Experimental Study of the Cooldown Process for Near-Wellbore Rocks at Sustained Extraction of Geothermal Energy

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Abstract

The results of experimental study of the temperature potential decrease (cooldown) for near-wellbore rocks during extraction of geothermal energy have been provided; the study methodology has been described. The results of the dynamic pattern analysis for the temperature fields of the Earth’s rocks in adjacent layers of a single-well system for sustained extraction of thermal energy based on the physical modelling of the process on a test rig have been presented. The findings of mathematical processing and approximation of experimental study results have been provided. Possibility of their application to a full-scale single-well system for extraction of geothermal energy has been justified. Evaluation of the change in temperature effect radius for a single-well collection system at its operation during 25 years and more for various heat transfer fluid velocities has been performed.

Keywords: Renewable energy sources, geothermal energy, single-well system for extraction of geothermal energy, physical modelling of the ground cooldown.

INTRODUCTION

In recent years, the necessity of stable energy supply and energy security for most countries has come to the fore of their internal and external policy. Today, leading energy companies around the globe become increasingly interested in implementation of distributed energy generation. For this reason, the utilization of energy sources based on renewable energy sources (RES) is a crucial task. The renewable energy sources include: solar and wind energy, energy of minor rivers, geothermal energy, tidal energy, and energy received from biomass. All listed sources of alternative energy except for geothermal energy have serious drawbacks — territorial and climatic constraint and rather high unit cost of equipment installed power which poses significant limitations on their application. Geothermal energy can be conventionally split into the thermal energy of steam and hydrothermal sources and petrothermal energy — the energy of the Earth’s hot dry rocks [1]. Steam and hydrothermal resources in contrast to the energy of deep hot dry rocks are located only locally and their common usage is impossible.

The main potential advantage of the energy sources based on petrothermal resources over conventional sources as well as over most unconventional energy sources is that petrothermal resources can be used almost globally and intensity of their usage is limited only by engineering level of drilling technologies. In this connection, petrothermal potential can be considered a strategic resource of any country and the development of geothermal energy extraction methods and creation on their basis of energy sources which functioning does not depend on climatic, seasonal or territorial factors will enable to improve efficiency and reliability of energy supply in particular for autonomous consumers, and hence improve living standards.

Generally, extraction and transportation of deep geothermal energy to the surface involves creation of a ground circulation system (GCS) [1, 2] in the Earth’s rock mass at the depth determined by the thermal load of a consumer [3]. Analysis of publications on this subject shows that two implementation variants of the method are mainly used in the world’s practice: “open” multi-well method [4–7] and “closed” single-well method [8–10] of geothermal energy.

Preference in application of a single-well system which does not require rather costly purification of the heat transfer fluid is also driven by the fact that currently in the world there is a great number of unexploited plugged and abandoned wells of various depths. Part of these wells can be successfully used for heat and power supply for isolated consumers (well drilling accounts for 70–80% of the total capital costs for creation of such systems) [11–13].

DESCRIPTION OF EXPERIMENTAL IMPLEMENTATION OF THE COOLDOWN PROCESS FOR NEAR-WELLBORE ROCKS OF THE EARTH DURING THE USE OF A SINGLE-WELL SYSTEM FOR COLLECTION OF GEOTHERMAL ENERGY

The special feature of sustained operation of double-pipe single-well systems for collection of geothermal energy is transformation of temperature fields of the rocks around the well, the so called “cooldown” [14]. This article presents results of the physical modelling of such processes performed on a specially created test rig.

The test rig for modelling of cooldown process for near-wellbore rocks of the Earth enables to perform studies and determine the following:
- the intensity of temperature variations for a mass of various rocks in different parts of the temperature effect zone, including near the outer surface of the well;
- the radius of the temperature effect of a single-well system for collection of geothermal energy in various rocks of the Earth;
- the effect of the heat transfer fluid velocity on the cooldown of the Earth’s rocks;
- the effect of the initial temperature of the heat transfer fluid on the intensity of cooldown of various types rocks.

The main element of the test rig is the Earth’s rocks model made as a cylinder with the diameter of 0.32 m and the total length of 10 m composed of serially connected 4 parts each 2.5 m long. At the centre of the cylinder a channel 3 mm in diameter is located which is used to transport the heat transfer fluid at specified temperature (schematic diagram of the rocks model and the view of the test rig are presented in Fig. 1 and 2, correspondingly). Geometrical characteristics of the Earth’s rocks model are selected based on 1:100 scale to the full-scale (actual) single-well collection system 1000 meters long which is located in the 300 mm diameter well.

**Figure 1.** Schematic diagram of the rocks model in the test rig for modelling of the cooldown process for near-wellbore rocks of the Earth: $T_{I1a}$, $T_{I1b}$, $T_{I2}$, $T_{I3}$, $T_{I4}$, $T_{I5}$ – temperature sensors in the radial section of part 1; $T_{II1a}$, $T_{II1b}$, $T_{II2}$, $T_{II3}$, $T_{II4}$, $T_{II5}$ – temperature sensors in the radial section of part 2; $T_{III1a}$, $T_{III1b}$, $T_{III2}$, $T_{III3}$, $T_{III4}$, $T_{III5}$ – temperature sensors in the radial section of part 3; $T_{IV1a}$, $T_{IV1b}$, $T_{IV2}$, $T_{IV3}$, $T_{IV4}$, $T_{IV5}$ – temperature sensors in the radial section of part 4; $T_{bottom}$ and $T_{top}$, $T_{bottom}$ and $T_{top}$, $T_{bottom}$ and $T_{top}$, $T_{bottom}$ and $T_{top}$, $T_{bottom}$ and $T_{top}$ – temperature sensors for the channel wall in the bottom and top area of parts 1–4 correspondingly, $T_{in}$ – water temperature at the rocks model inlet, $T_{out}$ – water temperature at the rocks model outlet, EH1-EH4 – electric heaters.

**Figure 2:** View of the test rig for modelling of the cooldown process for near-wellbore rocks.
During performance of experimental studies for modelling of cooldown process for near-wellbore rocks of the Earth, a geothermal gradient 5 °C/100 m was selected for the well length (on average geothermal gradient is 2 to 6 °C/100 m), which in conversion to the scale-based model corresponds to 5 °C/m, where the temperature values for the ground and the heat transfer fluid at the channel inlet were equal and constituted $t_0 = 30°C$. To evaluate the effect of the heat transfer fluid velocity on the decrease of the temperature potential of the near-wellbore rocks over time, experimental studies were performed at various values of water velocity in the range of 0.25 to 1.5 m/s, which is stipulated by the least value of hydraulic resistance in the specified velocity range for the actual single-well extraction system [15]. The implementation of the set geothermal gradient of the ground was performed in steps with initial maintenance of constant temperature at each part (36.25 °C, 48.75 °C, 61.25 °C and 73.75 °C, correspondingly). Distribution of initial temperatures over the parts of the rocks model is presented in Fig. 3.

**Figure 3:** Temperature variation over the parts of the rocks model during performance of experimental studies for modelling of the cooldown process for near-wellbore rocks of the Earth: 1-4 – temperatures of the outer surface of the parts 1 to 4 of the rocks model, 5 – theoretical temperature gradient on the outer surface of the parts of the rocks model

**FINDINGS OF EXPERIMENTAL STUDIES**

Experimental studies for modelling of the cooldown process for near-wellbore rocks of the Earth were performed as follows:

- the heat transfer fluid in a tank was heated to the set temperature of 30°C;
- the heat transfer fluid velocity was set from 0.25 to 1.5 m/s;
- the parts of the rocks model were evenly heated to the set temperatures (see Fig. 3);
- after stabilization of the temperature field of the rocks model, the heat transfer fluid began to flow at the set velocity; at the same time the temperature patterns of the ground which characterize the rate of the temperature field transformation were registered with temperature sensors radially located in the centre of each part (see Fig. 1) in on-line mode at frequency of 1 kHz. Fig. 4 shows, as an illustration, i.e. temperature patterns in the radial midsection of the fourth part of the rocks model for the period from the start of the heat transfer fluid flow to the actual stabilization of the process.

**Figure 4:** Temperature patterns in the midsection of the fourth part of the rocks model at fixed time intervals from the start of heat transfer fluid flow $\omega = 1.5$ m/s to the actual stabilization of the process: 1 – at initial time, 2 – after 30 seconds, 3 – after 5 minutes, 4 – after 15 minutes

After completion of the experimental study, all measured values were registered in the report file which was then processed in a special program written using Python programming language. The main functional purpose of the program is mathematical analysis of available data and building of corresponding characteristic curves. One of the main findings of the experimental study is determination of the relationship between the temperature variation rate $\frac{\Delta t}{\Delta t}$ in the fixed points of the rock and time, for which purpose being set by a specific variation value (in this case the decrease) of the temperature $\Delta t = 0.3$ °C the time during which this variation occurred was determined and the start time of the specific experimental study was also registered.
Generally, the function behaviour pattern $\frac{\Delta t}{\Delta \tau} = f(\tau)$ for a fixed point of the rocks mass is represented by some curve 1-2-3-4 shown in Fig. 5. At this, the peak intensity of the point 3 increases with approaching to the channel wall and also with deepening along the channel. Fig. 6 shows such relationships collected for all points of the rocks mass registered during testing at various heat transfer fluid velocities ($a - \omega = 0.25$ m/s, $b - \omega = 0.75$ m/s and $c - \omega = 1.5$ m/s). As can be seen in Fig. 6, at insignificant scatter of points for all values of the heat transfer fluid velocity a definitive behaviour of the functions $\frac{\Delta t}{\Delta \tau} = f(\tau)$ can be rather distinctly observed. At this, the time of the actual stabilization of these relationships increases with increase of the water velocity (i.e. thermal output of the collection system).

Figure 5: Qualitative behaviour of the function $\frac{\Delta t}{\Delta \tau} = f(\tau)$

Figure 6: Relationships of temperature variation rates $\frac{\Delta t}{\Delta \tau} = f(\tau)$ for all fixed points of the rocks model.
As can be seen in Fig. 6, the relationships \( \frac{\Delta t}{\Delta \tau} \) take the form of hyperbolas (actually this is the right part \((3-4)\) of the curve \(1-2-3-4\) (see Fig. 5), shifted relative to the Y-axis due to the fact that the temperature perturbation caused by the medium flowing along the channel is propagated in the rocks model volume not instantaneously. For this reason, the extremums of functions \( \frac{\Delta t}{\Delta \tau} \) appear sequentially in time (at temperature sensors located in the radial section of the parts of the rocks model) when moving away from the channel. Therefore, the relationships presented in Fig. 6 are adequately described by hyperbola equation (see equation 1). As an example, the Fig. 7 shows approximation (determination factor \(R^2 = 0.997\) of the temperature variation rate for the channel wall at the fourth part of the Earth's rocks model at the heat transfer fluid velocity of \(1.5\) m/s.

\[
\frac{\Delta t}{\Delta \tau} = \frac{k}{\tau}
\]

where: \(k\) – the factor which characterizes the hyperbola concavity.

![Figure 7: Approximation by equation of the temperature variation rate for the channel wall of part No. 4 of the rocks model at the heat transfer fluid velocity of 1.5 m/s](image)

**Table 1: \(k\) factors characterizing concavity of the hyperbola**

<table>
<thead>
<tr>
<th>Part 1</th>
<th>Part 2</th>
<th>Part 3</th>
<th>Part 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer fluid velocity 0.25 m/s</td>
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<td></td>
</tr>
<tr>
<td>(T_{Ib}^{1b})</td>
<td>0.521570189301136</td>
<td>(T_{Ib}^{2b})</td>
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<tr>
<td>(T_{Ib}^{2b})</td>
<td>0.643538350608774</td>
<td>(T_{Ib}^{3b})</td>
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<tr>
<td>(T_{Ib}^{3b})</td>
<td>0.703552658034735</td>
<td>(T_{Ib}^{4b})</td>
<td>1.028308329587055</td>
</tr>
<tr>
<td>(T_{Ib}^{4b})</td>
<td>0.704634514622911</td>
<td>(T_{Ib}^{5b})</td>
<td>1.061003061175653</td>
</tr>
</tbody>
</table>

| Heat transfer fluid velocity 0.75 m/s | | | |
| \(T_{Ib}^{1b}\) | 0.595009315298760 | \(T_{Ib}^{2b}\) | 1.270787111784152 | \(T_{Ib}^{3b}\) | 1.582313730527064 | \(T_{Ib}^{4b}\) | 1.883181712990024 |
| \(T_{Ib}^{2b}\) | 0.779050319198531 | \(T_{Ib}^{3b}\) | 1.384245609651028 | \(T_{Ib}^{4b}\) | 1.893096532413778 | \(T_{Ib}^{5b}\) | 2.16464300786856 |
| \(T_{Ib}^{3b}\) | 0.830186218797053 | \(T_{Ib}^{4b}\) | 1.521940086623894 | \(T_{Ib}^{5b}\) | 2.158229944356304 | \(T_{Ib}^{6b}\) | 2.483075737046028 |
| \(T_{Ib}^{4b}\) | 0.874964124885425 | \(T_{Ib}^{5b}\) | 1.591988009893714 | \(T_{Ib}^{6b}\) | 2.399671896906920 | \(T_{Ib}^{7b}\) | 2.822943250097679 |

| Heat transfer fluid velocity 1.5 m/s | | | |
| \(T_{Ib}^{1b}\) | 0.699230570878636 | \(T_{Ib}^{2b}\) | 1.443170406065716 | \(T_{Ib}^{3b}\) | 1.693343304820167 | \(T_{Ib}^{4b}\) | 2.349149360095043 |
| \(T_{Ib}^{2b}\) | 0.899271742886061 | \(T_{Ib}^{3b}\) | 1.59431305513800 | \(T_{Ib}^{4b}\) | 1.95462161390287 | \(T_{Ib}^{5b}\) | 3.01464673240512 |
| \(T_{Ib}^{3b}\) | 0.957157409424404 | \(T_{Ib}^{4b}\) | 1.818486345614596 | \(T_{Ib}^{5b}\) | 2.441075616937310 | \(T_{Ib}^{6b}\) | 3.624395519441603 |
| \(T_{Ib}^{4b}\) | 1.015082104713923 | \(T_{Ib}^{5b}\) | 1.989045365594771 | \(T_{Ib}^{6b}\) | 2.771877052214271 | \(T_{Ib}^{7b}\) | 4.487634665968685 |
After completion of the temperature values approximation for all known points (temperature sensors), hyperbola equations were determined in the radial sections of the four parts of the rocks model, where $k$ factors have the highest significance (see equation 1), as they determine concavity of the hyperbola, and hence, the time of its approaching to asymptote, i.e. actually this factor determines the decrease of the temperature variation rate over time (temperature stabilization time) at a given point of ground. Therefore, the analysis of experimental data helped to determine approximating equations and $k$ factors for all temperature sensors located in the middle of the rocks model parts (see Table 1).

Considering that in the actual system propagation of the temperature perturbation can occur at large distances (more than 16 km) from the borehole, the relationship between $k$ factor and the distance was analysed (moving away of a given point from the borehole) and it was discovered that this relationship is adequately described by the equation (2), so that the resulting curves can be extrapolated to large distances. Factors of approximating equations obtained through approximation are given in Table 2. As an illustration of this statement, Fig. 8 shows the relationship for $k$ factor variation.

By substituting the equation (2) in (1), universal relationship (3) is obtained for determination of the temperature stabilization time at the distance $r$ from the channel in the rocks model, using the values for $a$, $b$ and $c$ factors from Table 2. Fig. 8 shows approximation of the hyperbola concavity factor $k$ versus distance relative to the channel wall at the water velocity of 0.75 m/s.

\[ k = a \cdot r^b - c \]  
where:  
- $a$, $b$ and $c$ – approximating equation factors;  
- $k$ – hyperbola concavity factor;  
- $r$ – distance from the channel surface, [m]

\[ \Delta t = \frac{a \cdot r^b - c}{\tau} \]  

Table 2: Equation (3) factors obtained through approximation

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
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<td><strong>Heat transfer fluid velocity 0.25 m/s</strong></td>
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<td></td>
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<td>Part 1</td>
<td>0.089592</td>
<td>0.178007</td>
<td>0.521237</td>
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<td>Part 2</td>
<td>0.072998</td>
<td>0.230369</td>
<td>0.867046</td>
</tr>
<tr>
<td>Part 3</td>
<td>0.097682</td>
<td>0.255714</td>
<td>0.955982</td>
</tr>
<tr>
<td>Part 4</td>
<td>0.101973</td>
<td>0.309642</td>
<td>1.101659</td>
</tr>
<tr>
<td><strong>Heat transfer fluid velocity 0.75 m/s</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part 1</td>
<td>0.116651</td>
<td>0.205935</td>
<td>0.594897</td>
</tr>
<tr>
<td>Part 2</td>
<td>0.053538</td>
<td>0.427973</td>
<td>1.267577</td>
</tr>
<tr>
<td>Part 3</td>
<td>0.125682</td>
<td>0.441342</td>
<td>1.578235</td>
</tr>
<tr>
<td>Part 4</td>
<td>0.094348</td>
<td>0.540724</td>
<td>1.876373</td>
</tr>
<tr>
<td><strong>Heat transfer fluid velocity 1.5 m/s</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part 1</td>
<td>0.120608</td>
<td>0.225715</td>
<td>0.699123</td>
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<tr>
<td>Part 2</td>
<td>0.058453</td>
<td>0.529404</td>
<td>1.436458</td>
</tr>
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<td>Part 3</td>
<td>0.105744</td>
<td>0.551875</td>
<td>1.675871</td>
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<tr>
<td>Part 4</td>
<td>0.196415</td>
<td>0.558623</td>
<td>2.342184</td>
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</table>
Figure 8: Approximation of the hyperbola concavity factor k versus distance relative to the channel wall at the water velocity of 0.75 m/s: 1 – k = 0.116651 \cdot r^{0.00220125} - 0.594897, 2 – k = 0.053533 \cdot r^{0.00427973} - 1.267577, 3 – k = 0.125682 \cdot r^{0.00481142} - 1.576235, 4 – k = 0.094348 \cdot r^{0.00540724} - 1.876373

For evaluation of the temperature effect radius propagation we utilize the equation (4) as per [16] using the data obtained through experimental studies, namely: rock temperatures at the channel wall at the corresponding moment of time. Being given by the slope of the tangent line of the temperature patterns (see Fig. 4) equal to 0.3 °C, the temperature effect radius r is determined from equation (4), i.e. the distance from the channel wall at a given moment of time at which the rocks temperature differs from the initial value by less than 0.3 °C. Propagation of the temperature effect radii over time for the heat transfer fluid velocities of 0.25, 0.75 and 1.5 m/s is shown in Fig. 9.

\[ T(r, t) = \frac{1}{\ln(m)} \left( T_1 \ln \frac{R}{r} + T_2 \ln \frac{R}{R_0} \right) + \sum_{n=1}^{m} \left[ J_0(\mu_m \alpha) \frac{V_0}{R} \frac{R}{R_0} \times e^{-\mu_m \alpha R} \right] \times \left[ T_0 - \frac{T_1 J_1(\mu_m \alpha)}{J_0(\mu_m \alpha)} - \frac{T_2 J_2(\mu_m \alpha)}{J_0(\mu_m \alpha)} \right] \]

where: \( R_0 \) – borehole radius, m; \( R \) – distance from borehole at which the rocks temperature is equal to the initial natural value, m; \( r \) – distance between \( R_0 \) and \( R \) at which the rocks temperature is determined; \( T_0 \) – initial value of the rocks temperature, K; \( T_1 \) – rocks temperature at the borehole, K; \( T_2 \) – natural initial value of the rocks temperature at the corresponding depth, K; \( m \) – ratio of \( R \) to \( R_0 \); \( \mu \) – roots of characteristic equations determined as per [14]; \( J_0 \) – Bessel function of the first kind; \( F_0 = \frac{\alpha r}{R_0^2} \) – Fourier number, where \( \alpha \) – temperature conductivity of the rocks, m²/s, \( \tau \) – operation time of a single-well collection system, s.
Figure 9: Variation of the temperature effect radii for the parts of the rocks model at various heat transfer fluid velocities: Fluid velocities: a) $\omega=0.25$ m/s, b) $\omega=0.75$ m/s and c) $\omega=1.5$ m/s). 1, 2, 3 and 4 – curves for parts 1-4 of the rocks model correspondingly.

All relationships shown in Fig. 9 were formed through processing of experimental data obtained when performing studies at the rocks model executed in geometrical scale of 1:100 to the actual system. Consequently, the transfer of coordinates, distances, etc. to the full-scale system can be made using this scale. The scale over time can be obtained based on the Fourier number analysis.

The Fourier number (see equation 5) is a non-dimensional time scale, i.e. at the same values of this criterion two similar systems are in the same state, therefore the Fourier number is also called the Fourier criterion. Considering that the geometrical scale of the rocks model to the full-scale system is 1:100, and thermal and physical characteristics of the rocks are the same, it is possible to determine the scale over time (see equation 6) which is $1:10000$ at conditions mentioned above. Therefore, based on the Fourier criterion for thermal processes the results of experimental studies can be applied to the actual single-well collection system including over time.

$$F_o = \frac{a \cdot \tau}{R^2} \tag{5}$$

where: $a$ – temperature conductivity factor, m$^2$/s;
$\tau$ – time, s;
$R$ – distance (radius for the cylindrical system), m.

$$F_{o_m} = \frac{F_{o_f}}{\frac{R_m^2}{R_f^2}} = \frac{\alpha_m \cdot \tau_m}{\frac{R_m^2}{R_f^2}} = \frac{\alpha_f \cdot \tau_f}{\frac{R_m^2}{R_f^2}} \Rightarrow \frac{\alpha_m}{\alpha_f} \cdot \frac{\tau_m}{\tau_f} = \left( \frac{R_m}{R_f} \right)^2$$

$\Rightarrow 10000 \cdot \tau_m = 1 \cdot \tau_f \tag{6}$

where: $\alpha_m$ – temperature conductivity factor of the rocks model, m$^2$/s;
$\alpha_f$ – temperature conductivity factor of the rocks in a full-scale system, m$^2$/s;
$\tau_m$ – duration of temperature potential decrease process in the model, s;
$\tau_f$ – duration of temperature potential decrease process in the full-scale system, s;
$R_m$ – radius of temperature front propagation in the model, m;
$R_f$ – radius of temperature front propagation in the full-scale system, m.

Considering the geometrical and time scale, it can be seen from Fig. 9 that, for instance, after 1 year or 8760 hours (8.76 hours in the model conditions) of operation of a single-well collection system the temperature effect radius at the depth of 750–1000 m will settle at the distance of 35 m at velocity of 0.25 m/s, 42 m at velocity of 0.75 m/s and 45 m at velocity 1.5 m/s. After 25 years ~ 219,000 hours (21.9 hours in the model conditions) of operation of a single-well collection system at the same velocities and depths, the temperature effect radius will increase to 50, 62 and 65 m correspondingly.

CONCLUSION

The results of performed experimental studies and the subsequent mathematical analysis allowed with sufficient accuracy for practical use:

1) Determine the rocks temperature variation rates during extraction of geothermal energy;
2) Determine the temperature effect radii for a single-well collection system 1000 m long at the geothermal gradient $5^\circ$C/100 m;
3) Obtain empirical relationship for determination of the temperature stabilization time at any distance from the borehole.

ACKNOWLEDGEMENT

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