

Predictive Modeling and Detection of Insulation Failure in a Natural Gas Pipeline Transmission System

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Abstract: In this paper, a model/software that can predict insulation failure in a natural gas pipeline transmission system was developed by applying established principles of heat flow and gas dynamics. By using the model/software, one will not only know when insulation failure occurred but the location in the long distance pipeline where it occurs. This will reduce the problems associated with late detection, with its adverse consequences such as hydrate formation and pipeline blockage, and explosion and fire!

I. Introduction

In natural gas pipeline transmission systems, insulation is performed to reduce heat losses from the pipe. Corrosion, excavation, natural forces, incorrect operation and other forces (such as pipeline vandalization, accidents, etc.) may lead to insulation failure [Offshore Technology Report, OTO 98 162, 1998]. If insulation is working properly, then the only loss will be due to frictional resistances and the gas would be delivered at the expected temperature and pressure conditions. However if insulation fails, then there will be additional heat losses apart from that due to frictional resistances, thus the gas will be delivered at a lower temperature, and excessive heat losses, may cause operational problems such as hydrate formation and blockage of pipelines and explosion which may be accompanied by fire!, thus the need to detect failure quickly to avoid these adverse consequences [Taylor, J. R. 1994]: [<http://ops.dot.gov/stats/stats.htm>, 2009]. Current failure detection methods include right of way inspection and computational pipeline modeling involving elaborate dynamic simulators and extensive field data collection and analyses, which because of the subsea/swampy and difficult terrain of the usual pipeline right of way and the huge costs, makes them difficult to detect early failures. Thus in this paper, a predictive model/software that can detect early insulation failures in natural gas pipeline transmission systems was developed and is presented.

II. Modeling

The predictive model/software was based on heat conduction and Fourier's equation of one dimensional steady heat flow in a hollow cylinder [D. Rajshput, 2009], [Welty, J., C. E. et al, 2008], [A. Herrán-González, et al, 2009], which is given by:

$$q_n = -KA \frac{dT}{dr} \quad (1.1)$$

The heat flux q_n (W/m^2) is the heat transfer rate in the n direction per unit area perpendicular to the direction of the heat flow (that is the radial direction)

K ($\text{W}/\text{m} \cdot \text{K}$) is the thermal conductivity of the pipeline in the direction n .

A ($2\pi RL$) is the total surface area, where R is the internal radius of the pipeline and L is the length of the pipeline in meters.

$\frac{dT}{dr}$ (K/m) is the temperature gradient in the direction n

Thus consider an un-insulated gas pipeline of length, L as shown in fig. 11



Fig.1-1. An uninsulated natural gas pipeline

Heat loss from the pipe comprise of three (3) kinds [Perry, R. H., 1997].)[M. Abbaspour, 2008],[K. Gersten, 2001] namely:

1. Heat loss by convection from the inside pipe fluid
2. Heat loss by conduction across the pipe thickness: r_2-r_1
3. Heat loss by convection to the outside pipe fluid

Thus the overall heat loss, Q is given in terms of the temperature gradient between the inside fluid, T_i and the outside fluid, T_o and the thermal resistances of the 3 kinds above as:

$$Q = \Delta T / \sum R_i \quad i=1,2,3 \tag{1.2}$$

Where

$$\Delta T = T_i - T_o$$

$\sum R_i$, the thermal resistances of the 3 kinds as shown in fig.1.2.



Fig.1.2 : thermal resistances of uninsulated pipeline wall segments

Therefore

$$Q = \frac{T_i - T_o}{\frac{1}{(2\pi \cdot r_i \cdot h_i \cdot L)} + \frac{\ln(r_2/r_1)}{(2\pi \cdot K_p \cdot L)} + \frac{1}{(2\pi \cdot r_o \cdot h_o \cdot L)}} \tag{1.3}$$

In the case where the heat coefficients, h_i , h_o , are very large (the usual case in natural gas pipelines), the first and last terms in the denominator of eq.1.3 approximate zero, thus the equation reduces to:

$$Q = \frac{T_i - T_o}{\frac{\ln(r_2/r_1)}{(2\pi \cdot K_p \cdot L)}} \tag{1.4}$$

Rearranging:

$$Q = \frac{2\pi K_p L \cdot (T_i - T_o)}{\ln\{(r_2/r_1)\}} \tag{1.5}$$

This heat loss causes temperature drop in the flowing fluid, thus the overall heat loss is [Ouyang, L., and K. Aziz, 1996]:

$$Q = MCp(T_{in} - T_{out}) \tag{1.6}$$

But

$$T_i = (T_{in} + T_{out})/2 \tag{1.7}$$

Combining equations and rearranging:

$$T_{out} = \frac{\{\alpha 1 - L/2\} T_{in} + \{L\} T_o}{\{\alpha 1 + L/2\}} \tag{1.8}$$

Where

$$\alpha 1 = \frac{MCp \cdot \ln(r_2/r_1)}{2\pi Kp} \tag{1.9}$$

, which gives the outlet temp for the case of no insulator (naked pipe). If the pipe is now insulated as shown in fig 1.3:

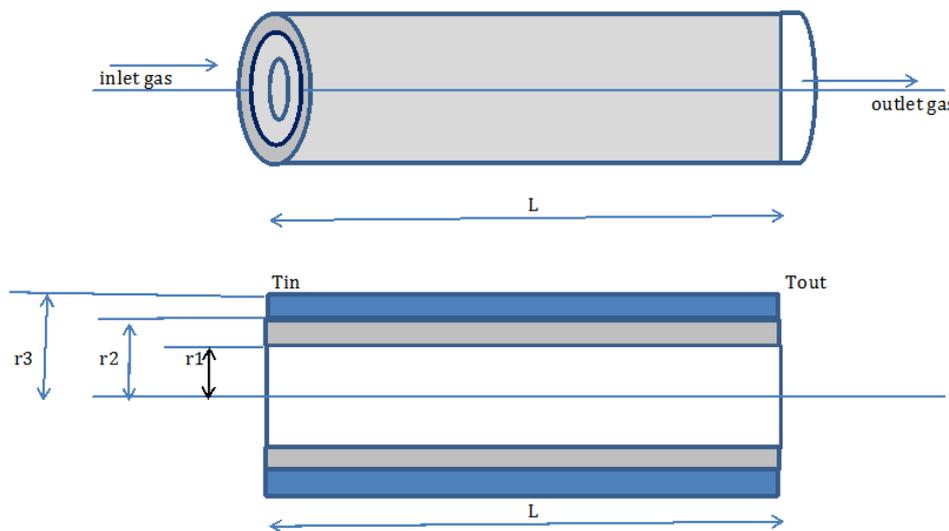


Fig.1.3: an insulated natural gas pipeline

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Heat loss from the pipe comprise of 4 kinds namely:

1. heat loss by convection from the inside pipe fluid
2. heat loss by conduction across the pipe thickness: $r_2 - r_1$
3. heat loss by conduction across the insulator thickness: $r_3 - r_2$
4. heat loss by convection to the outside pipe fluid

Thus the overall heat loss, Q is given in terms of the temperature gradient between the inside fluid, T_i and the outside fluid, T_o and the thermal resistances of the 4 kinds above as:

$$Q = \Delta T / \sum R_i, \quad i=1-4 \tag{1.10}$$

Where

$$\Delta T = T_i - T_o$$

$\sum R_i$, the thermal resistances of the 4 kinds as shown in the fig1.4.



Fig.1.4 : thermal resistances of insulated pipeline wall segments

Therefore

$$Q = \frac{T_i - T_o}{\frac{1}{(2\pi \cdot r_i \cdot h_i \cdot L)} + \frac{\ln(r_2/r_1)}{(2\pi \cdot K_p \cdot L)} + \frac{\ln(r_3/r_2)}{(2\pi \cdot K_{ins} \cdot L)} + \frac{1}{(2\pi \cdot r_3 \cdot h_o \cdot L)}} \quad (1.11)$$

In this case where the heat coefficients, h_i , h_o , are very large, the equation reduces to:

$$Q = \frac{T_i - T_o}{\frac{\ln(r_2/r_1)}{(2\pi \cdot K_p \cdot L)} + \frac{\ln(r_3/r_2)}{(2\pi \cdot K_{ins} \cdot L)}} \quad (1.12)$$

Rearranging:

$$Q = \frac{2\pi K_p K_{ins} L (T_i - T_o)}{\ln\{(r_2/r_1)^{K_i} \cdot (r_3/r_2)^{K_p}\}} \quad (1.13)$$

This heat loss causes temperature drop in the flowing fluid, thus the overall heat loss is:

$$Q = M \cdot Cp (T_{in} - T_{out}) \quad (1.14)$$

But

$$T_i = (T_{in} + T_{out})/2 \quad (1.15)$$

Combining equations 1.13, 1.14, 1.15 and rearranging:

$$T_{out} = \frac{\{\alpha 2 - L/2\} T_{in}}{\{\alpha 2 + L/2\}} + \frac{\{L\} T_o}{\{\alpha 2 + L/2\}} \quad (1.16)$$

Where

$$\alpha 2 = \frac{M Cp \cdot \ln\{(r_2/r_1)^{K_i} \cdot (r_3/r_2)^{K_p}\}}{2\pi K_p K_i} \quad (1.17)$$

, which gives the outlet temp for the case of no insulation failure.

If insulation failure, of thickness t , now occurs at length X from the beginning of the pipe, as shown in fig 1.5.

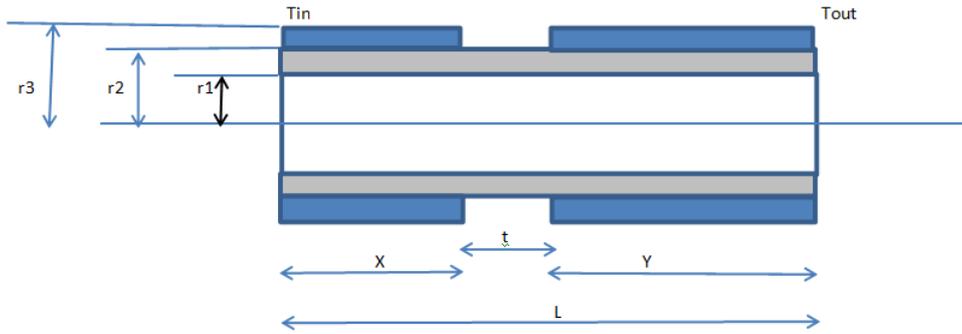


Fig.1.5. an natural gas pipeline for the case of insulation failure

Thus while the heat losses (and the exit temperatures) from the no insulation failure segments; X and Y are determined from eqs 1.13 and 1.16. And, for the case of insulation failure segment, X, the heat loss is determined from eqs 1.5 and 1.8. Thus, using the equations, the exit temperatures, T_1 , T_2 , T_{out} , in each segment can be determined as follows:

$$T_1 = \left(\frac{\alpha_2 - X/2}{\alpha_2 + X/2} \right) T_{in} + \left(\frac{X}{\alpha_2 + X/2} \right) T_o \quad (1.18)$$

$$T_2 = \left(\frac{\alpha_1 - t/2}{\alpha_1 + t/2} \right) T_1 + \left(\frac{t}{\alpha_1 + t/2} \right) T_o \quad (1.19)$$

$$T_{out} = \left(\frac{\alpha_2 - Y/2}{\alpha_2 + Y/2} \right) T_2 + \left(\frac{Y}{\alpha_2 + Y/2} \right) T_o \quad (1.20)$$

Combining to eliminate the intermediate temperatures, we have:

$$T_{out} = \left[\frac{(\alpha_2 - X/2) (\alpha_1 - t/2) (\alpha_2 - Y/2)}{(\alpha_2 + X/2) (\alpha_1 + t/2) (\alpha_2 + Y/2)} \right] T_{in} + \left[\frac{X (\alpha_1 - t/2) (\alpha_2 - Y/2)}{(\alpha_2 + X/2) (\alpha_1 + t/2) (\alpha_2 + Y/2)} + \frac{t (\alpha_2 - Y/2)}{(\alpha_1 + t/2) (\alpha_2 + Y/2)} + \frac{Y}{(\alpha_2 + Y/2)} \right] T_o \quad (1.21)$$

Note that

$$Y = L - X - t \quad (1.22)$$

Equation 1.21 gives the outlet temperature as a function of the thickness, t of insulation failure and the distance, x from the pipe inlet where it occurs.

III. Simulation

Table 1.1 below shows typical data/operating conditions of a gas pipeline:

Table 1.1 Typical data/operating conditions of a gas pipeline:

Pipe	
Nominal external diameter mm	622.2
Wall thickness, mm	22.2
Pipe thermal conductivity W/mK(carbon steel)	45.35
Insulation	
Concrete thickness mm	50
Concrete thermal conductivity W/mK(high density concrete)	2.67
Temperature profile	
Fluid	
(°C)	45.94
OD of pipe (°C)	45.58096

OD of coating 1 (°C)	37.77258
OD of coating 2 (°C)	18.81682
Ambient (°C)	15
Operating conditions	
Gas flow rate MMSCFD	749.8658
Inlet temperature °C	60
Inlet pressure bar	147.5
Ambient temperature °C	15
Gas properties	
Gas gravity kg/m ³	0.182
Gas specific heat capacity J/kgK	2170

The modeling in the previous section showed outlet temperatures for the three possible conditions as follows:

Case 1: temp for the case of no insulator (naked pipe)

Case 2: outlet temp for the case of no insulation failure

Case 3: outlet temperature for the case of insulation failure at length, X from pipeline inlet

Using the equations above and the data in table 1.1, the outlet temperatures in each case are generated, for varying failure length, X and constant thickness, t

A Spreadsheet template (MS Excel Visual Basic edited code) was developed and used.

IV. Results and Analyses

The results are shown graphically in fig.1.6.

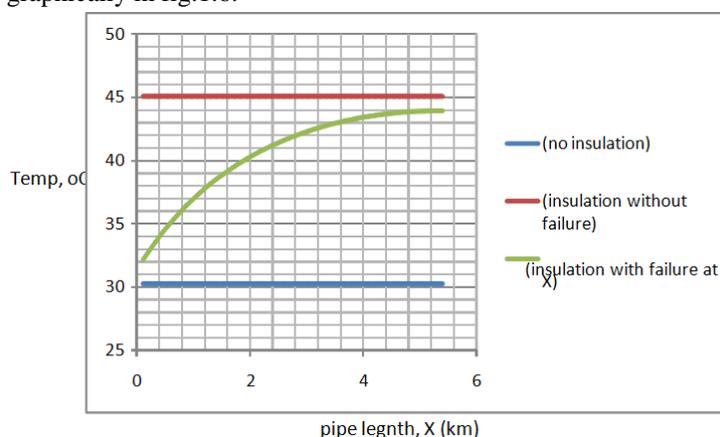


Fig.1.6. Exit temp.for the case of insulation failure thickness, t of 0.01 L) vs pipe distance, X

Thus for gas pipeline inlet temperature of 45.57°C, the exit temperature for a span of 5.4 km is 45°C for the case of normal operation of no insulation failure, while that of non insulated pipe is constant at 30°C showing that more heat is lost for non insulated pipe. Of the effect becomes, more pronounced in long distant pipelines for the insulation failure case, the temperature is lowest if the failure occurs at the inlet of the pipe and rises exponentially towards the non failure case at the end of the pipe.

V. Conclusion

In this project, a simple but efficient model that can predict insulation failure in a natural gas pipeline was developed by applying established principles of heat flow and gas dynamics. All that is required are the inlet and exit temperature/flowrate of the pipeline. By using the model, one will not only know when insulation failure occurred but the location in the long distance pipeline where it occurs. This will reduce the problems associated with late detection, with its adverse consequences such as hydrate formation and pipeline blockage, and possibly explosion/fire!

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