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EFFECT OF ATMOSPHERIC TEMPERATURE AND SOIL LOAD ON FLOW IN HIGH DENSITY POLYETHYLENE (HDPE) PIPE

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ABSTRACT

In a bid to reduce the incessant failure of buried pipes, due considerations have been given to the effects of external factors on the pipe structure while the effects of such factors on flow in buried pipes remain unknown. This paper employs the versatility of Comsol Multiphysics to numerically simulating flow in buried pipes in order to examine the effects of atmospheric temperature and soil loads on the temperature, pressure and velocity of fluid. The results show that the temperature, pressure and velocity of water in an unburied HDPE pipe at a distance 1.52m from the inlet are 303.9K, 101235.8Pa and 1.19m/s respectively. Considering the effects of atmospheric temperature on water at the same point in HDPE pipe buried at a depth of 1m in Sandy soil results in a temperature of 293.15K, pressure of 101780.4Pa and velocity of 2.651m/s. Combining effects of soil loads with atmospheric temperature results in a change of these values to 303.91K, 90457.81Pa and 823423.6m/s. The results reveal a need for due consideration of the effects of atmospheric temperature and soil loads on flow in buried pipes before fixing the operating conditions of the pipeline.

Keywords: atmospheric temperature, soil load, HDPE pipe, comsol multiphysics, temperature, pressure, velocity.

1. INTRODUCTION

The long distances over which fluids are transported and their operating conditions have made it necessary to bury pipes in order to protect them from mechanical damages and reduce environmental hazards. Buried pipes are used in water distribution, sewage disposal, transportation of petroleum products, etc. Although the soil cover is expected to keep buried pipes safe, it has been observed that they still fail. Pratt *et al* (2011) noted that pipeline failure is a common occurrence that results in damage to surrounding land and infrastructure. In an attempt to limit and possibly put an end to pipe failures, the interaction between external factors and the pipe structure has been studied.

The common causes of pipe failure have been identified as manufacturing defects, human errors, in-situ failures and corrosion. In their research work on failure modes and mechanisms in gray cast iron pipe, Makar *et al* (2001) identified porosity, produced by air being trapped in the metal as it solidifies, as the most common manufacturing defect in pit cast pipes. They also identified design problems as one type of human error that can contribute to pipeline failures. Cassa (2008) listed internal fluid pressure, super-imposed live loads, vertical soil pressure, self-weight of pipes and its contents, improper material choice, and hydraulic factors such as losses, thrust, water hammer and negative pressures within the pipe among factors that accelerate in-situ failure. Based on the causal agent, the external corrosion of pipes has been classified as differential cell corrosion, stray current corrosion, and bacteriological corrosion.

Makar *et al* (2001) defined the term failure modes as the actual manner in which pipes fail, rather than the mechanisms that cause the failure. They noted that these modes depend on the pipe diameter. Failure modes include circumferential cracking, longitudinal cracking, bell shearing, spiral cracking, bell splitting and corrosion pitting and blow-out holes. It can be inferred from the discussions of Misiunas (2005) and Makar *et al* (2001) on failure modes that the nature of the forces responsible for most pipe failures can be determined from the failure mode.

Asides operational factors and material characteristics, Rajani and Kleiner (2001) stated that the physical environment of the pipe has a significant impact on the deterioration rate. They carried out a comprehensive review of the structural deterioration of water mains and noted that the high breakage frequency of water mains during winter has been attributed to increased earth loads exerted on the buried pipes, i.e., frost loads. Habibian (1994) analyzed the distribution system of Washington (DC) Suburban Sanitary Commission and observed an increase in water main breakage rate as the temperatures dropped. He related the breakage rates to the water temperature at the system intake rather than to the ambient air temperature, reasoning that although their monthly averages are similar, ambient air temperatures display sharp fluctuations while water temperatures are better surrogates for underground pipe environment. He concluded that the water temperature drop, rather than the absolute water temperature, had a determining influence on the pipe breakage rate. Pratt *et al* (2011) observed that the failure rate of both cast iron and reinforced concrete pipes peaked in mid-winter, which was attributed to an increase in soil moisture content causing soil expansion. They noted that the environmental conditions that have the most significant correlation to failure rates are temperature and soil moisture. These authors jointly suggested a correlation between atmospheric conditions and pipe failure.

As seen from the aforementioned, most of the attention has been on the structure-the pipe whereas, the pipes exist because they have to convey one fluid or the other which makes the fluid the most important part of the

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system. Cassa (2008) defined pipe failure as the inability of a pipe to carry out its intended functions. The intended functions of a pipe include the transportation of fluid from one point to the other and delivery of such fluid in the required quantity and quality. Even at times when the quantity of fluid delivered remains the same, the quality might be compromised due to the effects of several external factors. This compromise might go unnoticed if it does not come in the popular forms. However, such compromise may endanger plant and animal lives as well as other infrastructure in the fluid distribution system. This has necessitated the study of the effects of external factors on flow in buried pipes. Thus, this work examines the effect of atmospheric temperature and soil loads on flow in high density polyethylene (HDPE) pipe.

2. THEORETICAL BACKGROUND AND NUMERICAL METHOD

Five basic equations governed this study. They are presented in the vector form as follows:

Continuity equation: $\nabla \bullet (\rho \boldsymbol{u}) = 0$ ……………….. (1)

Conservation of momentum equation: $\rho(u \bullet \nabla)u = \nabla \bullet \left[-PI + (\mu\nabla u + (\nabla u)^T) - \frac{2}{3}(\nabla \bullet u)I\right] + F$ .. (2)

Heat transfer equation: $\rho C_p u.\nabla T = k\nabla^2 T + Q$ ..... (3)

Darcy's law: $\mu = -\frac{\boldsymbol{k}}{\mu}\nabla p + \rho g \nabla D$ ……………... (4)

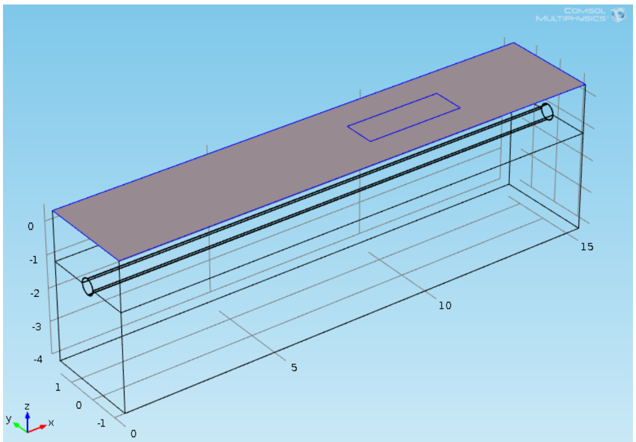
Von Mises stress criterion: $-\nabla\sigma = Fv$ ……………. (5)

In the buried HDPE pipe, the boundary conditions are specified as:

$U = V = W = 0$ at pipe wall.
$U = U_{in}$,
$T = T_{initial}$ at inlet: $x = 0$m
$P = P_{atm}$ at outlet: $x = 15$m
$T = T_{amb}$; $P = P_{atm}$ at the soil surface: $z = 0$
The initial condition is: $T_{fluid} = 20^oC$

Comsol Multiphysics, Version 4.3b was used for simulating the effect of atmospheric temperature and soil load on flow in a buried HDPE pipe in order to determine the change in pressure, velocity and temperature of the fluid as a result of these external factors. Comsol Multiphysics, version 4.3b is a partial differential equation solver which runs the finite element based on a variety of iterative methods. Nikishkov (2004) defined the Finite Element Method (FEM) as a numerical technique for solving problems which are described by partial differential equations or can be formulated as functional minimization. According to him, a domain of interest is represented as an assembly of finite elements for which approximating functions are determined in terms of nodal values of a physical field which is sought. Usually, values inside finite elements can be recovered using nodal values. In this study, four modules of Comsol Multiphysics - Heat transfer, Laminar flow, Darcy's law and solid mechanics modules were coupled.

In order to capture the effects of soil load on the buried pipe, a geometry that enables the application of this load was created. It has a block of length 15m, depth 4m and breadth 3m which was cut at a depth of 1m. A semi-circular groove was then created in each of the two parts to accommodate the pipe. Also, a cylinder representing the fluid was drawn in the pipe. The entire geometry was discretized using free tetrahedral elements with varying sizes to suit each domain of study used. 60, 878 domain elements, 8578 boundary elements, and 1046 edge elements were generated.



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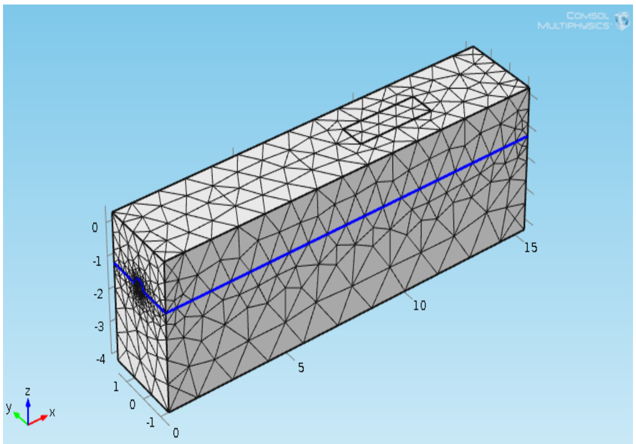

(b)

Figure-1. (a) The 3D Model. (b) The Mesh distribution.

3. RESULTS AND DISCUSSIONS

The analysis was carried out for HDPE buried in two soil types (sandy and clayey soils) conveying either water or natural gas. The first set of analysis involved HDPE pipe conveying fluids above the ground surface, that is, unburied. The second set of analysis considered pipes buried in the different soil types. However, the effects of soil loads were neglected, thus the solid mechanics module was not included. The third set captured the effects of soil loads alongside atmospheric

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temperature. The results of the simulation of flow of water in HDPE pipe buried at a depth of 1m in clayey soil at an atmospheric temperature of 310K (37ºC) are shown in Figures 2, 3, 4, 5 and 6.

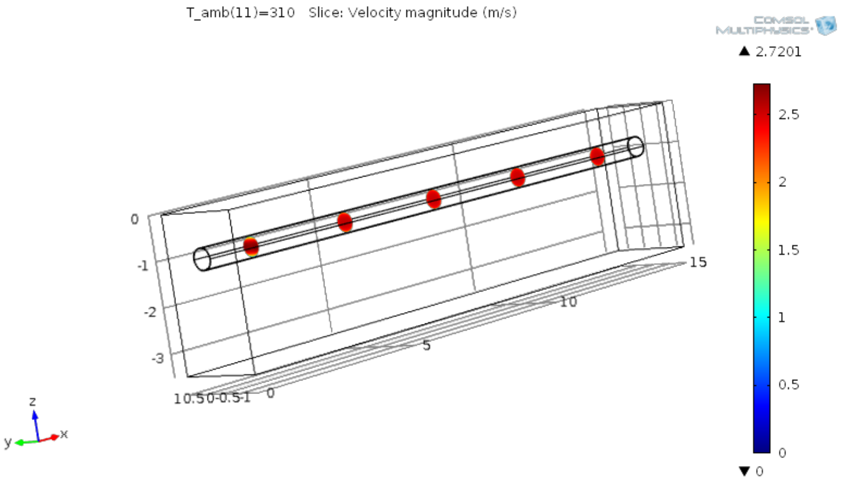

Figure-2. 3D Plot of the velocity distribution in HDPE Pipe (conveying water) buried in clayey soil.

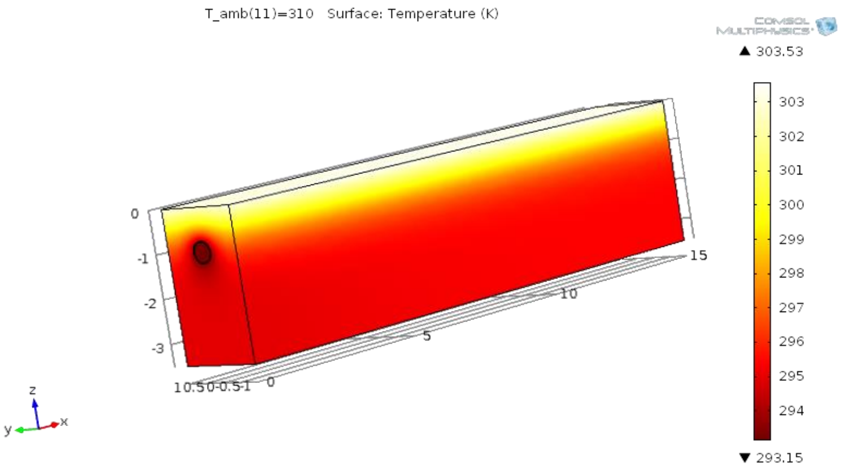

Figure-3. 3D Plot of the temperature distribution in clay soil at ambient temperature of 310K with water flowing in a buried HDPE pipe.

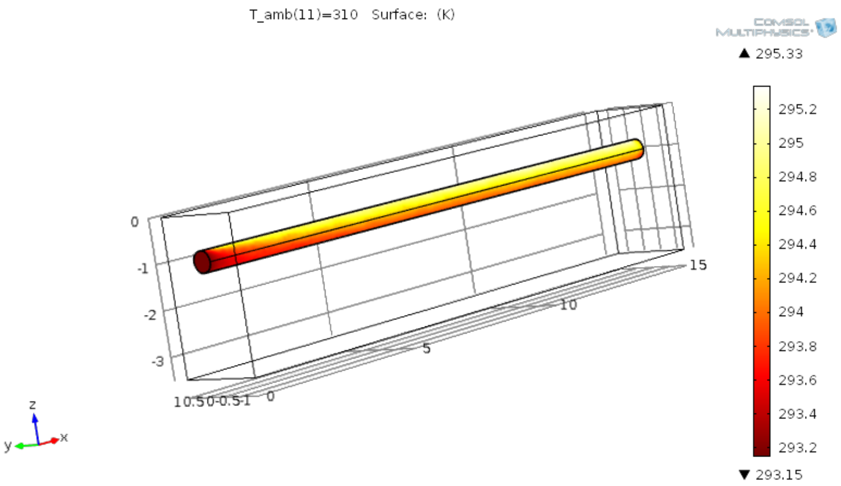

Figure-4. 3D plot of temperature distribution in HDPE pipe (conveying water) buried in clay.

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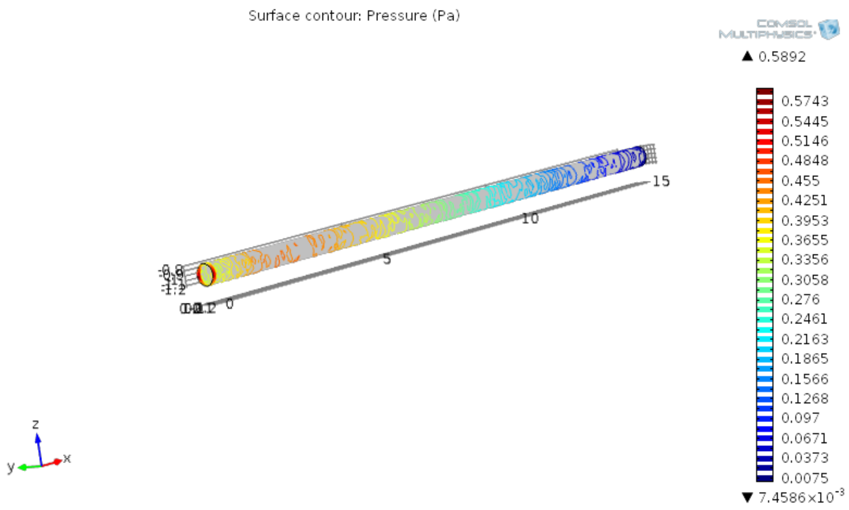


Figure-5. 3D plot of the pressure distribution in HDPE pipe (conveying water) buried in clay.

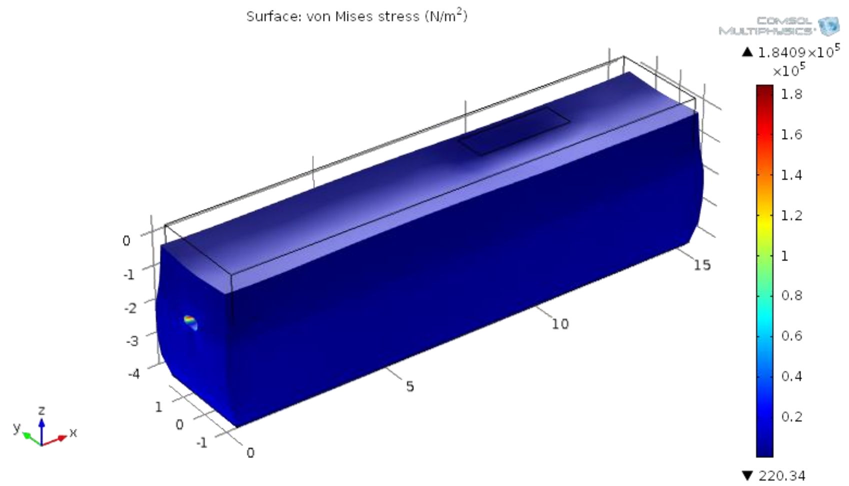
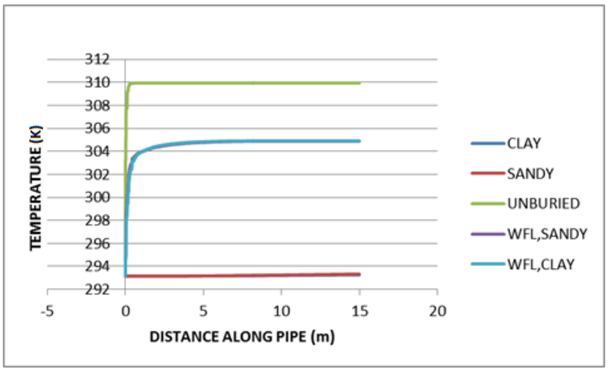


Figure-6. 3D Plot of the stress distribution in clayey soil at ambient temperature of 310K with water flowing in a buried HDPE pipe.

Temperature distribution: Figure-7 is interpreted results of the simulation of the flow of Natural gas and water in buried and unburied High Density Polyethylene pipe at an ambient air temperature of 310K. Figures 7 (a) and (b) compare the temperature distribution in HDPE pipe carrying natural gas when the pipe is unburied, buried in clayey soil with and without consideration of soil loads, and buried in sandy soil with and without the consideration of soil loads. As expected, the maximum temperature is obtained when the pipe is unburied and the minimum temperature is obtained when the pipe is buried without consideration of the soil loads. The increase in temperature observed when the soil load is considered is due to the increase in flow velocity as the flow rate is constant and the flow area is reduced due to deformation caused by the overlaying soil load as well as other live loads. Also, the slight difference observed in the temperature distribution in pipe buried in sandy soil and the one buried in clayey soil is due to the difference in the thermal conductivities of the two soils. Similarly, the difference in the amount of increase in the fluid temperature when the fluid is water is due to the different thermal conductivities of the two fluids.



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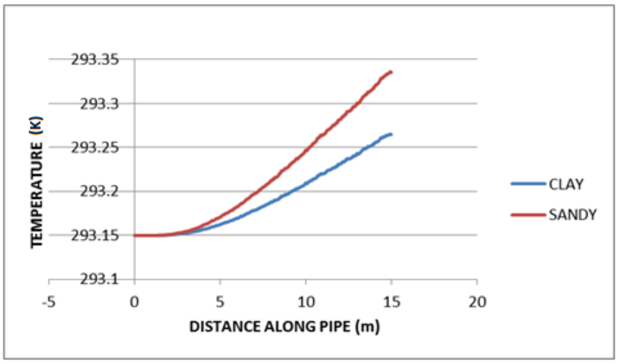

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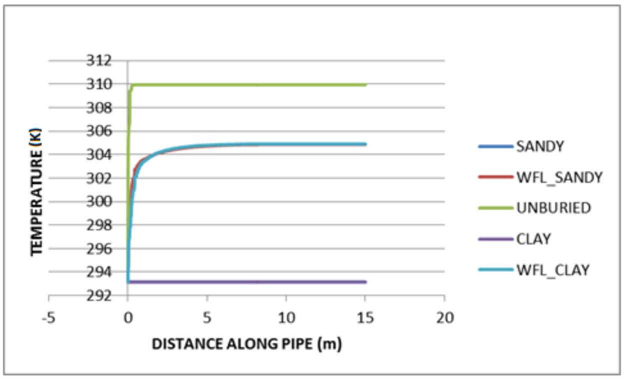

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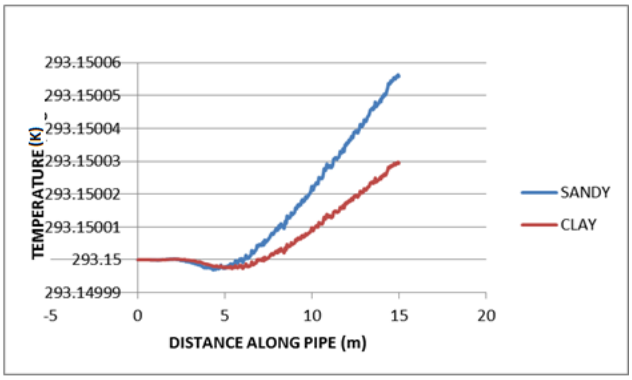
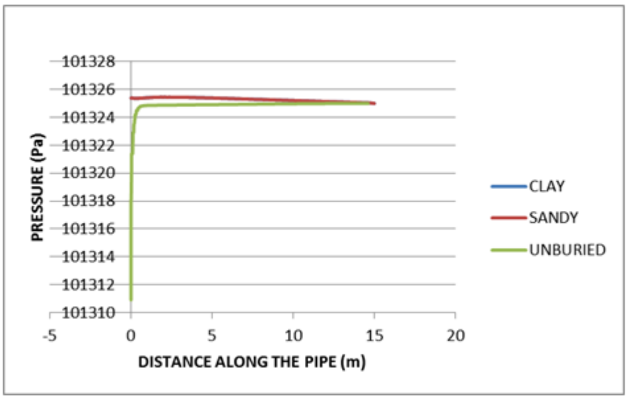


(d)

Figure-7. (a) Temperature distributions along the centre of unburied HDPE pipe and HDPE pipe buried in Sandy and Clayey soils. (b) Temperature distribution along the centre of HDPE pipe buried in Sandy and Clayey soils. (c) Temperature distribution along the centre of unburied HDPE pipe and HDPE pipe buried in sandy and clayey soils. (d) Temperature distribution along the centre of HDPE pipe buried in Sandy and Clayey soils.

Pressure Distribution: It is observed from the Figure-8 that when the pipe is buried, there is an initial increase in the pressure which is followed by a decrease to the atmospheric pressure as the pipe discharges at atmospheric pressure. Whereas, for the unburied pipe which is above the ground surface, there is a rapid increase in pressure and then the pressure remains constant. For the case in which the effects of the soil loads were considered, it is observed that the pressure is majorly dependent on the stress exerted on the wall of the pipe by the applied external loads, with negligible contribution coming from temperature effects. From Figures 8(b) and (d), the pressure is higher in the absence of live loads which indicates that increase in loads reduces the fluid pressure. Water, being an incompressible fluid, experiences a significant decrease in fluid pressure.



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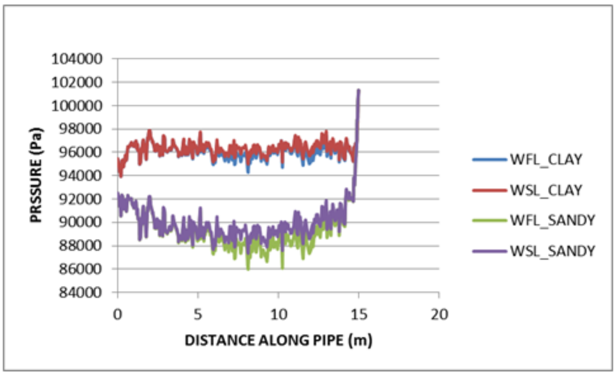

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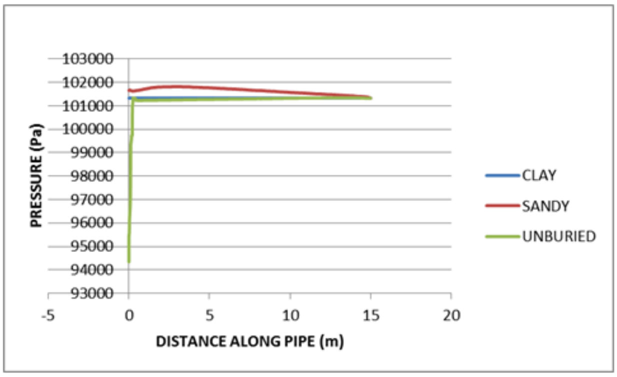

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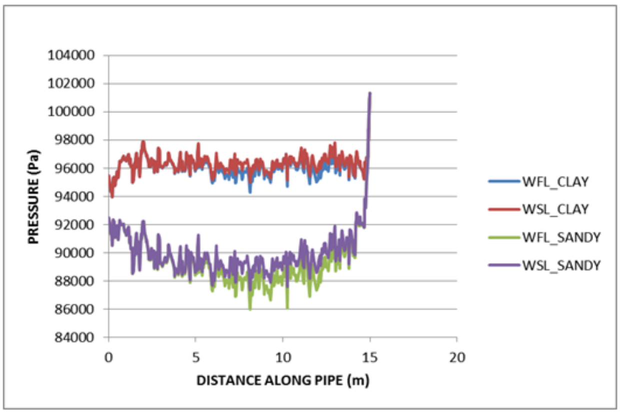
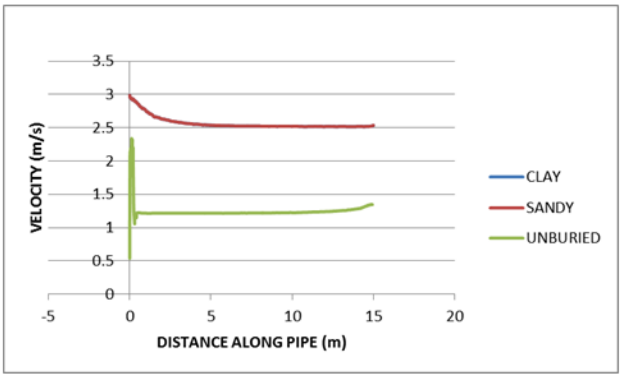


(d)

Figure-8. (a) Pressure distribution along the centre of unburied HDPE pipe and HDPE pipe buried in clayey and sandy soils. (b) Pressure distribution along the centre of HDPE pipe considering the effects of soil load and live loads. (c) Pressure distribution along the centre of unburied HDPE pipe and HDPE pipe buried in sandy and clayey soils. (d) Pressure distribution along the centre of HDPE pipe considering the effects of soil load and live loads.

Velocity Distribution: Figures 9(a) and (c) show a correlation between temperature and velocity distributions. The flow velocity is grossly affected by the temperature of the fluid. Upon introduction of the effects of soil load, a tremendous increase in flow velocity is observed. This is a response to the constriction caused by the applied external soil load. From Figures 9(b) and (d), the region between 9m and 11m along the pipe, where a live load was applied experienced a greater constriction and thus, a further increase in flow velocity. The difference observed between pipes buried in different soil types is due to the variation in density and thus the difference in the response to force exerted per unit area since pressure varies directly with density. The major difference between water and natural gas is in the value of the flow velocity which is much higher for water. This is because water is an incompressible fluid with a much higher density.



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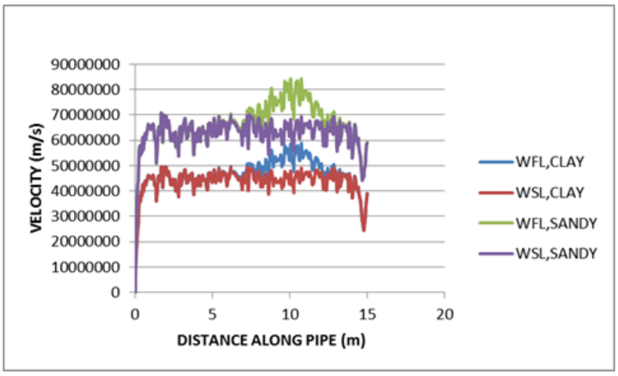

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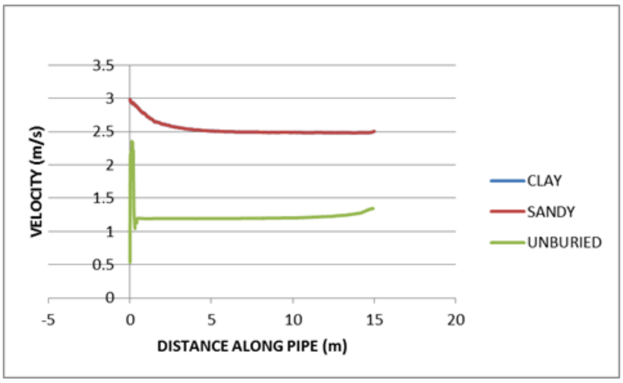

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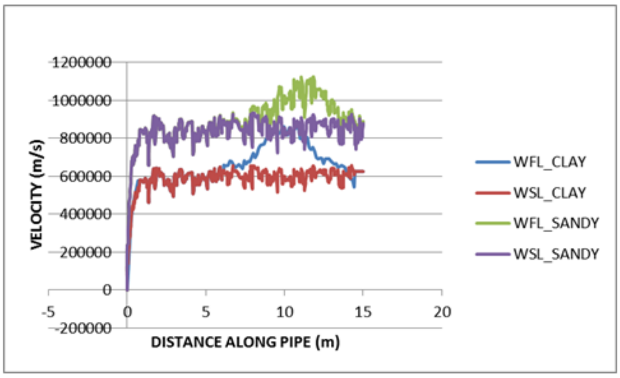

(d)

Figure-9. (a) Velocity distribution along the centre of unburied HDPE pipe and HDPE pipe buried in clayey and sandy soils. (b) Velocity distribution along the centre of HDPE pipe considering the effects of soil load and live loads. (c) Velocity distribution along the centre of unburied HDPE pipe and HDPE pipe buried in sandy and clayey soils. (d) Velocity distribution along the centre of HDPE pipe considering the effects of soil load and live loads.

Variation of the atmospheric temperature between 290K and 310K reveals a similar rate of temperature drop when the atmospheric temperature is less than the fluid temperature. This is illustrated by Figure-10.

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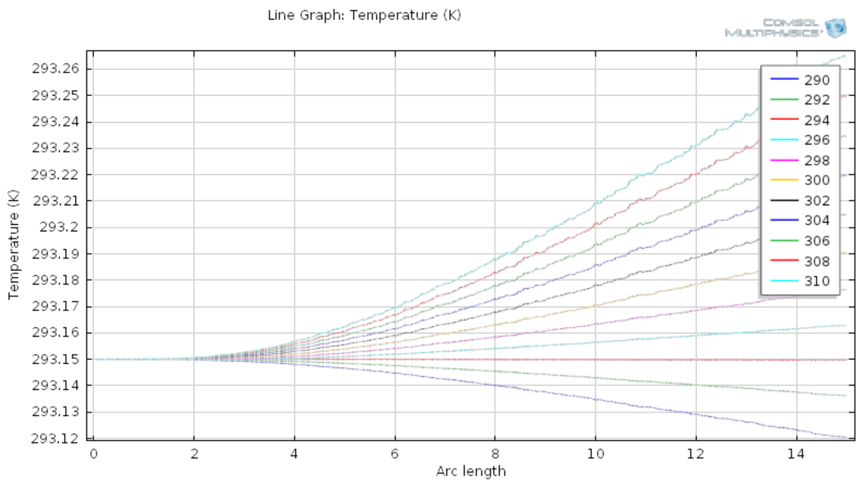

Figure-10. Effect of varying atmospheric temperature on fluid temperature.

4. CONCLUSIONS

Having used COMSOL Multiphysics to model the interaction between the pipe and the ground, the velocity, temperature and pressure distributions of fluid in the buried pipe were obtained. From the analysis of these distributions, the following conclusions stemmed out.

a) The variation in the temperature of fluid in buried pipes when the effect of soil load is not considered is very negligible as the soil absorbs most of the heat from the atmosphere. However, a significant increase is observed upon consideration of the effect of soil loads although the temperature doesn't get as high as that in an unburied pipe. Also, the increase in fluid temperature along the length of the pipe is steady.

b) When the effect of the soil load is neglected, the increase in flow velocity, though little, is significant. The reduction in flow area due to the compression of the pipe by the pressure from the soil causes a large increase in the flow velocity upon consideration of the effects of soil loads alongside the atmospheric temperature.

c) In the same vein, the increase in pressure upon consideration of the effect of atmospheric temperature only is quite negligible. However, the soil load causes a great decrease in the pressure of fluid in a buried pipe.

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