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Review of Deliverability Models Used in Geothermal Reservoir Simulations

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ABSTRACT

Production wells on deliverability are often used in modelling geothermal fields, especially for simulations of future scenarios. The mass flow rate is calculated by multiplying the productivity index by mobility and the difference between flowing bottom-hole pressure and the reservoir block pressure. Here three options are considered for calculating the bottom-hole pressure: (i) constant, (ii) dependent on enthalpy, and (iii) dependent on enthalpy and flow rate.

To implement Models (ii) and (iii) a wellbore simulator is used to generate the functional dependence of the bottom-hole pressure on enthalpy and enthalpy and flow rate, respectively. The standard method for implementing Model (iii) is to use a table look-up for the bottom-hole pressure but we have also used a 2D rational polynomial representation.

All three methods are tested on future scenario simulations of the Wairakei-Tauhara geothermal system. It is found that the most complex method (iii) gives the least conservative results i.e. the most optimistic predictions of future production.

1. INTRODUCTION

In simulations of the past history of geothermal fields, at Wairakei-Tauhara and Ohaaki for example, usually a record of mass flow versus time for each well is available and can be used as part of the input to AUTOUGH2 (Yeh *et al*., 2012), the University of Auckland's version of TOUGH2 (Pruess *et al*., 1999). However for simulating future scenarios the mass flow is not known *a priori* and it is necessary to switch over and run the wells on "deliverability". The deliverability mode specifies that the flow rate from the well will decline as the reservoir pressure at the feed-zone declines. In the formulation of the deliverability option available with TOUGH2 the mass flow of each phase (β=w for water and β=s for steam) is given by:

$$q_{m\beta} = \frac{k_{r\beta}}{\nu_\beta} \text{ PI } (P_\beta - P_{wb}) \tag{1}$$

Here, for each phase: $q_{m\beta}$ is the mass flow, $k_{r\beta}$ is the relative permeability, P_β is the pressure and ν_β is the kinematic viscosity, PI is the productivity index and P_{wb} is the flowing bottom-hole pressure. The TOUGH2 manual provides the following formula for calculating the PI in the case of steady radial flow, attributed to Coats (1977) and Thomas (1982):

$$(PI)_l = \frac{2\pi(k\Delta z)_l}{\ln(r_e/r_w)+s-1/2} \tag{2}$$

Here, Δz_l denotes the layer thickness, $(k\ \Delta z)_l$ is the permeability-thickness product in layer l, r_e is the grid block radius, r_w is the well radius, and s is the skin factor. If the well is producing from a grid block which does not have cylindrical shape, an approximate PI can be computed by using an effective radius

$$r_e = \sqrt{A/\pi} \tag{3}$$

where A is the grid block area; e.g., A = Δx Δy for an areal Cartesian grid. Coats (1977) points out that (2) applies for steady-state flow and for semi-steady-state (or pseudo-steady-state) the following amended formula should be used:

$$(PI)_l = \frac{2\pi(k\Delta z)_l}{\ln(r_e/r_w)+s-3/4} \tag{4}$$

This is the version given by Matthews and Russell (1967) and in the classical paper by Dietz (1965).

The key parameter in the deliverability formula is the flowing bottom-hole pressure P_{wb}. If the reservoir pressure in both phases falls below P_{wb} then the well will not produce.

The simplest implementation of deliverability assumes P_{wb} is constant but this is not very satisfactory as it ignores the fact that a higher pressure is required to push water up a well than for a mixture of water and steam. Another difficulty in using (1) is that it applies only to wells that have a single feed-zone which is often not the case. With TOUGH2 there is an option that allows for wells on deliverability to have multiple feeds and there is another option for single feed zone wells to have a flowing bottom-hole pressure that is dependent on flow rate and production enthalpy, but both options cannot be used together. To improve on the approaches available in TOUGH2 probably requires the fully coupled solution of reservoir flow and wellbore flow. This approach was taken by Hadgu *et al.* (1993, 1995) who coupled the reservoir simulator TOUGH (Pruess, 1987) with the wellbore simulator WFSA (Hadgu and Freeston, 1990). A similar approach was used by Bhat *et al.* (2005) who coupled the wellbore simulator HOLA (Bjornsson, 1987) with TOUGH2 (Pruess, 1999). A coupled reservoir-wellbore-pipeline model for The Geysers, based on the reservoir simulator TETRAD (Vinsome and Shook, 1993) was discussed by Butler and Enedy (2010).

Saied *et al*. (2013) used the finite element package COMSOL to investigate a coupled wellbore-reservoir problem with one injection well and one production well. A similar problem was investigated by Nandanwar and Anderson (2014) using the reservoir simulator TOUGH2-EGS (Xiong *et al*., 2013) coupled with some custom software for modelling the injection well and the production well.

Tokita and Itoi (2004) set up a wellbore simulator that included coupled flow in the reservoir surrounding the wellbore, but it was not applicable to multiple wells in a large-scale reservoir model.

There have been some coupled wellbore-reservoir simulators, with non-isothermal capability, developed for oil and gas reservoirs (e.g. Pourafshary *et al*., 2009; Livescu *et al*., 2010).

However none of these fully coupled reservoir-wellbore simulators run very fast and they have not been used for modelling real geothermal systems. An alternative approach discussed by Murray and Gunn (1993) is to carry out the wellbore and reservoir simulations separately. They used the WELLSIM simulator (Gunn and Freeston, 1991) to generate a wellbore look-up table to be used with the reservoir simulator TETRAD. A similar approach was implemented by Pritchett (1995) as an option with the STAR reservoir simulator. This approach is also available in TOUGH2 which allows the input of a table of flowing bottom-hole pressures for a range of flow rates q_m and enthalpies h:

$$P_{wb} = P_{wb}(q_m, h) \tag{5}$$

The difficulty with (5) is that the look-up table will depend on secondary parameters such as wellhead pressure P_{wh}, feed-zone depth z and wellbore radius r_w, thus requiring the generation of a new look-up table for each set of these secondary parameters. By interpolating on these tabular data, (5) can be directly inserted into the well source term, (1). The combination of (5) and (1) provide an implicit evaluation of flow rate q_m but the reservoir flow equations that include the quasi-steady approximation to wellbore flow given by (5) can be solved with little added computational expense compared to the case where no wellbore flow effects are considered. One of the advantages of representing wellbore flow effects through tabular data is that it is possible to use different wellbore simulators and different two-phase flow correlations to generate (5) without any changes to the TOUGH2 code.

2. IMPLEMENTATION OF DELIVERABILITY

In the present study three representations of the flowing bottom-hole pressure are used:

(i) $P_{wb} = \text{constant}$

(ii) $P_{wb} = P_{wb}(h)$

(iii) $P_{wb} = P_{wb}(q_m, h)$

Model (i) is a standard option in TOUGH2 whereas (ii) is a local option available only in AUTOUGH2. As discussed above (iii) is also available in TOUGH2. For many geothermal wells their production enthalpy is relatively stable over time but there are some whose performance varies. A few examples from Wairakei are shown in Figure 1. For wells with a nearly constant production enthalpy such as WK24 (all liquid) or WK228 (dry steam) obviously Model (i) is adequate for representing P_{wb} but for wells like WK15 and WK72 either Model (ii) or (iii) is required. For all three models some external simulations with a wellbore simulator are required to calculate the model parameters.

Model (i). For the case of a constant bottom-hole flowing pressure two approaches were used for calculating P_{wb}. The simplest, somewhat arbitrary approach is to set it at a fixed value (say 5 or 10 bar) below the starting reservoir pressure. The logic behind this approach is that typically the pressure gradient in a geothermal reservoir is above the hydrostatic profile for the corresponding reservoir temperatures and the bottom-hole pressure corresponding to this hydrostatic profile is close to the minimum pressure required to make the well flow. The second approach used is to run a wellbore simulator for various flow rates, calculating the bottom-hole pressure each time and then extrapolating to a zero flow rate to calculate P_{wb}. For each wellbore simulation the enthalpy was kept fixed at the measured or estimated production enthalpy for the well. Clearly this procedure is not satisfactory for a well whose enthalpy changes significantly over time.

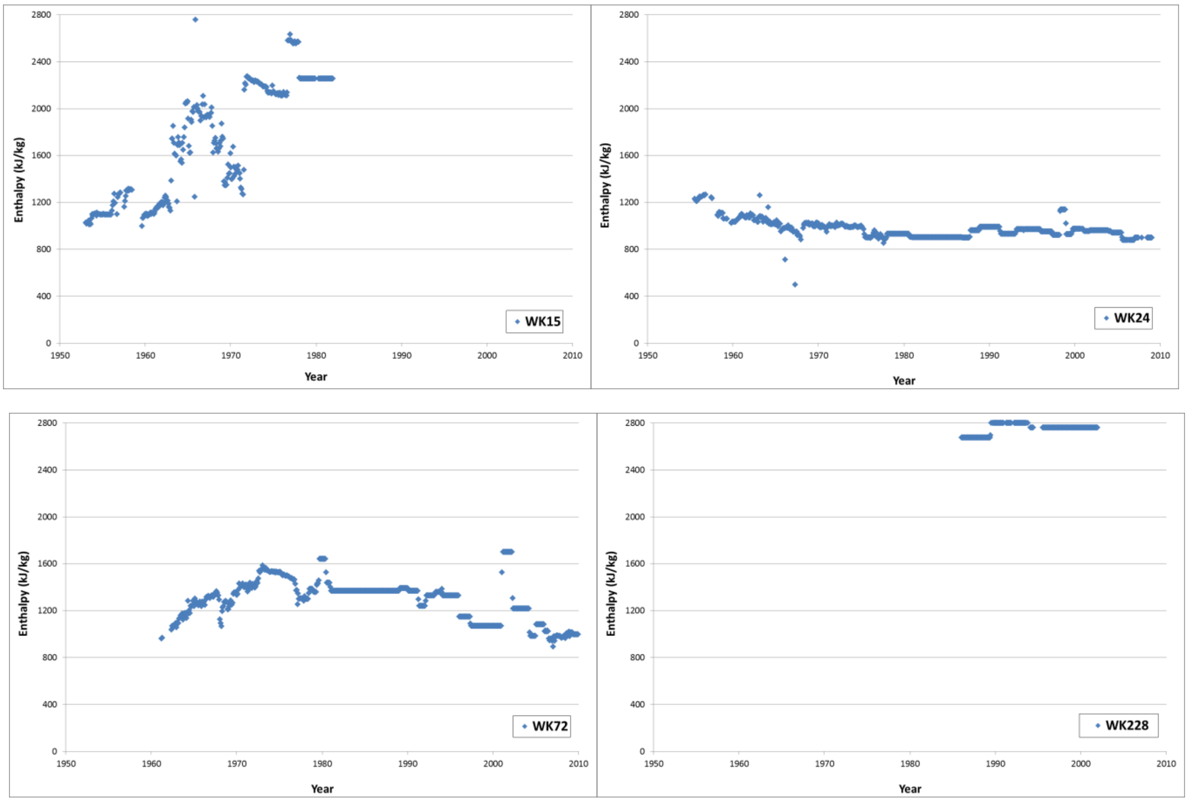

Figure 1: Enthalpy vs time for Wairakei wells WK15, WK24, WK72 and WK228

Model (ii). In this case a wellbore simulator was used to calculate P_{wb} for various enthalpies using a typical flow rate. Examples of the curves produced, for various feed-zone depths, are shown in Figure 2.

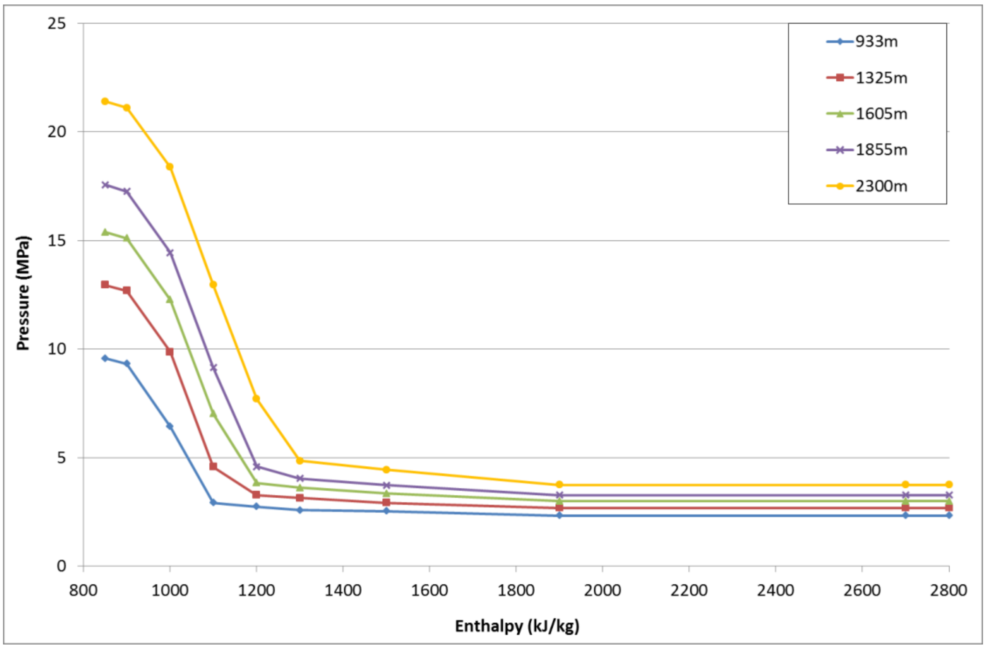

Figure 2: Typical bottom-hole flowing pressure curves used in the Tauhara II modelling study. The depths correspond to the midpoints of some layers in the model. A well-head pressure of 1.5MPa was used.

The curves shown in Figure 2 were generated for a flow rate of ~100t/hr. However not all wells are producing at a rate close to this value and the flow rate may vary with time.

We experienced some difficulty in using curves like those shown in Figure 2 for representing multi-feed wells. Our technique for dealing with multi-feed wells is to treat each feed as a separate well with a P_{wb} defined by a curve, from a plot like Figure 2, appropriate for the depth of the particular feed. The difficulty arises when one feed cuts off completely and the conditions in the other feeds then change significantly, causing a spurious sudden change in the predicted behavior of the well.

Model (iii). To overcome the difficulties experienced in using Model (ii) it was decided to investigate the more general case where P_{wb} is allowed to depend on both flow rate and enthalpy. The well TH12 was used as an example and a table look-up for P_{wb} as a function of enthalpy and flow rate was generated with the wellbore simulator GWELL (Aunzo, 1990; Aunzo *et al*., 1991). A contour plot of the table is shown as background in Figures 8 and 16 below.

3. RESULTS FOR TH12

To test the three approaches presented above for calculating P_{wb} in (1) we used one of the future scenarios set up for our modelling investigation of the Tauhara II Project (O'Sullivan and Yeh, 2010) carried out for Contact Energy Limited. In particular we ran the future scenario three times using each of Models (i) – (iii) for representing the future behaviour of one particular well (TH12). The production enthalpy, mass flow rate, steam flow rate, flowing bottom-hole pressure and reservoir pressure in the feed-zone block are shown in Figures 3, 4, 5, 6 and 7, respectively.

Unfortunately the enthalpy for TH12 does not change very much, declining by only 60-80kJ/kg over 60 years (see Figure 3). Thus TH12 does not provide a very severe test of the three methods for representing P_{wb}.

In terms of predicting the future mass and steam production from TH12 Model (ii) is the most pessimistic, Model (iii) is the most optimistic and Model (i) produces results in between (see Figures 4 and 5).

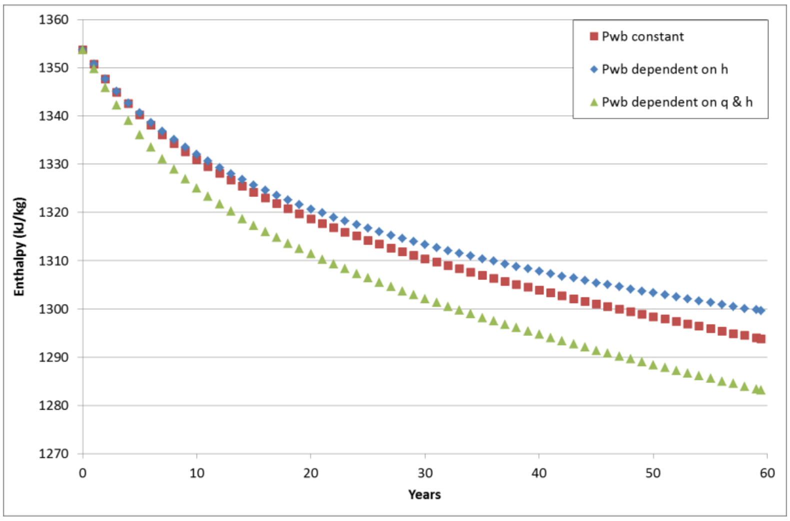

Figure 3: Production enthalpy for TH12

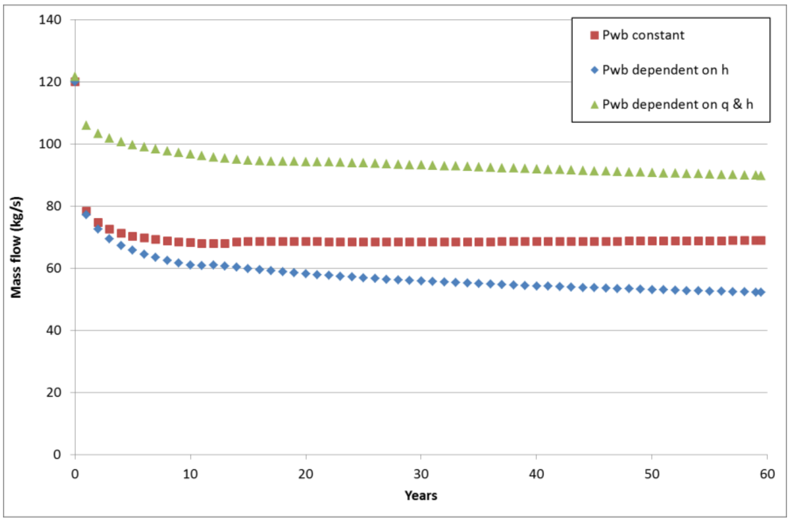

Figure 4: Mass flow rate for TH12

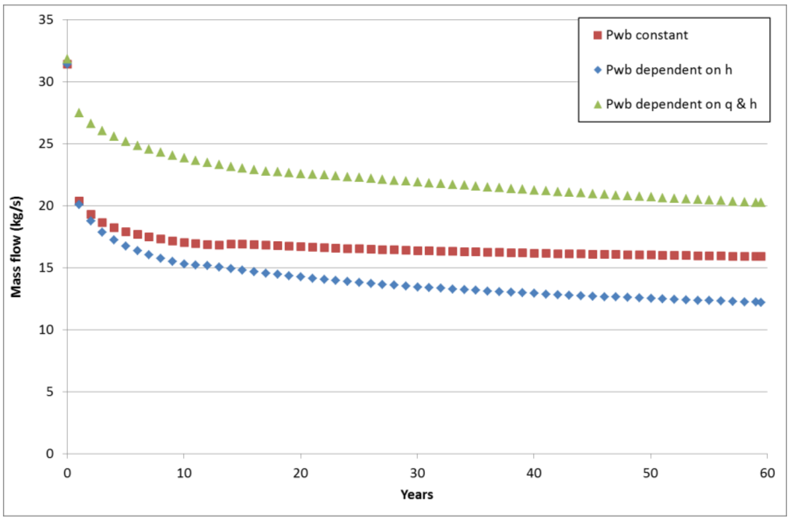

Figure 5: Steam flow rate for TH12

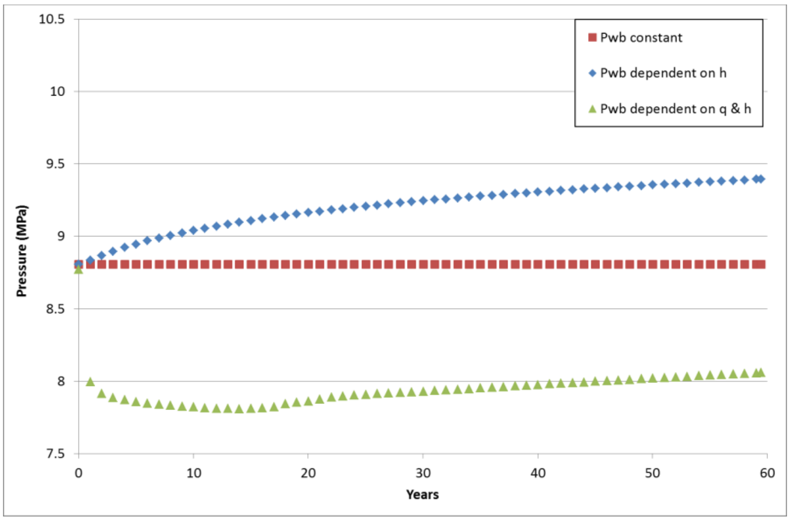

Figure 6: Flowing bottom-hole pressure at the feed-zone for TH12

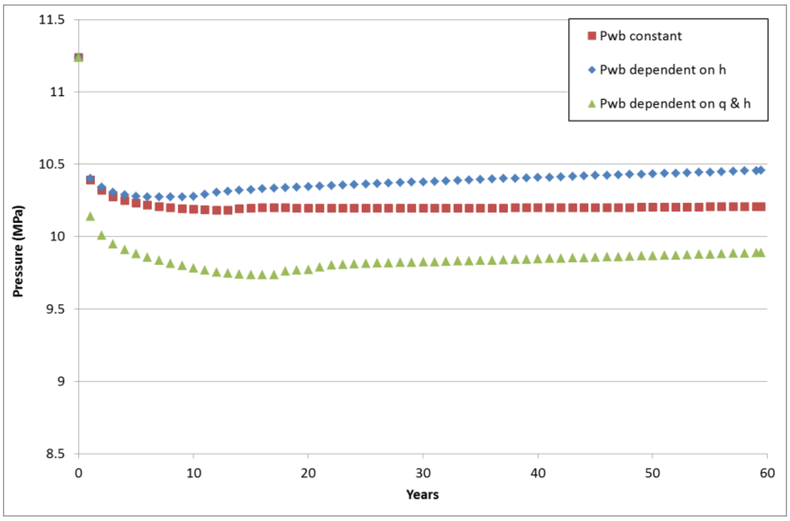

Figure 7: Reservoir pressure at the feed-zone for TH12

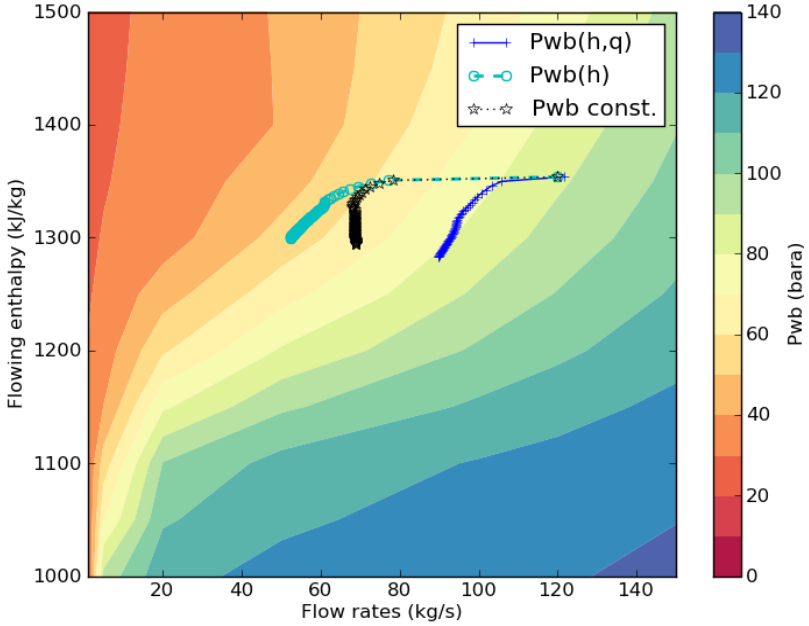

Figure 8: Contours of P_{wb} as a function of flow rate q_m and enthalpy h for well TH12 with simulation results superimposed.

The three trajectories plotted in Figure 9 show how the enthalpy and flow rate track over time for each of the three deliverability models.

For the results shown above the measured flow rate of 120t/hr for TH12 was used to generate the parameters for Model (i) and Model (ii), with the productivity index (PI in (1)) adjusted to give an initial flow rate of 120t/hr. However as shown in Figure 4 and Figure 6, respectively, the mass flow rate and flowing bottom-hole pressure are different for the three methods for representing P_{wb}. Thus the differences in the results can be attributed more to the inconsistency of model parameters rather than differences in the models used. To overcome this problem the model parameters were adjusted to try to make the average bottom-hole pressure, over 60 years, similar for all three models (see Figure 9).

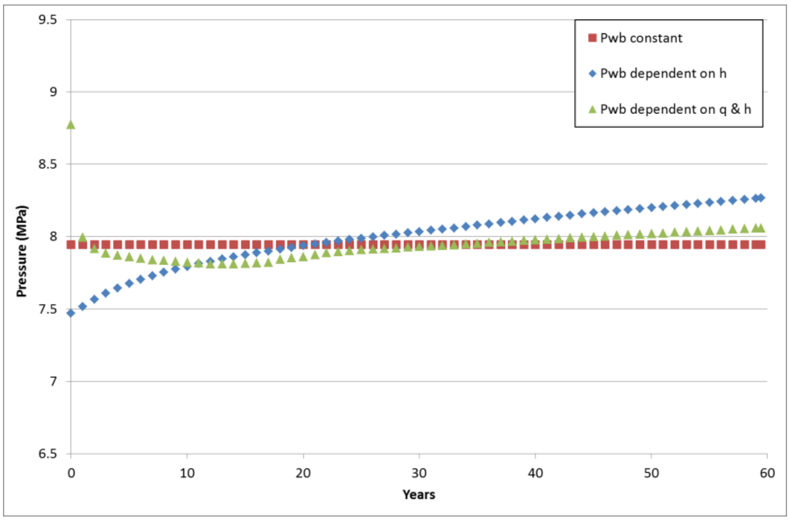

Figure 9: Flowing bottom-hole pressure at the feed-zone for TH12. Adjusted model parameters.

The corresponding enthalpies and mass flows are shown in Figure 10 and 11, respectively. Now the differences in the results for Model (ii) and Model (iii) are very small, which is not surprising as the enthalpy is almost constant.

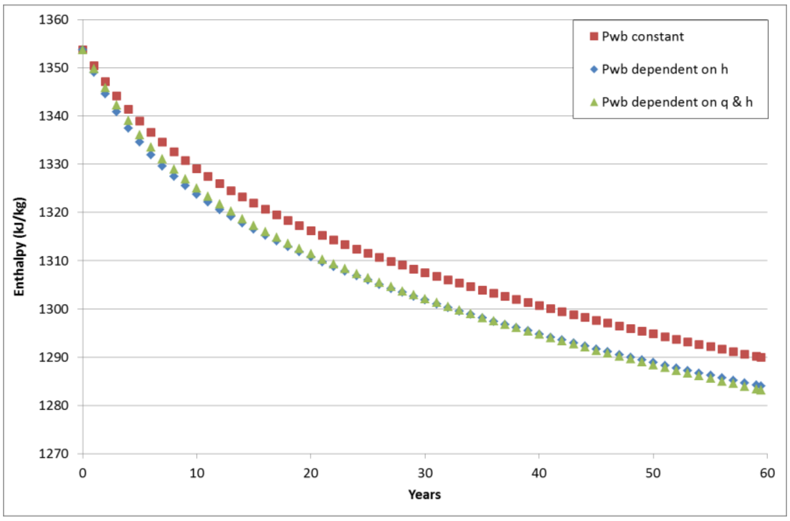

Figure 10: Production enthalpy for TH12. Adjusted model parameters.

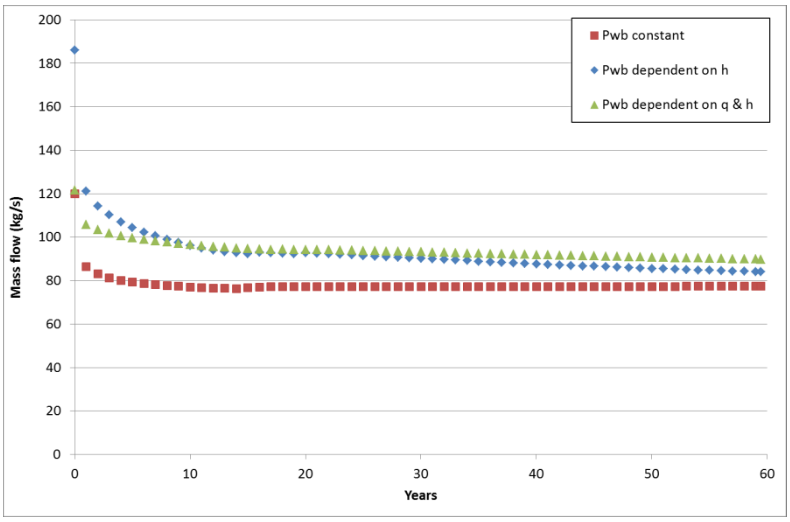

Figure 11: Mass flow rate for TH12. Adjusted model parameters.

4. RESULTS FOR TH12 – NEARBY MAKE-UP WELLS

As a third and more severe test of the three deliverability models a simulation was carried out with make-up wells added in close enough to TH12 to affect the pressures there. The same parameters were used as in the simulations whose results are shown in Figures 3-7.

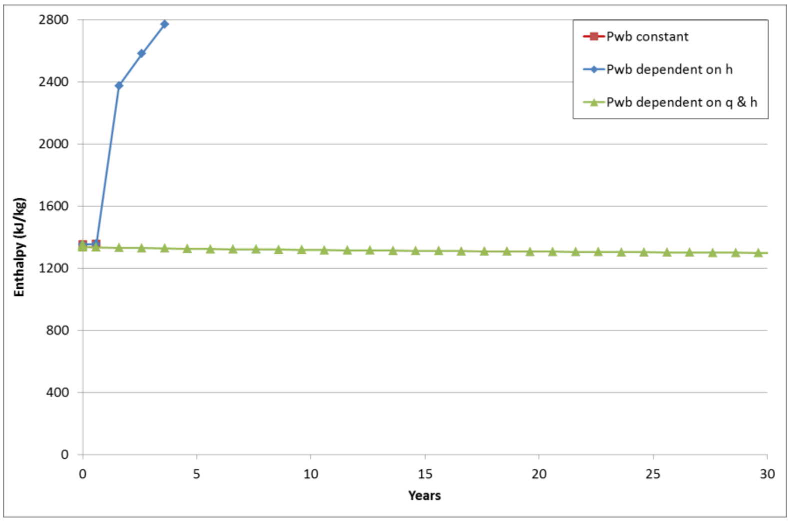

Figure 12: Production enthalpy for TH12, with nearby make-up wells

Results are plotted in Figures 12-15. Now there are very significant differences in the behavior of the three models with Models (i) and (ii) predicting an earlier halt to production whereas with Model (iii) production continues on past 30 years (the simulations were stopped then because Models (i) and (ii) failed so early).

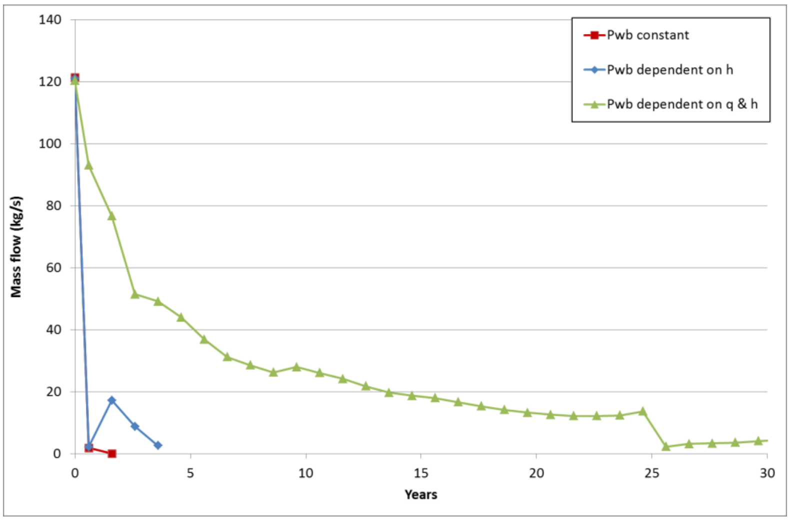

Figure 13: Mass flow rate for TH12, with nearby make-up wells

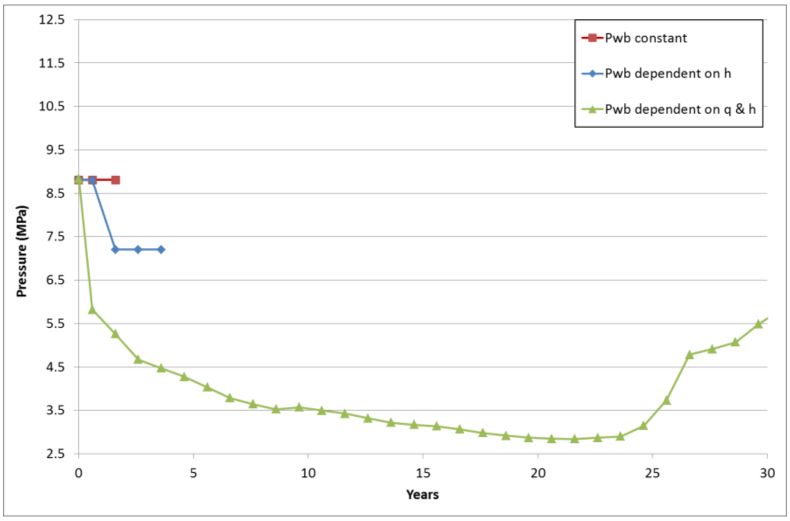

Figure 14: Flowing bottom-hole pressure at the feed-zone for TH12, with nearby make-up wells

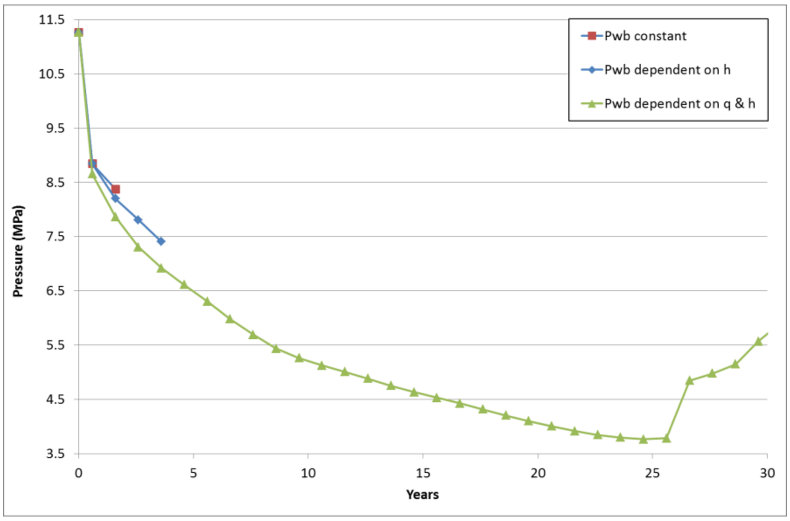

Figure 15: Reservoir pressure at the feed-zone for TH12, with nearby make-up wells

Now the trajectory of enthalpy and flow rate with time is much more variable (see Figure 16). For the Model (i) deliverability TH12 fails quickly when production from the nearby make-up wells causes the reservoir pressure to drop too low. For Model (ii) the TH12 enthalpy increases quickly as the reservoir pressure drops, as shown in Figure 15, and then the well fails. For Model (iii) the enthalpy rises at first but after a time declines to all liquid conditions.

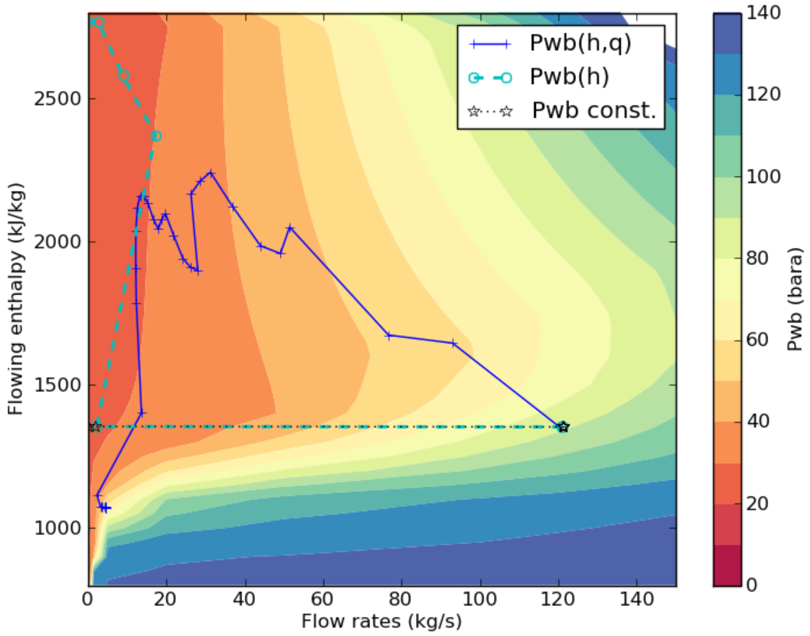

Figure 16: Contours of P_{wb} as a function of flow rate q_m and enthalpy h for well TH12 with simulation results superimposed for the case when nearby make-up wells are included

5. CONCLUSIONS

The results above show that simple models of deliverability are adequate if the behavior of a well is not very variable over time, but if large changes in enthalpy and/or flow rate occur then the table look-up deliverability model should be used. It takes some time and effort to generate the look-up table required for each production well in the model.

However this approach is not adequate for a multi-feed well and more research is required to develop an efficient model for representing coupled wellbore-reservoir behavior.

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