A New Approach to Production Log Analysis

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This contribution presents a new approach to production log analysis. It employs a line search optimizing procedure to minimize the variance between log survey measurements and the equivalent predictions from theoretical physical models. The main features are:

- **Transfer functions** coupling the actual specific properties of the fluid elements to the sensor responses taking into consideration the constitutive physical relations and the physical rheology of the current flow pattern and fluid system in exposure to the sensor surroundings.

- **Dynamic flow models** are coupled in a continuity principle for mono- and multi-phase flow. For a given thermodynamic state and assumed flow flux, the phase velocities, flow regime, pressure gradient, velocity and distribution slip together with longitudinal and lateral heat transfer in the flow environments for the log survey are computed as a complete set of result parameters. The physical models are based on general continuity, constitutive relations and documented correlations.

- **Correlations for the physical fluid properties**, concerning density, viscosity and surface tension based on one or more references at definite thermodynamical states.

- **Statistical modules** for filtering, variance estimates, curve fits and regression analysis between general properties and parameters in the multiphase flow hierarchy.

- A **line search optimizing module** based on golden section unidimensional search. The search directions are based on a conjugated direction propagation principle. This line optimization splices together the operational log measurements and the theoretical predictions. The search is made with respect to the multiphase flow fluxes as free variables.

Applicability of the system goes beyond conventional PLT analysis in that the uncertainty of each sensor is brought into consideration in the analysis. The determination of a given flow parameter can hence be performed in a flexible manner with a quality-weighted utilization of the downhole readings. This approach is general in nature and can easily accommodate new logging and interpretation techniques as well as improvement in flow analysis.

**INTRODUCTION**

Production logging (PL) is one of the few tools available for direct monitoring of the dynamic reservoir and well inflow performance. Especially in the mature stages of field production, it has proved vital to the understanding of reservoir depletion, cross-flow, breakthrough and coning problems or recompletion requirements. Traditionally, however, PL-data has been used mainly for qualitative analysis, the reason most probably being the unreliability of existing models in describing the complex multiphase well inflow behaviour. Consequently a vast amount of information collected in expensive PL operations is rarely actively used for quantitative reservoir-management purposes.

This has been the motivation for the development of a new approach to production log analysis. In the following, the background and the principles of the system are described together with two examples that illustrate the performance of this concept.

**REVIEW OF PRODUCTION LOG ANALYSIS (PLA)**

Some of the most advanced current PLA models utilize flow regime maps that are based on observations at ideal surface conditions for small pipe diameters. The sensor responses require explicit correlation charts based on a variety of assumed parameters. An empirical slip and pressure-gradient function is then found from these maps and the explicit corrected measurements. The flow rates are derived from this. These principles have many drawbacks. A flow map referred to laboratory conditions with
definite fluid properties cannot be extrapolated directly to downhole conditions. Any flow regime prediction needs to be closely related to downhole conditions. More elaborate principles of statistical tool behaviour and flow physics needs to be given higher status than in present PLA models. Explicit chart corrections for the PL sensors should be replaced by implicit computations based on the in-situ physical and dynamical fluid behaviour. This has been the motivation for this approach to analysis of PL measurements. The genesis of this principle of analysis was described by Nuland and Nerby (1986), where the OLGA (oil and gas pipeline simulator) system was connected to optimization logic to perform production log analysis.

MODEL DESCRIPTION

The system input comprises sensor readings, physical fluid properties, well deviation, internal diameter and assumed roughness of the well/toolstring-body (The latter can also be computed internally.) The required relative accuracies for the different sensors downhole are needed as input for the numerical flow analysis. Optional inputs are the surface oil, gas and water production rates, and the relative certainties for these different measurements.

The main results from the system are the phase velocities, the cross-sectional phase distribution, the areal-averaged phase fractions and the different contributors to the total pressure gradient such as fluid/pipewall friction, fluid/tool-body friction, gravitational and inertial acceleration. The following flow regimes are presently handled by the system: oil/gas/water—mist, bubble/slug flow; water/oil—dispersed, emulsion and churn flow. Monophase flows are treated as limits of the flow patterns mentioned. In three-phase flow of gas, oil and water, the oil and water are treated as completely mixed and interacting with free gas as the second homogeneous phase. This is a simplification of a complicated three-phase flow regime, but is an acceptable approach when one liquid phase volumetrically dominates the other liquid.

The system enables analysis of PL measurements at shut-in or flow conditions, from a deep water/oil zone in monophase conditions, through dispersion of oil in water, and up to liquid/churn emulsification and churn flows. Monophase flows are treated as limits of the flow patterns mentioned. In three-phase flow of gas, oil and water, the oil and water are treated as completely mixed and interacting with free gas as the second homogeneous phase. This is a simplification of a complicated three-phase flow regime, but is an acceptable approach when one liquid phase volumetrically dominates the other liquid.

The system contains four main modules: PL measurement precomputations (Mod1), computation of physical fluid properties (Mod2), numerical multi- or monophase flow analysis (Mod3) and data management, display and plotting (Mod4).

MEASUREMENT PRE-COMPUTATIONS (Mod1)

The objective of the different precomputations is to correct implicitly for local fluid-mechanical effects on the sensor responses prior to utilization in the later flow analysis. The measurements are based on inline or fullbore spinner, densitometer, strain or quartz gauge readings, temperature, and optionally liquid hold-up capacitance sensors. Even if density data are not available, a complete analysis can still be performed if the pressure data are stable and of good quality. A typical tool string is illustrated in Fig. 1.

Spinner sensor

The aim of this subprocess is to convert spinner rotations into an equivalent mass-averaged fluid velocity at or close to the centre of the pipe. This velocity is a complex parameter including results of slip and phase-distribution effects. The following well-known relation is utilized independently of spinner type:

$$\omega = S_i \cdot U_{mf} + O_i$$  \(\text{(1)}\)

However, the total fluid viscosity and density of the fluid gives a non-linear correction on the parameters $S_i$ and $O_i$ in Eq. (1). In addition, three-dimensional eddies in the sensor environments can locally influence the $S_i$ factor especially around the inflow zones of a well. A dimensional analysis based on density, viscosity, angle of attack and a spinner with defined pitch, diameter, mass and bearing system gives:

$$\omega = \text{const} \cdot \left( \frac{\rho_f}{\mu_f} \right)^{0.53} \cdot \tan \alpha$$  \(\text{(2)}\)

This equation shows how three important variables influence the spinner response: the angle of attack between the spinner axis and the local resultant fluid vector, and the total density and viscosity of the well fluid. The computed slope ($S_i$) at each depth increment is corrected for the estimated fluid viscosity, density and fluid angle of attack based on a nominal reference slope from a static zone of the well. In this procedure, a function is defined:

$$F_i = (S_i - S_{ref})^2$$  \(\text{(3)}\)

Assume that $N$ passes up and down are available. An elimination of spinner passes in the slope computation of Eq. (1) is done until the best fit is obtained between the current slope ($S_i$) and the reference slope ($S_{ref}$) corrected by Eq. (2). This procedure ensures a correction for local eddies and fluid rheology effects on the spinner in the estimation of $U_{mf}$. The algorithm is outlined in Fig. 2.