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# A novel autonomous inflow control device design and its performance prediction

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ABSTRACT

In long horizontal wells, premature water or gas breakthrough is usually encountered due to the imbalanced production profile. This imbalanced phenomenon could be caused by the heel–toe effect, reservoir anisotropy, reservoir heterogeneity or natural fractures. Once coning occurs, water/gas fast track will be generated, leading to the reduction in oil production. Inflow control devices (ICDs) are usually installed in the completion sections to maintain a uniform inflow by generating an additional pressure loss. However, none of current ICDs are perfect enough to meet all the ideal requirements throughout the well's life.

In this paper, a novel autonomous inflow control device (AICD) design is proposed based on the combination of two fluid dynamic components, with the splitter directing the flow, and the restrictor restricting the flow. Based on the combination of the flow pattern transformation criterion, homogenous model, two-fluid model, and pipe serial–parallel theory, a unified model of oil–water two-phase flow is developed to predict both the flow distributions and pressure drops through the splitter, which is then compared with the computational fluid dynamics (CFD) results. Also the rules of oil–water two-phase flow through the disk-shaped restrictor are studied by numerical simulation.

The results show that the unified model compares well with the CFD results. The average error percentage between the model and CFD results for flow distribution is 10.02%, while that for pressure drop is 11.25%. Both the model and CFD results show that the flow distributions in different paths of the splitter will be adjusted automatically according to the fluid's specific property, thus different fluids will enter the restrictor differently, and result in varying flow resistances. Specifically, oil, being more viscous, tends to take the restrictive path, enter the restrictor radially, and result in minimal flow restriction; while water, being less viscous, tends to take the frictional path, enter the restrictor tangentially, begin spinning rapidly near the exit, and result in obvious flow restriction. This autonomous function enables the well to continue producing oil for a longer time while limiting the water production; hence the total oil production is maximized. The investigation conducted in this study also further enriches the theory of hydrodynamic calculation for oil–water two-phase flow in complex pipelines.

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## 1. Introduction

In long horizontal wells, premature water or gas breakthrough is usually encountered due to the imbalanced production profile. This imbalanced phenomenon could be caused by the heel–toe effect, reservoir anisotropy, reservoir heterogeneity or natural fractures (Wang et al., 2011). Once coning occurs, water/gas fast track will be generated, and then oil production may severely decrease due to the limited flow contribution from the non-coning regions. To eliminate these issues, inflow control devices (ICDs) are placed in the screen joints to balance the production inflow profile across the lateral length and to compensate for permeability variations (Grubert et al., 2009; Livescu et al., 2010).

Currently, various ICDs have been developed in the industry. These ICDs can be divided into passive inflow control devices (PICDs) and autonomous inflow control devices (AICDs). They are distinguished by the fact that whether their flow resistance ratings (FRRs) are constant. The PICDs are usually installed to maintain a uniform inflow by generating an additional pressure drop. They

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**Nomenclature**

| | |
|---|---|
| $A$ | cross section area, m$^2$ |
| $C$ | coefficient, dimensionless |
| $d$ | hydraulic diameter, m |
| $f$ | Moody wall friction coefficient, dimensionless |
| $g$ | gravitational acceleration, m/s$^2$ |
| $L$ | length of pipe, m |
| $n$ | number, dimensionless |
| $p$ | pressure, Pa |
| $Q$ | flow rate, m$^3$/day |
| $R$ | bending radius of the elbow, m |
| Re | Reynolds number, dimensionless |
| $S$ | wetted perimeter, m |
| $v$ | velocity, m/s |
| $\alpha$ | pipe inclination angle from horizontal, degree |
| $\gamma$ | half the radian corresponds to the wetted perimeter of lower water layer, rad |
| $p$ | pressure drop, Pa |
| $\eta$ | volumetric fraction, dimensionless |
| $\theta$ | bending angle of the elbow, rad |
| $\mu$ | viscosity, Pa s |
| $\rho$ | density, kg/m$^3$ |
| $\sigma$ | tension, N/m |
| $\tau$ | wall friction, Pa |

*Subscript*

| | |
|---|---|
| *c* | continuous phase |
| *con* | contraction cross section |
| *cono* | contraction cross section oil |
| *conw* | contraction cross section water |
| *cr* | critical |
| *d* | dispersed phase |
| *D* | downstream |
| *Do* | downstream oil |
| *Dw* | downstream water |
| *e* | elbow |
| *f* | frictional path |
| *fp* | pipe in the frictional path |
| *i* | interface between oil and water layers |
| *inc* | inclination |
| *m* | mixture |
| *o* | oil |
| *p* | pipe |
| *r* | restrictive path |
| *rpe* | expanded pipe in the restrictive path |
| *rps* | shrunken pipe in the restrictive path |
| *sef* | sudden expanded fitting |
| *ssf* | sudden shrunken fitting |
| *U* | upstream |
| *Um* | upstream mixture |
| *Uo* | upstream oil |
| *Uw* | upstream water |
| *v* | velocity |
| *w* | water |

use the restriction mechanism (Aadnoy and Hareland, 2009; Vela et al., 2011), the friction mechanism (Brekke and Lien, 1994; Visosky et al., 2007), or incorporating both the mechanisms (Coronado et al., 2009; Garcia et al., 2009; Youl et al., 2011) to generate the pressure drop. Their FRRs are fixed, but unfortunately, once water/gas coning does occur, the low-viscosity water/gas will take over the well, thus rendering the PICD useless and decreasing the oil production significantly. AICD is a new concept, which will generate a much higher flow resistance once water/gas coning occurs, thereby the water/gas production is limited while the oil production is guaranteed. The Counterweight Flapper AICD (Crow et al., 2006) uses the difference between the oil and gas densities to control the opening or closure of a flapper; however, the movable flapper is prone to malfunction, and the device cannot control water coning effectively due to the small difference between the oil and water densities. The RCP valve (Aakre et al., 2013; Mathiesen et al., 2011, 2014) uses the balance of the dynamic pressure and static pressure to control the position of a movable disk; however, the disk may be damaged by the pressure difference exerted on it if the difference is larger than a certain value. And the Equiflow AICD (Least et al., 2012, 2013; Zhao et al., 2014) uses the balance between the inertial force and viscous force in the fluid to change the passages; however, the device has only a small oil viscosity range available for each specific design.

Since a typical well with ICDs is usually in production from 5 to more than 20 yr, the long-term reliability of such device is crucial to the well's overall success. Thereby the ICDs should satisfy specific requirements in every phase of the well's life, so as to minimize or eliminate the undesirable results (Zeng et al., 2013). However, none of current ICDs are able to accomplish that.

In this paper, a novel AICD design is proposed to overcome the limitations of current ICDs, and the development of such design concept is then described in detail. To better understand the directing performance of oil–water two-phase flow through the splitter, a unified model is developed, which is then compared with the computational fluid dynamics (CFD) results. Last but not the least, the rules of oil–water two-phase flow through the disk-shaped restrictor are also studied by numerical simulation.

## 2. Novel autonomous inflow control device design

The novel autonomous inflow control device (Fig. 1) is proposed based on the combination of two fluid dynamic components, with the splitter directing the flow, and the restrictor restricting the flow.

As it can be observed from Fig. 1, the splitter comprises two parallel flow paths from top to bottom, the restrictive path and the

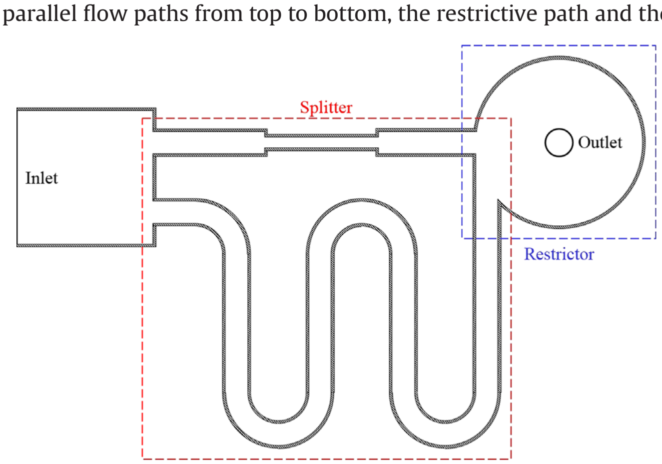


**Fig. 1.** Structure diagram of the novel autonomous inflow control device design.

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