THERMAL ANALYSIS OF UMBILICAL CABLES

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Abstract. *The main purpose of this paper is to present the methodology applied in order to evaluate the thermal performance of a submarine composite umbilical, composed by power, signal/control and hydraulic functions. The analyses were performed aiming to the umbilical design selection and optimization by considering the thermal properties of its components for long-term operating conditions.The circulating current at the power cores generates heating that may lead their neighbouring components to experience higher temperatures than their allowable limits. Umbilical was modeled using a finite element tool (Flux2D®) under a set of operating conditions, such as umbilical in free air, in seawater and in confined tubes at production platforms, to ensure that the umbilical design complies with the specification and is suitable for operation. Discussion on the obtained results are also presented.*
Flux2D® is a finite element software, licensed by CEDRAT, for electromagnetic and thermal simulation based on the two-dimensional geometry of the device under evaluation and its materials physical properties.

Keywords: *umbilical cable, thermal analysis, FEA*

1. INTRODUCTION

In order to overcome flow assurance challenges and thus accelerate revenue and enhance recovery from oil field developments subsea pumps are utilized, and powering these devices result in new umbilical designs. The inclusion of power transmission functions to production control umbilical presents designers and manufacturers with a new set of challenges.

Powering a subsea pump requires umbilical conductor sizes greater than those of traditional production control umbilicals.

A subsea umbilical integrated cable is usually composed by steel tubes, hydraulic hoses, optical, power and signal cables as per Fig.1.

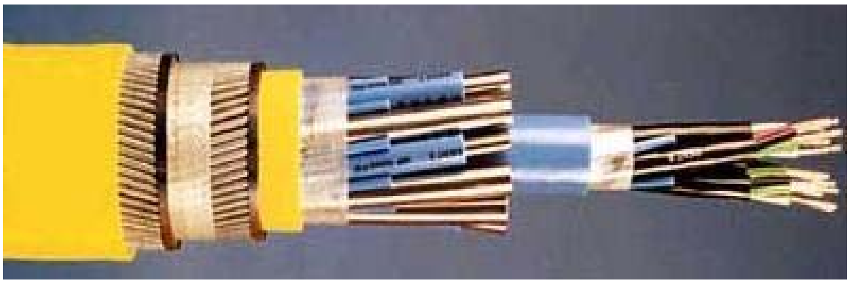


Figure 1. Electro hydraulic umbilical

As current passes through the power conductors they are heated by Joule effect causing a raise in the internal temperature of the umbilical. Copper or aluminum conductors can conduct a large amount of current before melting but long before the conductors melt, their insulation can be damaged by the heat.

Umbilical designers shall consider the temperature limits of each material in the umbilical structure. For traditional power umbilicals, temperature limits are typically defined by the limits of insulation, usually 90°C. For electro hydraulic umbilicals that include additional components, such as super duplex tubes, however, the maximum temperature may be limited by corrosion phenomena. To assure that the power transmission requirements can be met without exceeding the temperature limits of the component materials, detailed thermal analysis has to be performed to determine current capacity under a variety of operating conditions. Reducing operating temperature may result in increasing the conductor size.

When designing the power transmission system, engineers consider many factors such as the relationship between conductor size, current capacity and voltage drop, and how these factors affect other parts of the umbilical system, such as riser system behavior and installation loads.

Effective pump umbilical design solves power transmission losses, component interaction, riser system behavior and installation concerns to arrive at a reliable solution.

Increased power transmission requirements create challenging dynamics with the umbilical, such as heat generation from power conductors and electrical interference with signal cables.

Computer modeling offers a cost effective solution for designing different umbilical cables. Modeling and simulation has proven its ability to predict cable behavior with high accuracy mainly at first design level. After the theoretical evaluation the umbilical cable is submitted to rigorous tests to ensure the umbilical systems reliability during installation phase and throughout service life.

The focus of this paper is to present the methodology used to evaluate thermal behavior of umbilical cables under operational conditions, perform a case study for a simple umbilical geometry and finally compare the results with analytical calculation based on IEC 60287 Standard (2001a, 2001b).

2. METHODOLOGY

The thermal analyses are performed using a commercial software named Flux2D® (Cedrat, 2005) which is a computational package dedicated to electromagnetic and thermal calculation through the finite element method (FEM).

These simulations directly use the geometry of the device under evaluation and the physical properties of its components materials, building what is commonly called virtual prototype. This numerical approach allows the design to be faster and more refined, besides reducing considerably the number of real prototypes until the final product. These characteristics are especially attractive at first level of design when many cross-section alternatives have to be compared.

The simulations are carried out considering a steady state approach and the two-dimensional geometry of umbilical with its regions of interest. Figure 2 presents umbilicals cross-sections already manufactured.

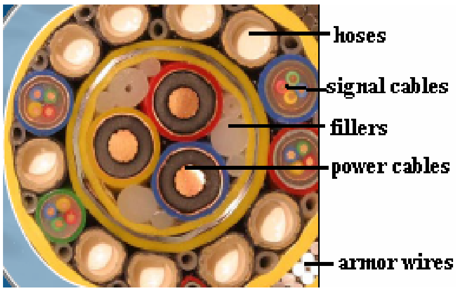


Figure 2. (a) Typical electro hydraulic umbilical cross-section (b) Challenging power umbilical

When designing an electro hydraulic umbilical it is important to ensure that the heat generated by the power cores will not exceed the temperature limits of adjacent components, such as hoses and steel tubes.

Thus, from a thermal point of view the cable design is focused on the ability of transferring heat from the conductors to the outer surface. This depends on materials used and the number of layers in the construction. In this sense, the temperature raise is the most important parameter, but this is governed by the ambient temperature for the given location and the maximum temperature applicable to the insulation and cable construction. For example, for buried cables if the soil is warm it absorbs less heat and consequently the heat transfer is reduced. For cables installed in air, the presence of solar radiation and wind may have profound effects on the cable rating.

2.1. Heat Transfer in Power Cable Systems

Current rating computations of power cables require solution of the heat transfer equations, which define a functional relationship between the conductor current and the temperature within the cable and in its surroundings.

The ampacity for a cable is thus based on physical and electrical properties of the material, the construction of the conductor, the insulation composition, ambient temperature, and environmental conditions adjacent to the cable. When multiple cables are bundled together, each contributes to heat the bundle and diminishes the amount of cooling air that can flow past the individual cables.

The two most important tasks in cable ampacity calculations are the determination of the conductor temperature for a given current loading, or conversely, determination of the tolerable load current for a given conductor temperature. In order to perform these tasks, the heat generated within the cable and the rate of its dissipation away from the conductor must be calculated. The ability of the surrounding medium to dissipate heat plays a very important role in these determinations, and varies widely because of several factors such as ambient temperature and wind conditions.

Heat transfer can be achieved by conduction, convection and radiation. Thermal conduction occurs without transport of matter and the heat transfer is determined by the existence of a temperature gradient. Only this type of heat transfer is possible in solid bodies. The basic relation of conduction is known as the Fourier's law:

$$q = -k\frac{d\theta}{dx} \quad (1)$$

The heat flux q (W/m^2) is the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer, and is proportional to the temperature gradient $\frac{d\theta}{dx}$ in this direction. k is the thermal conductivity (W/m.K) and is a characteristic of the material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

Thermal convection presupposes heat transfer on the surface that separates a solid body from a fluid, or inside a mixture of fluids. A macroscopic transport of matter is associated. Regardless of the nature of the convection process, the rate equation is of the form:

$$q = h(\theta_s - \theta_{amb}) \tag{2}$$

where q, the convective heat flux (W/m^2), is proportional to the difference between the surface temperature and the ambient temperature, θ_s and θ_{amb}, respectively.

This expression is known as Newton's law of cooling, and h (W/m^2.K) is the convection heat transfer coefficient.

Thermal radiation is energy emitted by the cable or duct surface. The heat flux emitted is given by the Stefan-Boltzmann law:

$$q = \varepsilon\sigma_B\theta_s^{*4} \tag{3}$$

where θ_s^* is the absolute temperature (K) of the surface, σ_B is the Stefan-Boltzmann constant (σ_B =5.67 x 10^{-8} W/m^2.K), and ε is a property of the surface called emissivity.

If radiation is incident upon a surface, a portion will be absorbed, and the rate at which energy is absorbed may be evaluated from knowledge of the surface absorptivity, α. Since the cable both emits and absorbs radiation, radiative heat exchange can be modeled as an interaction between two surfaces. Assuming the cable surface is a gray surface ($\varepsilon=\alpha$) the net rate of radiation exchange between the cable and its surroundings is

$$q = \varepsilon\sigma_B(\theta_s^{*4} - \theta_{amb}^{*\,4}) \tag{4}$$

For cables installed in air, convection and radiation are important heat transfer mechanisms from the surface of the cable to the surrounding air. Convection heat transfer may be classified according to the nature of the flow. Forced convection takes place when the flow is caused by external means, such as wind, pump or fan. In contrast, for natural convection, the flow is induced by buoyancy forces, which arise from density differences caused by temperature variations in the air. In order to be somewhat conservative in cable rating computations, we usually assume that only natural convection takes place at the outside surface of the cable.

Determination of the heat convection coefficient is perhaps the most important task in computation of ratings of cables in air. The value of this coefficient varies between 2 and 25 W/m^2.K for natural convection and between 25 and 250 W/m^2.K for forced convection.

The finite element software used to perform thermal analyses has some limitations, such as two-dimensional behavior and direct modeling only of thermal conduction. The remaining thermal exchanges can only be modeled through boundary conditions.

The components of umbilical cables are modeled as solid bodies whose thermal conductivity properties are known and a convection coefficient is imposed on outer sheath to simulate the thermal exchange with the surrounding environment. The heat conduction in air is often neglected in cable models.

In the analysis of heat transfer in a cable system, the energy conservation plays an important role. At any instant, there must be a balance between all energy rates, as measured in joules per second (W). The energy conservation law can be expressed by the following equation:

$$W_{ent} + W_{\text{int}} = W_{out} + \Delta W_{st} \tag{5}$$

where W_{ent} is the rate of energy entering the cable, which can be generated by adjacent cables or by solar radiation. W_{int} is the rate of heat generated internally in the cable and ΔW_{st} is the rate of change of energy stored within the cable. The value of W_{out} corresponds to the rate at which energy is dissipated by conduction, convection and radiation.

Transient and steady thermal states can be simulated, being steady thermal state the situation when the temperature field does not vary with respect to time. The obtainable results in both applications are space distribution of temperature inside and on the boundary of the computation domain, characterized by the umbilical cable, and the thermal flux through the boundary surface.

Thus, the definition of the finite element problem requires a computation domain and boundary conditions, i.e. to define the regions where the temperature field is studied and the values of the state variable (temperature) on computation boundaries.

Three types of sources can be imposed: heat sources, heat flux density and temperature. These can be uniform or space dependent and imposed on boundary lines to represent heat transfer effects. In the presented case study, the power resulting from circulating current on power conductors is the imposed heat source.

Besides the components thermal properties and the heat sources the solver also needs spatial and temporal information about the initial temperature to set up conditions on first time step and begin the computation.

2.2. Cables in air

For an insulated power cable installed in air, conduction is the main heat transfer mechanism inside the cable. Suppose that the heat generated inside the cable (due to joule, ferromagnetic and dielectric losses) is W_t (W/m). Another source of heat energy can be provided by the sun if the cable surface is exposed to solar radiation. Energy outflow is caused by convection and net radiation from the cable surface. Therefore, the energy balance equation at the surface of the cable can be written as

$$W_t + \sigma D_e^* H - \pi D_e^* h(\theta_e^* - \theta_{amb}^*) - \pi D_e^* \varepsilon \sigma_B (\theta_s^{*4} - \theta_{amb}^{*4}) = 0 \tag{6}$$

where θ_e^* is the cable surface temperature (K), σ is the solar absorption coefficient, H the intensity of solar radiation (W/m^2), σ_B Stefan-Boltzmann constant, ε emissivity of cable outer sheath, D_e^* cable external diameter (m) and θ_{amb}^* ambient temperature (K).

This equation is usually solved iteratively. In steady-state rating computations, the effect of heat from solar radiation and heat loss caused by convection are taken into account by suitably modifying the value of the external thermal resistance of the cable.

3. CASE STUDY

A typical application was modeled with the focus on the spatial distribution of temperature inside the umbilical.

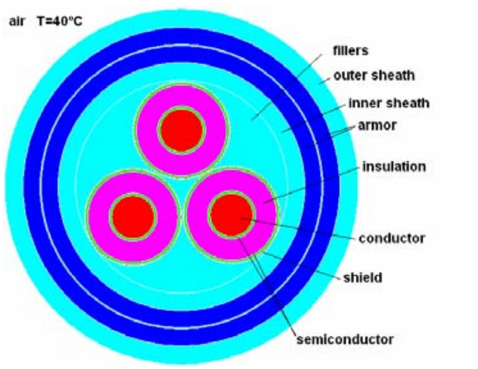


Figure 3 – Umbilical components

Power cores of 95mm^2 subjected to a circulating current of 212A are the main heat sources. An electrical analysis was previously performed to determine the power through conductors and metallic shields which are responsible for the heat input in system. For this umbilical the power on copper cores is 10.4W/m and on shields 0.4W/m. The condition simulated was an umbilical cable in air subjected to an ambient temperature of 40ºC. The convection coefficient was set to 9.0W/m^{2}ºC. The materials properties are assumed to be constant on the temperature range analyzed.

Table 1 – Thermal properties of materials

Component	Material	Thermal conductivity (W/mK)
Conductors	Copper	391
Semiconductor and insulation	EPR	0.2
Metallic shield	Copper	391
Armor	Steel	46
Fillers	LDPE	0.3
Sheath	HDPE	0.45

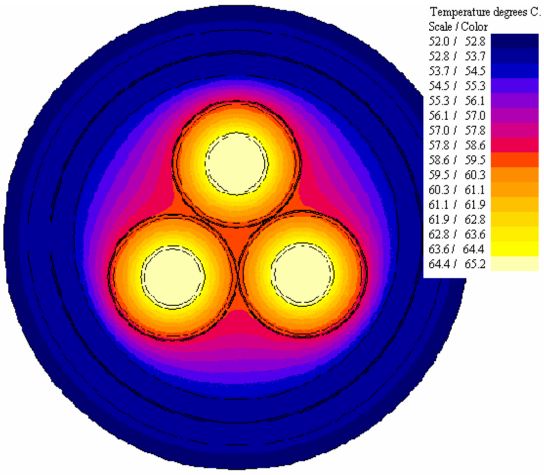


Figure 4 – Thermal results

Results obtained from the simulation are presented on Fig. 4. Besides the condition in air, umbilicals can also be simulated inside the I-tube, in seawater or buried, the key difference being changes on boundary conditions applied to the umbilical outer sheath.

4. COMPARISON BETWEEN NUMERICAL AND ANALYTICAL METHODS

Analytical methods have the advantage of producing current rating equation in a closed form, whereas numerical methods require iterative approaches to find cable ampacity. However, numerical methods provide much greater flexibility in the analysis of complex cable systems and allow representation of more realistic boundary conditions. In practice, analytical methods have found much wider application than the numerical approaches. There are several reasons for this, the most important one is probably historical since cable engineers have been using analytical solutions based on IEC Publication for a long time. Computations for a simple cable system can often be performed using pencil and paper or with the help of a hand-held calculator. Numerical approaches, on the other hand, require extensive manipulation of large matrices and have only become popular with an advent of powerful computers.

Calculation of current-carrying capability of electric power cables is subject of several international standards. The main international standards are those issued by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronic Engineers (IEEE). The analytical model used for the comparison was based on Standard IEC 60287 (2001a; 2001b).

The method begins by dividing the physical object into a number of volumes, each of which is represented by a thermal resistance. The thermal resistance is defined as the material's ability to impede heat flow. The thermal circuit is then modeled by an analogous electrical circuit in which voltages are equivalent to temperatures and currents to heat flows.

The maximum permissible current rating means the current that applied continuously until reaching steady state will produce the maximum allowable conductor temperature. We will present here the analysis of the steady-state conditions, which could be a result of either constant or cyclic loading. This steady state is the only condition considered when calculating the permissible current rating.

The current-carrying capability of a cable system will depend on several parameters, the most important are:

- number of cables and different cable types in the installation under study;
- cable construction and materials used for the different cable types;
- the medium in which the cables are installed;
- cable location with respect to each other.

The parameters appearing in the calculation can occasionally involve very complex expressions and empirical equations or curves that will not be shown in this paper. For a detailed discussion on their derivation refer to IEC 60287 Standard (2001a , 2001b).

The unknown quantity is either the conductor current I or its operating temperature θ_c (ºC). In the first case, the maximum operating conductor temperature is given, and in the second case, the current is specified. The permissible current rating is derived from the expression for the temperature rise above ambient temperature (IEC 60287, 2001a):

$$I = \left[\frac{\Delta\theta - W_d [0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)} \right]^{0.5} \tag{7}$$

where T_1, T_2, T_3 and T_4 are the thermal resistances, n is the number of conductors in the cable, W_d the dielectric losses per unit length per phase, R is the alternating current resistance of conductor, $\Delta\theta$ is the temperature rise above ambient temperature and λ_1, λ_2 are the ratio of total losses in metallic sheaths respectively to the total conductor losses.

4.1. Power Losses

A power cable consists of several components, the most basic being the conductor and the insulation which can be seen in any power cable. There are four heat sources produced by losses: cable conductor, metallic sheath/screen, armoring and dielectric.

The loss that occurs in the cable conductor is proportional to the conductor resistance and to the square of the circulating current. This loss normally represents the largest heat source in the cable. When the cable carries alternating currents the conductor resistance increases due to the skin and proximity effects, which are accounted for in the finite element software used.

The magnetic field flowing in the conductors induce fields in the metallic screen which cause currents to flow in the screen and generate losses. There are two types of losses which occur as sheath eddy loss and the sheath circulating loss. The sheath circulating loss is reduced since the three cables are placed close together. However, the closer formation results in a greater eddy loss and also increases the mutual heating of the three cables.

Armored single-core cables for general use in alternating current systems usually have nonmagnetic armor. This is because of the very high losses that would occur in closely spaced single-core cables with magnetic armor. Armoring of two-core or three-core cables can be either magnetic or nonmagnetic. Steel wires or tapes are generally used for this purpose. When nonmagnetic armor is used, the losses are calculated as a combination of sheath and armor losses.

4.2. Thermal Resistances

The heat path from cable conductors to the surrounding environment go through the following items: insulation, metallic shield, bedding, armor, outer sheath and environment.

The thermal resistance of metallic layers is so small in comparison with others that can be neglected. The total thermal resistance of each layer can be split up into two factors, one being essentially the thermal resistivity of the material and the other a function of the material through which the heat passes, called geometric factor.

Heat transfer phenomena are more complex for cables installed in free air than for those located underground. The external thermal resistance of cables in air can be written as

$$T_4 = \frac{1}{\pi D_e^* h (\Delta\theta_s)^{1/4}} \tag{8}$$

where h ($W/m^2K^{5/4}$) is the heat transfer coefficient embodying convection, radiation, conduction and mutual heating.

For the condition used in the case study the geometric factors and thermal resistances were calculated following IEC 60287 (2001a ; 2001b) relations and were found to be:

Table 2 – Parameters of analytical method

T_1: thermal resistance between conductor and sheath (K.m/W)	0.666
T_2: thermal resistance between sheath and armor (K.m/W)	0.078
T_3: thermal resistance of external serving (K.m/W)	0.062
T_4: thermal resistance of surrounding medium (K.m/W)	0.372
λ_1 : sheath loss factor	0.003
λ_2 : armor loss factor	0.056
W_d : dielectric loss (W/m)	0.016
R :conductor resistance at 64ºC (Ω/km)	0.232

The ambient temperature was set to 40ºC and for a current rating of 212A the resulting conductors temperature was 64ºC.

As can be noted from Tab. 2 the analytical and the finite element methods are iterative since the conductor resistance depends on its temperature.

Comparing the results from the analytical calculation to the conductors temperature resulting from simulation (from 64.4ºC to 65.2ºC) the maximum error was around 2%.

Considering uncertainties regarding properties materials and estimation of boundary conditions the results are pretty satisfactory and the simulation performed is suitable for thermal evaluation of umbilical cables.

5. SENSITIVITY ANALYSIS

A set of sensitivity analysis was performed in order to determinate the influence of different parameters, such as materials properties and environmental conditions.

Based on these analyses we can draw some conclusions concerning the influence and importance of different input data, especially for parameters which are not well known.

As the dielectric is the closest component to the heat source its properties affect conductors temperature more than variation on for example, sheaths properties. Therefore a sensitivity analysis was carried out focused on dielectrics material.

Four ethylene propylene rubber (EPR) and a tree-retardant cross-linked polyethylene (TRXLPE), all of which are in commercial production and are presented on Fig. 5 (Qi and Boggs, 2006).

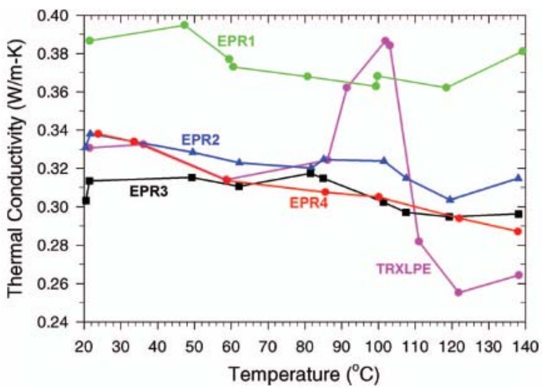


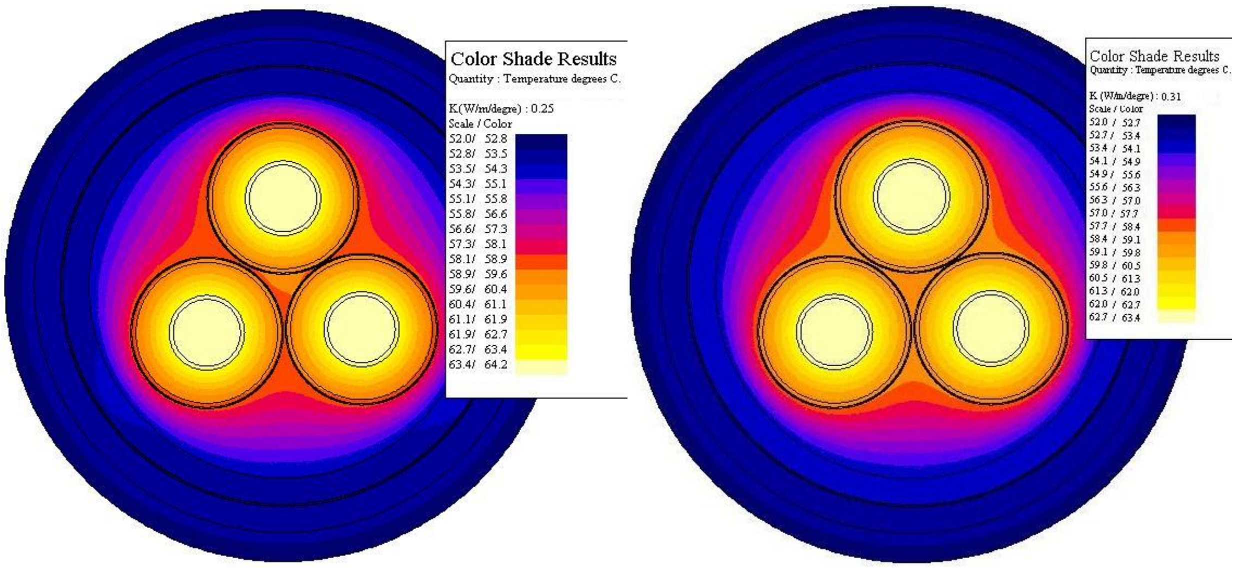
Figure 5 – Thermal conductivity as a function of temperature (Qi and Boggs, 2006)

We can see thermal properties of EPR are very stable from 20 ºC to 140 ºC with only a slight decrease in the thermal conductivity. The properties of the TRXLPE are similar to the majority of EPR compounds up to about 80 ºC when properties are affected by melting of the crystallites. Above 120 ºC the TRXLPE is essentially amorphous and has a lower thermal conductivity than EPR compounds.

Considering the conductors temperature range, resulting from case study, the cable compounds properties were obtained at 65 ºC : EPR1 k=0.37 W/m.K, EPR2 k=0.33 W/m.K, EPR3 and TRXLPE k=0.32 W/m.K, EPR4 k=0.31W/m.K.

The minimum (k=0.25 W/m.K) and the maximum (k=0.40 W/m.K) thermal conductivity points on curve were also analyzed. The main results are presented on Fig. 6.

In order to evaluate the influence of boundary conditions, a sensitivity analysis was performed varying the convection coefficient in the range of natural convection, between 2 W/m^{2}K to 25 W/m^{2}K. Results are shown on Fig.7.



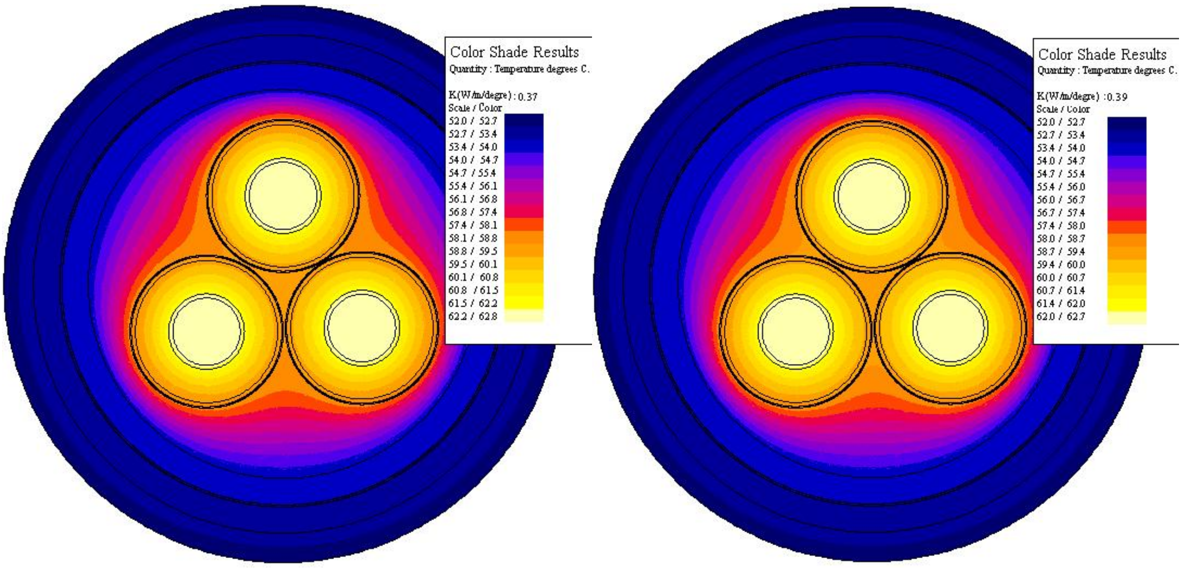
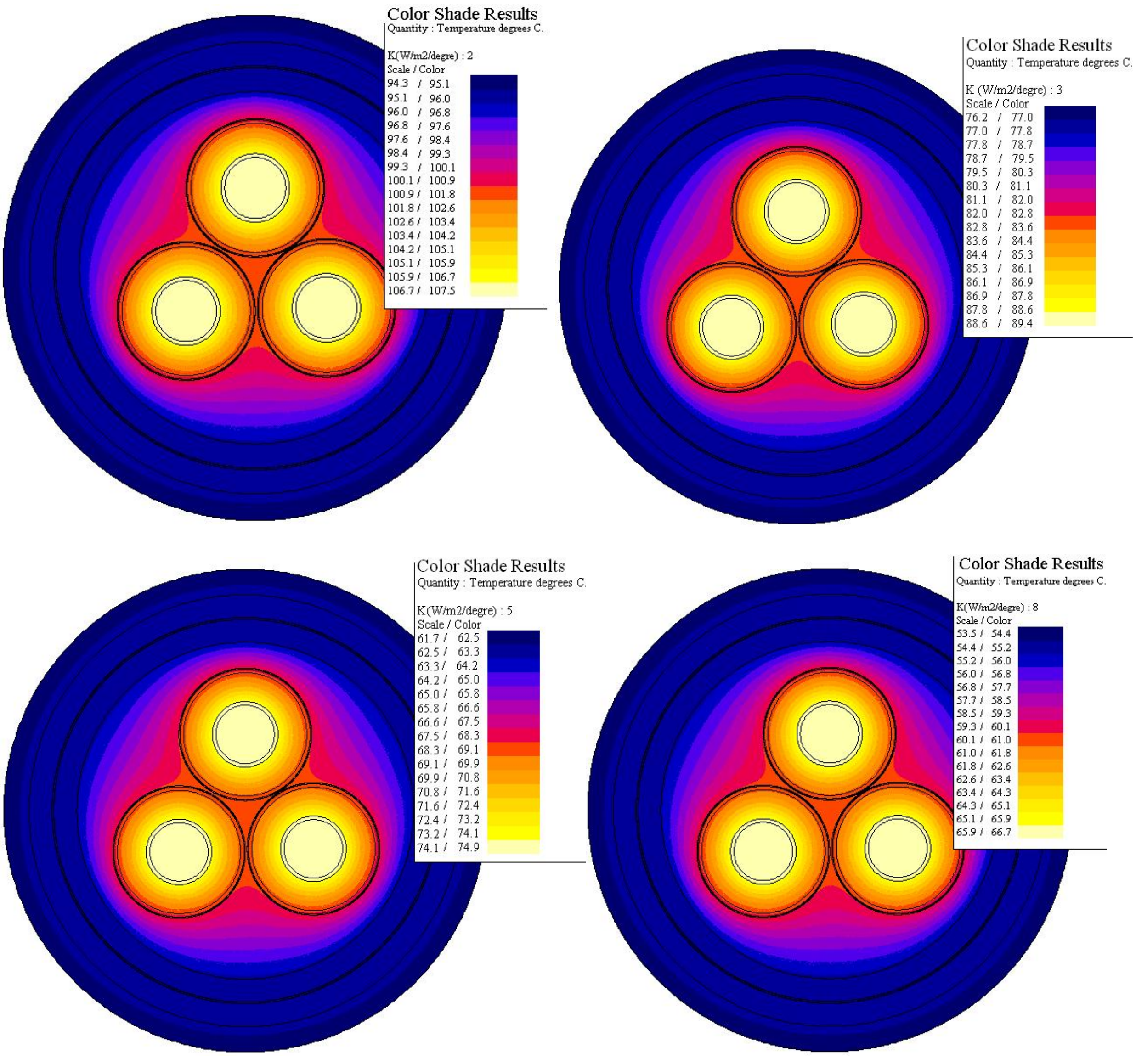


Figure 6 – Sensitivity analysis : thermal conductivity of dielectric



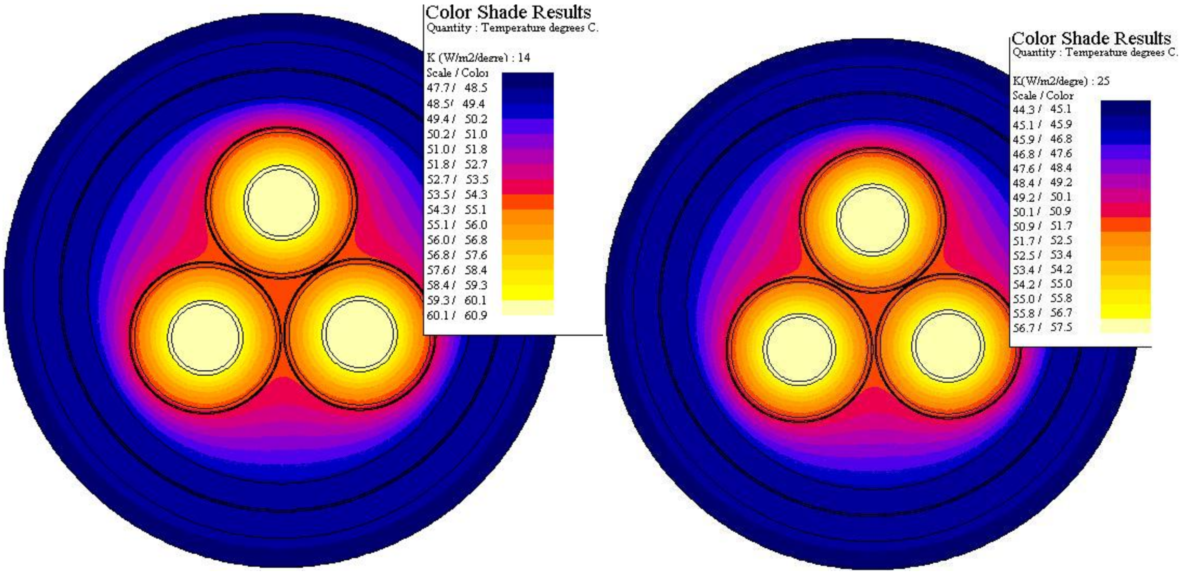


Figure 7 – Sensitivity analysis: convection coefficient

6. CONCLUSIONS

The current-carrying capability of cables depends on thermal resistances of insulation and the medium surrounding the cable. For a cable laid underground, this resistance accounts for more than 70% of the temperature rise of the conductor. For underground installations, the external thermal resistance depends on thermal characteristics of the soil, the diameter of the cable, the depth of laying, mode of installation and on the thermal field generated by neighboring cables. For cables in air, the external thermal resistance has a smaller effect on cable rating.

Changes of cable parameters such as dielectrics thermal conductivity, have a relatively small influence on the conductor temperature, while environmental conditions such as convection coefficient highly affect the temperature.

The thermal results for a three-core umbilical cable were satisfactory compared to the available calculation based on IEC60287 Standard. Some uncertainties still exist mainly regarding boundary conditions imposed to the model, which were shown to affect substantially the results.

Therefore, further work should be carried out including thermal measurements on field or at test benches in order to validate and calibrate model assumptions.

7. ACKNOWLEDGEMENTS

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