Scilab case study project on

Thermal Fault Localization in Pipelines Using Inverse Heat Conduction and Xcos Simulation

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Abstract

Thermal faults in pipelines may occur due to insulation damage, leakage, or local heat loss. These faults disturb the normal temperature distribution and reduce thermal efficiency. In this simulation-based case study, a Scilab and Xcos based method is developed to detect and localize a thermal fault in a pipeline. This work is not a direct replication of a single research paper; the reference papers were used only to support the background concepts of inverse heat conduction, thermal monitoring, and sensor-based temperature analysis.

All experiments were performed using simulated thermal data. No real pipeline hardware, real temperature sensors, real pipeline measurements, or experimental validation were used in this case study. The pipeline is modeled as a one-dimensional transient heat conduction system. Scilab is used to simulate normal and faulty temperature profiles using the finite difference method. Simulated sensor readings with small artificial noise are generated to represent measurement-like conditions. An inverse estimation method is applied by comparing simulated sensor temperature data with simulated model data and selecting the fault condition with minimum error. A fault index is also used to locate the region of maximum temperature deviation. Xcos is used to visualize the dynamic thermal response under weak, medium, and severe simulated fault conditions.

1. Introduction

Pipelines are widely used in thermal systems, process industries, power plants, chemical plants, and fluid transportation systems. In many of these applications, temperature monitoring is important because abnormal temperature variation may indicate insulation damage, leakage, or unwanted heat loss. If such thermal faults are not detected early, they can reduce system efficiency and may lead to unsafe operating conditions.

The motivation for this case study is to understand how a localized thermal fault affects the temperature distribution of a pipeline and how such a fault can be estimated using limited temperature information. In real pipeline monitoring systems, sensors may not be available at every point along the pipe, and direct observation of insulation damage or local heat loss may not always be possible. Therefore, a simulation-based approach is useful for studying the temperature behavior, testing the fault localization method, and visualizing the effect of different fault severities before applying such methods to real systems.

In this simulation-based case study, the pipeline is considered as a one-dimensional heat conduction system. A normal temperature profile and a faulty temperature profile are generated in Scilab using simulated thermal data. The fault is represented as a local heat loss region, which produces a temperature drop near the damaged portion of the pipe. No real pipeline measurements are used in this study.

The inverse heat conduction idea is used to estimate the simulated fault location from temperature data. Instead of directly observing the fault, the temperature response is analyzed to identify where the fault effect is maximum. An inverse estimation method is used by comparing simulated sensor temperature data with simulated model data and selecting the case with minimum error. A fault index method is also used to locate the position where the temperature deviation is highest.

Xcos is used as the graphical simulation environment to represent the dynamic thermal response of the system. The Xcos model shows how the simulated pipeline temperature changes when weak, medium, and severe fault conditions are applied. Therefore, Scilab provides the numerical and spatial analysis, while Xcos provides a clear dynamic visualization of the simulated thermal fault behavior.

2. Problem Statement

Thermal faults in pipelines are difficult to detect when the fault is not directly visible from outside. A fault such as insulation damage, leakage, or local heat loss may not immediately stop the system, but it can slowly reduce thermal efficiency. In a healthy pipeline, temperature changes smoothly along the length of the pipe. When a fault occurs, additional heat loss takes place near the damaged region and a local temperature drop appears in the temperature profile.

The main problem in this case study is to identify the location of such a thermal fault using temperature response data. In real pipeline monitoring systems, temperature sensors are usually available only at limited positions along the pipeline. In this case study, that condition is represented using simulated sensor locations. These simulated sensor values may also contain small artificial noise. Because of this, the exact fault location cannot be found by direct observation alone. It has to be estimated from the available temperature information.

In this work, a 1 m long pipeline is considered as a simulation model. The left side of the pipe is maintained at a higher temperature and the right side is maintained at a lower temperature. A thermal fault is introduced between 0.45 m and 0.55 m. This fault is modeled as an additional heat loss region. The normal and faulty temperature profiles are calculated using a one-dimensional finite difference heat conduction model in Scilab.

The solution approach has two main parts. First, Xcos is used to create a dynamic block model that shows how the simulated pipeline temperature response changes under weak, medium, and severe fault conditions. Second, Scilab is used to calculate the spatial temperature distribution, generate simulated sensor readings, perform inverse estimation, and compute the fault index.

The aim is to estimate the simulated fault location from the simulated temperature response. In the inverse estimation method, different assumed fault locations and fault strengths are tested. For each case, the simulated sensor temperatures are compared with the sampled simulated sensor temperature values. The case with the lowest error is selected as the estimated fault condition. Along with this, the fault index method is used to find the position where the temperature deviation between normal and faulty profiles is maximum.

3. Basic concepts related to the topic

3.1 Heat Conduction

Heat conduction is the transfer of heat through a solid material due to temperature difference. Heat always flows from a high-temperature region to a low-temperature region. In this case study, the pipeline is assumed to have a higher temperature at the left side and a lower temperature at the right side. Because of this temperature difference, heat flows along the length of the pipe.

For a simple one-dimensional pipeline, temperature is assumed to vary mainly along the axial direction of the pipe. This means the temperature is studied with respect to position *x* and time *t*. The transient heat conduction equation can be written as:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

where T is temperature, t is time, x is position along the pipe, k is thermal conductivity, ρ is density, and c_p is specific heat. This equation explains how temperature changes with time inside a solid body due to heat conduction.

The equation can also be written using thermal diffusivity α:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

Thermal diffusivity shows how quickly heat spreads through the material. The thermal diffusivity value used in this case study is selected as a simulation parameter to demonstrate the fault localization method.

3.2 One-Dimensional Pipeline Model

A real pipeline is three-dimensional, but for this case study the pipe is simplified as a one-dimensional system. This assumption is made because the main aim is to study how temperature changes along the length of the pipe. The pipe length is taken as 1 m, and the position along the pipe is represented from x = 0 m to x = 1 m.

The left end of the pipe is kept at 90°C and the right end is kept at 40°C. These two ends are treated as fixed boundary temperatures. The inner points of the pipe are updated using the heat conduction equation.

3.3 Finite Difference Method

The finite difference method is a numerical method used to solve differential equations using small divisions. In this case study, the pipe is divided into 201 points. Instead of solving the heat equation continuously at every point, the temperature is calculated at these selected grid points.

The second derivative of temperature is approximated as:

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} \approx \frac{\boldsymbol{T}(\boldsymbol{i}-\mathbf{1}) - \mathbf{2}\boldsymbol{T}(\boldsymbol{i}) + \boldsymbol{T}(\boldsymbol{i}+\mathbf{1})}{\boldsymbol{dx}^2}$$

Here, *T(i)* is the temperature at the current point, *T(i-1)* is the temperature at the left neighboring point, and *T(i+1)* is the temperature at the right neighboring point. This equation shows that the temperature change at one point depends on the temperatures of its neighboring points.

The temperature is updated using:

$$\boldsymbol{T_{new}} = \boldsymbol{T} + \boldsymbol{dt}\left[\boldsymbol{\alpha}\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} + \boldsymbol{loss}\right]$$

where *dt* is the time step. The loss term is zero for a normal pipe and non-zero in the fault region.

3.4 Thermal Fault Representation

A thermal fault is represented as an additional heat loss in a selected region of the pipeline. In this case study, the fault is assumed between 0.45 m and 0.55 m. This region loses more heat compared to the remaining healthy pipe.

The fault loss term is written as:

$$\boldsymbol{loss} = -\boldsymbol{fault\_value} \times (\boldsymbol{T} - \boldsymbol{T_{amb}})$$

where $fault\_value$ represents the strength of the fault, *T* is the local temperature, and $\boldsymbol{T_{amb}}$ is the ambient temperature. The negative sign shows that heat is being removed from that region. If the $fault\_value$ is increased, the temperature drop becomes larger.

In this simulation, the fault value is treated as a local heat-loss strength parameter and not as an experimentally measured material property.

3.5 Simulated Sensor Measurements and Noise

In practical systems, temperature sensors are placed only at selected locations. It is not always possible to measure temperature at every point of the pipeline. In this case study, 15 sensor positions are used along the pipe.

The actual temperature profile is calculated at many points, but sensor readings are taken only at selected positions. Small artificial random noise is added to the simulated sensor readings to represent measurement-like conditions. This makes the simulation closer to practical monitoring conditions because sensor readings may contain small errors due to instrument accuracy, environmental conditions, or signal disturbance.

3.6 Direct and Inverse Heat Conduction

In a direct heat conduction problem, the thermal condition is already known and the temperature distribution is calculated. For example, if the fault location and fault strength are known, the temperature profile of the pipe can be calculated.

In an inverse heat conduction problem, the temperature data is known first, and the unknown thermal condition is estimated from that data. In this case study, simulated temperature readings are used to estimate the assumed fault location and fault strength.

The inverse estimation is done by trying different assumed fault locations and fault values. For each case, the simulated sensor temperature is compared with the sampled sensor temperature value. The error is calculated as:

$$\boldsymbol{S} = \sum \left[\boldsymbol{T}_{sampled} - \boldsymbol{T}_{simulated} \right]^2$$

3.7 Fault Index

Fault index is a simple method used to locate the fault region. It is calculated by comparing the normal and faulty temperature profiles:

$$\boldsymbol{FI}(\boldsymbol{x}) = \left| \boldsymbol{T}_{fault}(\boldsymbol{x}) - \boldsymbol{T}_{normal}(\boldsymbol{x}) \right|$$

If the difference between normal and faulty temperature is high at a particular location, it means the fault effect is strong there. The location where the fault index is maximum is taken as the estimated fault location.

In this case study, the actual fault centre is 0.500 m and the fault index method estimates the location near 0.490 m. This shows that the fault index method can identify the fault region with small error.

3.8 Xcos Thermal Response Model

Xcos is used to build a graphical dynamic model of the thermal system. The Xcos model contains heat input, temperature difference calculation, heat transfer factor, fault trigger, fault severity branches, thermal balance, and temperature response blocks.

The Xcos model shows how the pipeline temperature response changes with time. Before fault activation, the response follows a normal heating trend. After the fault is activated, the response changes depending on fault severity. Weak fault gives a smaller temperature reduction, while severe fault gives a larger temperature reduction.

Thus, Scilab is used for spatial temperature calculation and inverse fault localization, while Xcos is used for visualizing the dynamic thermal response of the system.

4. Research Paper Reference and Original Work

This case study is not a direct replication of any single research paper. The title, problem formulation, Scilab implementation, Xcos model, simulated data generation, inverse estimation procedure, plots, and final fault localization workflow were developed specifically for this project. The research papers were used only as reference sources to understand the background concepts of inverse heat conduction, pipeline thermal monitoring, and distributed temperature sensing. Therefore, the present work should be understood as an original simulation-based case study inspired by concepts from the listed references, not as a direct implementation of one complete research paper.

Research Paper	Concept Adapted	Adaptation in This Case Study
Hybrid Approach for Solution of Inverse Heat Conduction Problems	Inverse estimation using the difference between measured and computed temperatures.	The unknown fault location and fault strength are estimated by minimizing the error between sampled sensor temperatures and simulated temperature values.
A Computational Model of Thermal Monitoring at a Leakage in Pipelines	Localized thermal anomaly produced near a pipeline leakage/fault.	The pipeline fault is modeled as a localized heat-loss zone from 0.45 m to 0.55 m, producing a temperature dip in the faulty profile.
Distributed Temperature Sensing: Review of Technology and Applications	Temperature monitoring along the length of a system for detecting abnormal thermal behavior.	Fifteen simulated sensor locations are placed along the pipeline, and small noise is added to represent practical sensor measurement conditions.

Table 1: Research concepts adapted for the present case study

Thus, the papers support only the conceptual foundation of the case study. The Scilab code, Xcos model, simulated data generation, inverse estimation procedure, plots, and final fault localization workflow were developed specifically for this project and are not a direct replication of any single research paper.

5. Flowchart

The flowchart summarizes the case study methodology from problem definition and model formulation to Scilab and Xcos implementation. Xcos is used for dynamic fault response visualization, while Scilab is used for forward simulation, sensor data generation, inverse estimation, fault index localization, and sensitivity analysis. The combined outputs are used for numerical result comparison and observations.

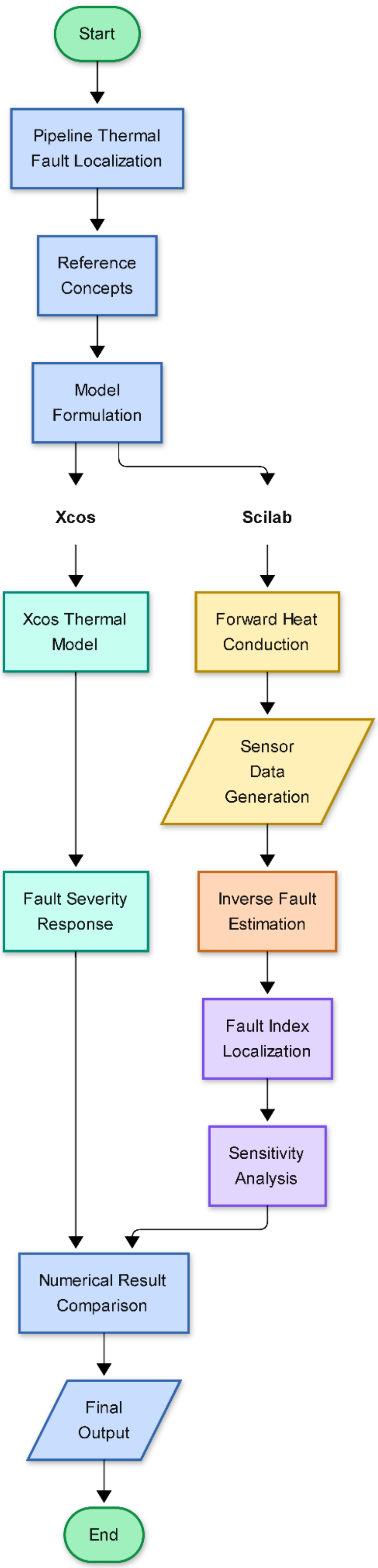

Figure 1: Flowchart of the thermal fault localization methodology.

6. Software/Hardware Used

Operating System: Windows 11

Software: Scilab 2026.1.0 and Xcos

Hardware: Personal laptop/PC with standard processing capability

No physical pipeline hardware, temperature sensors, fiber optic sensor, or data acquisition system was used in this case study. The pipeline, thermal fault, sensor readings, and fault localization process are represented using Scilab simulation logic and Xcos block modeling.

7. Procedure of Execution

The execution of the Scilab and Xcos files can be carried out as follows:

1. Open **Scilab 2026.1.0**.
2. Set the Scilab working directory to the **Codes** folder using the cd command.
3. Execute the main Scilab file named **run_case_study.sce**.
4. The main file automatically calls the dependency file **pipeline_dependency.sci** and runs the complete Scilab simulation.
5. After execution, the following Scilab plots are generated:
    - Temperature variation along the pipeline
    - Normal and faulty temperature profile
    - Simulated sensor readings along the pipeline
    - Inverse estimation from simulated sensor temperature data
    - Error variation for different assumed fault locations
    - Fault index for locating thermal fault
    - Effect of fault strength on temperature profile
6. The Scilab console displays the numerical results such as temperature drop, estimated fault location, minimum error value, fault index location error, and fault strength comparison.
7. Open the **Xcos** folder from the project directory.
8. Open the Xcos model file in Xcos.
9. Run the Xcos model using the simulation start option.
10. The Xcos simulation generates the dynamic thermal response graph for weak, medium, and severe simulated fault conditions.

8. Results

8.1 Temperature Variation Along the Pipeline

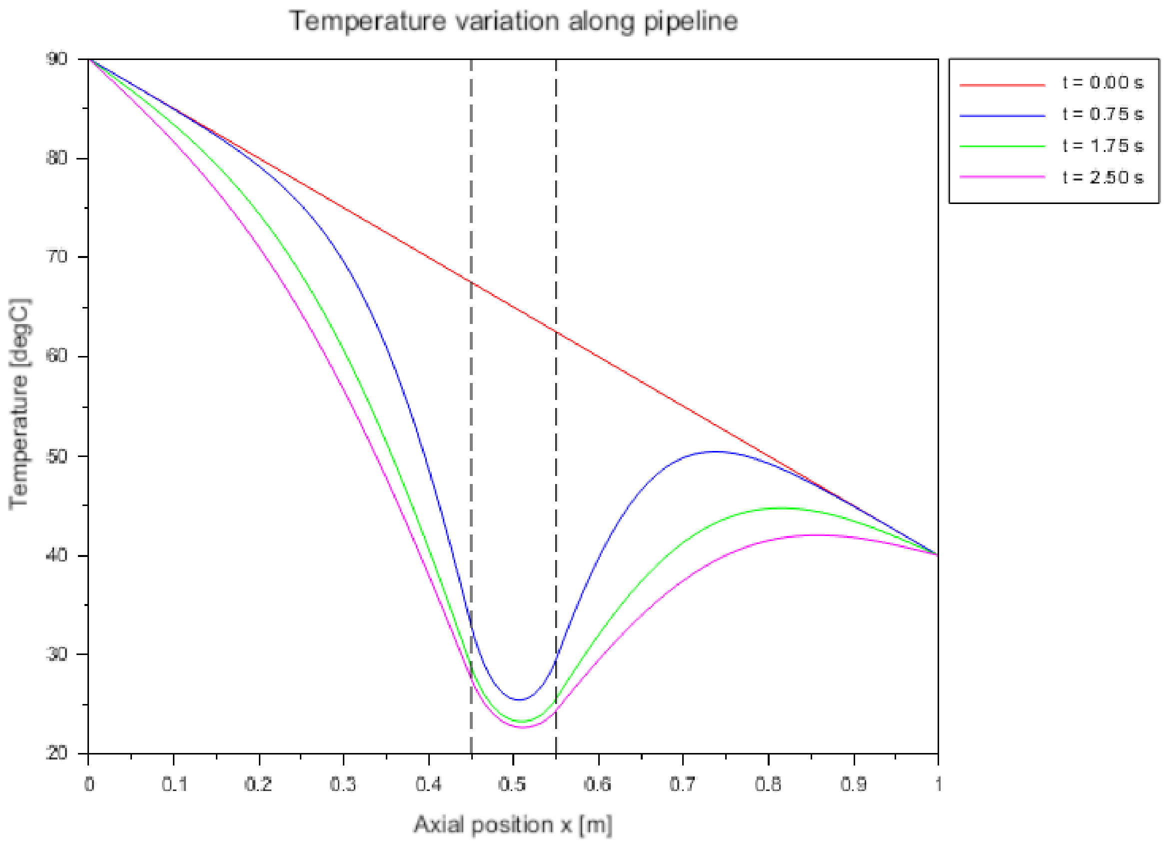

Figure 2: Temperature variation along the pipeline at different time levels.

This plot is generated from the Scilab forward heat conduction model. The pipeline length is taken as 1 m and divided into 201 grid points. The left boundary temperature is fixed at 90°C and the right boundary temperature is fixed at 40°C. The fault is introduced as a localized heat loss region between 0.45 m and 0.55 m with a fault strength value of 8. During simulation, temperature profiles are stored at selected time levels and plotted together.

The vertical dashed lines indicate the fault region. It can be observed that the temperature profile develops a clear local drop near the fault zone as the simulation progresses. This occurs because additional heat loss is applied only in the fault region. Hence, the plot confirms that a localized thermal fault produces a visible disturbance in the pipeline temperature distribution.

8.2 Normal and Faulty Temperature Profile

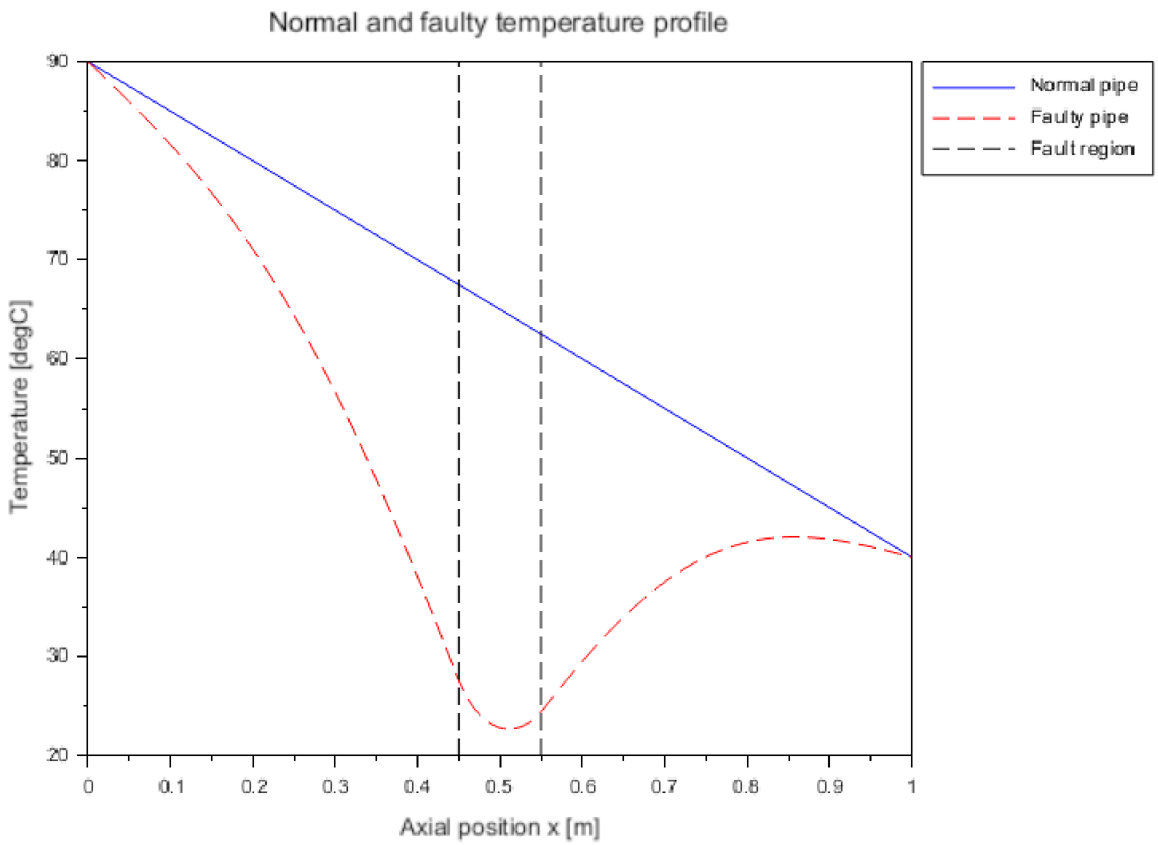

Figure 3: Comparison of normal and faulty temperature profiles.

This plot is generated by running the forward heat conduction model for two conditions: normal pipeline and faulty pipeline. In the normal case, no extra heat loss is applied, so the temperature varies smoothly from the hot end to the cold end. In the faulty case, an additional heat loss term is applied only between 0.45 m and 0.55 m.

The graph clearly shows that the faulty pipeline has a sharp temperature dip near the fault region, while the normal pipeline remains smooth. This confirms that the introduced fault behaves like a localized thermal loss. The difference between these two profiles is later used for fault index calculation and fault localization.

Numerical Results: Normal temperature at fault centre = 65.00°C, faulty temperature at fault centre = 22.79°C, temperature drop = 42.21°C.

8.3 Simulated Sensor Readings Along the Pipeline

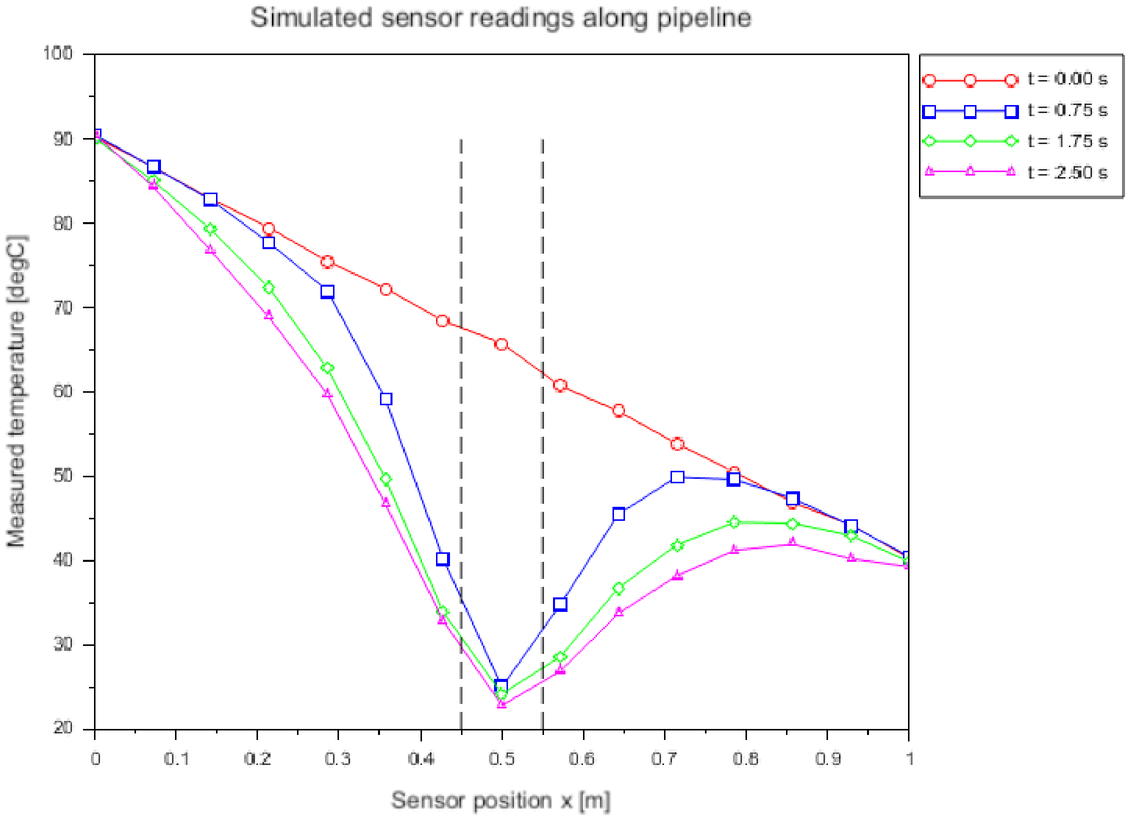

Figure 4: Simulated sensor readings along the pipeline.

This plot is generated by sampling the simulated temperature profile at 15 equally spaced sensor locations along the 1 m pipeline. Since temperature data is usually available only at selected locations in practical monitoring systems, these sensor points represent limited sensor sampling along the pipeline. A small artificial noise value of 0.4 is added to the simulated sensor readings to represent measurement-like uncertainty.

The graph shows temperature readings at different time levels. Even with limited sensor points and small noise, the temperature reduction near the fault region can still be observed. This indicates that the simulated sensor-based temperature monitoring approach can identify abnormal thermal behavior in the pipeline model.

Main parameters used: Number of sensors = 15, sensor range = 0 m to 1 m, noise value = 0.4, fault region = 0.45 m to 0.55 m.

8.4 Inverse Estimation from Simulated Sensor Temperature Data

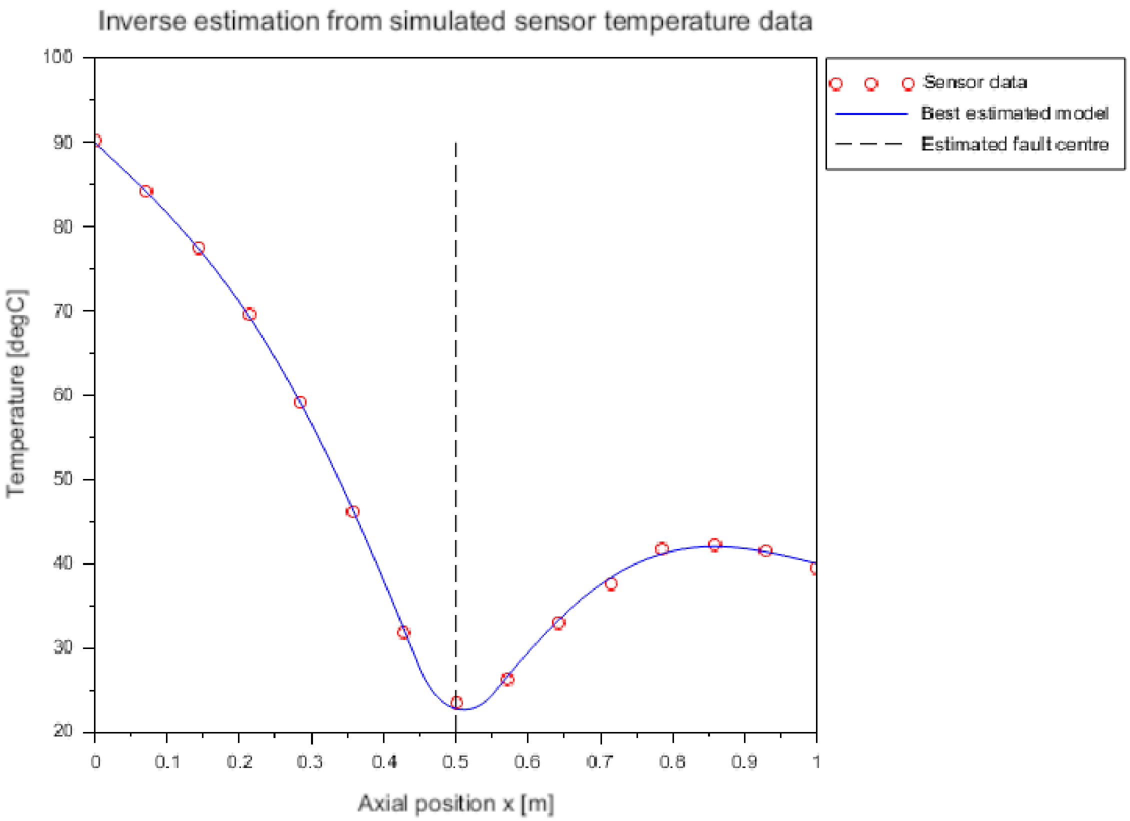

Figure 5: Inverse estimation using simulated sensor temperature data.

This plot is obtained from the inverse estimation part of the Scilab code. The final faulty temperature values at the 15 simulated sensor locations are treated as sampled simulated sensor data. Different assumed fault locations and fault strength values are tested, and for each case the simulated sensor temperatures are compared with the sampled sensor temperature values.

The red points represent the simulated sensor temperature data, and the blue curve represents the best estimated temperature profile obtained from the minimum error condition. The estimated fault centre is shown by the vertical dashed line. The close matching between the simulated sensor points and the estimated profile shows that the inverse estimation method is able to reconstruct the simulated fault condition from limited simulated sensor data.

Numerical Results: Actual fault centre = 0.500 m, estimated fault centre = 0.500 m, actual fault value = 8.0, estimated fault value = 8.0.

8.5 Error Variation for Different Assumed Fault Locations

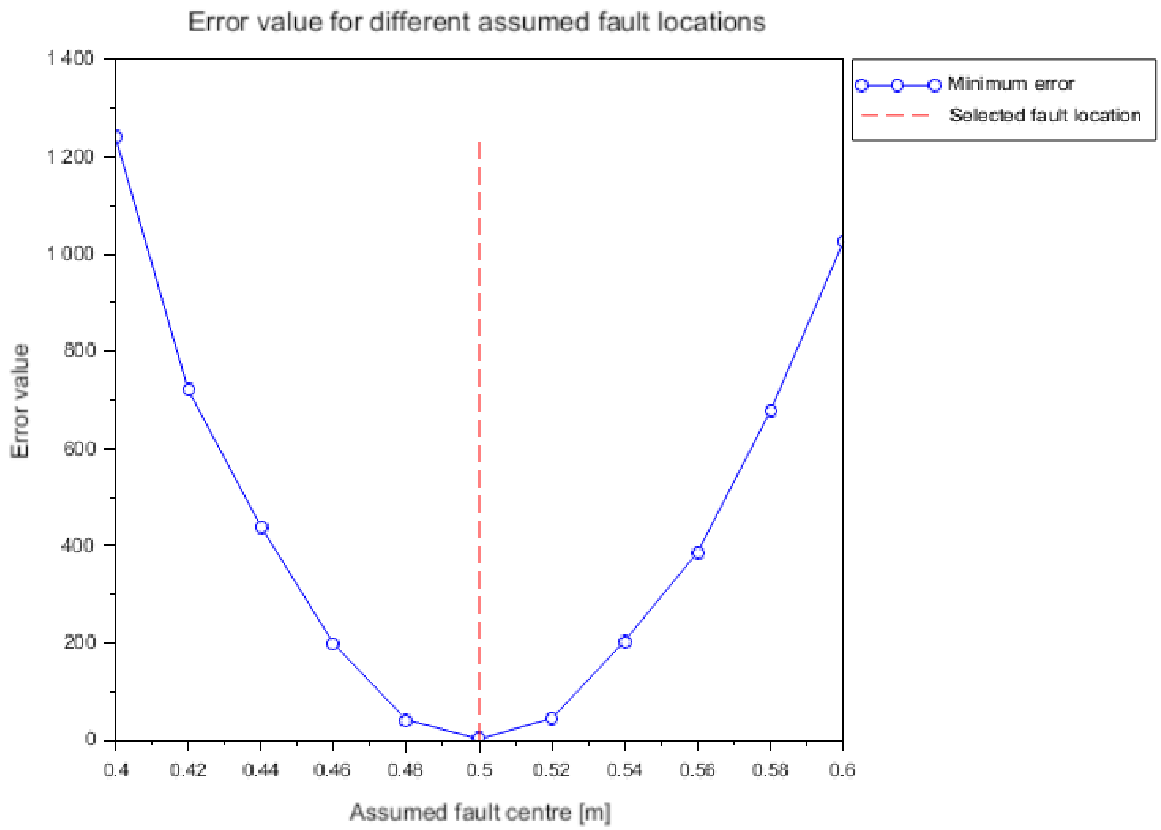

Figure 6: Error variation for different assumed fault locations.

This plot is generated during the inverse estimation process. The Scilab code tests different assumed fault centre locations from 0.40 m to 0.60 m and compares the simulated sensor temperatures with the sampled sensor temperature values. For each assumed location, the sensor-model error is calculated using the sum of squared temperature differences.

The graph shows that the error value decreases near the actual fault location and reaches its minimum at 0.500 m. This minimum error point is selected as the estimated fault centre. Therefore, this plot supports the inverse heat conduction approach used in the case study, since the minimum error occurs at the actual fault centre.

8.6 Fault Index for Locating Thermal Fault

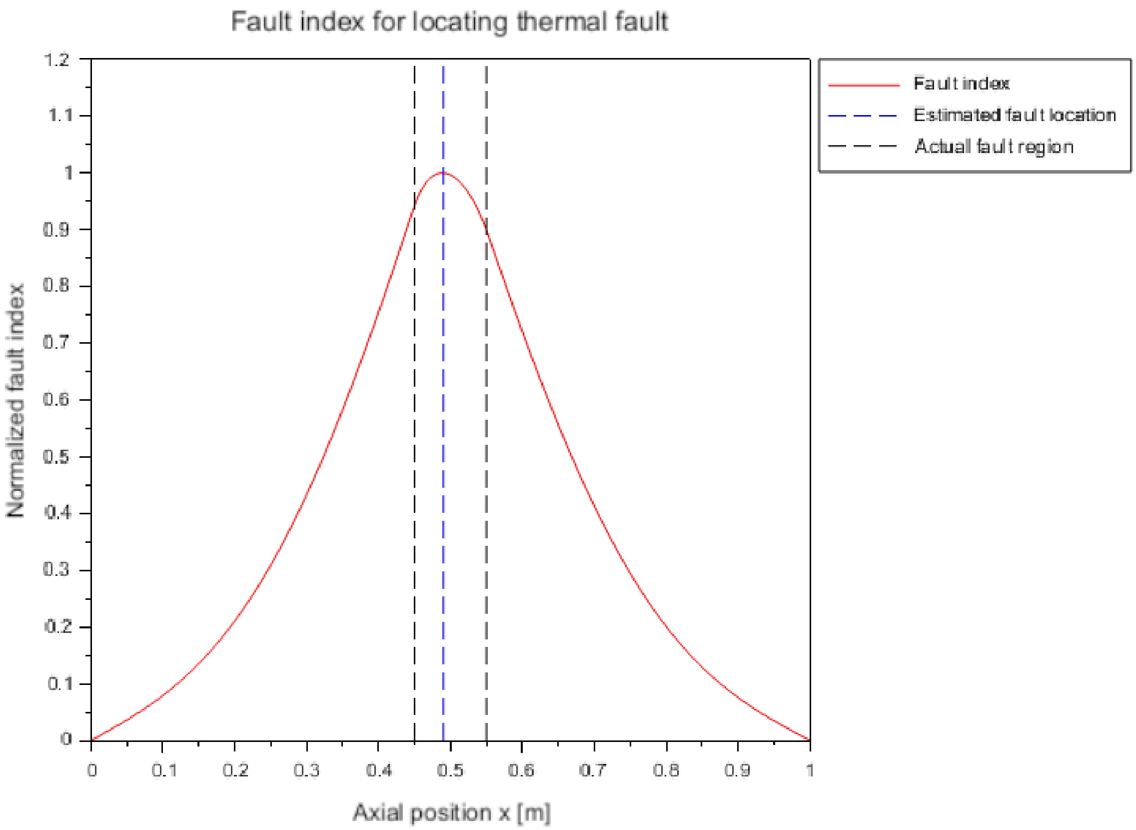

Figure 7: Fault index for thermal fault localization.

This plot is generated by comparing the final normal and faulty temperature profiles. The fault index is calculated as the absolute temperature difference between the two profiles at each position along the pipeline. The obtained value is normalized so that the maximum fault index becomes 1.

The peak of the fault index occurs near the actual fault region. This indicates that the temperature deviation between the normal and faulty pipe is highest at the fault location. The estimated location from the fault index is 0.490 m, which lies inside the actual fault region of 0.45 m to 0.55 m.

Numerical Results: Actual fault centre = 0.500 m, fault index estimated location = 0.490 m, location error = 0.010 m.

8.7 Effect of Fault Strength on Temperature Profile

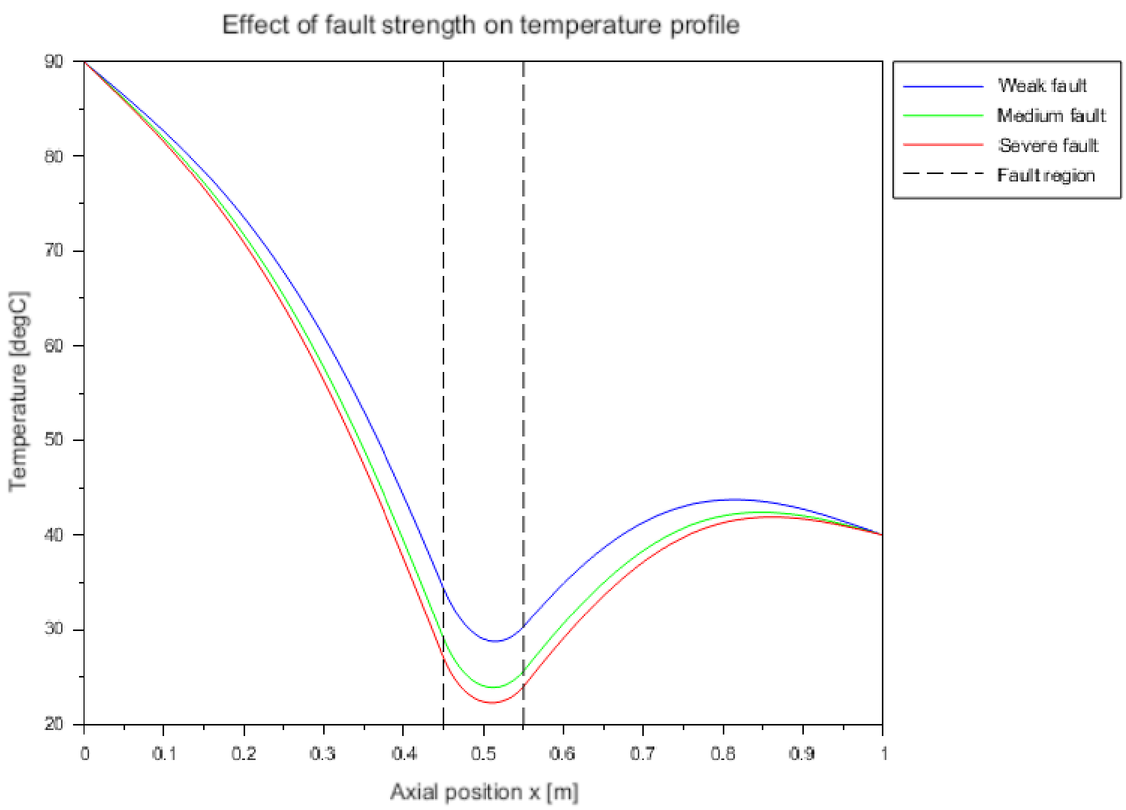

Figure 8: Effect of fault strength on temperature profile.

This plot is generated by repeating the Scilab heat conduction simulation for three different fault strength values. The weak, medium, and severe fault cases are represented using fault values of 3, 6, and 9 respectively. In each case, the fault is applied in the same region between 0.45 m and 0.55 m.

The graph shows that as the fault strength increases, the temperature drop near the fault region also increases. The weak fault produces a smaller dip, while the severe fault produces the deepest dip. This confirms that the model is sensitive to the intensity of the thermal fault.

Numerical Results: Weak fault centre temperature = 29.01°C, medium fault centre temperature = 24.05°C, severe fault centre temperature = 22.38°C.

8.8 Xcos Block Diagram Model

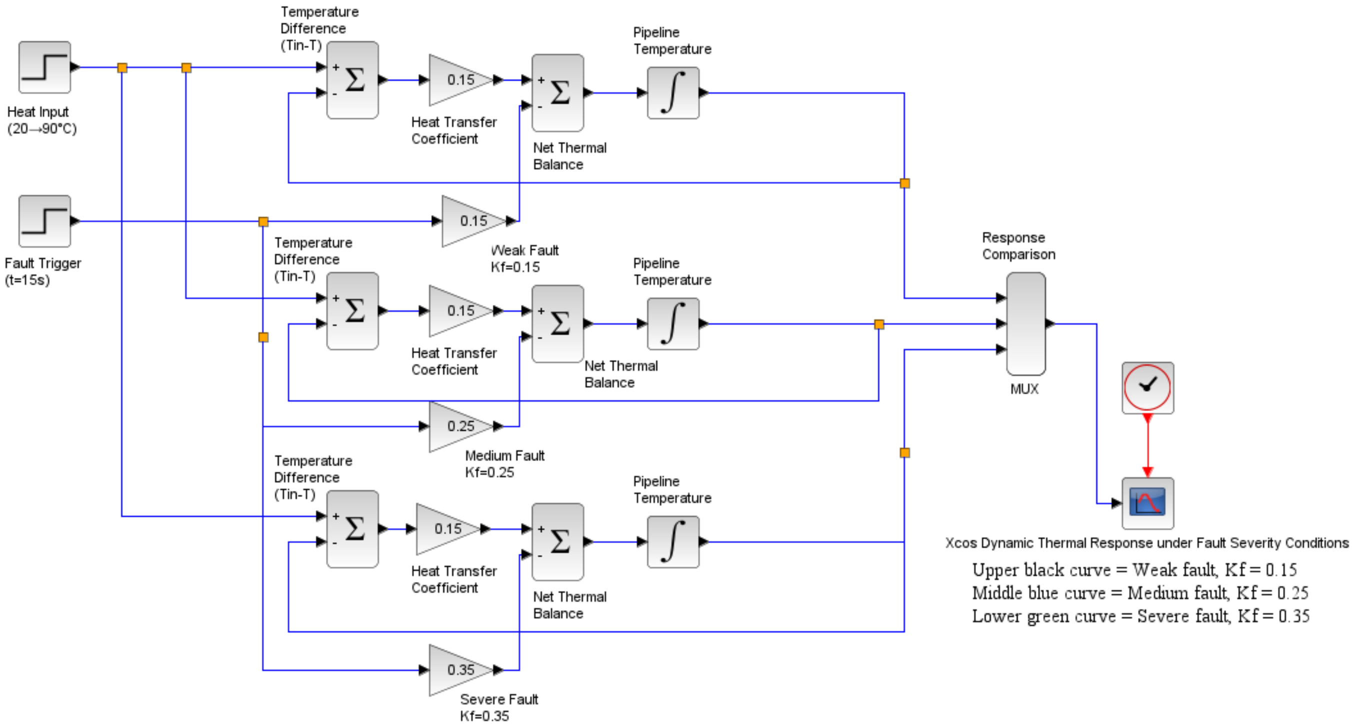

Figure 9: Xcos block diagram for dynamic thermal fault response.

The Xcos block diagram represents the dynamic temperature response of the pipeline under different fault severities. The model is based on the reduced thermal balance:

$$\frac{dT}{dt} = K_h(T_{in} - T) - K_f F(t)$$

Here, Tin is the heat input, T is the pipeline temperature, Kh is the heat transfer coefficient, Kf is the fault severity coefficient, and F(t) is the fault trigger signal. The temperature difference block calculates (Tin - T), the gain Kh = 0.15 controls the heating rate, and the integrator gives the pipeline temperature response with time.

The fault is activated at 15 s. Three fault branches are used: weak fault Kf = 0.15, medium fault Kf = 0.25, and severe fault Kf = 0.35. The MUX block combines the three responses and sends them to the scope for comparison.

The Xcos model is a reduced-order simulation model used only for dynamic response visualization, while the Scilab model is used for spatial fault localization. This Xcos model does not represent experimental pipeline testing.

8.9 Xcos Dynamic Thermal Response

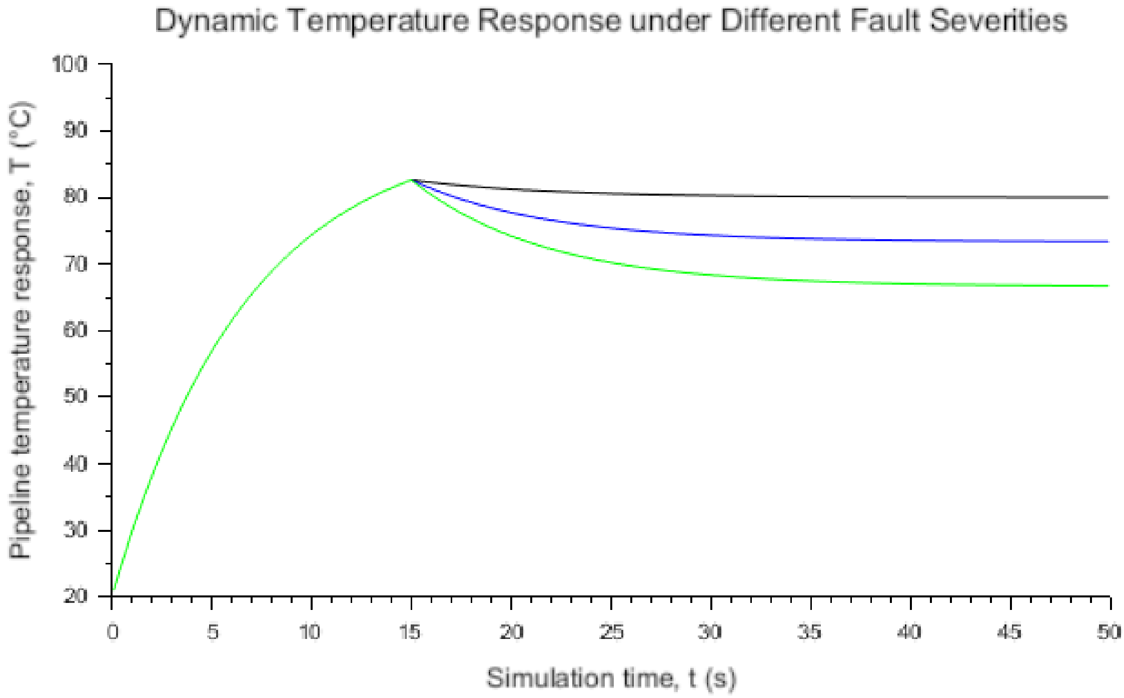

Figure 10: Xcos dynamic response for weak, medium, and severe fault conditions.

This plot is generated from the Xcos block diagram by comparing three simulated fault severity responses in the same scope. In the Xcos scope output, the horizontal axis t represents simulation time in seconds, and the vertical axis y represents the simulated pipeline temperature response in degree Celsius. From 0 s to 15 s, all three responses follow the same heating trend because the fault trigger is not active. During this period, the simulated pipeline temperature increases from about 20°C to nearly 82°C due to the applied heat input.

At t = 15 s, the fault trigger is activated. After this point, the three responses separate according to the applied fault severity. As labeled in the Xcos block diagram, the upper black curve represents the weak fault response with Kf = 0.15, the middle blue curve represents the medium fault response with Kf = 0.25, and the lower green curve represents the severe fault response with Kf = 0.35. The weak fault response remains at the highest temperature level, the medium fault response settles at an intermediate level, and the severe fault response gives the lowest final temperature. This occurs because higher fault severity represents greater simulated heat loss from the system.

8.10 Summary of Simulation Results

The main numerical values obtained from the Scilab console are summarized in Tables 2 and 3. Table 2 presents the fault localization results, while Table 3 compares the effect of fault strength on the temperature response.

Quantity	**Value**
Fault region considered in the model	0.45 m to 0.55 m
Actual fault centre	0.500 m
Estimated fault centre from inverse estimation	0.500 m
Actual fault value	8.0
Estimated fault value	8.0
Normal temperature at fault centre	65.00°C
Faulty temperature at fault centre	22.79°C
Temperature drop at fault centre	42.21°C
Minimum sensor-model error	2.471
Fault index estimated location	0.490 m
Fault index location error	0.010 m

Table 2: Fault localization results

Fault Condition	Fault Value	Temperature at Fault Centre	Minimum Temperature
Weak fault	3.0	29.01°C	28.75°C
Medium fault	6.0	24.05°C	23.89°C
Severe fault	9.0	22.38°C	22.27°C

Table 3: Fault strength comparison

From Table 2, the inverse estimation method predicts the simulated fault centre as 0.500 m, which is the same as the actual fault centre assigned in the simulation. The fault index method gives an estimated location of 0.490 m, with an error of 0.010 m. Table 3 shows that the temperature at the fault centre decreases as the fault value increases, indicating that higher fault strength produces a stronger local temperature drop.

9. Observations

i. The normal pipeline temperature profile shows a smooth variation from the hot boundary to the cold boundary, while the faulty profile shows a clear temperature drop near the fault region.

ii. The localized heat loss introduced between 0.45 m and 0.55 m produces a distinct thermal disturbance, which confirms that the fault effect is limited mainly to the damaged region.

iii. The simulated sensor readings show that the fault region can still be identified in the model even when temperature data is sampled only at limited sensor locations with small artificial noise.

iv. The inverse estimation method gives the estimated fault centre as 0.500 m, which matches the actual fault centre used in the simulation.

v. The fault index method estimates the fault location as 0.490 m, giving a small location error of 0.010 m.

vi. The error variation plot shows that the minimum sensor-model error occurs near the actual fault location, supporting the inverse heat conduction approach used in the case study.

vii. The fault strength study shows that increasing the fault value results in a lower temperature at the fault centre. This indicates that stronger faults produce higher local heat loss.

viii. The Xcos response confirms the same trend dynamically. The severe fault condition gives the lowest temperature response, while the weak fault condition gives the highest response.

ix. Overall, the Scilab and Xcos simulation results are consistent with each other. Scilab provides spatial fault localization, while Xcos provides dynamic visualization of fault severity.

x. Since this case study is based completely on simulated thermal data, the results should be interpreted as numerical simulation results and not as experimental validation.

10. References

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