

# THERMO-ECONOMIC SIMULATION OF THE THERMAL INSULATED EQUIPMENT USED IN STEAM INJECTION WELLS BY FINITE VOLUMES METHOD

Matheus Darós Pagani

Luciano Magno Costalonga Varejão

Lucia Catabriga

Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES

**Abstract.** Steam injection is a common EOR – Enhanced Oil Recovery – method that consists in injecting steam inside the formation in order to increase or allow production. During the flow of steam to the formation a lot of heat is lost to the environment through the injection equipment, and this may compromise the recovery efficiency in some cases. There are a few strategies able to reduce the heat loss during the flow, including the use of thermal insulation in the equipment that compose the injection column and the fluid transport pipeline. Usually, those insulated tubing and pipeline are more expensive than the common equipment, because of the difficulty of manufacture and boarded technology, and also are more difficult to install. These limitations must be evaluated comparing the expected cost and the simulated benefit in order to determine if the use of thermal insulation is economically viable in each project and what kind of insulation should be used in each case. This paper describes a computational method to run these thermo-economic simulations and demonstrates its applicability and reliability in some steam injection scenarios.

**Keywords:** EOR. Steam Injection. Thermo-Economic Simulation. Insulated Columns. Computational Simulations. Finite Volumes.

## 1. INTRODUCTION

Thermal recovery methods are common operations widely used in oil production fields in order to increase oil production or diminish its decline over time. These methods are based on adding heat to the reservoir to expand the oil in-place, reduce oil viscosity, provide drive energy and thereby improve the displacement efficiency of injected fluid (Ertekin, et al., 2001). The use of recovery methods is crucial in situations where the oil production is not economically viable to continue (or begin) without the use of recovery. Primary and secondary recovery methods usually act recovering the pressure energy of the formation by injecting gas or water in the formation or by stimulating the flow using driven layers of fluid (Almeida, 2004). Thermal recovery methods are capable of improving the production of wells that have already exhausted their internal reservoir energy even with primary and secondary recovery methods. By altering the properties of the reservoir fluid itself, these thermal methods can recovery up to an additional of 15% of the amount of oil in place after the energy provided by all other recovery methods declined (Tzimas, et al., 2005).

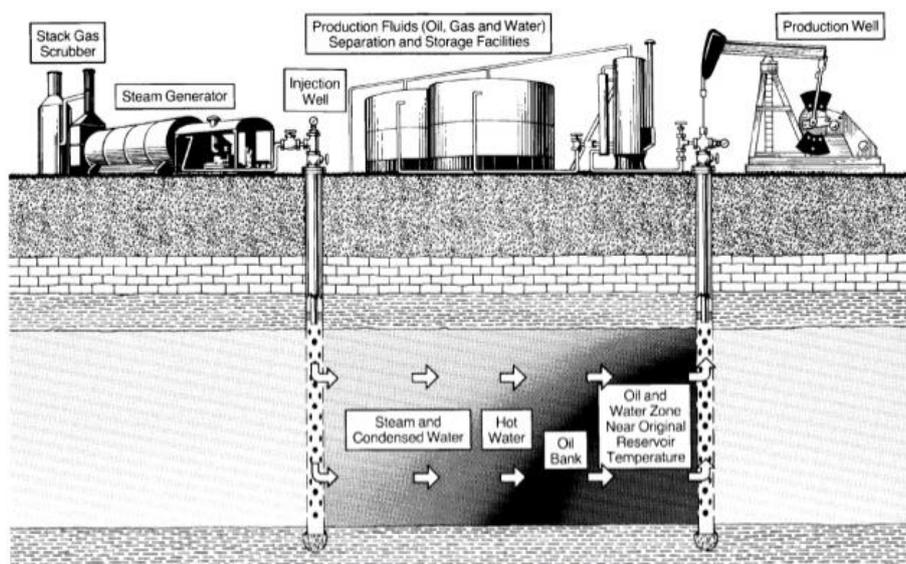


Figure 1 - Steam Flooding

The steam injection operation is a thermal recovery method that consists in injecting steam inside the well and making it flow inside the formation. The steam arrives at the formation with large amounts of thermal energy per unity of mass and is able to largely increase the oil temperature in a well spread area before losing its energy (Prats, 1986). As seen in Fig. 1, the steam is generated at a Steam Generator usually fueled by gas and flows through surface lines until injected in

the well head. The steam flows down inside an injection column and when it reaches the reservoir it blends with the oil and turns into water, and then the resulting mixture is pumped up through a production column.

The viability of using steam injection (or other recovery methods) depends on its effectiveness in improving the production and on its cost, in a way that the expected increase in production is greater than the operation costs plus the operational risks. Due to the complexity of the phenomena and the large scale of the operations the expected effectiveness and the risks are most of the times unknown in advance, and must be estimated through simulations in order to pre-determine the viability of the operation (Solrud, 2012).

The effectiveness of the steam injection operation depends on the amount of heat per unity of mass is present in the flow at the point where the steam enters in the reservoir. In practical conditions, the higher the delivered steam quality to the formation, more oil can be recovered (Sarathi & Olsen, 1992). Since the steam flows great distances from the source to the injection point, it is prone to losing great amounts of heat to the ambient that surrounds the flow line and the injection tubing, since the steam temperature is usually much higher than the medium. This amount of heat can be greatly diminished by using thermal insulated equipment to ensure that the steam flow reaches the reservoir with high quality. Since this kind of equipment are submitted to conditions of high pressure and high temperature, and due to the usually confined space for their installation, high technology insulation materials and measures are required to provide layers of insulation to the steam flow (Lombard, et al., 2008). Simulating the effect of the use of one insulation technology and comparing it to its cost allows the planning of the best cost-effective solution for oil recovery operations using steam injection.

The first fluid injection operations to recover oil started in the 60s, and soon the first injection models were developed. The pioneer model was proposed by Ramey as a first attempt to describe the operation through equations (Ramey, 1962). In this first model Ramey considered the flow as steady state, non-compressible and single phase, neglected Kinect energy, frictional loss and a constant heat transfer coefficient to soil along the well, and solved the momentum balance equations analytically to get approximate pressure and temperature distributions along the well. Later on Satter complemented Ramey`s model to consider the variation of the heat transfer coefficient along the well (Satter, 1965), and then Holst and Flock further complemented Satter`s model to consider the Kinect energy and frictional loss effects (Holst & Flock, 1966). Later on, Willhite proposed a way to calculate the heat transfer coefficient accounting the heat exchanges with the formation by using a table of coefficients depending on injection time and soil properties (Willhite, 1967). In the late 60s Earlougher described a method to include two phase correlations in the model, but considering there is no Slip Ratio between the phases (Earlougher, 1969). These models are base to most of the injection models that are used nowadays.

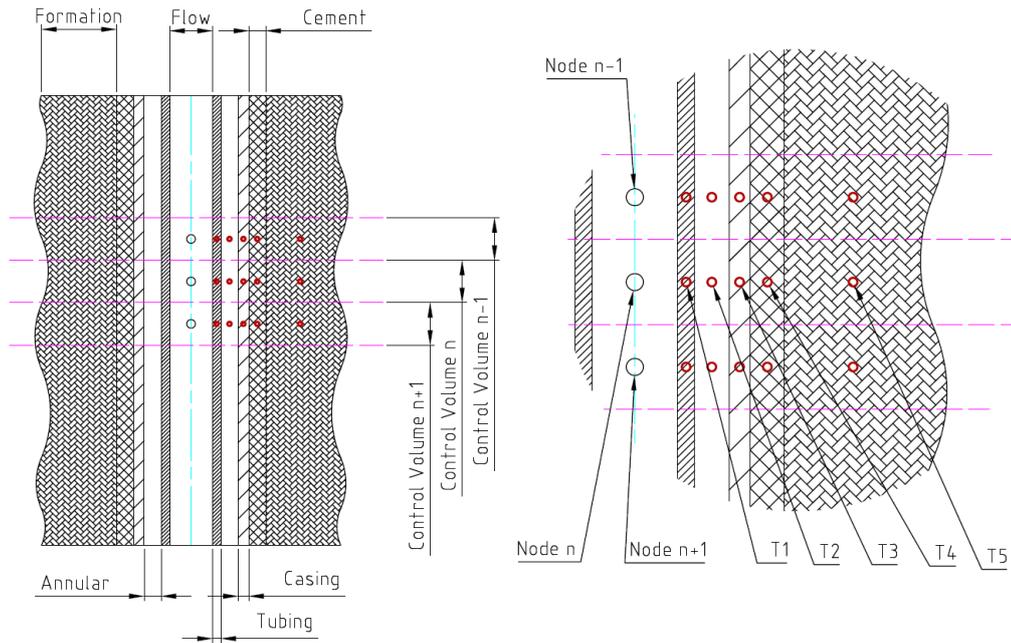
The model presented in this paper is based on these first models presented in the 60s using the computational resources available nowadays and is focused in addressing the simulation needs of the equipment manufacturers and users that need to correlate the effectiveness of one insulation technology and its cost and benefits. This model geometry and boundary conditions are described and detailed for this application.

This paper also demonstrates the solution process applied to numerically solve the model by using thermodynamic correlations and equations, finite volume dimensional discretization and solution process. This model is simulated and the results for a set of experiments are shown according to the conditions of each experiment. These simulations are then validated using the selected set of experiments where the simulation results are compared with reference values.

The final goal of this paper is to demonstrate that these simulation results can be applied to thermo-economic analysis in order to determine the most cost-effective equipment to be used in the injection operation from an array of possible candidates that fit the requirements of the operation.

## 2. MODEL

Our model is based on the discretization of the domain by using the Finite Volumes method applied to the fluid flow (Patankar, 1980). The domain is considered to be the piping and tubing that connects the flow source to the formation. The flow domain is set to be unidimensional representing the flow line inside these tubing that runs axially trough the injection line. The heat exchange domain is considered to be bidimensional and cylindrical, representing the flow, the layers of solids and fluids within the line up to the layer in contact to the ambient.



**Figure 2 - Discrete domain model**

The model is built upon a mesh of control volumes that compose the flow line from the source to the formation. Each control volume has a nodal point between its faces that represents the physical quantities and fluid properties in that control volume. There is only one nodal point to represent the axial fluid flow inside the volume, and one reference point in the middle of each radial layer between the flow line and the ambient. In the Fig. 2 are represented some nodal points inside some generic control volumes in the mesh placed in a section of the well, where the middle of the domain is the axial flow line and the outer is the formation.

The first boundary condition of the model is located at the first nodal point – the source point – that is the source equipment output, which is assumed as given by the readings of instruments and measurements, where the pressure, temperature and fluid properties are all determined. The next boundary condition is the temperature of the ambient or of the formation, that can be a function of depth or position, or simply a constant.

The model assumes that the temperature of two following nodes are almost equal, thus it does not consider the heat exchanged axially through the well. Also it assumes that the steam flow speed is the same as the condensed water flow speed. Even though the temperature of the flow and the equipment of the domain does change with time, the model considers that the temperature of a node is not a function of time, since the transient effect occurs in a small time range when compared to the overall length of the injection operations, and the local oscillations during the operation does not impact significantly the final result.

With these boundary conditions and assumptions, it is possible to calculate the heat exchanged between the flow and the formation in each volume by applying Fourier's law for concentric cylinder layers (Incropera, et al., 2006). As well, the pressure drop can be calculated considering the gravitational, frictional and acceleration pressure effect by using the Bernoulli law applied to tubing (Fox, et al., 2011).

Knowing the heat lost between one node and the next, it is possible to balance the heat loss with the decrease of internal enthalpy (Incropera, et al., 2006), thus knowing the enthalpy of the next nodal point. Similarly, it is possible to determine directly the pressure of the next point knowing the pressure of the previous nodal point and the pressure loss between these two.

Knowing the pressure and the enthalpy of the following point it is possible to determine the remaining thermodynamic properties by using steam tables (Throm, 2005) and correlations (Wagner & Kurse, 1998).

### 3. NUMERICAL FORMULATION

In order to numerically solve the model, the heat flux and pressure drop that occur inside the domain must be numerically quantified by formulations that match the simplification hypothesis adopted and the physical conditions that are considered in the model.

Considering the domain as a fluid flow inside a cylindrical tubing surrounded by cylindrical layers of material, the heat exchange between the fluid and the surrounding material can be calculated using Fourier's law for cylindrical geometries. Considering that the temperature of any point in the domain do not change with time, the radial heat flux between two points in the same axial position in the domain is function only of the radial distance between them, the thermal conductivity of the material between them and the difference of temperature of these two points. Since there may

be many different layers with many different materials between the fluid and the external boundary, the thermal resistance must be evaluated as an equivalent thermal resistance calculated as the composition of serial cylindrical resistances. The heat lost by the flow inside one of the finite volumes can be calculated by:

$$q = (T_i - T_e) / R_{eq} \quad (1)$$

where  $q$  is the heat loss,  $T_i$  is the temperature of the fluid,  $T_e$  is the temperature of the surrounding material, that can be the atmosphere, ocean water or the soil around the well, and  $R_{eq}$  is the equivalent resistance of the layers, that can be calculated in function of the resistances of each layer combined (Incropera, et al., 2006). The thermal resistance of solid layers can be calculated by the equation:

$$R = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} \quad (2)$$

where  $R$  is the thermal resistance of the layer,  $r_1$  is the radius of the internal face of the layer,  $r_2$  is the radius of the external face of the layer,  $L$  is the length of the finite volume, and  $k$  is the thermal conductivity of the material of the layer (Incropera, et al., 2006). This same equation can be used to calculate the thermal resistance of fluid layers enclosed between two walls by replacing the thermal conductivity  $k$  by an adapted conductivity value  $k_{eff}$ . The adapted conductivity value used in the cases of concentrically aligned cylinders can be calculated using the Dropkin's and Somerscales' correlation (Dropkin & Somerscales, 1965).

The thermal resistance of fluid layers that exchange heat through natural or forced convection can be calculated by the equation:

$$R = \frac{1}{h2\pi r_i L} \quad (3)$$

where  $h$  is the coefficient of convection, that can be calculated in function of the average Nusselt number  $\overline{Nu}_D$ , the thermal conductivity of the fluid  $k$  and the diameter  $D$  of the face where the convection occurs, by the equation:

$$\overline{Nu}_D = \frac{hD}{k} \quad (4)$$

This average Nusselt number can be calculated in various ways depending on the conditions of geometry, temperature difference and flow speed (Incropera, et al., 2006).

Transparent layers allow the heat exchange by radiation as well, so its effect can be accounted through a radiation effect that can be calculated by the equation:

$$R = \frac{1}{h_{rad}2\pi r_i L} \quad (5)$$

where  $h_{rad}$  is a radiation coefficient that can be calculated by the equation:

$$h_{rad} = \varepsilon\sigma(T_i^2 + T_e^2)(T_i + T_e) \quad (6)$$

where  $\varepsilon$  is the surface emissivity,  $\sigma$  is the Stephen-Boltzmann constant, and  $T_i$  and  $T_e$  are the temperatures of the faces exchanging heat by radiation.

The heat conduction from the last layer of a well equipment to the soil can be calculated using an equivalent thermal resistance to the conduction to the soil by using the coefficients described by Willhite to calculate the heat flowing in the formation (Willhite, 1967). In this case, the thermal resistance can be calculated by:

$$R = \frac{f(t_D)}{2\pi k_{soil}} \quad (7)$$

where  $f(t_D)$  is the time-function that modifies the soil resistivity coefficient according to the injection time, the soil diffusivity and temperature (Willhite, 1967), and  $k_{soil}$  is the thermal conductivity of the soil material.

A fluid with a given enthalpy  $h^{en}$  at the beginning of a finite volume, in a flux of mass of  $m$  that loses an amount of heat  $q$ , calculated by Eq. (1), will lose enthalpy due to the conservation of energy (Incropera, et al., 2006). The variation of enthalpy can be calculated by:

$$\Delta h^{en} = \frac{q}{m} \quad (8)$$

The pressure loss of the flow inside a finite volume can be accounted using the principle of Bernoulli in order to balance the changes in hydrostatic pressure, flow speed and friction (Fox, et al., 2011). The pressure loss can be calculated by the equation:

$$\frac{dp}{dx} = \left(\frac{dp}{dx}\right)_{acc} + \left(\frac{dp}{dx}\right)_{grv} + \left(\frac{dp}{dx}\right)_{frc} \quad (9)$$

where  $\frac{dp}{dx}$  is the pressure variation inside the finite volume, which have an axial size of  $dx$ . Considering that the finite volume now has an axial size of  $\Delta x$ , each component can be calculated as:

$$\begin{aligned} \Delta P_{Grv} &= \rho g \sin \theta \Delta x \\ \Delta P_{Acc} &= \rho u \Delta u \\ \Delta P_{frc} &= -\frac{f \rho u^2}{2D} \Delta x \end{aligned} \quad (10)$$

where  $\rho$  is the homogeneous density, that can be calculated using the Void Pressure (Woldesemayat, 2006),  $g$  is the acceleration of gravity,  $\theta$  is the inclination of the line to a horizontal reference,  $u$  is the average flow speed and  $f$  is the friction factor, that can be calculated using the Moody diagram (Fox, et al., 2011).

The average flow speed at a finite volume can be calculated in function of the volumetric flow by the equation:

$$u = \frac{1}{A} \int \vec{u} \cdot dA = \frac{\dot{Q}}{A} \quad (11)$$

where  $A$  is the area of the cross-section of the tubing, and  $\dot{Q}$  is the volumetric flow, that can be calculated by the equation:

$$\dot{Q} = \dot{m} v \quad (12)$$

where  $v$  is the specific volume of the fluid.

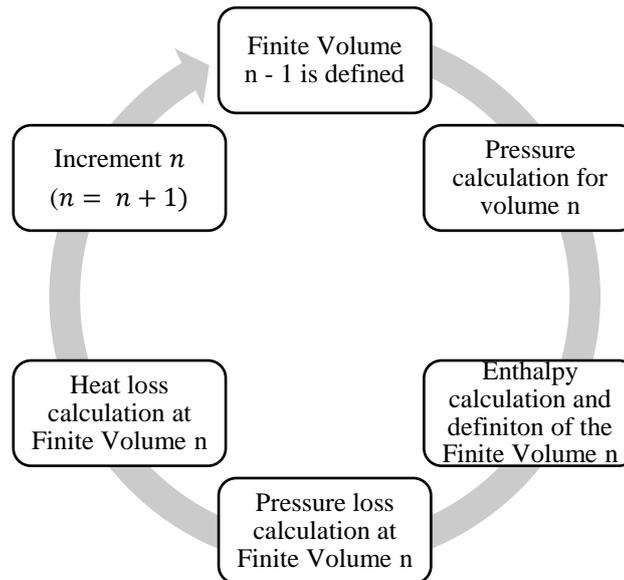
The thermodynamic properties of the fluid are calculated through thermodynamic correlations when at least two independent properties are known. The correlations for steam are normalized through the IAPWS-IF97 norm (Throm, 2005).

#### 4. SIMULATION PROCESS

All the input variables must to be specified for the user before the simulation process begin. These input variables define various objects and their properties: the fluid source, where the flow, pressure, temperature and quality are specified; the flow line, where the geometrical and physical information about the piping and tubing, the casing and the formation, where present, are specified; the ambient, where the average temperature, wind speed, water speed, water temperature and geothermal gradient are specified; and the simulation parameters, where the convergence tolerance and size of the mesh elements are defined.

The simulation process begins at the first finite volume approximating the physics properties in function of the flow input and the initial geometry. Then, the process is repeated over and over sequentially for each finite volume in the domain, considering the variation of the geometry and boundary conditions through the domain, in order to determine the state of the flux and the flow in each finite volume, as well as the heat loss.

At each step of the simulation process the fluid and flow state are calculated in function of the state of the previous volume and the pressure loss and heat exchange that occurred in this previous volume, and then the heat flux and pressure drop for this current volume are calculated in function of its state.



**Figure 3 - Simulation Process Diagram**

Figure 3 illustrates the simulation process of one loop. The previous volume is always defined, either because it is the first volume – that can be defined by the flow input information – or because it was calculated in the previous loop iteration.

In most cases the process is executed once from the beginning to the end of the domain, converging in one execution of the operation. In some cases, where the input pressure or mass flow is not defined, the process is cyclical, because an initial estimative for the missing value must to be consecutively corrected until the difference between one cycle and another is smaller than a defined tolerance.

After the process is executed from beginning to end and the required tolerance is met, where applicable, the numerical solution is extracted using post-processing methods for drawing graphs and tables with the simulation data.

## 5. THERMO-ECONOMIC ANALYSIS

Even though knowing the pressure, temperature and quality profiles is useful for the operation, the really important value for thermo-economic analysis is the final quality of steam at bottom hole, since it impacts two main components of the economic viability of the operation: the amount of resources spent per unit of time and the overall recovery factor of the injection operation.

A low quality value at bottom hole means that the steam has low heat capacity to deliver to the formation per unit of mass, and also is less capable of penetrating the formation (Aziz & Settari, 1979), and increasing this final quality means increasing the resources spent in order to compensate the heat losses during the steam flow.

The use of insulated tubing is useful to reduce the heat loss during the steam flow, but it also increases the operation cost due to the high price of these equipment when compared to common tubing. Because of that, the fundament of the thermo-economic analysis of steam injection operations is to compare the cost of the equipment with the final benefit and account the risks and gains for each option.

Since the amount of oil recovered in function of the delivered steam quality is not direct, varying widely from well to well depending on various reservoir conditions (Aziz & Settari, 1979), the thermo-economic analysis must limit itself to the reduction of costs linked to the reduction of resources needed to deliver the same quality at bottom hole. This is done by estimating the overall heat loss by balancing the input enthalpy of steam and the simulated output enthalpy at bottom hole. This value can be calculated by the equation:

$$Q \left[ \frac{KJ}{s} \right] = M \left[ \frac{Kg}{s} \right] * H \left[ \frac{KJ}{Kg} \right] \quad (13)$$

where  $Q$  is the total heat loss,  $M$  is the mass flow and  $H$  is the enthalpy difference between the input at the source and the simulated output at bottom hole. This heat loss value can be converted to a mensal energy value  $E$  by the equation:

$$E \left[ \frac{KJ}{month} \right] = Q \left[ \frac{KJ}{s} \right] * 30 \left[ \frac{injection\ days}{month} \right] * 24 \left[ \frac{hour}{day} \right] * 60 \left[ \frac{min}{hour} \right] * 60 \left[ \frac{s}{min} \right] \quad (14)$$

The cost of the unit of energy can be calculated by the cost of a unit of mass of fuel and the amount of energy that can be extracted from this unit of mass of fuel by the equation:

$$S \left[ \frac{\$}{month} \right] = \frac{E \left[ \frac{KJ}{month} \right]}{Jc \left[ \frac{KJ}{Kg} \right] * \%e} C \left[ \frac{\$}{Kg} \right] \quad (15)$$

where  $S$  is the monthly converted cost of the heat loss during the injection,  $Jc$  is the amount of usable fuel energy in one unit of mass of the fuel,  $\%e$  is the efficiency of the conversion of fuel energy into steam enthalpy, and  $C$  is the cost per unit of mass of fuel.

This monthly cost value can be calculated from the simulation result of every configuration candidate for a steam injection operation, so that every equipment has a labeled cost, given by the equipment provider, and a labeled equivalent monthly cost given by the simulation results. This way, every configuration candidate can be compared over initial investment (to purchase the equipment) and monthly savings (by reducing the equivalent monthly cost).

The direct procedure to compare the possible candidates about their thermo-economic outcome is:

- I. Table each candidate equipment about their cost, simulated heat loss and simulated pressure drop for the same input conditions;
- II. Select the case that provided the most suitable value of final quality and pressure at bottom hole;
- III. Adjust the input conditions of each other cases to match the selected case output at bottom hole;
- IV. Quantify the operational cost for the flow input of each case;
- V. Compare the initial cost and the operational cost of each case to determine the best investment according to the interest rate that is applicable.

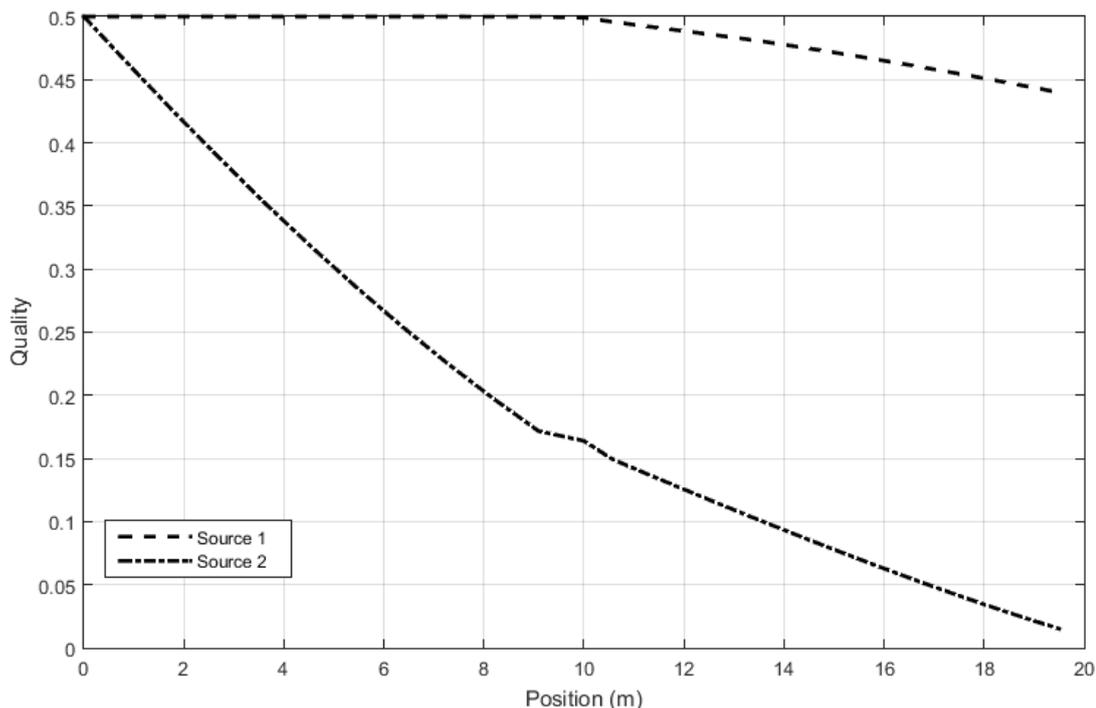
## 6. NUMERICAL EXPERIMENTS

The model is applied to simulate a set of numerical experiments where the first is a validation case intended to provide means to evaluate the results physical consistence. The simulation data for validation is shown at Tab. 1.

**Table 1 - Simulation data for validation experiment**

Source 1			Surface Line		
Flow	0.001	Kg/s	Length	10	m
Pressure	1	Bar	Internal Diameter	0.0101	m
Quality	50	%	External Diameter	0.0143	m
Temperature	372.756	Kelvin	Material	Steel	API
Source 2			Inclination		
				0	degrees
Flow	0.001	Kg/s	Well		
Pressure	5	Bar	Length	9.5	m
Quality	50	%	Internal Diameter	0.0699	m
Temperature	424.986	Kelvin	External Diameter	0.0889	m
Ambient			Casing Internal Diameter	0.1647	m
Temperature	372.756	Kelvin	Inclination	-90	degrees
Wind Speed	0	m/s	Material	Steel	J55

This validation case with unrealistic ambient temperature has a source named Source 1 that provides steam at the same temperature as the ambient, and a source named Source 2 that provides team at temperatures higher than the ambient. Also, the surface line is considered horizontal and without any kind of friction. In this case the result of the simulation for pressure and quality for Source 1 is expected to follow up to the wellhead unaltered.



**Figure 4 - Simulation result for validation experiment**

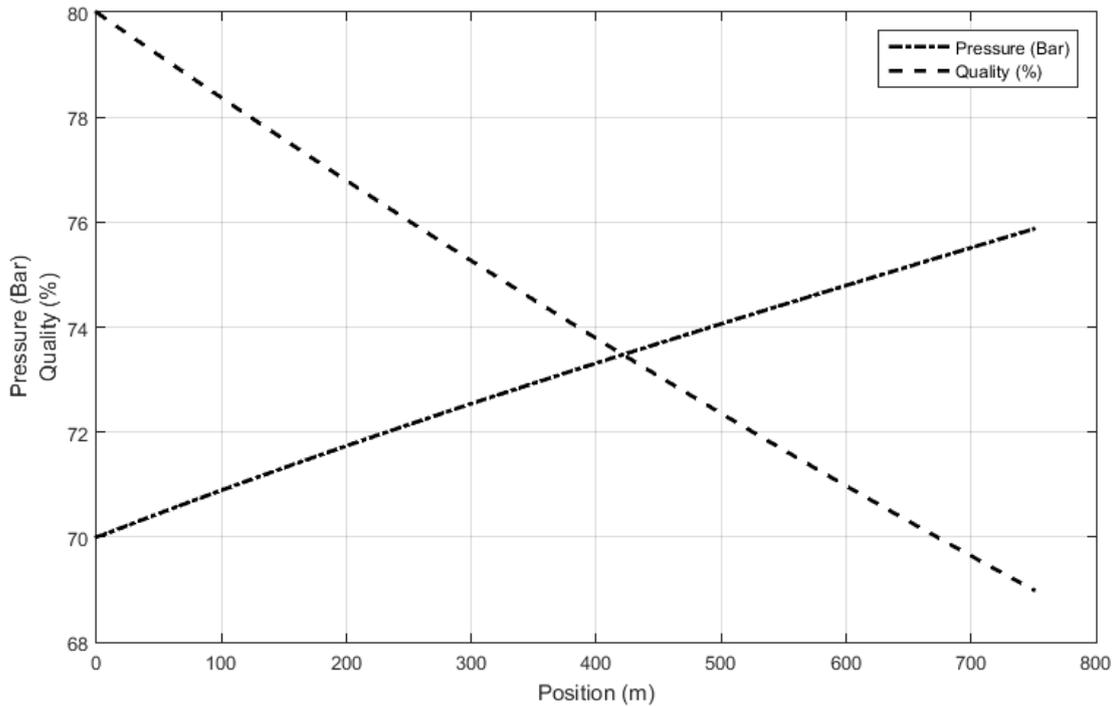
Figure 4 shows the simulated results for the validation experiment. This graph shows result of the profiles of quality through the line for both cases using Source 1 and Source 2. The case using the Source 1 is similar to what is expected according to the given conditions for this validation, where the quality of the steam provided by the source do not decrease because there is no temperature gradient thus no heat loss until it meets the well head, where the conditions change. The case using the Source 2 have a decline in quality since the beginning of the line due to the always present temperature gradient.

Dias Jr. and Romero have simulated an array of cases of steam injection with the PIPESIM® software (Dias Junior & Romero, 2014), where they consider the flow of steam from a source through a surface line and then inside the well down to the formation. The experiment 2 data are shown in Tab. 2.

**Table 2 - Base simulation data for experiment 2**

Source		Surface Line	
Flow	4.5 Kg/s	Length	10 m
Quality	80%	Internal Diameter	12 in
Pressure	70 Bar	Inclination	0°
Well		Ambient	
Tubing	API 4.5"	Temperature	15 ° C
Casing	API 7"	Wind speed	5 m/s
Depth	750 m	Soil thermal conductivity	0.22 W/mK
Inclination	90°	Metal thermal conductivity	50 W/mK

The simulation of experiment 2 yields the results for pressure and quality profile as shown in Fig. 5.



**Figure 5 - Quality and pressure profile for experiment 2**

Figure 5 illustrates the simulation result for the pressure and quality profile along the flow line using the given base conditions shown in Tab. 2. These results are compared with the ones present in the reference at the well head position and at the well bottom position in Tab. 3.

**Table 3 - Results at well head and bottom well for experiment 2**

	Well head		Well bottom	
	Pressure (bar)	Quality (%)	Pressure (bar)	Quality (%)
Dias Jr. and Romero, 2014	69.99	79.9	76.0	68.58
Our model	69.99	79.9	76.1	68.65

Table 3 data demonstrates that the results in the well head matched with a precision higher than 99.99%, since we can see no difference between the values as they are shown. The results for pressure at the well bottom is 0.13% different than the base reference, and the result for quality is 0.10% different than the base reference.

Al Shaibi's team have developed a custom solution of theirs to simulate steam injection (Al Shaibi, 2015). Al Shaibi demonstrates in his paper how the simulation results of their solution are compared to real data provided by electrical instruments and how to use this data to calculate the apparent thermal conductivity of multilayered insulated tubing. The results for their simulations for four different equipment tested each in different operation conditions, namely experiment 3, are shown in Tab. 4.

**Table 4 - Base data for experiment 3**

Case	Input Flow (BPD)	Input Pressure (PSIa)	Input Temperature (F)	Input Quality (%)	Casing	Tubing	Keq (BTU/hr.ft.F)
Vendor 1	201	1249.70	572.4	73	9 5/8"	3 1/2" x 4 1/2"	0.070
Vendor 2	356	1208.95	568.2	48	9 5/8"	3 1/2" x 4 1/2"	0.040
Vendor 3	250	1250.70	572.5	70	9 5/8"	3 1/2" x 5 1/2"	0.059
Vendor 4	242	1254.70	572.9	65	9 5/8"	3 1/2" x 4 1/2"	0.065

Using these results as base data for a new simulation it is possible to compare the results for this experiment. The new simulation uses the equivalent conductivity result as an input for the simulation, which was an unknown value at Al Shaibi's simulation, and takes the casing temperature and heat loss as a simulation result, which were known values at Al Shaibi's simulation.

**Table 5 - Results for simulation of experiment 3**

Case	Average of the measured casing temperature (F)	Measured heat loss (%)	Average of the simulated casing temperature (F)	Simulated heat loss (%)
Vendor 1	190.0	8.0	196.8	8.3
Vendor 2	185.9	7.5	187.2	7.6
Vendor 3	145.6	3.7	152.9	3.8
Vendor 4	180.5	7.0	184.1	7.2

Table 5 demonstrates the measured values given by Al Shaibi's paper in comparison with the simulated values. It is possible to see that the simulated values for the average casing temperature is, in average, 2.7% higher than the measured values, and the simulated values for heat loss is in average 2.8% higher than the measured heat loss.

Table 6 defines a set of parameters that can be used as an example of the thermo-economic analysis direct procedure described in Section 5.

**Table 6 - Equipment candidates**

Equipment	Price (US\$)	Heat loss (%)	Pressure loss (%)
Candidate A	380,000.00	20	6
Candidate B	450,000.00	12	9

These candidates reach similar outputs at bottom hole with input parameters shown in Tab. 7.

**Table 7 - Initial conditions for candidates**

Equipment	Steam flow	Input pressure
Candidate A	3.35 kg/s	69.8 bar
Candidate B	3.00 kg/s	70.0 bar

These input conditions have an equivalent operational cost, and each candidate have an initial cost due the purchase price. These two costs are compared at Tab. 8.

**Table 8 - Cost comparison**

Equipment	Initial cost	Daily operational cost
Candidate A	380000	800
Candidate B	450000	620
Difference	70000	-180

In this scenario, using the Candidate B equipment over Candidate A equipment is a choice that means investing the price difference value – USD 70,000.00 – at the beginning of the steam injection operation in order to reduce the daily cost by the operational cost difference – USD 180.00. Depending of the interest rate adopted in the application, this trade off may be advantageous or not. If the adopted investment interest rate is usually low, applying the initial cost difference to save in the following years is a good investment. But if the adopted investment interest rate is higher, it is better to opt for the candidate with the least initial cost – Candidate A – and apply the price difference in another application that will return a monthly revenue bigger than the operational cost difference. Other factors such as operational risks and equipment duration must as well integrate the analysis in order to better determine the best candidates.

## 7. CONCLUSION

By the contents of this paper it is possible to conclude that the steam injection method can be modeled as the fluid flow of steam through a unidimensional line that exchanges heat in two dimensions with the surrounding of the line. It is possible to model the heat loss and pressure drop along the line and to numerically solve this model by the thermodynamic equations shown and by applying the finite volume method.

It is possible to conclude that the numerical solution can be solved through a solution process that resolves volume by volume, starting in the first volume with enough given conditions and then looping to the next volumes until the conditions of the last volume is found. This process can be cycled to determine lacking initial conditions when needed.

This solution process allows the conclusion that the steam quality, pressure and temperature profiles can be found as a simulation result in such manner that can be validated with well-defined conditions and experiments, such as the ones demonstrated in this paper, where the simulated results followed closely the expected results both in quality and quantity.

Also, it is possible to conclude that this final solution result for steam quality can be used to evaluate the thermo-economic viability of configuration candidates for equipment to integrate a steam injection operation, even though the greater evaluation that would be the impact of the steam quality in the oil recovery is not in the scope of this analysis.

Due to the demonstrated characteristics of this approach, it is possible to conclude that this simulation method is a viable solution for ranking and studying equipment candidates for using in steam injection operations, as well as determining optimal source flow parameters to obtain certain flow conditions at the bottom hole.

In overall, this simulation method is, as it currently stands, sufficient to simulate many important properties of steam injection operations with a good precision and reliability, but surely can be improved in many ways to improve the precision, depth and range of the analysis.

## 8. REFERENCES

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