The method of wells' efficiency estimation

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Abstract Wells are used as water intakes for economic activities. They are also commonly used in lignite mining for dewatering purposes. Ageing of the well screen is a natural process occurring during the well exploitation. It is a phenomenon occurring as a result of screen clogging. As a result entrance losses increase together with the costs of water pumping. Based on the existing knowledge the article presents parametric methods for identifying hydraulic state of the well screen. According to Darcy's assumptions the inflow to the well may be laminar if velocity is relatively low. However, according to Jacob's equation the drawdown in the well depends on the laminar flow coefficient in the aquifer zone as well as non-laminar coefficient in borehole zone. Hitherto used methodology of assessing the state of the wells uses Jacob's assumptions. The methodology developed in AGH-UST assumes that the value of entrance losses depends on the pumping rate. When velocity is relatively low the dependence between drawdown and pumping rate is linear. When the pumping rate increase, the non-laminar flow zone extend into aquifer. To identify laminar or non-laminar velocities in the vicinity of borehole, multi-stage hydraulic tests in wide-scale pumping rate are needed. The article presents the results of field multi-stage hydraulic tests conducted for two chosen wells. First one is a research well used by the Laboratory of Hydrology and Hydraulics in AGH-UST, the other is a dewatering well exploited in a lignite mine. The test results were interpreted on the basis of AGH-UST methodology. The developed methodology allows to choose maximal pumping rate which sudden increase of hydraulic losses of the well screen does not occur. Correct selection of pumping rate may increase the well's lifetime and limit the costs of pumping through reduction of entrance losses in the well screen.

Key Words well efficiency, well screen aging, well loss, dewatering of lignite mines

Introduction

Wells are operated in different hydrogeological conditions. They can be used for mine dewatering and water supply utility. Aging is the natural process in wells. Due to the different use of the wells, they have different operating time. Aging causes a drop in wells' productivity and an increase in the well loss. This results in an increase in pumping energy consumption, and thus the costs of the intake functioning. Effective working time is influenced by the drilling method, selection of the filter and gravel, the effectiveness of well activation. Method of filtering the well also depends on its usage, type of aquifer (permeability, porosity of the medium, fracturing, the nature of water table), the desired yield, the type of pumping equipment, as well as the requirements of the operator (Dąbrowski *et al.* 2004). Extension of the operating time of a deep water intake is possible by the proper exploitation and monitoring of working conditions. In the case of a decrease in the efficiency, an examination of well technical condition is carried out. For this purpose, one may use macroscopic methods and hydraulic tests.

Monitoring the technical condition of wells is done using video techniques. TV Inspections allow to evaluate construction errors or changes caused during the exploitation of the intake and allow for the identification of damaged wells (Jodłowski & Piąstka 2008).

Hydraulic tests are a parametric method and rely on pumping research tests carried out in the well. Interpretation of results allows to determine both the hydrogeological parameters of the aquifer and hydraulic parameters of the well. According to Dąbrowski *et al.* (2005) pumping test allows to:

- identify the characteristics of the interaction: the well - the aquifer,
- examine the well in terms of its rational exploitation,
- quantitatively evaluate of the characteristics of the layer like: the infiltration of water from adjacent layers, a test of its boundary conditions, etc.

Results of macroscopic examination and testing of hydraulic wells are used for the selection of methods for restoration of the well.

The most common cause of decrease in performance is clogging of the filter screen (Pólik 1991). The prevalent well problem occurring in various types of aquifer have been described in the work of Driscroll (1995), Treskatis *et al.* (1998), Wójcik (1986), Houben *et al.* (1999), Houben &

Treskatis (2007). Review of the aforementioned literature allows for distinguishing different types of well screen clogging:

- *chemical* induced by chemicals (e.g. carbonates, iron minerals),
- *biochemical* that occurs with the help of bacteria that cause the transformation of chemical reactions,
- *electrochemical*, which occurs in connection with the formation of an electrostatic potential difference in the flow of water on the surface of the filter,
- *mechanical*, which occurs as a result of deposition of rock particles on well screen.

Precipitation and deposition of particulate organic and inorganic matter on the filter and in the borehole zone increases the hydraulic resistance which impede the flow of water into the filter (Wójcik 1986). It is important therefore to maintain such a state of the filters to avoid reduction in operating efficiency.

Well hydraulics

Due to the interaction between the well and the aquifer, three characteristic zones can be distinguished:

- the outer zone of the well covering aquifer (I),
- borehole zone (II),
- zone inside the well (III).

In the aquifer the movement of underground-water is laminar, and shall be in accordance with Dupuit's assumptions. The size of drawdown of water surface (S) is a function of well productivity (Q), the conductivity of the aquifer, specific yield, the distance of a given point from the axis of the well and time of pumping. In fissure and fissure-karst aquifers, the presence of turbulent flow conditions is possible (Atkinson at al. 2010).

In borehole zone the nature of the flow depends on the effective diameter of the filtering gravel. With significant yields of wells and a small effective diameter of particles, flow can be turbulent. As the distance from the hole grows, the apparent seepage velocity decreases and the flow becomes laminar. Turbulences contribute to the clogging of the filter. The result of this process is the increase of the hydraulic resistance and the emergence of a significant well loss. A drop in unit yield of the well is the consequence.

Groundwater accumulates inside the well and is then pumped with the pump unit. A characteristic feature is auto-regulation of drawdown and performance of wells as a result of overlap between the characteristics of the pumping system, the aquifer and the filter of the well (Klich *et al.*

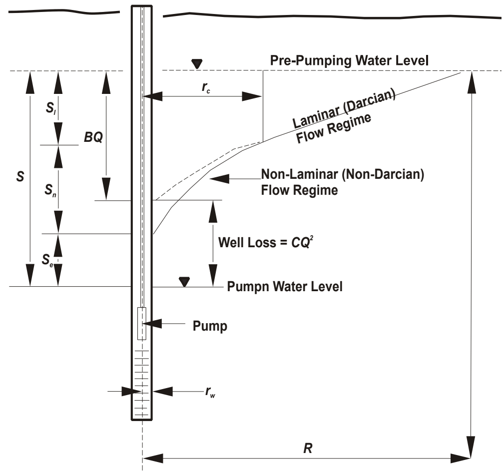

Figure 1 *Components of drawdown in well (Atkinson at. al. 2010); S – total drawdown in the well, S_l – the drawdown at relatively low velocity in the laminar (Darcian) flow, S_n – the drawdown at relatively high velocity in the turbulent flow (non-Darcian), S_e – entrance losses odue to „screen effect" and turbulent flow through the screen or gravel pack, R – radius of influence, r_w – the radius of the borehole, Q – pumping rate, B – laminar flow coefficient, C – non-laminar flow coefficient*

1998).

Hydraulic resistance, caused by laminar and/or turbulent flow in the aquifer and in the borehole zone cause drawdown (Fig. 1). Jacob gave the equation for the drawdown in pumped well (Kasenow 2007):

$$S = BQ + CQ^2 \qquad (1)$$

where:
$B = B_1 + B_2$
B_1 – linear aquifer-loss coefficient
B_2 – linear well-loss coefficient
C – non-linear well-loss coefficient
Q – the yield of well,
BQ – drawdown in the well,
CQ^2 – the well-loss [m].

In practice, only the influence of the non-linear well losses on the efficiency can be established, because it is seldom possible to take B_1 and B_2 into account separately (Kruseman and Riddel).

This issue was described by Bierschenk (Kasenow 2001). Rorabaugh gave the Jacob's formula, in which he permitted the existence of a tide when power exponent in the expression CQ is different from 2 (Siwek, 1978 and 1979). The relationship takes the form of the equation:

$$S = BQ + C_RQ^n \quad (2)$$

In Poland, Sozański later proposed an algebraic method to determine the resistance coefficient of wells (1985). Implementation of methodology for conducting pumping tests and interpretation of their results for wells was proposed by Klich (1998). General issues relating to the evaluation of the technical conditions of observation wells was also raised in the work of Marciniak (1999), which is devoted to the methodology of identification of hydrogeological parameters, as well as in the work of Dąbrowski (2005), devoted to documenting the exploitation of resources of undergroundwater intakes.

The above-mentioned works describe methods of describing the well loss, which is the difference between the level of water surface in the borehole area and the water level in the well itself. The hydraulic loss is determined by the state of filter clogging. A measure of the well loss is the value of the turbulent flow resistance coefficient in the well and in the borehole area - C. The lower the value of the coefficient, the higher the well efficiency factor. According to Walton classification, the coefficient should not exceed 0.0003 h^2/m^5 (Dąbrowski & Przybyłek 2005)

Interpretation of multi-stage hydraulics test

The steps-drawdown test was first performed by Jacob in 1947. From that time methodology of performing these test has developed. Nowadays the step-drawdown test is a single-well test in which the well is pumped at a low constant discharge rate until the drawdown within the well stabilizes. The pumping rate is then increased to a higher constant-discharge rate and the well is pumped until the drawdown stabilizes once more. This process is repeated through at least three steps, which should all be of equal duration, say from 30 minutes to 2 hours each (Kruseman & Riddel 1994).

In theory the drawdown tests constant discharge rate should be maintained. However, in practice maintaining constant pumping rate is impossible. Drawdown increment changes the pumping head. As a result, pump's efficiency is reduced. This affects the stability of the drawdown. Pumping rate and pumping head are therefore in close mutual autoregulative relationship and fluctuate during the test. Regulation of the pumping rate and the location of the water table are dependent on pump's characteristic H=f(Q), but also on aquifer resistance coefficient and well resistance coefficient.

Maintaining constant discharge rate requires the use of expensive devices that regulate pump's power. Because of that, a new method of performing pumping tests has been developed. The method is based on the assumption of discharge rate fluctuations in step-drawdown test. Step-drawdown test does not require breaks necessary for the water table to stabilize as well (Klich *et al.* 1998). It responds to auto-regulating nature of the flow rate-drawdown parameters. The pumping at a given level should last until steady-state flow conditions occur. When step-drawdown is performed, all data is monitored and recorded online. This allows for accurate monitoring of the pumping, the statistical analysis of data and calculation of the asymptotic values for each time series. Yields of well in subsequent stages should increase from the values close to zero to the maximum pumping rate with the maximum possible number of stages.

During small flow efficiencies, water flow may be laminar in both the aquifer and in the well. Well-loss may occur at higher pumping stages. According to this assumption, the calculations are performed using different equations.

When velocity of flow is laminar in well screen relationship between drawdown and pumping rate is linear. It could be described by following equation:

$$S = BQ + C'Q = (B+C')Q = DQ \quad (3)$$

where:
S – total drawdown in the well, [m];
Q – yield of well, [m^3/h];
B – linear aquifer-loss coefficient [s/m^2];
C' – linear well-loss coefficient, [s/m^2];
D – substitute resistance coefficient for laminar flow through the aquifer and the well, [s/m^2].

When velocity of flow is turbulent in the well is described by Jacob equation (1).

Verification of these assumptions was conducted basing on the results of pumping tests. These were conducted in a laboratory research well and in a lignite mine.

Multiple hydraulic lab-test

Research station is the property of AGH-UST and is located in Krakow city center. The well has a depth of 16 m. The aquifer consists of Neogene layers, composed mainly of gravel and sand lying on Miocene clays. Water-bearing capacity of these deposits is very high. Flow to the well hole is radial. The border of the water supply area is set by the natural banks of the Vistula river valley. Filtering gravel was carried along the active part of the filter. Diameter of the well screen is 225 mm.

The test of the well was conducted through a 10-stage pumping. Measurements were carried out from zero to maximum flow rate Q_{max} = 35.64 m^3/h. A ten-stage pumping which lasted 40 minutes was conducted. Figure 2 depicts the sequence

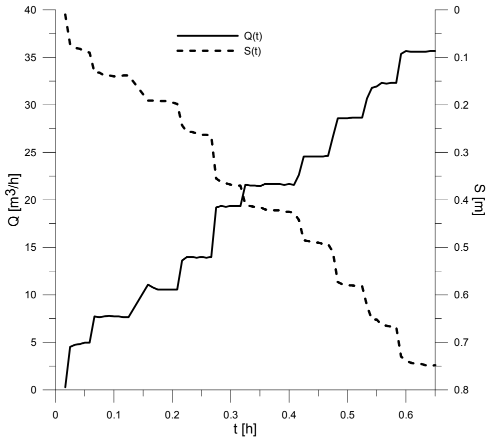

Figure 2 *Course of multi-stage pumping test in AGH-1 well*

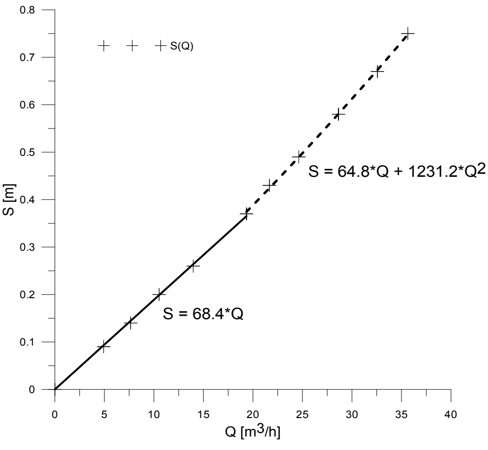

Figure 3 *AGH-1 well hydraulic test interpretation*

of pumping while in Figure 3 graphical interpretation of pumping test results is shown.

The statistical analysis of the results of measurements on subsequent stages of the pumping shows that under the values of Q = 19.35 m^3/h and S = 0.37 m there is a linear relationship between Q and S. This indicates a laminar flow through the aquifer medium. Once these values are exceeded, the nature of the graph changes from linear to exponential. This means turbulent character of the water flow in the borehole area.

For laminar flow (Q < 19.35 m^3/h) the resistance coefficient D is 68,4 s/m^2. While for turbulent flow (Q > 19.35 m^3/h) zone on filter coefficients take the values: B = 64,8 s/m^2 and C = 1231,2 s^2/m^5. The test shows that the well reaches its optimal hydraulic parameters if the yield is 19.37 m^3/h. Pumping of water with greater efficiency will lead to accelerated aging of the well.

Multiple hydraulic field test

Multi-stage pumping test was carried out for well 29-ZE. It is a dewatering well located in a lignite mine. The mine is located in the central part of Poland. Well includes Quaternary and Tertiary layers, and its depth is 100 m. The measurements were carried out from Q = 0 m^3/h to Q = 48 m^3/h. Short five-stage pumping was conducted. Data was recorded at a frequency of 1 s. Saved time series data were used to calculate the asymptotic values for the functions Q = f(t) and S = f(t). The searched values were obtained using a logarithmic extrapolation of the measured data. The results describe the flow parameters for steady flow conditions. Figure 4 presents the course of pumping for 29-ZE well, while in Figure 5 hydraulic interpretation of test results is shown.

Analysis of results for a well-ZE 29 indicates that during the entire pumping laminar flow occurred in both the aquifer and in the well. For a dewatering well the substitute resistance coefficient for laminar flow in the well and the aquifer was D = 1656 s/m^2.

Conclusions

Multi-stage research pumpings allow for conducting hydraulic tests of wells throughout the entire field of work of the water intake. They can be used for intake wells and dewatering wells used in mining. The conducted research revealed that for small velocity of flow, there is a linear relationship between performance and drawdown in the well, in accordance with Darcy law. The increase in flow velocity creates turbulence zone in the borehole area. This increases the hydraulic resistance. These conditions may cause an increase in the costs of water pumping, as well as accelerated aging of the well filter. Multistage pumping test method allows to determine the maximum pumping rate at which the accelerated aging does not occur.

The study was conducted for a well pumping the water from porous media. In the next phase of research carried out in the AGH-UST it is planned to conduct multi-stage test pumping of wells working in fissure media.

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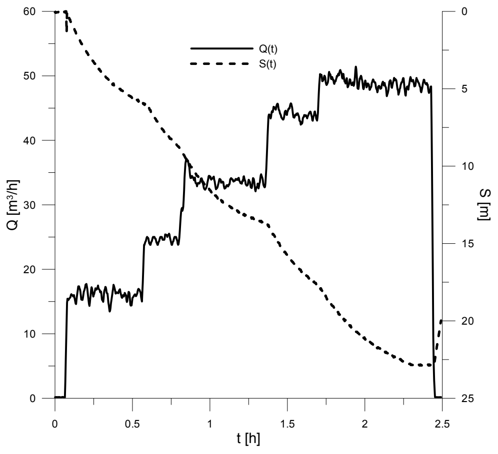

Figure 4 *Course of multi-stage pumping test in 29-ZE well*

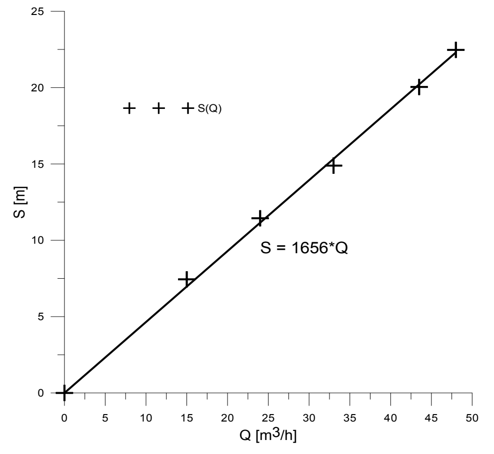

Figure 5 *29-ZE well hydraulic test interpretation*

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