Horizontal Wells

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Introduction:

In the environmental community of geologists and engineers there is much agreement about the utility of Horizontal Wells in remedial activities. Unfortunately, the knowledge of the design theory is has not caught up with practice and far too often I see horizontal wells and trenches designed improperly and ineffectively.

In this brief paper we will go through simple design features and programs which will enable the practitioner to design effective collection and distribution wells for both compressible and non-compressible flows—for both air and water systems.

Water and non-compressible fluids

We'll tackle this one first because it is simpler and more direct. The problem is the one of the filter gallery piping. One of the first places that this theory was developed was for backwashing sand filters. In the backwash it is imperative that the water distribution be uniform so that the filter bed can be cleaned adequately.

The application to horizontal wells is straightforward: How does one get uniform distribution along the length of the well, insuring that there is even collection or distribution of the liquid being pumped to or from the horizontal well?

Over the years, I have seen lots of questionable practice and one wonders why certain deigns were developed. The problem, apparently is an incomplete understanding of the nature of hydraulics and how to distribute losses along a pipe or how to add flow to a pipe. By example, a bad design of a horizontal air sparging well contained 200 feet of horizontal well which contained over 150 feet of well screen. The geologist who designed it wondered why it didn’t work. The problem with well screen is that it has too great an open area. The air was distributed in the formation in the first 20 feet of screen, and the remaining screen was an entire waste of resources. Similarly, while a drain system with the same type of configuration might be more effective, it would be highly dependent upon the formation permeability. In effect, it could serve just as well as a large horizontal hole where the screen could promote or enable differential formation flow into the pipe and along the pipe and then out into another formation where local hydraulics permit. Likely? Maybe not, but possible for pollution to transfer? Yes definitely.

The most effective type of distribution system is one which is tailored to the piping system. Note, this does not imply that one can buy perforated pipe at the local garden/hardware store and use it successfully. In order for the installation to be successful, the system needs to be designed and tailored to the piping system.

Orifices and Pipe Losses

The formula for energy losses through a nozzle or orifice plate is the same, just the coefficient of discharge is different. That formula is shown in Equation 1:

$$Q = Cd*Ao* [2gh]^{0.5} \qquad \text{Equation (1)}$$

Where Cd is the discharge coefficient, Ao is the area of the orifice and 2gh is the acceleration of gravity times the hydraulic head. All of it has to be in the same appropriate units. The coefficient of discharge is between 0.59 and 0.61 for most orifice plates, depending upon Reynolds Number for the fluid system. Michael Duchene and Edward A McBean reported the head loss coefficients on a number of different piping systems as equal to 0.6 to 0.66 depending upon the depth of burial and the depth of flow in the distribution piping. They principally experimented on piping systems which had four openings around the pipe[i]. The also accounted for differences in hydraulic head on the various openings due to their location on the pipe.

Now the challenge is to get the losses and the flow through the orifice holes equal to the flow in the pipe. This can require a bit of ingenuity in the design process. The ideal situation is to design the distribution system so that the flow and the losses at the end of the pipe are zero.

One way of designing the system would be to analyze the pipe at each perforation for the flow Q-q, which provides a new Velocity Vq, and a new set of friction losses for the next length of pipe between the perforations. This would require n+1 different frictional calculations for head loss and friction in the length of the perforate pipe. That's just unrealistic and extremely cumbersome.

An old article in a text book from the 1960's provides a good answer[ii]. In that, they suggested that with a pipe of constant diameter, the head losses through the nozzle were approximately equal to the friction losses equal to about 1/3 the frictional flow in the pipe.

Put in scientific terms, the friction head or h_f is equal to the value shown in Equation 2:

$H_f = (KQ_o^2/L^2)^* \, (l - l^2/L + l^3/L^2)$ Equation .2

Where K is the hydraulic coefficient equivalent to the head losses in the total length of the pipe at full flow conditions; L is the length of the pipe, *l* is the fractional length of the pipe where the losses are occurring, and Q_o is the total flow in the pipe at maximum conditions. Remember that you will need to have the head greater than the hydraulic head on the outside of the pipe.

Another way to look at the solution to the problem is to perform an analysis across the orifice. In a simple case we have $q_n = C*A_o^2*[2gh]^{0.5}$ If the value of C is 0.60, and the value of the large pipe flow is Q and the individual orifice value is q, and the hydraulic head differential between the inside of the pipe and immediately outside the pipe is h_d which accounts for the submergence of the pipe. If you set the nozzle losses greater than the pressure head against the pipe plus the pipe friction, the design works.

An example will help. I have a 3" pipe 300 feet long. I want to distribute 100 gallons per minute through it uniformly. Head losses through the length of the pipe are 4.47 feet of head loss per 100 feet. The pipe is submerged by 3 feet of water. The total head loss is then 4.47 * 3+3 = 16.41 feet of head or just about 5 PSIG.

I want to use 30 nozzles or orifices, and each one should take about 3.33 gpm.

The nozzle size should be $q = 0.60\ A^2[2gh]^{0.5}$ In the proper units q = 7.42*10-3 Cubic feet per second, $g = 32.18$ ft/ second^2 and h = 16.41 ft. Running the numbers that gives A^2 as $5.381*10^{-4}$ Square feet or 0.0775 square inches. That translates to a hole of approximately 0.0987 inches in diameter or a 3/32 inch hole. The water will flow out uniformly. The water will also flow in uniformly.

Compressible Flow

Compressible flow occurs in air and other gases. The formula must account for a few more variables such as the initial and final states and temperatures. As the air crosses the orifice it changes temperature, decreasing sharply as it expands from the nozzle. In order to prevent the formation from plugging into an ice flow, one must account for the change in temperature across the orifice, and preferentially keep the gas temperature above freezing to avoid ice formation.

The equations for compressible gas flow across a nozzle are a bit different.

For this we need to introduce an entire new set of terms:

In general, equation (2) is applicable only for incompressible flows. It can be modified by introducing the expansion factor to account for the compressibility of gases.

$$(3) \qquad \dot{m} = \rho_1 \, Q = C \, Y \, A_2 \, \sqrt{2 \, \rho_1 \, (P_1 - P_2)}$$

Y is 1.0 for incompressible fluids and it can be calculated for compressible gases.[3]

Calculation of expansion factor

The expansion factor Y, which allows for the change in the density of an ideal gas as it expands isentropically, is given by:

$$\mathrm{Y} = \sqrt{r^{\frac{2}{k}}} * \left(\frac{k}{k-1}\right) \{(1 - r\text{^}(k - 1/\mathrm{k}) \,/(1 - \mathrm{r})) * \; ((1 - \frac{\frac{\mathrm{dp\text{^}4}}{\mathrm{do}^4}}{1 - \left(\frac{\mathrm{dp}}{\mathrm{do}}\right)^4 \mathrm{r}\left(\frac{2}{\mathrm{k}}\right)}\}$$

$$Y = \sqrt{r^{2/k}\left(\frac{k}{k-1}\right)\left(\frac{1-r^{(k-1)/k}}{1-r}\right)\left(\frac{1-\beta^4}{1-\beta^4 \, r^{2/k}}\right)}$$

For values of β (ratio of orifice diameters) less than 0.25 β^4 approaches 0 and the last bracketed term in the above equation approaches 1. Thus, for the large majority of orifice plate installations:

$$(4) \qquad Y = \sqrt{r^{2/k}\left(\frac{k}{k-1}\right)\left(\frac{1-r^{(k-1)/k}}{1-r}\right)}$$

where:

Y = Expansion factor, dimensionless

r = P_2/P_1 (Absolute pressures)

k = specific heat ratio (c_p/c_v), dimensionless, but for air it is 1.4 which is good enough for most cases, unless one really has a heavy vapor concentration in the gas. Or get Cv and Cp from the Internet on sites such as: http://www.engineeringtoolbox.com/spesific-heat-capacity-gases-d_159.html

Substituting equation (4) into the mass flow rate equation (3): and making a few substitutions using the Gas Law, we get:

$$(5) \qquad Q_1 = C\, A_2 \sqrt{\frac{2ZRT1}{M}\left(\frac{k}{k-1}\right)\left[(\frac{P2}{P1}\right)^{\frac{2}{k}} - \left(\frac{P2}{P1}\right)^{\frac{k+1}{k}}}$$

Where T1 is the initial temperature,

and thus, the final equation for the non-choked (i.e., sub-sonic) flow of ideal gases through an orifice for values of β less than 0.25:

where:

k = specific heat ratio (c_p / c_v), dimensionless

m = mass flow rate at any section, kg/s

Q_1 = upstream real gas flow rate, m^3/s

C = orifice flow coefficient, dimensionless

A_2 = cross-sectional area of the orifice hole, m^2

$P1$ = upstream gas pressure, Pa with dimensions of $kg/(m \cdot s^2)$

$P2$ = downstream pressure, Pa with dimensions of $kg/(m \cdot s^2)$

M = the gas molecular mass, kg/mol (also known as the molecular weight)

R = the Universal Gas Law Constant = 8.3145 J/(mol·K)

$T1$ = absolute upstream gas temperature, K

Z = the gas compressibility factor at P1 and T1 and , dimensionless—but most of the time it is 1 for air at environmental temperatures generally encountered.

A final check of the velocity of the gas through the orifice, as it should not exceed the speed of sound and it should be checked for temperature to insure that the gas vapor which contains water will remain above freezing. This is important for both vacuum extraction and vapor venting horizontal wells (under pressure).

The entire program is easily arranged on an Excel spreadsheet, and the total orifice size and pressure drop and gas flow can be easily calculated. Then using the same essential data, select a drill size and a spacing which is suitable to the length of the horizontal well. A brief calculation of the total orifice size and appropriate area is very straight forward and easily performed.

The procedure is a bit of trial and error to find the right quantity and orifice size, but well worth the trouble. An installation of 12 lines of 1600 feet each in the Louisiana clays successfully removed over 100 tons of chloroform and carbon tetrachloride in the ground in a period of around 6 months. The figures are not precise because the air permit had to be re-drafted when the site started to over run their air permit for toxics discharge. The air control equipment required 99.9% removal, and the remedial equipment was in danger of exceeding the permitted limit of 10 tons of toxics discharged to the air.

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[i] Water Resources Bulletin, Vol 28, No 3, June 1992, American Water Resources Association. Article by Duchene and McBean

[ii] Water Supply and Wastewater Disposal, by GM Fair and GC Geyer, John Wiley and Sons, NY, pp686-689