TRANSIENT MODELING OF THE CHURN-ANNULAR TRANSITION IN VERTICAL PIPES

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Abstract. Numerical results obtained with the HyTAF (Hyperbolic Transient Annular Flow) model (Gessner and Barbosa, 2010; Alves et al., 2012) are presented and compared with transient churn-annular flow data obtained in a large-scale vertical two-phase flow loop (Waltrich, 2012). The model is also validated against an extensive collection of literature data for steady-state churn and annular flows in vertical pipes. The transient flow analysis is based on data for pressure and flow rate induced transients and provides comparisons for onset of the churn-annular transition, pressure drop and void fraction. The model was able to predict both steady state and transient flow conditions with a 20% deviation, which is a typical figure for successful one-dimensional models.

Keywords: numerical modeling, transient flow, churn-annular transition, annular flow, churn flow

1. INTRODUCTION

Transient annular flows with transitions to and from sub-annular flow patterns (e.g., churn and slug) are encountered in liquid loading in vertical and slightly inclined gas wells. This phenomenon is initiated when the upward gas velocity in the well falls below a critical value, at which point the liquid associated with the produced gas, which was initially flowing upwards, begins to fall back. This flow reversal destabilizes the flow in the well and increases the hydrostatic backpressure on the reservoir, thus reducing the production rate. As the upward co-current annular flow pattern must prevail along the entire wellbore to guarantee that there is no liquid accumulation at the bottomhole, it is a necessary condition for any mathematical model to accurately predict the transition from an acceptable flow regime (annular flow) to an unacceptable one (churn flow) in order to properly characterize liquid loading in gas wells.

Although major efforts have been made to predict the flowing conditions at which gas wells remain out of the liquid loading region using flow reversal correlations, these do not capture the dynamics of the loading sequence. Correlations such as that of Turner et al. (1969) are used by operators to design production systems in such a way that it will flow at gas rates capable of lifting all liquids out of the well, but they cannot be used to understand how serious the loading occurrence is or how quickly it will impair production (Falcone and Barbosa, 2013). In order to analyse the loading sequence, detailed numerical modeling of the wellbore flow is necessary.

The objective of this paper is to present steady-state and transient simulation results of gas-liquid flow in the churn-annular regime using the HyTAF (Hyperbolic Transient Annular Flow) code (Gessner and Barbosa, 2010; Alves et al. 2012; Alves et al. 2013; Alves, 2014). HyTAF is a one-dimensional multiple-field model for churn and annular flows. The model is based on a finite-difference solution algorithm derived from the Split Coefficient Matrix Method (SCMM) (Chakravarthy et al., 1980). The results are compared with a database comprising more than 1500 data points for steady-state churn and annular flows for pipe diameters between 19 and 75 mm and liquid and gas mass fluxes as large as 1000 and 700 kg/m$^2$.s, respectively. The transient analysis was compared with churn-annular flow data generated for pressure-induced and flow-rate induced transients in a 42-m long, 0.048-m ID test section (Waltrich, 2012). Agreement between the model and the experimental data was within 20% for all main macroscopic variables. Flow phenomena associated with the transition to churn flow and reversal of the liquid film are explored in the manuscript.

2. MODELING

2.1 Governing equations

The mathematical model has been described in detail elsewhere (Gessner and Barbosa, 2010; Alves et al. 2012; Alves et al. 2013; Alves, 2014), so only its main features will be presented here. The liquid is split between a continuous liquid film on the pipe wall and droplets entrained in the gas core. The main assumptions of the model are as follows: (i) one-dimensional flow, (ii) no pressure change across phase interfaces, (iii) adiabatic walls, (iv) no phase change, (v) negligible droplet inertia, so that a momentum equation can be written for the homogeneous mixtures of gas and entrained droplets. The assumptions can be justified based on the large aspect ratio (length/diameter) of the channels encountered in practice, high phase velocities and large density difference between the phases. Although the
model is compared with data for nearly isothermal air-water systems (low compressibility), the incorporation of energy equations in the model is justified by: (i) the transformation of one of the mass balance equations into an equation for pressure through thermodynamic relations, and (ii) the stability brought to the system of algebraic equations by the coupled solution of the momentum and energy equations. The governing equations in non-conservative form are given by — see Gessner (2010) and Alves (2014) for a full derivation:

\[
\frac{\alpha_g}{\alpha_g^2} \left( \frac{\partial \rho}{\partial t} + \frac{u_c \partial \rho}{\partial x} \right) + \rho_g \left( \frac{\partial u_g}{\partial t} + \frac{u_c \partial u_g}{\partial x} \right) - \alpha_g \rho_g \frac{\partial \rho e T_e}{\partial x} = 0
\]

\[
\frac{\alpha_e}{\alpha_e^2} \left( \frac{\partial \rho}{\partial t} + \frac{u_c \partial \rho}{\partial x} \right) + \rho_e \left( \frac{\partial u_e}{\partial t} + \frac{u_c \partial u_e}{\partial x} \right) - \alpha_e \rho_e \frac{\partial \rho e T_e}{\partial x} = M_e - M_f
\]

\[
\frac{\alpha_f}{\alpha_f^2} \left( \frac{\partial \rho}{\partial t} + \frac{u_c \partial \rho}{\partial x} \right) + \rho_f \left( \frac{\partial u_f}{\partial t} + \frac{u_c \partial u_f}{\partial x} \right) - \alpha_f \rho_f \frac{\partial \rho e T_e}{\partial x} = M_f - M_e
\]

where \( \Delta u = u_c - u_f \), \( \alpha \) is the volumetric fraction, \( \rho \) is density, \( u \) is the local instantaneous velocity, \( M \) is the interfacial mass flux, \( p \) is the thermodynamic pressure, \( e \) is the internal energy, \( h \) is enthalpy, \( F \) represents force per unit volume and \( g \) is the gravitational acceleration. The superscripts \( \nu, \text{int} \) and \( w \) represent the non-viscous term, interfacial term and wall term of the friction forces, respectively. The subscripts \( g, c, e \) and \( f \) correspond to the gas phase, homogeneous core, entrained fraction and liquid film, respectively. The independent variables \( t \) and \( z \) represent time and the axial coordinate along the vertical tube.

### 2.2 Closure relationships and boundary conditions

The churn-to-annular transition was correlated using the well-known Wallis criterion for flow reversal (Wallis, 1969) given by:

\[
u^*_{in} = u_g \frac{\rho_g}{\sqrt{\rho_k \alpha_f (\rho_f - \rho_k)}}
\]

Therefore, if the local instantaneous dimensionless gas velocity falls below unity, closure relationships for churn flow are applied.

The rates of droplet deposition and entrainment per unit volume in the annular and churn flow regions were calculated using the modified correlations of Hewitt and Govan (1990) as presented by Ahmad et al. (2010). The latter authors extended the Hewitt and Govan (1990) correlations based on the experimental data of Barbosa et al. (2002) to include the churn flow region. The wall shear force per unit volume in annular flow regime was calculated from the Kosky and Staub (1971) friction coefficient correlation; in churn flow, the method of Jayanti and Brauner (1994) was used. The interfacial friction force per unit volume in churn flow was calculated using the friction coefficient correlation of Jayanti and Brauner (1994); in annular flow, the interfacial friction coefficient correlation of Hewitt and Whalley (1978) was used.

At the bottom end of the vertical tube (inlet), the following parameters are set (phase mass fluxes and temperatures): \( G_{in}, G_{lin}, T_{in}, T_{lin}, e_{lin} \), the fraction of the liquid flow rate entrained as droplets in the gas core, is also set. This is usually close to zero when the liquid is injected in the tube via a porous wall section. A pressure boundary (\( P_{out} \)) is set at the top end of the tube. This set of boundary conditions was chosen so as to be in accordance with the practice in two-phase flow experimentation. In the numerical simulations of the experiments of Waltrich (2012), the time-dependent boundary conditions derived from the experimental data were used as input parameters in the model.
The mass fluxes and entrained fraction at the tube inlet are translated into native variables of the balance equations (phase fractions and velocities) using the 'triangular relationship' (Hewitt and Hall-Taylor, 1970) between the film thickness, the film flow rate and the wall shear stress in annular flow. For churn flow, an equivalent relationship was established using the friction coefficient and liquid holdup correlations of Jayanti and Brauner (1994). The conversion from temperature and pressure into entropy was accomplished using the equations of state available in the REFFPROP 8.0 (Lemmon et al., 2009) source code.

2.3 Numerical solution and statistical parameters

The governing equations were solved with the Split Coefficient Matrix Method (SCMM), which was initially developed by Chakravarthy et al. (1980) for gas dynamics and later adapted by Romstedt (1990) and Städtke (2006) to two-phase homogeneous and non-homogeneous flows, respectively. The SCMM is based on the partition of the coefficient matrix of the system of partial differential equations in two parts, each of which associated with eigenvalues having the same sign (positive or negative). The analytical steps are described in detail by Gessner (2010) and Alves (2014). Alves (2014) also presents the numerical discretization via the finite difference method and the solution of the algebraic system of equations using the PARDISO algorithm (Schenck et al., 2000, 2004). The numerical code was implemented in Fortran and the physical properties were calculated using the subroutines of REFFPROP 8.0 (Lemmon et al., 2009).

According to the grid sensitivity analysis performed by Alves (2014), a grid size of \( \Delta z = 0.2 \) m was considered sufficiently accurate for the predictions of the experimental data of Waltrich (2012) for a 42-m long pipe. However, to accommodate the shorter test sections investigated in the steady-state analysis (as short as 1.7 m) without the need for a variable grid size, \( \Delta z = 0.01 \) m was used in all simulations. A time step, \( \Delta t \), of 1 ms was used in all transient and steady-state simulations unless indicated otherwise.

All comparisons between numerical results and experimental data were made in terms of three statistical parameters, namely, the absolute average deviation (AAD), the root mean square (RMS) error and the systematic error (Bias), defined respectively by:

\[
\text{AAD} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\text{calc}_{i} - \text{exp}_{i}}{\text{exp}_{i}} \right|
\]

\[
\text{RMS} = \frac{1}{n} \sqrt{\sum_{i=1}^{n} \left( \frac{\text{calc}_{i} - \text{exp}_{i}}{\text{exp}_{i}} \right)^{2}}
\]

\[
\text{Bias} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\text{calc}_{i} - \text{exp}_{i}}{\text{exp}_{i}} \right)
\]

where ‘exp.’ is the experimental value associated with a given data point and ‘calc.’ is the value calculated with the numerical model. ‘n’ is the number of data points.

3. RESULTS

3.1 Steady-state comparison

This section evaluates the overall ability of the model in predicting the steady-state experimental data obtained from the open literature — see Alves (2014) for a full description of the experimental facilities. All film thickness and liquid holdup data were converted to homogeneous core volumetric fraction (core fraction) and to gas volumetric fraction (void fraction), respectively (unless indicated otherwise). The inlet droplet entrained fraction was taken as 0.01\% for all simulations. This is because the injection of liquid in the test facilities was mostly through porous inserts at the pipe walls or through means that facilitate the development of annular flow.

Figure 1 shows all annular flow pressure gradients for 552 data points. For this comparison the AAD, RMS and Bias are 16.2\%, 0.92\%, and 3.84\%, respectively. The churn flow pressure gradient comparison is shown in Fig. 2 for 293 data points. The statistical parameters are AAD=18.5\%, RMS=1.56\% and Bias=11.2\%. A reasonably good agreement can be observed for both flow regimes, with 72.8\% and 68.3\% of the points within the ± 20\% range for annular and for churn flows, respectively.

The overall comparison of the liquid film mass flux in annular flow is presented in Fig. 3 for 360 data points. The resulting statistical parameters are AAD = 21.1\%, RMS = 1.57\% and Bias = 2.81\%, with 55.0\% of the points in the ±20\% range. A comparison of the void/core fraction for the annular flow (open symbols) and churn flow (dark symbols) regimes is presented in Fig. 4 for 651 data points, which resulted in AAD = 7.45\%, RMS = 0.61\% and Bias = 6.54\%, with 91.5\% of the data points falling in the ±20\% range.
Overall, there has been a clear tendency for the model to better represent the annular flow data for larger diameter pipes (Belt et al., 2009; Waltrich, 2012; Yuan et al., 2013). For churn flow, the deviations were larger, as was the scatter in the experimental data. This is due to the larger fluctuations characteristic of this flow pattern. The pressure gradient data was somehow overestimated by the numerical model in both churn and annular flows, as was the liquid film mass flux (available only for annular flow).

The void/core fraction deviations were much smaller for annular flow. In churn flow, however, the experimental data of Costigan (1997) showed a much larger deviation, which may be related to the experiments being conducted at lower gas superficial velocities (closer to slug flow). The experimental data of Govan et al. (1991), Waltrich (2012) and Yuan et al. (2013) present much smaller deviations, which is in agreement with the predictions of the other parameters (pressure gradient and liquid film mass flux).

3.2 Transient comparison

This section presents the results of a comparison of the numerical model with the experimental data for transient churn and annular flows obtained by Waltrich (2012). For all simulations, the flow was initiated using nominal values of the initial boundary conditions until a stable solution of the flow field was reached. After this, the transient boundary conditions were enforced, which could be either a change of mass flux at the bottom of the test section (mass flux-induced transient) or choking at the top of the test section (pressure-induced transient). In both cases, the flow pattern transits between churn and annular flows along the test section until a new stable condition is reached. It must be mentioned that the initial stabilization period is necessary to initialize all variables with physically coherent values, thus providing a consistent basis for the transient simulation, in which the boundary conditions may oscillate significantly.

Five pressure-induced transients and three mass flux-induced transients were performed as part of this project (Alves, 2014). Here only one case of each type of transient will be presented, being Case 1 a pressure-induced transient and Case 2 a mass flux-induced transient. In Case 1 the outlet pressure is the only variable controlled experimentally, and fluctuations or changes in other variables such as inlet mass fluxes are responses to that pressure change. In test Case 2, the inlet liquid mass flux is the only variable controlled experimentally. Any fluctuations or changes in other variables such as inlet gas mass flux or pressure outlet are responses of the system to that input.

Both cases are discussed based on the transient pressure drop behavior at four different pipe locations and on the transient void fraction behavior at two different pipe locations. Table 1 shows the initial and final boundary conditions
of the transients. The last two lines show also the expected flow pattern to be encountered in the beginning of each simulation and at the end, where (A) stands for annular flow and (C) for churn flow.

Figure 5 shows (a) the instantaneous experimental outlet pressure, (b) the inlet liquid and (c) and inlet gas mass fluxes during the Case 1 transient test. The pressure increase in the test section, as well as the decrease in the liquid and gas mass fluxes, result from the constriction imposed by the outlet choke. These three profiles are used as boundary conditions in the hyperbolic numerical model.

### Table 1 – Nominal values of initial ‘I’ and final ‘F’ steady-state parameters of the transients.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{in}}$ (I) [kg m$^{-2}$s$^{-1}$]</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>$G_{\text{in}}$ (F) [kg m$^{-2}$s$^{-1}$]</td>
<td>390</td>
<td>289</td>
</tr>
<tr>
<td>$G_{\text{in}}$ (F) [kg m$^{-2}$s$^{-1}$]</td>
<td>290</td>
<td>19</td>
</tr>
<tr>
<td>$P_{\text{out}}$ (I) [kPa]</td>
<td>150</td>
<td>383</td>
</tr>
<tr>
<td>$P_{\text{out}}$ (F) [kPa]</td>
<td>500</td>
<td>240</td>
</tr>
<tr>
<td>Expected Flow Pattern (I)</td>
<td>(A)</td>
<td>(C)</td>
</tr>
<tr>
<td>Expected Flow Pattern (F)</td>
<td>(C)</td>
<td>(A)</td>
</tr>
</tbody>
</table>

Figure 5 – (a) Transient outlet pressure boundary condition for Case 1. (b) Transient inlet liquid mass flux boundary condition for Case 1. (c) Transient inlet gas mass flux boundary condition for Case 1.

Figure 6 shows the behavior of the calculated $u^*_gs$ at different distances from the inlet together with the Wallis criterion (Wallis, 1969) for the churn-annular transition ($u^*_gs = 1.0$). The model predicts a flow transition from annular to churn flow at around 15 seconds into the test, which is seen to occur more or less uniformly along the test section, i.e., with very little delay between the different positions. The distinct values of $u^*_gs$ at the beginning of the test, visible during the annular flow period, result from the steady-state axial pressure gradient, which causes a significant variation of density and superficial velocity as a function of distance. Figure 7 depicts the transition region in more detail in order to illustrate the time delay between the different transitions.

A distinct feature of the experimental data (boundary condition), which is reflected on the model results, is the strong temporal fluctuations of the pressure and flow rate signals in the churn flow region. These are clearly associated with the oscillatory nature of the liquid film flow in this flow pattern.

Figures 8 and 9 show the variation of pressure drop defined as the difference between the outlet pressure and the pressure measured at the positions indicated in the figures. The agreement between the model and data is generally
good, with a certain tendency for the model to overpredict the data in annular flow. In the churn flow region, however, the scatter inherently associated with the data precludes any detailed visual comparison with the model in this region.

![Figure 6 – Transient numerical dimensionless gas superficial velocity for Case 1.](image)

![Figure 7 – Detail of transition region of Fig. 6.](image)

Figure 6 – Transient numerical dimensionless gas superficial velocity for Case 1.

Figure 7 – Detail of transition region of Fig. 6.

![Figure 8 – Comparison between transient experimental and numerical pressure drop at z=0.0 m and z=20.37 m for Case 1.](image)

![Figure 9 – Comparison between transient experimental and numerical pressure drop at z=9.17 m and z=32.59 m for Case 1.](image)

Figure 8 – Comparison between transient experimental and numerical pressure drop at z=0.0 m and z=20.37 m for Case 1.

Figure 9 – Comparison between transient experimental and numerical pressure drop at z=9.17 m and z=32.59 m for Case 1.

Figures 10 and 11 show the variation of the void fraction as a function of time for z = 4.08 m and z = 38.73 m, respectively. Violent fluctuations in the void fraction signal of Waltrich (2012) are observed for both positions. The amplitude of the oscillations is much higher in churn flow as seen in these results due to the large waves characteristic of this flow pattern. In order to allow a better assessment of the numerical model, the experimental data were smoothened using an adjacent averaging technique (Press et al., 1992) with a 100 points window. Again, the agreement between the model and the smoothened data is satisfactory, as the model is capable of picking up the trends associated with the annular-churn transition.

![Figure 10 – Comparison between transient experimental and numerical void fraction at z=4.08 m for Case 1.](image)

![Figure 11 – Comparison between transient experimental and numerical void fraction z=38.73 m for Case 1.](image)

Figure 10 – Comparison between transient experimental and numerical void fraction at z=4.08 m for Case 1.

Figure 11 – Comparison between transient experimental and numerical void fraction z=38.73 m for Case 1.

For Case 1, the statistical analysis resulted in values of AAD, RMS and Bias for the pressure difference equal to 12.3%, 0.13%, and -3.63%, respectively. For the void fraction, the AAD, RMS and Bias were calculated as 12.9%, 0.12% and -10.6%, respectively.
Figure 12 shows the input experimental data/boundary conditions used in the numerical simulation of Case 2. In this case, the transient behavior is triggered by a sudden increase of the inlet liquid mass flux. According to the visual observations of Waltrich (2012), the flow started as stable annular flow, but suffered a transition to churn flow following the sudden increase in liquid mass flux.

Figures 13 and 14 show the calculated $u_{gs}^*$ as a function of time for different pipe locations, indicating that according to the Wallis (1969) flow reversal criterion, the flow passes from annular to churn at approximately 90 seconds into the run. After the solution reaches a somewhat stable condition in churn flow, a numerical instabilities provoked by the time-dependent nature of the boundary condition lead to transitions to annular flow and back to churn flow. The change in closure relationships and the already highly oscillating gas mass flux boundary condition generate peaks in the local instantaneous gas velocity. These spurious flow pattern transitions occur throughout the pipe and are not a localized phenomenon. They are also unrealistic and should be ignored. When time-smoothened boundary conditions are used using an adjacent averaging technique (Press et al., 1992), only the strong oscillations at $u_{gs}^* \approx 1.0$ persist (see Fig. 14), as a result of the substantial rise in liquid velocity (see Fig. 12.b).
observation of the void fraction profiles in Fig. 17 reveals that those are caused by a sharp decrease in void fraction predicted by the model at the transition point, which gives rise to a localized inverted peak in the gravitational component of the total pressure gradient along the entire test section. The sharp decrease in void fraction, in turn, is due to the increase in liquid flow rate that triggers the flow regime transition. Despite the slight under prediction of the void fraction in the first part of the test (steady-state annular flow), the general agreement between the model and the data can be considered satisfactory for the conditions of Case 2.

The statistical analysis for Case 2 resulted in the following parameters for the pressure difference: AAD=11.88%, RMS=0.153% and Bias=-3.10%. For the void fraction, the statistical parameters were: AAD=7.94%, RMS=0.093% and Bias=-4.88%.

In Case 2, during the sharp change in the liquid mass flux boundary condition that triggered the annular to churn transition at around 90 s, the solution oscillated heavily (even after smoothening the high-frequency oscillations in the boundary conditions). This behavior is certainly undesirable and, to investigate its cause, two additional simulations were performed. It was hypothesized that two main factors could be contributing to the numerical oscillation: the
change in closure relationships for annular and churn flows and the change between a three-field and a two-field formulation (no entrained liquid field), which was adopted when it was not possible to determine the rates of droplet entrainment and deposition in churn flow from semi-empirical correlations. Therefore, Case 2 was simulated again (with smoothened boundary conditions), however, this time the program was locked in the two-field formulation, but still allowed to transition between the flow patterns. As can be seen in Fig. 18, the oscillations during the annular to churn transition persisted, and the output results were fairly similar to the ones obtained initially. The simulation of Case 2 with the same restrictions as above, but considering the interfacial and wall friction factor correlations to be that of churn flow (Jayanti and Brauner, 1994), made the oscillations in the dimensionless gas superficial velocity disappear (see Fig. 19). The nominal values of the initial and final steady states, however, remained unchanged.

The pressure difference behavior for the all-churn flow case is shown in Figs. 20 and 21. The representation of the initial and final steady states was almost identical to the original simulation with a three-field formulation and different closure relationships for annular and churn flows. The difference that arose during the transition, however, almost disappeared and the overall agreement with the experimental curve in this region was greatly improved. The void fraction behavior is shown in Fig. 22 and, similarly to the pressure difference, the end steady states are in good agreement with the original simulation. The most noticeable difference is the absence of the marked void fraction decrease during the transition. Once again, the representation of this region was greatly improved by considering churn flow only during the entire simulation.

An analysis of the latter simulation of Case 2 (two-field formulation and churn flow closure relationships only) suggested that, when the change in liquid mass flux associated with the flow regime transition is large, the use of sharp transitions between the closure relationships is not advised. Numerical interpolation between closure relationships for different flow patterns could be used to deal with the extreme redistribution and oscillation of the variables when the flow regime transits between annular and churn flow. In the present situation, when only churn flow relationships were considered, the calculated interfacial shear stress was higher, and the oscillations created by the change in the boundary condition could be dampened.
Figure 22 – Comparison between transient experimental and numerical void fraction at (a) z=4.08 m, (b) z=24.46 m and (c) z=38.73 m for Case 2.

4. CONCLUSIONS

The purpose of this work was to evaluate the performance of the HyTAF model in solving gas-liquid annular and churn flows and the transition between them, which is closely related to the phenomenon of liquid loading in wells. The model results were compared with an extensive steady-state database (covering the majority of the available data in the open literature) and to a recently obtained transient dataset (Waltrich, 2012).

For steady state, the numerical results agreed with the experimental data for the pressure gradient, phase fraction and liquid mass flux (annular flow) to within ±20%, which can be considered satisfactory. The quantitative agreement is visibly better for annular flow, but the trends for churn flow are also well predicted.

The analysis of the pressure-induced transient case demonstrated that the numerical model was quite successful in describing the annular to churn transition. The transient case triggered by a change in the inlet liquid mass flux were simulated and also presented a generally good agreement. Numerical issues associated with the flow regime transition predicted in this case have been explored. In both cases, the behavior of the pressure gradient and void fraction was well predicted in both flow regimes, with average absolute deviations smaller than 13%.

5. ACKNOWLEDGEMENTS

The authors thank the sponsors of the JIP on Liquid Loading in the operation of gas fields: Mechanisms, prediction and reservoir response, coordinated by Texas A&M University, of which the Federal University of Santa Catarina (UFSC) and TU Clausthal are participating universities. Marcus Alves thanks the CNPq for the PhD scholarship at UFSC (Grant n 142781/2008-8), and for the one-year internship scholarship at Texas A&M University (Grant n 201817/2010-1). We also thank CENAPAD/Unicamp, for providing access to their supercomputing facility where the computer program was run.

6. REFERENCES


