DIAGNS: AN INTERACTIVE WORKSTATION-BASED SYSTEM FOR WELL TEST DATA DIAGNOSTICS AND INVERSION

Keith L. McLaughlin
Terrence G. Barker
Lawrence A. Owusu
S. K. Garg

S-Cubed
La Jolla, California, USA

Key Words:pressure transient analysis, well testing, automated well test analysis. geothermal software

ABSTRACT

DIAGNS is a workstation-baed computer system intended for evaluation, routine processing, analysis, interpretation, and inversion of pressure-transient test data from geothermal wells. The package contains four main modules:

(1) the "Preprocessor": an interactive graphical system to evaluate, interpret. and "deglitch pressure and flowrate records for subsequent use by the other program modules.

(2) the "Deconvoluter". which may be used to deconvolve intricate pressure/ flow histories to obtain a "unit response function" to a single flow rate step,

(3) the "Type Curve" interactive module, for use in making preliminary estimates of reservoir properties (useful for initiating the "Inverter"). and,

(4) the "Inverter" module, which performs nonlinear least-squares estimation of reservoir model parameters (such as permeability, porosity, boundary locations. skin, storage, etc.) for a variety of standard reservoir models. Confidence limits, correlation and covariance matrices are also estimated to help appraise the reliability of the reservoir model parameter values obtained.

1. INTRODUCTION

Knowledge of the permeability structure of a geothermal system is essential for a quantitative prediction of heat and mass that may be recovered from the hydrothermal reservoir (Garg. *et* al., 1990). Formation permeability is best estimated from pressure transient tests. These tests typically consist of producing (and/or injecting) one or more wells at controlled rates and monitoring downhole pressure changes within the producing well itself (drawdown/buildup/fall off tests) or in nearby shutin observation wells (interference tests). The measured pressure history is the response of the reservoir to the imposed flow disturbance (*i.e.*, productioniinjection). Pressure transient data may be analyzed to yield quantitative information regarding (1) formation permeability and storativity, (2) the presence of barriers and leaky boundaries, (3) the condition of the well (*i.e.*, damaged or stimulated). and (4) the presence of major fractures close to the well.

Interpretation of pressure transient data constitutes an inverse problem. A mathematical model is used to relate pressure changes to flow rate history, and to infer formation parameters. (It is implicitly assumed here that the "mathematical model" is representative of the physical processes operating within the reservoir such that "model parameters" are identical with "formation parameters"). Traditional methods for data interpretation rely almost exclusively upon graphical representations of mathematical models. A comprehensive review of standard graphical techniques may be found in well test monographs by Matthews and Russell (1967) and by Earlougher (1977). More recently, several software packages have been developed to aid in the interpretation of pressure transient data. These computer programs make it possible to speed up traditional graphical techniques by rapid preparation of graphs. Automated inversion of pressure transient data is featured by more advanced software packages (nee *e.g.*, Home, 1990).

Software packages for automated pressure transient data inversion have been developed for oil/gas reservoirs and for groundwater aquifers. These packages are often difficult to apply to geothermal well tests. however. The line source solution, together with its many variants (*e.g.*, double-porosity. a well intersecting a single fracture. *etc.*), forms the hasis for most of the available software packages for automated well test analysis. This model assumes that the productioniinjection well(s) fully penetrates an aquifer of uniform and homogeneous permeability. In a geothermal reservoir, the hulk of formation permeability is associated with thin stratigraphic units and/or a fracture network, and the performance of a well depends upon whether it intersects one or more of these permeable horizons. The well is open to the reservoir only at the depths where it intersects the permeable zones, and for the balance of its depth the well penetrates relatively impermeable rock. For a geothermal reservoir, "formation thickness" is usually unknown and must be determined from well test data. A consequence of partial penetration in geothermal well tests is that, for small flow/shutin times, the well often exhibits a pressure response resembling that of a spherically symmetric source/sink (not a line source/sink). Our experience with analyzing geothermal well tests indicates that geothermal applications require a greater variety of mathematical models than are incorporated in presently available computer programs.

As far as the present authors are aware, existing software packages require the user to preprocess the pressure and flow rate histories prior to automated inversion. Modern pressure transient data acquisition systems (downhole capillary tubing with automatic surface recording) result in very large data files. Very often. the pressure data contain spurious signals (*e.g.*, those resulting from purging of capillary tubing), gaps (instrument failure), and offsets. In addition, the data may be affected by daily barometric and temperature variations, by earth tides. and by seasonal (*e.g.*, rainfall) effects. Filtering the pressure data to eliminate noise and undesired high frequency oscillations is a nou-trivial task. Most hydrothermal wells produce a mixture of water and steam at the surface. Great care is required in accurately monitoring water and steam flow rate histories. In our experience, flow rate histories (flow amplitude, shutin/start times. *etc.*) during geothermal well tests are often only poorly known. Thus, it is not always a simple matter to ascribe the observed pressure changes to variations in discharge/injection rates. Another difficulty in analyzing geothermal well test data arises from non-isothermal (and possibly two-phase) flow in geothermal wells. Changes in wellbore temperature during and after an injection test often result in anomalous pressure response (*i.e.*, decrease in measured pressure during injection and increase in measured pressure during falloff); such pressure data are useless for inferring formation properties.

2. DIAGNS

We envision automated well test analysis as a three-step process (Figure 1). The three steps are not necessarily sequential; it may be necessary to iterate back and forth. The first step consists of pre-processing the pressure and flow data. Pressure data pre-processing removes gaps and "glitches", and filters the pressure data (in combination with flow data) to remove high frequency noise. Pressure data filtering is in many cases essential for reducing pressure record files to a manageable size (*i.e.*, from tens ofthousands of points to hundreds or at most thousands of points).

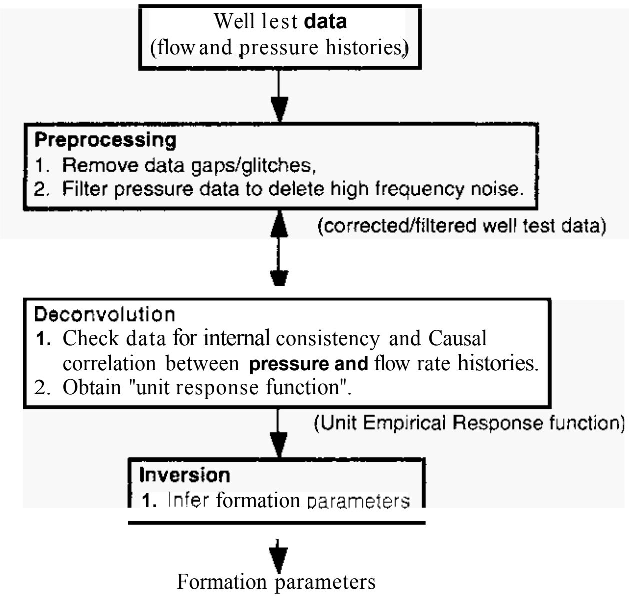


Figure 1. Steps in well-lest analysis

Well tests **can** rarely he carried out with the **tlow** rate held exactly constant. Furthermore. tests arc frequently performed which involve deliberately changing the flow rate **in** a series of sleps. Even the simplest test involves a minimum of two flow rate steps (stamp and shutdown). Modern deconvolution techniques, developed in recent years in seismic and optical signal processing, provide an efficient means for **constructing** an empirical "unit response function" from measured pressure and flow rate histories. The "unit response function" is the pres**sure** response of the reservoir to a unit step change in flow rate. The deconvolution procedure (second step) allows one to determine the degree to which individual time-series representing well flow rates and measured pressure response are causally related. (This will help identify and reject the anomalous pressure response observed in many injection tests). In addition, deconvolution can be used to check data **for** internal consistency (*e.g.*, start/shutin times for flow, relative flow-rate amplitudes, *etc.*), and detect (and perhaps correct) any secular trends in pressure data.

The final (third) step consists of inverting the "empirical unit response function" to obtain the formation propenies. The inversion technique will in general be iterative in character, involving automatic successive forward modeling and parameter adjustment. The starting parameter **values** for the automatic inversion algorithm may be obtained **using** conventional graphical techniques.

3. SYSTEM DESCRIPTION

DIAGNS is designed to provide a workstation-based tool to help the geothermal reservoir engineer estimate reservoir charactenstics from **wcll** tcst data. The system has four major modules: Preproc, Decon. Type, and Invert. Each module **is** a free-standing interactive program that reads and stores data from a system database (see Figure **2).**

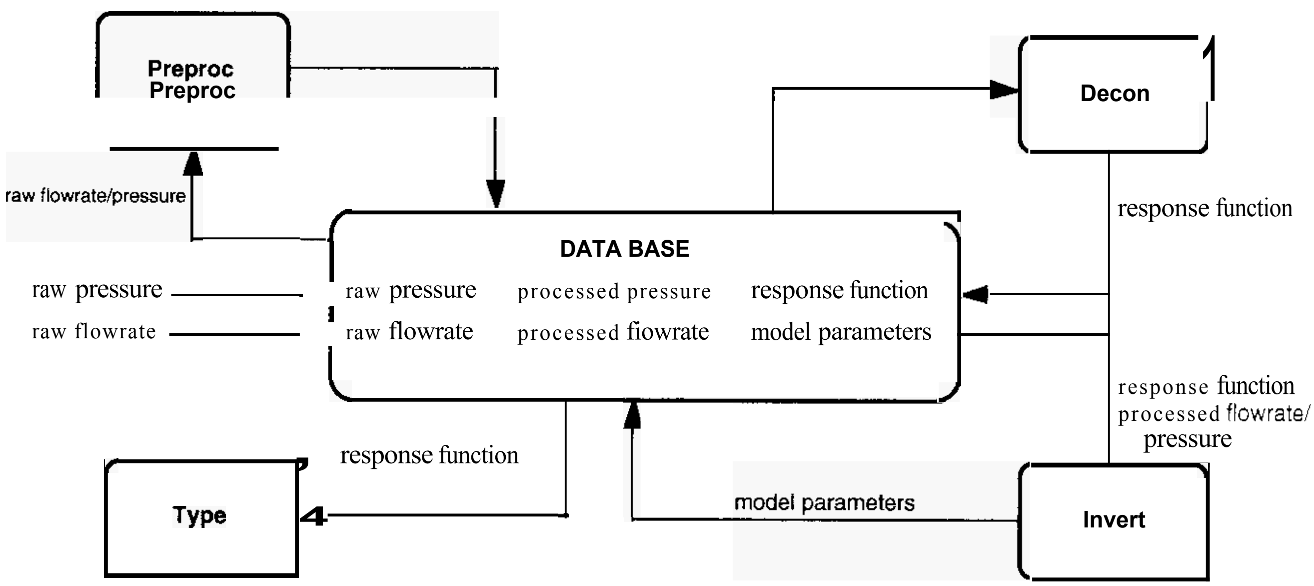
1) A pre-processor (Preproc) is first used to display "raw" pressure transient data and flow **rate** data from any set of wells in the database. This "raw" datn is conditioned to obtain "processed" data. This step **in** the processing **is** interactive and may include removal of had data points. filtering of diurnal noise, interpolation of data dropouts, removal of redundant datn, combining separate data sets, and removal of **pressure** spikes and steps due to purges in capillary tubes. Data may be filtered and re-sampled to *my* desired sample rate. The processed data is then stored in the database for use by the other two modules in the system.

2) After pre-processing, the user may wish to estimate the pressure transient response from a complicated well test hy deconvolution (Decon). In this module it is assumed that the pressure response in a wcll is a linear convolution **of** the flow rate in another **(or** the same) well with **a** response function. **Several** diffcrent methods and options are available for the user to perform the deconvolution. The response function is recorded in the database. This result may be compared to type response curves andlor passed on to the inversion routine (Invert).

3) The response curve may be plotted and compared to a variety of possible models using type curves (Type). The user may decide at this point to adopt a given model, return to the deconvolution module to improve the response function, or proceed to a formal inversion of the data to obtain reservoir characteristics.

4) The reservoir engineer will finally invert (Invert) the data to estimate reservoir characteristics such as permeability and porosity from the response function using one of **several** available reservoir models. Different models may be compared as alternative hypotheses and the best model chosen. The parameters of each inversion may be saved in the database for future reference.

The DIAGNS system was developed on a UNIX-based workstation using the X Window Systems graphical protocol. The interactive graphical user interface (GUI) has a uniform "look-and-feel" utilizing the Motif tool kit. It has been **a** goal of the project to use common function/ subroutine libraries and data formats as much as possible throughout the System. A common **software** architecture has been adopted foreach of the main modules (Preproc, Decon, Type, and Invert) and each mod-



ule uses a single library for reading and writing to the database. A data format for each of the data structures has been defined and is common to each element of the system. In addition, a common plotting library is used to plot pressure, flow rate histories. and response functions versus time.

Data flow for DIAGNS is shown in Figure 2. Raw flowrate and pressure history data is examined in the preprocessor and processed pressure and flowrate data is produced. This processed data can be used as input to the deconvolution module or the inversion module. The deconvolution module uses the processed pressure and flowrate data to produce a response function. This response function may be used as input to either the type curve module or the inversion module. The type curve module may be used to compare the response function with one or more families of type curves for different reservoir models. The inversion module is finally used to make quantitative estimates of reservoir characteristics for one or more chosen models.

4. MATHEMATICAL MODELS FOR INVERSION

Geothermal reservoir and wellbore flow is more complex than that of oil reservoirs and groundwater aquifers because of (1) non-isothermal processes. and (2) partial penetration effects. The differential equations describing water/steam flow in porous/fractured media are highly nonlinear, and must be solved numerically; numerical solutions are difficult to apply to well test interpretation. However, Grant (1975) and Garg (1980) have shown that, with certain simplifying assumptions. the pressure behavior of a single- or two-phase geothermal well can be approximated by isothermal single-phase models. Geothermal wells often produce from thin stratigraphic units and/or fractures which constitute only a small fraction of *the* open interval of the well. Far a geothermal reservoir. "formation thickness" is usually an unknown. Partial penetration in geothermal well tests often results in geothermal wells exhibiting (at small flow/shutin times) a pressure response resembling that of a spherically symmetric source/sink (not a line source/sink).

Apart from the fact that geothermal well tests require more diverse mathematical models, the inversion of a "unit pressure response function" from geothermal well tests differs little from that for oil/groundwater reservoirs. Many analytical or semi-analytical solutions exist for the pressure response of a well to a unit change in the flow rate; a convenient compilation is given by Streltsova (1988). Table 1 lists the models installed in the current Inversion module of DIAGNS.

5. COMPUTING ENVIRONMENT

The DIAGNS system is designed to operate on UNIX scientific workstations. The preferred environment is a Sun Microsystems "SPARCstation" with a minimum of 16 megabytes of RAM and a minimum of 100 megabytes of disk space to store the pertinent data and the DIAGNS system. The graphical user interface in DIAGNS is based on OSF Motif and X-Windows (X11-R5).

6. REFERENCES

Earlougher, R. C., Jr. (1977). Advances in Well Test Analysis. *Monograph Series, Society of Petroleum Engineers*, Dallas, Texas.

Garg, S. K. (1980). Pressure Transient Analysis for Two-Phase (Water/Steam) Geothermal Reservoirs. *Soc. Pet. Eng. J.*, vol. 20, pp. 206–214.

Table 1.

1. Single Porosity Finite (Wellbore)	infinite: $kh, \phi c_t h, C, s, Pi, a$ cucularboundary: $kh, \phi c_t h, C, s, P_i, \alpha, r_e$ linear boundary $kh, \phi c_t h, C, s, P_i X_a, X_b, Y_c, Y_d$
2. Double Porosity (Warren and Root)	infinite: $kh, \phi c_t h, C, s, \omega, \lambda, P_i, a$ circular boundary $kh, \phi c_t h, C, s, \omega, \lambda, P_i, a, r_e$ linearboundary: $kh, \phi c_t h, C, s, \omega, \lambda, P_i, X_a, X_b, Y_c, Y_d$
3. Double Porosity (Gradient Flow)	infinite: $kh, \phi c_t h, C, s, \omega, \lambda, P_i, a$ circular boundary: $kh, \phi c_t h, C, s, \omega, A, P_i, a, r_e$ linear boundary $kh, \phi c_t h, C, s, \omega, \lambda, P_i, X_a, X_b, Y_c, Y_d$
4. Double Porosity (Hantush)	infinite: $kh. \phi c_t h, C, s, \omega, \lambda, P_i, a$ circular boundary: $kh, \phi c_t h, C, s, \omega, A, P;, a, r_e$ linear boundary $kh. \phi c_t h, C, s, \omega, \lambda, P_i, X_a, X_b, Y_c, Y_d$
5. Composite System	infinite: $(kh)_1, (\phi c_t h)_1, C, s, \delta, \gamma, r_c, P_i, a$ circular boundary $(kh)_1, (\phi c_t h)_1, C, s, \delta, \gamma, r_c, P_i, a, r_e$ linear boundary: $(kh)_1, (\phi c_t h)_1, C, s, \delta, \gamma, r_c, P_i, a, X_a, X, Y_c, Y_d$
6. Single Porosity (Line Source)	infinite: $kh, \phi c_t h, P_i, a$ linear boundary: $kh. \phi c_t h, P_i, a X_a, X_b, Y_c, Y_d$
7. Point Source	infinite: $k, \phi c_t, P_i, a$ linear boundary: $k, \phi c_t, P_i, a, X_a, X_b, Y_c, Y_d$