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Modelling of natural gas pipe flow with rapid transients-case study of effect of ambient model

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Abstract

The paper presents a study of gas pipeline to soil heat transfer. The effect of simplifications of the heat transfer model is investigated. Studied are steady, one dimensional unsteady and two dimensional unsteady models of the pipe wall and soil. Flow conditions at the pipeline inlet are varied. The effects of rapid changes in gas mass flow rate and temperature at the pipeline inlet are studied. The case presented is representative for export natural gas pipelines, containing offshore and buried sections along the route. Results are compared to experimental data from an existing export natural gas pipeline.

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Keywords: pipeline transmission; pipe hydraulic flow; heat transfer; natural gas

1. Introduction

The effect of simplifications in the heat transfer model of a gas pipeline and the ambient soil is investigated. Of interest is the accuracy of hydraulic flow calculation when rapid transient flow conditions occur at the pipeline inlet. The aim of the study is to determine the relative importance of the heat storage term and the enhancement of such a non-steady heat transfer model from one dimensional radial to a two dimensional domain. The studied cases are for the same pipeline layout. Both the effects of rapid changes in mass flow rate and temperature of the gas at the pipeline inlet are studied. The pipeline case is characteristic for gas export pipelines from the Norwegian Continental Shelf. Experience with such pipelines is that during transient flow the calculation results from the models are less accurate than desired, Helgaker [1]. The transients studied in this work are changes in flow, pressure

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and temperature due to the packing and unpacking of the pipeline originating from fluctuations in demand. Understanding the causes of the deviations during transient flow is highly significant. The network is likely to be in a transient state, steady state is the exception. Transients are occurring on the minute time scale; the period of interest to follow a single transient to the system ranges from hours to several days.

Nomenclature

σ	2H/D, H=Distance from top of soil to centerline of pipe (m), D=Internal pipediameter (m)
H_{amb}, H_{sea}	Heat transfer coefficient between thermal domain and ambient air, respectively sea (W/m^2K)
k_s	Soil thermal conductivity (W/mK)
α_s	Thermal diffusivity (m^2/s)
ρ	Density (kg/m^3)
p	Pressure (Pa)
Z	Compressibility factor
T	Temperature (K)
$\dot{m}$	Mass flow rate (kg/s)
u	Gas velocity (m/s)
θ	Angle of incline (pipe element)
f	Darcy-Weissbach friction factor
A	Pipeline internal cross sectional area (m^2)
x	Distance along pipeline (m)
C_v	Gas specific heat at constant volume (J/kgK)
C_p	Specific heat at constant pressure (J/kgK)
h	Enthalpy (J)
q	Rate of heat-transfer per unit time and unit mass of the gas (W/kg)
q_b	Heat flux at boundary (W)
U	Overall heat transfer coefficient to ambient (W/m^2K)
h_i	Inner wall film coefficient (W/m^2K)
h_w	Conductive term for the thermal resistance of the pipe wall layers (W/m^2K)
h_o	Film coefficient representing heat transfer to the ambience, acting on pipe outer wall (W/m^2K)
r_s	Radial thickness of soil domain (m)
r_e	Equivalent soil radius (m)
SCADA	Supervision Control And Data Acquisition
KP	Kilometer Post: distance in km from pipeline inlet

2. Modelling Case

The study uses a generic model of a natural gas pipeline representing the characteristics of export gas pipelines on the Norwegian Continental Shelf. The 40 inch carbon steel pipe has a 44 mm thick steel wall with a 6 mm outer plastic anti corrosion coating. The length of the offshore pipeline is 100 km. The pipeline elevation profile is kept horizontally level. The first and final 10 km of the pipeline is onshore and buried to a depth of 2 m (top of soil to pipe centre line). The middle section of the pipeline is lying on the seabed exposed to an ocean current. The ambient air temperature is 278.15 K. Sea water temperature is 277.15 K, the current velocity across the pipeline is 0.1 m/s. Two types of transients are studied (Figure 1). The first is a step change in mass flow rate at the pipeline entrance. Ramp-up and ramp down times are 60 seconds with several days of steady mass flow rate levels. Inlet gas temperature is kept constant. The second transient is a step change in inlet temperature (from 303.15 K to 308.15 K), while keeping the inlet mass flow constant. These transients represent extreme cases of real inlet transients. Soil thermal conductivity k_s = 3 W/mK and thermal diffusivity α_s =$1.2x10^{-6}$ m^2/s. The flow model is recently published by Helgaker [1], Langelandsvik [2], and Chazcykowski [3]. It is a compressible flow model suitable for single phase gas mixtures. The model is an implicit finite difference discretization of the Navier Stokes equations. The governing equations for one-dimensional compressible flow result from averaging the 3-dimensional equations across the pipe cross section. The derivation of these equations is described by Helgaker [1] and Langelandsvik [2] (eq.1 to eq.3).

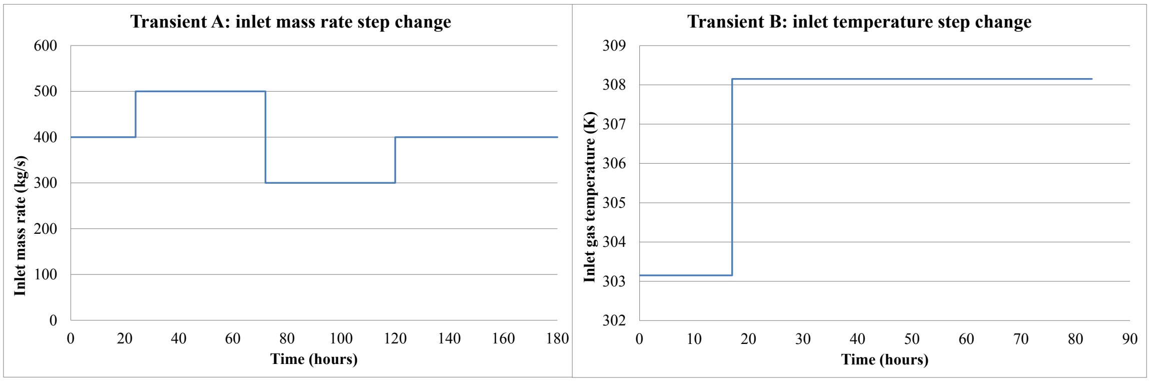

Figure 1: inlet mass flow rate and temperature transients used in the numerical study.

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u)=0 \tag{1}$$

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}=-\frac{\partial p}{\partial x}+\rho g\sin\theta-\frac{1}{2}\rho u^2\frac{f}{D} \tag{2}$$

$$\rho C_v\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)+u\left(\frac{\partial p}{\partial T}\right)_\rho\frac{\partial u}{\partial x}=\frac{f\rho u^3}{2D}-\frac{4U}{D}\left(T-T_a\right) \tag{3}$$

Heat transfer between the gas inside the pipe and the ambient is represented in the final term of the energy equation (eq. 3). Through defining q as the rate of heat-transfer per unit time and unit mass of the gas (W/kg) for the thermal exchange with the environment, the energy equation can be rewritten as:

$$\rho C_v\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)+u\left(\frac{\partial p}{\partial T}\right)_\rho\frac{\partial u}{\partial x}=\frac{f\rho u^3}{2D}-\rho q \tag{4}$$

The advantage of using the energy equation in this form is that the flow domain can be coupled directly to the thermal domain by exchange of thermal energy at the pipe wall, instead of using an overall heat transfer coefficient for the entire thermal domain. It is worth noticing that the first term on the right hand side of equation 3 is the internal energy dissipation due to the turbulent wall friction of the gas while the second term represents the energy exchange with the environment. The pipe flow model uses calculation elements with a length of 1 km each. Based on previous work in Helgaker et al. [4], a grid spacing of 1 km has been shown to be sufficient when modelling the flow of gas through long distance export pipelines. The following boundary conditions apply: the inlet mass rate and temperature are specified (base line 400 kg/s and 30 °C), and at the outlet pressure is specified (9 MPa). Thermo-physical properties of the flow are calculated using the BWRS equation of state as described by Starling [5].

2.1 Heat exchange models

Three different models of the thermal domain are compared. Underlying assumption for the models is that soil heat transfer in axial direction may be neglected; radial heat transfer is dominant.

Steady state model: the steady state model is similar to the model described in Langelandsvik [2]. This model is commonly used for modelling the ambient in gas pipe flow. The heat flux from the gas in the pipeline to the ground and vice versa is represented as a single heat transfer coefficient solely based upon the thermal resistance of the pipe wall layers and the soil. The Dittus Boelter correlation shown in Incropera and DeWitt [6] is used for the inner film coefficient h_i. The conduction through the wall layers, Langelandsvik [2], can be expressed as follows:

$$h_w = \sum_{i=1}^{n} \ln\left(r_{oi} / r_{ii}\right) / \mathrm{k}_i \tag{5}$$

In this formula, n is the number of wall layers, k_i is the thermal conductivity of wall layer i and r_{oi} and r_{ii} are the outer and inner radius of wall layer i respectively. The outer film coefficient h_o is based upon an exact steady state solution of 2D heat conduction equation, using the appropriate shape factor as shown in Incropera and DeWitt [6]. Another configuration is when the pipe is lying on the seabed exposed to sea water currents. In such case h_o can be expressed in terms of the Nusselt number. The correlation as proposed by Zukauskas [7] is used. The resulting expression for U is according to Langelandsvik [2]:

$$U = 1/\left(1/h_i + r_i h_w + r_i/(r_o h_o)\right) \tag{6}$$

An assumption of equation 6 is that the soil surface boundary condition is isothermal as described in Ovuvorie [8].

1D radial unsteady model: few relevant studies about unsteady heat transfer of long buried pipelines can be found in the literature. In these studies the heat conduction through the soil is often considered as a 1 D radial problem. On the other side, unsteady conductive heat transfer for the case of a hollow cylinder is studied extensively, offering exact as well as numerical solutions. Examples of pipeline specific studies, using numerical approximations, are Osiadacz [9] and Nicholas [10]. Particularly the latter work is of interest, studying the propagation of thermal fronts through a buried pipeline and the impact of neglecting the ground storage term in the heat transfer model. The work from Nicholas [10] uses a 1D radial unsteady thermal conduction model of the ambience together with a 1D pipe flow model. Here the case is made that the use of a single heat transfer coefficient may be adequate for the steady state approach but not when thermal transients are present in the pipeline. To verify this, the ground is represented as a series of concentric shells. Each shell has uniform thermal properties and the thickness of the shells increase with radial distance from the pipe. Unfortunately, this work does not fully disclose the numerical methods used to solve the ground thermal problem, but appears in approach similar to the 1D radial unsteady model presented in this paper. The conclusions of Nicholas [10] are that representing the heat flux between soil and gas as a steady state heat transfer coefficient when modelling transient pipe flow, leads to inaccuracies of gas temperatures and pipeline inventories. The initial thermal response of gas inside the pipeline is over/under predicted when a steady state thermal model is employed. Heat transfer inside the pipe wall can be ignored when time scales of flow changes are larger than 30 seconds, but not the heat capacity of the wall.

Our 1D radial unsteady model solves the 1D radial form of the unsteady heat equation using a finite difference scheme. An extensive description of this model and its coupling with the flow model is provided in Chaczykowsky [3] and Helgaker et al. [11]. The model consists of coaxial cylindrical layers surrounding the pipe. The gas temperature is coupled through the film heat transfer coefficient at the inner wall of the innermost layer (the pipe wall) and the ambient temperature is imposed as surface temperature on the outermost layer. The temperature field varies both in time and in the radial spatial dimension, but not angularly. For the transient problem, the flow parameters and the ambient heat exchange model are calculated separately during each time step. Each simulation is started by setting up a steady state flow condition and corresponding thermal gradient in the pipe wall and soil layers. The steady state is achieved by running the transient model with constant boundary conditions over a sufficient number of time steps. In each time step, the changes in the thermal model are calculated first, using the gas temperature of the previous time step as input. The resulting values for q for each pipe element are subsequently used in the flow calculation. One problem arising is how to define the total radial thickness, r_s, of the soil domain. An initial approach is to set r_s equal to the depth of burial form the top of the soil to the pipe most outer layer. As discussed in Helgaker et al [11], this approach gives a smaller thermal domain compared to the 2D case and a too short steady state conduction path. The energy exchange between gas inside the pipe and the ambience in steady state is then overestimated. A known way to improve upon the latter is to use a so-called equivalent, or effective soil layer radius. This is for example used by the multiphase flow simulation software OLGA as documented in OLGA documentation [12]. The equivalent soil layer radius, based upon isothermal boundary conditions is:

$$r_e = 0.5D\left(\sigma + \sqrt{\sigma^2 - 1}\right) \tag{7}$$

2D unsteady model: published work of a two dimensional approach to soil heat transfer of buried pipelines are mostly limited to steady state case. Barletta et al. [13], studied the steady periodic heat transfer of buried offshore pipelines numerically. The transient case is the annual temperature variation on the seabed in shallow water. In this work the periodical non-steady heat 2D heat conduction problem is transformed and solved numerically as a steady problem. In Gu et al. [14], the effect of soil heat storage on a case of alternating hot-cold fluid entering a buried oil pipeline is modeled numerically. This paper does not clarify how the heat transfer is coupled to the flow and how oil temperatures inside the pipeline are calculated. The paper studies the effect of moisture transfer and moisture phase change upon the temperature distribution in the ground. In Barletta et al.[15], 2D unsteady heat transfer of a completely buried pipeline is investigated. Both step-rise (rapid transient) and smooth rising case (slow transient) are studied and compared with an 1D radial unsteady model. In the model, only the soil heat transfer is modelled, not the flow of the gas inside the pipe. The problem investigated is that of pipeline start-up; i.e. initially the flow is at standstill and the thermal domain at equilibrium. The start-up of flow through the pipeline is then modelled by changing the pipe wall temperatures accordingly in one 2D plane. The response of the soil domain upon the temperature change at the wall is then evaluated through the dimensionless thermal power exchange at the wall per unit length.

The contribution and novelty presented in our work is that we investigate the unsteady heat transfer for a buried pipeline using full thermal coupling between compressible fluid flow and the thermal domain over an entire pipeline length, and, using a 2D representation of the pipe wall and soil. The 2D unsteady model couples the thermal soil domain to the energy equation of the flow model similar to the 1D radial unsteady model, using the gas temperature and resulting pipe wall heat flux. For buried sections, each pipe flow calculation element has a corresponding 2D thermal model of the pipe wall and soil through the plane perpendicular to the pipe axis. The system is shown schematically in Figure 2.

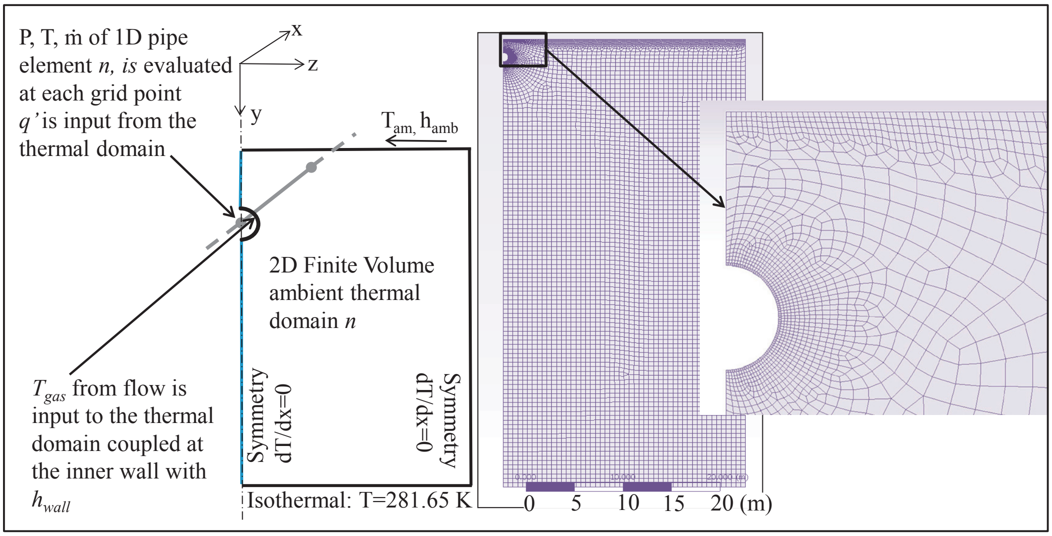

Figure 2: 2D model description and detail of finite volume grid of each soil slice.

The 2D thermal domains form 2D 'slices' of the soil, discretized using a Finite Volume grid with the program FLUENT. The physical dimensions of these 2D soil domains are 50*25 meters and the pipe wall layer is modelled with perfect thermal contact to the soil. The size of the domain is chosen sufficiently large for the thermal gradients to be near zero at the vertical and lower borders. The symmetry along the y-axis is utilized to reduce the size of the model. On the lower and right hand side border of the domain, Neumann boundary conditions are employed with zero heat flux. Ambient temperature is coupled to the top border of the domain through a convective boundary condition employing heat transfer coefficient of 50 W/m^2K. The grid was refined until the steady state heat transfer rate at the inner wall for T_{gas}=303.15 K and $T_{ambient}$=278.15 K did not change more than 1% with further refinement. This was evaluated after letting the solution converge to a residual of the energy equation of $1*10^{-9}$. Only the energy equation for the solid domains is solved. In Fluent, the discretization scheme for the energy equation is second order upwind in space and first order implicit in time. The under relaxation factor for the energy equation is set to one, and the V cycle multigrid solver is used. At the pipeline inner wall, a convective heat transfer boundary condition is used. The gas temperature is defined as the fluid temperature and a fixed value for the film coefficient (1650 W/m^2K). Radiative heat transfer is ignored, as gas temperatures are low. The resulting heat transfer through the boundary is calculated in Fluent [16] by summation of the net heat exchanged at each element on the boundary.

3 Results

In the pipeline scenario studied here, there are three distinct heat transfer regimes along the pipeline (as discussed in Ramsen et al.[17]. For the initial buried part (10 km), the gas is hotter than the environment; heat is transferred from gas to environment. The second part of the pipeline (80 km) is subsea and subjected to much higher heat transfer rates. The gas will cool down to ambient seawater temperature and then start to receive heat from the seawater to balance a drop in the internal energy due to the expansion of the gas (second term to the left of eq. 3) as the gas pressure drops downstream along the pipeline. At the end of the subsea part, the gas temperature will be approximately 0.5 K below the seawater temperature. The locations of interest to evaluate the response of the flow parameters upon the transients are at the end of the first buried part of the pipeline, the end of the offshore part and the pipeline exit. The case of a fully buried pipeline with σ=3.58 (soil surface to centre line of pipe is 2 m) is used. From eq. 5 and eq. 6, the overall heat transfer coefficient U is calculated to be 2.9 W/m^2K. The equivalent soil layer radius of the 1D radial unsteady model is 4.2 m.

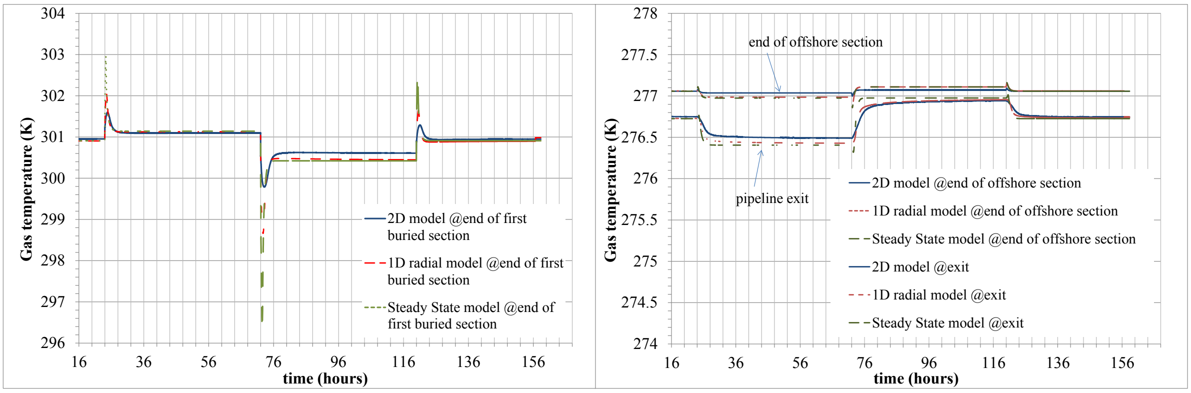

Figure 3: Left:gas temperature response on inlet mass rate transients at end of first buried section (upper three curves in left graph), end of offshore section (top three curves in right graph) and pipeline exit (lower three curves in right graph).

Figure 3 and Figure 4 show that there is a significant difference in gas temperature response to the inlet mass transients but **not** in gas pressure. In the first buried section, the difference in gas temperature between the three heat transfer models is the largest. For the second mass rate change, the difference between the steady and 2D unsteady model is as large as 4K. At the end of the offshore section, the temperature differences are much smaller, 0.3K. At the pipeline exit the differences between the models increases to 0.5 K. At the first location, the difference is 2.7 K, at the exit 1.5 K. We look in more detail at the response in the first buried part, where the differences between the models are largest. Considering the initial mass rate change (at t=24 hrs), the sudden increase in inlet gas velocity will lead to compression of the gas already inside the pipeline and thus a resulting sharp temperature increase. Initially, more gas per time unit will flow into the inlet than can flow out at the outlet (fixed outlet pressure). The pipeline inventory increases first and maximally at the pipeline inlet side and gradually declines towards the exit. The initial compression and temperature rise is than at maximum at the first buried section and declining towards the exit. This is the main reason that the spike in the temperature response at the end of the offshore section and pipeline exit is small compared to the first location. The qualitative and quantitative differences in calculated gas temperature between the 1D radial unsteady model and the 2D unsteady model are small compared to the difference with the 1D steady model. The difference between the steady and non-steady models can be explained from the heat storage capacity of the pipe wall and nearby soil layers. The difference in gas temperature response between the models can be explained as follows: For the steady state model, the U value remains constant in time. Therefore the thermal energy exchange over the pipe wall with the environment will still be governed by the term $4U/D*(T_{gas}-T_{ambient})$. The film coefficient U is based on steady conduction throughout the entire soil domain, and has a long thermal time constant. The sudden increase in the gas temperature will result in a modest increase in the heat flux between gas and environment according to the last term in the energy equation. For the unsteady thermal models, the instant thermal response of the pipe wall and surrounding soil layers to the change in gas temperature leads to a much higher heat flux at the pipe inner wall. This inner wall heat flux is directly coupled to the heat equation, as the term: $4U/D*(T_{gas}-T_{ambient})$ is replaced with thermal energy change of the gas due to the instantaneous inner wall heat flux. The pipe wall and soil immediately around it are allowed to respond to the gas temperature change by storing the thermal energy before conducting it further out through the soil domain. This difference in energy exchange is shown in Figure 4 at the right hand side.

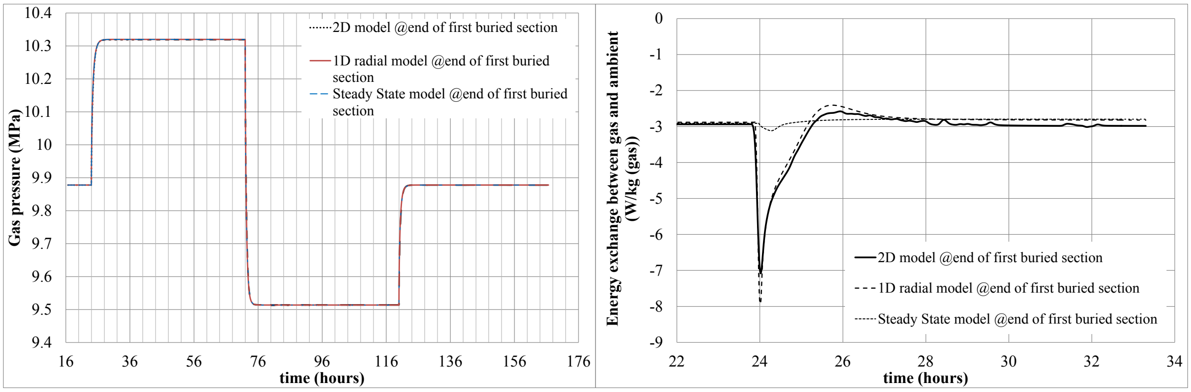

Figure 4: Right: gas pressure response to inlet mass rate transient at end of first buried section. Note that the all three models result in pressure profiles so close to each other that the lines are indistinguishable. Left: Energy exchange between gas and ambient at KP10 during the first inlet temperature transient at end of first buried section.

The difference between the models is smallest at the end of the offshore section. Because the heat transfer coefficient between the pipe and the seawater is so high, the differences in energy exchange between the models in response to the mass rate transient is reduced at this location.

For the inlet temperature transient, calculated temperature and pressure response are shown in Figure 5. The unsteady models both have a similar pressure and temperature response and show that including heat storage in the surrounding pipe wall layers and soil delay the gas temperature response following a thermal inlet transient. The energy exchange between the gas and the environment is also in this case an order of magnitude higher for the unsteady models compared with the steady model in response to the inlet temperature transient. It takes longer for the gas flowing through the pipeline to achieve a new steady state temperature at each location along the buried parts of the pipeline when ambient heat storage is allowed; the first gas at higher temperature streaming into the inlet is cooled down by the colder pipe wall and soil until these are gradually heated up to a new steady state equilibrium with the streaming gas. Again, there are no significant differences between the 1D and 2D unsteady model. The two dimensional geometrical aspect of a buried pipe is also in this transient case of limited importance compared to the effect of including the heat storage term in the thermal domain. At the end of the offshore section, the high heat exchange rate with the seawater has cooled down to ambient the gas that entered the pipeline at higher temperature; the models therefore show no significantly different response at this location and at the exit. The response in pressure at the end of the first buried part shows a small, but noticeable pressure peak. This caused by the hotter gas entering the pipeline having a lower density. In order to maintain the same mass rate, momentarily the flow velocity increases. The new hotter gas entering the pipeline experiences some compression due to the inertia of the slower, colder gas already inside the pipeline. With the unsteady models, the hotter gas flowing into the pipeline is initially cooled down due to heat storage in the wall and soil in the first buried section, which is not the case with the steady model. This small bump in pressure is therefore less with the unsteady models. The difference amounts to 25 KPa.

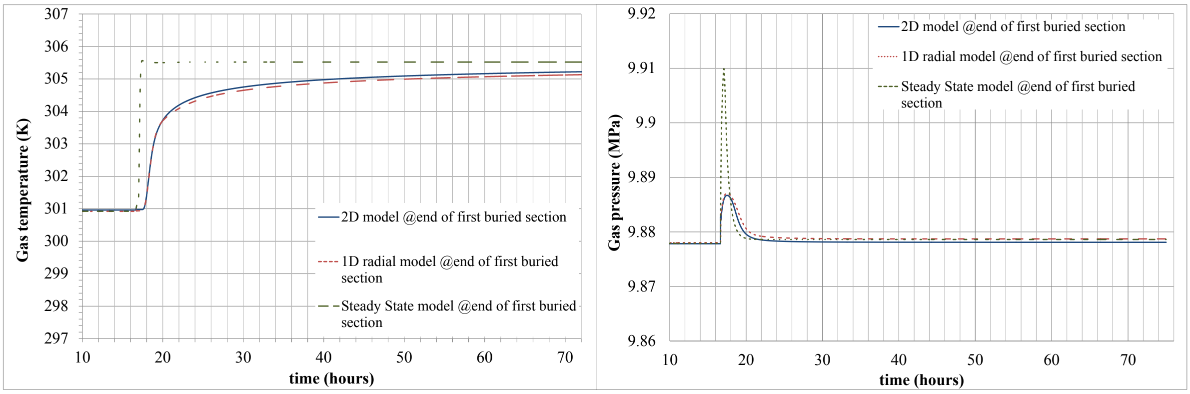

Figure 5: 2 m burial depth. Left:gas temperature response on inlet temperature transients at the end of the first buried section (upper three curves, left hand y-axis. Right: gas pressure response to inlet temperature transient at the end of the first buried section .

4 Experimental verification with real pipeline case.

The real pipeline case is that of an export gas pipeline. The 1016 mm bore pipeline has a length of 658 km (642 km is offshore). The first part of the pipeline, from inlet to the offshore landfall has been modelled using the 1D radial unsteady model. The pipeline elevation profile is shown in Figure 6.

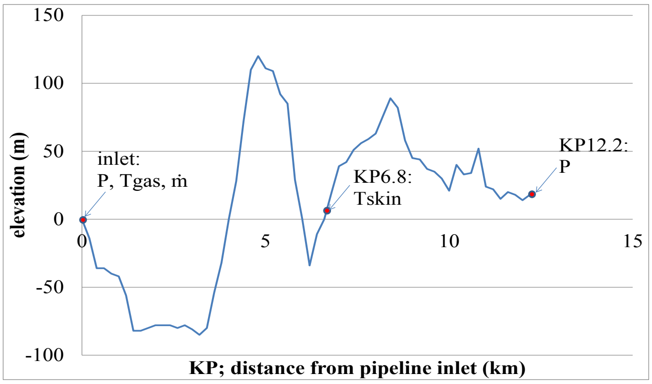

Figure 6: Pipeline elevation profile and measurement locations

For part of this route, the pipeline goes through two short subsea sections (sounds). For the majority of the subsea section, the pipeline lies buried under the seabed. On the land sections, the pipeline is buried in sand filled ditches to an average depth of 2 m. The thickness of the soil layer is based upon pipeline design and recent survey data. Real pipeline data is obtained from the SCADA system at Gassco AS at the pipeline entrance (Pressure, temperature and flow rate) and at the offshore landfall at KP12.2 (gas pressure). Pipe skin temperature (pipe outer wall) measurement is available at KP6.8. The pipeline elevation profile is shown in Figure 6.

The following real case of Figure 7, containing both rapid inlet mass rate and inlet gas temperature changes is used in the flow model with both the 1D steady and 1D radial unsteady heat transfer model. The calculated inlet pressures from the models are compared to the measured pressure, as shown in Figure 7. With both models, the inlet pressure calculations match the measurements almost exactly. In Figure 8, the calculated skin temperature response versus measured temperature response at KP7 is shown to the left, while to the right the relative differences for both models is shown. The results clearly demonstrate the ability of the 1D radial unsteady heat transfer model to predict the gas temperatures more accurate than the steady state model in response to inlet mass rate and temperature transients. The steady state model has a maximum deviation of 2.5 K in calculated temperature in response to rapid changes in inlet conditions, with the 1D radial model this is less than 0.5 K. It is worth noticing that the temperature deviations with the steady state model are occurring because the gas temperature rises/sinks too fast in response to a transient. This is in full agreement with the results from the modelling study. The temperature deviations with the 1D radial unsteady model are over-predictions occurring at the peaks in the gas temperature inside the pipe in response to the transients at the inlet. Further study is needed to identify the cause of these peaks, e.g. inaccurate thermal properties in the model or other influencing factors like convective heat transfer due to soil moisture.

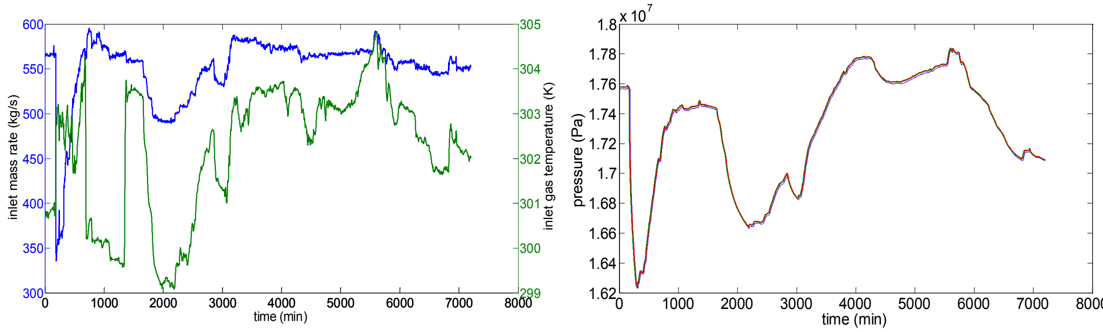

Figure 7:Left:inlet mass flow rate (blue line) and inlet temperature (green line) of real case 1. Right: inlet pressure; blue is measured, red calculated with steady state thermal model, the green line is the pressure calculated with unsteady 1D radial thermal mode; this is coinciding with that of the steady state thermal model (red line).

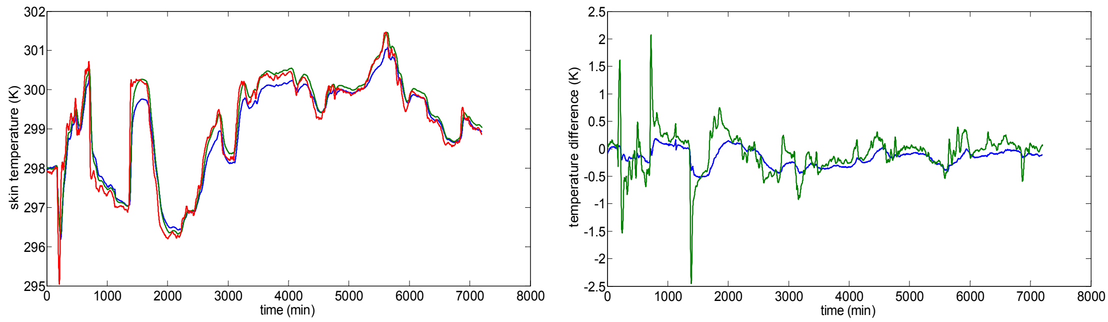

Figure 8: Pipe skin measurement KP6.8; blue line is measured skin temperature, red line is skin temperature calculated with steady state thermal model, green line is skin temperature calculated with unsteady 1D radial thermal model. Right:difference between measured and calculated skin temperature at KP6.8; green line is steady state model, blue line is 1 D radial model.

4 Conclusions

Studied is the effect of the heat transfer model on pipe flow calculation during transient. The response to an inlet gas mass rate transient is shown to be different to that of an inlet gas temperature transient. The results demonstrate that a steady state model of the ambient and soil cannot accurately represent the ambient heat exchange when rapid transients in the inlet flow occur. The reason is that inlet flow transients result in rapid temperature changes of the gas inside the pipeline. These can only be dissipated in the surrounding pipe wall and soil at a rate determined by the thermal resistance of the entire thermal domain. For both transients, the heat exchange during transient flow is underestimated. The unsteady models allow heat storage in the pipe wall and soil resulting in higher instantaneous heat exchange rates. This dampens the temperature response of the gas inside the pipeline in response to the inlet transient. The results show that inclusion of the soil heat storage term in the heat exchange model has a large influence on the thermal accuracy of the calculated pipe hydraulic flow subject to an inlet flow transient. The effect on pressure calculation was found to be minor. The choice between a 1D radial versus 2D unsteady heat transfer model has a much smaller impact: for this case both models shows a similar response to the transients. Significant improvements in thermal calculation accuracy of transient pipe flow can be achieved by implementing a 1D radial unsteady heat transfer model of the soil instead of the currently used steady state model. The experimental results are in agreement; the experimental verification demonstrates the improvement potential the 1D radial unsteady model has over the steady state model. The remaining temperature deviations are related to the peaks of the gas temperature inside the pipe in response to the inlet transients. Further study is needed to identify the cause(s) of this.

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