DEVELOPMENT OF A COMPUTER PROGRAM FOR THE SIMULATION OF GAS PERMEATION THROUGH THE WALLS OF FLEXIBLE PIPES

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Abstract. *The design of flexible pipes, used in the petroleum industry, must consider a great number of failure modes. Among them, the problems due to chemical corrosion in the metallic layers that constitute the armors are of the foremost importance. These armors are protected by polymer sheaths, internally and externally, forming one annular space. The gas that is transported by the flexible pipe permeates continuously through the polymer sheaths, increasing the pressure in the annular space. This work presents the transient numerical method and results obtained with a computer code capable of simulating the process of permeation of gases through polymer walls considering the radial and axial directions. The program is capable of predicting the chemical composition in the annulus, at given design conditions of the flexible pipe. Temperature distribution in the radial direction is also calculated in order to consider the variation of mass diffusion coefficients with temperature. The venting process of the annular space, that is used for this kind of equipment, is considered in the simulations.*

Keywords*: flexible pipes, gas permeation, transient mass diffusion.*

1. INTRODUCTION

The design of flexible pipes, used in the petroleum industry, must consider a great number of failure modes. Among them, the problems due to chemical corrosion in the metallic layers that constitute the armors are of the foremost importance. These armors are protected by polymer sheaths, internally and externally, forming one annular space. The gas that is transported by the flexible pipe permeates continuously through the polymer sheaths, increasing the pressure in the annular space. The gas composition resultant in each annular space and the possibility of water condensation are simulation results of interest.

This work presents the transient numerical method and preliminary results with a computer code capable of simulating the process of permeation of gases through polymer walls considering the radial and axial directions. The geometry simplification of the flexible pipe is conducted using one approach very similar to the approach proposed by Benjelloun-Dabaghi et al (2002).

The computer program developed uses the finite volume method for the solution of partial differential equations. The program is capable of predicting the chemical composition in the annulus, at given design conditions of the flexible pipe: geometry of the pipe and working conditions. Temperature distribution in the radial direction is also calculated in order to consider the variation of mass diffusion coefficients with temperature and to predict condensation in the annulus. The venting process of the annulus is considered in the simulations with one adequate model.

The computer program developed has application on the design of flexible pipes used in the petroleum industry.

2. PHYSICAL MODEL

The gas permeation though the radial layers of the flexible pipe is modeled using partial differential equations. Equation 1 presents the conservation of one chemical component using cylindrical coordinates. Cylindrical coordinates are the obvious choice considering the geometry of the flexible pipe. Differences of concentration in the tangential direction are not considered in the calculation. The coefficient of diffusion of the gaseous component A in the polymer B is strongly dependant on temperature, and this dependence must be considered.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(D_{AB}\ r\frac{\partial C}{\partial r}\right)+\frac{\partial}{\partial z}\left(D_{AB}\frac{\partial C}{\partial z}\right)+\dot{N}_A=\frac{\partial C}{\partial t} \tag{1}$$

where C is the gas concentration, r the radial coordinate, z the axial coordinate, D_{AB} the mass diffusion coefficient and t the time.

In the limits of the radial layers boundary conditions are needed. The concept of solubility is used for that. In the boundaries the concentration of one particular component is calculated from its partial pressure and solubility of the component in the polymer material. This property is also dependant on temperature.

$$C = S \cdot p \tag{2}$$

where S is the mass solubility and p the partial pressure of the gas.

In the interfaces between different polymer materials the concentration may be different, but not partial pressure of the component. This behavior introduces discontinuities in concentration distributions. Nevertheless, partial pressure distributions don't present these discontinuities. The solution of the differential equations for different gas components is conducted using one numerical model, due to the complex geometry that characterizes the problem.

Since temperature distribution has strong impact over diffusion coefficients and solubility, the program also calculates radial temperature distribution. Differential equation 3 is used for this task.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k\ r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{3}$$

where T is the temperature, k the thermal conductivity, ρ the density and c_p the specific heat.

The time scales for energy and mass diffusion are very different. Steady state temperature distribution should be obtained in a few hours, while the mass diffusion takes many days to achieve one similar condition. This difference between time scales permit to consider only the steady state condition for temperature distribution. Another simplification is introduced considering that temperature variations occur only in the radial direction. It is not true if the entire flexible pipe is considered, but it is if only a small length is considered. The simulation strategy is to consider small lengths, in different parts of the flexible pipe. This is necessary because the simulation of the entire length of the pipe would require exaggerated grid and computational resources. The hypothesis commented reduces equation 3 to the much simpler equation 4.

$$\frac{\partial}{\partial r}\left(k\ r\frac{\partial T}{\partial r}\right)=0 \tag{4}$$

Equation 4 is solved analytically in the beginning of a new simulation. This permits to compute diffusion coefficients and solubility in any part of the domain that these parameters are needed.

2.1. Numerical solution

The numerical solution for the gas concentration is obtained with a computer program written in C# language, developed specifically for this purpose. Equation 1 is solved for each gas component transported by the flexible pipe: CH_4, CO_2, H_2S, H_2O. The program is flexible enough to include new gas components on the simulation, provided that mass diffusion coefficients are available. The diffusion of the gas components is simulated simultaneously, but with the hypothesis that the diffusion of each component does not affect the diffusion of the others.

The finite volume method is used for the numerical solution on a two-dimensional structured mesh in cylindrical coordinates. The transient simulation uses a fully implicit scheme in order to improve robustness. The finite volume method and the advantages of the fully implicit scheme are discussed extensively in the literature, as in Versteeg and Malalasekera (2007).

2.2. Geometry simplification

The many layers that constitute one flexible pipe are shown in figure 1. Clearly, it is a complex three dimensional geometry that must be simplified in order to conduct two dimensional simulations. The approach used for this simplification is to consider that the wires that compose the armors are rings, instead of spirally wounded like in the real geometry.

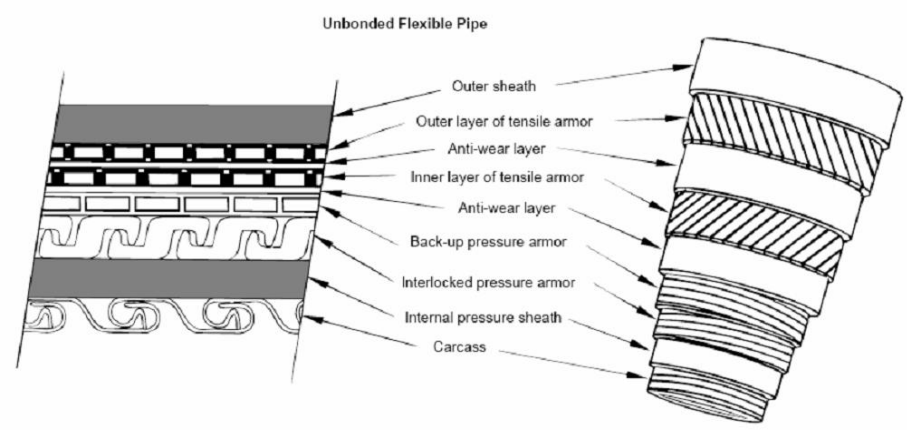

Figure 1. Three dimensional geometry of one typical flexible pipe

Two different geometry simplification models are used, one for tensile armors and other for pressure armor.

2.2.1 Geometry simplification: Tensile armor

The wire disposed in spiral form is modeled as rings. The following parameters, for a given armor are necessary: number of wires (n); width of the wires (b); angle between the wire and the pipe axe (α); internal radius of the armor layer (R). From these parameters, the helix step (h) can be calculated using eq. 5.

$$h = \frac{2\pi R}{\mathrm{tg}\,\alpha} \tag{5}$$

The projection of the wire width in the axial direction is calculated with equation 6. This parameter will be the width of the ring.

$$b' = \frac{b}{\sin\alpha} \tag{6}$$

The projection in the axial direction of the space between two wires is given by equation 7. This parameter will be the distance between rings.

$$j' = \frac{h}{n} - b' \tag{7}$$

The program uses the parameters b' and j' to automatically build the grid.

2.2.2 Geometry simplification: Pressure armor

Pressure armor, like tensile armor, is disposed in spiral, but its cross section presents one complex geometry that must be simplified. The approach used for this simplification is to maintain the void fraction of the design, modeling this armor the same way as the tensile armors: considering the spiral as a ring. This way, the void volume of the annulus modeled is maintained. Typical configuration of the pressure armor is shown in figure 2.

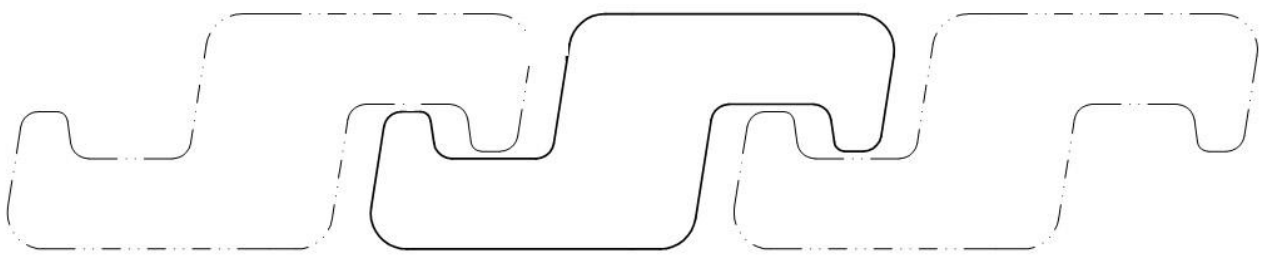

Figure 2. Cross section of pressure armor

Three relevant parameters should be used from the design of the pressure armor in order to model this layer: helix step (w); cross section width (l); area of the cross section (A_z). The helix step should be evaluated under normal conditions (not distended or compressed).

It is easy to verify that the parameters b′ and j′, used to simplify the geometry also for the tensile armors, can be evaluated by eq. 8 and 9.

$$b' = \frac{A_z}{l} \tag{8}$$

$$j' = w - b' \tag{9}$$

2.3. Automatic grid generation

The grid is generated automatically using the pipe design data. The following information about each layer is required: material of the layer, internal diameter (ID) and external diameter (OD). Special parameters are necessary to characterize the armors, as discussed in the previous section.

Figure 3 presents one typical grid generated by the simulation program. In addition to the pipe design data, only the minimum number of volumes in the directions r and z are required. One algorithm was developed to guarantee at least one volume at each different layer, even if the layer is very fin. The resultant grid may have more volumes than the minimum specified by the user, if necessary to describe the geometry.

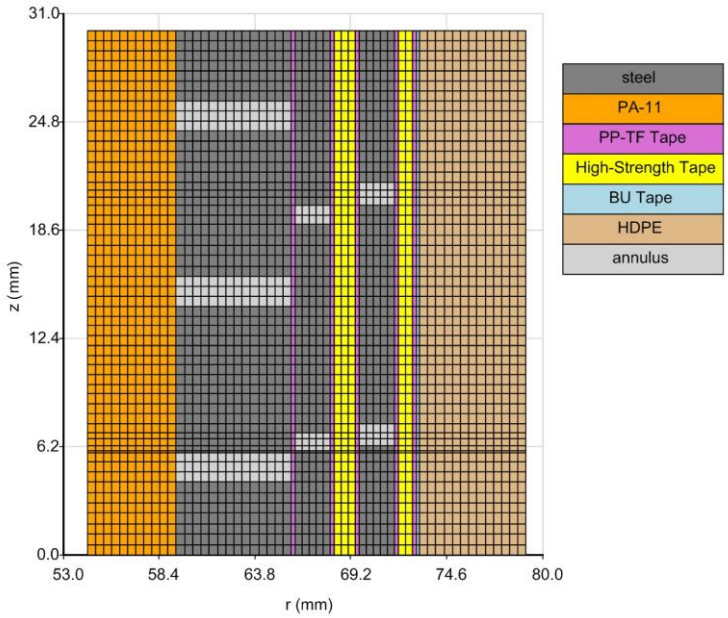

Figure 3. Grid generated automatically based on design data of the flexible pipe

2.4. Venting valve model

Under operational conditions, the pressure in some of the annular spaces present in the flexible pipe tends to increase due to the gas permeation through its layers. Some of the annular spaces are vented to prevent pressure increase. The venting mechanism is simple: the gas in the annular space is released to atmosphere every time the pressure reaches a given limit. This requires one model to include this venting mechanism in the numerical simulations performed by the program.

The program advances the time of the simulation in time-steps. Just after the solution of the system of equations, using the finite volume method, the total pressure in the annular space is calculated. This total pressure P_{total} is just the sum of the partial pressures P_i of the components considered in the simulation (equation 10).

$$P_{total} = \sum_{i=1}^{N} P_i \tag{10}$$

The parameters that should be available to the model of the venting valve are the pressures of opening (crack) and closure (reseat). If the total pressure P_{total} given by equation 10 is higher than the opening pressure P_{open}, partial pressure of each component present in the annular space is recalculated using equation 11.

$$P_i^{new} = \frac{P_{close}}{P_{open}} P_i^{old} \tag{11}$$

where P_{close} is the pressure at which the venting valve closes.

This simple model reduces the pressure in the annular space but does not modify its composition.

2.5. Boundary conditions

In order to evaluate the temperature distribution in the radial direction the most internal and external temperatures must be supplied as boundary conditions. With these boundary conditions, eq. 4 is solved analytically only one time, at the beginning of the simulation. The thermal conductivity of the materials that constitutes the flexible pipe must be known.

The total pressure in the bore and the volumetric composition of the gas being transported must be supplied by the user. From these data, the most internal concentration can be evaluated for each component, according to eq. 2. This equation is also used in the interface between different polymer sheaths. At these interfaces, the partial pressure is the boundary condition. Due to different solubility in the materials of the interface, the distribution of concentration is not continuous.

2.6. Diffusion coefficients

The coefficients of mass diffusion and solubility are strongly dependent on temperature when the diffusion of gases in polymers is considered. For this particular type of diffusion, Klopffer and Flaconnèche (2001) and Flaconnèche et al. (2001) suggest the use of Arrhenius Law (eq. 12 and 13) to consider the temperature influence over these diffusion coefficients.

$$D(T) = D_0 \cdot \exp\left[-\frac{E_D}{R\,T}\right] \tag{12}$$

$$S(T) = S_0 \cdot \exp\left[-\frac{\Delta H_S}{R\,T}\right] \tag{13}$$

where T is the temperature, R the universal gas constant and D_0, S_0, E_D and ΔH_S are parameters obtained with curve fittings. The parameters D_0, S_0, E_D and ΔH_S, present in eq.12 and 13, should be determined for each pair of gas and polymer considered in the simulation. One simple curve fitting procedure is used for this task, based on experiments with the actual polymers used for the pipe manufacturing.

In the beginning of a new simulation, eq. 4 is solved analytically and the radial temperature distribution is obtained. This permits to compute diffusion coefficients and solubility in any part of the domain that these parameters are needed.

2.7. Water condensation

Water will condense in one particular annular space if the partial pressure of water, P_{H2O}, at this annular space exceeds the saturation pressure, P_{sat}, during one time-step. The vapor saturation pressure at each annular space can be evaluated using the radial temperature distribution previously calculated.

The water condensed during one time-step is calculated using eq. 14. This equation is used only if the condensation condition is achieved: $P_{H2O} > P_{sat}$.

$$\Delta m = \Delta\rho \cdot V_{annulus} \tag{14}$$

where Δm is the mass of liquid condensed during the time-step, $V_{annulus}$ is the volume of the annulus and $\Delta\rho$ is the difference between the density of the water in the annulus and the saturation density, given by eq. 15.

$$\Delta\rho = \rho_{H2O} - \rho_{sat} \tag{15}$$

The water condensed is integrated in time in order to have the total water condensed. If condensation occurs, the partial pressure of water is corrected so that $P_{H2O}=P_{sat}$.

3. RESULTS

In the end of the transient simulation the program produces one final report. This report presents the final volumetric composition of each annular space and the partial pressure of each gas component. The saturation properties in the annular spaces are also presented so that the user can instantly check if water condensation has occurred. In order to check the consistency of results a series of graphs and contours can be produced.

Figure 4 shows the temperature distribution in the flexible pipe walls. The program presents this result as color contour or as a graph. The heat transferred through the wall is also presented, in Watts per meter of pipe.

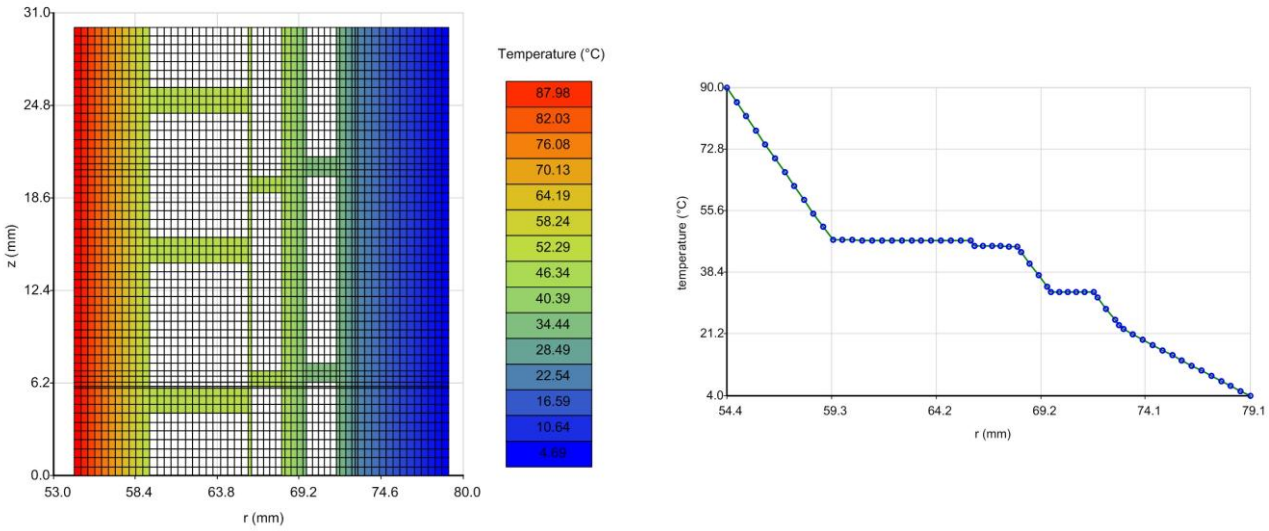

Figure 4. Temperature distribution in the flexible pipe walls

The concentration does not present one continuous distribution due to the different materials used in the flexible pipe and different solubility coefficients. Due to this, partial pressure distribution is presented in order to check physical consistency. Figure 5 presents the distribution of partial pressure in the calculation domain.

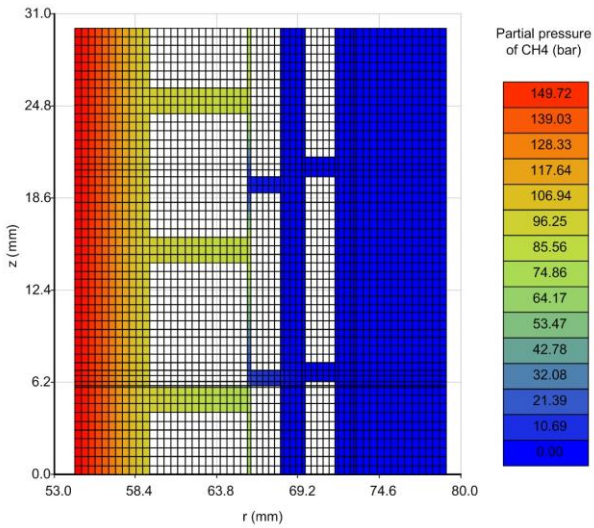

Figure 5. Temperature distribution in the flexible pipe walls

During the simulation, the partial pressure of each gas component in each annular space is recorded and can be shown as a function of time. Figure 6 shows the typical "saw tooth" behavior of the pressure in the annular space that occurs just after the pressure reach a certain level and the venting valve starts to actuate. It is important to observe that only some of the annular spaces are vented.

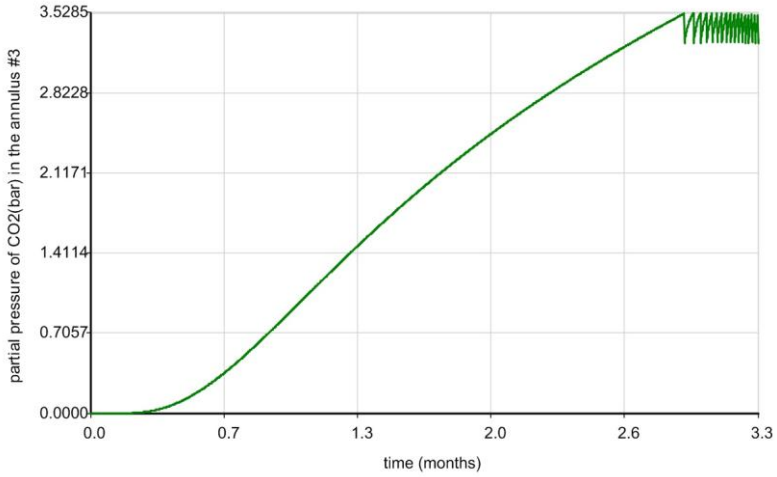

Figure 6. Evolution in time of partial pressure of CO_2 in the annular #3: venting valve actuates in the end of simulation

At the current stage of program development experimental data with prototypes are not available. Due to this, validation of the results was not conducted.

5. CONCLUSIONS

The program described in the present work can be used as one auxiliary tool for the design of flexible pipes used in the petroleum industry. It uses the finite volume method to solve the transient gas permeation of gases through the walls of a flexible pipe. Some particularities that characterize the problem are considered in the simulations: geometry of the flexible pipe, venting valve actuation, water condensation.

At the current state of development, the program shows physically consistent results but validation through comparison with experimental tests have not started yet. Diffusion properties of some polymer materials are not available in the literature and must be obtained with experimental tests. Due to this, evaluation of grid and time step influence over the results was not conducted.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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