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Thermal Analysis for Underground Power Cables with Different Arrays in Hot Places

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Abstract

In this paper, the electrical cables have been studied numerically and the effect of soil on its cooling has been investigated. The thermal conditions applied for hot climate temperature such as in south of Iraq data. Different cables arrays for three phase connections of electricity were done (horizontal, vertical and inclined (Which is new compared to previous researches) arrays). The arrangement of cables was buried and passed underground level for mechanical and electrical protection in addition to cooling them by conduction of low soil temperature. The cables of 19 strand wire (7mm diameter for each) homogeneously distributed inside a layer of insulation according to standards. The cables were placed at the centre of soil domain to utilized from a uniform temperature distribution due to the cold soil temperature in hot places. Heat flux assumed to flow from the outer surface of cable insulation to determine the temperature distribution in the domain and cables for selection of good insulation at peak electrical loads and hot weather conditions. The results showed that the maximum temperature was for the medium cable and that the electrical cables in hot areas should be buried underground at a depth of approximately 4 m to keep them from mechanical and electrical damage.

Keywords: cables, cable arrangement, heat flux, underground cable.

1. Introduction

Electrical cables are widely used in distribution networks and power transmission. Although overhead lines are prioritized for electrical transmission lines, since they are ensuring secure operation, safety of life, and aesthetic appearance in intense settlement areas. When voltage, current and transmitted power are increased, it needs a simple structure of cables to quite rigid structure by increased mechanical, environmental and heat strains. Analytical and numerical approaches are accepted for defining power capacity of cables. IEC 60287 standard is used for analytical approaches in homogeneous ambient weather conditions and on easy geometries. The surrounding environment formation of a cable with some materials have different thermal properties, variable temperature limits, and cable heat sources, make difficulty of analytical solution. Therefore, the numerical solution can be used only. The most favorite numerical solution among many numerical solutions is the finite element method to based on power cables structure [1-3]. Calculations in thermal analysis are made usually by using only boundary temperature conditions, geometry, and material information. Because of problem difficulty, the power parameters effects on temperature or temperature effects on power parameters are very rare performed [4]. Dehning et al., 2006 [5], and Zimmerman, 2006 [6] calculated the theoretical fundamentals to determine the temperature distribution around and in a power cable. Their aim is to get the heat distribution by voltage applied consideration, current, and power cable electrical parameters. Karahan et al., 2009 [7] modeled an electric-thermal model of 10 kV, XLPE insulated medium power cable and 0.6 / 1 kV, PVC four-core insulated of low voltage electric cable are simulated by ohmic losses account. Electrical cables are exposed to mechanical, thermal, and electrical stresses simultaneously by current passing and applied voltage. In addition, in the dielectric material structure the chemical changes occur. Electrical treeing and partial discharges significantly reduce the cable life. When power cables exposed to high temperatures, thermal stresses on aging happen on the cables (Malik et al., 1998 [8]). The favorite materials for wires of cable industries are Copper and Aluminum because their volume resistivity is 0.01724 Ω-mm^2/meter and 0.28264 Ω-mm^2/meter at 20 Deg. C, respectively.

The aim of study to simulate the different cables system arrays to know the lower temperature for each one and its insulation layers and to research the effect of soil temperature on underground cables temperature by using finite volume numerical method.

2. Problem description

The model of case study is shown in Fig. 1 and 2. There are three electrical cables situated in different arrays position (vertical, horizontal and inclined). The strand wire diameter is 7mm. The distance between each other cable is 75 mm. The insulation thickness is 4.5mm. The underground layer is (500×500)mm. There are 19 strand Aluminum wire for each cable distributed as presented in Fig. 2 covered by layer of insulation. Heat is transferred from the cable core to surrounding soil by the effect of current passing. The assumptions that heat generated with different values begins from 700W/m^2 increasing to get 3500W/m^2 to see its effect with and without ambient temperature effect.

3. Mathematical formulation

The electrical conductors generates energy on a shape of heat throughout passing the electrical current from any end to another terminal. This generated heat is calculated depending on the area, length, temperature, and material type of conductor by the relation:

$$Q = \rho \frac{I^2 L}{A} \tag{1}$$

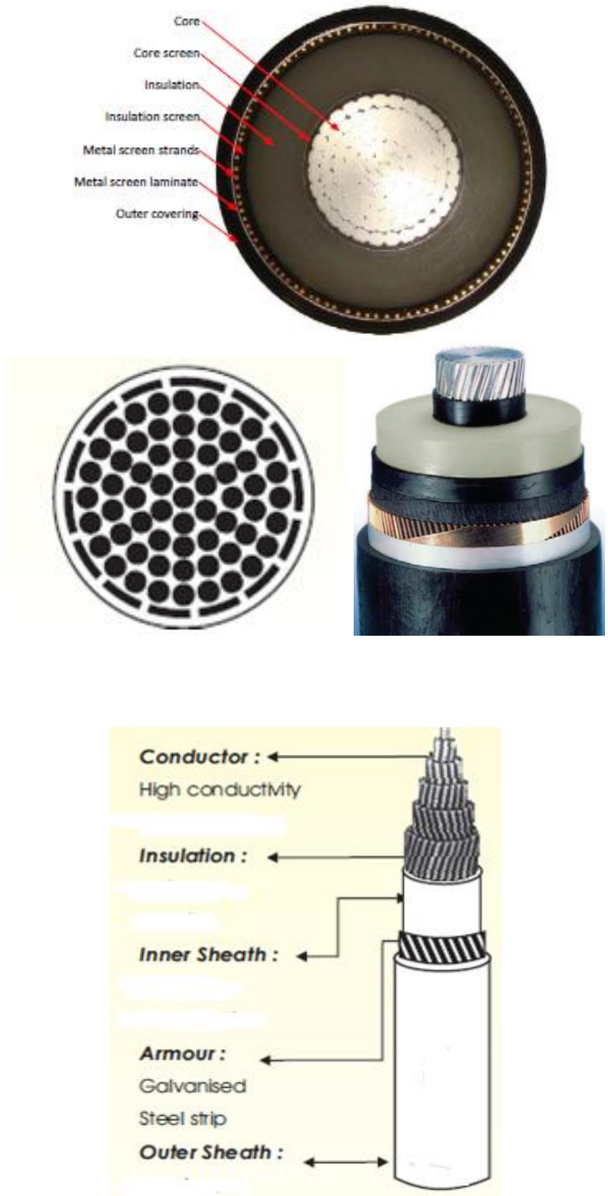

Fig. 1 Shapes of cable types

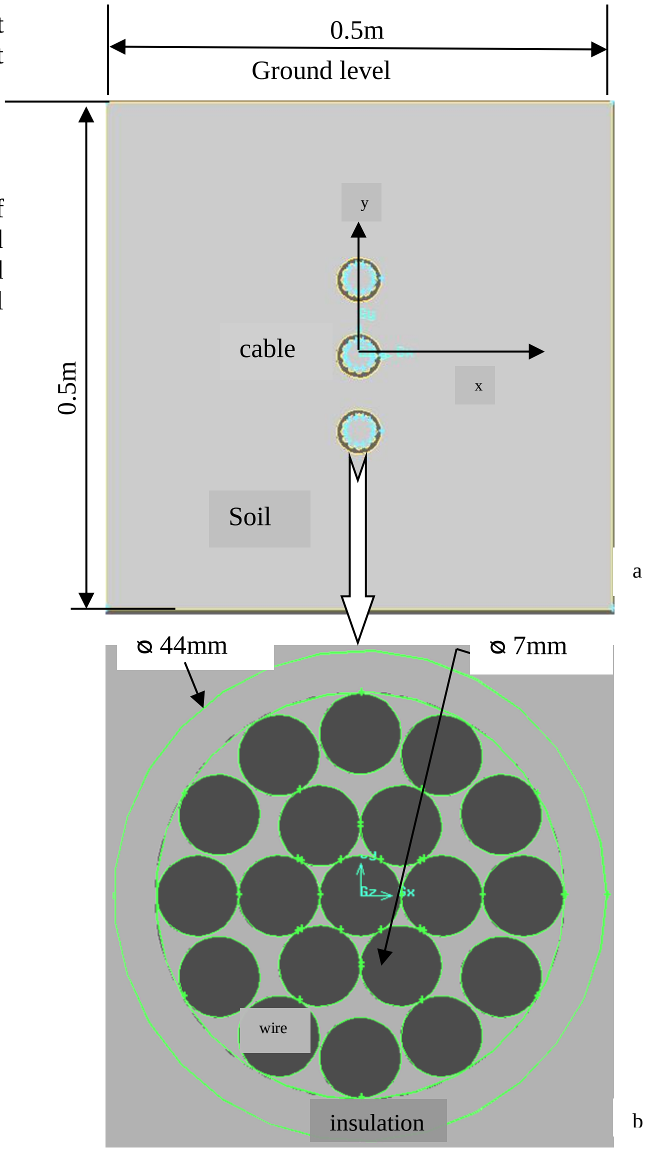

Fig. 2 a- physical model, b- cable section (wire strands and insulation layer)

The electrical resistance of the cable might be expressed by the formula:

$$R = \frac{\rho\, L}{A} \tag{2}$$

Therefore,

$$Q = I^2 R \tag{3}$$

The mathematical description of the applied boundary conditions is given by Eq. (4,5 and 6).

$$k \frac{\partial T}{\partial x}\Big|_{x=0.25,-0.25} = 0$$ for the boundary region (right and left) edge (4)

$$k \frac{\partial T}{\partial y}\Big|_{y=0.25,-0.25} = 0$$ for the boundary region (bottom and upper) edge (5)

$T(x, 0.25) = 50℃$ (third case) for the boundary region top edge (6)

From the heat conduction equation can be calculate the temperature at certain point [9]:

$$\frac{\partial}{\partial x}\left[k\,\frac{\partial T(x,y)}{\partial x}\right]+\frac{\partial}{\partial y}\left[k\,\frac{\partial T(x,y)}{\partial y}\right]=-Q\;(T(x,y) \qquad (7)$$

4. Cable properties

In present paper, some of cable properties are taken from the following table1. Number of core (strands) is 19.

Table 1
Cable properties [10]

Number of cores	Nominal Thickness of Insulation	Min. Thickness of Inner Sheath	ARMOUR: Galvanised Round Steel Wire Nominal Diameter	ARMOUR: Galvanised Flat Steel Strip Nominal thickness	Nominal Sheath Thickness for Unarmoured cables	Minimum sheath Thickness for Armoured cables	Approx. Over All Diameter: Unarmoured	Approx. Over All Diameter: Armoured	Approx. Weight of Cables: Unarmoured	Approx. Weight of Cables: Armoured	Max. DC Conductor Resistance at 20 C	Current Ratings: Direct in ground	Current Ratings: In Ducts	Current Ratings: In Air
No.	mm	mm	mm	mm	mm	mm	mm	mm	Kg/Km	Kg/Km	Ohm/Km	Amps.	Amps.	Amps.
2	0.9	0.3	1.4	–	1.8	1.24	11.6	13.2	210	460	7.41	32	27	27
3	0.9	0.3	1.4	–	1.8	1.24	12.2	13.8	254	515	7.41	27	24	24
4	0.9	0.3	1.4	–	1.8	1.24	13.1	14.7	305	590	7.41	27	24	24
5	0.9	0.3	1.4	–	1.8	1.24	14.2	15.8	356	665	7.41	27	24	24
6	0.9	0.3	1.4	–	1.8	1.24	15.2	16.8	415	740	7.41	20	18	18
7	0.9	0.3	1.4	–	1.8	1.24	15.2	16.8	445	755	7.41	20	17	17
10	0.9	0.3	1.4	–	2.0	1.40	19.3	19.4	615	940	7.41	18	15	15
12	0.9	0.3	–	0.8	2.0	1.40	19.8	20.0	710	1014	7.41	17	14	14
14	0.9	0.3	–	0.8	2.0	1.40	20.8	20.9	790	1130	7.41	16	13	13
16	0.9	0.3	–	0.8	2.0	1.40	21.9	21.9	900	1240	7.41	15	13	13
19	0.9	0.3	–	0.8	2.0	1.40	22.9	23.0	1025	1380	7.41	14	12	12
24	0.9	0.3	–	0.8	2.0	1.40	26.6	26.6	1275	1730	7.41	13	11	11
30	0.9	0.3	–	0.8	2.0	1.56	28.1	28.6	1520	2000	7.41	12	10	10
37	0.9	0.4	–	0.8	2.2	1.56	30.8	30.8	1850	2350	7.41	11	10	10
61	0.9	0.4	–	0.8	2.2	1.56	38.1	38.0	2910	3600	7.41	9	8	8

5. Numerical model

The numerical pattern of the heat conduction equation solution is expected. Hence, the square domain with a height of 0.5 m and width of 0.5 m is used in numerical computations (Fig. 2 a, b). The assumptions that all sides of the boundary region of soil have the same temperature as a first case, while changing the upper wall (ground level) temperature to be (50^oC) which represents ambient temperature in summer season (August month in Iraq). But in other case made the cables underground of distance 1.5m to decrease the surrounded soil temperature. This temperature value is specified by the standards [11,12].

To solve the heat conduction equation numerically, the Finite Volume Method (FVM) is applied as shown in Eq. (4, 5, 6, 7). By using the segregated solver to solve the algebraic form of the governing equation using First Order Upwind scheme. The energy equations is used by SIMPLE algorithm of CFD (Computational Fluid Dynamics) to discretize the computational domain to find the temperature distribution, maximum and minimum temperature within entire underground power cable system. Mesh discretization is done by regular size grid. Mesh dependency is presented by using six mesh sizes, then the results of average domain temperature compared with other different mesh sizes are listed in Table 2 below for $700W/m^2$ heat flux from the cable. It was observed after five mesh sizes, there is no significant effect on the value of temperature. Therefore, this mesh size (fifth) is used in numerical solution of present study. The convergence of residuals used for energy equation is selected to be 10^{-6} which results good accuracy for numerical solution in FLUENT code.

Table 2
Mesh size with temperature

Mesh	Average domain temperature (K)
Mesh 1 (Number of nodes=5125)	412.233
Mesh 2 (Number of nodes=6712)	391.915
Mesh 3 (Number of nodes=8428)	325.875
Mesh 4 (Number of nodes=12133)	310.347
Mesh 5 (Number of nodes=15567)	307.594
Mesh 6 (Number of nodes=18915)	306.912

6. Results and Discussions

In this paper, There are many results accumulated to study the arrangements of cables when passing underground in comparison with other studies.

The present numerical study (Fig. 3 a) is validated with previous study of Karahan and Kalenderli [13]. They used a region of (0.02 m ×0.04m) which is included three phase cables (R, S, T) with forth neutral phase. They divided the region into 7212 elements by using finite element method, their shape of cables arrangement of delta shape but the forth neutral phase bottom them. The hot three phases shown in Fig. 3 b because of current passing but the forth is cold since there is no current flow throughout it). There is no study similar to present study in boundary conditions, therefore the researcher select [13] for comparison which simulated by finite element numerical method for channel contained the cables to narrow space outside it but present study depicts the three free cables generate the heat from wire circumference to outside direction therefore the cables have low temperature while there is a higher temperature distribution outside them. The maximum temperature for both works is 346 K for present study but it 345.631 K for [13].

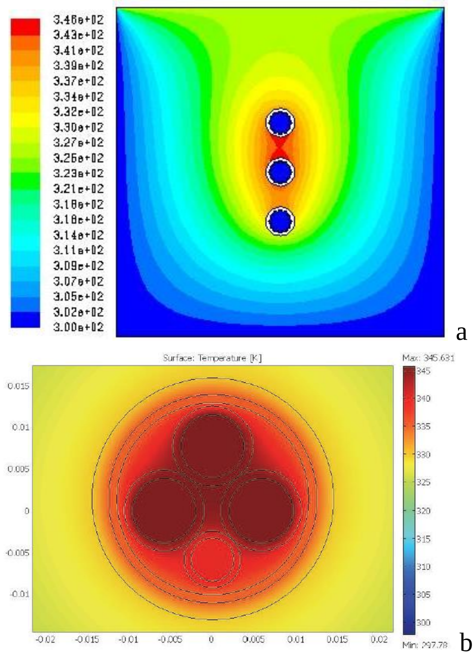

Fig. 3 temperature distribution for (a) present study, (b) Karahan and Kalenderli [13]

Fig .4 (a and b) shows the underground three cables passing with inclined array (45^o tilt angle) when the soil temperature surrounds the cable has the same temperature (300 K) with the same heat flux of cables (700 W/m^2). It is observed that maximum temperature happened to middle cable (S-phase) because it posses the maximum heat flux from the neighbor cables (R,T phases) in addition to its generated temperature effect. The marshalling of wires inside soil layers will not affect the contour of surrounded temperature but when the cables drifting away from others this effect will disappear. The curve of Fig. 4-c accentual the previous paragraph that the middle cable (red points) has the maximum temperature especially on the sides but the other phases have the same temperature profile (green and black points). But when the cables are involved near the ambient effect of upper surface temperature is 326K (the condition of ambient temperature in Iraq in many days of August), the configuration of temperature contour surrounds the three phase cables is depicted in Fig.5(a). The effect of high ambient temperature is very large which lead to increase the maximum domain temperature from 331K in Fig.4 to 338K in present case. This temperature may be lead to failure of cables when the electrical loads pass throughout them are high. So, the middle and upper cables put up with effect of high temperature flux resulted by this approach shown in curve with (red and green colors) but the lower effect is on the lower cable (black) since it distant from atmosphere.

Fig. 6 exhibits the vertical cables array with same temperature of surrounded soil to indicate the maximum temperature around the middle cable with about one Kelvin larger than the other phases. So, it has the same temperature on two sides for middle cable opposite to the others as offered from red curve with same trend to others around them (green and black curves). This temperature ranges increased from 338K as maximum temperature to be 346 in Fig. 7 when the system undergoes the effect of ambient temperature from the above wall surface of ground .This effect transports to cables that are near the ground surface because of conduction between the upper soil layers of earth and cable that resulted by convective heat transfer from ambient air and ground surface that considered as constant temperature in boundary conditions of FLUENT code programming. The leverage of ambient air temperature is robustly on upper and mid cables as presented in green and red curves respectively. The unbalanced red curve since the higher temperature happens between the upper and mid cables and low effect between the mid and lower (black) cables because the distance from ground surface plays important role in heat transfer and temperature in addition to heat generation by cables their selves.

Fig. 8 elucidates the horizontal orderliness of cables which has the same temperature distribution of vertical array shown in Fig. 6 because it has the same boundary conditions and processing. But the arrangement of horizontal array differs that previous vertical array when it exposed to high ambient temperature near the upper surface of soil containing these cables because they far away from the ground surface in comparison with vertical one as shown in Fig. 9. This differenced with Fig.7 will increase the conduction heat transfer resistance which leads to decrease the cables temperature in Fourier conduction equation. So, the temperature distribution around the cables temperature differs from Fig.6 because the temperature distribution around any cable is not uniform but it symmetric, as a result to atmospheric temperature effect but the mid cable remains has higher temperature ranges than others.

To ensure the electrical underground cables are not affected with high ambient temperature, they might be buried underground level to guaranteed depth.

Fig. 10 propounds the temperature of underground soil depth in August [14]. So, when it depended in this study as theoretical value, the researcher boosts the depth with 1.5m with domain to create stable soil temperature of 35^{o}C. To ensure good cable cooling and be far from the hot air temperature as shown in Fig. 11 to present there is no effect of ambient temperature and the system is not effected with it to give similar results in Fig.5 to maintain the cables at low temperature to avoid the cables insulation failure.

For improvement the result that accumulated before in present paper. The following curves are placed in the following. Due to the previous results the flux was used as 700 W/m^2, in these curves the multiples of this value are presented .

Fig.12 shows the minimum and maximum temperature calculated around the inclined cables array when different heat flux supplied by strand of wires inside as a result to current flow naturally or by short circuit which happens since the connection of wire or part of wire to ground leads to pass high electrical power i.e high current. All temperature curves increased gradually with increasing the heat flux from minimum temperature (321K) in left and right cables with low current (low heat flux 700 W/m^2) out the higher temperature in middle cable because it is effected by heat transferred from the side cables. So, the higher minimum temperature is recorded (330K) for maximum left, maximum right and minimum middle cable at 700 W/m^2 since the effect of left and right cables on the middle. All temperature values match between the maximum left and minimum middle cable as a result to heat transferred from one cable to another and the middle strongly effected at two sides. In this array, the danger temperature are the higher (maximum) because they might be lead to cable failure (466K) which is over than the ignition point of insulation.

The same curve trend in Fig. 12 is done for results of vertical cables array for temperature that resulted by heat flux from the losses of Aluminium wires produced by passing current which presented in Fig. 13. Due to this arrangement, the maximum temperature is recorded for middle and right (upper) cable that all curve temperature coincides since the effect of ambient temperature (50^{o}C) on upper cable in addition to adjacent place for each other with effect of two margin cables on the middle. The left (lower) cable has the minimum temperature since it far away from ambient, follow it in minimal the right (upper) at the sides of cable which are not opposite to ambient or mid cable side. That the mid cable has higher minimum or maximum temperature in comparison with other cables since the effect of heat flux from them.

Fig, 14 depicts the minimum and maximum temperature of horizontal cables arrangement which indicates coincide of more curves because the cables have the same impact from the atmosphere temperature and the edge cables have the same minimum and maximum temperature but the mid is the higher than both cables.

Fig.15 articulates average temperature for all arrays of cables (horizontal, vertical and inclined). The higher average temperature is for vertical mid cable due to effect of ambient temperature and side cables heat flux, but the lower temperature for left inclined (lower position) because it is distant from ambient effect. This effect is apparent in Fig. 16 which shows the higher average temperature for middle cable for all arrangements follow it the right which is approaches to ambient surface for both inclined and vertical arrays, so the left (lower) cable is minimal.

The above maximum temperature must be taken in consideration when dealing with cables erection and design to prevent failure of insulation that protect the wire from electrical damage and current leakage especially when dealing with underground cables that are in contact with sand, salt, soil, and water media.

7. Conclusions

From the previous results, the following conclusions might be recorded:

1- The maximum cable temperature was done by middle cables because of heat flux of side neighbour cables.

2- The minimum cable temperature was recorded by left (or lower) cable since it was far from ambient effect and heat flux of other cables.

3- When the designer or worker in electrical cables erection would design the power cables position, he must take in consideration the maximum cables temperature so that undergo the maximum power (and /or current) of end loads.

4- The insulation material types must taken in account to status of ambient temperature and heat dissipated from cables at the designation of power cables according to higher insulation limit with temperature at no change in electrical conductivity for wire and insulation.

5- The cables must buried underground of appropriate level reaches to 4m to ensure staying cables temperature under the ambient temperature at hot places (south of Iraq) and cool the hot cables as a result to power flow.

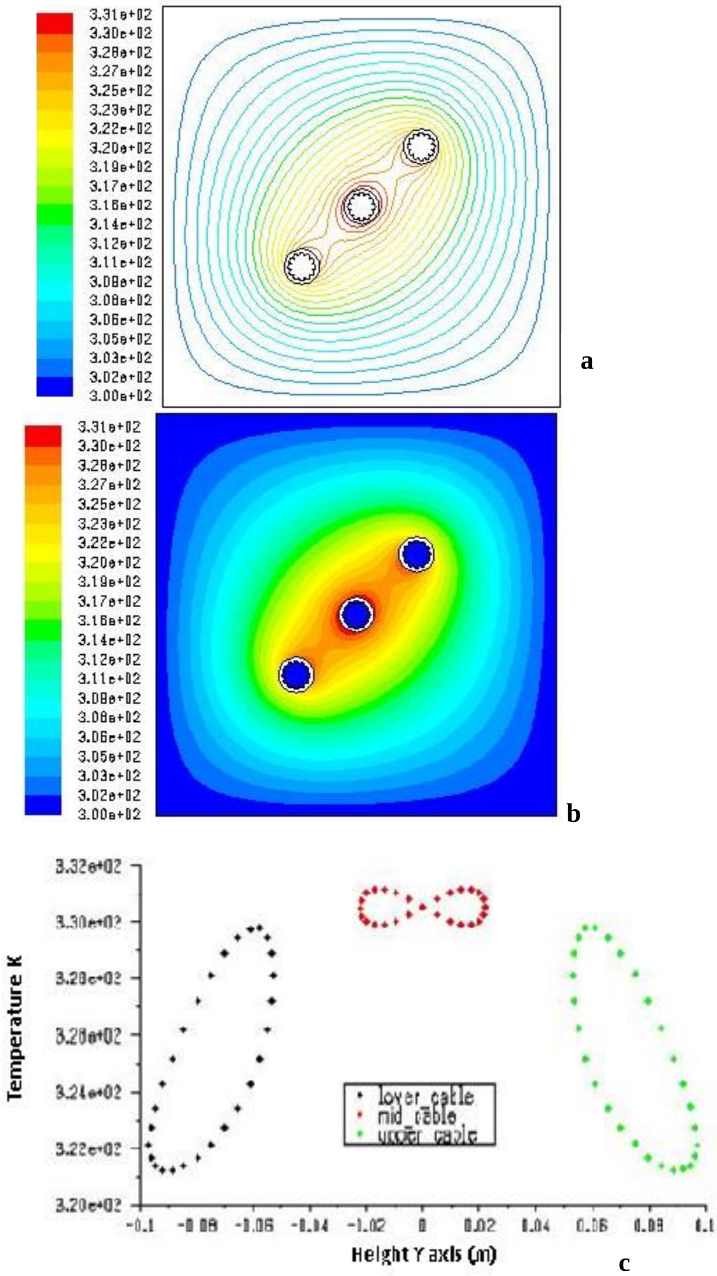

Fig. 4 static temperature of inclined arrangement of cables underground with same temperature of soil

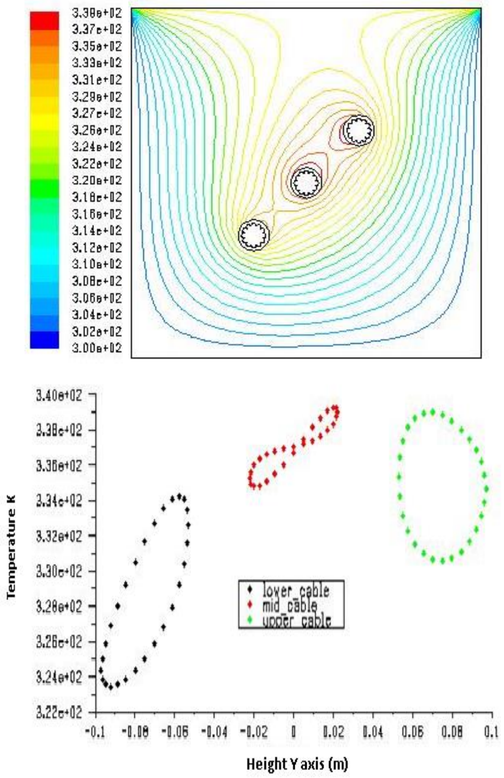

Fig. 5 static temperature of inclined arrangement of cables underground with same temperature of soil except the upper is the same as ambient temperature

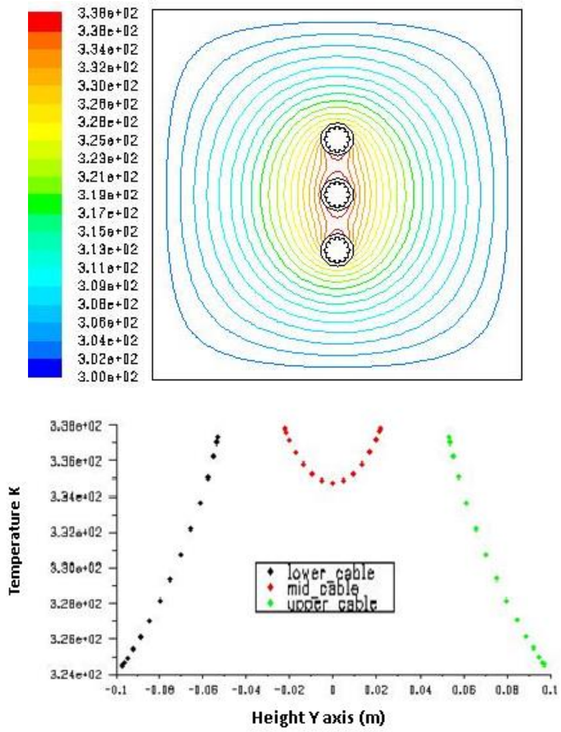

Fig. 6 static temperature of vertical arrangement of cables underground with same temperature of soil

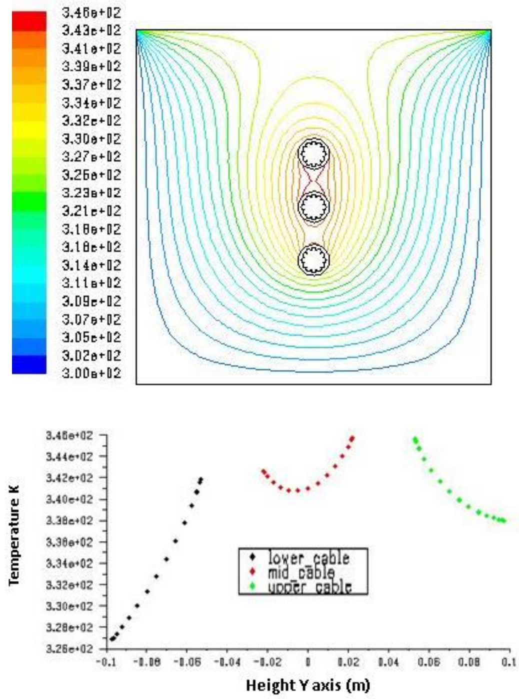

Fig. 7 static temperature of vertical arrangement of cables underground with same temperature of soil except the upper wall is the same as ambient temperature

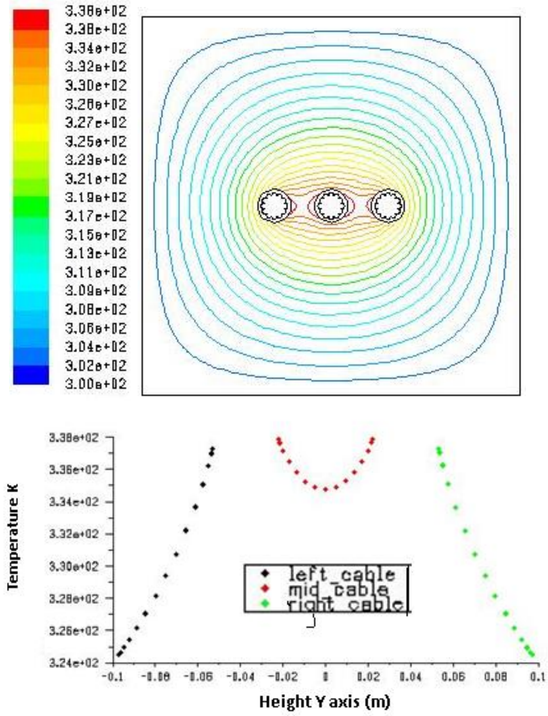

Fig. 8 static temperature of horizontal arrangement of cables underground with same temperature of soil

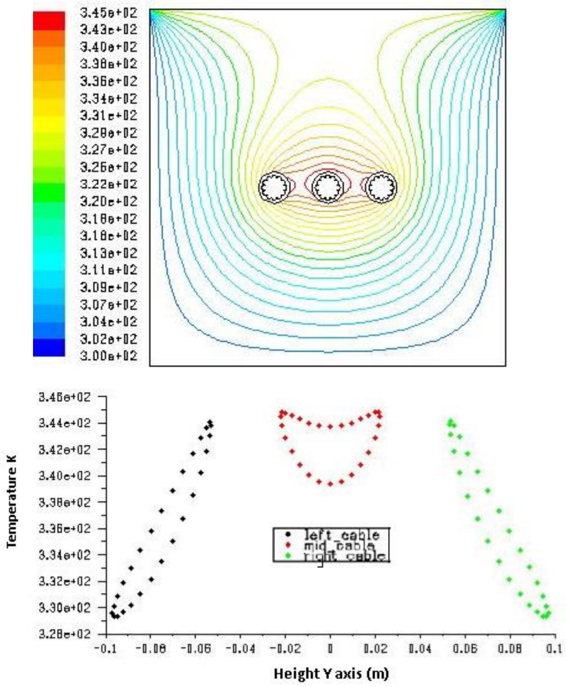

Fig. 9 static temperature of horizontal arrangement of cables underground with same temperature of soil except the upper wall is the same as ambient temperature

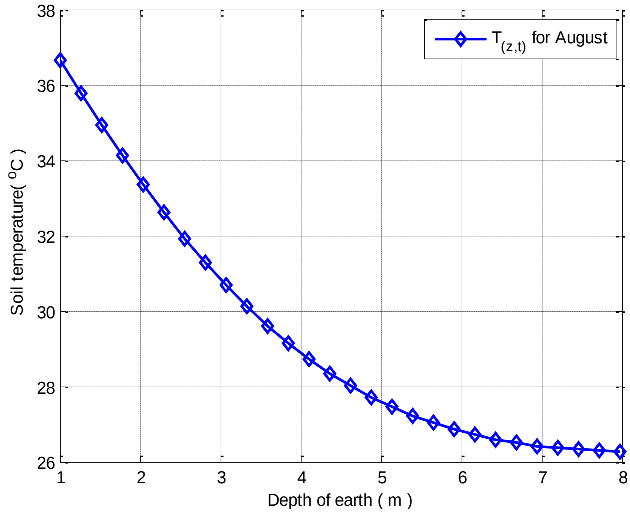

Fig. 10 soil temperature with relation to earth depth [14]

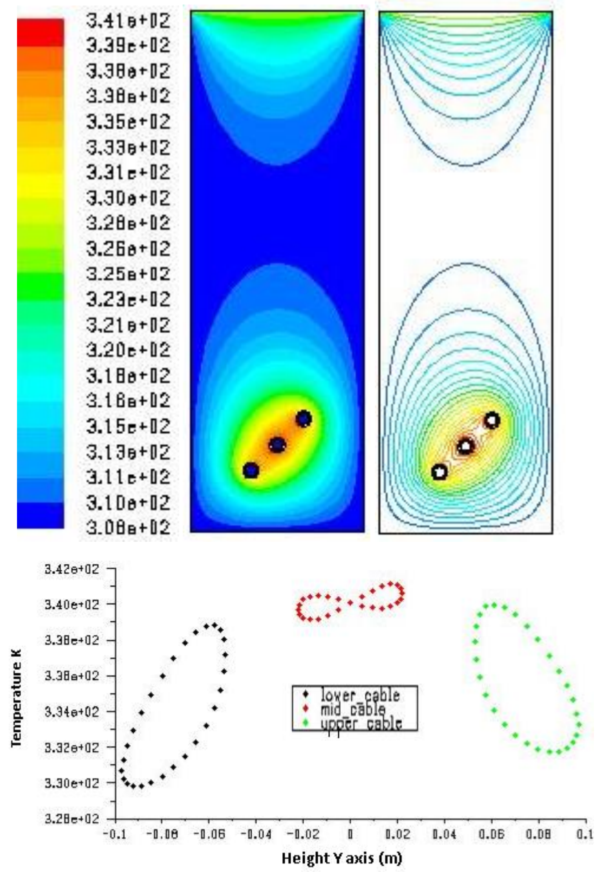

Fig. 11 static temperature of inclined arrangement of cables underground with same temperature of soil except the upper wall is the same as ambient with 1.5m depth temperature

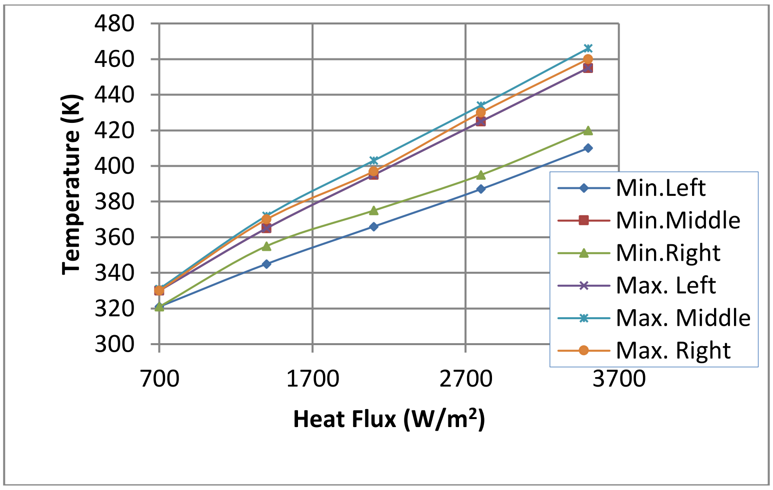

Fig.12 temperature resulted on the left, middle and right cables by applying different heat flux for inclined cables array

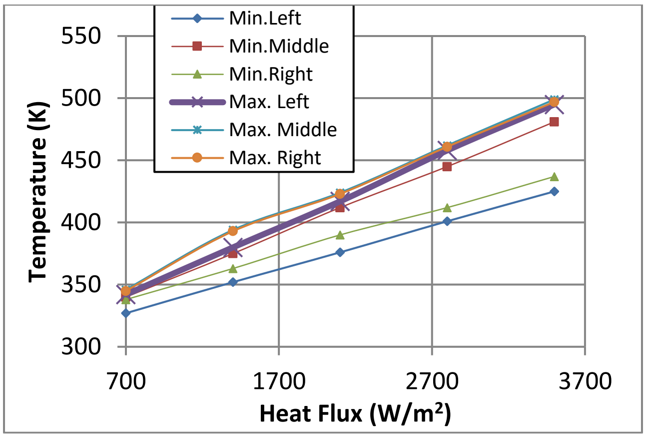

Fig. 13 temperature resulted on the left, middle and right cables by applying different heat flux for vertical cables array

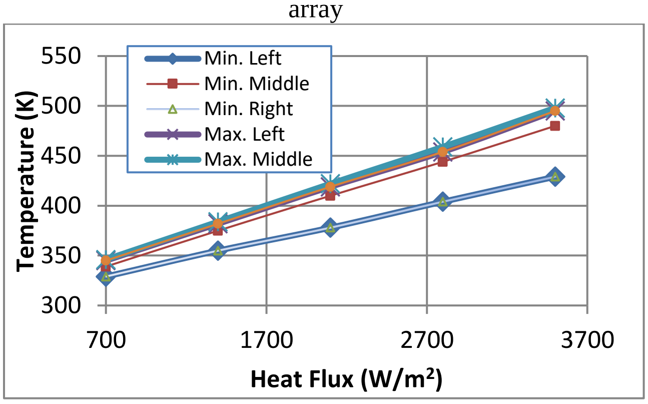

Fig. 14 temperature resulted on the left, middle and right cables by applying different heat flux for horizontal cables array

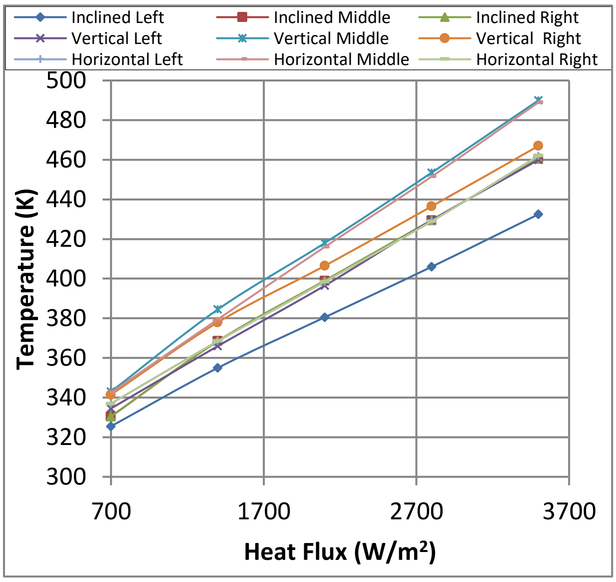

Fig.15 temperature resulted on the left, middle and right cables by applying different heat flux with different arrangement

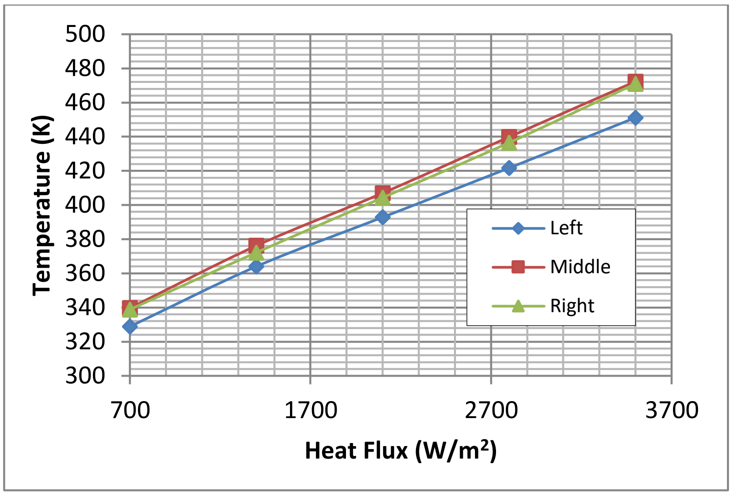

Fig.16 the average temperature resulted on the left, middle and right cables by applying different heat flux

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Nomenclature

Symbol	**meaning and unit**
ρ	electrical resistivity of conductor material(Ω-mm^2/m)
I	electrical current passing through the conductor and insulation (Ampere)
L	conductor length (m)
A	conductor cross sectional area (m^2)
Q	heat flux generated by cable (W/m^2)
R	electrical resistance of wire (Ω)
T	temperature (K)
x,y	dimensions (m)
k	thermal conductivity, W/(m K).