TOWARD INTEGRATING GEOTHERMAL RESERVOIR AND WELLBORE SIMULATION: TETRAD AND WELLSIM

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SUMMARY - A hybrid coupling of the TETRAD reservoir simulator and the WELLSIM wellbore simulator is presented. Accurately modelling wellbore flow during a reservoir simulation provides characteristics at the wellhead rather than the usual output of wellbottom parameters. The coupling approach used involves an initial generation of *wellbore tables* by WELLSIM. These tables contain wellhead parameters corresponding to a wide range of potential feed conditions for each production well, or group of production wells, and TETRAD interpolates between these parameters during a simulation run. An example problem is provided, and the relative advantages in terms of computational time, convergence characteristics and accuracy are discussed, with respect to a recent *explicit* approach to reservoir/wellbore simulator coupling.

INTRODUCTION

Geothermal reservoir and wellbore simulators are used separately by reservoir engineers to assess reservoir and wellbore performance respectively. Although both types of simulators are being continuously improved, allowing more complex reservoir and wellbore behaviour to be modelled, it has only been recently that attempts have been made to comprehensively link the two types of simulator. This paper describes one such attempt; a simple interfacing between the WELLSIM geothermal wellbore simulator, and the TETRAD multi-purpose reservoir simulator, through a recent modification to the WELLSIM package.

MODELLING GEOTHERMAL SYSTEMS

Completely modelling an entire geothermal production system would require simulating: the behaviour of the reservoir, and its response to production and reinjection; the fluid flow in the production and reinjection wells; and the flows in the above-ground steam gathering and reinjection network. Simulators exist for all three of these components of the production system: for example, TETRAD (e.g. Faulder and Shook, 1991) and TOUGH (e.g. Pruess, 1987) for reservoir simulation; WELLSIM (e.g. Gunn and Freeston, 1991) and WFSA (e.g. Hadgu, 1989) for wellbore simulation; and non-linear pipe network simulators, for example, the simulator described by Huang and Freeston (1992) and TAPS (e.g. Vinsome, 1992).

Although the flows and fluid conditions in each of these parts of the system are all interdependent, the complexity of the behaviour has restricted modelling of the system to either each part individually, or to specific subsets of the complete system. An example of this latter approach is TAPS, which simulates the reservoir, wellbore and piping network system for *dry* steam flow only.

Where each part is modelled individually, the output of one module is used as the input to the next. Reservoir simulators generally have a very simple model for the wells built into them, but these ignore the complexity of the flow, caused because the flow is in many cases two-phase. The advantage of modelling the wellbore flow appropriately is in being able to match observed conditions *at the surface* against reservoir simulator output parameters. The generation of wellhead parameters enables modellers to more accurately forecast long term geothermal reservoir depletion behaviour, on the basis of individual well deliverabilities. This provides a mechanism to be able to predict field makeup well requirements as well as the overall generation capacity of a geothermal system.

One important reason that reservoir simulators generally simple their representation of wells is due to computational time constraints. One of the main areas of research in enhancing reservoir simulator performance is to reduce computational time, and unfortunately, accurately modelling the nature of the two-phase flow in each well explicitly, is a time-consuming calculation.

TETRAD RESERVOIR SIMULATOR

TETRAD Version 10.0 is a commercially-available multiphase, multicomponent, finite difference, three-dimensional simulator (refer Faulder and Shook, 1991). It can' model geothermal reservoirs with single or dual porosity (i.e. naturally fractured reservoir) behaviour, and can run on any platform with a FORTRAN 77 compiler. With the inclusion of PC-based pre- and post-processing graphics software, and flexible code dimensioning, it is particularly well suited to current 486 PC-based platforms.

To reduce computation times, TETRAD features a wide range of options for solving mass and energy balances for each gridblock at each timestep implicitly, including fully, linearised, dynamic, sequential and IMPES. In addition,

the program features both 3-D Cartesian and radial grid systems, along with options to model irregular grids and for local grid refinement.

In order to model both individual well and field deliverabilities, TETRAD contains options for specifying wellbore bottomhole pressure and rate constraints, and surface separator rate constraints. The separators can be used to group deliverabilities from multiple wells for the purpose of developing a single overall field deliverability calculation that is critical for the assessment of geothermal resource capacity. A new shell program, *AIM,* uses non-linear optimisation to automate the calibration of the reservoir model.

RESERVOIR/WELLBORE FLOW

In TETRAD, flow in the reservoir to the wellbore follows the assumptions common to many current reservoir simulators: steady-state, isothermal, single phase liquid flow, governed by Darcy's law for a homogeneous, single porosity horizontal reservoir.

For a well completed in a single gridblock the downhole flow rate of any phase into a completion interval is given by:

$$W = \left(\frac{k_{ri}}{\nu_i}\right) PI(p_r - p_f) \qquad (1)$$

where:

- W = mass flowrate of phase i
- k_{ri} = phase i relative permeability evaluated at gridblock conditions
- ν_i = phase i viscosity evaluated at gridblock conditions
- p_r = gridblock pressure
- p_f = feed (i.e. bottomhole) wellbore pressure in the centre of the completion interval
- PI = completion interval productivity index defined as:

$$PI = \frac{2\pi khC}{\ln\left(GF\,\frac{r_e}{r_w}\right) + s} \qquad (2)$$

where:

- k = $\sqrt{(k_x k_y)}$, where k_x and k_y are gridblock permeabilities
- C = constant to convert flowrates to appropriate imperial or metric units
- GF = geometrical factor derived from analytical solutions for wells located in gridblocks with impermeable boundaries, specific gridblock geometries, or non-centred well locations
- r_e = $\sqrt{(L_x L_y)}$, where L_x and L_y are the gridblock lengths
- r_w = wellbore radius
- s = dimensionless skin surrounding the wellbore

For high flowrates associated with turbulent flow, equation (1) is replaced by a non-linear inflow performance relationship specified by a power law equation.

The modelling of multilayer flow in TETRAD Makes use of a wellbore fluid gradient calculation, to relate deepest feed flowing pressures fiom different depths to a common reference datum point, which is often associated with the shallowest fluid entry depth in the model. The wellbore fluid gradient calculation effectively models wellbore fluid flow between layers, and relies on simplifying assumptions to approximate complex fluid dynamics. The key is the wellbore fluid gradient itself. A user can specify one of several different methods to calculate a cumulative gradient along the wellbore. The reason for multiple methods is that each uses assumptions which may be more valid for one situation than another. The various methods are as follows.

1). A user defined fluid gradient that is assumed constant for the entire interlayer wellbore length between fluid entry points.
2). A simulator calculated fluid gradient that is uniform for the entire interlayer wellbore length between fluid entry points. This is based on the averaged fluid properties of the entry points.
3). A simulator calculated fluid gradient that varies along the interlayer wellbore length between fluid entry points. This calculation is bound by the fluid properties at each entry point.
4) A simulator calculated fluid gradient that is based on the formation pressure gradient adjacent to the fluid entry points.

In addition to the use of a fluid gradient to model interlayer wellbore flow, TETRAD provides the user with the option of including friction as part of the wellbore pressure gradient calculation.

This multilayer flow methodology approximates single or two-phase wellbore flow between layers for multi-entry feed points. In order to model fluid flow up the entire wellbore length to the wellhead, the entire process becomes a hybrid approach of coupling the fluid gradient calculation between layers, with a separate calculation from the uppermost fluid entry point to the wellhead. This separate calculation for TETRAD involves a coupling with the WELLSIM wellbore simulator in an approach described below.

WELLSIM WELLBORE SIMULATOR

WELLSIM Version 2.2 is a commercially-available steady-state, three component (i.e. H_2O, CO_2 and NaCl) simulator (refer Gunn and Freeston, 1991), and runs in a PC environment. It can model liquid, two-phase, and superheated steam flow, heat transfer with the surrounding formation, and multiple feed zones. In addition to the simulation of production wells, wells can be modelled as reinjecting liquid through a single outflow into the reservoir. At each feed, a deliverability or injectivity relationship can be user specified, or program generated, with a linear, quadratic, or Dower law equation.

The commercial version of WELLSIM contains five different sets of two-phase flow correlations for simulating production wells (i.e. Aziz, Duns and Ros, Hagedorn and Brown, Orkiszewski, and the WELLSIM proprietary calculation), as unfortunately, no one set of flow correlations has been effectively demonstrated as applicable to all types of wells. Probst *et al.* (1992) compared these flow correlations, along with two others, using a customised version of WELLSIM, and gave some preliminary criteria to match correlations to well types.

WELLSIM sits on top of a database management system written in the Paradox Application Language, and allows the entry of measured downhole and deliverability data. Both statistical and graphical matching analyses can be performed by WELLSIM using this data.

WELLBORE/RESERVOIR SIMULATOR COUPLING

The first explicit coupling of a geothermal wellbore and reservoir simulator was described by Hadgu *et al.* (1993). This involved linking the WFSA wellbore simulator with the TOUGH reservoir simulator. WFSA is a steady-state wellbore simulator that can model pure water discharge, with multiple feed zones that can either produce or accept liquid or two-phase fluid. At each feed zone a linear or quadratic pressure deliverability relationship can be specified. WFSA incorporates one two-phase flow correlation, and this is an earlier version of the current WELLSIM proprietary correlation.

At each well, the simulation requires the wellhead pressure, wellbore geometry and the productivity indices describing the deliverability relationship at each feed zone, to be entered. It also requires reservoir parameters at each feed. These parameters, which are provided by TOUGH, include reservoir pressure, temperature, enthalpy, density and kinematic viscosity. The simulation evaluates the mass flowrate and pressure at each feed zone, and thus the mass flowrate at the wellhead.

It does this by an iterative process, whereby an initial deepest feed pressure is guessed. This allows the mass flowrate at that depth to be calculated. WFSA determines the flow parameters up the wellbore until the next feed zone depth. A local heat and mass balance is then performed to provide the feed mass flowrate, which is driven by the difference between the wellbore and reservoir pressure at that depth. This process is repeated at each feed zone, and the calculated wellhead pressure is compared with the specified value. The initial guess for the deepest feed pressure is altered, and the simulation is repeated. This continues until the calculated and specified wellhead pressure values are within a pre-specified tolerance.

TETRAD WELLBORE TABLES

TETRAD has no *explicit* coupling with a comprehensive wellbore simulator. Instead, it reduces the wellbore simulator calculations to a set of discretised ***wellbore tables*** in order to model wellbore flow. This methodology is commonly used in oil and gas reservoir simulation to describe multiphase oil/gas/water wellbore flow from shallowest feed to wellhead conditions, for example, three major black-oil simulators in use today: VIP-ENCORE, ECLIPSE-100 and SIMBESTII.

At the present time in TETRAD these lookup tables are restricted to single component water systems, although a CO_2/brine system can be modelled if it is assumed that the fluid composition does not vary significantly. However, the addition of a multicomponent CO_2/brine table is a relatively straightforward extension of the approach used here. Beyond this restriction, the lookup tables are able to reflect the full complexity of a standalone wellbore simulation including isenthalpic, adiabatic, or heat transfer flow; and unlimited well configurations including deviated wellbores.

There are certain important reasons why commercial reservoir simulators rely on discretised wellbore lookup tables to model wellbore flow. These include:

1) ***Significant savings in computational time***
Modelling reservoirs with high levels of exploitation frequently involve simulating in excess of one hundred production wells. If each well is modelled explicitly with a wellbore simulator the computational costs can quickly become prohibitive. Table lookups, on the other hand, are computationally efficient and quick to perform with large numbers of wells.

2) ***Reduced abortive*** *runs*
Geothermal wellbore simulators can encounter flow regimes and conditions that lead to convergence difficulties, and may require repeated runs with different wellbore discretisations to converge. When these calculations are performed separately from the reservoir simulation, convergence issues can be resolved and eliminated prior to running the reservoir simulation so that the risk of an aborted large scale reservoir simulation run is minimised.

3) ***Reduced numerical convergence difficulties***
Since wellbore simulators generally rely on complex flow regime correlations with inherent discontinuities, the resultant series of well deliverability curves may require smoothing. Without such smoothing the wellbore flow calculations may lead to anomalous oscillations or inaccurate flow representations in the reservoir simulator. The use of wellbore tables calculated externally from the reservoir simulator gives the user an opportunity to review and smooth any such discontinuities as required.

TETRAD's geothermal wellbore calculation option allows the user to specify a table of wellhead conditions (pressures and enthalpies) associated with specific shallowest feed conditions (i.e. pressures, mass flowrates, and temperatures, if single phase; or drynesses, if two-phase). TETRAD determines shallowest feed conditions during a simulation, and can determine the corresponding wellhead conditions, by trilinear interpolation between the discrete values in the table. Each wellhead pressure and enthalpy value in the table is a function of three deepest feed parameters: for two-

phase zone entry: pressure, mass flowrate and dryness; or for single phase entry: pressure, mass flowrate and temperature.

Both wellhead pressures and enthalpy difference values are contained in each wellbore table. The enthalpy difference values are simply the differences in enthalpy from the deepest feed to the wellhead. Furthermore, each wellbore table comprises two main components, a temperature table and a quality table. The values in the temperature table are used when the flow from the reservoir is single phase liquid, or dry/superheated steam, whereas the quality table values are used when the flow entering the wellbore is two-phase.

A separate table can be developed for each well, or group of wells, that are considered to behave in a similar fashion. One or more production wells already defined in the TETRAD input file may be assigned to a particular table. Wells that have similar shallowest feed depths, casing and liner configurations, and fluid compositions, might be all represented by the same table. TETRAD has no limits to the number of different wellbore tables that may exist in a TETRAD input file.

The TETRAD table option can be used to model both single and multiple feed zones. Unlike the TOUGH/WFSA coupling however, the modelling of multiple feed zones is accomplished by a hybrid coupling technique that begins with the use of wellbore lookup tables, as described above, to model wellbore flow from the shallowest entry point to the surface. Flow from deeper entry points up to the wellbore is calculated by TETRAD using one the several possible wellbore hydraulic gradient options described earlier. These wellbore hydraulic gradients can be further refined if desired to account for friction losses.

The accuracy of this hybrid approach is subject to the quality of the calculations from the deepest to shallowest entry, and will be most sensitive to the wellbore length between these two depths. As long as a sufficient number of discrete variables are used for the lookup table, the flow calculation from the shallow entry point to wellhead should closely replicate the explicit calculation done by a standalone wellbore simulator.

WELLSIM'S TETRAD TABLE OPTION

Previously, TETRAD wellbore tables were created by running a wellbore simulator a large number of times, and manually feeding the results in the appropriate ASCII format into a TETRAD input file, through the use of a text editor.

WELLSIM's *TETRAD table generation facility* allows an entire sequence of simulations to be performed over the desired range of two-phase and single phase (i.e. liquid and dry/superheated steam) feed zone conditions, and this results in the creation of a TETRAD wellbore table in the appropriate format. The resultant file can be incorporated into the main file specifying the rest of the input parameters to TETRAD, and a reservoir simulation can be immediately performed.

A specific data type exists in WELLSIM's database containing the information that is required by WELLSIM to generate a single TETRAD wellbore table. However, a series of table generations can also be performed by WELLSIM to create a *series* of TETRAD wellbore tables. Although running the entire sequence of simulations is cpu-intensive, it is only required once. In the explicit approach, where the deepest feed pressure is adjusted until a match is found between the calculated and specified wellhead pressure, the entire calculation is reperformed even when the change in the input value of deepest feed pressure is small. The current approach only requires a new interpolation to be performed. Each table can be made as sparse or as detailed as required, depending on the level of accuracy required in the reservoir simulation as a whole.

Each TETRAD table generation in WELLSIM can be specified as isenthalpic, adiabatic, or allowing for heat transfer. In the isenthalpic option all the enthalpy difference values in the wellbore table are set to zero. The isenthalpic option calculates enthalpy change allowing for the effects of potential energy only, whereas the heat transfer option takes into account the effects of heat transfer with the surrounding rock formation. This latter option requires a static formation temperature profile to be entered into WELLSIM for the well, in addition to rock and casing conductivity, rock thermal diffusivity and the discharge period.

Both NaCl and CO_2 can be specified as being present in the wellbore fluid. Currently, there is no allowance in the wellbore table to account for the effect of changes in fluid composition over time. However, if this was a critical factor, a particular production well could be assigned to a different wellbore table at a specified simulation time. TETRAD allows a reassignment of tables at any stage during a simulation run.

Because different wells in different parts of a field may be modelled more appropriately with different two-phase flow correlations (assuming that flow in the well is in fact two-phase), different wellbore tables can be generated using different two-phase flow correlations. For example, a field with a localised high enthalpy production zone, where the rest of the wells produce from lower enthalpy wells, might have wellbore tables for the former wells generated using the WELLSIM flow correlation, whereas the latter wells might be more suited to the Duns and Ros flow correlation (refer to Probst *et al.*, 1992). Any well that has significantly differing enthalpy characteristics during its lifetime could also be handled by reassigning its related table at an appropriate period during the simulation.

One of the difficulties with a direct coupling of a wellbore simulator to a reservoir simulator is in cases where the wellbore simulator does not converge, or the input parameters are outside its normal range of operation. Because the wellbore tables are produced prior to the

reservoir simulation convergence problems are not produced within the wellbore module itself.

Where flow in the well *chokes,* WELLSIM sets the wellhead pressure to zero. As WELLSIM generates the wellbore table it also flags values in the table where the solution did not converge, or the input parameters caused the calculation to go out of range. Non-convergence is generally caused by inappropriate selection of the simulation depth increment, and is a particular problem with the Orkiszewski flow correlation, which has a distinct discontinuity at some fluid velocities. WELLSIM allows the user to specify the number of retry attempts should the simulation not converge, which can be zero if desired. Should the simulation fail, WELLSIM will reduce the simulation depth increment, and reattempt the solution.

Flagging the non-convergence and other problem cases in the TETRAD input file, allows the user to change these values if required. New values might be produced by running WELLSIM separately for the problem cases, or zeroes might be appropriate.

As noted above, TETRAD requires that the values in the wellbore tables be relatively smooth, or the interpolation between values may produce oscillations or inaccurate representation of the flow. WELLSIM allows the user to check the smoothness of the solution by plotting two-dimensional slices through the resultant "deliverability surface". Graphical slices across the wellbore table can be made in the quality or temperature tables, and produced for constant values of feed pressure, temperature or quality.

EXAMPLE PROBLEM

The following example problem is used to illustrate the performance of the wellbore table lookup methodology in TETRAD. This problem is based on sample problem #1 described by Hadgu *et al.* (1993) using the TOUGH/WFSA coupled code. Since not every detail about the previous example problem is available in their paper, it is not possible to ensure that the two models are identical. However, enough information is presented as to allow some comparisons between direct and indirect coupling.

In this sample problem a single well is completed in 2 layers in a 9x9 rectangular grid with gridblocks 200 m in length and each 500 m thick, an overlying caprock 500 m thick, and the well located in the centre gridblock x=5, y=5. Other reservoir model details include:

Reservoir temperature	=	190 °C
Layer 1 initial pressure	=	90.5 bar
Layer 2 initial pressure	=	133.8 bar
Layer 1 permeabilities	=	10 mD
Layer 2 permeabilities	=	20 mD
Reservoir porosity	=	0.1
Initial fluid saturations	=	100% liquid
Initial mass in place	=	4.91×10^9 kg
Wellbore skin	=	0
Well geometrical factor	=	0.3575
r_w	=	0.2 m
r_e	=	$\sqrt{(L_x L_y)}$

where L_x and L_y are gridblock lengths.

The well parameters include:

Bottom feed depth	=	1250 m
Shallowest feed depth	=	750 m
Wellhead pressure	=	7 bara
Wellbore diameter	=	0.2 m
Two-phase correlation	=	WELLSIM correlation

Sixteen discrete table values were used for both mass flowrates and shallowest feed pressures. The wellbore fluid gradient option chosen set the interlayer wellbore gradient to the averaged layer fluid gradient.

Using the above wellbore/reservoir parameters and the hybrid coupling described previously, the problem was run on a 486/33 MHz PC, and required approximately 50 cpu seconds to run. The results are shown in Figures 1 and 2. Since flashing occurs in the well above the shallowest feed zone, as noted by Hadgu *et al.* (1993), the frictional pressure gradient in the wellbore between the two feed zones is low compared to the gravitational gradient. Thus the assumptions used in TETRAD for the hybrid approach are good in this case. The results between this table lookup methodology and the direct coupling presented by Hadgu *et al.* (1993) appear similar, although some differences in flowrates and pressures occur which may be due to different parameter specifications.

In Figure 3 the above problem was rerun using two additional flow correlations, Duns and Ros, and Aziz, to show the sensitivity of results to these correlations. As expected, total discharge rates vary significantly between the three correlations, which is consistent with differences in the flow regimes predicted by the three correlations. Actual field data would be required to determine which correlation is appropriate for a given well. However, the results of Probst *et al.* (1992), would tend to imply that the Duns and Ros correlation would be the most suitable in this instance.

In Figure 4 the above problem was again rerun, this time using a user-specified interlayer wellbore gradient to show the sensitivity of results to this part of the calculation. As the gravitational gradient between the upper and lower feed zones is manually increased from a simulator calculated value of about 0.084 bar/m to 0.101 bar/m, the effective resistance to flow in this section of the wellbore becomes evident via reduced rates from the lower entry and overall discharge rate. An alternative method to model actual wellbore friction losses would be to use the optional friction calculation noted previously.

The results from this example problem demonstrate the viability of using wellbore lookup tables, in combination with interlayer wellbore gradient calculations, as an efficient, alternative methodology to direct coupling between wellbore and reservoir simulators.

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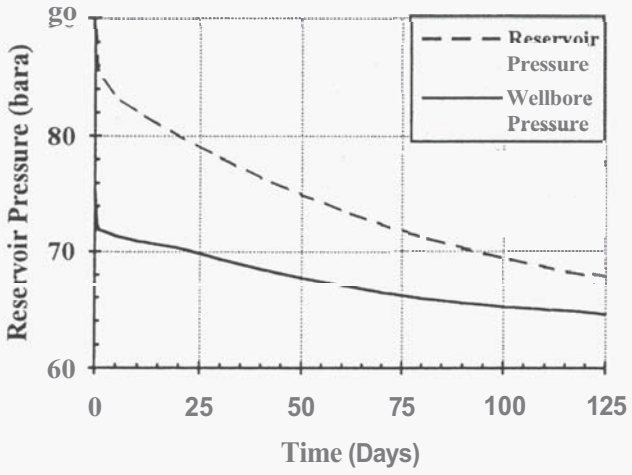

Figure 1: Example Problem: reservoir and wellbore pressures (at depth of shallowest feed zone)

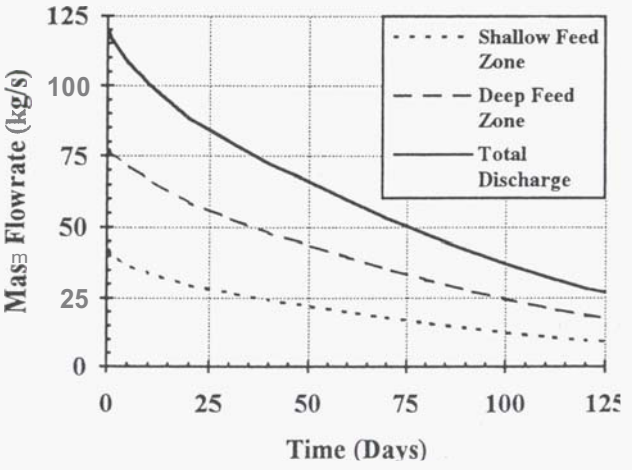

Figure 2: Example Problem: mass flowrates at each feed zone, and the total discharge

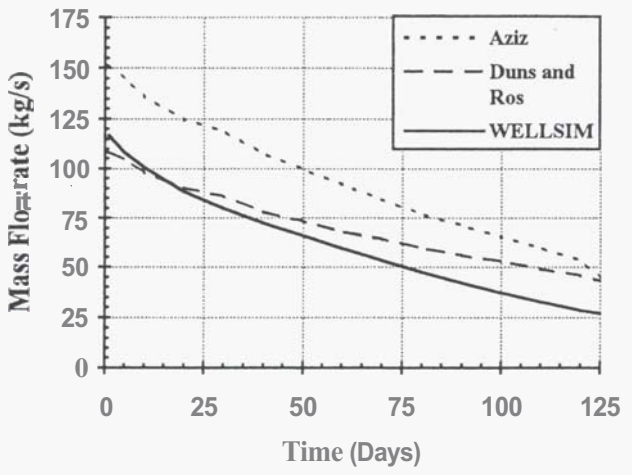

Figure 3: Example Problem: effect of flow correlation on discharge rates

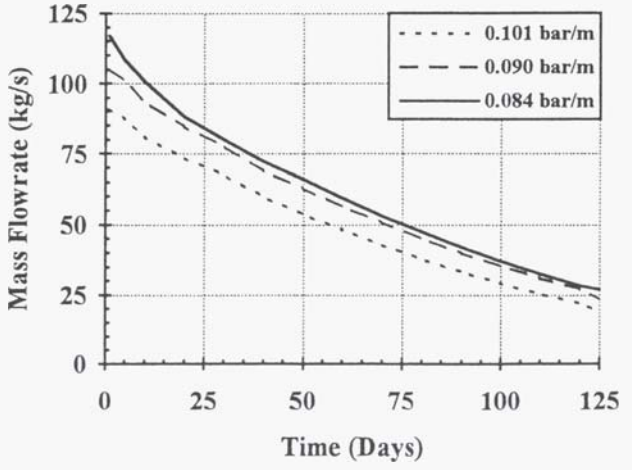

Figure 4: Example Problem: effect of interlayer gradient on discharge rates