Application of advanced chemical process design methods to integrated production modelling

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ABSTRACT

The main objective was to apply advanced numerical methods, first developed for the solution of chemical engineering processes, to petroleum engineering problems; specifically the modelling of hydrocarbon flows from underground reservoirs, through wells, flowlines, risers and processing equipment. This is, essentially, a pressure bounded problem where the reservoir pressure and the reception facilities pressure are fixed at a given instant in time and the production rate adjusts accordingly. The equation oriented approach was used as the basis of the numerical algorithms. The entire process, from reservoir to end-user, can be viewed as a digraph where the physical equipment items form the nodes and edges, collectively referred to as objects. Each object is described by a set of equations – founded on the conservation principles – with variables shared between object equations depending on the connectivity of the digraph. The algorithms assemble the entire set of equations into a large sparse matrix which is then reduced to block triangular form for solution. The paper gives an overview of this methodology. The results of two integrated production modelling (IPM) case studies are summarised, highlighting the important predictions and describing how these are used to resolve key techno-economic decisions in oil and gas design. It is concluded that the application of these methods, first developed for the solution of chemical processes, provides an efficient approach for the solution of petroleum engineering problems, in this case IPM, resulting in highly accurate and physically representative predictions generated in practical engineering timeframes.

1 INTRODUCTION

The simulation of chemical engineering processes has advanced considerably over the last three decades, as computer hardware has improved, and new numerical methods have been developed. This trend looks set to continue as parallel processing techniques are exploited in conjunction with affordable multi-processor machines.

At present, commercial process simulation software can be separated into either of two classifications: *sequential modular* or *equation oriented*. The first commercially available simulators were based on the sequential modular approach. For this method, individual modules are developed for each *unit operation* in the flowsheet. These modules 'operate' on their input streams to produce their output streams. The separate modules are then solved in a sequence determined by the topology of the flowsheet to

form the solution of the entire flowsheet. Where recycle streams appear, as is often the case, iteration is required to converge the solution for the flowsheet (Westerberg et al. 1978).

The equation oriented approach is quite different from the sequential modular method. To our understanding, the approach was first proposed in the 1960s (Westerberg and Sargent, 1964) as a general method by which transient chemical processes may be simulated. However, it was not until the 1980s that the first commercial process simulator became available (Pantelides, 1988). For this approach, each unit operation is viewed as being defined by a set of equations, explicitly known to the algorithms, that relate the variables in the output streams to those in the inputs streams. The entire flowsheet is then described by a large set of non-linear equations with adjacent unit operations sharing variables in connecting streams. The algorithms then solve the system of equations simultaneously by one means or another. A comprehensive review of the equation-oriented simulation approach can be found elsewhere (Biegler et al., 2000).

This paper describes the application of the equation oriented method to the solution of petroleum engineering problems in an object-oriented environment, specifically the modelling of hydrocarbon flows in production systems and processing equipment. The equation oriented method is very general in its formulation, and while this makes it very versatile in application, different physical problems have their own nuances which must be accounted for if the solution algorithms are to be robust. This paper also highlights some of the particular difficulties that necessitate a degree of specialisation for the solution of these problems.

2 METHODOLOGY

2.1 Mathematical Modelling of Networks

In mathematical terms, petroleum production systems, comprising of wells, flowlines, risers and processing facilities, form *digraphs* of nodes connected together by branches or edges (Wilson and Watkins, 1990). Figure 1 shows an example digraph formed by a four well subsea production system together with separation and recompression processing facilities.

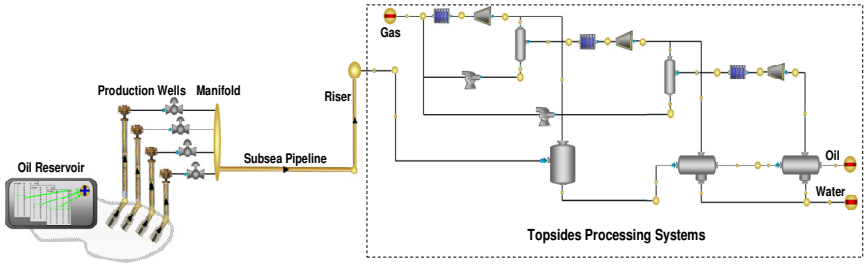

Figure 1: Subsea Production System with Processing Facilities

In this analysis, all single input / single output equipment items are defined as branches with all other equipment items defined as nodes. Therefore, pipelines and risers are defined as branches together with other equipment items such as chokes, pumps or compressors. Equipment items with the potential for multiple inputs or multiple outputs, for example manifolds or separators, are defined as nodes in this analysis.

To solve network problems, such as the one shown in Figure 1, it is necessary to balance the pressures and flows throughout the system, together with conserving mass and energy across the network. To balance the pressures and flows, functional relationships are required for all branches allowing their pressure drop / flowrate behaviour to be quantified. Introducing these functional relationships, represents the first significant departure from conventional process simulation, which is usually restricted to the solution of only mass and energy balances across unit operations. For this analysis then, pressure drop / flowrate equations were introduced for all branch-like unit operations. For pipe flows, these equations were based on the momentum conservation equation.

Compared to the sequential modular method, the equation oriented approach is significantly more general and consequently has much greater flexibility when posing the problem. In view of this, it is able to solve a much wider class of problems. The first step in the application of the method, is to formulate the entire set of equations describing the behaviour of a particular problem. Each unit operation contributes its own equations and variables. However, the topology or connectivity of the network implies that adjacent unit operations share variables. In general, the system of equations formulated is non-linear and can be rearranged to take the general form:

$$\underline{F}(\underline{x}) = \underline{0} \tag{1}$$

$$\underline{F} = (F_1, F_2, \cdots, F_i, \cdots, F_{N-1}, F_N)^T \tag{2}$$

$$\underline{x} = (x_1, x_2, \cdots, x_j, \cdots, x_{M-1}, x_M)^T \tag{3}$$

Initially, M > N and the system of equations contains more unknowns than equations. Before solution, (M – N) specifications are required to reduce the degrees of freedom to zero. To achieve this, it is usual to specify boundary conditions for the network, such as the reservoir pressures and delivery pressures, and model parameters, such as pipeline diameters and pump duties. An advantage of the equation oriented approach is that any set of specifications is permitted, provided the resulting system of equations forms a mathematically well-posed problem. This offers significant benefits over traditional solution methods, because problems can be solved more flexibly. After the imposition of specifications, the equations form the N × N system:

$$\underline{F}(\underline{y}) = \underline{0} \tag{4}$$

$$\underline{y} = (y_1, y_2, \cdots, y_j, \cdots, y_{N-1}, y_N)^T \tag{5}$$

The nature of most production system networks (of practical size) is that they are represented by hundreds, or even thousands, of equations originating from the individual unit operations. However, each equation usually only depends on a small number of variables in the solution vector. Therefore, these systems naturally form very large *sparse matrices* (i.e. containing a high proportion of zero elements). For such systems, there is considerable benefit to be gained by analysing the system of equations to identify the most efficient decomposition strategy. To do this, the equation system is first represented by its *incidence matrix* and then row and column manipulations are used to convert the system to block triangular form (Duff *et al*, 1986). An example of a

simplified block triangular system is given schematically in Figure 2. The system is reduced to a set of much smaller blocks that may be solved separately from top to bottom. Figure 3 shows the block triangularised matrix describing the model given in Figure 1. The topology of this model, coupled with its specifications, yields one block for the wells and subsea systems and the rest of the system is lower triangular. Figure 3 also emphasises the natural sparsity of the problem.

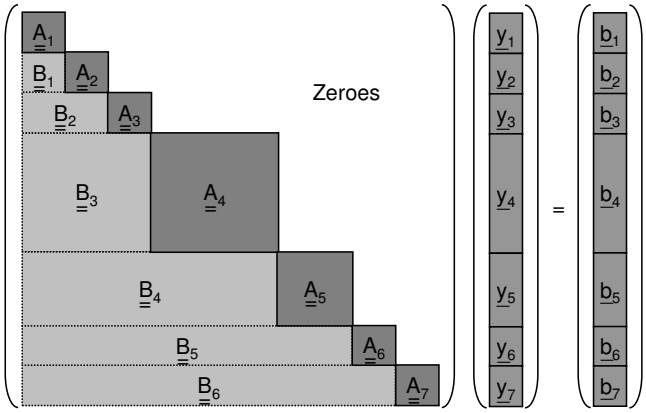

Figure 2: Simplified Schematic of Block Triangularity

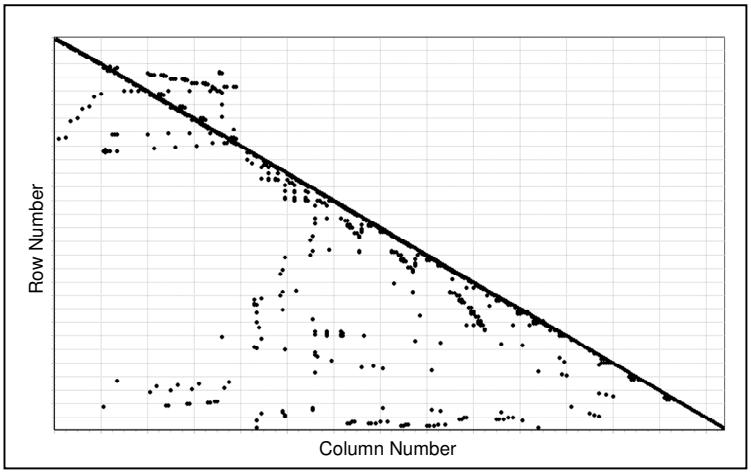

Figure 3: Example of a Triangularised Matrix

The block triangularised form is closely related to the topology of the problem and its particular specifications. If a flowsheet is structured such that it is possible to solve the unit operations sequentially, arriving at the product stream in a single pass, then the block triangularised form will be close to lower triangular with only small blocks for each unit operation. However, if recycles or loops are added, that link unit operations in one location to those elsewhere in the flowsheet, then larger blocks are created. In any case, some level of sparsity is exhibited and block decomposition methods can be exploited.

In general, the blocks emanating from the block triangularisation are multidimensional and an appropriate method is required to solve each individual block. This analysis uses a globally convergent variant of Newton's method (Burden and Faires, 2001). If the sub-system of equations represented by a block is:

$$\underline{G}(\underline{z}) = \underline{0} \tag{6}$$

Then the iterative map defined by Newton's method is given by:

$$\underline{z}^{k+1} = \underline{z}^{k} - \left[\underline{\underline{J}}^{k}\right]^{-1} \underline{G}^{k} \tag{7}$$

Where $\underline{z}$ is a subset of the variable set $\underline{y}$ and $\underline{G}$ is a subset of the equation set $\underline{F}$. The superscripts k and k+1 refer to the old and new iterates respectively. The matrix $\underline{\underline{J}}$ is the Jacobian matrix whose elements are defined as:

$$J_{i,j} = \frac{\partial G_i}{\partial z_j} \tag{8}$$

For this analysis, the Jacobian matrix was initialised with analytic derivatives where possible, and finite difference estimates when analytic differentiation was not possible. Computing the Jacobian can be computationally expensive and it is often unnecessary to calculate it exactly at each iteration. For this work, a hybrid method was implemented based on Broyden's least-change secant update (Broyden, 1965) coupled with analytic updates for those elements that are available cheaply. This hybrid method is computationally efficient and avoids the problem of 'fill in' where zero elements receive non-zero values at subsequent updates.

Using the iterative map represented in Equation (7), it is possible to solve the block of equations $\underline{G}$ before moving on to the next block. Once all the blocks have been solved, then the entire network solution has been achieved.

2.2 Physical Models for Unit Operations

The unit operations required to simulate hydrocarbon production systems include reservoirs, wells, trees, manifolds, flowlines and risers, together with other equipment items, such as pumps, compressors, expanders, separators, heaters, coolers, chokes, valves and non-return valves. The physical models for these are quite diverse and it is impractical to attempt to describe them all here. Hence, this discussion is confined to tubings, flowlines and risers. These are all examples of diabatic multiphase flows in cylindrical tubes, albeit with typically different diameters and inclinations. The modelling of these is based on the spatial integration of the steady state conservation equations for mass, momentum and energy. Since the flows are generally multiphase, appropriate closure models are required to quantify the holdups of the phases and the frictional losses. Various published models have been incorporated, for example Hagedorn and Brown (1965), Beggs and Brill (1973, 1991), Taitel and Dukler (1976), Ansari *et al* (1994) or Fan *et al* (2007) as well as proprietary models such as OLGA-S two phase and three phase.

To guarantee accuracy and efficiency of spatial integration, a high-order adaptive method was used based on a Cash-Karp Runge-Kutta scheme (Cash and Karp, 1990). Thus, accurate integrations are usually assured, even if the equations being integrated undergo steep gradient changes, because the integration step length is modified to resolve these changes. Figure 4 presents the results of integration along an uninsulated subsea pipeline in which hydrate formation occurs. The pipeline temperature profile (Figure 4) shows two gradient discontinuities which have been resolved by the integrator. Reference to the corresponding pressure-temperature profile on the phase diagram (Figure 5) shows that these discontinuities occur when phase boundaries are crossed. In the region where hydrate is forming the heat of formation helps to maintain the fluid temperature, which gives rise the flatter region on the temperature profile plot.

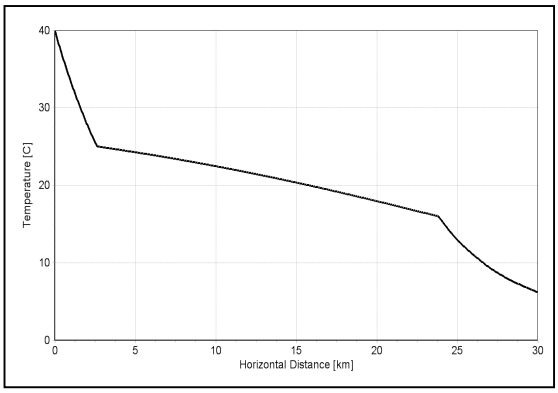

Figure 4: Temperature Profile of Flow in Uninsulated Subsea Pipeline

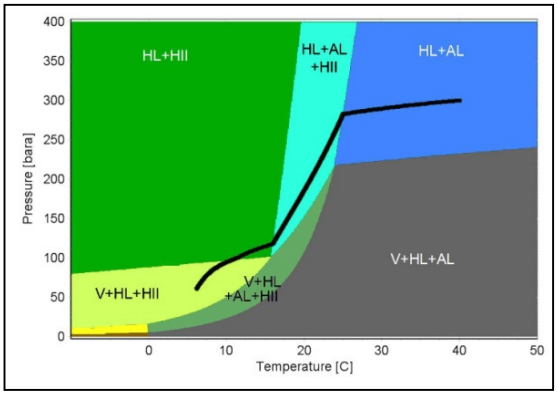

Figure 5: Phase Envelope of Flow in Uninsulated Subsea Pipeline

For integration along pipes, it is important that discontinuities, such as phase boundaries or flow regime transitions, are resolved accurately. Failure not to do so introduces 'noise' which can prevent solution convergence. This is a problem that arises frequently in network solvers that use fixed pipe segment lengths; where it is observed that alternating flow regime transitions, in one or more segments, can prevent convergence. To avoid this, small integration steps can be fixed, however, this may slow unnecessary the pipe integrations in regions where no phase boundaries or flow regimes transitions occur.

2.3 Particular Difficulties

As with chemical processes, the solution of hydrocarbon production systems also encounters several difficulties. Leaving aside the problems in common, such as mathematical ill-posedness, arising from under-specification, over-specification or structural singularity perhaps, there are several problems that are particular to systems of this kind. Three important examples are:

Flow Reversal. As the branch pressure drop / flowrate characteristics are solved in conjunction with the mass and energy equations, it is quite common for flow reversals to occur, either momentarily at a particular iterate, or in the final solution. To account for this, the equations describing each unit operation must be formulated to permit negative flows, even if the behaviour itself would not be observed in practice. In some cases, the solution achieved may not be physical because of the modelling assumptions made about reverse flow behaviour in some unit operations. However, it is still useful to have the solution because this then informs the engineer of potential problems with the physical posing of the problem. The possibility of flow reversals, and the need to handle these satisfactorily, represents another significant difference between the modelling of conventional chemical processes and hydrocarbon production systems.

Ill-Conditionedness. The mathematical models describing several of the unit operations in hydrocarbon production systems can exhibit ill-conditioned behaviour, with the solutions displaying 'elevated' sensitivity to their specifications. Most notable of these are pipelines operated at high flow rates where the outlet pressure approaches atmospheric. The ill-conditionedness arises because of the expansion of the fluid at low pressures, leading to higher velocities and rapidly increasing frictional pressure losses. Figure 6a shows pressure profile results for a 10 km pipeline carrying a multiphase oil-gas-water mixture. The graph shows that increasing the flowrate from 240 to 260 Mstb/d causes the outlet pressure to reduce from 47 to 7 bara. At the lowest flowrate, the pressure gradient is almost linear. However, as the flowrate increases the gradient becomes increasingly non-linear towards the outlet. As a result, the behaviour of the outlet pressure becomes very sensitive to comparatively small variations in the flowrate.

'Negative' Pressures. The equations describing the pressure drop / flowrate behaviour of branches in the network are usually posed in a simplified form that can permit the calculated pressure drop to exceed the inlet pressure, for certain unphysical specifications. For example, for a given inlet pressure, if the flowrate into a pipeline is increased, a critical value of flowrate is reached where the pressure at the outlet is reduced to zero. For all flowrates greater than this critical value, the outlet pressure is always zero. Hence, above the critical flowrate, the equation describing the pressure drop / flowrate behaviour becomes indeterminate on flowrate. Now this indeterminacy presents difficulties during solution because the equations provide no information about which direction to proceed in order to balance pressures in the network. For this analysis, this problem has been resolved by introducing negative pressures. This is done by fixing physical properties calculations at some lower bound positive pressure, but allowing the equations themselves to predict negative pressures. Figure 6b shows the integrated pressure profile along a 20 km pipeline for three different flowrates. While the solutions shown are unphysical, the fact that the dependency on flowrate is maintained means that the solution algorithms know which way to return to a physically sensible domain. This greatly improves the performance of the algorithms because they can act in a wider solution domain.

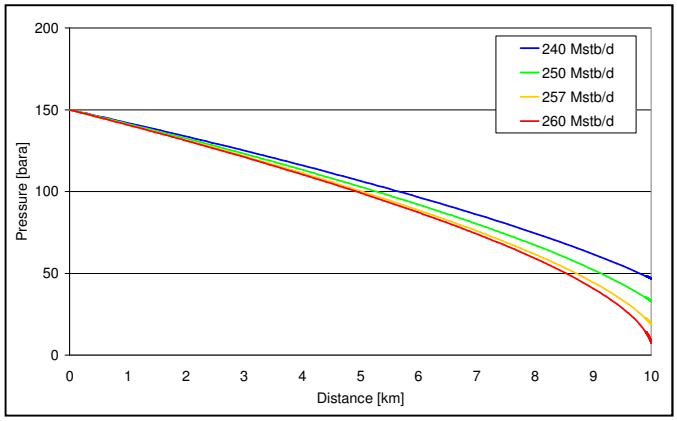

Figure 6: Results illustrating ill-conditionedness

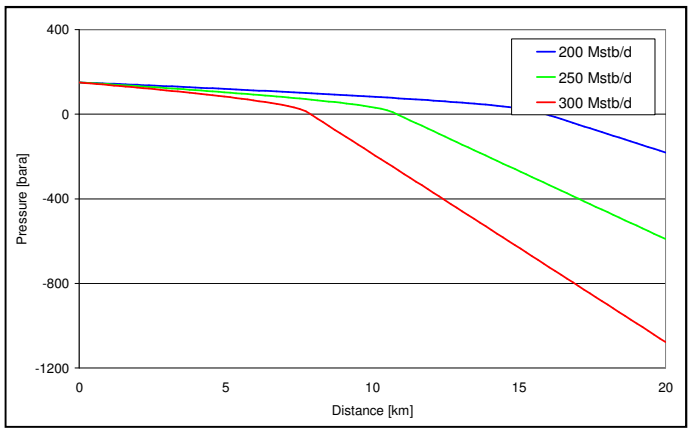

Figure 7: Results illustrating negative pressure issues

3 RESULTS AND DISCUSSION

An integrated production modelling (IPM) tool has been developed by FEESA using the numerical methods discussed in this paper. This section summarises the results of two case studies, highlighting important predictions that exemplify how such methods have been used to resolve key techno-economic decisions in oil and gas design.

3.1 Case Study 1: Corrosion Constrained Production Profiles

This case study is based on a combined IPM, Flow Assurance and Corrosion Management study carried during the conceptual design phase of an oil and gas development. The project consisted of several subsea multiphase tiebacks to a processing facility, one such tieback is illustrated in Figure 8. For this particular tieback the "Base Project" was a drill centre from an oil reservoir with relatively low carbon dioxide concentration (~0.4mol%). However during this conceptual phase more resources were found in the area from another field with a higher carbon dioxide concentration (~7mol%). The economically favourable tieback solution for this

"potential future project" was as a daisy chain tieback to the "base project", as shown in Figure 8. However, compared to the rest of the project, there was a greater uncertainty about the reservoir information for the "potential future project". This uncertainty would be resolved by further exploration wells, but these were not scheduled until after the construction phase of the base project had already begun.

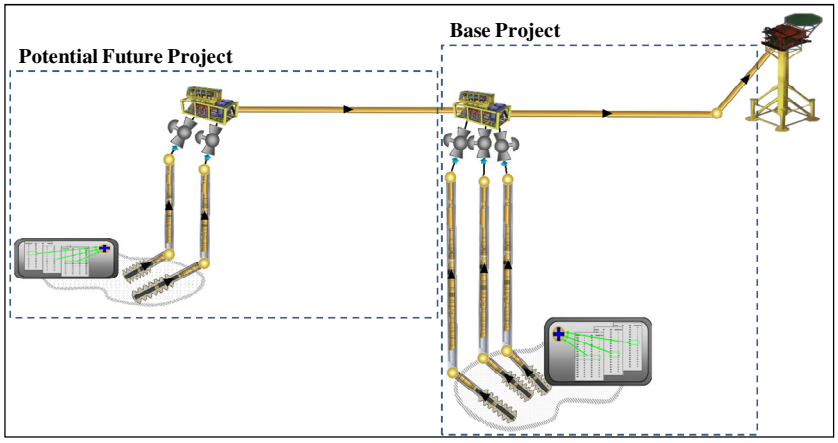

Figure 8: Schematic of Case 1

The development team wanted to know what the minimal amount of additional pre installation was required to allow the potential of tying back this unproven reserve. One of the largest subsea engineering concerns was the pre-investment needed in the base case flowlines to maintain integrity against carbonic acid corrosion from the high carbon dioxide future potential wells. One solution was to clad the base case flowlines with Corrosion Resistant Alloy (CRA). However, the increased associated cost of CRA was considered too large for a reservoir that may never be developed.

Like many developments, the carbon steel flowlines will be protected by corrosion inhibitor chemicals injected at the manifolds. However, corrosion inhibitors have a finite efficiency and injection systems have a finite availability, hence some corrosion of the carbon steel pipeline will still occur throughout life. To account for this, a corrosion allowance is added to the pipeline wall thickness, such that this amount of wall can be corroded and the pipeline can still maintain its pressure rating. Clearly, for the same type of corrosion inhibitor and inhibitor injection system a larger corrosion allowance is required for the system with the high carbon dioxide potential future fluids than without.

Therefore a study was performed to determine how much additional high carbon dioxide oil could be produced for every additional millimetre of corrosion allowance. From this and the uncertainty of the additional reserves, the operator could determine a sensible level of pre-investment.

This corrosion allowance was calculated by integrating the corrosion rate at each point in the network throughout the 20 year design life of the development. To calculate the corrosion rates, parameters such as temperature, pressure, phase flow rates and local carbon dioxide partial pressures were required and inputted into the operator's in-house corrosion rate modelling package. These input parameters change from location to location (such as upstream and downstream of the point where low and high carbon

dioxide fluids blend) and with time, as the flowrates and compositions from each well changes as the reservoirs deplete.

It was also important to keep track of other flow assurance constraints in the system, particularly wax and hydrate avoidance; wax deposition was avoided and long unplanned shutdown cooldown times before hydrate conditions were obtained by keeping the fluids as warm as possible. High temperatures are however bad for corrosion as like most chemical reactions, corrosion rates can nearly double with a 10ºC increase in temperature.

Therefore to look at all these contrasting issues fairly and rigorously, the system was modelled from reservoir to the first stage of separation using the thermal hydraulic IPM simulator described in this paper. The main features used in this simulation were:

1. The ability to model from reservoir to reception facility. Thereby fewer arbitrary design margins would be added to the model than were absolutely necessary. For example, flowing wellhead temperatures were calculated at each point in time for all wells, rather than specified as it is not possible to determine a wellhead temperature that is conservative for both corrosion and hydrate management, for example.

2. Pressure specified network simulation; this ensured a good assumption of inlet enthalpy flowrate into the network from the reservoirs, permitted the modelling of flow through wellhead chokes (and the associated temperature change) and allowed the flow assurance engineer to investigate a range of production profile scenarios other than those carried out by the reservoir engineer, such as a range of studies favouring the lower carbon dioxide producing field, for example. The base case reservoir was represented as a look-up table of reservoir pressure and produced fluid watercut and GOR versus cumulative oil, which was generated from reservoir simulator results. The potential future reservoir was represented as a similar table from an analogue field, scaled to the expected recoverable reserves of this field.

3. Rigorous compositional modelling; where the components are not just "tracked" but the physical properties of the fluids at each point in the network were calculated based on the compositions at these locations, hence the thermal hydraulic behaviour of all the wells and flowlines were a function of the compositions flowing through them. The CPA equation of state from InfoChem's Multiflash was used for phase equilibria and physical property calculations due to its superior ability to model carbon dioxide partitioning with the aqueous and oil phases when compared to standard cubic equations of state and hence get the best estimate for carbon dioxide partial pressures for the corrosion calculation.

Figure 9 plots typical annual average corrosion rates (i.e. taking into account the effectiveness and availability of the corrosion inhibitor) for the base project tieback alone for 20 years (A alone) and if the potential future project starts five years later, allocating production between the old and new wells in the most optimal way to extend production plateau (A+B Optimal Rate). The rate changes through time as all key inputs for the corrosion calculations (temperatures, pressures, watercuts, velocities, and partial pressure of carbon dioxide etc) change through time,

especially for the A+B case were the relative rates from the high and low carbon dioxide change through time to maintain plateau rate for as long as possible.

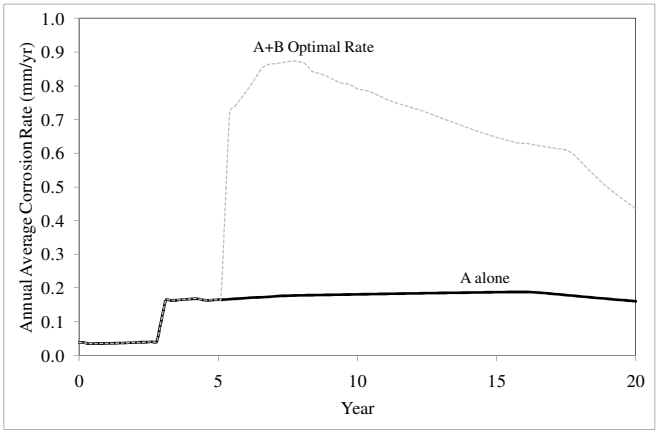

Figure 9: Corrosion Rate Through Time

Figure 10 plots results from seven different development scenarios, in addition to "A alone" and "A+B Optimal Rate", they are a series of variations of A+B, where the high carbon dioxide field (B) is shut in at different times before the end of the design life. On the left hand side of Figure 10, the integrated corrosion rate through time (i.e. the amount of corrosion allowance used up until that point in time) is plotted, on the right hand side is the cumulative oil produced from this tieback.

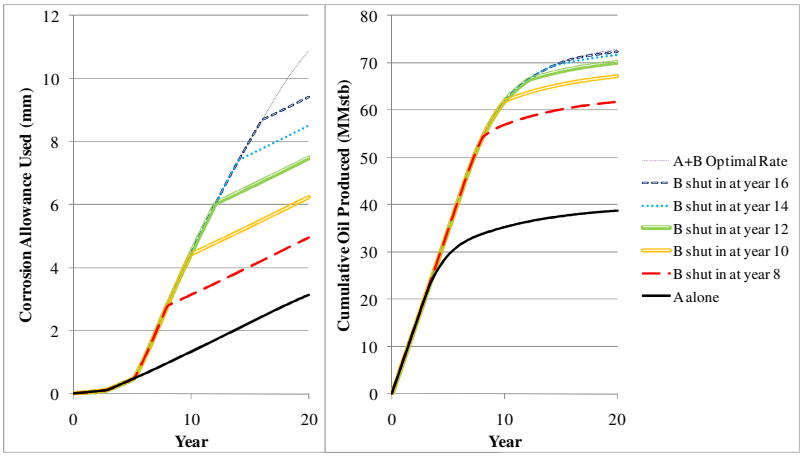

Figure 10: Example Results from Case 1

As can be seen in Figure 10, the base project (A alone) would only require 3mm of corrosion allowance. However, for an additional 2mm of corrosion allowance, a further ~23 million barrels of oil could be produced from the potential future project. From that point on there is a law of diminishing returns; another 2mm only gives another 8 million barrels, etc. Many alternative development strategies were investigated in this way to allow the Operator to make informed decisions on minimal investments for the base case projects facilities to still allow the uncertain "future potential" development. This

method can also be used when investigating the potential of tying back new fields to existing facilities, where inspection pigging can be carried out to assess what corrosion allowance remains in the system and design life engineering studies can be carried out to assess how else it could be used.

3.2 Case 2: Long Gas Condensate Tieback

Many of the main flow assurance concerns of long distance gas condensate tiebacks are associated with the hold-up of liquids in the pipeline. Hydrate inhibitor storage sizing, restart rates and slugcatcher surge volume sizes can all depend on the ability to model the liquid content of the flowline. As shown in Watson *et al* (2008), in the early stages of design, uncertainties in flowline bathymetry can cause larger errors in the predicted total liquid content than, for example, the choice of stratified flow model. Figure 11 reproduces the plot from their study showing how total liquid content varies with added undulations to the coarse bathymetry for a range of flow rates.

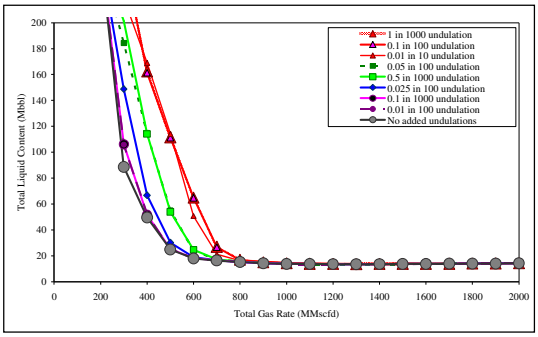

Figure 11: Sensitivity of Liquid Content to Bathymetry (Watson *et al* 2008)

In later stages of design, more detailed bathymetries are available for the pipeline route; elevation data points to the nearest 1m along the length of the pipe can sometimes be available, though as noted in Zakarian *et al* (2009) these must be processed by Pipeline Engineers to account for free spanning, asperity depression and seabed intervention. Once this is done, the as-laid bathymetry of a 100km pipeline could consist of tens of thousands of data points. Such data sets cannot practically be used in most simulators, as it would force them to take too small a step to simulate the pipeline in a reasonable timeframe. As a result, various methods have been developed to simplify such geometries whilst attempting to keep all the salient features of the geometry (i.e. total length, angle distribution, total climb) . Such methods are described in Zakarian *et al* (2009), who also proposed a new method. However, all these methods require at least one arbitrary step, where the engineers determine in a non-automated fashion whether or not the simplified profile looks good and is sufficiently detailed. Evidently, this can yield to over-simplification of the original bathymetry that may lead to the errors described above. Furthermore, after the simplification procedure, the engineer must make another arbitrary decision as to how these pipe sections are discretised for the numerical fixed-step integration.

With the Cash-Karp Runge-Kutta adaptive stepping method mentioned in Section 2.2, the uncertainty due to arbitrary decisions in pipeline simplification can be kept to a minimum.. Such routines can detect and resolve important discontinuities properly, hence changes in gravitational pressure drop, caused by large changes in liquid hold-up,

for example, are resolved properly. Hence, integration steps are only taken where necessary for that particular integration and the step size will change to suit the particular conditions (velocities, temperatures, flow regimes, etc) of every integration to ensure numerical accuracy and robustness.

Figure 12 shows results from two numerical methods in Maximus; fixed stepping (left hand side graph) and adaptive stepping (right hand side graph). The multiphase flow model of choice is Fan et al., 2007. In each graph are plots of total liquid content versus stock tank gas rate for five geometry scenarios:

- Full; using the full bathymetry data from the Pipeline Engineers; i.e. 1m sections (over 100,000 data points).
- 10m; using the Zakarian *et al* (2009) method to simplify the full bathymetry into 10m sections
- 50m; using the Zakarian *et al* (2009) method to simplify the full bathymetry into 50m sections
- 100m; using the Zakarian *et al* (2009) method to simplify the full bathymetry into 100m sections
- 500m; using the Zakarian *et al* (2009) method to simplify the full bathymetry into 500m sections

As can be seen, all methods give practically the same results given the accuracy of the input data and multiphase models.

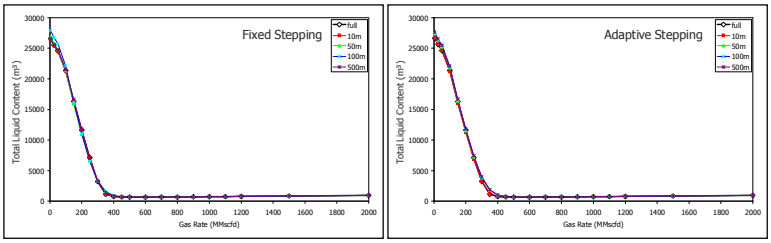

Figure 12: Liquid Content vs Bathymetry Simplification, Fixed vs Adaptive Stepping

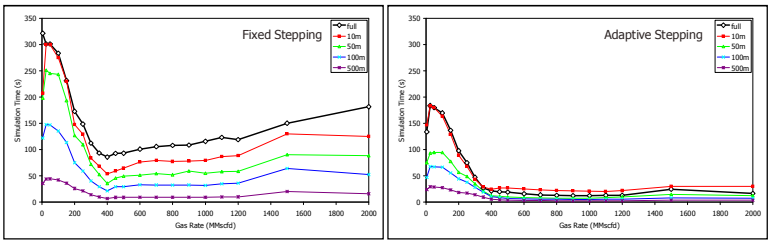

Figure 13: Simulation Time vs Bathymetry Simplification, Fixed vs Adaptive Stepping

Figure 13 plots the CPU time taken to carry out each simulation, as can be seen:

- The Cash-Karp Runge-Kutta adaptive stepping method implemented in the IPM model described in this paper is typically ten times faster than a traditional fixed stepping method at high rates. High velocities at high rates caused only minor difference in hold-up between the tens of thousands of upward and

downward sloping sections, so numerically the method could take larger steps and still ensure numerical accuracy within the tolerance set by the user. This is particularly important for an IPM simulator as systems normally operate at high rates.

- The adaptive stepping method was typically twice as fast as the fixed stepping method at low rates. The difference is less obvious at low rates as the adaptive stepping method had to cut down step sizes to resolve the larger differences between upward and downward sloping section.

Therefore certainly for IPM simulators, which focus on Normal Operating conditions, rather than turndown, adaptive stepping techniques are a viable alternative to the more arbitrary bathymetry simplification methods available. However, the two methods could be combined to obtain the optimum balance between simulation speed and fidelity, especially if low rate simulations were important for the development.

4 CONCLUSIONS

If done correctly, using what are to the Upstream Oil and Gas Industry modern numerical methods, improving the thermal hydraulic multiphase flow modelling fidelity of an Integrated Production Modeller does not necessarily lead to slower solutions. Firstly, network simulations can be more stable if their branches are more numerically stable and behave closer to the real system. Secondly, the results they obtain can be useful for many other engineering disciplines and hence key techno-economic issues can be investigated robustly and quickly in an early stage of design by reducing the time taken for such disciplines to react to the latest production profile and add their constraints to the next one.

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