Thermal imaging, thermal conductivity of soil and heat loss from buried pipelines

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1. Introduction

Thermal management is a critical function in Oil & Gas transportation, where conservation of the thermal energy would provide a better operating envelop. The temperature of oil pipelines, at as high as 100°C, is significantly higher than the temperature of the surrounding subsea water and clay. Therefore heat is lost from the oil pipelines to the surrounding environment. Heat lost along the length of the pipeline leads to a temperature loss from inlet to outlet. The pipeline must be designed to ensure that the temperature drop is small enough to maintain oil flow and avoid unwanted deposition of wax, which occurs at a critical temperature of about 50°C. Sometimes stalls in the flow are necessary as pipes are habitually shut down for maintenance; therefore it is essential to know the time lag in which the oil will reach this critical temperature. The drop in temperature depends on the thermal conductivity of the pipeline and its surroundings and so there is a need to know the thermal properties of the backfill soil (clay or sand) and to utilise this low thermal conductivity to provide thermal insulation. Understanding the thermal conductivity and specific heat capacity of the soil is thus important for subsea pipeline designs.

Traditionally over the years no credit was given to the thermal barrier of the soil backfill cover above the pipeline, due to the uncertainty of the thermal conductivity of the soil cover. It was treated as safety margin, but in the recent past more effort has resulted in improved data, hence increased confidence in soil thermal conductivity leading to cost saving being made by reducing the insulation of buried pipelines. As an example, Figure 1 shows the drop in fluid temperature in a pipeline buried under 600mm of soil cover. The effect of thermal conductivity of the soil cover on heat loss from pipeline is evident. A soil with thermal conductivity of 1.5 W/mK can retain approximately 10°C higher temperature than a soil with thermal conductivity of 2 W/mK along a length of 10 km. Figure 2 demonstrates the benefit of giving credit to the soil cover in circumstance, where the pipeline have to be buried to meet the legislation or for UHB requirements. Figure 3 shows the increase in OHTC with the increase in soil thermal conductivity. All the above examples have shown that evaluating the soil thermal conductivity accurately can lead to accurate flow assurance calculations and thus efficient designs.

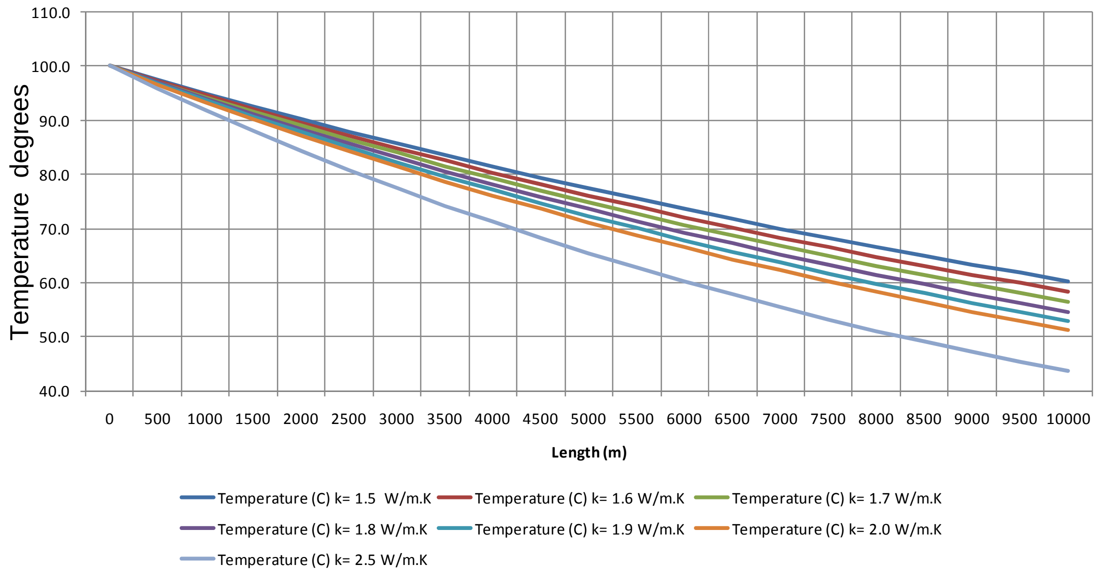

Figure 1. Temperature drop along a pipeline buried in 600mm soil cover

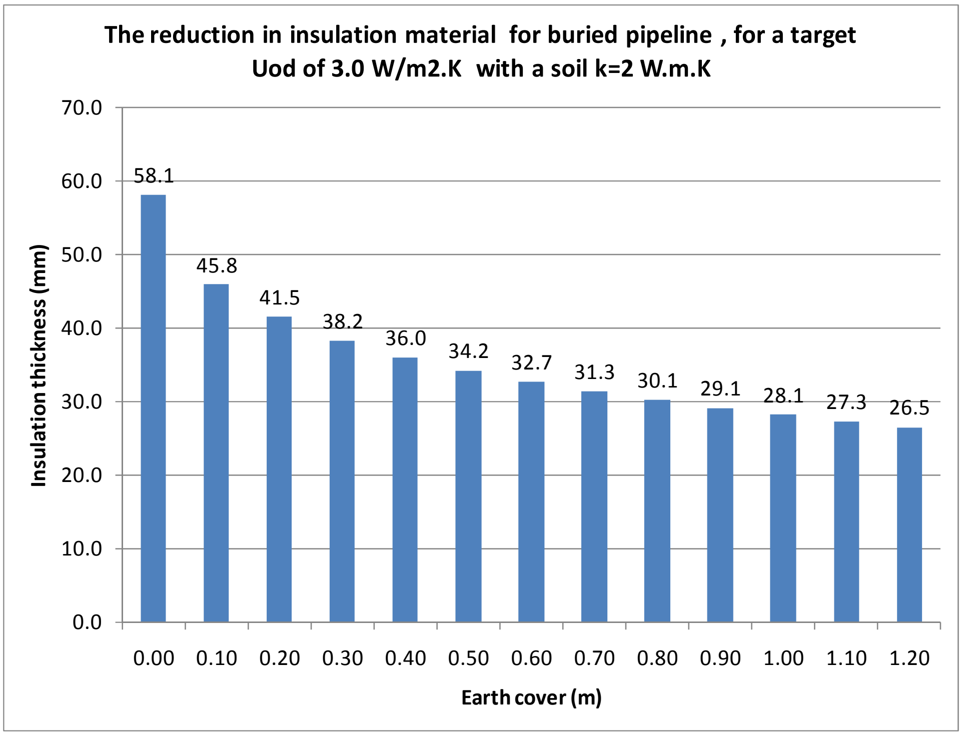

Figure 2. Effect of soil cover of insulation requirements

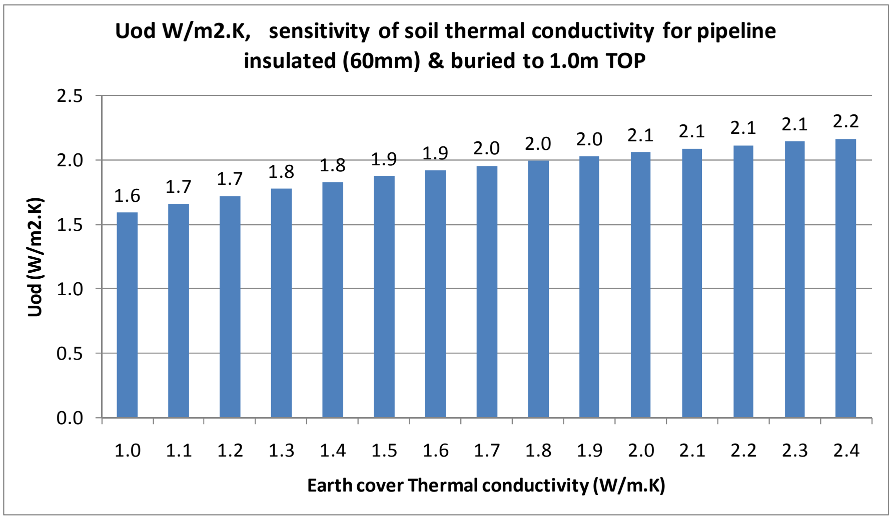

Figure 3. Effect of soil thermal conductivity on OHTC

Thermal conductivity is usually measured in the lab with a thermal probe. It is a long needle containing both heating and temperature measuring components. The needle is pushed into the soil and a recorded amount of current is passed through the heater element and the resulting variation of temperature with time is used to deduce the thermal conductivity of the soil. The applicable procedure is described by ASTM D5334 (2000) and thermal needle probe has been discussed in several papers (Mitchel & Kao 1978, among others). This method of measuring soil conductivity has many limitations in that the measurement is local and prone to soil voids, cracks, moisture content variation, and the temperature gradient applied is not that of seabed.

This paper presents a new laboratory investigation in which thermal conductivity of offshore clay is measured using thermal imaging technique under a thermal gradient similar to that in the field. A simple small-scale experiment setup was used to model a cross section of a buried pipeline surrounded by offshore clay. Offshore clay was uniformly placed around a pipeline (3 cm diameter) which can carry water at a given temperature. Thermal images of the cross section of the pipe and clay, taken at regular intervals, were used to understand the heat loss from the pipe and thermal gradient in the clay.

Depending on the subsea conditions and availability of materials, buried pipelines may be backfilled using different soils (blocky clay, sandy clay mixture etc.) Sometimes this backfill soil is of higher water content or is not sufficiently compacted due to the backfilling process. The effect of this on the thermal properties of the backfill was investigated in this investigation. The experimental results show the importance of the degree of consolidation of the backfill in determining the heat loss from the pipeline.

It is to be stressed that the presented investigation is preliminary and further research in this area is needed to improve and confirm initial findings.

2. Review of Literature

Heat transfer can take place by conduction, convection and radiation. Farouki (1986) showed that heat transfer in saturated soils is mainly due to conduction through the solid framework and the pore water. Brandon & Mitchell, (1989) and Kersten (1949) looked into the effect of particle size distribution. The main factors that affect the thermal conductivity of saturated soil are mineral composition of soil, particle size distribution (PSD), density, water content and temperature.

Well graded soils are better conductors of heat than poorly graded soils. This is because the smaller grains can fit into the gaps between the larger grains, which increase the bulk density and mineral-to-mineral contact area (Brandon & Mitchell 1989). For a given density and moisture content, the conductivity is relatively high in coarse grained soils such as sand, and lower in fine grained soils such as clay (Kersten 1949, Cathie, et al. (2005).

Abu-Hamdeh and Reeder (2000) investigated the effects of density, moisture content, salt concentration and organic matter on thermal conductivity. For the soils they studied, the thermal conductivity ranged from 0.58 to 1.94 for sand, form 0.19 to 1.12 for sandy loam, from 0.29 to 0.76 for loam and from 0.36 to 0.69 w/mK for clay loam. They showed that;

- an increase in bulk density at a given moisture content increased the thermal conductivity
- increase in moisture content at a given bulk density increased the thermal conductivity
- clayey soil generally had lower thermal conductivity than sandy soil.

In the absence of specific laboratory data, there are empirical equations that relates thermal conductivity of clay to its water content and dry density. One such equation is given below.

$$k = 0.144 \times \left[a \times \log(w) - b\right] \times 10^{c\gamma_d} \qquad (1)$$

where a, b and c are parameters which for clay are suggested as (Kersten (1949) ,Cathie et al (2005)) 0.13, 0.029 and 0.6245 respectively, γ is dry density, w is water content. A more relevant series for clay is attributed to Kersten (1949) and the parameters are 0.13, 0.029 and 0.6245 respectively. Rawat et al (1979) suggested that the maximum error with the Kersten method was 25%.

Newson et al. (2002) suggests another relationship between water content (w) and thermal conductivity of north sea clay as below.

Thermal conductivity, $k = 3.674\ w^{-0.316}$ (2)

Laboratory tests from high water content deepwater clays are documented by Young et al. (2001). The undisturbed soil samples had thermal conductivities ranging from 0.65 to 1.25 W/mK and the remoulded samples were in the region 0.8 – 1.05 W/mK

Newson, T.A and Brunning, P. (2004) provided thermal conductivity test results for with varying moisture content as shown in the figure below.

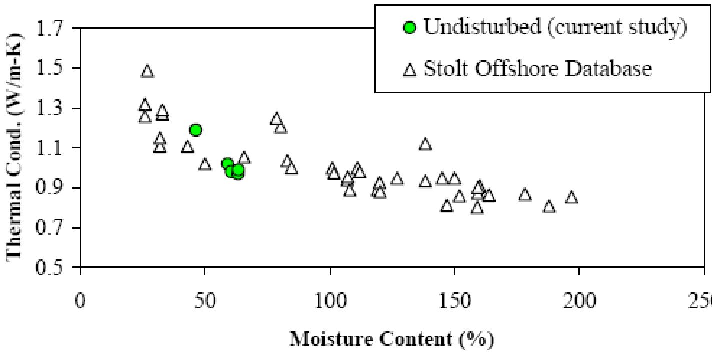

Figure 4. Thermal conductivity data from Newson, T.A and Brunning, P. (2004),

3. Experimental Equipment and Setup

3.1. Thermal Imager

The thermal imager used is a "Landguide M4" camera, and is the smallest, lightest and one of the most advanced thermal imagers in the world. Details of the Landguide M4 are given below with its picture.

- Temperature measurement range of -20 to 250°C
- Sensitivity of 0.12°C
- Detects temperature differences as high resolution, 8-bit thermal images
- Built in laser locator to accurately pinpoint hotspots
- 1GB memory (can store up to 1000 images)

Figure 5. The Landguide M4 camera

The thermal imager produces high quality thermal images that can be analysed on-site or stored for post-processing. Many different measurement modes allow precise analysis of the thermal image.

The basis for IR imaging technology is that any object whose temperature is above 0 K radiates infrared energy. The amount of radiated energy is a function of the objects temperature and its relative efficiency of thermal radiation, known as emissivity. Radiated energy is proportional to the body's temperature, raised to the 4th power. This energy can be measured and a thermal imager converts this to the corresponding temperature. As with all measuring instruments, a initial calibration ensures that distance and other environment conditions are accounted for in the conversion process and thus leading to accurate temperature measurement.

3.2. Experiment Apparatus

In order to use the thermal imager, we need to have direct view of the soil/pipe cross section. This is not possible if the experiment is carried out in a container. Therefore, a special setup has been made in which the pipe and soil are placed horizontally such that the cross section of the soil/pipe can be seen from above as shown in Figure 6. The apparatus simulates a subsea pipeline buried in soil and is set up in plan, so that thermal images can be taken from above. The pipe can be flushed with water of different temperatures and the depth at which the pipeline is buried can be altered by changing the amount of clay. North Sea offshore clay (water content of ~45%) obtained from a core sample was used in the experiments. The clay was compacted uniformly around the brass pipeline. The pipe was 30 mm in diameter and the clay was placed to a cover of 50 mm from the outer side of the pipe. The thickness of the clay layer was 15 mm. Ice cubes were placed inside the water at the top edge of the test container though out the test. This was to ensure that the boundary temperature for water is keep close to 0°C.

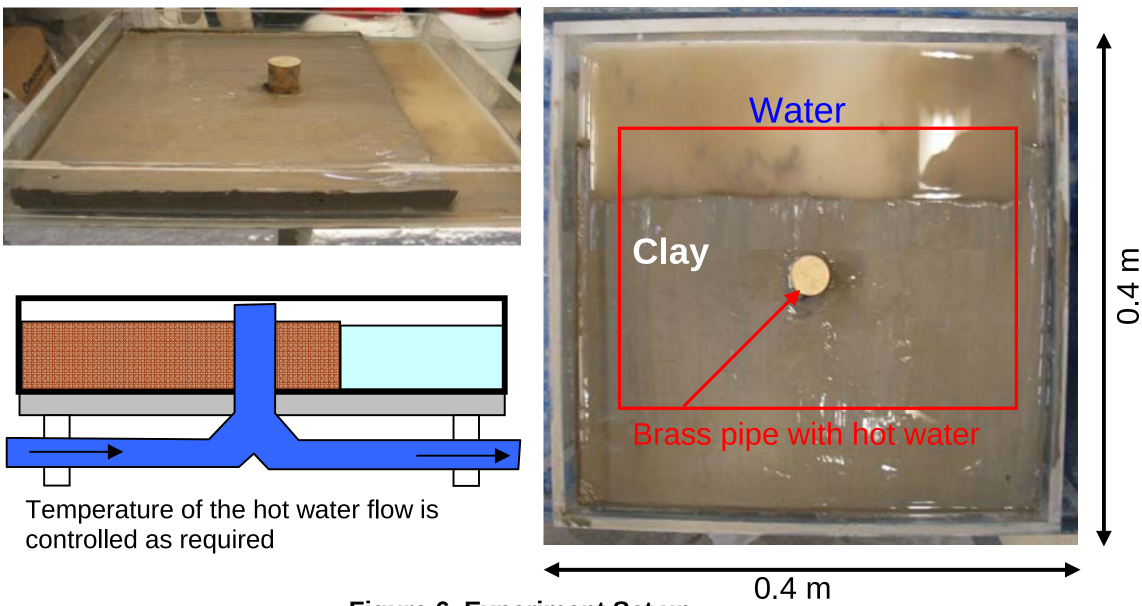

Figure 6. Experiment Set up

3.3. Test Program

The aims of the experiment into calculate the thermal conductivity of offshore clay using thermal images under a thermal gradient similar to that in the field. The effect of different backfill material on the thermal lose was also investigated.

Two temperature controlled water baths were used in the experiment, one at 20°C and another at 40°C. Initial steady state condition of 20°C pipeline was obtained by passing the 20°C water through the brass pipe for about 15 minutes.
Once steady state was well established with 20°C in the pipe, hot water at 40°C was passed through the brass pipe and thermal images were taken every 30 s till steady state at 40°C was attained (~15 minutes). The cooling down was then carried out by passing 20°C water through the pipe. Thermal images were captured at steady state conditions of 20°C hot pipe, heating up of the pipeline from 20°C to 40°C (every 30s), steady state at 40°C and during cooling down from 40°C to 20°C (every 30s).
The temperature of the water and the clay at free field (further way from the pipe) was monitored throughout the test using temperature probes for subsequent checking and calibrating of the data.

Second part of the investigation looked at how different backfill material may affect the thermal gradient from the pipe. Four three different backfills were investigated at steady state hot pipe conditions under;

1. Compacted backfill (normal case)
2. Weakly compacted backfill, to simulate when the clay for backfill has been weakened by remoulding and absorption of excess water
3. Sand backfill, to study the effect of heterogeneity on thermal properties
4. Sand and clay backfill (50/50 by weight), for a further study into the case of sand inclusions in the clay

4. RESULTS

4.1. Calculating thermal conductivity

A typical thermal image obtained during the heating up of the pipeline is shown in

Figure 7. From a thermal image, it is possible to retrieve temperature data from every pixel. Figure 8 shows the relationship between temperature and radius for images 431 and 432, and Image 488 which is a steady state image at 40°C pipe. The x-axis shows distance in metres from the pipe edge and the clay/water interface shown clearly at approximately 0.05m.

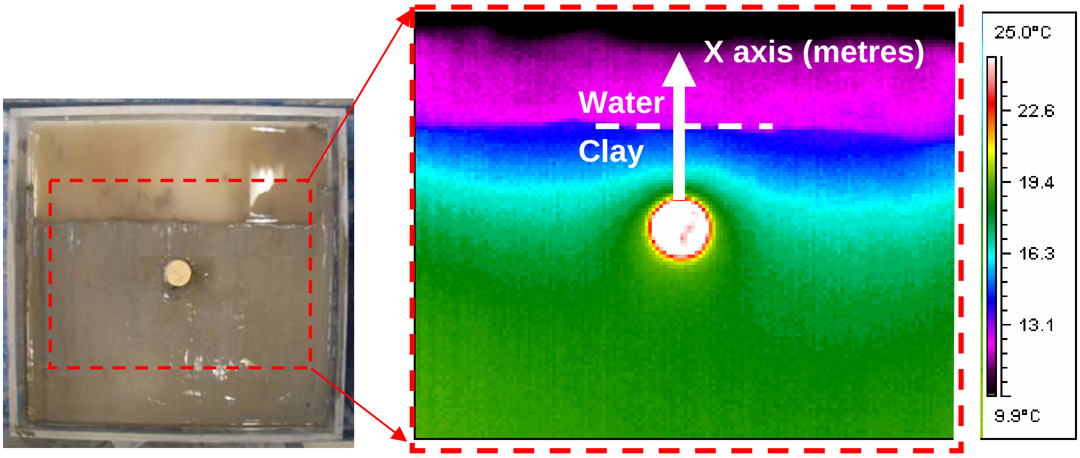

Figure 7. Typical thermal image

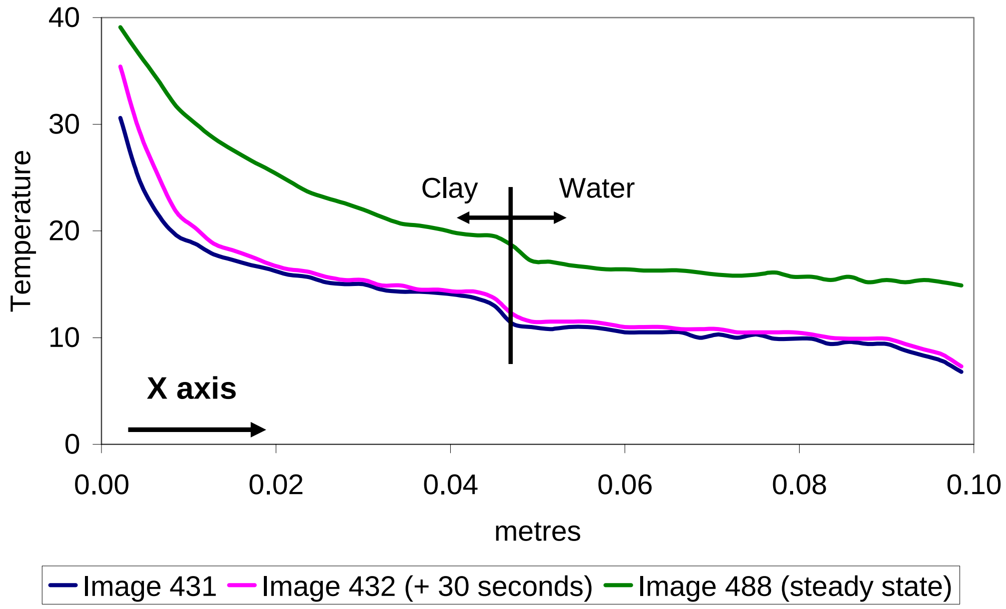

Figure 8. Temperature change with radius for Images 431 (heating phase), 432 (heating phase) and 488 (steady state)

In the following analysis, Image 488 (the steady state image) is used. The water in the pipe had been flowing at 40°C for a sufficient amount of time for the surrounding clay and water to reach a steady state (approximately 15 minutes). Figure 9 shows the experimental data fitted to a best fit line.

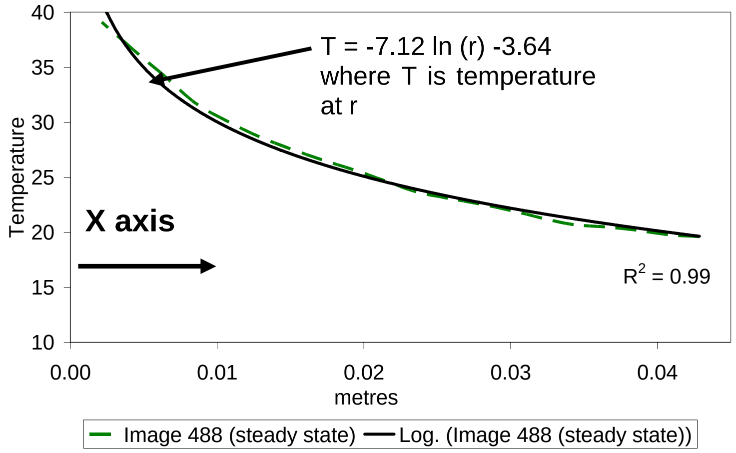

Figure 9. Temperature change in clay at steady (image 488)

Heat flow, Q, radically outwards, and thermal conductivity, *k,* are related as given below.

$$Q = \frac{2.\pi.k.L.(T_1 - T_2)}{\ln(r_2/r_1)} \qquad (3)$$

where, *L* is the length of the pipe, *r* is radial distance from the pipe and *T* temperature at *r*. Q was calculated to be 0.5W based on temperature difference in the inlet and outlet water flow and also based on the radiation temperature loss to surroundings. *K* can now be calculated as 0.937 W/mK based on the results shown in Figure 9. Figure 10 plots the predicted variation of temperature with distance for values of *k* of 0.85, 0.95, 1.05, 1.15. The plot also shows the actual measure temperature variation. It is clear form that the thermal conductivity of this offshore clay is approximately 0.95 W/mK.

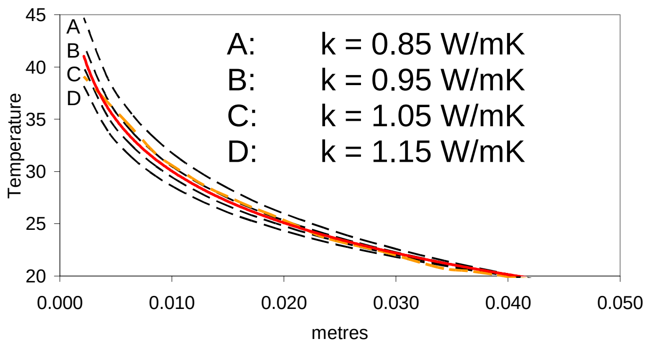

Figure 10. Superposition of a range of k values onto steady state data

We can use the empirical equations to compare the measured thermal conductivity with the predictions; equation (1) in literature review, $k = 0.144 \times [a \times \log(w) - b] \times 10^{c\gamma_d}$ with Cathie et al (2005) suggesting the a, b and c are parameters to be 0.13, 0.029 and 0.6245 respectively, and γ is dry density in kg/m^3. The water content was measured as 0.45 and the dry density as 1.77 g/cm^3 (1770 kg/m^3). This gives an estimated value of thermal conductivity of 0.86 W/mK. Rawat et al (1979) suggested that the maximum error with the Kersten method was 25%. Thus the value is well within that bracket (10% difference). Based on Newson et al. (2002), equation (2), the predicted thermal conductivity is 1.1 W/mK.

4.2. Advantage of thermal images

During heating phase of the pipe images 431 and 432 were taken with a 30 second interval between. These are shown in Figure 11.

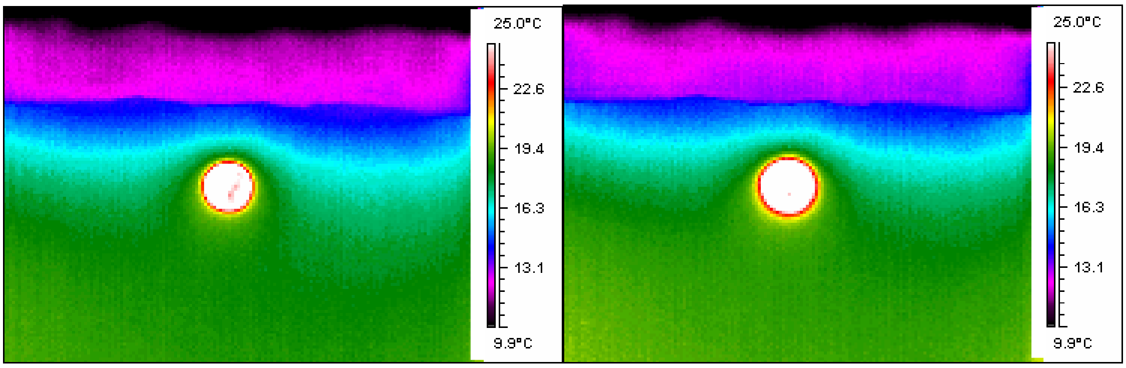

Figure 11. Image 431 and Image 432

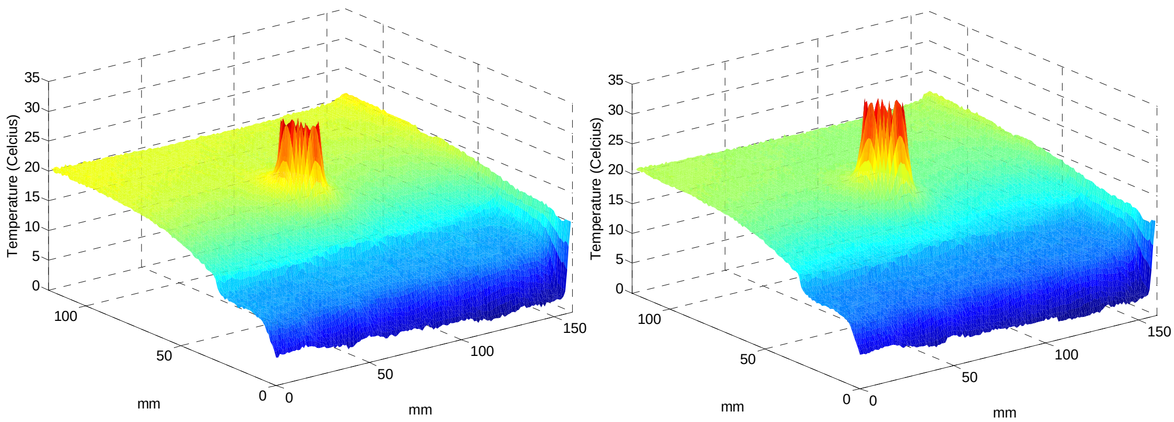

Figure 12. Image 431 and 432 in 3D plot

These thermal images are very useful to find the overall temperature change in the 30s as we could get this by simple subtraction and obtain the change of temperature in a spatial manner as shown in Figure 13.

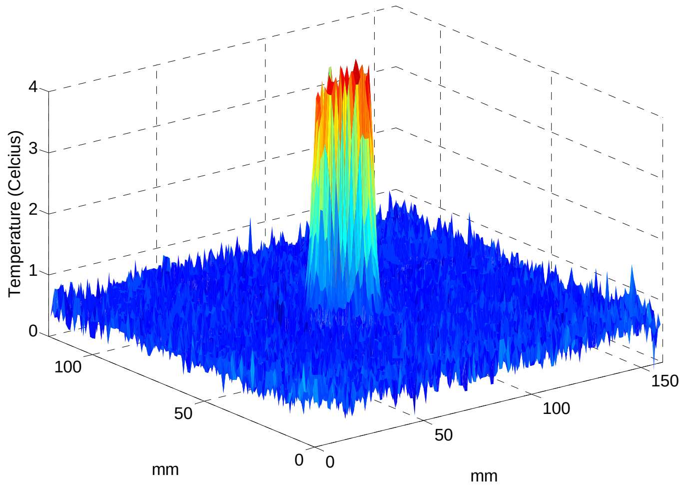

Figure 13. Image 432-431

5. Different Backfills

During the backfilling process, depending on the seabed soil conditions and soil type, disturbances of sand or crumbling of clay lumps usually occur. Thus backfill clay/sand can vary in content and composition. Water can be trapped in between inter-lump voids and water absorbed by lumpy clays. This generally results in the backfill having higher moisture content than the surrounding clay or sand. This may result in the voids between lumps being filled with water, slurry and sand. It is therefore difficult to understand the exact thermal properties of a backfill soil. There is very limited research of thermal conductivity of backfill soils.

The following thermal images are of different backfills on the pipe.

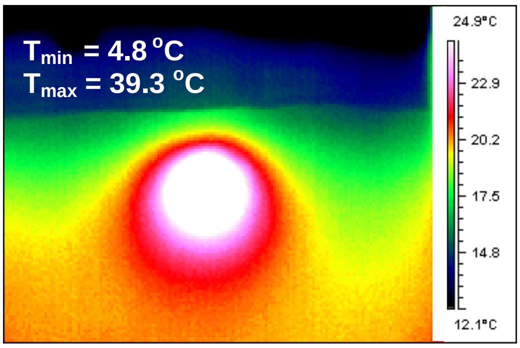

Figure 14. Steady state compacted clay backfill

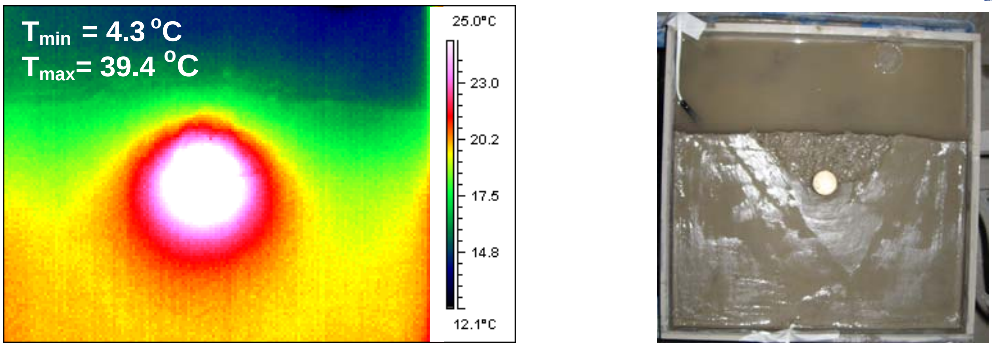

Figure 15. Steady state weakly compacted clay backfill

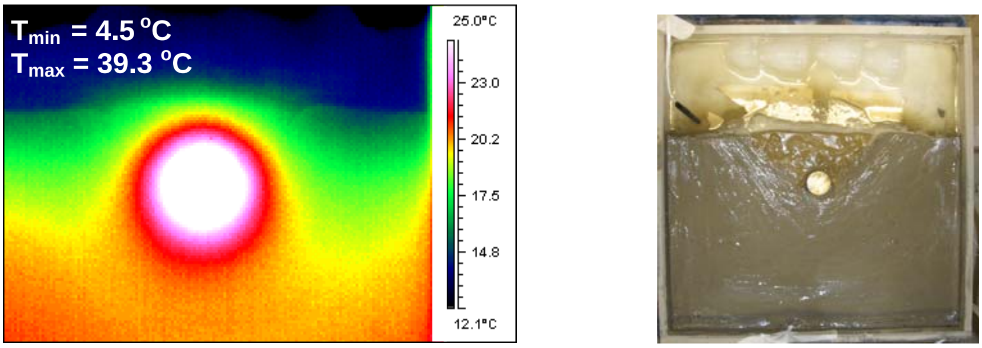

Figure 16. Steady state sand backfill

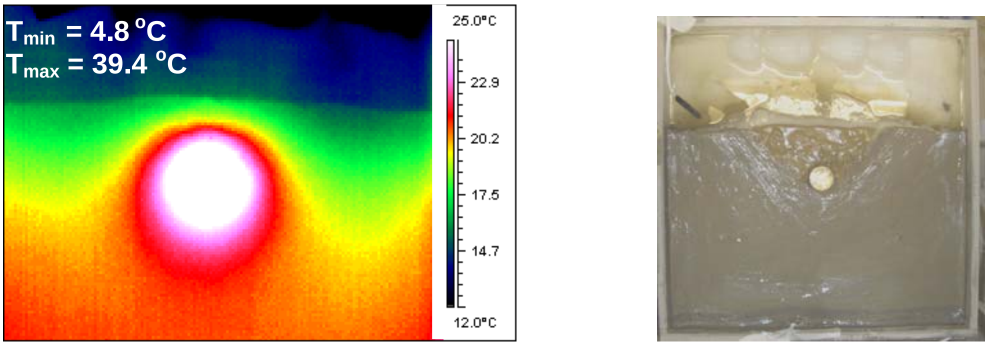

Figure 17. Steady state sand and clay backfill

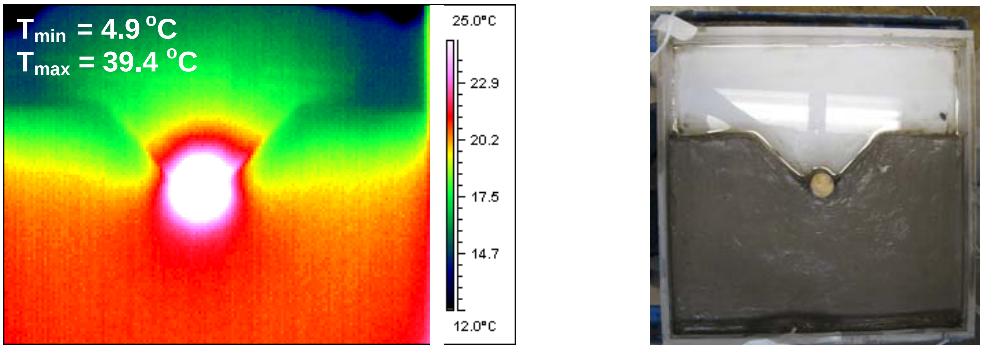

Figure 18. Steady state with no backfill

Figure 19 show the temperature profile in compacted backfill compared with that of weak backfill. It is clear from the figure that weak clay has a slightly higher thermal conductivity than compacted clay. Figure 20 show the temperature profile in sand backfill and sand& clay mixture backfill. The result shows that there is no prominent difference in the temperature profile of sand backfill and sand/clay mix backfill.

It is to be stressed that these observations are preliminary as there are limitations on the current experimental setup. Further research in this area is needed to confirm the initial observations of this experiment.

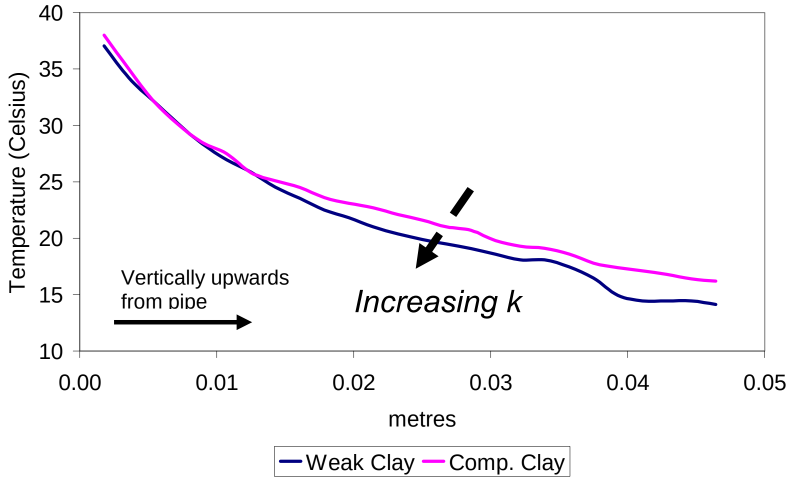

Figure 19. Comparison of compacted backfill and weak backfill

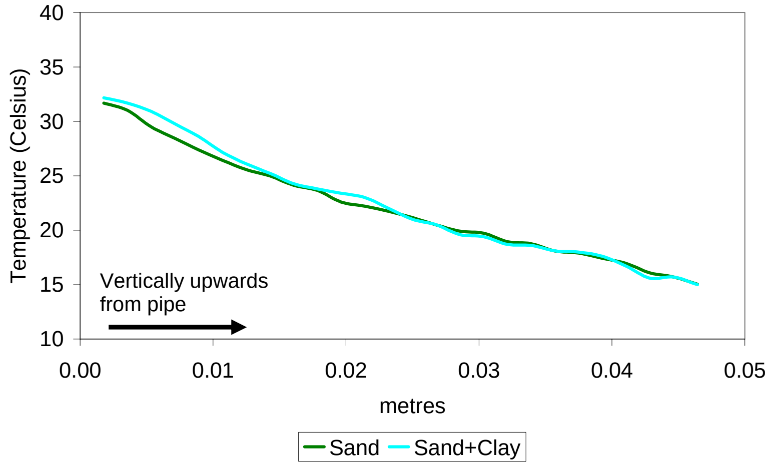

Figure 20. Comparison of sand backfill and sand/clay backfill

6. Pipeline insulation and thermal methods

Thermal methods can be broken down into two categories, those used to prevent wax deposition by keeping the Hydrocarbon fluid above the cloud point and those used to remediate wax deposition. Hydrate formation temperature is normally below the wax appearance temperature.

6.1. Passive Insulation Systems

Passive systems can be categorised as a preventative solution which in effect keeps the hydrocarbon fluid hot so the cloud point is never reached during normal production down to a turn production flowrate. Traditional insulation systems have used a 'wet' insulation material, which is typically polyurethane, polypropylene, rubber or glass reinforced plastic, etc.

Conventional Insulation

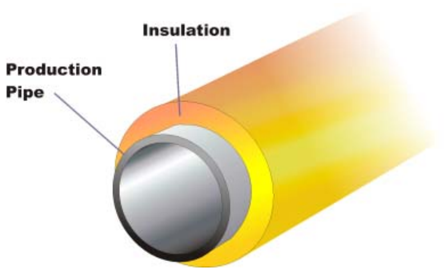

Figure 21. Conventional Insulation Systems

These materials are limited to conductivity or 'k' values of between 0.1 and 0.3 W/mK. To reduce the heat loss from the system requires an increase in the thickness of the insulation, however buoyancy effects limit the overall thickness. As a result of these properties, the overall heat transfer coefficient or U value is limited to approximately 2 W/m^{2}K.

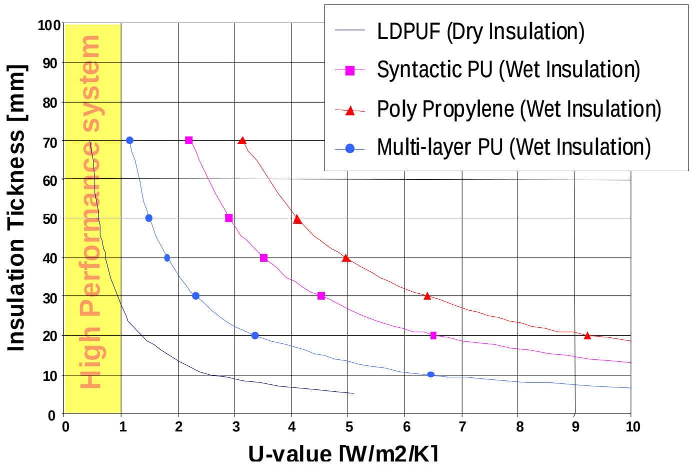

Figure 22. Insulation Thickness v U Value

6.2. Critical Impact of earth covers on other pipeline in the same trench.

Today the appropriate softwares are available to simulate scenarios of in place operation to understand the conditions during the life of field operation. Normally the design temperature of pipeline is defined based of the maximum expected operation temperature of the fluid in the pipeline. In-order to reduce installation cost smaller pipelines (service lines) are often piggy-backed to the bigger pipeline, in gas field development where hydrate management is by continuous injection of inhibitors the pipelines are only coating with corrosion coating, say 3LPP. So a piggy-back line can experience temperature higher than the operating temperature of the fluid it is transporting. This is presented in the simulation below.

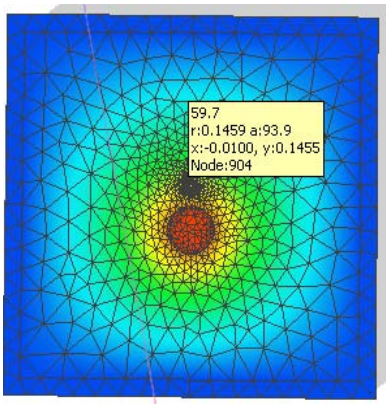

Figure 23. Numerical Modelling

6.3. HIGH performance thermal barrier

For U values below 2 W/m^{2}K, dry insulation materials have to be used. This requires the use of materials such as Aerogel, polyurethane foam or rockwool etc. These materials take their insulation properties from the pockets of gas trapped in their structure and as a result can achieve U values of approximately 1 W/m^{2}K or better. The presence of water severely degrades the performance of dry insulation and a pipe-in-pipe system is therefore required to ensure these low U values.

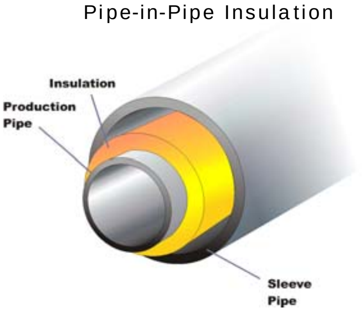

Figure 24. PIP Insulation System

The current trend is to develop systems with lower ‘k’ values to reduce the thickness of insulation and recent applications have shown by the creation of a partial vacuum in the system, U values of 0.5 W/m^{2}K can be achieved. However, for many deepwater and long distance tie-back applications lowering the U value may still not provide adequate thermal management because of low reservoir temperatures or high wax or hydrate formation temperatures. It is in these scenarios that some form of active heating is critical to facilitate production for the development, which is not covered in this paper.

The benefit of earth cover on top of pipeline for a pipe in pipe systems is less compared to the WET insulation system, as there is high thermal barrier achieved within the pipe in pipe DRY insulation material (form).

7. Conclusion

This paper highlights the importance of accurate thermal conductivity assessment of soils for pipeline insulation and presents a new technique, using thermal imaging, to evaluate the thermal conductivity of soils. It is to be noted that the findings in this paper are preliminary and further research in this area is recommended to confirm the initial observations presented in this paper.

8. Acknowledgement

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