MODELLING PIG TRAIN DYNAMICS IN NATURAL GAS PIPELINES

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The velocity of pigs in natural gas pipelines can be erratic due to the compressible nature of the gas. Low pipeline pressure means that there is less dampening effect. This can lead to high acceleration, high pig velocity and subsequent deceleration of the pig or pig train. Knowledge of the pig train velocity profile is important to allow inspection of gas lines using an Ultrasonic pig train or understanding the start-up characteristics of isolation plug trains following a tie-in or platform bypass for example. Single pigs can be subject to high accelerations that can lead to pig damage or loss of MFL (Magnetic Flux Leakage) data due to high velocity. This can be mitigated to some extent using bypass or controlled bypass using an onboard valve. For pig trains, this is not possible due to the multiple pigs, liquid batches and the need to maintain the spacing between the pigs. This paper examines the motion of pig trains and how this can be determined using modelling. Examples are also examined using case studies.

Introduction

The motion of pigs and pig trains in gas pipelines is important in general to avoid surprises. Missed inspection data, damage to pigs or in the extreme case, fatality due to the high speeds leads to the need to understand pig acceleration, peak velocity and how the pig or train might be brought under control. The drivers for modelling the pig or pig train velocity are as follows: -

- Understanding the velocity profile of the pig or pig train in the gas pipeline;
- Determination of velocities and high accelerations that could occur and are undesirable for tasks such as inspection;
- Evaluating the ability to bring the situation under control – what steps can be taken to force lower pigging velocity for instance.

There are many instances of pigging with gas where understanding of the maximum pig velocity would be useful. Investigations into incidents involving gas pipeline pigging often require a detailed understanding of this aspect of the pig motion. Scenarios where undesirable velocity effects can arise are as follows: -

- Low pressure / low density gas;
- Changes in pipe specification at a road crossing for instance (Heavy wall thickness to light wall);
- Hilly terrain;
- Change in pipeline diameter (dual or multi-diameter pipelines);
- Pig start-up;
- Reduction in gas pressure along the line resulting in high velocities downstream;
- Deep water to shallow water with resulting change in density and back pressure;
- Presence of liquid in a gas line resulting in variable back pressure.

Any one of these or combination can lead to velocity variations that need to be understood. This is generally best not left to chance. Modelling of the scenario is the best way to understand the motion, investigate any sensitivity and allow possible solutions to the accelerations and high speeds to be investigated.

Low density or gas pressure compared to the changes in pig differential pressure is the underlying main reason for local velocity instability. A high pressure line (100 bars) with small variations in pig friction at a bend for instance will not suffer from adverse accelerations. On the other hand a pig in a dual diameter pipeline with line pressure of 25 bars will experience a high acceleration from small to large diameter.

This paper investigates these issues and provides some examples of simulations performed in recent years. The basis of the calculation method is set out. Single pigs are discussed with model output for an MFL inspection tool, the same tool with bypass and the tool fitted with active bypass to control the pig speed. The ability to predict and control the speed of pig trains is then discussed. Sizing and optimisation of the liquid batch length to achieve this is presented. Finally, an overview of on-going research into the motion of pigs in two phase (gas liquid) systems is briefly presented. The drivers for doing this work are provided and the current status discussed.

Basics of the model

Modelling pig and pig train dynamics in gas pipelines requires a solution to two equations: -

1. The continuity equation (The change in mass of a control volume is equal to the flow in and out);
2. The momentum equation (The forces acting on the control volume determine the flow velocity)

The two PDEs (Partial Differential Equations) result in two equations and two unknowns, gas velocity and pressure against distance and time. Much of the effort involves solving these equations efficiently, accurately and in a stable manner. The pig model makes use of these equations both upstream and downstream of the pig or pig train.

Boundary conditions determine the flow-rate into the pipeline and pressure controlled at the outlet as one possible scenario. Initial conditions could be a gas at rest with a stationary pig / pig train in readiness for start up. Alternatively, the pig could be introduced into a flowing pipeline and at a given location. The pig friction or differential pressure can be varied along the route depending on the features encountered (bends, thick walled pipe, changes in diameter etc). Additionally, the elevation of the pipeline changes due to the topology of the line. Figure 1 shows the situation schematically while Figure 2 shows the model.

The motion of the pig is determined simply from Newton's law relating mass, acceleration and the forces acting on the pig. These forces are due to pressure upstream and downstream of the pig, pig friction and the weight component acting axially in a sloped section of line.

The pressures are determined from solving the system of PDEs (Partial Differential Equations) and the friction and angle from the location of the pig.

The model used here is based upon MATLAB® and uses the dynamic modelling environment, SIMULINK™. Other modelling and simulation software tools are available commercially. Code is written for each of the blocks in the system and the various changing variables are feedback at each time step in the simulation as necessary inputs to the next time-step.

Figure 2 shows the various components of the model: -

1. The upstream pipe section controls the pressure and velocity in the section of pipe upstream of the pig train. The motion within the gas is modelled in this component;
2. The downstream pipe section does the same for downstream of the pig train;
3. The pig train DP component models the resistance of the pig or pig train in terms of the DP of each pig, depending on its location in the pipe and the frictional resistance of any liquid present;
4. The pig motion component calculates acceleration based on the pressure front behind the pig, in front of the pig and the frictional resistance. The mass of the whole train is taken as the mass of the system. Bypass is also built into this block;
5. Elevation effects provide the back pressure and weight component from the pig train and any liquid in the line as it negotiates the various elevations in the line;
6. The File component takes all the outputs and stores them for post processing;
7. The Scope is a simple graphical output for observing the various outputs as the model proceeds.

As noted above, pressure changes upstream and downstream of the pig or pig train depending on the motion of the pig. It is this pressure that determine the motion of the pig amongst other things such as the inlet flow and back pressure in the line. In a low pressure gas, the density of the gas is low and so the pig train can reach much higher velocities than in a high pressure situation.

Figure 3 shows pressures upstream and downstream of the pig at a given moment in time along the pipeline. Note that in a gas pipeline, the pig velocity does not necessarily equal the inlet velocity due to losses in the system and transient motion of the pig.

Figure 4 shows the velocity profile or response of the pig to a restart, resulting acceleration, peak velocity and eventual slowing down (a) for a low pressure gas (30 bars) and (b) the same pig in a high pressure gas (100 bars). The pig motion is more damped in the higher pressure line. As the gas pressure increases, then the control gets better and better as the density increases into dense phase. Ultimately, if the density becomes very high – similar to a liquid for example – then full control is available.

Motion of Single Pigs in gas lines

Before taking a look at pig trains in more detail, the ability to model single pigs in a compressible environment and ways of controlling the motion of these pigs is examined. As explained before, low pipeline pressure or high pig differential pressure can result in high accelerations and therefore elevated velocities. A single pig compared to a pig train with large liquid batches, has a small mass and so accelerations and decelerations can be high as shown by the simple equation: -

$$\ddot{x} = \frac{F}{m}$$

The force (due to the pressure differential) divided by the small pig mass provides the acceleration. The pig will accelerate quickly but also slow down quickly. The opposite is expected with a long pig train due to the large mass of liquid.

The drivers for modelling the single pig scenario are as follows: -

- High velocities in gas pipelines can be undesirable and result in high loads on bends and other features as well as the pig. Some indication of the expected velocities can help to understand what loads would be expected in such circumstances;
- Low pressure gas lines can lead to erratic motion and it may be required to show what minimum pressure is required to adequately control the pig velocity within a range;
- Inspection pigging using MFL (Magnetic Flux Leakage) for instance is generally limited to a range of velocities. If the pigging velocity is too high, then data from areas of the line can be missed and it can be useful to understand how much will be missed and how this can be avoided (i.e. what is the minimum line pressure required to control the pig velocity);
- Dual diameter pigging can result in high velocities as the pig exits the high friction, small diameter section into the large diameter. The result is a potential "champagne cork" effect;
- Flooding of pipelines can result in high velocities when there are steep sections of pipe due to the weight of liquid acting behind the pig. The minimum back pressure required to avoid such excursions is a useful input to a pre-commissioning campaign.

In many circumstances, there is little that can be done to control the high velocity. For example at the low pressure end of a pipeline, the gas flow will naturally increase as the line pressure drops. This can lead to higher velocities than required for an inspection run for instance. The options are to alter flows as the tool nears the end of the line or employ a pig with bypass (fixed bypass or with a control valve).

Figure 5 shows three analyses performed on an MFL (Magnetic Flux Leakage) tool in a high flowing 36" line with an obstruction using the following configurations: -

1. The standard tool with no bypass;
2. The tool with a fixed bypass;
3. Use of a bypass control valve.

In the final analysis, a simple feedback loop is used to control the valve on the pig. The odometer sends a signal telling the system the pig velocity, this is compared with a set position and after a time delay, the valve position is adjusted. The pigs are run in a line with a gas flowing at 4 m/s. The target velocity is 2.5 m/s. The pig encounters an obstruction such as a dent or reduced bore section in the line and the model predicts the velocity response.

The output shows the following: -

1. The case with no bypass shows the least change in velocity due to the momentum of the pig. The pig stops momentarily and then accelerates as the pressure builds and moves the pig. However, the pig is travelling faster than required in the first place;
2. The case with a fixed bypass shows the pig stops at the obstruction, again waits for the differential pressure to build up and then accelerates to a high velocity but takes some half kilometre to return to the steady state;
3. Finally, the controlled bypass case shows the following: -
   - The steady state motion is unsteady due to the simplified control system used in the analysis. No attempt to model a PID (Proportional, Integral, Differential) type controller is made and so a certain amount of hunting for the set point is observed. Pigs with this type of controller on board move in steady state in a much more controlled manner than shown here;
   - The pig also stops momentarily as the pressure builds up across the pig and then accelerates. However, the duration of the acceleration is much less and steady state motion is resumed after a much shorter distance than the fixed bypass case.

The model predicts the peak velocities and provides an indication of how it might be possible to control the speed of the tool and the best method selected. Figure 6 shows another use of the model in predicting the motion of a pig through a check valve in a gas pipeline. In this case, the motion of the pig was animated – the outputs from the simulation were linked to a model of the pig and check valve. This is possible with a SIMULINK^{TM} software bolt on.

Finally, Figure 7 shows a flooding operation where a single pig is run down a riser to flood the line. The result is high velocity when there is no back pressure. The model is then used to predict the minimum back pressure required to safely take the tool down the riser in a controlled fashion.

Motion of Pig Trains

A pig train is defined here as a series of pig separated by a liquid batch in a gas pipeline – i.e. gas upstream and downstream of the train. Batching pigs with a high sealing efficiency are used to contain the liquid within the batch. By its very nature, a pig train cannot have bypass as this would break up the train so the control methods listed above are not applicable. Examples of pig trains are in UT inspection of gas pipelines where a liquid couplant is required or an isolation pig train following repair or cut out of a pipe section in a gas pipeline. An example is shown in Figure 8. The typical pig train is also shown – a UT pig batched in a liquid train for the inspection of a gas line.

Unlike the single pig, the pig train has a relatively large mass due to the length of liquid and number of pigs. The result is that accelerations are low but decelerations are also low. If the speed increases, then it takes time for the steady state to be resumed: -

$$\ddot{x} = \frac{F}{m}$$

In addition, due to the length of the pig train, then the effect of the line topography is exaggerated. In a steep section of pipeline, head of liquid means that a higher pressure is required to drive the pig. Once the pipeline slope evens out, this excess pressure must be dissipated and the effect is an increase in velocity. The effect is exaggerated if there is a liquid hold up in the pipeline. The same effect is seen as a pig train arrives at a riser for example.

The offset for this is the effect of liquid losses in the batch. As the pig train speeds up, the differential pressure of the train also increases. Whereas the pig differential pressure remains relatively constant (maybe dropping slightly), the liquid losses increase and it is this effect that helps to some extent to control the velocity of the pig train. Coupled with the momentum of the heavy train, these two aspects help to control the pig train velocity. The effect of liquid slug size is shown in Figure 9.

The question is then how much liquid is required in the pig train to control speed – i.e. how long should the train be. Given that setting up a train in the line is generally a difficult exercise then there are limitations on the volumes of liquid that can be put in the line. Putting liquid into a gas line is never an easy exercise especially offshore. At the other end of the line, getting liquid out at the receiving side is generally an issue since many gas pipelines are not set up to handle liquids or this much liquid in one go. Therefore, optimising the batch size (for speed control, pipeline conditioning or avoiding gas ingress to a UT, Ultrasonic tool for instance) is of the essence.

Dual diameter pipelines make the issue even worse as there is even more tendency to accelerate at the increase in diameter.

Therefore, the drivers for modelling the motion of pig trains in gas pipelines comes down to the following: -

1. Determining the maximum pig train velocity given pig differential pressures and the elevation or topology of the pipeline;
2. Optimising the length of the pig train – from a pig speed control point of view (other issues such as avoiding gas ingress to an inspection tool may add to this);
3. Minimising the volumes of liquid involved and therefore liquid handling problems at the launch and receive end of the line;
4. Ability to position a pig train effectively in a given location in a pipeline (coupled with good pig tracking).

By way of an example, we consider the motion of a pig train for inspection of the line in a 20" gas pipeline. The line starts in deep water and then enters a shallow water area. The line elevation is initially steep as the pig train comes from deep water and then levels out. The model is set up to determine the velocity profile as the pig train moves from deep water to shallow water. Figure 10 shows the output for a given liquid batch volume. Sensitivity analysis allows the length of the liquid slugs to be varied to see the effect and optimise the pig train.

A second example shows the start up of an isolation pig train in a gas pipeline. In this example, many of the pigs are high in differential pressure and may even need to be reversed on start up depending on how they are inserted into the line. The line in question is 30" and two platforms or shippers feed gas into the system to initiate pig train motion. Outlet pressure is maintained at a constant 50 bars.

The output is shown in Figure 11. The pig train acceleration is low but reasonably high velocities are reached. The deceleration is also low and several kilometres of travel occur before a steady state velocity is achieved. In this case the line is reasonably on the level and there are no elevation effects.

For any given case it is possible to provide a chart of maximum pig train velocity against slug size for input into the pig train design for the pipeline.

Future developments

The examples above for both single pigs and for pig trains involve single phase gas either side of the pig or pig train. Any liquid in the system is assumed to be in the pig train or is assumed to be contained in a single slug immediately in front of the train/pig. The development of a similar model for two phase gas / liquid systems is ongoing. The level of complexity is increased considerably as there are now four equations to contend with: -

- Gas continuity;
- Gas Momentum;
- Liquid continuity;
- Liquid momentum.

Temperature effects are ignored for now and so the energy equation is not brought into the system. The result is four simultaneous PDEs with gas velocity, liquid velocity, pressure and gas fraction.

The efforts to model this are ongoing and some success has been achieved, albeit without the introduction of a pig at this stage. The drivers for providing a simplified model with pigging are as follows: -

1. Many pipelines operate as two phase systems and the liquid content affects the speed of the pig in many ways. This needs to be understood;
2. Many gas liquid systems have wax issues and so the amount of liquid available to effectively carry away wax ahead of the pig needs to be understood to allow safe and effective pigging;
3. Comparison of output with commercially available software such as OLGA would allow a check to be carried out from a pigging point of view on the output from such codes. These simulations consider many complex matters but when it comes to pigging, there is no comparison available at this stage;
4. Knowledge of the flow of liquid into liquid handling facilities is important during pigging to avoid overloading slug catchers for example.

An initial view of output from the model is developed in this work is shown in Figure 12. This is very much in its development stages but seems to show the correct trends. Many stability issues are evident with the code and solution technique. The following aspects are required: -

- Development of a stable solution method;
- Comparison with field data and published data;
- Comparison with OLGA;
- Integration with the pigging model discussed above.

Summary

The development of a model for prediction of the velocity profile of pigs in gas pipelines is a useful tool for aiding decision making on speed control, pig train design and feeding into safe and effective pigging programs. The ability to control pig speed is determined by many factors including pig design, gas pressure, flow rate, elevation profile of the line, liquid content and so on. The pig speed does not equate to the inlet flow velocity and so modelling is required to determine what is happening with the pig.

The model developed in this work has been applied to single pigs (no bypass, fixed bypass and variable bypass pigs) for inspection and cleaning and pig trains for isolation and pipeline inspection. The model used in this work has been applied to many industry projects including Woodside Pluto gas pipeline, the H7 bypass project for ConocoPhillips and Gassco and for several dual diameter pigging projects at Statoil. Based on this background and experience, a move to include two phase flow is now being examined. The author would like to thank these companies and others for the opportunity to develop this work on real life problems.

Figure 1, Schematic of the model

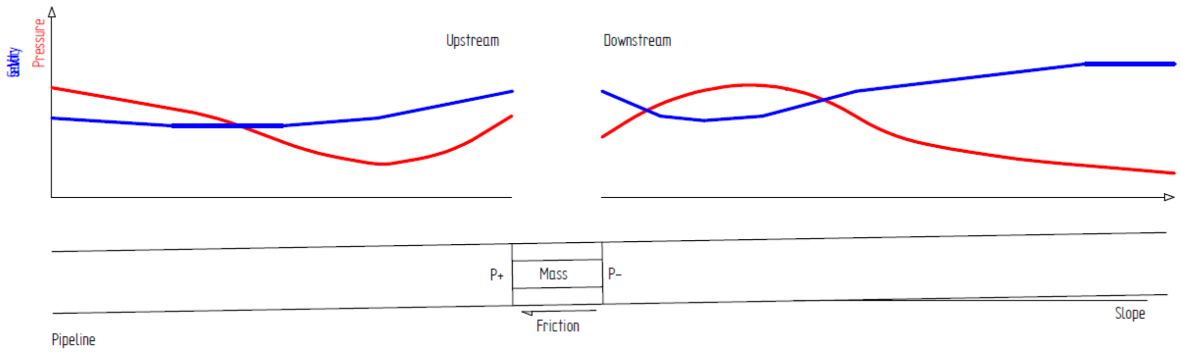


Figure 2, The SIMULINK™ model

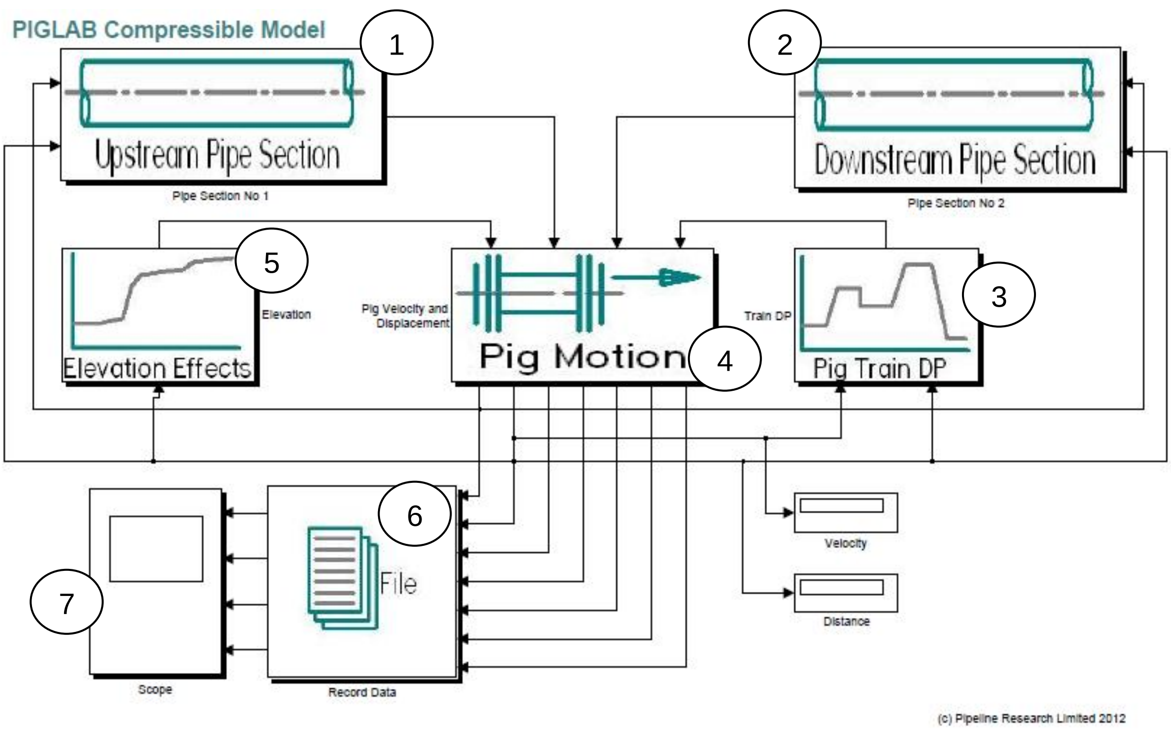


Figure 3, Pressure and gas velocity either side of the pig at a given time

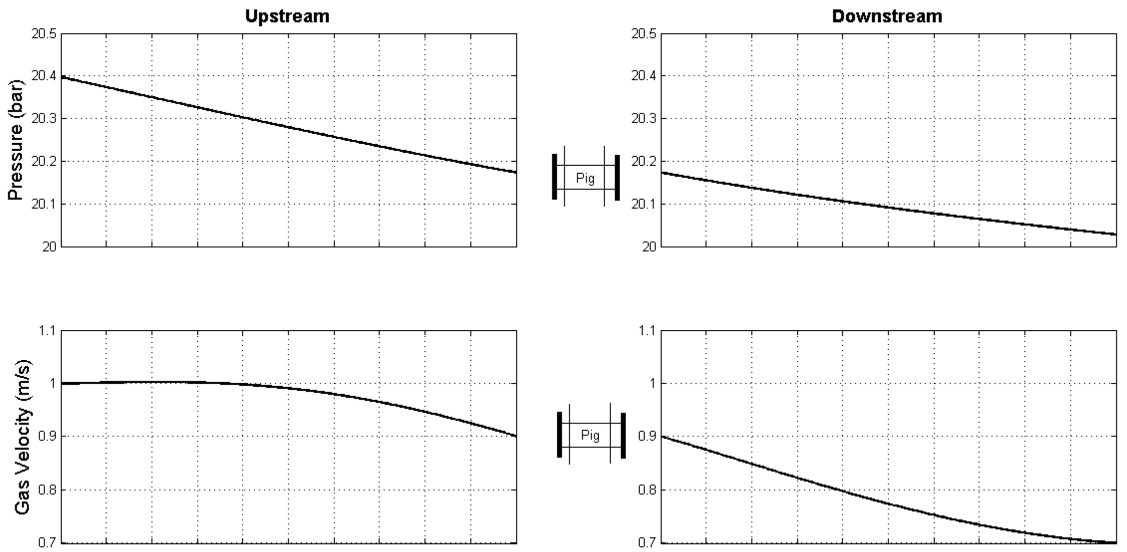


Figure 4, Effect of pressure on the motion of a pig

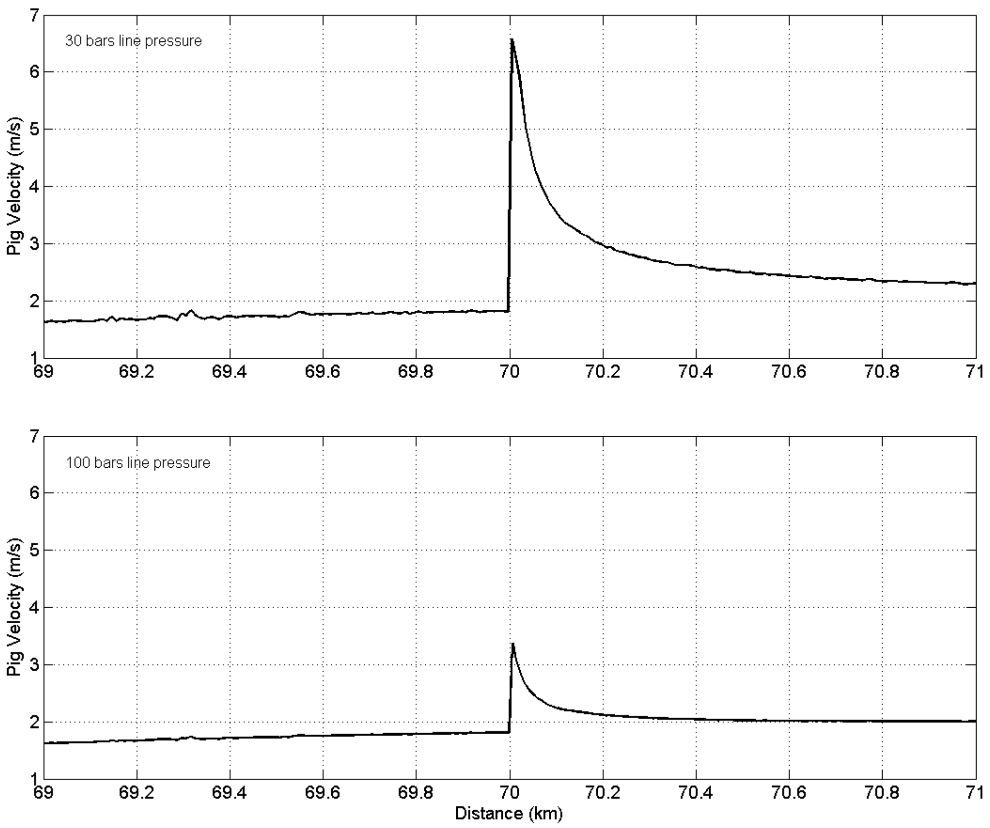


Figure 5, Comparison of no bypass, fixed bypass and bypass control

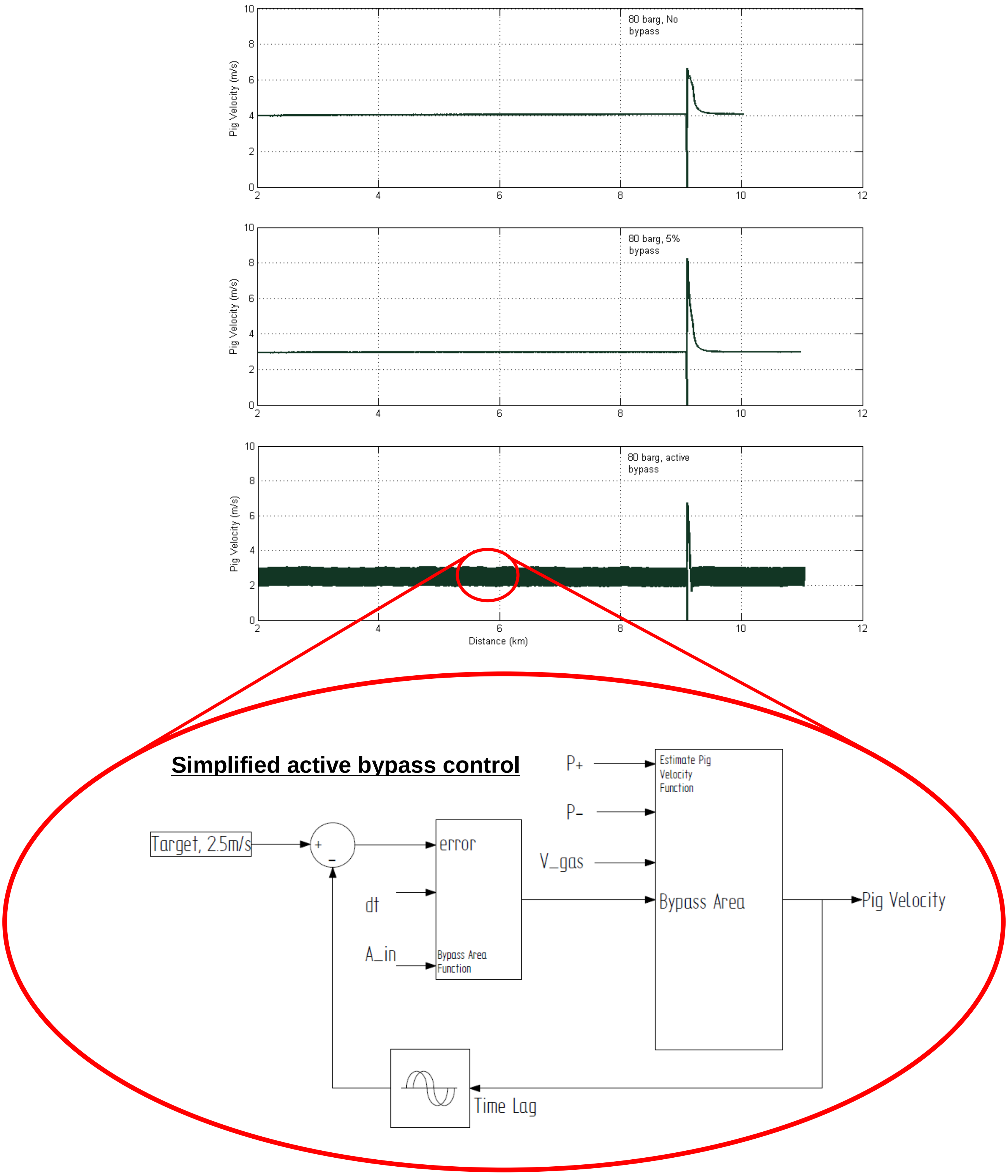


Figure 6, Motion of a Pig through a Check Valve with animation

Linking simulation output to animation to produce a different type of output

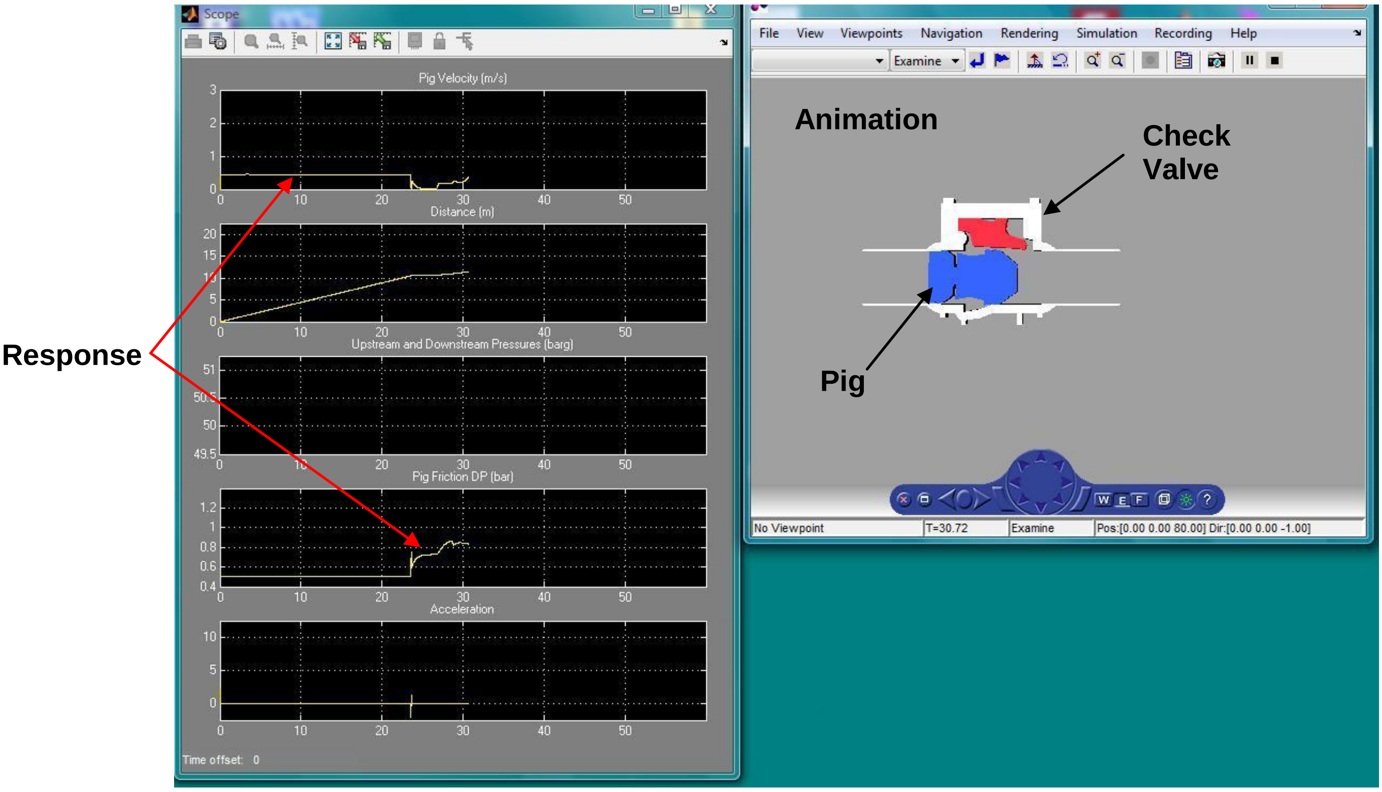


Figure 7, Flooding a riser with no back pressure during pre-commissioning

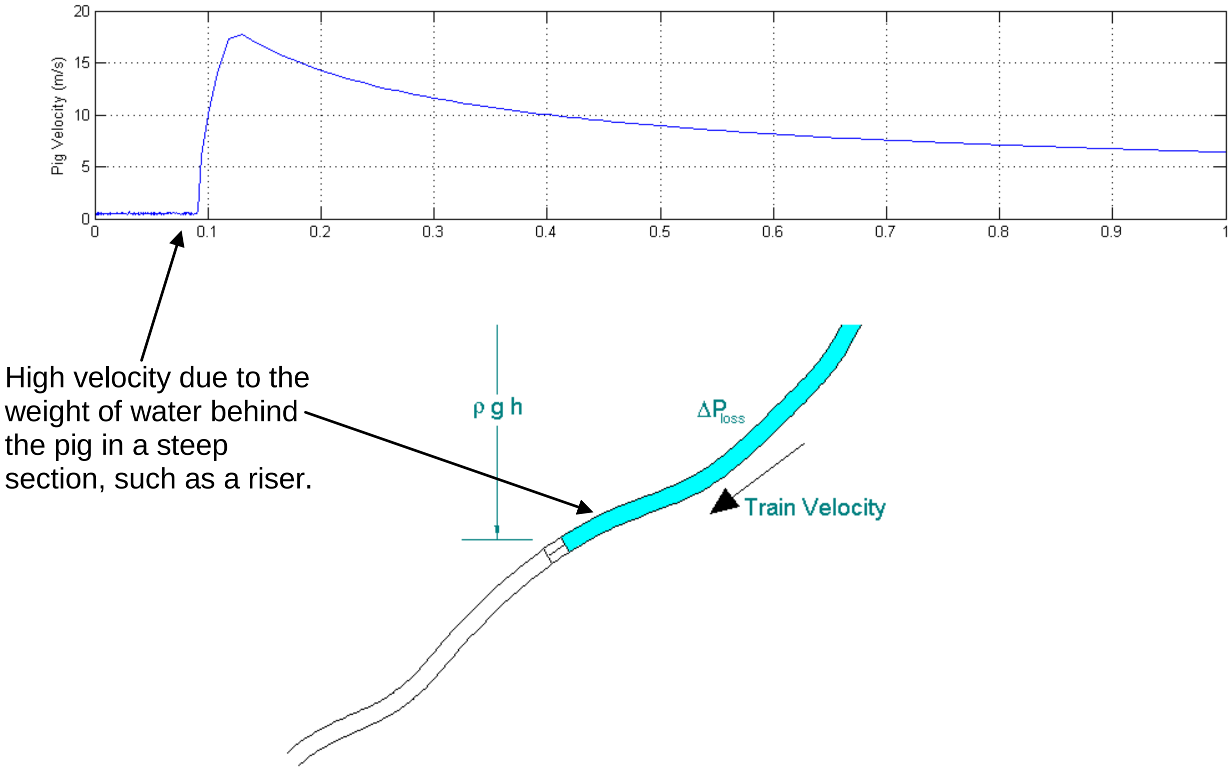
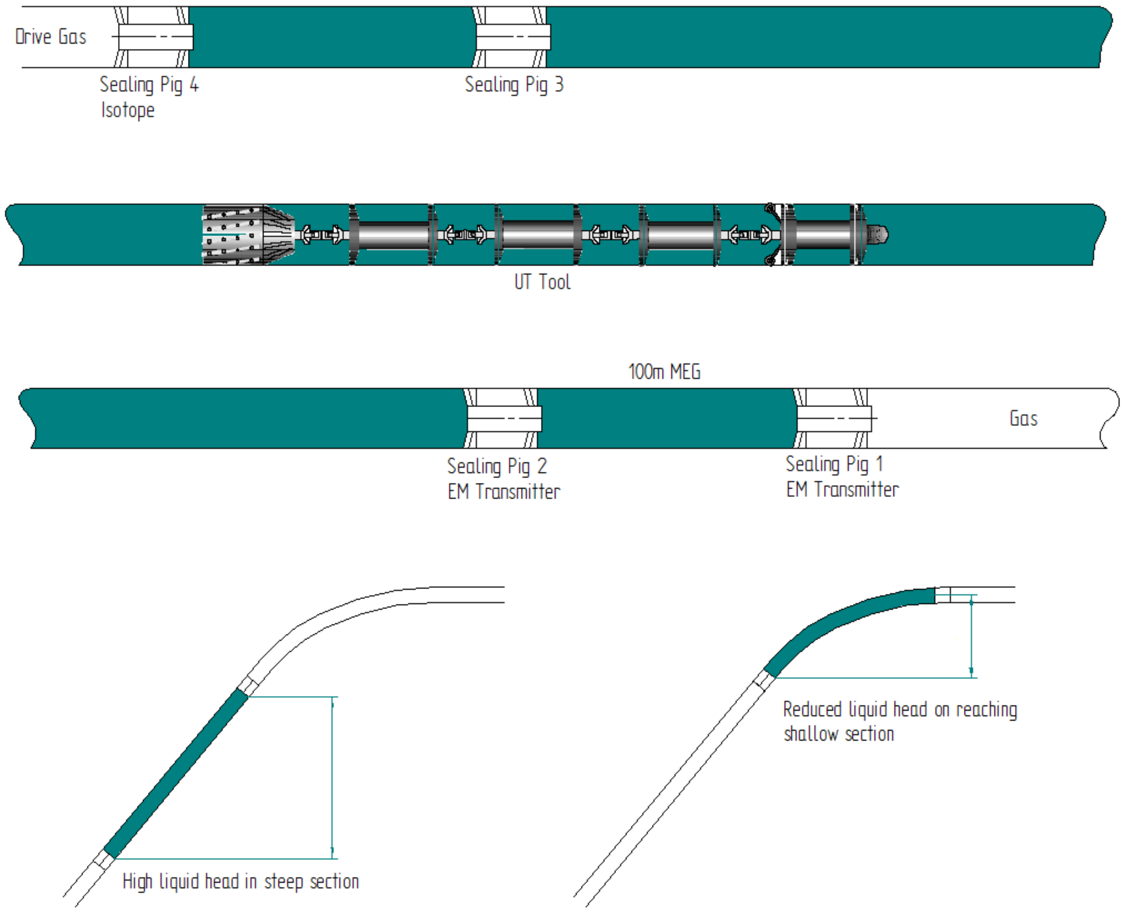


Figure 8, Example of an isolation pig train / effect of elevation



The effect of the reduction in liquid head is to accelerate the train

Figure 9, Effect of liquid batch size on the train DP

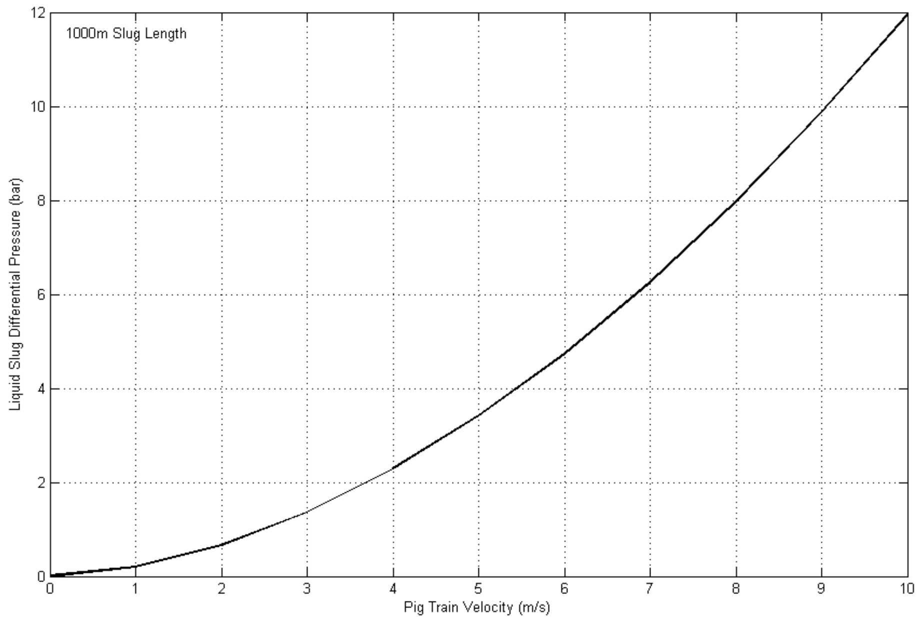


Figure 10, Output for 20" Gas Pipeline pig train velocity profile

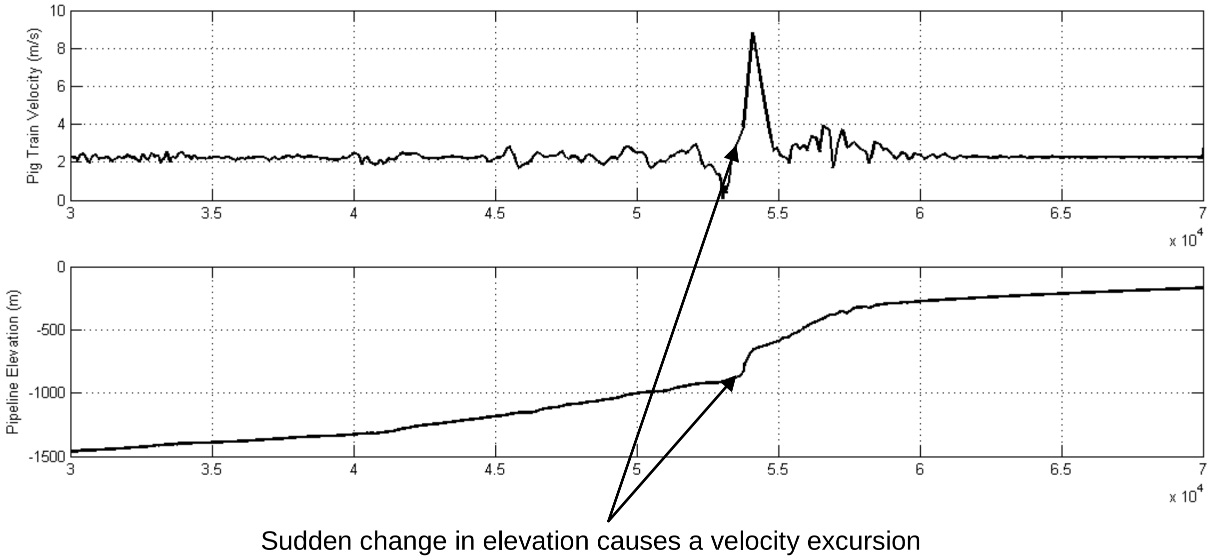


Figure 11, Start up of an isolation train

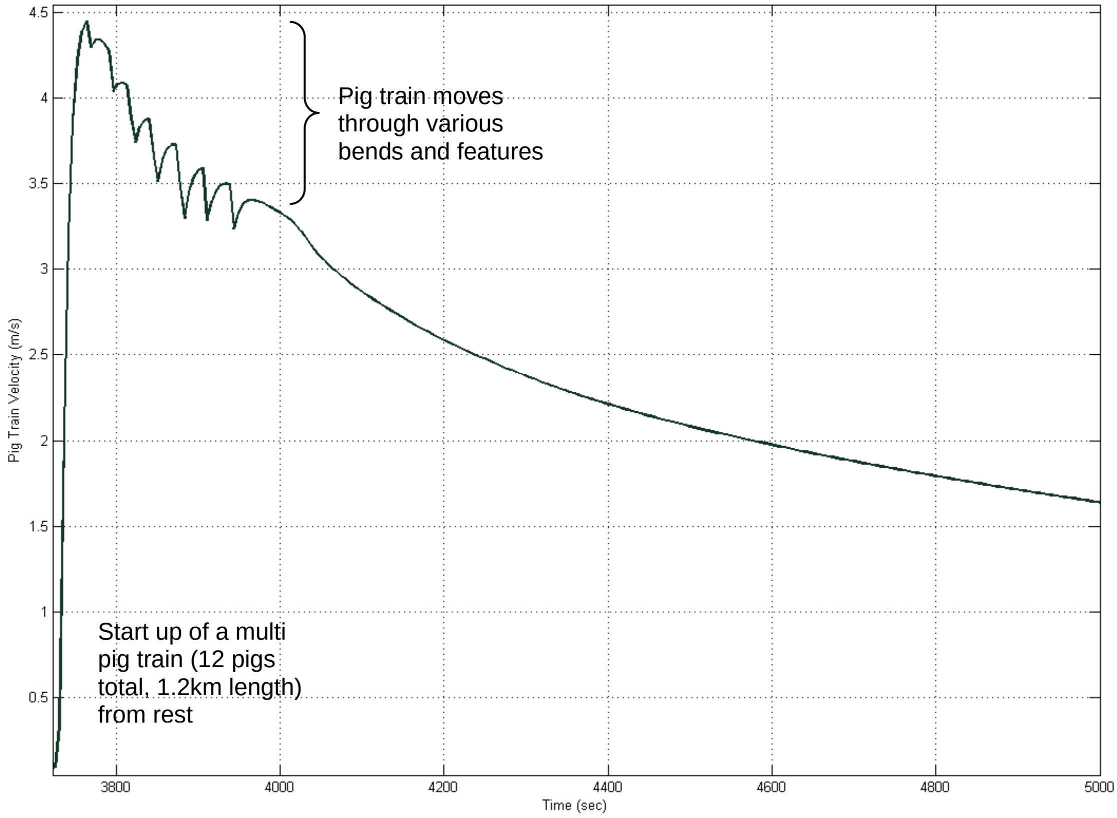
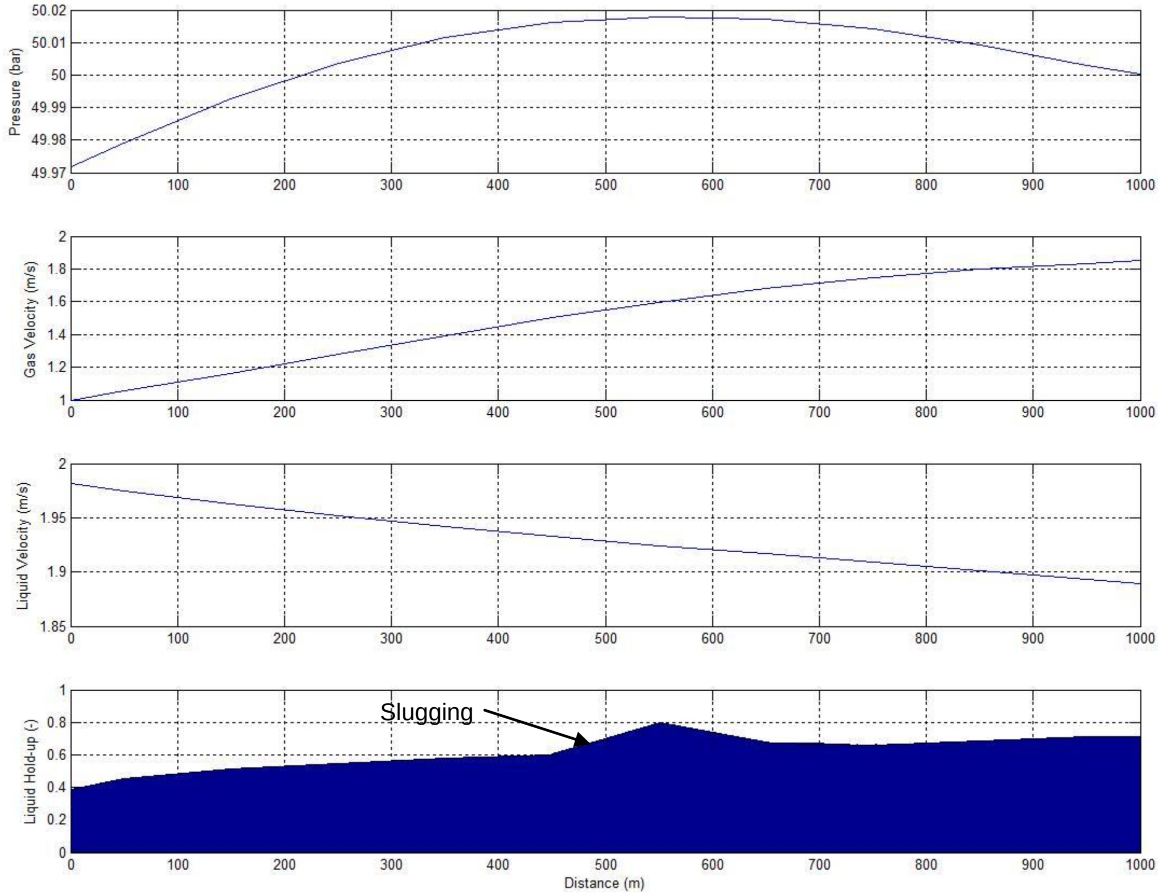


Figure 12, Output from two phase gas/liquid model (Output at instance in time)



Notes