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Comparative Study on Passive Inflow Control Devices by Numerical Simulation

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Abstract: In long horizontal wells, the production rate at the heel is typically higher than that at the toe. The resulting imbalanced production profile may cause early water or gas breakthrough into the wellbore. Once coning occurs, well production may severely decrease due to limited flow contribution from the toe. To eliminate this imbalance, inflow control devices (ICDs) are placed in each screen joint to balance the production influx profile across the entire lateral length and to compensate for permeability variation.

Currently, there are four different Passive ICD designs in the industry: nozzle-based, helical channel, tube-type and hybrid channel. They respectively use restriction mechanism (nozzle-based), friction mechanism (helical channel) or both mechanisms (tube-type and hybrid channel) to achieve a uniform inflow profile. However, the reality is that none of these ICDs alone meets the ideal requirements of an ICD designed for the life of the well: high resistance to plugging and erosion, high viscosity insensitivity. Therefore, the selection and optimization of ICDs for a specific reservoir are still required to be further studied.

In this paper, 4 numerical models of these ICDs with same flow rating resistance were developed to characterize the flow performance based on computational fluid dynamics. The results show that the throttle pressure drop depends mainly on fluid properties, flow rate and geometry parameters of each ICD. For all four ICDs, the throttle pressure drop increases along with fluid viscosity, density and flow rate. The helical channel ICD occupies first place with corrosion resistance, while hybrid channel ICD has least viscosity sensitivity. The parameter optimization of each ICD was researched as well. For a specific reservoir, we will have the ICD with a best pressure drop composition by optimizing its structural parameter, which has a best corrosion resistance and least viscosity sensitivity.

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1 Introduction

In long horizontal wells, the production rate at the heel is typically higher than that at the toe. The resulting imbalanced production profile may cause early water or gas breakthrough into the wellbore. Once coning occurs, well production may severely decrease due to limited flow contribution from the toe. To eliminate this imbalance, inflow control devices (ICDs) are placed in each screen joint to balance the production influx profile across the entire lateral length and to compensate for permeability variation.

The purpose of inflow control device (ICDs) is to effectively balance well production throughout the entire operational life of the completion to optimize hydrocarbon recovery. Since a typical well with ICDs can be in production from 5 to more than 20 years, the long-term reliability of such a device is crucial to the well's overall success. The significant factor in the reliability of an ICD is its ability to maintain a uniform influx over the well life. If an ICD is not able to maintain a uniform flux rate, increased localized production rates will occur and the well will become unbalanced. This will render the ICD ineffective, leading to premature water and/or gas breakthrough and possible loss of sand control. At some stage in a well's life, water may break through into the wellbore in certain sections due to heterogeneity of the formation and/or vertical fractures. Ideally, once this occurs, flow contribution from these water-producing zones should not be greater than the oil-producing sections.

An ICD must have certain performance features during every phase of a well's life to minimize or eliminate the undesirable results. At the beginning of drilling and production process, the ICD must have a high plugging resistance for drilling fluid, completion fluid and mud flow back assurance. If the minimum flow area of device is too small, it may plug during this period, and this failure can significantly reduce or even halt production. During peak production, the ICD will be exposed to high flow rates and must be erosion-resistant. If erosion or plugging occurred at this stage, it is deemed ineffective. In the production decline stage, an ICD must continue to provide inflow control. If an ICD is not able to maintain a uniform flow, increased localized production will occur and lead to premature water or gas breakthrough. At eventual water onset, the ICD should provide an increase to flow resistance. If the flow resistances created by water and oil are equal or not much difference, the ICD will have not enough capability for oil producing and water controlling.

2 Modeling and Analysis

Currently, there are four primary types of passive ICD designs in the industry: nozzle-based (restrictive), helical channel (frictional), tube-type (combination of restrictive and friction) and hybrid channel (combination of restrictive, some friction and a tortuous pathway). They use four different methods to generate a pressure drop.

Since typical long horizontal wells required inflow control are in completion with multiple ICDs, the design flow rate in this paper ranges from $0\sim30\text{m}^3/\text{D}$. All the four ICDs are designed to have the same flow resistance rating (FRR) of 0.8, the numbers of FRR represent the equivalent pressure drop magnitude expected in pressure units of bar when flowing at the following conditions: fluid density of 998.2kg/m^3, fluid viscosity of 1cP, and flow rate of $30\text{m}^3/\text{d}$ [Abdelfattah, Banerjee, Garcia et al. (2012)].

All the mechanical models of these four designs are developed withSOLIDWORKS, which then imported to GAMBIT where hydraulic model was obtained by using boolean operation and subsequently mesh was generated. Each of these designs has two inlets and one outlet. Both annulus inlet and base pipe inlet are set as velocity-inlet in FLUENT, while outlet set as outflow and the rest as wall. For flow direction assurance, the base pipe inlet is setup with a flow rate of $5\text{m}^3/\text{d}$. Since the gravity influence is so small in the models, we do not take it into consideration. By using SOLIDWORKS, GAMBIT as pre-processing and FLUENT as post-processing, three-dimensional modeling (Fig.1), meshing (Fig.2) and results (Fig.3) viewing were accomplished.

The pressure distribution of the four designs is shown in Figure 4. Owing to different mechanisms, ICDs show different mechanical geometries, and the pressure loss occurs at different position vary a lot both in range and methods.

The nozzle-based ICD uses fluid constriction to generate an instantaneous differential pressure across the device [Vela, Viloria-Gomez, Caicedo et al. (2011)]. This method essentially forces the fluid from a larger area down through small diameter ports, creating a flow resistance. The benefits of nozzle-based ICD are its simplified design and easier adjustment immediately before running in a well should real-time data collected during the well indicates the need to change flow resistance. The disadvantage of nozzle-based ICD is the small diameter ports required to create flow resistance, which make it prone to both erosion from high-velocity fluid-borne particles during production and susceptible to plugging, especially during any period where mud flow back occurs.

The helical channel ICD uses surface friction to generate a differential pressure across the device [Visosky, Clem, Coronado et al. (2007)]. The helical channel de-

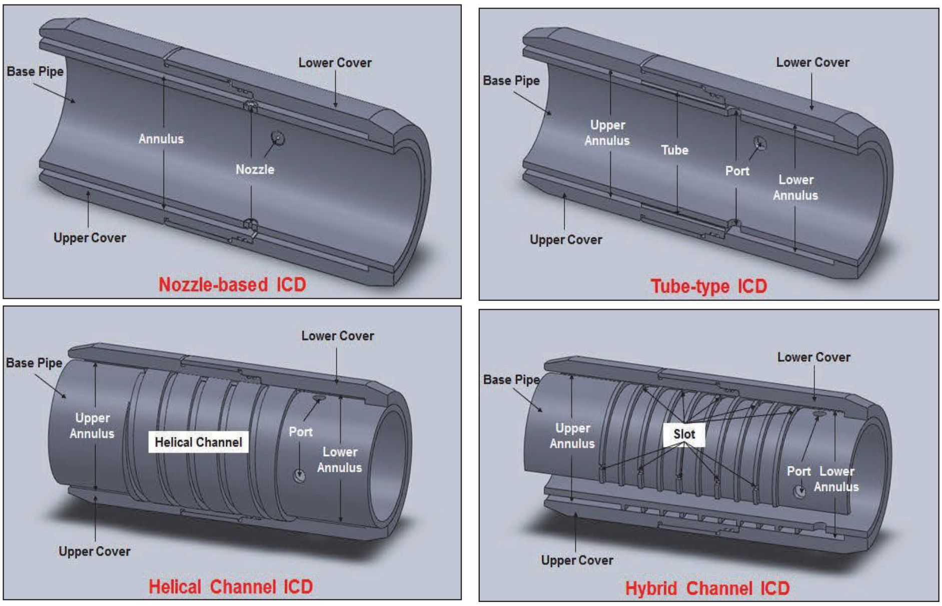

Figure 1: Half Section View of Each ICD.

sign is one or more flow channels that wrapped around the base pipe. This design provides for a distributed pressure drop over a relatively long area, versus the instantaneous loss using a nozzle. Because the larger cross-sectional flow area of the helical channel ICD generates significantly lower fluid velocity than the nozzles of a nozzle-based ICD with a same FRR, the helical channel ICD is more resistance to erosion from fluid-borne particles and resistant to plugging during mud flow back operations. The disadvantage of helical-channel ICD is its flow resistance is more viscosity-dependent than the nozzle-based ICD. This characteristic could allow preferential water flow should premature water breakthrough occur.

The tube-type ICD design incorporates a series of tubes. The primary pressure drop mechanism is restrictive, but in long tubes [Youl, Suhana, Regulacion et al. (2011)]. This method essentially forces the fluid from a larger area down through the long tubes, creating a flow resistance. Because of the additional friction resistance, the larger cross-sectional flow area of the tube-type ICD generates lower fluid velocity than the nozzles of a nozzle-based ICD with a same FRR, the tube-type ICD is more resistance to erosion from fluid-borne particles and resistant to plugging during mud flow back operations. However, since the friction resistance is much less than the local resistance, the tube-type ICD is less viscosity-dependent than the helical channel ICD with a same FRR.

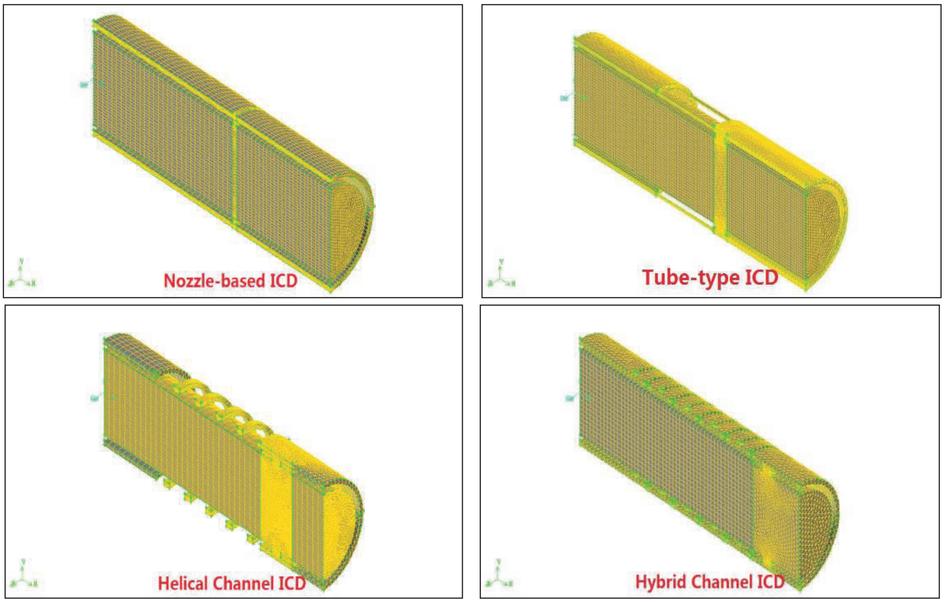

Figure 2: Half Section View of Computing Grid.

The hybrid ICD design incorporates a series of flow slots in a maze pattern [Garcia, Coronado, Russell et al. (2009)]. Its primary pressure drop mechanism is restrictive, but in a distributive configuration. A series of bulkheads are incorporated in the design, each of which has one or more flow cuts at an even angular spacing. Each set of flow slots are staggered with the next set of slots with a phase angle thus the flow must turn after passing through each set of slots. This prevents any jetting effect on the flow path of the downstream set of slots which may induce turbulence. As the production flow passes each successive chamber that is formed by bulkheads, a pressure drop is incurred. Pressure is reduced sequentially as the flow passes through each section of the ICD. Without the need to generate the pressure drop instantaneously, the flow areas through the slots are relatively large when compared to the nozzle design of same FRR, thus dramatically reducing erosion and plugging potential.

However, according to previous analysis, the reality is that none of these ICDs alone meets the ideal requirements of an ICD designed for the life of the well: high resistance to plugging, erosion and high viscosity insensitivity. Thereby the ICD selection and parameters optimization for a specific reservoir still requires for further study.

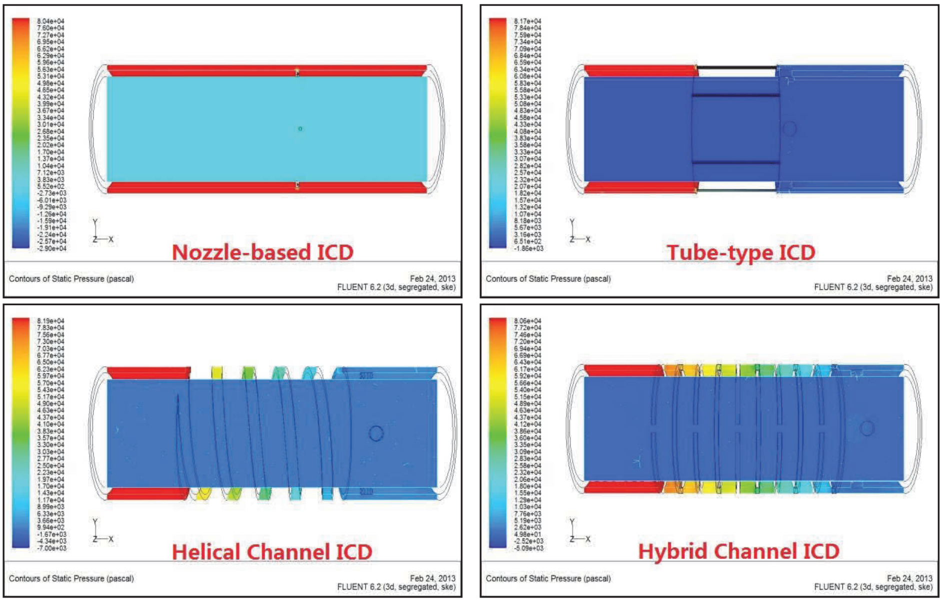

Figure 3: Contours of Static Pressure.

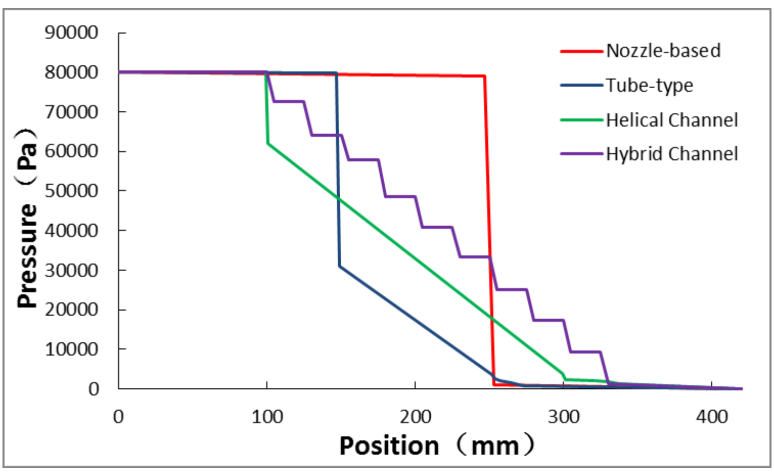

Figure 4: Pressure Distribution Graph.

3 ICD Type Selection and Parameter Optimization

In order to improve ICD type selection, as well as generate and unify the comparison criteria, four ICD geometries with same FRR were flow-tested as previously described. However, as is observed above, not all ICD geometries have the same flow performance characteristic. Therefore, it is not straight forward to determine which ICD geometry would offer a best performance under specific operational conditions.

Since the function of ICDs is adapted to FRR, if the FRR of an ICD doesn't match the specific reservoir section in completion using multiple ICDs, increased localized production will occur and lead to premature water or gas breakthrough. Thereby the relationships between FRR and structural parameters of each ICD require for further researched. It is necessary to optimize the structural parameters of each ICD, thereby the optimized ICDs placed at specific reservoir section can maintain a uniform flux rate. Although not all ICDs have same geometry and structural parameters, the parameters that affect the FRR can sum up in minimum flow area (restrictive) and flow path length (friction).

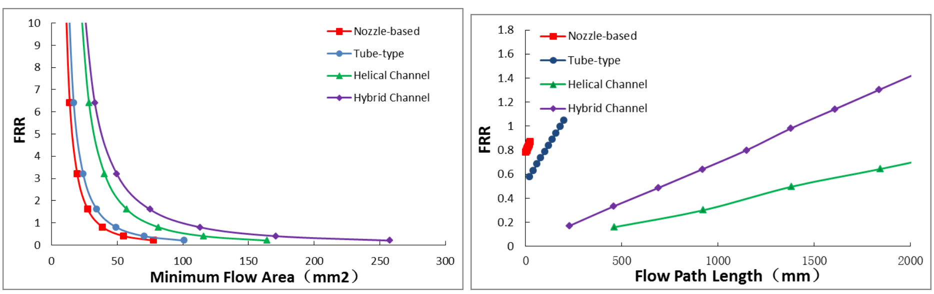

Figure 5: FRR verus Structural Parameters of Each ICD.

The relationships between FRR and minimum flow area are shown in Figure 5. The FRR of these four designs increases rapidly with the decrease of minimum flow area. During production, formation fines that are produced through the screen also pass through the ICD. The fines can and will erode an ICD over time if the fluid velocity is high enough and fines are in the flow scream. If the device has eroded seriously, it is deemed ineffective. The rate of erosion will depend on the following factors: particle size, particle concentration, and fluid velocity. The first two factors are dependent on well conditions, while the third is dependent on ICD geometry and design. As previously described, these four ICDs use different methods to generate a pressure drop, which perform as different mechanical geometries. The minimum flow area plays a very important role in the ICD selection for high-velocity fluid since it would affect the erosion resistant and plugging probability. Since the helical channel ICD uses frictional mechanism to generate the pressure drop instead of restrictive, its larger minimum flow area generates significantly lower fluid velocity than the nozzles of a nozzle-based ICD to achieve the same FRR. The nozzle-based ICD crosses FRR=0.8 at the 39.37mm^2 mark, the tube-type at 49.16mm^2, the helical channel at 81.25mm^2, and the hybrid channel at 113.75mm^2. This indicates that for the four designs tested, helical channel ICD is most resistance to erosion from fluid-borne particles and resistant to plugging during mud flow back operations. A helical channel ICD thus will provide best results in this regard due to its both lager minimum flow area and smaller maximum flow velocity.

The relationships between FRR and flow path length are shown in Figure 5. The FRR of these four designs increases linearly with flow path length. The point where the curves cross Y-axis is where the frictional flow resistance is 0 in theory. The hybrid channel ICD crosses the Y-axis at the 0.0034 FRR mark, the helical channel at 0.0351 FRR, the tube-type at 0.5362 FRR and the nozzle-based ICD at 0.7698 FRR. This indicates that for the four designs tested, the nozzle-based mainly depends on restrictive mechanism, while the hybrid channel and helical channel depend on frictional. The FRR increase of nozzle-based ICD is higher than the other ICDs due to its higher maximum flow velocity. However, since the flow path length of nozzle-based ICD is so short, its impact on FRR has been small. On the contrary, the flow path length has a great effect on FRR of helical channel and hybrid channel ICD.

Since not all ICD geometries have the same flow performance characteristic, pressure drops created by different fluids through the four ICDs (with the same FRR) vary a lot. In this regard, fluid property is a key performance characteristic that need to be considered when selecting the proper ICD configuration for an application. Thereby it's necessary to develop three projects to describe annulus flow rate, density, and viscosity sensitivity of all these four designs (with a same FRR of 0.8).

Project 1 researched on annulus flow rate sensitivity. Annulus flow rate (m3/D) as follows: 0, 2.5, 5, 10, 20, 30. The relationships between annulus flow rate and pressure drop change of different designs (compared to 30m3/D) are shown in Figure 6. The pressure drop of all these four designs increases with the annulus flow rate, and the increase is higher and higher. The annulus flow rate sensitivity of these designs is nearly the same, with nozzle-based ICD more sensitivity under a low flow rate while tube-type under a high flow rate.

Project 2 researched on fluid density sensitivity. Since typical density of oil, water and the mixed range from 800 to 1000kg/m3, fluid density (kg/m3) as follows: 800, 850, 900, 950, 1000. The relationships between fluid density and pressure drop change of different designs (compared to 1000kg/m3) are shown in Figure 6. The pressure drop of all these four designs increases linearly with fluid density. The fluid density sensitivity of these four designs is not that difference, with nozzle-based ICD the most sensitivity, hybrid channel ICD the second, helical channel ICD the third, and tube-type ICD the least.

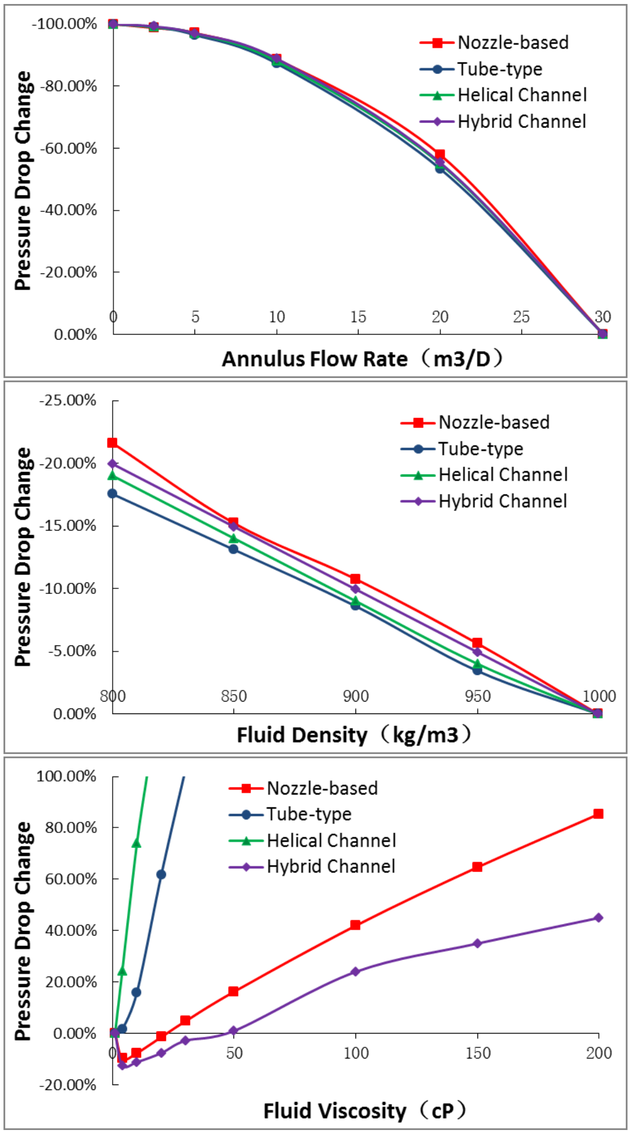

Figure 6: Sensitivity Analysis of Fluid Parameters

Project 3 researches on fluid viscosity sensitivity. Since typical viscosity of oil, water and the mixed range from 1 to 200cP, fluid viscosity (cP) as follows: 1, 4, 10, 20, 30, 50, 100, 150, 200. The relationships between fluid viscosity and pressure drop change of different designs (compared to 1 cP water) are shown in Figure 6. The pressure drop of all these four designs increases with fluid viscosity. The point where the curves cross X-axis is where the higher-viscosity fluid has the same pressure drop as water. The helical channel ICD crosses the X-axis at the 1cP mark, the tube type at 5 cP, the nozzle-based at 23 cP and the hybrid channel ICD at 50 cP. This indicates that for the four designs tested, the hybrid channel ICD is the most insensitive to viscosity variations. In production wells with higher-viscosity oil (more than 10 cp.), ICD type selection becomes a critical factor due to the larger difference in viscosity between the oil and produced water. The pressure reduction mechanism in an ICD in this situation must have the lowest sensitivity to viscosity to exhibit an increase in resistance to flow if premature water breakthrough were to occur, thereby maintain an even flow profile across the entire lateral wellbore. A hybrid channel ICD thus will provide best results in this regard due to its lower sensitivity to viscosity.

Fig. 7 shows the pressure drop versus annulus flow rate for the ICDs with a same FRR of 0.8. Each ICD was tested with different fluid viscosities (water, 4, 30, and 200 cP). As can be observed, the nozzle-based and hybrid channel ICD are less fluid-viscosity-independent than the other two ICDs tested.

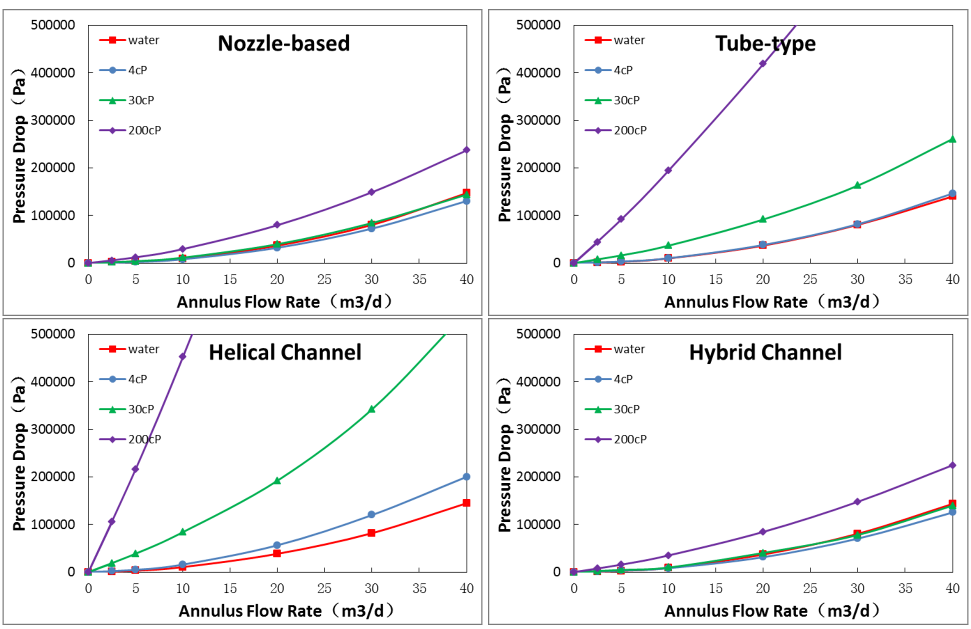

Figure 7: Comparison pressure loss data through various ICD types and designs with varying flow rates and fluid viscosities.

Above all, ICD type selection mainly depends on minimum flow area and viscosity sensibility. In production wells with higher-viscosity oil, the pressure reduction mechanism in an ICD in this situation must have the lowest sensitivity to viscosity to exhibit an increase in resistance to flow if premature water breakthrough were to occur due to the larger difference in viscosity between the oil and produced water, thereby maintain an even flow profile across the entire lateral wellbore. The nozzle-based and hybrid channel ICD thus will provide best results in this regard due to their lower sensitivity to viscosity. In production wells with higher-velocity, the ICD in this situation must have the larger cross-sectional flow area which generates significantly lower fluid velocity, thereby the ICD is more resistance to erosion from fluid-borne particles and resistant to plugging during mud flow back operations. The helical channel and hybrid channel ICD thus will provide best results in this regard due to its both lager minimum flow area and smaller maximum flow velocity.

4 Conclusions

- Although not all ICDs have same geometry and structural parameters, the parameters that affect FRR can sum up in minimum flow area (restrictive) and flow path length (friction). And FRR increases with flow path length and the decrease of minimum flow area.

- The pressure drop of all these four designs increases with the annulus flow rate, density and viscosity. However, pressure drops created by different fluids (especially the viscosity) through the four ICDs vary a lot.

- ICD type selection mainly depends on minimum flow area and viscosity sensibility. In production wells with higher-viscosity oil, the nozzle-based and hybrid channel ICD will provide best results in this regard due to their lower sensitivity to viscosity. In production wells with higher-velocity, the helical channel and hybrid channel ICD will provide best resistance to erosion and plugging in this regard due to its both lager minimum flow area and smaller maximum flow velocity.

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