Autonomous Flow Control Valve or "intelligent" ICD

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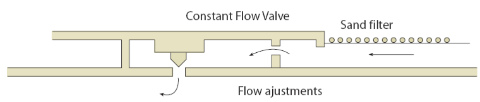
Abstract

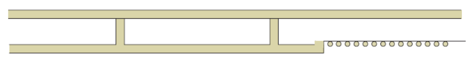
Long horizontal wells require Inflow Control Devices (ICD) to optimize production and to maximize recovery. Water or gas coning have previously led to major losses, so ICDs are always installed in these types of wells.

The ICDs in current use consists of restrictions to create pressure drop and to reduce flow rate locally. However, the flow rate depends on the pressure drop. With depletion the pressure profile will therefore change, and may still cause coning at late production times.

This note presents a new invention, an autonomous ICD that maintains constant flow rate over the life of the field, eliminating water or gas coning. Furthermore this ICD can be tailored to follow any wanted flow profile, and is therefore an important tool for optimal reservoir management.

Increased recovery is the main advantage with the new valve.





Background

Norsk Hydro (now integrated into Statoil) is the operator with most long horizontal wells on the Norwegian Continental Shelf. In the early 1990s a number of thin reservoirs required long wells, but to Norsk Hydros surprise, water breakthrough came very early. The conclusion was that these wells were subjected to water coning. These types of wells are always equipped with ICDs to delay water breakthrough. Norsk Hydro applied for patents for this first ICD technology. This will be discussed later.

Figure 1 shows a typical coning problem in a long well in a thin reservoir. Because the production tubing is very long, there is a considerable pressure drop in the tubing itself. The oil at the far end (the toe) has to overcome this pressure drop. The oil at the heel does not see this pressure drop. The consequence is that the flow rate is higher at the heel than at the toe. The area close to the heel will produce more hydrocarbons, resulting in coning of the water-oil-contact or the gas-oil-contact. When water or gas production start, the process will accelerate. Over time water production increases, leading to reduction in oil production and water disposal problems. More important is the recovery aspect. Most of the oil near the toe will not be produced, and new wells are required to drain this. The recovery aspect is of extreme importance for the wells.

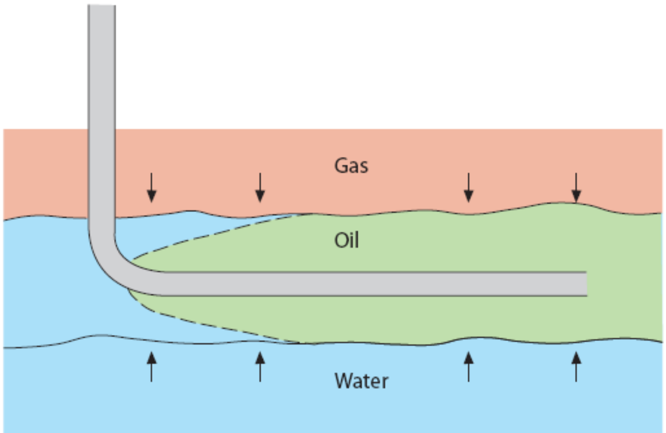


Figure 1: Coning in a long horizontal well.

To overcome this problem ICDs are installed at every connection in the production tubing. Figure 2 shows that by applying flow restrictions, coning can be reduced. Ideally the entire water (or gas)-oil-contact should be parallel to the production tubing. If the waterfront enters the tubing over the entire length, ultimate recovery has taken place.

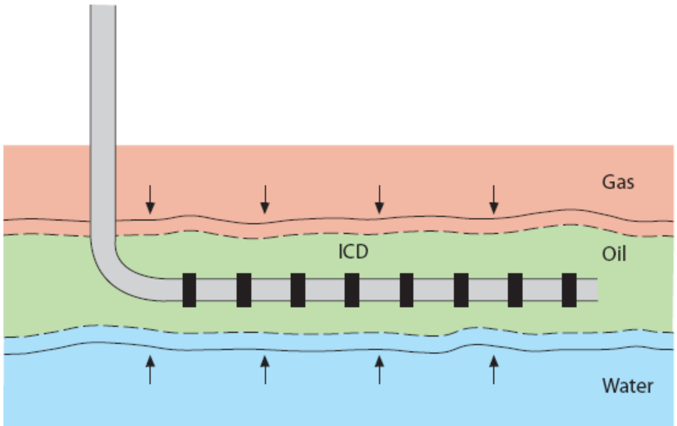


Figure 2: Avoiding coning by applying ICDs.

Limitation with current ICDs

The Appendix discusses the most important ICDs that are offered today. They are all based on a restriction principle, and can simply be modelled as a nozzle.

Because of reliability in a harsh environment, more complicated mechanisms requiring electronics are avoided. These inflow restrictions are very reliable. To minimize erosion, ceramic inserts are often used. They are very functional and the individual flow rates are simply obtained by plugging several of the 10 nozzles prior to installation. To sum up, they are robust and function well.

There is one major drawback. This relates to flow changes as the reservoir pressure declines. This will be explained in the following.

<u>There are three different pressure drops that control the fluid flow in a long horizontal well:</u>

- The reservoir drawdown pressure controls the flow capacity of the well. Other parameters of the radial flow equation are the permeability, exposed rock area and the fluid viscosity.

- The pressure drop along the horizontal production tubing leads to inflow coning at the heel of the well. This pressure drop is a function of the cumulative flow throughout the production tubing. For the high capacity wells in Norway we have laminar flow (viscosity dependent) at the toe. As the cumulative flow increases towards the heel, the flow becomes turbulent (density dependent). The flow rate versus pressure drop is highly non-linear and varies with the degree of depletion.

- The pressure drop characteristic across the Inflow Control Device is also an important parameter. Modelling shows that the restriction has normally turbulent flow, which is density dependent and non-linear.

Hydraulic flow in a conduit can in simple terms be explained as:

Laminar flow: $\Delta P \sim \mu Q$
Turbulent flow: $\Delta P \sim \rho Q^2$

where: ΔP is the pressure drop
Q is the flow rate
μ is the fluid viscosity
ρ is the fluid density

Furthermore, the inflow from the reservoir is defined by Darcy's law:

$$\Delta P = \frac{Q\mu}{2\pi kh} \ln\left(\frac{r_e}{r_w}\right)$$

To model the oil flow from the reservoir to the vertical production tubing, one starts from the reservoir, through the ICDs, into the production tubing, and finally the cumulative flow through the tubing. The pressure drop this oil is exposed to is as follows:

- Laminar flow from the reservoir (viscosity dependent)
- Turbulent flow through the ICD (density dependent)
- Laminar/turbulent through the production tubing (both viscosity and density dependent).
- Turbulent from the heel of the well.

Clearly the pressure drop flow rate relationship for the well is complex and highly non-linear. It is also sensitive to fluid viscosity which can vary considerably. When the reservoir pressure declines, the relative flow through the various ICDs will therefore change. Simulations show that coning may still occur during reservoir depletion.

The FloReg™ ICD[1]

There are severeal ICDs on the market, Weatherfords FloReg™, Baker Oil Tools Equalizer™, Schlumbergers (Reslinks) ResFlow™, and several Norsk Hydro patents. A brief description is presented in the Appendix. All these have in common that they function as a nozzle. For the FloReg™, ten nozzles are used, and the flow is varied by plugging one or more of these nozzles. Below is the performance characteristic for this tool.

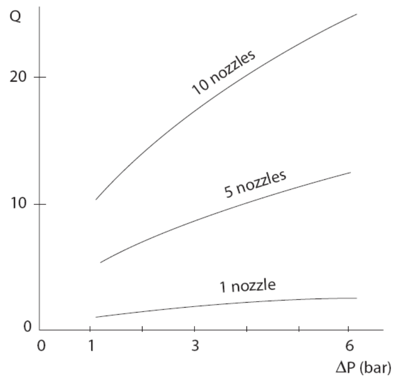


Figure 3: Flow rate – Pressure drop simulations for the FloReg™ ICD.
Curves for 1, 5 and 10 nozzles are shown.

The non-linear characteristic is clearly seen in Figure 3. There is one way to overcome the problem outlined above, and that is to control the flowrate over the entire life of the reservoir. This is explained in the following.

The BECH autonomous flow control valve (patent pending)

It is obvious that the non-linearity of traditional ICDs leads to relative flow change between the heel and the toe of the horizontal well during depletion.

The new invention overcomes the drawback simply by providing constant flowrate regardless of the state of the pressures. The flowrate will remain constant during the entire depletion phase. During installation the valves will be set to ensure that the entire reservoir is depleted before water or gas breakthrough.

The new valve is actually a constant flow controller. Figure 4a shows the simplest version. One observes that it only consist of a spring-loaded membrane with a needle, keeping the simplicity and robustness. The reservoir pressure is choked through a nozzle. The required flow rate is set here. The oil goes into a chamber where the compensator is consisting of a needle and a nozzle. When the reservoir pressure drops, the needle will open maintaining constant flow. Figure 4b shows another design where the membrane is replaced by a piston. In this case, a seal is provided on both sides of the piston to avoid dirty oil to plug piston movement.

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[1] *FloReg is a registered trademark by Weatherford Corp.*
Equalizer is a registered trademark by Baker Hughes Inc.
ResFlow is a mark of Schlumberger Ltd.

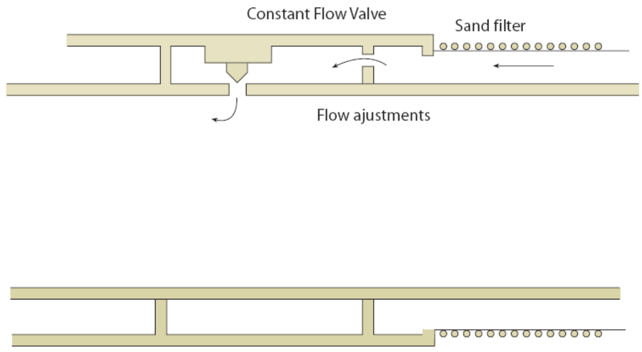

Figure 4: Principle of the BECH autonomous flow control valve.

Figure 5 shows the flow characteristics of the new valve as compared to a traditional ICD. The new valve can be calibrated both for constant flow, increasing flow and decreasing flow as shown in Fig. 5. This means that for complex reservoirs an optimal design can always be found. The new ICD can actually be used as a *designer ICD* for advanced reservoir depletion design.

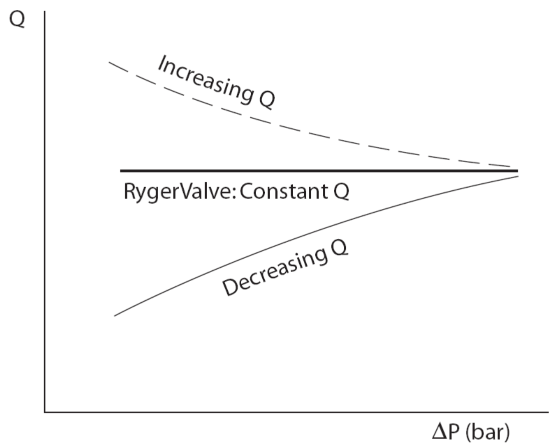

Figure 5: Performance characteristics for the BECH autonomous flow control valve. The horizontal axis is the pressure drop from the reservoir to the production tubing.

How the BECH autonomous flow control valve ("designer ICD") works

Figure 6 shows two different designs. The major principle is that we need a flow adjustment part. This can be obtained by using a screw or a needle, or plugging a number of nozzles to obtain the desired rate. This section can be termed the *flow set point*.

The flow goes into a chamber which has a lower pressure due to the set point restriction. Here is a spring loaded membrane or piston that is connected to a needle. This is termed the *compensation* part. If the pressure from the reservoir or inside the production tubing varies, the piston will move accordingly and ensure a constant flow through the piston/nozzle that enters the production tubing.

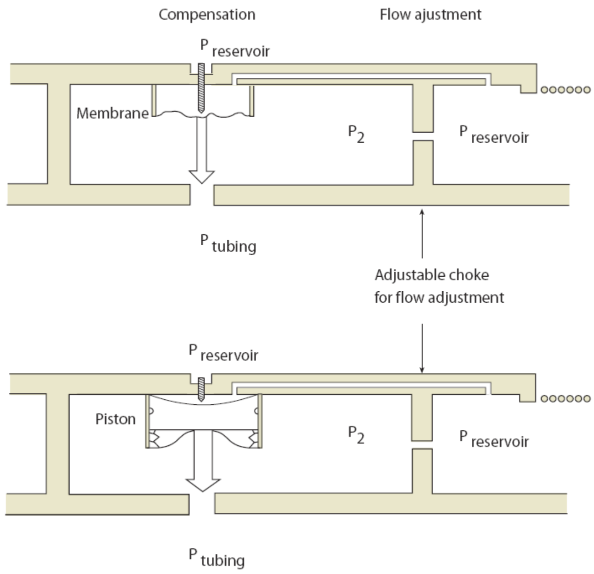

Figure 6: Two designs, upper a membrane, lower a piston.

Figure 6 shows a design of a prototype valve. It can be designed with a spring loaded piston acting on a needle in a nozzle, or it can simply be design as a membrane. The membrane must of course have a spring constant mimicking the function of the piston version.

In the following will the physics be explained:
The reservoir pressure is reduced through the flow setting nozzle. A force balance on the piston gives:

$$P_{reservoir}A - P_2A - KX = 0$$

A force balance between the chamber and the production tubing gives:

$$P_2 - P_{tubing} = K_v \rho Q^2$$

where: $P_{reservoir}$ = reservoir pressure on the outside of the system
P_2 = pressure in chamber after flow setting
P_{tubing} = pressure in production tubing
A = area of piston
X = displacement of spring loaded piston
K_v = nozzle constant
K = spring constant
ρ = fluid density
Q = flow rate of fluid

Combining the equations above results in the characteristic equation for the constant flow rate controller:

$$P_{reservoir} - P_{tubing} = \frac{KX}{A} + K_v \rho Q^2$$

$$Q = \sqrt{\frac{1}{K_v \rho}\left\{\left(P_{reservoir} - P_{tubing}\right) - \frac{KX}{A}\right\}}$$

The spring force *KX* is calibrated to move when the differential pressure is varied. The expression under the root sign of the expression above is always constant, leading to a constant flow rate. A large differential pressure leads to a large displacement *X*, such that:

$$P_{reservoir} - P_{tubing} = \frac{KX}{A}$$

It is well known that the density is fairly constant over the lifetime whereas the viscosity may vary considerably. One of the properties of the constant flow valve is that it is only sensitive to fluid density, not to viscosity.

Figure 7 illustrates a design of a prototype valve. To avoid impurities to enter the mechanism, the entire piston is oil-filled and enclosed within two seals.

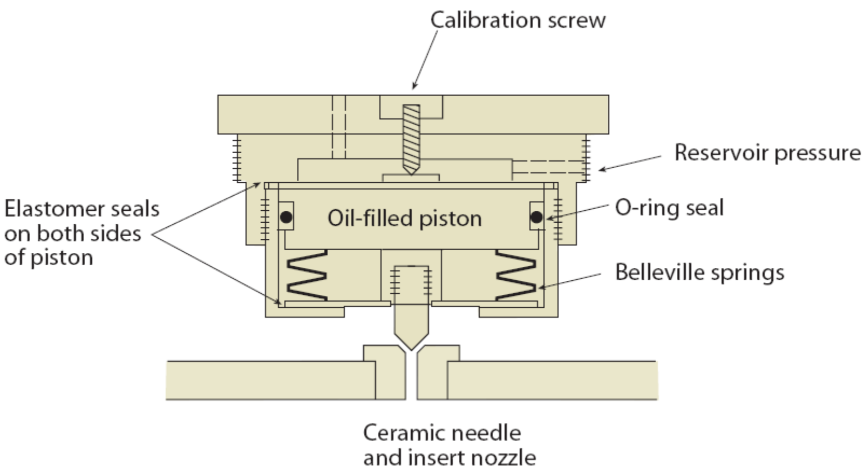

Figure 7: Prototype design of the BECH autonomous flow control valve

Status of the BECH autonomous flow control valve

We foresee the following products from this technology:

- Constant flow ICD will be the main product. These are easy to apply as the individual flow rates depend on the permeability distribution. Because it gives constant flow we do not need to be concerned about reservoir pressure depletion.

- The BECH autonomous flow control valve can also be calibrated for increasing flow if difficult reservoir conditions demands it. Examples are if both WOC and GOC are approaching the wellbore, or if the well is intersecting two reservoirs with no communication. For this case the valve can be calibrated for both increasing or decreasing flow with reservoir pressure depletion.

Abbreviations:

ICD	Inflow control device
WOC	Water-oil contact
GOC	Gas-oil contact

Appendix A: Current IDC Technology

There exist a number of patents regarding inflow control technology, but a few major players mainly cover the commercial market. In the following will a short description be given of the dominating suppliers, by discussing some central patents.

Baker Oil Tools
To our knowledge Baker is the major supplier of ICD technology today. Their main product is the Equalizer ICD. It differs from others because the flow restriction is not a nozzle, but a helical path around the pipe, providing for a long narrow conduit causing pressure drop. It is still just a restriction, where the flow rate changes with the pressure drop.

Schlumberger-Reslink
Schlumberger acquired Reslink in 2006 mainly to obtain the rights for their ICD technology. Their product is called ResFlow. It consists of a number of nozzles placed around a collar. The flow rate is chosen by plugging a given number of nozzles. The flow rate is also here changing with the pressure drop.

Weatherford
Weatherford is another major supplier of ICD technology. Presently they are licensing from Norsk Hydro. At present they offer the FlowReg tool, which functions similarly to Reslinks Resflow tool, although there are differences in design.

Weatherford has also patented other types. US 6,371,210 B1 shows a variable flow valve consisting of a spring-loaded sliding sleeve. This type of tool is difficult for several reasons. Firstly, the control action is based on a dynamic pressure across the sleeve. These solutions are inherently unstable. Our solution is based on a static pressure drop, providing a much more stable solution. Secondly, the sliding sleeve is subjected to friction and also exposed to debris, which can easily lock the sleeve. Remember also that for the ICD there is a relatively small pressure drop so friction may easily be larger than the forces on the sleeve.

Norsk Hydro (now Statoil)
This company operates most of the long horizontal wells on the Norwegian Continental Shelf. In the early 1990's Norsk Hydro got water breakthrough after producing a horizontal well for a short time. At this time, water and gas coning became utmost important for reservoir management. In 1993 Norsk Hydro obtained a patent for an ICD. This patent has to our knowledge been licensed to several completion string suppliers. The core of the patent is a restriction or a nozzle that reduces flow rate. Both Reslinks and Weatherfords ICD may be considered related to Norsk Hydros patent.