Thermal Analysis of Submarine Power Cable Considering Natural Convection

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Abstract: Conventional Energy production techniques consume fossil fuels and thus contributes to anthropogenic climate change. Migration from conventional and centralized energy production centers to green energy have generated the demand to look for alternate sources i.e. tidal and wind and location (ocean) for energy production. Ocean energy with vast potential and varying methods of generation has emerged as an alternate to fulfil the energy demand. However, transportation of this generated energy and distribution of energy across the marine environment require a new incite to the existing methods of calculation for sea floor temperature rise due to buried power cables. These methods neglect the effect of natural convection which is a significant factor for high permeable North and Baltic Sea surface composition. These seafloor are largely composed of Gravel and coarse sand. This study encompasses two scenarios of heating of ocean floor 1) Energy production (Wind Power Station) 2) energy transmission across the seas connecting neighboring landmasses. The simulation results show that neglecting natural convection underestimate the seafloor temperature rise which could be disastrous to the flora and fauna in cable vicinity and can cause permanent change to the sea bed.

Keywords: Submarine power cable, Natural convection, FEM, Heat transfer, Power transmission.

1. Introduction

The first submarine cable to carry electricity was laid across the Isar river in Bavaria, Germany during 1811. The importance and development in technology and design of submarine power cables in terms of capacity and length has increased since then and in the past two decades, with advent of offshore renewable energy such as wind, marine and tidal installation, a network of cables are laid near and far from the shore line. The generated energy from these decentralized power production centers, which are far from industrial/consumption centers has generated the demand to reassess the power transmission systems. Submarine power cables are used to transmit the power across or from a water body. The installation and maintained of this system is cheap and a huge requirement is at horizon due to increasing demand of green energy. However, the generated energy is causing minimum environmental damage but the transportation of this energy emitting heat into the surrounding seabed can cause serious damage to the flora and fauna.[1 2]

Submarine power cables are of two type based on the current (i) High Voltage Alternating Current (HVAC) and (ii) High Voltage Direct Current (HVDC). AC cables are either 3 phase bundled in core or three separate cable, while HVDC may be monopolar (bundled together) or bipolar (separately lay).

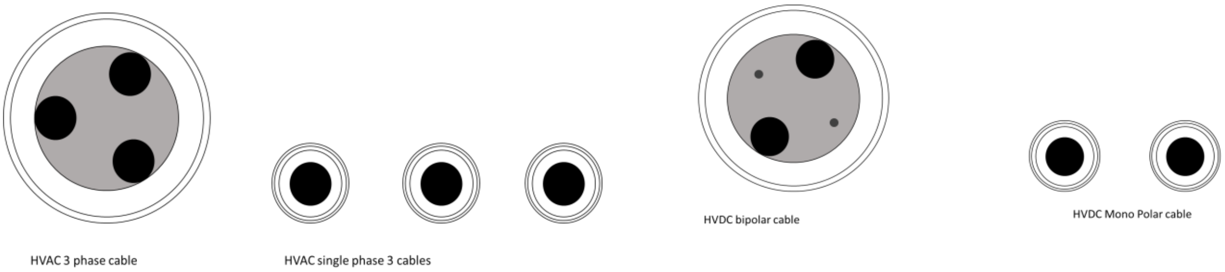


Figure 1: Showing two different kind of submarine power cable system and arrangement.

Both of these power cables dissipate heat into the surrounding due to Joule losses (I^2R). Typically, HVAC cables are used for transmission distance of 150-180 km., above this distance, the transmission losses become high and HVDC is more cost effective. Cables laid on the seafloor dissipate heat in their surrounding water and is washed away. These installation are not permitted as they can alter the marine inhabitants & the cables can strangle with ship anchors in near shore scenarios. Therefore, cables are buried between the depths of 1.5 m-2.5 m under the seabed depending upon the scouring currents.

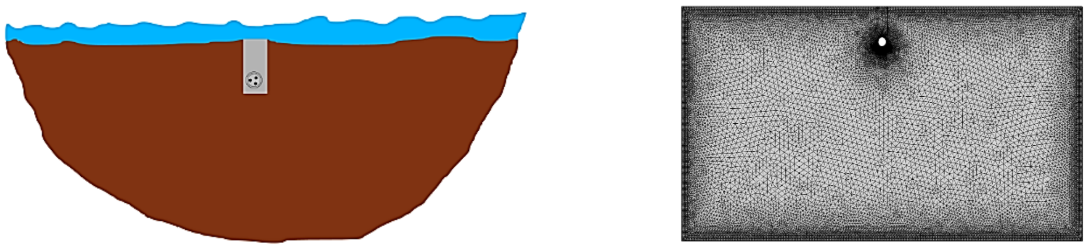
To cope with the situation of damage to the marine environment German environmental authority (Nationalparkverwaltung Niedersächsiches Wattenmeer) & German environmental authority (Bundesamt für Naturschutz) has recommended a 2K rise limit above the cable axis at 0.3 m below the seafloor, 0.2 m in Exclusive Economic Zone.

A calculation method based on Line Source Model (LSM) is applied in general given by IEC for the temperature field distribution around these cables. This method is not suitable to compute the complex seabed scenario. The controversy over application of this method is discussed in detail. [3,4,5,6] A Finite Element based approach is applied by Brakelmann[7] Stammen [8], In their study they consider heat transfer from cable due to conduction and convection. Convective heat transfer is imposed using and average convective heat transfer coefficient term based upon the low and high tide. These calculations are done only considering sediments with very low hydraulic permeability. However, near-shore marine and estuarine sediments tends to show variations horizontally and vertically over short distances, with a corresponding variation in thermal properties. Furthermore, the hydraulic regime in such an area is one of high activity, and as such, contributes to potential scour problems. Therefore, conventional land approaches are not directly applicable to the ocean environment.

In most cases, near shore backfill is in saturated condition. Most of the seabed in North and Baltic Sea are consisting of (1) clean granular sediment, poorly graded quartzite sands (2) fragmented glacial deposits. Clean quartzite sands with high thermal conductivity and permeability is ideal for heat dissipation and moisture replenishment. However, near the shore sandy-silt and sludge is also found. [9] Experiments has suggested that placing the offshore cables in sand and gravels with high permeability avoids the formation of 'Hot spots' around the cable thus preventing failure in insulation. [10] Placements of these power cables is gravel and highly permeable sand generates density driven flow adding to the mechanism of heat transfer.

Heat and mass transfer in a porous media is a complex phenomenon. Calculation of heat transfer neglecting natural convection for the grain size more than 6mm result in under estimation of temperature field [11]. Coupling temperature driven buoyancy and heat transfer in porous media also explain the maximum temperature directly above the cable and not on either sides of the cable as reported by Brakelmann & Stammen[12].

Figure 2: Schematic diagram showing submarine cable is trench. a) Uniform bed b) Finite element model of the



system. Red box in figure 1a showing the control volume.

To our knowledge based on Literature survey no such study in performed to observe the natural convection due to submarine power cable embedded in porous seabed (coarse sand and gravel). Therefore, a mathematical model is setup to observe the near shore and off shore heat transfer around the cable under varying cable temperature and seabed soil conditions with native and modified backfilling of the trench.

In this study, a 2D numerical model is established to simulate the effect of natural convection around the buried submarine power cable. An investigation is performed to see the effects of change in permeability of the seafloor. The finite element package COMSOL Multiphysics is used to couple the heat transfer and convective fluid flow among the pores using flow equations.

2. Finite Elements coupled Heat and Mass transfer model

A detailed theoretical and experimental study related to convective flow of fluid in bounded and unbounded porous media is available. Theoretical work by Lapwood[13] which was confirmed by Katto & Masuoka [14] neglected the viscous effect, thus significant error arises near the solid boundaries in absence of boundary layer effect. Numerical solutions for the natural convection in enclosed porous media using Darcy's law is presented by many authors Chen [15] Farouk & Shayer [16] and Himasekhar& Bau[17] work on a heated cylinder in semi-infinite and bounded porous media is a noteworthy contribution.

To model the problem unsteady laminar natural convection flow has been considered to model the flow due to internal heat generation in a water saturated porous sand. The free convection problem is model by introducing Boussinesq buoyancy term to the Brinkman's momentum equation, and then coupling the resulting velocities to the heat transfer in porous media equation.

$$\frac{\rho}{\epsilon_p}\frac{\partial \boldsymbol{u}}{\partial t} = \nabla.\left[-\mathrm{p}\mathbf{I} + \frac{\mu}{\epsilon_p}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) - \frac{2\mu}{3\epsilon_p}(\nabla.\boldsymbol{u})\right] - \left(\frac{\mu}{\kappa} + \beta_F|\boldsymbol{u}| + \frac{Q_{br}}{\epsilon_p}\right)\boldsymbol{u} + \boldsymbol{F}$$

$$\rho\nabla.\boldsymbol{u} = Q_{br}$$

The Boussinesq buoyancy term in equation (1) accounts for the lifting force due to thermal expansion. The boundary conditions for the Brinkman equations are all no-slip conditions.

Transient porous heat transfer equation

$$d_z(\rho C_p)_{eff}\frac{\partial T}{\partial t} + d_z\rho C_p\boldsymbol{u}\nabla T = \nabla.(d_z k_{eff}\nabla T) + d_z Q + Q_{vd} + Q_p + Q_{oop}$$

The heat diffusion equation for 3D is used to model the heat transfer in porous media. The width parameter d_z is fixed to 1m for 2D analysis. Effective values of heat transfer and thermal conductivity parameter are calculated as below.

$$(\rho C_p)_{eff} = \theta_p\rho_p C_{p,p} + (1-\theta_p)\rho C_p$$

$$k_{eff} = \theta_p k_p + (1-\theta_p)k$$

2.1 Initial Condition for Boussinesq Equation

Eq. 1 & Eq. 3 are strong nonlinear problem and represents convergence task for the most nonlinear solvers. Even without Boussinesq term, the Brinkman equations are nonlinear alone. Therefore, the coefficient of volumetric thermal expansion β is increase stepwise and use solution of previous step as initial condition. This iterative approach solve the problem of convergence.

In most of natural convection solution with various methods, the isothermal boundary conditions are assigned on the external boundaries of the submerged ground and the effects of seabed temperature change over the year is ignored. In this model we have considered the fluctuation of seabed temperature and assigned the measured value obtained from direct measurement in the Baltic Sea.

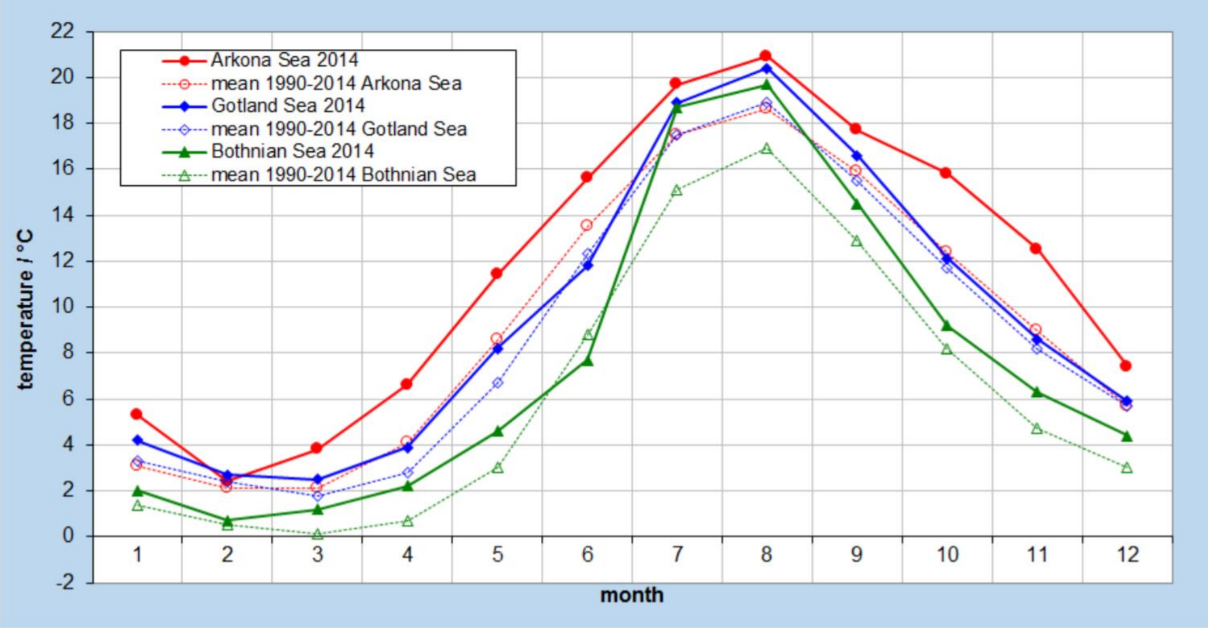


Figure 3: Fluctuation of seabed temperature change over a year in Baltic Sea.

3. Results & Discussion

Numerical simulation is performed to calculate the effect of natural convection due to submarine power cable in semi-infinite porous media. First the calculations are done to observe the buoyancy effect and the velocities are calculated. These velocities then used in calculation of temperature field considering the effect of natural convection. The cross flow velocity profile is not considered in these calculations. In case of strong cross flow the thermal plume will be shifted along the flow thus causing a different zone of heating. Sea bed temperature of 10^{o}C is assumed to match seabed temperature for Wind Power Station (WPS) case. This is a short term simulation running for 5days and a large variation in temperature is not expected. A maximum of 60^{o}C cable temperature is assigned for Wind Power Station (WPS) and 90^{o}C for power transmission along the seabed. A temperature of more than 90^{o}C in avoided in these XLPE cables to avoid melting of surrounding insulation for the conductor.

Temperature and flow boundary conditions are shown in figure 4 and the values are tabulated in Table 1. The system is modeled as close system only allowing energy transfer to the surrounding.

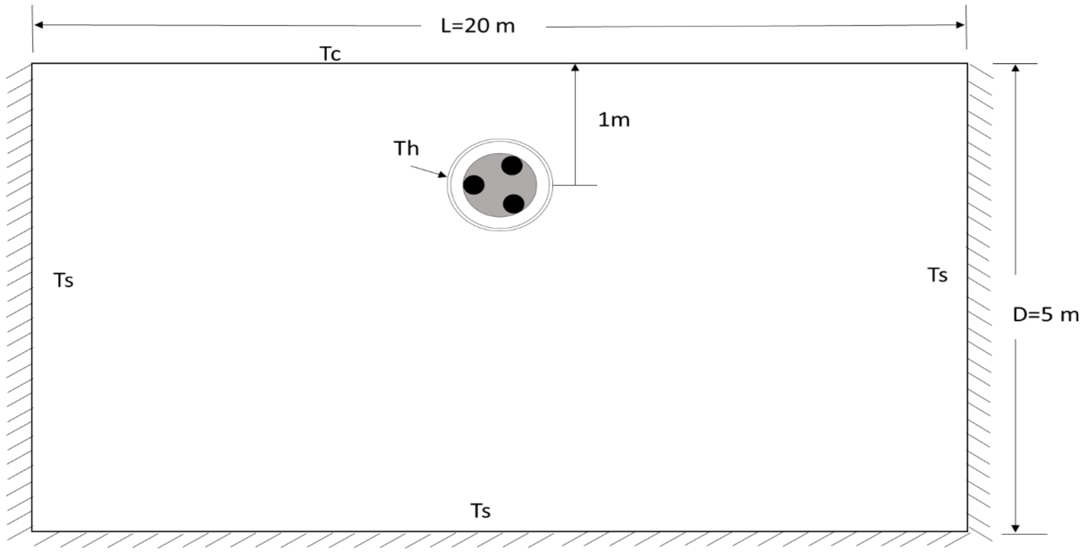


Figure 4: showing temperature and flow boundary condition. No flow is allowed from system to the surrounding.

As most of the submarine cables are laid with a calculated tensile stress, these cables are always in tension. Differential rise in temperature due to local soil condition cause the cable to expand at these location. Improper surrounding soil temperature calculation can cause insulator failure around the conductor, seabed temperature rise and worst case breaking of the cable due to "hot spot" generation.

Burying the cable deep into the seabed helps in avoiding the environmental criteria (2K criteria), but increases the budget of the project. Also it is difficult to retrieve the cable after the service life. On the other hand, shallow buried cable don't meet with the environmental criteria.

The following results indicate the heat transfer calculation only considering conduction equation are not sufficient in gravels and coarse sand with high permeability.

Table 1

Parameters (Sea water)	Values
Density	1029[kg/m^3]
Dynamic viscosity	0.00188[Pa*s]
Volumetric thermal expansion	170e-6[1/K]
Thermal conductivity	0.563[W/(m*K)]
Ratio of specific heat	1.004
Heat capacity at constant pressure	3985[J/(kg*K)]
Hydrostatic pressure	1.5[atm]

Parameters (Soil Matrix)	Values
Thermal Conductivity	2.0[W/(m*K)]
Heat capacity at constant pressure	1440[J/(kg*K)]
Density	2100[kg/m^3]

Calculation are performed for 5 days for Wind Power Station (WPS) and 1 year assuming a constant operating voltage, generating a constant temperature around the cable. A significant temperature rise due to natural convection is observed for gravel and coarse sand. These results indicate that natural convection must be considered in calculation when gravel and coarse sand with high permeability is encountered at the seafloor bed.

The limiting factor in cable efficiency is the ability of these cables to dissipate heat in the surrounding. Therefore, a high thermal backfill material is placed near these cables to dissipate the heat faster and avoid the hot spot formation. Simulations are performed to model this scenario for both short and long term effect. The results suggest as shown in figure xx that the existing model without considering the effect of convection underestimate the temperature rise in a gravel seabed.

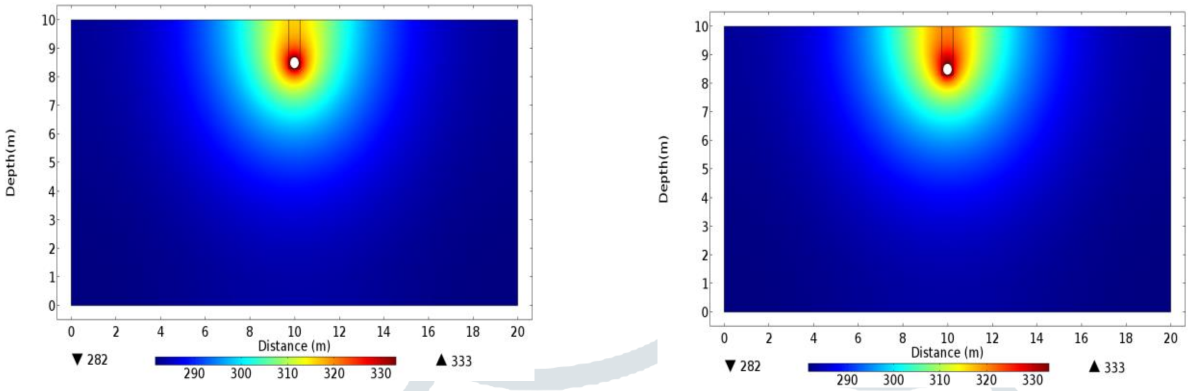


Figure 5: Evolution of temperature field after 365 days around the cable. a) Only conduction b) with natural convection $K=10^{-9}m^2$ c) with natural convection $K=10^{-8}m^2$ d) with natural convection $K=10^{-7}m^2$

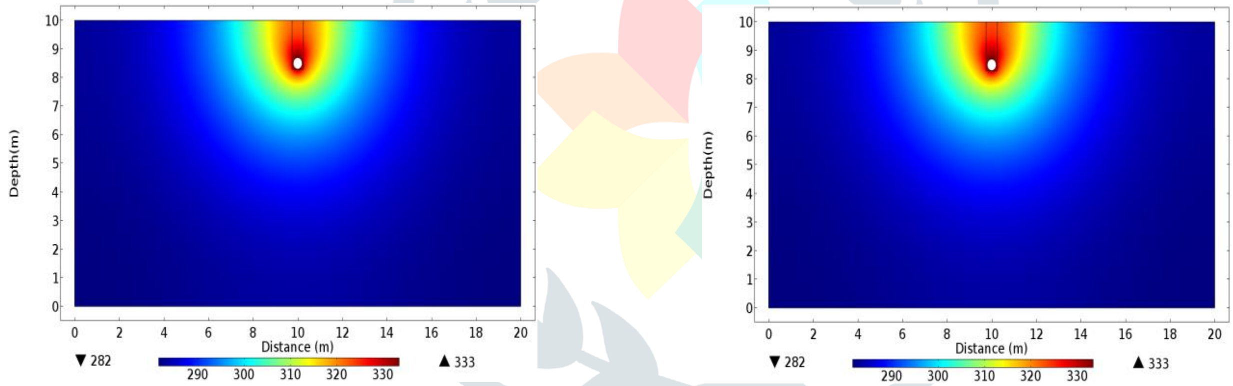
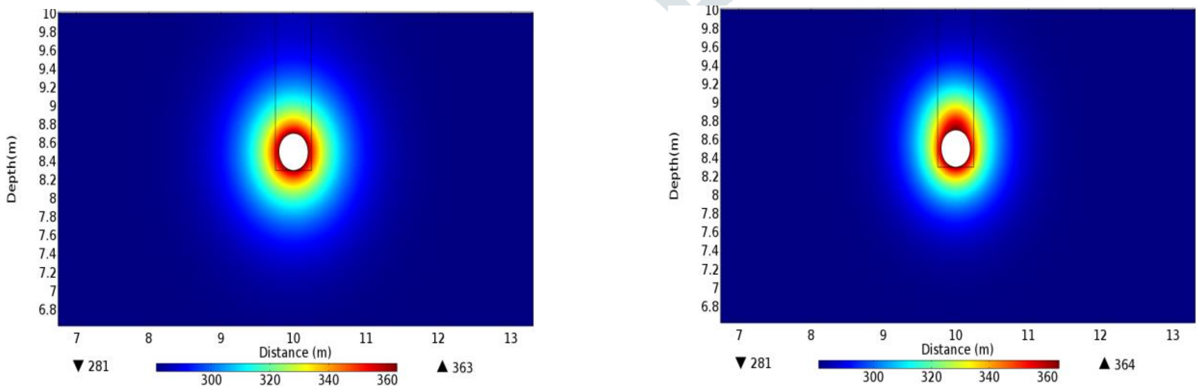


Figure 6: Temperature rise above the cable at 0.2 m depth from the surface considering low thermal conductivity of 2.0 W/m.K (native material) after 5 days a) without natural convection b) with natural convection.



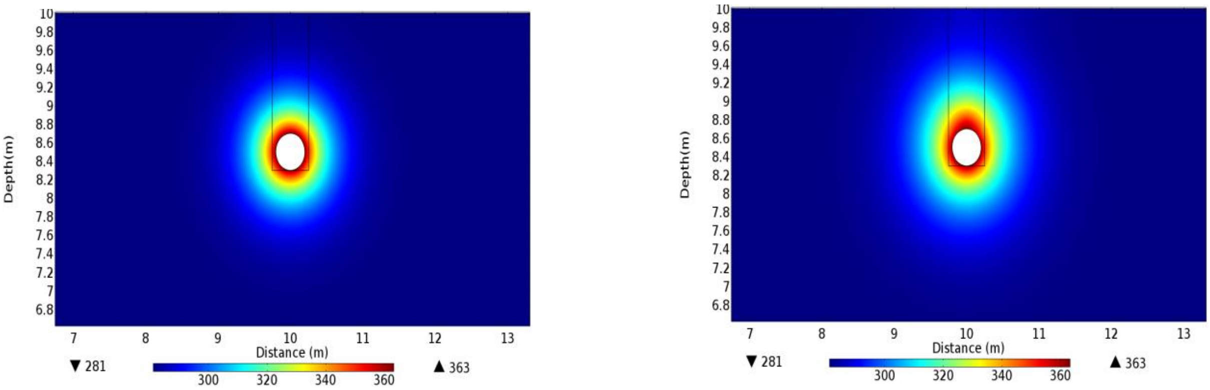


Figure 7: Temperature rise above the cable at 0.2 m depth from the surface considering high thermal conductivity of 3.5 W/m.K (trench backfill material) after 5 days a) without natural convection b) with natural convection.

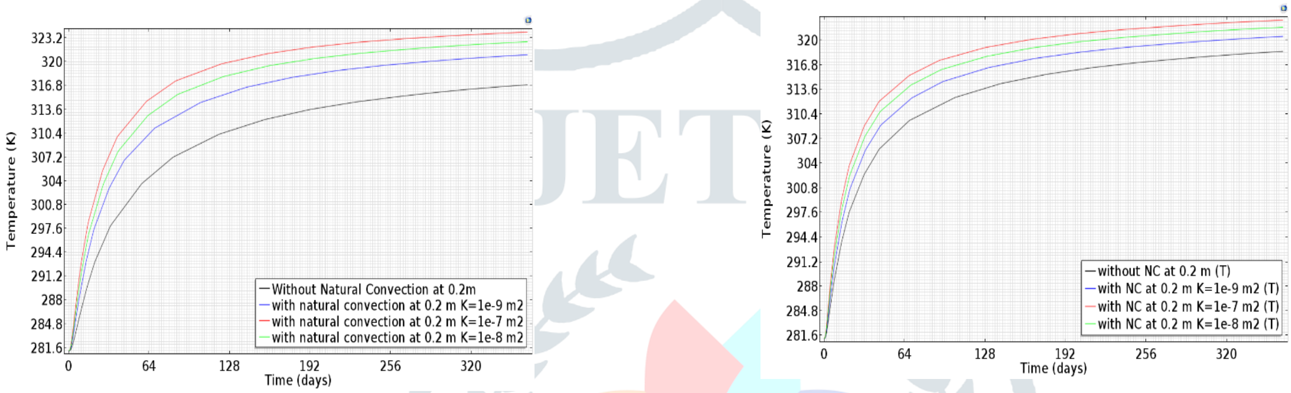


Figure 8: Temperature rise above the cable at 0.2m depth after 365 days a) in native soil b) with modified trench backfill.

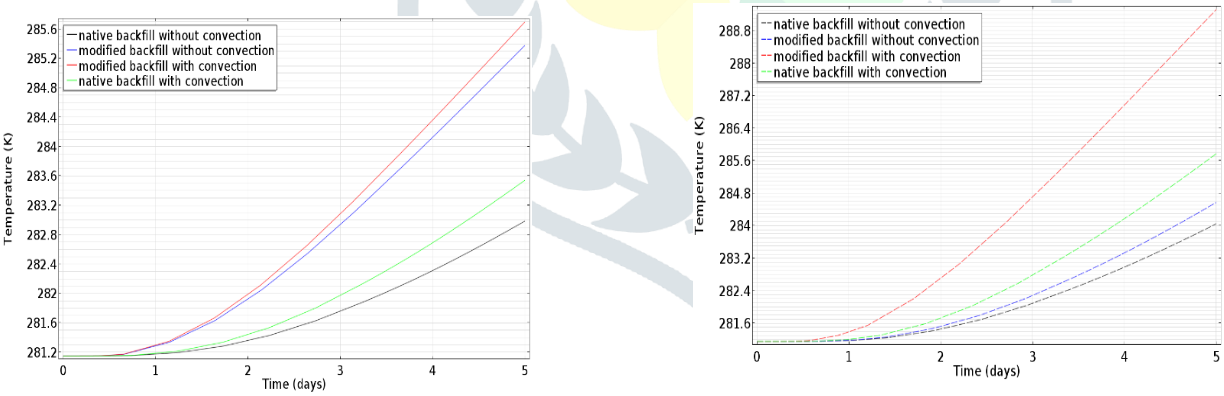


Figure 9: Temperature rise above the cable at 0.2m depth after 5 days a) in native soil b) with modified trench backfill.

Conclusions

Comparison of heat transfer characteristic with fine grain soils such as clayey and silty bed to that of coarse grain beds such as gravel and coarse sand suggest that, although coarse grain soils has the effect of natural convection which violates the 2K criteria it has the advantage of preventing hotspot formation around the cable thus damaging the insulation.

Concluding, it is emphasized that an optimum design brings not only an detail understanding of technical aspects related to electrical transmission by buried cables, but on the concept of multidisciplinary processing of the marine world.

To reduce the temperature to meet the 2K environmental criteria, cable trenches are filled with high thermal backfill material. These materials are less permeable as they are made up of more than 70% fine grain content. These modified backfill materials suppress the formation of convection cell formation due to low permeability. However, the technique work to reduce the heat accumulation near the cable, the method is costly and brings environmental constrains for implementation.

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