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Improving evaluation of the heat losses from arrays of pipes or electric cables buried in homogeneous soil

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ABSTRACT

The evaluation of the heat loss from finite arrays of horizontal buried cylinders is very interesting for many practical applications. A considerable effort has been done in the field of the electrical engineering to develop methods for calculating the thermal flux from the cables system to the ground surface through the soil. Nevertheless, the modeling hypothesis currently assumed for the case of arrays of a finite number of pipes-cables introduces approximations that can involve inaccuracies in calculation.

In this paper the extent of such inaccuracies is investigated by numerical techniques. Results show that the thermal resistance value of the worst refrigerated cylinder, obtained from numerical simulation, can result even 60% higher than the value calculated with standard IEC–IEEE method, while the thermal resistance of the whole array does not differ from the value obtained with the standard IEC–IEEE calculation method. Some correlating equations to obtain more accurate results in the thermal resistance calculation for the worst refrigerated cylinder are proposed.

1. Introduction

The heat loss from buried cylinders calculation is very interesting for several practical applications; for instance the district heating or electrical underground systems. Since the power-carrying capacity of the underground electrical cable depends mainly on the temperature at which the cable operates and, therefore, on heat dissipation, a considerable effort has been made in the field of electrical engineering to develop methods for calculating the heat transfer from the cables to the external environment through the soil.

The standards in use assume the existence of several series thermal resistances between the conductor outer surface and the external environment: the resistance of the insulation, conductor, armor, sheath and insulation; the resistance between the outer surface of the sheath and the ground surface; the ground surface-external air resistance.

The thermal resistance between the external surface of the sheath and the ground surface is investigated in this paper. In the electrical engineering literature this resistance is generally referred to as "T4". In this paper it will be called R_{CG}, while T will be the temperature.

The current calculation methods of the thermal resistance between the external surface of the cable and the ground surface, adopted in IEC [1,2] and IEEE [3], are based on the pioneer work of Neher and Mc Grath [4]. This approach assumes that the soil is homogeneous with uniform thermal conductivity; it utilizes the theoretical results available for the case of an infinite cylindrical isothermal surface in a semi-infinite space, and the method of the superposition of thermal fields to account for the presence of several cables. Exact solutions are achieved only for the case of a single cable or a couple of cables [5]; approximate solutions have been obtained for infinite cables array [6–8]. Different configurations have been investigated using a numeric simulation approach: multiple cable systems buried in ducts or in rectangular concrete duct banks [9–12]; effects of soil non-homogeneity [13], effects of structural steel [14] and backfilling [15]. The authors of this work conducted a study to evaluate the non-homogeneity backfilling effects and proposed an approximated mathematical model to calculate R_{CG} [16].

However the case of a finite elements number array of cylinders is still usually solved with the method proposed by Nether and Mc Grath. Among the hypothesis on which is based the method, there are the following:

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- The thermal field of a single cable is considered similar to that produced by a virtual line source, with the same heat flux per unit length of the real cable and put in its center.
- The thermal fields produced by each stand-alone cable are superposed. But in the real situation, the thermal field due to each cable is influenced by the presence of the other cables, even if they are "cold".

With the above statements, the Neher and Mc Grath calculation method [1–4] could be inaccurate for some real situations (a system formed by a finite number of cables). Aim of the present work is to investigate the extent of such inaccuracies by numerical techniques to obtain more accurate solutions for an array of horizontal, parallel, equispaced, isothermal circular cylinders, and to indicate correlations to correct the solutions carried out by IEC and IEEE methods.

2. Mathematical model

An array with an odd number $N_C = 2\,(n{-}1) + 1$ and an even number $N_C = 2n$ of horizontal, parallel, equispaced, isothermal circular cylinders (tubes, cables etc.) of infinite length in a semi-infinite space, with constant thermal properties and isothermal boundary surface, has been investigated. It has been assumed steady state. The same assumptions are made in the above mentioned standards in calculating the resistance R_{CG}.

For the numerical study, a finite space portion is considered, large enough as shown at the end of this section.

The thermal flow to the boundary of this finite portion is assumed to be zero. For arrays with an odd number of elements, the thermal field is symmetrical with respect to the vertical plane containing the axis of the central tube; for even number arrays, the thermal field is symmetrical with respect to the vertical plane midway between the two central tubes. The thermal flow is zero at the symmetry plane.

With reference to the reference system shown in Fig. 1, the thermal field is described by the equation:

$$\nabla^2 \cdot \mathrm{T} = 0 \tag{1}$$

With the boundary conditions:

$$\text{(a) at the ground surface}(y = h^*)\text{: } \mathrm{T} = \mathrm{T_G} \tag{2}$$

$$\text{(b) at the surface of each cylinder } (r = D/2)\text{: } \mathrm{T} = \mathrm{T_C} \tag{3}$$

$$\text{(c) at the vertical pseudo} - \text{boundary line}(x = x^*)\text{: } \frac{\partial T}{\partial x} = 0 \tag{4}$$

$$\text{(d) at the horizontal pseudo} - \text{boundary line}(y = 0)\text{: } \frac{\partial T}{\partial y} = 0 \tag{5}$$

$$\text{(e) at the left symmetry line}(x = 0)\text{: } \frac{\partial T}{\partial x} = 0 \tag{6}$$

Where x^* and h^* are the positions of the pseudo boundary lines.

The heat flux per unit length on the ground surface is given by:

$$q_G = -2\int_0^{x^*} \lambda_G \left(\frac{\partial T}{\partial y}\right)_{y=h^*} \mathrm{d}x \tag{7}$$

Radial and angular coordinates "r" and "α" are assumed on each cylinder. With reference to such system, the heat flux per unit length on the first cylinder surface (odd number of tubes) and on the k_{th} cylinder surface are, respectively:

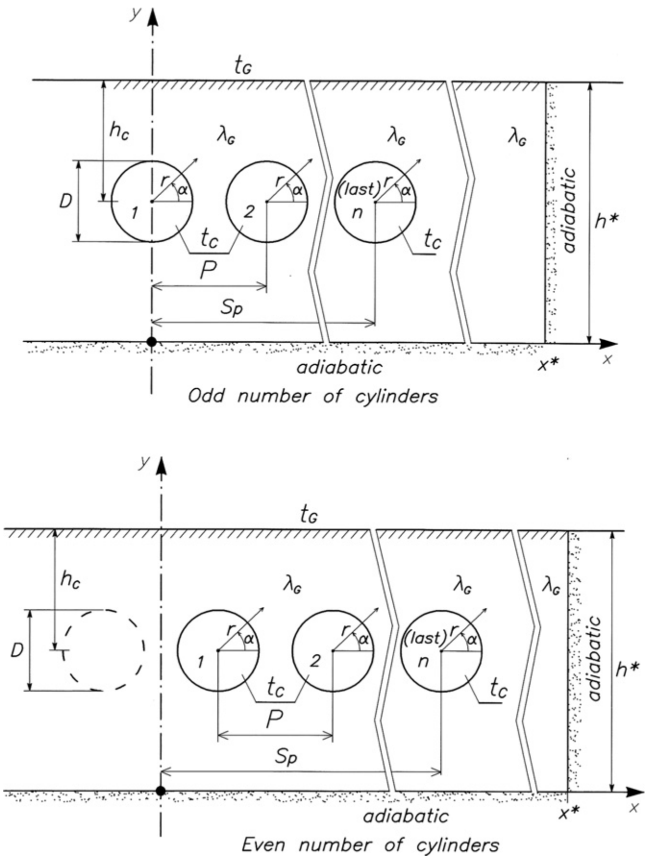

Fig. 1. Geometry and coordinate system.

$$q_{C1} = -2\int_{-\pi/2}^{\pi/2} \lambda_G \left(\frac{\partial T}{\partial r}\right)_{r=D/2} \mathrm{d}\alpha \tag{8}$$

$$q_{CK} = -\int_{-\pi/2}^{3\pi/2} \lambda_G \left(\frac{\partial T}{\partial r}\right)_{r=D/2} \mathrm{d}\alpha \tag{9}$$

The numerical model details, as the discretization of the grid system, the cylindrical polar grid and the Cartesian grid overlapping, and the solution procedure are the same described in [16].

For each configuration, the thermal flow from each cylinder, the thermal resistance $R_{NUM} = (T_C - T_G)/q_{CK}$ between cylinder and ground, and the thermal resistance of the whole array $R_{\mathrm{ARRAY}} = (T_C - T_G)/q_G$ have been calculated.

In electrical engineering, the main problem is to check that the temperature reached by the power cable insulation does not exceed the assigned limit value, so the interest is focused on the worst refrigerated cable. In thermal engineering, e.g. in the case of arrays of tubes in heating or cooling floors/ceilings, it may result more interesting to study the whole array resistance, so the attention has been put also on this topic.

For the worst refrigerated cylinder, and for the whole array, the R_{NUM}/R_{IEC} ratio has been evaluated, being R_{IEC} the thermal resistance value computed following the Standards [1,2]. On the basis of the described fields superposition method, in the case of an isothermal array of N_C cylinders investigated in this work, the R_{IEC} value given by the Standards for the J_{th} cylinder is: