RESEARCH Vol. 16, 2019

ISSN 2319–7757 EISSN 2319–7765

Indian Journal of Engineering

Predictive model to detect insulation failure and pipe leakage in natural gas transmission pipeline using simulation software

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Article History
Received: 10 February 2019
Accepted: 27 March 2019
Published: April 2019

Citation
Ukpaka CP, Puyate YT, Nwokide LC. Predictive model to detect insulation failure and pipe leakage in natural gas transmission pipeline using simulation software. *Indian Journal of Engineering*, 2019, 16, 135-166

ABSTRACT

Predictive model was developed to detect insulation failure and pipeline leakage in natural gas transmission line using simulation software known as EXTENDSIM9 SUIT. The computational fluid dynamics parameters for the flow of compressible gas in a pipeline includes density, temperature viscosity, pressure etc which changes along the transmission line due to frictional resistance, and may lead to fogging/ hydrate formation or sudden degradation of pipe materials like erosion which gradually leads to corrosion or rust, pitting etc. This anomaly is one of the major contributions to pipeline failure thus this developed model can be used to monitor and predict insulation failure along the natural gas transmission pipeline since there is a lot of the discrepancy between the

Computational Fluid Dynamics (CFD) parameters and their arrival components. Sensors where used to read and monitor fluctuation of fluid flow dynamics properties which was set to alert the indicator otherwise known as the decision block to analyze the results or records obtained from the constraint variable blocks which reads 12.5Km due east as the failed distance. From the sensitivity analysis result we observed that the model can predict insulation failure along the transmission line with 92.2% accuracy as it is sensitive to both small and large parameter difference and from our findings, the temperature increased exponentially along the failed area. When these anomalies are detected by this model; it triggers a maintenance shutdown on the affected area and record "time between failure and time between repair" by using (FDIMs) Fault Detection/Isolation and Maintenance Shutdown). Thus this model can be utilized to approve the readings of an Advanced Fiber-optic Distributed Temperature Sensors (DTS) or Distributed Acoustic detecting (DAS) in a gas transmission line.

Key words: Predictive model, detect, insulation failure, pipe leakage, natural gas transmission pipeline, simulation software

1. INTRODUCTION

Natural gas is a naturally occurring hydrocarbon gas mixture which is combustible as well as the main sources of energy for domestic and industrial uses. The composition made of mixtures of hydrocarbon, such as ethane, propane, butane, and pentanes as well as the presence of water vapor, hydrogen sulfide (H_2S), carbon dioxide, helium, nitrogen, and other compounds. The natural gas is classified as fossil fuel which is utilized as a vital source of energy for heating, cooking, and electricity generation. It is additionally utilized as a fuel for vehicles just as a chemical compound feedstock in the manufacturing of plastics and other monetarily imperative natural synthetic substances. Research conducted revealed that fossil fuel based natural gas is a non-sustainable power/energy source, because its end product after compete combustion are carbondioxide, water, heat etc [1].

Investigation conducted on transmission pipes revealed the significance of pipe diameter, the few characteristics and behavior as well as the effect on the functional parameters of transmission principle guiding the control process [1]. Further considered the significance of pipe dimension effect as well as material selection in pipeline construction in control system for detection of insulated failure which leads to leakages in pipeline; other factors that contribute to the pipeline failure include hydrate formation formed as a result of change in temperature in the internal flow of fluid in the pipeline [2]. The change will influence the pressure of flowing liquefied natural gas in the pipeline as well as the viscosity, density and other functional parameters will change as well.

Research work conducted on the significance of coating a pipeline reveals the prevention of corrosion and resting as a result of contract of external surface of the metal with the presence of moisture content, microbial activities and other environmental factors. Initially, major coating materials used on pipes are coal tar enamel but in the recent time the major materials used are fusion bon epoxy and other polymer materials [3].

The word insulation" can be described as a process that enhances protection or isolation of an existing system. The concepts of protection or isolation in pipeline are found necessary because of continuous failures currently observed by the oil companies. The insulation process of their pipelines enhance safety quality in terms of detection of regions, which is likely to fail as a result of malfunction in the process fluid, which in turn influence the integrity of the pipeline material [5-6]

The new technology adopted by the various coating company using polymer material product has rendered the initial approach of using tape coating system and coal-tax enamel system, because of the deficiency found in terms of insulation as well as the constrain when large diameter pipe is to be insulated. Research conducted on using tape coating and coal-tax enamel is more effective in small diameter pipe as well as fail when the environment is wet compared with coating using polymer materials [7]. The polymer materials possess high resistance to wet environment as well as reduce the failure rate of the pipe and enhance performance of the system. Research conducted by various Scientifics group revealed that the application of coal-tar poses high level of health challenges to the environment [8].

In natural gas transmission pipelines, insulation is performed in other to reduce heat loss from the pipe. However, some of the major reasons of insulation failure includes: Natural decay or deterioration because of maturing, which is quickened by excessive heat, moisture and dirt, chemical deterioration, mechanical damage and sunlight are main causes of insulation failure. Other causes may include excavation, incorrect installation and operation, pipeline vandalization, accidents etc.

This is widely used in chemical engineering to detect failure in chemical plant, petrochemical as well as in information technology, disaster recovery, meteorology, capacity and city planning, etc. (Schiff, 2002) however, it is found useful in detecting insulation failure in terms of pipeline leakage, which enhance reduction pressure, temperature as well as hydrate formation in pipeline. It consists of various factors which influence the future behaviors or results of the future failed system using extendsim9 software. This is achieved mostly by or relies on mathematical model simulation model built on the software as well as the system to identify the discrepancy between (functioning system) and faulty part of the system [8-9].

Failure of an insulator in natural gas transmission pipeline causes pressure drop along the pipeline. This is due to the fact that heat has been transferred either by conduction or convection from the liquid to the wall or from the encompassing to the liquid in this way causing operational instability which affects the flow and gradually leads to hydrate formation, which causes blockage along the pipeline. However, the following characteristics will be observed such as change in pressure, temperature and density which causes erosion, gradually leads to the exposure of corrosive (H_2S) chemical substances to the pipe material and when these anomalies are not detected on time it exposes the pipe metal to corrosion, pitting, pipe failure and eventually explosion. The aim of this research work is to use existing simulation software named Extendsim9 to detect insulation failure and pipe leakage in natural gas transmission pipeline.

2. MATERIALS AND METHODS

Extendsim9 Simulation Model

Just like other simulation technology, Extendsim9 is a multi-purpose simulation software with combination of mathematics, computer, physics and engineering, and graphical user interface using a combined logical representation to select few resources put together to build entire systems to a particular function [10]. To solve real – time pipeline flow on fluid mechanics and dynamics problems, it is ideal to have good knowledge of the fluid flow behavior as well as its properties to arrive at a better solution.

Table 1 LNG pipeline layers (NNPC)

Pipeline layers					
Layer	**Material**	**Wall Thickness** mm	**Heat capacity j/kg.k**	**Thermal conductivity w/m.k**	**Density kg/m³**
Transmission pipeline	Steel	12.7	500	50	7850
Corrosion allowance	Steel	1.5	500	50	7850
Anti-corrosion coating	Polyethylene	3.2	1020	0.02	1293
Insulation	Polyurethane	50	2300	0.03	950
	Air	10	1500	0.025	32
Outer shell	Steel	12.7	500	50	7850
Transmission Pipeline external Diameter 648.6mm					
Concrete thickness		50			
Concrete thermal conductivity W/mK		2.79			
Ambient temperature °C		15			

Mathematical Model Development

In developing a model, there are certain parameters to identify the type of flow before development;

- Compressibility: Compressible flow otherwise known as variable density flow, this is as result of dual nature of gases as the density, temperature changes, depending on the operational condition. For air, $10^{-5}\, m^2/N$ at 1atm. This is given by

$$K_C = \frac{1}{\rho}\left(\frac{d\rho}{dp}\right) \quad in \quad m^2 / N \tag{1}$$

- Prandtl number: This is used to determine the relative viscosity of the flow which satisfy it viscous or inviscid flow. For typical gas flow it values ranges from 0.7-1

$$Pr = C_p\mu/K \Rightarrow \frac{2165 \times 1.9534 \times 10^{-5}}{0.030} = 1.4 \tag{2}$$

Where, K = thermal conductivity, μ = dynamic viscosity, Cp = specific heat capacity at constant pressure.
Knudsen number is the ratio of fluid mean free path to the macroscopic length scale of a physical system.

$$K_n = \lambda / L \tag{3}$$

$$\text{Where, } \lambda = \frac{16\mu}{5\rho\sqrt{2\pi RT}} \tag{4}$$

$$L = \frac{\rho \partial x}{\partial \rho} \Rightarrow \rho \Big/ \frac{\partial \rho}{\partial x} \tag{5}$$

Where, λ = mean free path, μ = dynamic viscosity, R = universal gas constant, T = temperature, L = length (characteristic length)
Hence, If $K_n <$ 0.01 continuum will not hold.

Beyond this crucial range or Knudsen, number; If $0.01 < K_n < 0.1$ = slip flow, $0.1 < K_n < 10$ = transition flow, Kn > 10 = free molecule flow. From our calculations, K_n = 0.7. Therefore it is a continuum flow. From these; we can deduce that the flow is continuum, compressible and a viscous flow.

Modeling Considerations

This research considers continuum, compressible viscous flow along the natural gas transmission pipeline occurring in NNPC. This work tends to develop flow models that can be used to detect insulation failure and pipe leakage on the gas transmission line. The predictive models will be derived from the conservative continuity, momentum and energy equations, fluid/aerodynamics and heat transfer equations.

Mathematical Model Assumptions

The following model assumptions were considered during the research work as stated below: unsteady state because of the faulty part of the system; we intend to achieve steady state, gas flows are transonic or turbulent, heat loss by convection from the inside pipe flow, conservation of mass, momentum and energy, heat loss by convection to the outside pipe, heat conduction across the insulator, heat conduction across pipeline thickness, thermal resistance between the fluid and the insulated wall, the wall itself and the resistance between the wall and the insulator.

Basic Pipeline Equations Used For Modeling Gas Transmission Pipeline Flow

Fluid mechanics and aerodynamics offers a systematic structure that underlies physical disciplines which embrace empirical/ semi-empirical laws derived from flow measurement which is used to solve practical problems. The solution to a fluid dynamics problem typically involves the calculation of various properties of fluid such as flow velocity, pressure, density and temperature as a function of space and time which describe the behavior of fluid being transported at all points within the pipeline flow system. The basic equations are the continuity equations, momentum equations and energy equation [11].

Continuity Equation Development

The Continuum Equation: This implements the law of conservation of mass in a pipeline system which means that the actual mass flow in and out of the pipeline section is equal to the rate of change of mass within that section.

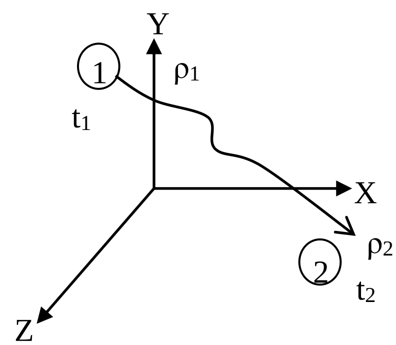


Figure 1 3- D Cartesian coordinate flow

Consider a flow in 3-dimensional Cartesian coordinate, the mass balance becomes

$$\begin{pmatrix} \textit{Rate of change of} \\ \textit{mass within the} \\ \textit{pipeline} \end{pmatrix} \begin{pmatrix} \textit{Rate of inflow} \\ \textit{of mass into} \\ \textit{the pipeline} \end{pmatrix} = \begin{pmatrix} \textit{Rate of outflow} \\ \textit{of mass from} \\ \textit{the pipeline} \end{pmatrix} \quad (6)$$

Analysis of equation (6) mathematically and considering total density flow from point (1) as initial to point (2) as the final flow.

$$\rho_1 \left(x_1, y_1, z_1, t_1\right) \quad (7a)$$

$$\rho_2 \left(x_{2,} \, y_2, z_2, t_2\right) \quad (7b)$$

Using Taylor's series to obtain the initial and first derivatives of the flow, and also truncating higher derivatives gives:

$$f\left(x_, y, z, t\right) = f\left(x_{0,} \, y_0, z_0, t_0\right) + \frac{(x - x_0)}{1!} f^1\left(x_{0,} \, y_0, z_0, t_0\right) + \frac{(y - y_0)}{1!} \quad f^1\left(x_{0,} \, y_0, z_0, t_0\right) + \frac{(z - z_0)}{1!} f^1\left(x_{0,} \, y_0, z_0, t_0\right) + \left(t - t_0\right) \quad (8)$$

Applying equation (8) into the equation (6) yields:

$$\rho_2 = \rho_1 + \frac{\partial \rho}{\partial x_1}\left(x_2 - x_1\right) + \frac{\partial \rho}{\partial y_1}\left(y_2 - y_1\right) + \frac{\partial \rho}{\partial z_1}\left(z_2 - z_1\right) + \frac{\partial \rho}{\partial t_1}\left(t_2 - t_1\right) \quad (9a)$$

Dividing equation (9a) by $t_2 - t_1$ throughout; we have

$$\frac{\rho_2 - \rho_1}{t_2 - t_1} = \left(\frac{\partial \rho}{\partial x}\right)\frac{\left(x_2 - x_1\right)}{t_2 - t_1} + \left(\frac{\partial \rho}{\partial y}\right)\frac{\left(y_2 - y_1\right)}{t_2 - t_1} + \left(\frac{\partial \rho}{\partial z}\right)\frac{\left(z_2 - z_1\right)}{t_2 - t_1} + \frac{\partial \rho}{\partial t} \quad (9b)$$

Taking the limits $t_2 - t_1$ on the RHS of equation (9b), we have

$$\text{Lim } t_2 - t_1 \left(\frac{\rho_2 - \rho_1}{t_2 - t_1}\right) = \Delta\rho / \Delta t$$

Where; $\left(\frac{x_2 - x_1}{t_2 - t_1}\right) = V_x \left(\frac{y_2 - y_1}{t_2 - t_1}\right) = V_y \left(\frac{z_2 - z_1}{t_2 - t_1}\right) = V_z$ are the velocities of the different Cartesian coordinates in x, y and z-directions respectively.

Substituting these ($\Delta\rho / \Delta t$; V_x; V_y, V_z) into equation (9b) we have,

$$\frac{\Delta\rho}{\Delta t} = V_x \frac{\partial\rho}{\partial x} + Vy\frac{\partial\rho}{\partial y} + V_z \frac{\partial\rho}{\partial z} + \frac{\partial\rho}{\partial t} \quad (10)$$

where $\Delta\rho / \Delta t$ = the time rate of change of density of a fluid as it moves through a space. Equation (3.10) can be written as

$$\frac{\Delta}{\Delta t} = \frac{\partial}{\partial t} + V_x \partial / \partial x + V_y \partial / \partial y + V_z \partial / \partial z \quad (11)$$

Considering the different directions of flow and substituting the flow velocity vector into equation (11) we have;

$$\frac{\Delta}{\Delta t} \equiv \frac{\partial}{\partial t} + \vec{i}\, V_x \partial / \partial x + \vec{j} V_y \partial / \partial x + \vec{k} V_z \partial / \partial z$$

$$\frac{\Delta\rho}{\Delta t} \equiv \frac{\partial\rho}{\partial t} + \nabla\left(\rho\vec{V}\right) \quad (12)$$

Where, $\vec{V} = \rho(i.V_2 + jV_y + kV_z) \equiv \vec{V} = \vec{i}\,.V_2 + \vec{j}\,V_y + \vec{k}\,V_z$

Is the flow velocity vector and

$\nabla \equiv \vec{i}\,\partial / \partial x + \vec{j}\,\partial / \partial y + \vec{k}\,\partial / \partial z$ Is the divergence vector

Where, $\partial / \partial t$ = local derivative, which is physically the time rate of change at a fixed point and $\left(\vec{V}.\nabla\right)$ = convective derivative or divergence velocity which is physically the rate of change due to the movement of the fluid element from one location to another in the flow field where the flow properties are spatially different. Or it is the time rate of change of the volume of a moving fluid element per unit volume. Within the control volume, the total change of density in a close loop is equal to zero. This means that:

$$\frac{\Delta\rho}{\Delta t} = 0$$

Hence, equation (12) becomes:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{V}\right) = 0 \qquad (13)$$

Thus, equation (13) is conservation of mass for continuity equation flow.

Momentum Equation Development

The momentum equation: This implements Newton's 2nd law when applied on a moving fluid element; which says that the net force on the fluid element equals its mass times the acceleration of the fluid element. Since it's a vector relation which can be split into x, y, and z-direction. The two major type of forces described by Newton's second law: Volume forces - This has to do with gravitational force which acts directly on the volumetric mass of the fluid element. Surface forces - This has to do with pressure distribution acting on the surface which is imposed by the outside fluid surrounding of the fluid element, and inner frictional forces or viscosity force acting on the surface through pushing or tugging.

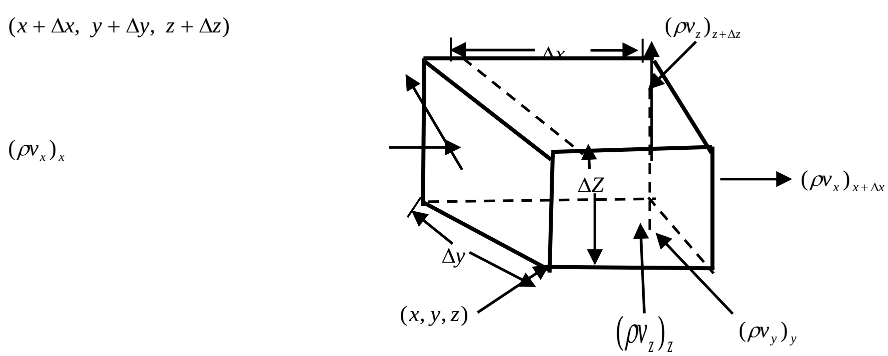


Figure 2 Momentum Balance for Elemental Volume on a 3-dimensional Cartesian Coordinates

For Momentum Balance (Momentum Transfer) of Fluid Flow in Pipeline;

$$\left\{\begin{array}{c}\text{Rate of momentum}\\ \text{Accumulated within}\\ \text{Pipeline}\end{array}\right\} = \left\{\begin{array}{c}\text{Rate of momentum}\\ \text{Entering pipeline}\end{array}\right\} - \left\{\begin{array}{c}\text{Rate of outflow of}\\ \text{momentum from}\\ \text{Pipeline}\end{array}\right\}$$

$$+ \left\{\begin{array}{c}\text{Summation of forces}\\ \text{acting on the}\\ \text{pipeline system}\end{array}\right\} \qquad (14)$$

Rate of accumulation $= \Delta x\, \Delta y\, \Delta z \dfrac{\partial}{\partial t}(\rho v_x)$ (15)

Rate of inflow of momentum = $\Delta x\ \Delta z\left((\rho v_x^2)_x\right) + \Delta x\ \Delta z\left(\rho(v_y\ v_y)_y\right)$ (16)

$+\ \Delta x\ \Delta y\left((\rho v_z)_z\right)$

Rate of outflow of momentum =

$$\Delta x\ \Delta z\left((\rho v_x . v_x)_{x+\Delta x}\right)\Delta x\ \Delta z\left(\rho v_y\ v_y\right)_{y+\Delta y} + \Delta x\ \Delta z\left(\rho vz\ vz\right)_{z+\Delta z} + \Delta x\ \Delta y\left((\rho v_z)_z\right) \quad (17)$$

Sum of forces acting on the system (the stress, pressure forces and the gravitational forces acting on the fluid)

$$= \left(\tau_{x.x}\right)_x\ \Delta y\ \Delta x + \left(p_x - p_{x+\Delta x}\right)\Delta y\ \Delta z + \rho g x \sin\theta\ \Delta x\ \Delta y\ \Delta z \quad (18)$$

i.e $\sum f_i = \left(\delta_x + p_x + F_y\right)$ → Summation of the forces acting on the system

Combining these equations into equation (14) gives;

$$\Delta y\ \Delta x \frac{\partial(\rho v_x)}{\partial t} = -\Delta y\ \Delta z\ \partial(\rho v_x . v_x) - \Delta x\ \Delta y\ \partial(\rho v_z . v_z)$$

$$\Delta x\ \Delta z\ \partial(\rho v_y . v_y) - \Delta z\ \Delta y\left(\tau_{zx}\right) + \rho g\ \mathrm{Sin}\ \theta - \Delta y\ \Delta z\left(p_{x+\Delta x} - p_x\right) \quad (19)$$

Dividing all through by $\Delta x\ \Delta y\ \Delta z$ gives;

$$\frac{\partial(\rho v_x)}{\partial t} = -\left(\frac{\partial(\rho v_x v_x)}{\partial_x} + \frac{\partial(\rho v_z v_z)}{\partial_y} + \frac{\partial(\rho v_z v_z)}{\partial_z}\right) - \left(\frac{\partial \tau_{xx}}{\partial_x} + \frac{\partial \tau_{yx}}{\partial_y} + \frac{\partial \tau_{zx}}{\partial_z}\right) - \frac{\partial p}{\partial_x} + \rho g\ \mathrm{Sin}\ \theta \quad (20)$$

Recall that $\rho g_x = \rho f_x$; $\lambda = \dfrac{-2}{3}\mu$ (21)

Applying **Navier-Stokes** rule on equation (20) Conservation of momentum equation and incorporating all the forces acting on the system yields:

$$\frac{\partial(\rho v_x)}{\partial t} + \frac{\partial(\rho v^2)}{\partial x} + \frac{\partial(\rho v_x v_y)}{\partial y} + \frac{\partial(\rho v_x v_z)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\lambda \nabla . \vec{V} + 2\mu \frac{\partial v_x}{\partial x}\right) + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[\frac{\partial v_x}{\partial Z} + \frac{\partial v_z}{\partial x}\right] + \rho f_x \quad (22a)$$

$$\frac{\partial(\rho v_y)}{\partial t}+\frac{\partial(\rho v_x v_y)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho v_x v_z)}{\partial z} = -\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v_y}{\partial x}+\frac{\partial v_x}{\partial y}\right)\right]$$
$$+\partial/\partial y\left(\lambda\nabla.\vec{V}+2\mu\frac{\partial V_y}{\partial y}\right)+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v_z}{\partial y}+\frac{\partial v_y}{\partial z}\right)\right]\rho f_y \qquad (22b)$$

$$\frac{\partial(\rho V_z)}{\partial t}+\frac{\partial(\rho V_x V_z)}{\partial x}+\frac{\partial(\rho V_y V_z)}{\partial y}+\frac{\partial(\rho V_z^2)}{\partial z} = -\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial V_z}{\partial z}+\frac{\partial V_z}{\partial x}\right)\right]$$
$$+\partial/\partial y\left[\mu\left(\frac{\partial V_z}{\partial y}+\frac{\partial V_y}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left(\lambda\nabla.\vec{V}+2\mu\frac{\partial V_z}{\partial z}\right)\rho f_z \qquad (22c)$$

Where, λ = bulk viscosity coefficient, μ = dynamic viscosity

Energy Equation Development

The energy equation: This implements the principle of first law of thermodynamics which states that total energy of a system and its surroundings remains constants when applied on the moving fluid element, the rate of change of energy inside the fluid element is equal to the net flux of heat into the element with additional rate of work done on the element due to body and surface forces.

$$\left\{\begin{matrix}\text{The Rate}\\ \text{of change}\\ \text{of energy inside}\\ \text{the}\\ \text{fluid element}\end{matrix}\right\} = \left\{\begin{matrix}\text{Net flux}\\ \text{of heat}\\ \text{into the}\\ \text{fluid element}\end{matrix}\right\} + \left\{\begin{matrix}\text{Rate of work done on}\\ \text{the fluid element due}\\ \text{to body and surface}\\ \text{forces}\end{matrix}\right\} \qquad (23)$$

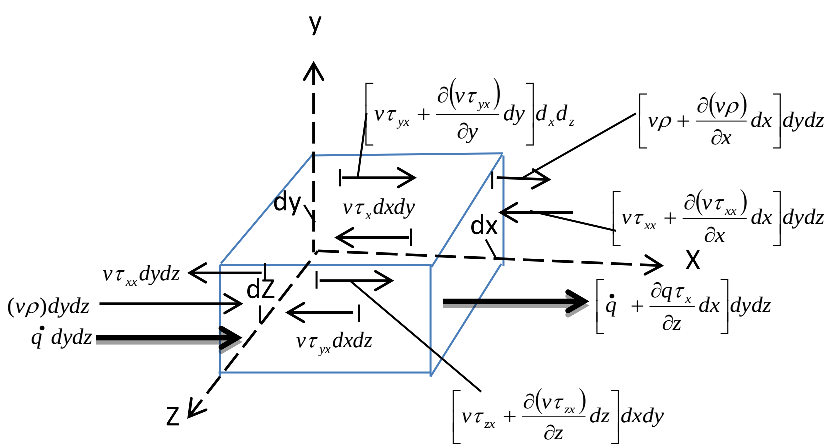


Figure 3 Energy Balance for Elemental Volume of Fluid Flow on a 3-D Cartesian Coordinates (x-direction shown only to avoid clustering)

From Figure 3, considering the work done only in the x-direction, we have:

$$\left[\begin{matrix}\text{The rate of work done}\\ \text{by the body force acting}\\ \text{on the fluid element moving}\\ \text{at a velocity}\end{matrix}\right] \rightarrow (\vec{v}) = \rho\vec{f}.\vec{v}\ dxdydz \qquad (24a)$$

Considering work done by the body forces are due to pressure in the x-direction, yields

$$\frac{\partial(v_x p)}{\partial_x}\, dxdydz \tag{24b}$$

Also, the rate of work done by shear stress in the x-direction, we have:

$$\frac{\partial(v_x \tau_{yx})}{dy} dxdydz \tag{24c}$$

Then the rate of work done on the moving fluid element due to both surface forces and volume forces in the x-direction is:

$$\left[-\frac{\partial(v_x P)}{dx} + \frac{\partial(v_x \tau_{xx})}{dx} + \frac{\partial(v_x \tau_{yx})}{dy} + \frac{\partial(v_x \tau_{zx})}{dz}\right] dxdydz \tag{24d}$$

Therefore the total rate of work done on the moving fluid element is the combination of surface forces and body forces in the x, y, and z-direction.

From equation (23), we have

$$\begin{Bmatrix} The\ net\ rate\ of\ work\ done \\ on\ the\ fluid\ element \\ due\ to\ body\ and\ surface\ forces \end{Bmatrix} = \left[-\left(\frac{\partial(v_x P)}{dx} + \frac{\partial(v_y P)}{dy} + \frac{\partial(v_z P)}{dz}\right) + \frac{\partial(v_x \tau_{xx})}{dx} + \frac{\partial(v_x \tau_{yx})}{dy} + \frac{\partial(v_x \tau_{zx})}{dz} + \frac{\partial(v_y \tau_{xy})}{dx} + \frac{\partial(v_y \tau_{yy})}{dy} + \frac{\partial(v_y \tau_{zy})}{dz} + \frac{\partial(v_z \tau_{xz})}{dx} + \frac{\partial(v_z \tau_{yz})}{dy} + \frac{\partial(v_z \tau_{zz})}{dz}\right] dxdydz + \rho \vec{f}.\vec{v}\, dxdydz \tag{24e}$$

Note that: $\frac{\partial(v_x P)}{dx} + \frac{\partial(v_y P)}{dy} + \frac{\partial(v_z P)}{dz} = \nabla.(P\vec{v})$ (24f)

Also from equation (23), the two reasons for heat flux into the fluid element is as a result of;

i. Volumetric heat e.g. absorption or emission of heat
ii. Heat transfer across the surface due to temperature gradients, (conduction)

Note that: $\begin{Bmatrix} \text{The mass of the} \\ \text{moving fluid element} \end{Bmatrix} = \rho dxdydz$

Also, $\begin{Bmatrix} For\ volumetric\ heat \\ on\ the\ fluid\ particles \end{Bmatrix} = \rho \dot{q}\, dxdydz$ (24g)

$$\begin{Bmatrix} \text{Heat transferred across} \\ \text{the surface (conduction)} \end{Bmatrix} = -\left(\frac{\partial \dot{q}_x}{dx} + \frac{\partial \dot{q}_y}{dy} + \frac{\partial \dot{q}_z}{dz}\right) dxdydz \tag{24h}$$

Recall that heat transfer by conduction is proportional to the local temperature gradient

Combining equation (24g and 24h), we have

$$\left[\rho \dot{q} - \left(\frac{\partial \dot{q}_x}{dx} + \frac{\partial \dot{q}_y}{dy} + \frac{\partial \dot{q}_z}{dz} + \right) dxdydz\right] \tag{25}$$

Where, $\dot{q}_x = -k\frac{\partial T}{\partial x}$; $\dot{q}_y = -k\frac{\partial T}{\partial y}$; $\dot{q}_z = -k\frac{\partial T}{\partial z}$

$\dot{q}$ = the rate of volumetric heat addition per unit mass, k = thermal conductivity

Therefore,

$$\begin{Bmatrix} The\ net\ flux\ of \\ heat\ into \\ the\ fluid\ element \end{Bmatrix} = \left[\rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\right] dxdydz \quad (26)$$

Also from equation (23), we have

$$\begin{Bmatrix} the\ time\ rate\ of\ change \\ of\ energy\ inside \\ the\ fluid\ element \end{Bmatrix} \rightarrow \left[\begin{pmatrix} the\ total\ energy\ of \\ a\ moving\ fluid \\ per\ unit\ mass \end{pmatrix} = \begin{pmatrix} its\ internal \\ energy\ per \\ unit\ mass \end{pmatrix} + \begin{pmatrix} its\ internal \\ energy\ per \\ unit\ mass \end{pmatrix}\right] \equiv Total\ energy = \left(e + \frac{v^2}{2}\right) \quad (27a)$$

When this is applied to a fluid passing through a fixed control volume and the mass of the moving fluid $= \rho dxdydz$, we have;

$$\begin{Bmatrix} the\ total\ energy\ of \\ the\ moving\ fluid \\ per\ unit\ mass \end{Bmatrix} = \rho\frac{\Delta}{\Delta t}\left(e + \frac{v^2}{2}\right) dxdydz \quad (27b)$$

Combining equations (27b), (26) and (24e), we have

Energy equation becomes

$$\rho\frac{\Delta}{\Delta t}\left(e + \frac{v^2}{2}\right) = \left[\rho\dot{q}\frac{\partial}{\partial x}\left(k\frac{\partial T}{dx}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{dy}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{dz}\right)\right] - \frac{\partial(v_x P)}{\partial x} - \frac{\partial(v_y P)}{\partial y} - \frac{\partial(v_z P)}{\partial z} + \frac{\partial(v_x \tau_{xx})}{\partial x} + \frac{\partial(v_y \tau_{yx})}{\partial y} + \frac{\partial(v_z \tau_{zx})}{\partial z} + \frac{\partial(v_y \tau_{xy})}{\partial x} + \frac{\partial(v_y \tau_{yy})}{\partial y} + \frac{\partial(v_y \tau_{zx})}{\partial z} + \frac{\partial(v_z \tau_{xz})}{\partial x} + \frac{\partial(v_z \tau_{xz})}{\partial x} + \frac{\partial(z\tau_{yz})}{\partial y} + \frac{\partial(z\tau_{zz})}{\partial z} + \rho\vec{f}.\vec{v} \quad (28)$$

Note that equation (28) is in non-conservation form

Transferring equation (28) to conservation form in terms of total energy, we have:

From the LHS of equation (28),

$$\rho\frac{\Delta\left(e+\frac{v^2}{2}\right)}{\Delta t} = \rho\frac{\partial\left(e+\frac{v^2}{2}\right)}{\partial t} + \rho\vec{v}.\nabla\left(e + \frac{v^2}{2}\right) \quad (29a)$$

But,

$$\rho\frac{\partial\left(e+\frac{v^2}{2}\right)}{\partial t} = \frac{\partial\left[\rho\left(e+\frac{v^2}{2}\right)\right]}{\partial t} - \left(e + \frac{v^2}{2}\right)\frac{\partial\rho}{\partial t} \quad (29b)$$

From flow vector velocity regarding divergence

Conservation of energy

$$\partial/\partial t\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \nabla.\left[\rho\left(e + \frac{V^2}{2}\vec{V}\right)\right] = \rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial V_x p}{\partial x} -$$

$$\frac{\partial(V_y p)}{\partial y}-\frac{\partial(V_z p)}{\partial z}+\frac{\partial V_x \tau_{xx}}{\partial x}+\frac{\partial V_y \tau_{yx}}{dy}+\frac{\partial V_x \tau_{zx}}{\partial z}+\frac{\partial V_x \tau_{xy}}{\partial x}+\frac{\partial V_x \tau_{yy}}{dy}+\frac{\partial V_x \tau_{zy}}{\partial z}+\frac{\partial V_z \tau_{xz}}{\partial x}$$

$$+\frac{\partial V_z \tau_{yz}}{dy}+\frac{\partial V_z \tau_{zz}}{\partial z}+\rho \vec{f}\vec{V} \qquad (30a)$$

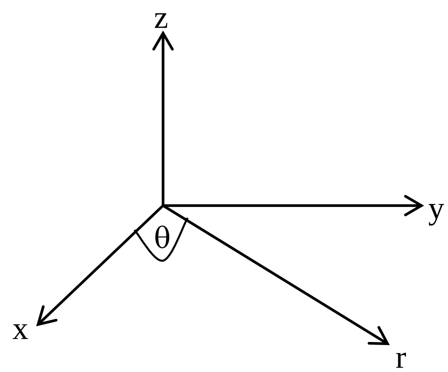
Equation (30a) is the conservation of energy and can be re-written as

$$\frac{\partial E_t}{\partial t}+\nabla . E_t\vec{v}=\frac{\partial Q}{\partial t}-\nabla . q+\rho\vec{f}.\vec{v}+\nabla . \tau_{ij}\vec{v} \qquad (30b)$$

Where e = internal energy, τ = shear stress, Where Q = total flux of heat into the element

$\vec{f}_x, \vec{f}$ = body force per unit mass acting on the fluid element in x-z direction

Application of Continuity, Momentum and Energy Equations on Pipeline For 3-dimensional cylindrical coordinate flow



Where,

X = r cos θ → r

Y = r sin θ → θ (31a)

Z = z → z

θ = Arctan (y/x)

Velocities for 3-dimensional cylindrical coordinates,

V_x = V_r

V_y = V_θ (31b)

V_z = V_z

For enthalpies in 3D cylindrical coordinates considering the r-direction as reference coordinates;

$h_1 = 1,\ h_2 = r,\ h_3 = 1$ (31c)

Converting the Conservation of continuity equation (13) into 3-dimensional cylindrical coordinates;

Continuity equation becomes ⇒

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho_r V_\theta\right) + \partial / \partial z \left(\rho V_z\right) = 0 \quad (32)$$

Also, Transforming Conservation of momentum equation (24g), (24h) and (24i) into 3-dimensional cylindrical coordinates;

Momentum equation becomes ⇒r - component

$$\rho\left(\frac{\partial V_r}{\partial t} + V_r\frac{\partial V_r}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_r}{\partial \theta} - \frac{V_\theta^2}{r} + V_z\frac{\partial V_r}{\partial z}\right) = -\frac{\partial p}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rr}\right) + \frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z} + \rho g r \quad (33a)$$

θ -component

$$\rho\left(\frac{\partial V_\theta}{\partial t} + V_r\frac{\partial V_\theta}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_\theta}{\partial \theta} + \frac{V_r V_\theta}{r} + V_z\frac{\partial V_\theta}{\partial z}\right) = -\frac{\partial p}{\partial \theta}\frac{1}{r}\frac{\partial \tau_{\theta\theta}}{\partial \theta} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\tau_{r\theta}\right) + \frac{\partial \tau_{\theta z}}{\partial z} + \rho g \theta \quad (33b)$$

z-component

$$\rho\left(\frac{\partial V_z}{\partial t} + V_r\frac{\partial V_z}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_z}{\partial \theta} + V_z\frac{\partial V_z}{\partial z}\right) = -\frac{\partial p}{\partial z}\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rz}\right) + \frac{1}{r}\frac{\partial \tau_{\theta z}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z} + \rho g z \quad (33c)$$

Transforming Conservation of Energy equation (30a) into 3-dimensional cylindrical coordinates, we have;

$$\frac{\partial E_t}{\partial t} - \frac{\partial Q}{\partial t} - \rho\left(f_r V_r + f_\theta V_\theta + f_z V_z\right) + \frac{\partial}{\partial r}\left(E_t V_r + pV_r - V_r\tau_{rr} - V_\theta\tau_{r\theta} - V_z\tau_{zz} + q_r\right) + \partial / \partial \theta$$
$$\left(E_t V_\theta + pV_\theta - V_r\tau_{r\theta} - V_\theta\tau_{\theta\theta} - V_z\tau_{\theta z} + q_\theta\right) + \partial / \partial z \left(E_t V_z + pv_z - V_r\tau_{rz} - V_\theta\tau_{\theta z} - V_z\tau_{zz} + q_z\right) = 0 \quad (34)$$

Where;

$$E_t = \rho\left(\frac{e + V^2}{2}\right) + \rho\vec{g} \quad (35a)$$

But,

$$\rho\vec{f} = \rho\vec{g} \quad (35b)$$

Where stress tensor τ_{ij}

$$\left.\begin{aligned}
\tau_{rr} &= 2\mu\frac{\partial V_r}{\partial r}-\left(\frac{2}{3}\mu-\mu_v\right)\nabla.\vec{V}\\
\tau_{\theta\theta} &= 2\mu\left(\frac{1}{r}\frac{\partial V_\theta}{\partial\theta}+\frac{V_r}{r}\right)-\left(\frac{2}{3}\mu-\mu_v\right)\nabla.\vec{V}\\
\tau_{zz} &= 2\mu\frac{\partial V_z}{\partial z}-\left(\frac{2}{3}\mu-\mu_v\right)\nabla.\vec{V}\\
\tau_{r\theta} &= \mu\left(r\,\partial/\partial r\left(\frac{V_\theta}{r}\right)+\frac{1}{r}\frac{\partial V_r}{\partial\theta}\right)\\
\tau_{rz} &= \mu\left(\left(\frac{\partial V_r}{\partial z}\right)+\frac{\partial V_z}{\partial r}\right)\\
\tau_{\theta z} &= \mu\left(\left(\frac{\partial V_\theta}{\partial z}\right)+\frac{1}{r}\frac{\partial V_z}{\partial\theta}\right)
\end{aligned}\right\} \quad (35c)$$

Energy dissipation function Φ

$$\Phi = 2\mu\left(\left(\frac{\partial V_r}{\partial r}\right)^2+\left(\frac{1}{r}\frac{\partial V_\theta}{\partial\theta}+\frac{V_r}{r}\right)^2+\left(\frac{\partial V_z}{\partial z}\right)^2+\mu\left(r\frac{\partial}{\partial r}\left(\frac{\partial V_\theta}{r}\right)+\frac{1}{r}\frac{\partial V_r}{\partial\theta}\right)^2+\mu\left(\frac{\partial V_r}{\partial z}+\frac{\partial V_z}{\partial r}\right)^2\right.$$
$$\left.+\mu\left(\frac{\partial V_\theta}{\partial z}+\frac{1}{r}\frac{\partial V_z}{\partial\theta}\right)^2-\left(\frac{2}{3}\mu-\mu_v\right)\left(\nabla.\vec{V}\right)^2\right)$$

(35d)

Enthalpy ⇒ $h_t = e + \dfrac{p}{\rho}+k$ (35e)

Combining equation (35a) – (35e) and substituting in equation (34) we have;

$$\frac{\partial}{\partial t}\left(\rho\left(e+k\right)\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho h_t V_r\right)+\frac{1}{r}\frac{\partial}{\partial\theta}\left(\rho h_t V_\theta\right)+\frac{\partial}{\partial z}\left(\rho h_t V_z\right)+\left(\frac{1}{r}\frac{\partial}{\partial r}\left(rQ_r\right)+\frac{1}{r}\frac{\partial Q_\theta}{\partial\theta}+\frac{\partial Q_z}{\partial z}\right)-$$
$$\left(\tau_{rr}\frac{\partial V_r}{\partial r}+\tau_{\theta\theta}\left(\frac{1}{r}\frac{\partial V_\theta}{\partial\theta}+\frac{V_r}{r}\right)+\tau_{zz}\frac{\partial V_z}{\partial z}\right)-\left(\tau_{r\theta}\left(r\frac{\partial}{\partial r}\left(\frac{V_\theta}{r}\right)+\frac{1}{r}\frac{\partial V_r}{\partial\theta}\right)+\tau_{rz}\left(\frac{\partial V_z}{\partial r}+\frac{\partial V_r}{\partial z}\right)\right.$$

$$+\tau_{\theta z}\left(\frac{1}{r}\frac{\partial V_z}{\partial \theta}+\frac{\partial V_\theta}{\partial z}\right)\Bigg]-V_r\left(\frac{1}{r}\partial\!\big/\!\partial r\left(r\tau_{rr}\right)+\frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta}-\frac{\tau_{\theta\theta}}{r}+\frac{\partial \tau_{rz}}{\partial z}\right)-V_\theta\left(\frac{1}{r}\frac{\partial \tau_{\theta\theta}}{\partial \theta}\right)$$

$$+\frac{1}{r^2}\partial\!\big/\!\partial r\left(r^2\tau_{r\theta}\right)+\frac{\partial \tau_{\theta z}}{\partial z}-V_z\left(\frac{1}{r}\partial\!\big/\!\partial \theta\left(r\tau_{rz}+\frac{1}{r}\right)+\frac{1}{r}\frac{\partial \tau_{\theta z}}{\partial r}+\frac{\partial \tau_{zz}}{\partial z}=Energysource\right. \quad (36)$$

Based on the above differential equations the internal flow parameters are obtained using software.

Recall that, $$\frac{\partial \rho(e+k)}{\partial t}+\nabla.\left(\rho(e+k)\vec{V}+p\vec{V}-\tau_{ij}.\vec{V}+\vec{q}\right) = 0 \quad (37a)$$

Using continuum equation, if only kinetic and internal energy are considered

$$\rho\frac{\Delta\left(E_t/\rho\right)}{\Delta t} = \frac{\partial E_t}{\partial t}+\nabla..E_t\vec{V} \quad (37b)$$

$$\rho\frac{\Delta\left(E_t/\rho\right)}{\Delta t} = \rho\frac{\Delta e}{\Delta t}+\rho\frac{\Delta\left(V^2/2\right)}{\Delta t} \quad (37c)$$

But from velocity vector $\vec{V}$ we deduce

$$\rho\frac{\Delta\vec{V}}{\Delta t}.\vec{V} = \rho\vec{f}.\vec{V}-\nabla p.\vec{V}+\left(\nabla.\tau_{ij}\right)\vec{V} \quad (37d)$$

Combining equation (37b), (37c) & (37d) and substituting in equation (30b) above we have;

$$\rho\frac{\Delta e}{\Delta t}+p\left(\nabla.\vec{V}\right) = \frac{\partial Q}{\partial t}-\nabla.q+\nabla.\left(\tau_{ij}.\vec{V}\right)-\left(\nabla.\tau_{ij}\right)\vec{V} \quad (37e)$$

But $$\Phi = \nabla.\left(\tau_{ij}.\vec{V}\right)-\left(\nabla.\tau_{ij}\right)$$ and (37f)

$$\vec{V} = \tau_j\frac{\partial ui}{\partial xj} \quad (37g)$$

Substituting equation (3.37f) into (3.37e) we have

$$\rho\frac{\Delta e}{\Delta t}+p\left(\nabla.\vec{V}\right) = \frac{\partial Q}{\partial t}-\nabla.q+\Phi \quad (38a)$$

Finally, equation (3.38a) can be written

$$\rho \frac{\Delta h}{\Delta t} = \frac{\Delta p}{\Delta t} + \frac{\partial Q}{\partial t} - \nabla . q + \Phi \qquad (38b)$$

Equation (38b) is the conservation of energy

$\vec{f}$ = force per unit mass, $\vec{g}$ = body force (acceleration due to gravity vector, e = internal energy per unit mass, E_t = total energy per unit mass in the control volume, $\frac{\partial Et}{\partial t}$ = the rate of increase of total energy in the control volume, $\nabla . E_t V$ = the rate of total energy lost by convection per unit volume, $\frac{\partial Q}{\partial t}$ = the rate of heat produced per unit volume by external force, $\rho \vec{f} . V$ = work done on the control volume per unit volume by the body force, $\nabla . q$ = the rate of heat lost by conduction per unit volume through the control surface, $\nabla . \tau_{ij} . \vec{V}$ = work done on the control volume per unit volume by the surface force

Heat transfer in gas transmission pipelines

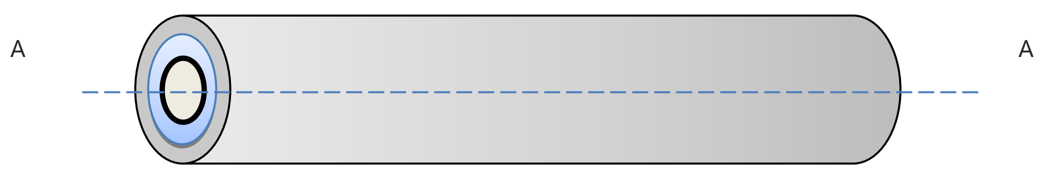


Figure 4 A simple insulated pipe (well- insulated pipe)

The process involves the described functional parameters as stated below: the heat loss by convection from the inside pipe fluid, heat loss by conduction across the pipe thickness $r_2 - r_1$, heat loss by conduction across the insulation thickness r_3-r_2, and heat loss by convection to the outside pipe fluid

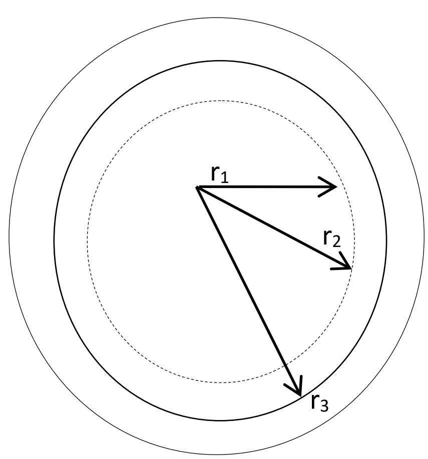


Figure 5 Systematic size view of the cylindrical insulated pipeline

From Fourier's law, heat transfer by conduction is given by;

$$q_x = \frac{-k\partial t}{\partial x} \tag{39a}$$

For conservation of energy on 3-dimensional cylindrical coordinate equation (39a) becomes

$$q_x = \frac{-k\partial t}{\partial x}, \quad q_y = -\frac{k\partial y}{\partial y}, \quad q_z = -k\frac{\partial y}{\partial z} \tag{39b}$$

Where, k = thermal conductivity

Recall that;

$$q_x - \left(q_x + \frac{\partial q_x}{\partial x}\partial x\right)\partial y \partial z = -\frac{\partial q_x}{\partial x}\partial_x \partial_y \partial_z \rightarrow \rho q - \left(\frac{\partial q_x}{\partial x} + \frac{\partial \mathring{q}_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)\partial_x \partial_y \partial_z \tag{39c}$$

Recall also that

$$q = \frac{\Delta T}{\Sigma r_i} \tag{39d}$$

Where, ΔT = $T_1 - T_E$ (inlet temp-arrival temp), $\sum r_i$ = thermal resistances

Thermal resistance (R) is defined as the ratio of change in temperature to the associated rate of heat transfer: the heat transfer between the fluid and the wall, the insulated wall itself is one resistance and the heat transfer between the insulated wall and the outside fluid

But the overall heat transfer coefficient can be calculated as

$$RA \tag{40a}$$

$$recall\ that\ R = {}^1/_U \tag{40b}$$

$$\frac{1}{UA} = \frac{1}{h_{ci}A_i + \sum(s_n/k_nA_n) + 1/h_{co}A_o} \tag{40c}$$

Where, R = heat transfer resistance m^2K/W, U = the Overall heat transfer coefficient W/m^2 K, K = the thermal conductivity of material in layer (W/(m.K)) S_n = thickness of the pipe mm, $h_{cl,o}$= inside or outside wall individual fluid convection heat transfer coefficient W/m^2 K

But total heat loss from the pipe

$$Q = MC\rho dT \rightarrow Q = MCp(T_i - T_E) \tag{41a}$$

Where,

$$T_E = T_i - \frac{Q}{MCp} \quad (41b)$$

$$\Delta T = T_i - T_E \quad (41c)$$

$$T_1 = \left(\frac{T_i - T_E}{2}\right) \quad (41d)$$

Where, T_i = inlet temperature, T_E = exit/arrival fluid temperature

Combining equation (40c) & (41c) and substituting in equation (39d) above; we have,

$$q = \frac{T_i - T_E}{\frac{1}{2\pi h_i r_i L} + L_c \frac{\left(\frac{r_j}{r_k}\right)}{2\pi k_i L} + L_c \frac{\left(\frac{r_k}{r_j}\right)}{2\pi k_j L} + L_c \frac{\left(\frac{r_l}{r_k}\right)}{2\pi k_j L} + \frac{1}{2\pi h_j r_l L}} \quad (42a)$$

Equation (42a) is written in C++ programming language Code used to simulate the total heat loss of the normal insulated system (without failure)

$$q = \frac{T_i - T_E}{\frac{1}{2\pi h_i r_i L} + L_c \frac{\left(\frac{r_j}{ri}\right)}{2\pi k_i L} + L_c \frac{\left(\frac{r_k}{ri}\right)}{2\pi k_j L} + \frac{1}{2\pi h_i r_k L}} \quad (42b)$$

Thus Equation (42b) is written in C++ programming language Code used to simulate the total heat loss of the failed insulated system.

Predictive Model Development

For Pressure

Consider the faulty part of the flow system to be one dimensional in the r-direction, neglecting other flow directions

This model is from Equation (33a), we have

$$\rho\left(\frac{\partial V_r}{\partial t} + V_r \frac{\partial V_r}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_r}{\partial \theta} - \frac{V_\theta^2}{r} + V_z \frac{\partial V_r}{\partial z}\right) = -\frac{\partial p}{\partial r} \frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rr}) + \frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z} + \rho g r$$

Therefore, equation (33a) is reduced to;

$$\rho \frac{\partial V_r}{\partial t} + V_r \frac{\partial V_r}{\partial r} = -\frac{\partial p}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rr}) + \rho g r \quad (43)$$

Assuming at steady state, the gravitational (body and volume forces) and surface forces are neglected, equation (43) becomes;

$$\rho\left(V_r \frac{\partial V_r}{\partial r}\right) = -\frac{\partial p}{\partial r} \quad (44a)$$

Recall that from aerodynamics equations for conservation of fluid momentum is given by;

$$\rho \frac{udu}{dx} + \frac{dP}{dx} = 0 \quad \equiv \quad \rho \frac{udu}{dx} = -\frac{dP}{dx} \quad (44b)$$

Hence equations (44a) and (44b) are similar

From equation (44a) $\rho\left(v_r \frac{\partial v_r}{dr}\right) = -\frac{\partial P}{\partial r} \equiv \rho \frac{\partial v_r^2}{dr} + \frac{\partial P}{\partial r} = 0$ (44c)

$$\frac{\partial}{\partial r}(P + \rho v_r^2) = 0 \quad (44d)$$

Upon integration;

$$\int \frac{\partial}{\partial r}(P + \rho v_r^2) = 0 \quad (44e)$$

$$P + \rho v_r^2 = k \quad (44f)$$

At r = 0, P = P_o, $V_r = 0$, $P_o + 0 = k$, $k = P_o$

Upon applying the boundary conditions, Equation (44f) becomes

$$P + \rho v_r^2 = P_o \quad (44g)$$

$$P - P_o = -\rho v_r^2 \quad (44h)$$

Therefore equation (41h) becomes;

$$P = P_o - \rho v_r^2 \quad (45)$$

Where, P_o = initial pressure, ρv_r^2 = compressible dynamic pressure or impact pressure, P = final pressure

For Temperature

This model is from Equation (30b), we have $\frac{\partial E_t}{\partial t} + \nabla . E_t \vec{v} = \frac{\partial Q}{\partial t} - \nabla . q + \rho \vec{f} . \vec{v} + \nabla . \tau_{ij} \vec{v}$

Assuming at steady state, the gravitational (body and volume forces) and surface forces are neglected, equation (30b) becomes;

$$0 = -\nabla . q \quad (46a)$$

Recall that from equation (11e), one dimensional flow equation (r-direction) becomes;

$$\nabla = \vec{\imath} \frac{\partial}{\partial r} \quad (46b)$$

Substituting equation (46b) into equation (46a) becomes;

$$0 = -\nabla . q_r \quad \equiv \quad \nabla . q_r = -\vec{\imath} \frac{\partial}{\partial r} . q_r \quad (47a)$$

Where, ∇ = divergence, q_r = heat flux (rate of heat transferred through the surface per unit time J/s), $\vec{\imath}$ = flow vector

But $q_r = kA \frac{dT}{dr}$

Equation (44a) becomes;

$$\nabla . q_r = -\vec{\imath}\frac{\partial}{\partial r}k\frac{\partial T}{\partial r} \quad \equiv \quad \frac{\partial}{\partial r}q_r = -\frac{\partial}{\partial r}k\frac{\partial T}{\partial r} \tag{47b}$$

$$\frac{\partial}{\partial r}q_r + \frac{\partial}{\partial r}k\frac{\partial T}{\partial r} = 0 \tag{47c}$$

Upon integration $\int \frac{\partial}{\partial r}\left[q_r + k\frac{\partial T}{\partial r}\right] = 0$ (47d)

$$q_r(r - r_0) + k(T - T_0) = c \tag{47e}$$

Where, C = constant

At these boundary conditions: $r = 0,\ T = T_0,\ q_r = q_r,\ T_0 + 0 = C,\ C = T_0$

Substituting these boundary conditions in equation (47e) we have;

$$q_r(r - r_0) = k(T - T_0) \tag{47f}$$

$$\frac{q_r}{k}(r - r_0) = k(T - T_0) \tag{47g}$$

Therefore, $T = T_0 - \frac{q_r}{k}(r - r_0)$ (48)

For Sensitivity (Temperature and viscosity)
This model is from Equation (38b), we have

$$\rho\frac{\Delta h}{\Delta t} = \frac{\Delta p}{\Delta t} + \frac{\partial Q}{\partial t} - \nabla . q + \Phi$$

Where, ρ = density, h = enthalpy, P = pressure, Q = volumetric heat capacity in J/m^{3}K (heat per unit volume), $\frac{\partial Q}{\partial t}$ = heat produced per unit volume by external force J/m^{3}K, q_r = heat flux (rate of heat transferred through the surface per unit time J/s), Φ = Dissipation function in seconds.

Assuming the pressure change is neglected, equation (3.38b) becomes;

$$\rho\frac{\Delta h}{\Delta t} = \frac{\partial Q}{\partial t} - \nabla . q + \Phi \tag{49a}$$

But, $\nabla . q = \frac{\partial q}{\partial r} + \frac{\partial q}{\partial \theta} + \frac{\partial q}{\partial z}$ (49b)

Therefore,

$$\rho\frac{\Delta h}{\Delta t} = \frac{\partial Q}{\partial t} - \left(\frac{\partial q}{\partial r} + \frac{\partial q}{\partial \theta} + \frac{\partial q}{\partial z}\right) + \Phi \tag{49c}$$

Assuming there is no heat produced by external force in the system, it means that;

$$\frac{\partial Q}{\partial t} = 0 \tag{49d}$$

Therefore, $\rho\frac{\Delta h}{\Delta t} = -\left(\frac{\partial q}{\partial r} + \frac{\partial q}{\partial \theta} + \frac{\partial q}{\partial z}\right) + \Phi$ (49e)

Considering one dimensional coordinate in r-direction, Equation (49e) becomes;

$$\rho \frac{\partial h}{\partial t} = -\frac{\partial q}{\partial r} + \Phi \quad (50a)$$

But, $q = kA\frac{dT}{dr}$ (50b)

Substituting equation (50b) into the R.H.S of equation (50a) we have;

$$\rho \frac{\partial h}{\partial t} = -\frac{\partial kA^{dT}/_{dr}}{\partial r} + \Phi \equiv \rho \frac{\partial h}{\partial t} = -\frac{kA\partial T}{\partial r \partial r} + \Phi \quad (50c)$$

At these boundary conditions; $t = 0,\ T_0 = T,\ r_0 = 0,\ r = L$

But $\partial h = C_p dT$ (50d)

Substituting equation (50d) into equation (50c) we have;

$$\rho \frac{C_p dT}{\partial t} = -\frac{kA\partial T}{\partial r \partial r} + \Phi \quad (51)$$

Note that for one dimensional coordinates;

$$\Phi = 2\mu\left[\left(\frac{\partial v_r^2}{\partial r}\right) - \left(\frac{2}{3}\mu\right)(\nabla.\vec{v})^2\right]$$

Input Parameters

Table 2 LNG operational data (NNPC)

Operational data					
Transmission pipelines	**Flow rate m^3/day**	**Inlet pressure KPa**	**Inlet temperature °C**	**Outlet pressure KPa**	**Outlet temperature °C**
1	2370	1098	50.3	652	42.80
2	3120	1108	51.1	656	44.45
3	3533	1113	50.5	615	45.12
4	4125	1181	50.4	625	45.85
5	4330	1280	51.6	402	41.51

Gas properties	
Natural Gas gravity kg/m^3	0.489
Gas specific heat capacity J/kgK	2165
Boiling point	-161.5^{0}C at 1atm
Freezing point	-182.6^{0}C
Flammability limits	4-5 by volume in air

Gas density	1.0926517kg/m^3
Ignition temperature	538^{0}C 1atm
Carbon content by weight	73
Hydrogen content	24
Oxygen content	0.4
Hydrogen/carbon atomic ratio	3.0-4.0
Relative density	0.72-0.8 at 15^{0}C
Octane no	120-130
Methane no	69-99
Viscosity μ	1.953x10^{-5}kg/m/s
Universal gas constant	8314.4J/kmol/K
Gravitational constant g	9.81m/S^2
Thermal conductivity k	0.030W/m^2.k

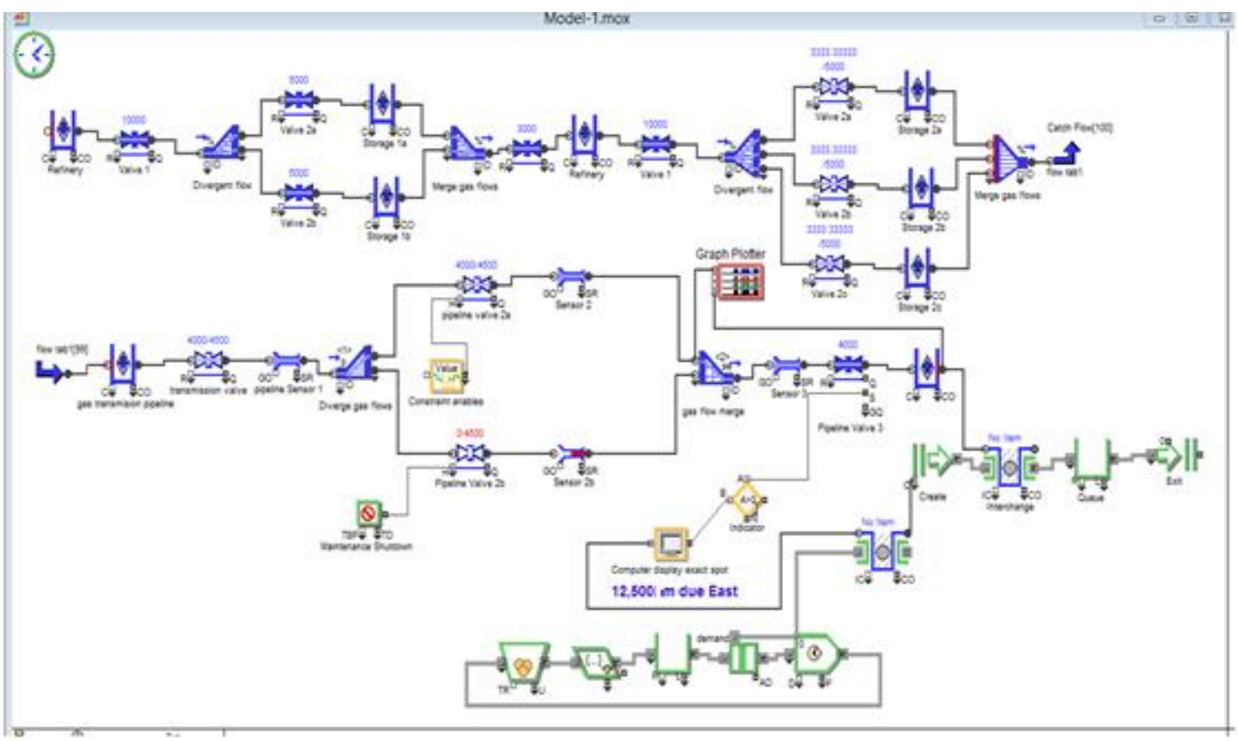
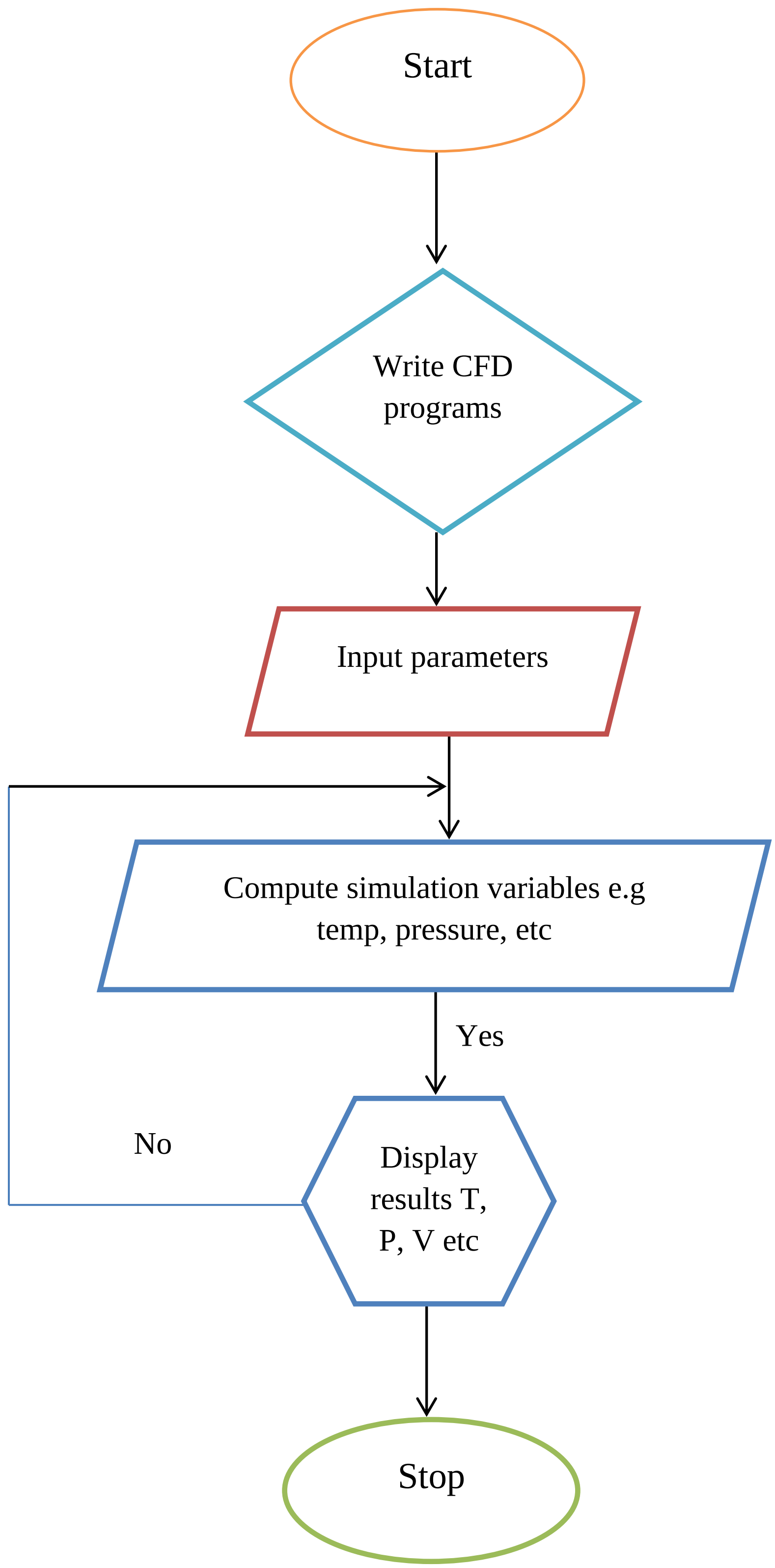


Plate 1 Simulation Model to Detect Insulation Failure in Natural Gas Transmission Pipeline

Plate 1 shows the prediction of insulation failure along gas transmission pipeline using a simulation model called Extendsim9 software.

Chart 1 Computational flow chart



3. RESULTS AND DISCUSSION

Overview

Predictive model to detect insulation failure and pipe leakage in natural gas transmission pipeline has been modeled and predicted. Normally, whenever there is a flow of compressible gas in a pipeline; density, temperature and pressure changes along the line due to gravitational/surface forces which may lead to sudden degradation of pipe materials like erosion which exposes the pipe to corrosion or rust, pitting etc. This is one of the reasons pipes undergo insulation process before installed in natural gas transmission lines in other to minimize hydrate formation, accumulation of corrosive chemical or substance like H_2S on the pipe material such that heat will neither be lost nor gained.

However, when there is sudden failure or failure due to aging of insulation materials on these pipelines, it poses some threats on the operational impacts whereby heat maybe lost or gained depending where the insulation failed either internal, external insulation or both which may cause the gas to flow at a lower temperature which may lead to condensation and freezing of gas along the pipeline, thereby causing hydrates formations, which will in turn cause pipe and equipment obstructions. When these anomalies are not detected on time, the possible adverse effects are explosion. In addition, insulation failure with adequate effect of high temperature also exposes the pipe to both internal and external corrosion, pitting and leakage.

The inability to detect insulation failures along the natural gas transmission pipelines on time has been a great challenge to the oil and gas industries. Although there has been series of transmission pipeline technologies which is used to monitor and detect leaks, as well as pipe blockage and can only detect pipe failures with minimal attention to insulation failure when pipes' materials are still intact. These inspections are carried out periodically as a survey (once in every 5 years), and thus; insulation may fail which may cause operational instability between these periods.

Insulation may fail, while the carbon-steel pipe is absolutely in good shape, this calls an attention for continual maintenance of the insulator in other to protect the pipe from corroding and the best way to optimize instrumentation and process control is to reduce the cost of maintenance strategy. Thus, a single model which can predict insulation failure on a natural gas transmission pipeline at the exact spot along the pipeline where this failure will occur on a real time basis has been modeled. These showcase the accurate distance measures and ensure timely intervention on the affected area, initiates a maintenance shutdown and record "time between failure and time between repairs (TBF/TBR)" thereby preventing pipeline failures and reduction of operation operational instabilities. This model can be used to validate the readings of an Advanced Fiber-Optic Distributed Temperature Sensors (DTS) as well as Distributed Acoustic Sensors (DAS) in a gas transmission line.

The complex study of instrumentation and process control, heat transfer, fluid mechanics and aerodynamics formed the basis at which this research was carried out. The LNG operational data which was subjected to Kalman filter and IQ-Rm PRO APIS software was also used to filter and generate data estimate and sensor reading analysis respectively.

The natural gas pipeline operational data was filtered by kalman filter software and most of these data were used to model the position of the pipe, the flow velocity along the pipeline and exact spot where insulation failure will occur through sensors, Extendsim9 3D camera window, computerized display block which calculates the exact spot where insulation failed and Decision block known as indicator which uses logic as one of its tool on the gas arrival temperature to control its decision.

Comprehensive Summary of Simulation Model development

The following developed models were used as the programing code for the software:

$$\frac{\partial}{\partial t}(\rho(e+k))+\frac{1}{r}\frac{\partial}{\partial r}(r\rho h_t V_r)+\frac{1}{r}\frac{\partial}{\partial \theta}(\rho h_t V_\theta)+\frac{\partial}{\partial z}(\rho h_t V_z)+\left(\frac{1}{r}\frac{\partial}{\partial r}(rQ_r)+\frac{1}{r}\frac{\partial Q_\theta}{\partial \theta}+\frac{\partial Q_z}{\partial z}\right)$$

$$\left(\tau_{rr}\frac{\partial V_r}{\partial r}+\tau_{\theta\theta}\left(\frac{1}{r}\frac{\partial V_\theta}{\partial \theta}+\frac{V_r}{r}\right)+\tau_{zz}\frac{\partial V_z}{\partial z}\right)\Bigg)-\left(\tau_{r\theta}\left(r\frac{\partial}{\partial r}\left(\frac{V_\theta}{r}\right)+\frac{1}{r}\frac{\partial V_r}{\partial \theta}\right)+\tau_{rz}\left(\frac{\partial V_z}{\partial r}+\frac{\partial V_r}{\partial z}\right)\right.$$

$$\left.+\tau_{\theta z}\left(\frac{1}{r}\frac{\partial V_z}{\partial \theta}+\frac{\partial V_\theta}{\partial z}\right)\right]-V_r\left(\frac{1}{r}\partial/\partial r(r\tau_{rr})+\frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta}-\frac{\tau_{\theta\theta}}{r}+\frac{\partial \tau_{rz}}{\partial z}\right)-V_\theta\left(\frac{1}{r}\frac{\partial \tau_{\theta\theta}}{\partial \theta}\right)$$

$$+\frac{1}{r^2}\partial/\partial r\left(r^2\tau_{r\theta}\right)+\frac{\partial\tau_{\theta z}}{\partial z}-V_z\left(\frac{1}{r}\partial/\partial\theta\left(r\tau_{rz}+\frac{1}{r}\right)+\frac{1}{r}\frac{\partial\tau_{\theta z}}{\partial r}+\frac{\partial\tau_{zz}}{\partial z}=Energysource$$

The model in equation (36) was derived from continuity, momentum and energy equations using the stated assumptions; and was written in C++ programing code in the simulation software which formed the basis for the 3-Dimensional internal flow:

$$q=\frac{T_i-T_E}{\frac{1}{2\pi h_i r_i L}+L_c\frac{\left(\frac{r_j}{r_k}\right)}{2\pi k_i L}+L_c\frac{\left(\frac{r_k}{r_j}\right)}{2\pi k_j L}+L_c\frac{\left(\frac{r_l}{r_k}\right)}{2\pi k_j L}+\frac{1}{2\pi h_j r_l L}}$$

$$q=\frac{T_i-T_E}{\frac{1}{2\pi h_i r_i L}+L_c\frac{\left(\frac{r_j}{ri}\right)}{2\pi k_i L}+L_c\frac{\left(\frac{r_k}{ri}\right)}{2\pi k_j L}+\frac{1}{2\pi h_i r_k L}}$$

The model in equations (42a), (42b) was derived from conservation of energy equation and heat transfer models after the stated assumptions were made and was also written in C++ programing language code used to simulate the total heat loss for the Normal insulated/functioning system and that of the failed or faulty part of the system along the pipeline

$$P = P_o - \rho v_r^2$$

$$T = T_0 - \frac{q_r}{k}(r - r_0)$$

These models in equation (45) and (48) were derived from conservation of momentum of the fluid element equations and conservation of energy equation after the stated assumptions were made. These also is written in C++ programming language Code used to simulate and predict the temperature/pressure profile for the Normal insulated/functioning system and that of the faulty or failed part of the system along the pipeline respectively.

$$\rho\frac{C_p dT}{\partial t} = -\frac{kA\partial T}{\partial r\partial r}+\Phi$$

While the model in equation (51) was derived from the combination of conservation of momentum, energy equation and heat transfer after the stated assumptions has been made. The model is written in programing code to achieve model sensitivity on the flow problem.

Due to the complicated nature of the models, Extendsim9 software is considered as the most suitable software to handle these problems numerically to achieve best possible results.

However, the above equations is solved simultaneously with the models describing the device behaviour (compressor, maps, valve equations, set points, choked or free flow, equations for simulated failures, resistance equations, etc.),which are the most accurate.

Methods used to validate this model

The simulation software is made up of discrete rate, discrete event and continuous model blocks which have series of developer's tool to enable any researcher write or develop its model for any type of real life problem ranging from engineering, architecture, medicals, security, aviation, manufacturing, productions etc. This model is a combination of these three.

The tank block which represent source in discrete model is regarded as the refinery where raw natural gas flow through the gathering pipeline has an infinite capacity and was set to infinity since gas flows from the refinery are continuous. This means that natural gas beneath the earth crust has an infinite flow capacity and therefore its exploration is always continuous

The flow of this natural gas is compressed using the compressor block tool and is being controlled by the valve block tool at the rate of 10000m^3/day. The gas flowed through the pipeline where it is diverged by diverge block tool which is set to proportional at the diverge proportionality of 1:1 to diverge the flow at the rate of 5000m^3/day to each segment and merge rate set to priority of outflows to merge the gas flows to different gathering pipelines down to the processing unit. At the processing plant, the valves are set to 3000m^3/day to control the rest of the flows to the transmission pipelines.

These merge and diverge block tools depicts its name in any model by diverging and merging of flows. Since tanks are used as source, it is also used as storage facility in Extendsim9 since it is known as residence block. The use of throw and catch block here is to minimize the number of blocks on this particular flow model. The good thing about this software is that it uses anything one can think of as well as defined within the acceptable range as block including 'text'.

The gas flow on the transmission pipeline has its flow rate at 3120m^3/day as the flow along the transmission pipelines are set to sensing flows and priority of outflows respectively. The sensor is set at every 2km along the transmission pipeline where constraint variables or unstable variables of aerodynamics are read and recorded by the look up table block otherwise known as constraint variable tool, through this recordings, it sends the recorded result to the decision block otherwise known as the indicator to compare and analyze the readings of the temperatures, density etc. Extendsim9 understands the language of Computational fluid dynamics (CFD) and therefore uses true or false strings and attributes to differentiate the range at which heat transfers either by convection or conduction, and their temperature gradients.

After the analysis, the decision block otherwise known as the model indicator is used to send feedback to both sensors and valves to initiate control of gas flow by closing the failed line arm and opening another arm of flow to diverge and merge flow to other pipes while automatically stopping gas flow to the affected area and also sends signal for a maintenance shutdown review. The computerized display function block is used to review the readings, calculate the failure distance from its current location and as well send feedback to the plotter and the indicator to declare the affected section/area 'failed' and therefore trigger shutdown repair while controlling the rest of the flow process to its final destination. With this, it sends feedback to the computerized display block to calculate and display the exact spot along the pipeline where the insulation failed. Every other block like interchange block, Resource item block, get, activity block, queue block are used for accuracy and accurate calculations to assist the decision block take its decisions. They also contribute to the successful flow of gas in other pipes along the pipeline.

The results were displayed in Tables and Figures and properly discussed.

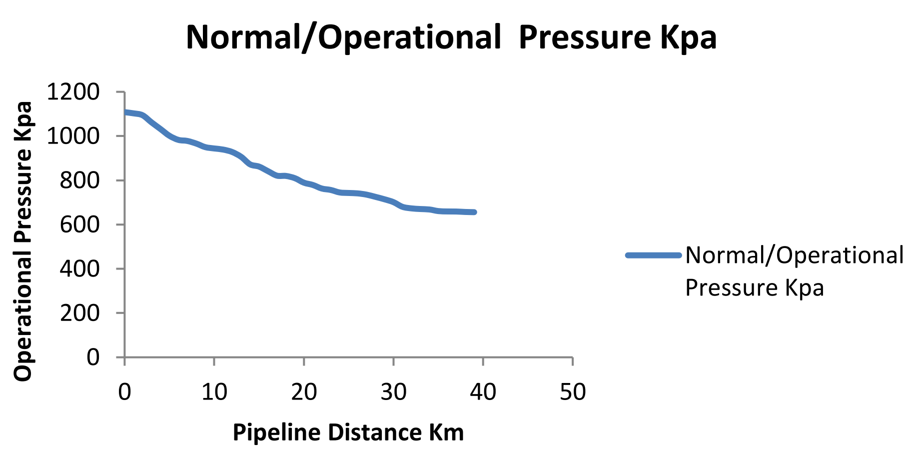


Figure 6 Normal/Field Operational Pressure versus Pipeline Distance

Figure 6 illustrates the relationship between Normal/Operational pressure and pipeline distance upon the influence of dynamic characteristics in the flow line. Decrease in pressure in pressure was observed with increase in pipeline distance, owing it to frictional resistances due to body and surface forces in terms of pressure forces and other environmental factors from our findings.

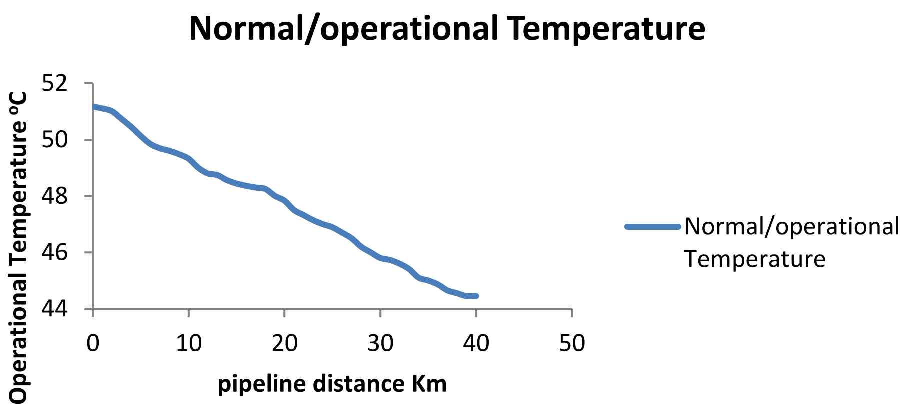


Figure 7 Normal/Field Operational Temperature versus Pipeline Distance

Figure 7 shows the NNPC operational data model in terms of temperature. From the graph, there is a decrease in temperature along the transmission line owing it to low viscosity in terms of temperature; thus, the initial and the arrival temperature and pressure is 51.172ºC- 44.45ºC.

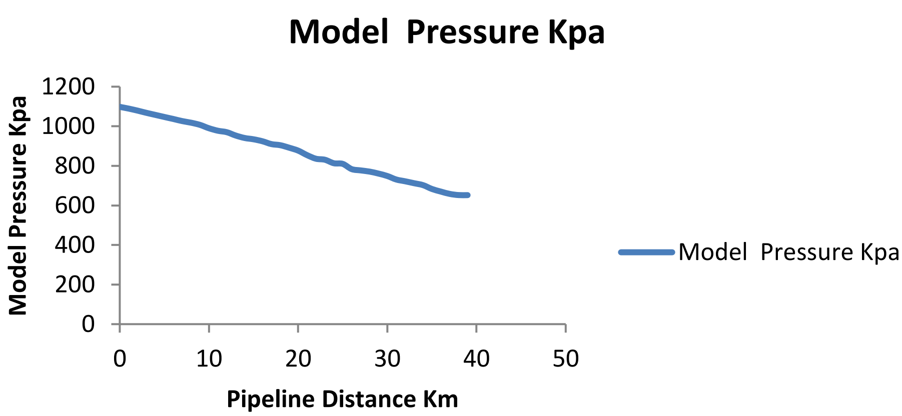


Figure 8 Model Pressure versus Pipeline Distance (without failure)

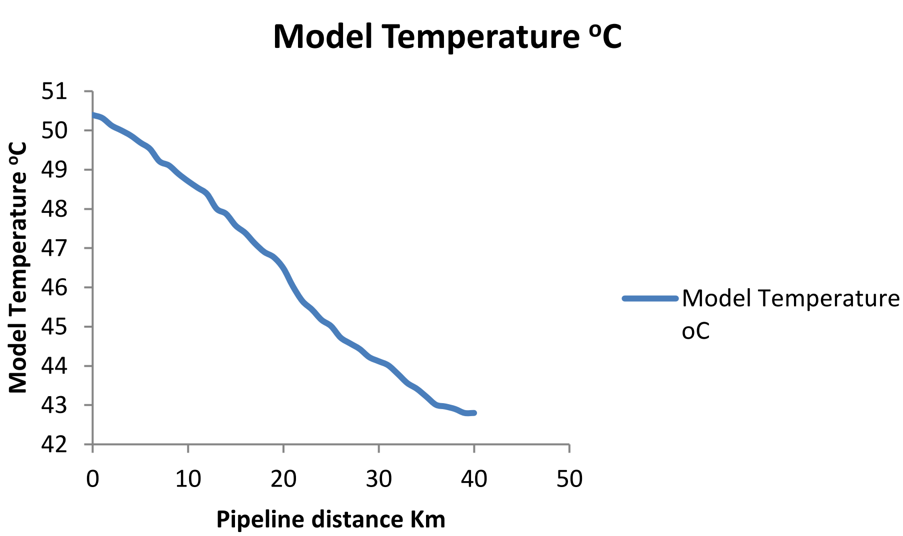


Figure 9 Model Temperature versus Pipeline Distance (without failure)

Figure 8 shows the relationship between modeled pressure and pipeline distance upon the influence of dynamic characteristics as the predictive model depicts the operational pressure. from our findings, it shows that the model was able to assert the readings of operational data as well as deduction of dynamic pressures at each kilometer along the transmission line.

Figure 9 shows the relationship between the model temperature and pipeline distance upon the influence of dynamic velocity in the flow line as the predictive model depicts the operational temperature. Therefore this model can be used to predict the future behaviours of any pipeline system.

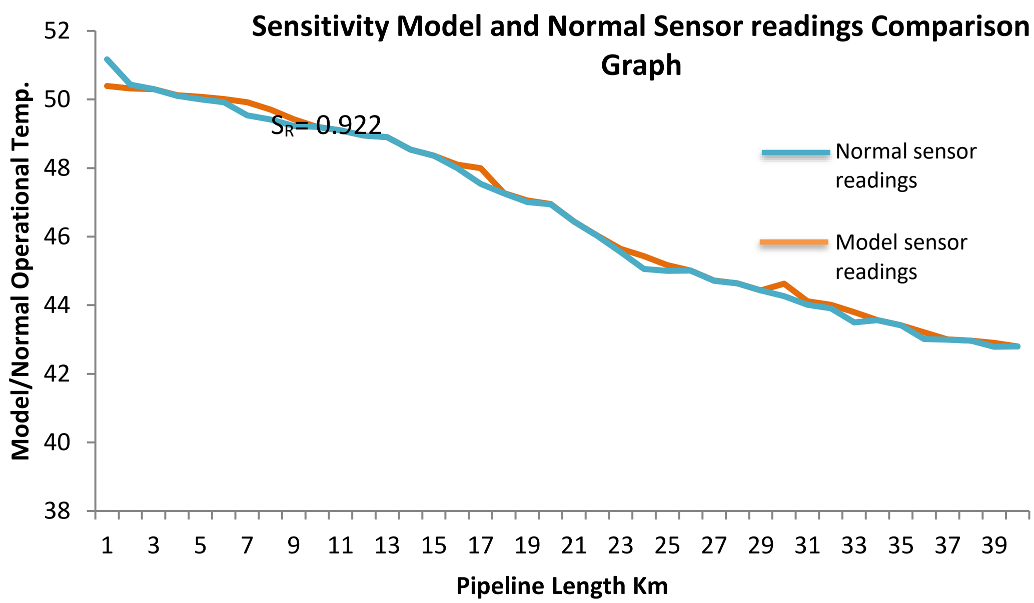


Figure 10 Model/Normal Operational Temperature verses pipeline distance

Figure 10 shows the sensitivity comparisons for both model and operational sensor readings in terms of temperature. From the graph, we observed that the sensitivity model and sensitivity normal/operational temperature is almost the same. This shows the rate at which the model is sensitive to real-life Computational fluid dynamics (CFD) readings with calculated sensitivity rate (S_R) of 0.922, which is 92.2%. This shows that the model can predict insulation failure along the transmission line with 0.982 accuracy i.e. 92.2 degree accuracy.

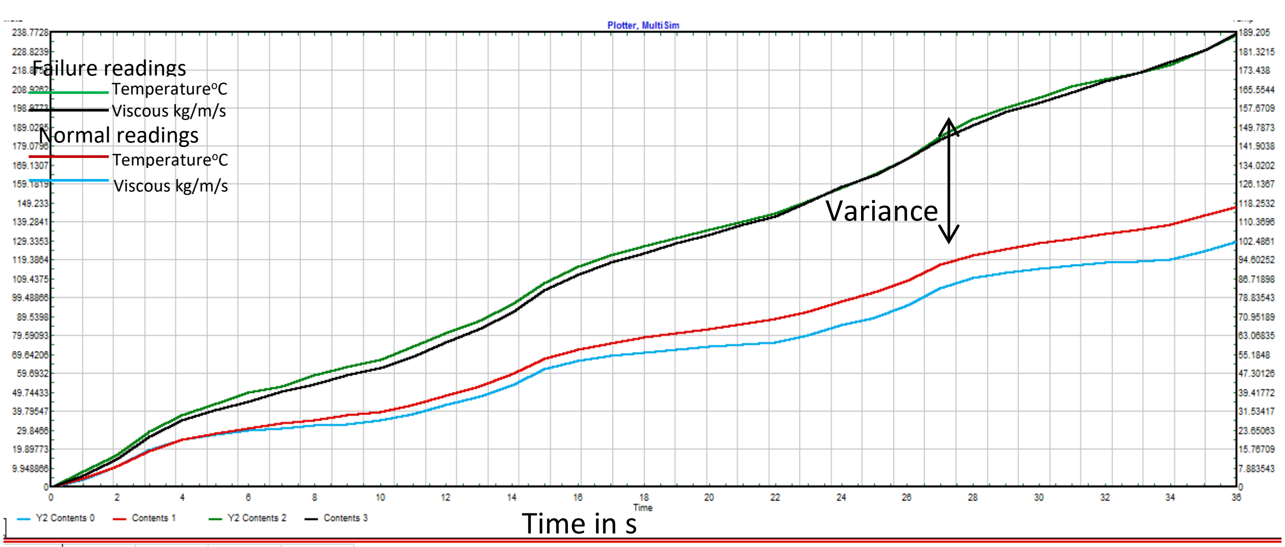


Figure 11 Sensitivity graph of normal/operational and failure sensor readings versus time

Figure 11 shows the component sensitivity readings for both failure and normal sensor readings in terms of temperature and viscosity. From the graph, we observed that at the failed part of the system, the temperature readings increased with an increase in viscosity while the sensor readings of the normal system (without failure) maintains a normal flow progression owing it to body and surface increase. From our findings, it shows that the failed or faulty part of the flow system maintained a rapid increase towards the exit of the flow owing it to heat transfer by conduction from the surrounding to the pipe wall which transfers to fluid flow. Also the graph showed the variance between the operational/normal sensor readings and the failure sensor readings which means that the model is sensitive to both large and small scale variation on the pipeline reading which enable it to generate error and detect fault along the transmission line.

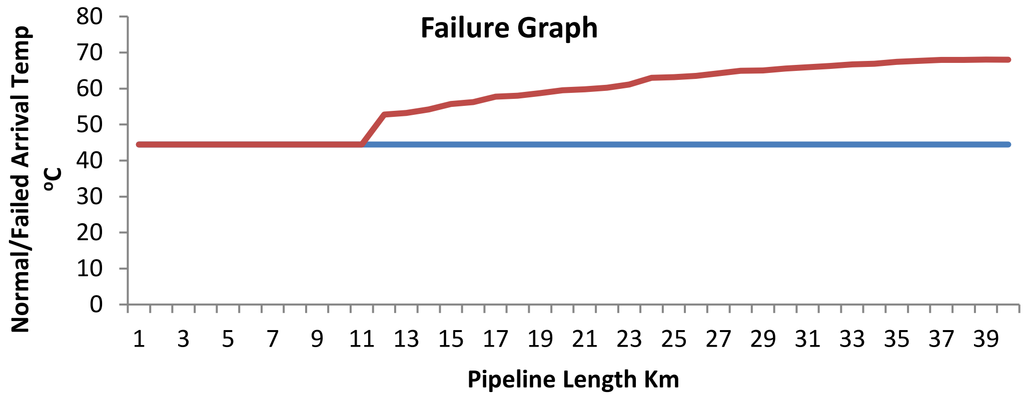


Figure 12 Graph of Normal/Failed arrival temperature versus Pipeline distance

The predictive model was used to predict the insulation failure along the transmission line using the arrival temperature as shown in Figure 12. This shows the arrival temperature for both normal (without failure) and the failed systems. From the graph; we observed that the normal (without failure) system maintained its arrival temperature level towards the exit of the flow while the failed or faulty part of the system increased its arrival temperature exponentially from 12.5km and maintained its increase towards the exit flow. From our findings, the increase found at the failed or faulty part of the system is as a result of erosion or pitting (leakage) found along the transmission line which made the fluid temperature depicts the surrounding temperature hence heat is transferred and because the rest of the pipe wall is well insulated, it maintained an increased temperature towards the exit of the flow.

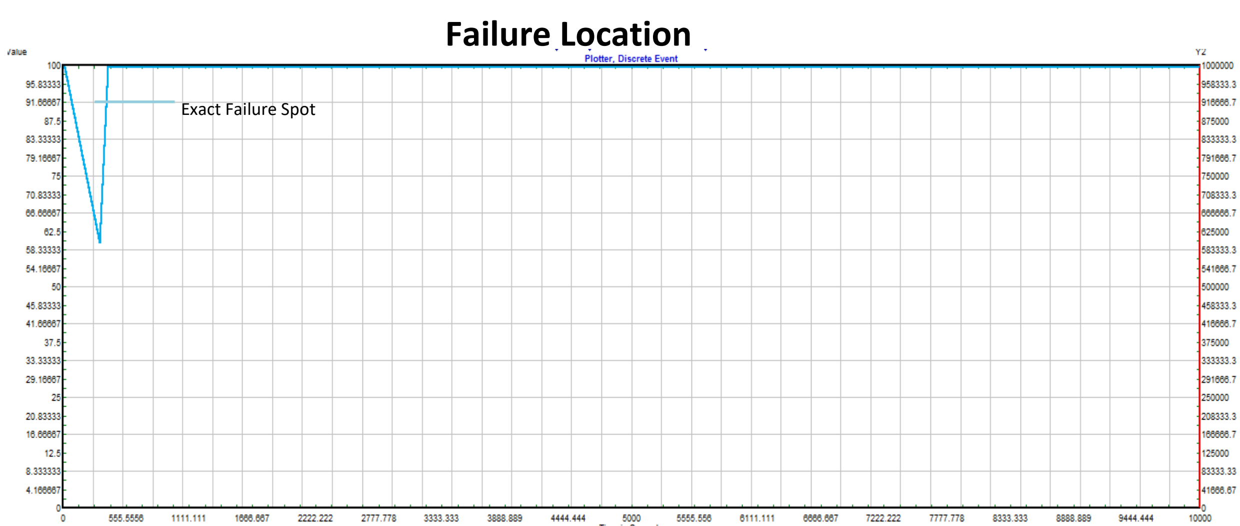


Figure 13 Graph Illustrating the Exact Location of the Failure

Once more, if the temperature of the surrounding is below the normal (without failure) system temperature, the failed part will also adapt to the surrounding temperature. For instance; in arctic region where we have a more freezing temperature, since gases are cryogenic in nature, tends to freeze if it adopt the surrounding temperature and this in particular leads to fogging or hydrate formation thereby causing pipe blockage along the transmission line. However, if the gas temperature adapts to a high surrounding temperature, with an absolute reoccurrences, it may lead to explosion, this calls for frequent checks on our gas transmission line in order to maintain the pipeline as at when necessary to avoid 'guess work' during inspection.

Figure 13 demonstrates failed area and pipe location against time shows the exact area of the failed insulator/leakage along the pipeline. From the computerized displayed function block (tool), it was shown that the calculated distance and the exact spot of failure along the pipeline using monitor indicating sensor which reads 12500m (12.5Km) due east from the simulated metering station (office). Here the exact spot where insulation failed along the pipeline is 12500m due east.

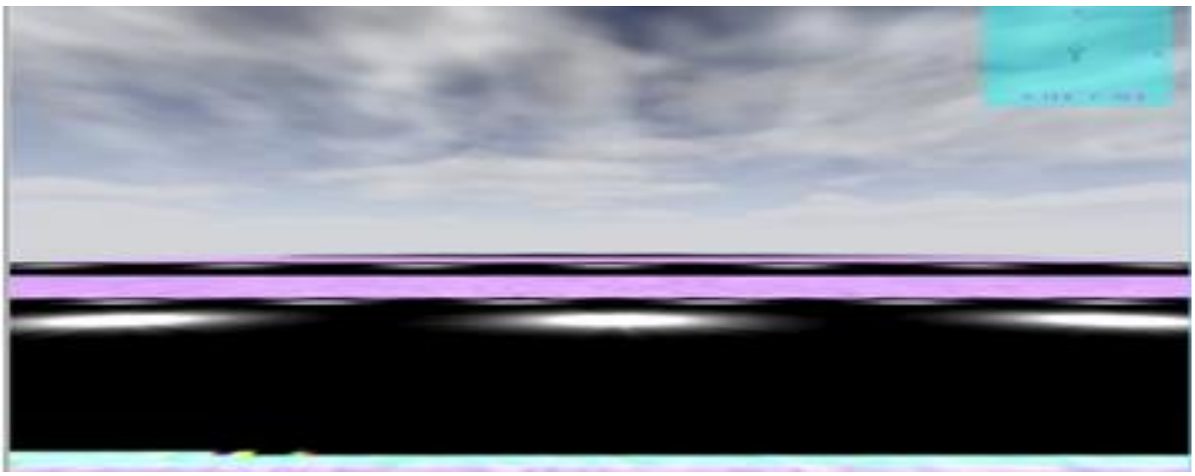


Plate 2 Extendsim9 3D Camera Model (Subsea Visual View for Exact Spot of Insulation Failure)

Plate 2 shows the 3D visual view of the failed insulator along the natural gas transmission for offshore pipelines using Extendsim9 3D phase from our observations, the dark part of the plate shows the well-insulated area while the spot-light areas are the failed spots or eroded part of the pipeline system. The area is covered with erosion of insulator and pitting/leaks.

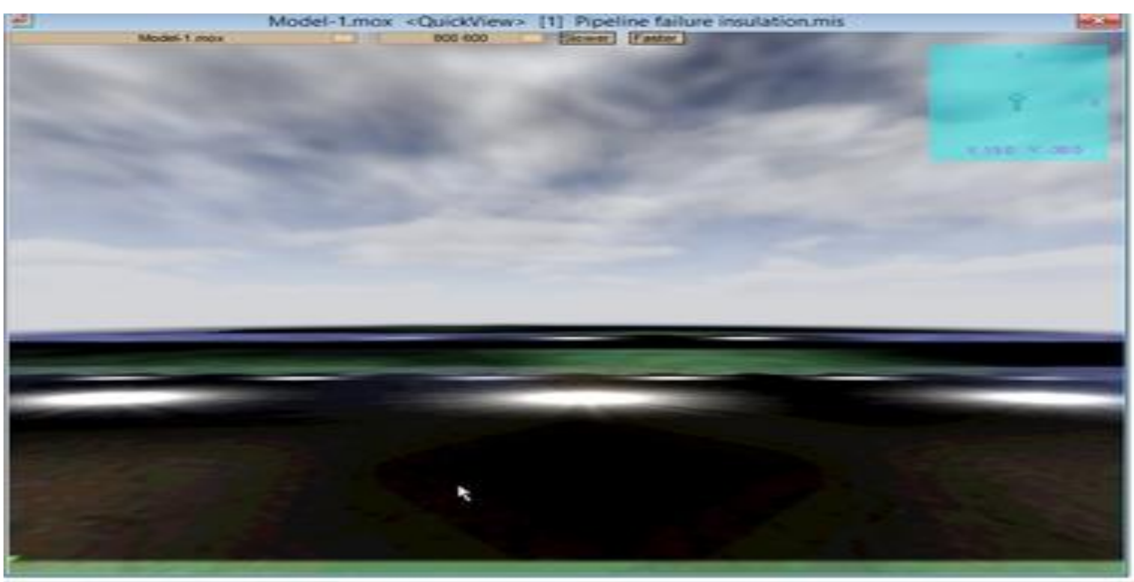


Plate 3 Extendsim9 3D Camera Model (Underground/Onshore Visual View for Exact Spot of Insulation Failure)

Plate 3 shows the 3D visual view of the failed insulator along the natural gas transmission for onshore pipelines using Extendsim9 3D phase from our observations, the dark part of the plate shows the well-insulated area while the spot-light areas are the failed spots or eroded part of the pipeline system. The area is covered with erosion of insulator and pitting/leaks.

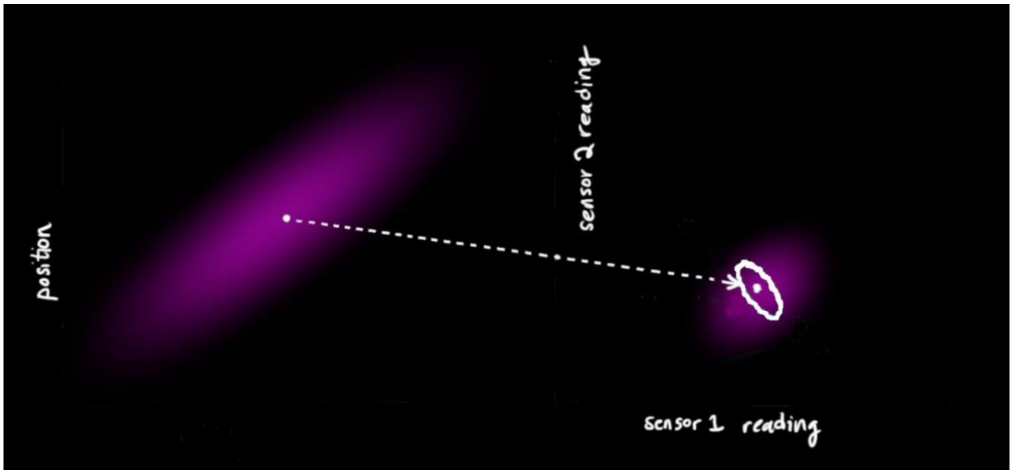


Plate 4 3-D shows the distance between the eroded spot and pitting along the failed distance

Plate 4 shows the cross section of the failed area and the distance between pits using the software 3D camera view from sensor readings. From our observations, the model was able to detect the spots where insulation failed along the pipeline:

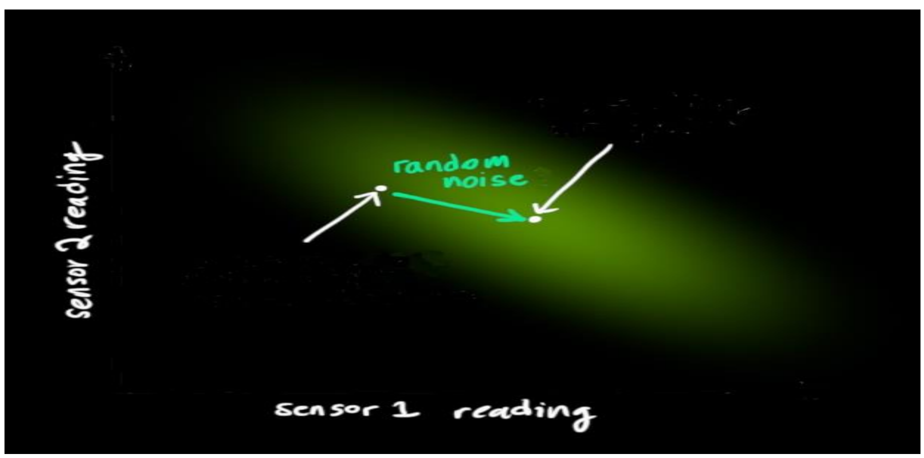


Plate 5 Sensor one and sensor two position reading

Plate 5 illustrates the model 3-D camera view; we observed that gas produces more noise as it approaches the failed area more especially within the erosion area as it expand from its control volume and decrease the noise level at the failed spot (leak or pit), these act as a warning signal during operation.

4. CONCLUSION

Generally, in gas flow measurement, the density of the gas changes as the pressure and temperature change. This change in density can affect the accuracy of the measured flow rate if it is uncompensated. When gas flow through pipes, it tends to experience pressure drop which occur as a result of friction resistance along the natural gas transmission line. Since gases are compressed, its density is a function of absolute temperature and absolute pressure, the change in density is proportional to the change in pressure or temperature. However, the study of instrumentation and process control, heat transfer and fluid mechanics formed the basis of this model. In this dissertation, a model that can predict insulation failures along natural gas transmission pipelines was developed, validated using sensitivity analysis which shows that the model can predict insulation failure on a real time basis since the rate of the model sensitivity is 0.982. From the analysis, it showed that the arrival temperature increased exponentially across the failed area due to the erosion and or leakages as the gas adopts the surrounding temperature and maintained a temperature increase towards the exit flow. This is due to the fact that the rest of the pipe walls are well insulated. In other words the model can detect failure using the arrival temperature. The display tools also displayed 12.500Km due east from its location as the exact spot of the failed insulator and a maintenance shutdown from the model was used to record time between "failures and time between repair". Also from the analysis, it showed that this model can read and interpret distributed temperature sensing devices or distributed acoustic sensing device along the pipeline. The result showed that this model can predict insulation failure along natural gas transmission pipeline on a real-time basis by analyzing the flow rate and temperature of the flowing gas along the line. This will solve the late detection of insulation failure problems for both insulation failures with/without pipe deterioration.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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