta = \angle(\boldsymbol{g}, Oy)$$
$$\alpha \text{ – opening angle,}$$
$$\beta \text{ – rortation angle,}$$





Does the magnetic field have an impact?

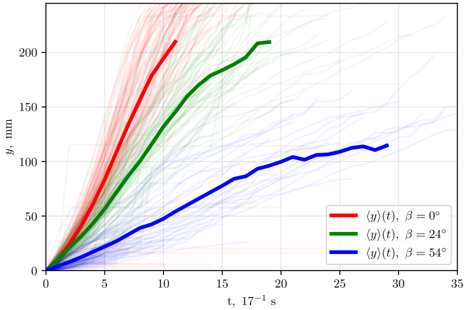


Fig. Dependence of the velocity of arc rise $\langle \dot{y} \rangle$ on the time($\alpha = 6°$). β is angle of rotation between $\boldsymbol{g}$ and electrodes.

Shoting with a high speed camera

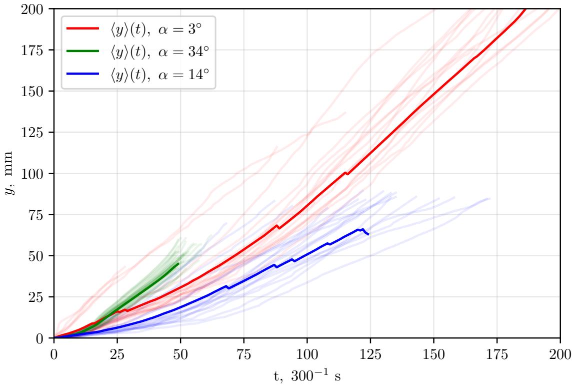


Fig. Dependence of $y(t)$ at different opening angles α.

Stabilization of the velocity

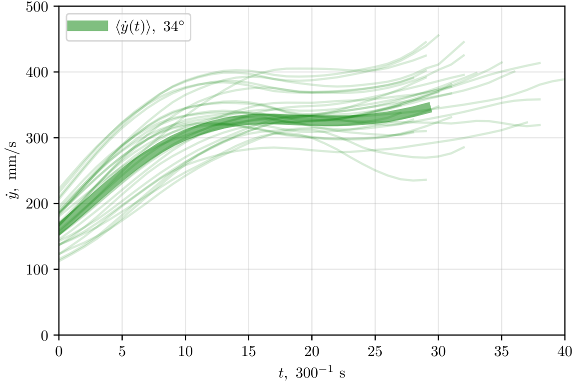


Fig. Dependence of $y(t)$ at different opening angles α.

Angles when the stable speed can not be reached

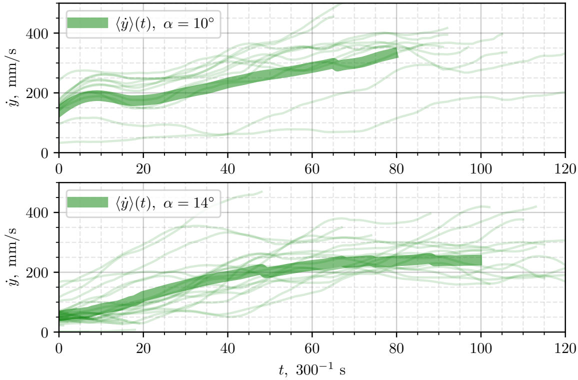


Fig. Dependence of the velocity of arc rise $\langle \dot{y} \rangle$ on time t at different opening angles.

All average stable velocities that we obtained

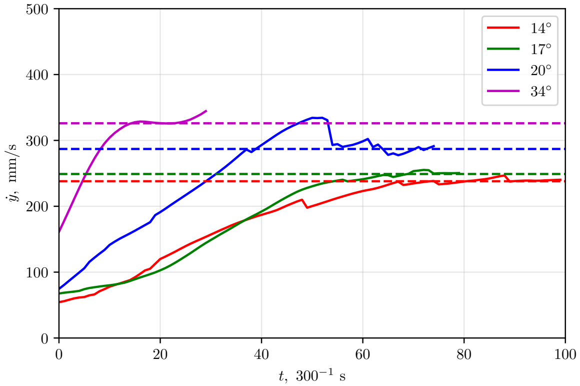


Fig. Dependence $\dot{y}(\alpha)$, dashed line corresponds to the average value $\langle \dot{y} \rangle(\alpha)$ over the considered interval.

Final plot

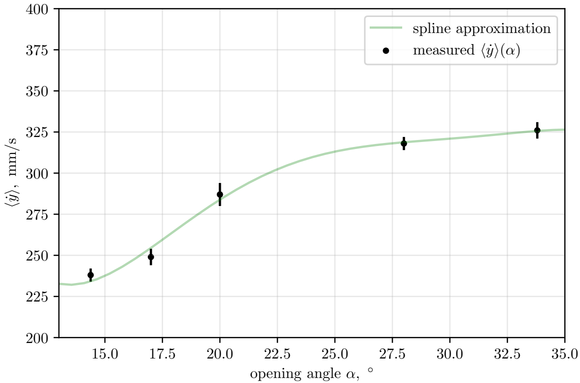


Fig. Dependence of the velocity of arc rise $\langle \dot{y} \rangle$ on the opening angle α between the electrodes.

Comparison of plots

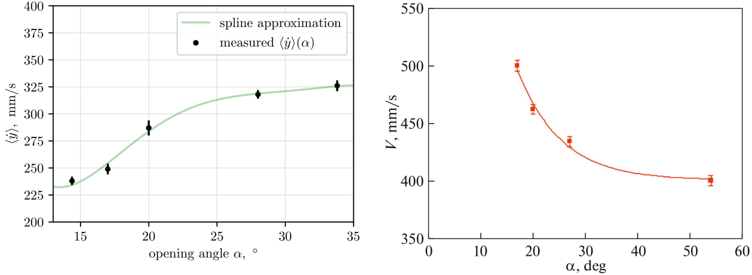


Fig. The different dependence is observerved. While our plot grows, the Almazova's plot decays.

Final Thoughts

1. The theory that is enough for modelling high voltage electric arc was studied.

2. The experimental setup was built. The data was gathered and processed.

3. The key role in up-movement of the arc is presented by pressure gradient.

4. The dependence of the average stabilized velocity $\langle \dot{y} \rangle_{\text{const}}$ to the opening angle α was obtained. The dependence conflicts with the results of Almazova's article.

5. We built the base for a further research: straight arc modeling; precise $\langle \dot{y} \rangle(\alpha, \ldots)$ measurements.

Literature used

- «Dynamics of Gliding Arc Climbing in a Unipolar Jacob's Ladder»
K. I. Almazova et al. 2020 Plasma Vol. 90, No. 7, pp. 1076–1079

- «Development of an arc root model for studying the electrode vaporization and its influence on arc dynamics»
Jindong Huo, JoAnne Ronzello et al. AIP Advances 10, 085324 (2020)
doi.org/10.1063/5.0012159

- Marina Lisnyak. Theoretical, numerical and experimental study of DC and AC electric arcs: Modeling and experimental investigations of default arcs propagating along the electric bus-bars for aeronautical applications. Plasma Physics. Université Orléans, 2018. English.
tel-01808258

Additions

In equation (1) p and π present these formulas:

$$p = \sum_a p_a = \sum n_a k_B T_a$$

$$\hat{\pi}_{i,j} = -\mu \left[\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) - \frac{2}{3} \nabla \cdot \boldsymbol{v} \delta_{ij} \right]$$