PREDICTION OF THE TEMPERATURE DISTRIBUTION OF PARTIALLY SUBMERSED UMBILICAL CABLES

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Abstract. *The objective of this work is to predict the temperature distribution of partially submersed umbilical cables under different operating and environmental conditions. The Fluent code was used to simulate the heat transfer and the air fluid flow of a part of a vertical umbilical cable near the air-water interface. The influence of parameters such as the heat dissipating rate, wind velocity, air temperature and solar radiation was analyzed. The influence of the presence of a radiation shield consisting of a partially submersed cylindrical steel tube was also considered. The air flow and the buoyancy-driven convective heat transfer in the annular region between the steel tube and the umbilical cable were calculated using the standard k-ε model. The radiation heat transfer in the annular region was also considered. The results indicate that the influence of a hot environment and intense solar radiation may affect the umbilical cable performance in its dry portion.*

Keywords: Umbilical cable, temperature distribution, radiation shielding, conjugate heat transfer

1. INTRODUCTION

Flexible risers such as flexible pipes and umbilical cables are finding increasing application in the marine environment and represent a crucial element of a floating production system. It represents an attractive alternative to a rigid riser since it does not require heavy compensation and tensioning devices at the top or riser manifold at the sea bed. At the same time, it offers ease of installation, retrieval and usage elsewhere. Flexible pipes and umbilical cables both work as composite pipes that are compliant and highly deformable in bending, but strong and stiff in response to internal pressure, external pressure, tension and torque. Umbilical cables generally consist of electrical conductors for signal and power transmissions that are surrounded by a number of protective layers. The protective layer is designed to secure the conductors from adverse chemical and mechanical damage.

One important aspect of the operation of umbilicals is related to its internal temperature. The internal electrical conductor may produce a high amount of heat in case the umbilical is used for electrical power transmission. In order to maintain the integrity and functionality of the umbilicals, the internal temperature should not be higher than around 90 ^{o}C. Usually the submersed part of the umbilical is adequately cooled by the surrounding seawater. On the other hand, the dry part above the sea level can reach high temperatures, especially if exposed to sun radiation.

The objective of this work is to predict the temperature distribution of partially submersed umbilical cables under different operating and environmental conditions. The influence of parameters such as the heat dissipating rate, wind velocity, air temperature and solar radiation is analyzed. The influence of the presence of a radiation shield consisting of a partially submersed cylindrical steel tube is also considered.

2. METHODOLOGY

An umbilical cable with 260 mm of external diameter is housed concentrically in a stainless steel tube of 500 mm of external diameter and 25 mm of wall thickness. The heat generated internally to the cable is 55 W/m. It was also considered the incident solar radiation on the steel tube (707 W/m^2). The temperature of the ambient air is considered of 40 ^{o}C (313 K), windless, which corresponds to the worst possible scenario. The sea water temperature is 25 ^{o}C (298 K). The heat generated in its length (7 m) is dissipated by heat transfer to the water for the submersed length (3 m) and also through the natural convection in the annular space between the umbilical surface and internal surface of the steel tube. This steel tube is heated by the sun radiation and cooled by the seawater, as it has 1 m of its length submerged.

The Fluent code was used for the solution of the equations of conservation of mass, momentum and energy to obtain the flow field, the temperature field and the heat loss. The software is based on the finite volumes formulation (Patankar, 1980). The equations are integrated for each control volume of the domain, creating a system of algebraic equations that are solved through iterative methods.

The main hypothesis adopted is related to the generation and transport of heat internally to the umbilical cable. The cross-section geometry of the umbilical cable is complex due to the configuration of the electrical conductors. In order for the calculations to yield reasonable approximate results, four different layers, each one with a constant thermal conductivity, were considered. The following values of the thickness and the thermal conductivity of each layer were considered:

- External radius of the umbilical cable: 130 mm
- Thickness of the 1st layer of the cable (outer layer): 8 mm (k = 0.24 W/m K)
- Thickness of the 2nd layer of the cable (shielding): 12 mm (k = 49.8 W/m K)
- Thickness of the 3rd layer of the cable (insulation): 30 mm (considered k = 0.3 W/m K)
- Thickness of the 4th layer of the cable (inner conductor): 80 mm (considered k = 62 W/m K)

The flow in the annular region is governed by the natural convection. Due to the dimensions of the system and to the temperature differences involved, the flow can be considered turbulent. The κ–ε turbulence model was chosen for the study because it is suitable for the present case, is one of the most validated and is used frequently in engineering problems. The following additional hypotheses were adopted for the modeling of the problem: steady-state; fluid with constant physical properties; and uniform radiative flux on half of the surface of the steel tube.

3. NUMERICAL MODEL

3.1. Schematic view and boundary conditions

Figure 1 shows the schematic view and boundary conditions for the problem studied.

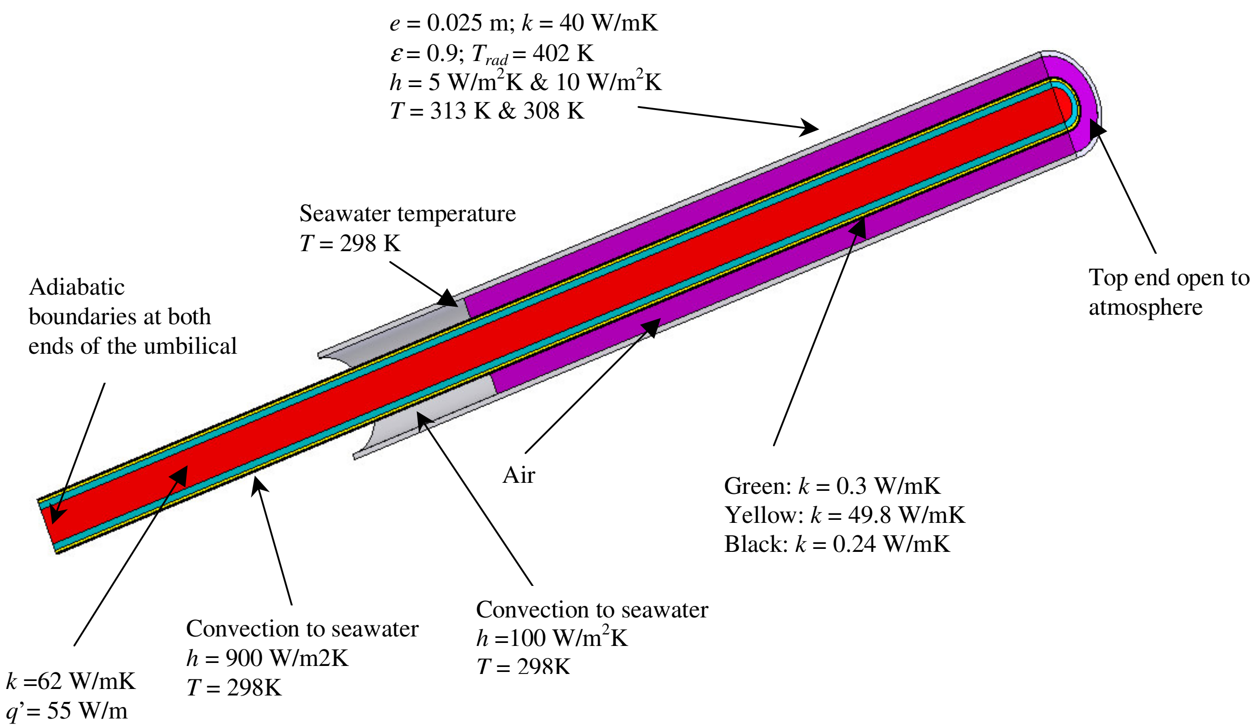

Figure 1 – Schematic view and boundary conditions

For the external surface of the stainless tube, a convective heat transfer coefficient of 5 W/m^{2}K was prescribed. It corresponds to the lowest possible convective coefficient, for the windless condition and natural convection due to the hot tube. For parametric studies purpose, it was considered also a convective coefficient of 10 W/m^{2}K, for a 3 m/s of wind velocity. It should be mentioned that higher velocities are possible in the sea environment but they are less critical as the intention of this paper is to perform critical heat dissipation studies.

The a convective heat transfer coefficient for the immersed part of the cable was set to 900 W/m^{2}K, corresponding to a seawater velocity of 0,25 m/s. This was the same value of the convective coefficient for the external surface of the stainless steel tube. The prescribed coefficient for the immersed annular region between the cable and the steel tube was 100 W/m^{2}K. Both seawater convection coefficients are conservative values.

The top end of the annular region is open to the atmosphere, where a pressure condition was prescribed. The bottom end of the annular region was closed by seawater at 25 ^{o}C (298 K). Both ends of the umbilical cable were considered adiabatic.

3.2. Governing equations

The steady state energy balance, with heat generation inside de umbilical cable, can be written as:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \nabla \cdot (\nabla T) + \frac{S_{ger}}{\rho c} \tag{1}$$

where t is the time, T is the solid temperature, ρ is its specific mass, c is its specific heat, k is its thermal conductivity and S_{ger} is the volumetric rate of conversion of electrical energy into internal energy of the solid material (layers).

The boundary conditions for the solid material were split in three types: specified heat rate, fixed temperature or convection coefficient calculated in the interface with the air flow in the annular region. The specified heat rates were: adiabatic surface; specified convection coefficient (h) and specified fluid temperature (T_∞). The heat rate $(\dot{q})$ with specified convection coefficient and fluid temperature can be computed by:

$$\dot{q} = Ah(T_s - T_\infty) \tag{2}$$

where A is the solid surface and T_s is its temperature.

The radiation shield was modeled as a shell, so that an energy balance involving solar radiation, convection with the air (wind), convection with the air between the shield and cable is performed. Inside the shield a one-dimensional conduction equation is solved. The incident solar radiation heat flux was imposed as 707 W/m^2, which lead to an environmental radiant temperature of 402 K. The emissivity of the shell was assumed as 0.9.

The buoyancy-driven air flow in the annular region between the umbilical cable and the radiation shield is described by the Navier-Stokes equations. In order to account for the turbulence effects on the flow, the Navier-Stokes equations are averaged and two additional equations, for the turbulent kinetic energy and for the rate of the dissipation, are also solved. The RANS equations for the air flow can be written in the symbolic notation as:

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{u}) = 0 \tag{3}$$

where $\vec{u}$ is the air mean velocity vector.

Momentum conservation equation

$$\rho \cdot \left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} \right) = -\nabla p + \rho \cdot \vec{g} + \mu_{eff} \nabla^2 \vec{u} \tag{4}$$

where p is the mean pressure, $\vec{g}$ is the gravitational acceleration, which originates the buoyancy forces inside the annular region, and μ_{eff} is the effective dynamic viscosity, which accounts for the turbulent momentum transport. The natural convection flow inside the annular region was modeled using the Boussinesq approximation which consider density variations only in the gravitational force term as

$$(\rho - \rho_0) \cdot \vec{g} \approx -\rho_0 \beta (T - T_0) \vec{g} \tag{5}$$

where β is the thermal expansion coefficient, and ρ_0 and T_0 are the reference values for specific mass and temperature, respectively.

Energy conservation equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{u}(\rho E + p)\right) = \nabla \cdot \left(k_{eff} \nabla T\right) \tag{6}$$

where k_{eff} is the effective conductivity, which includes the turbulent thermal transport.

The total energy E is defined as

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{7}$$

where h is the enthalpy.

3.3. Turbulence model and wall function

In order to account for the turbulence effects in the flow inside the annular region, the standard k-ε model was used (Tennekes and Lumley, 1972). One has to solve two additional transport equations which give the information of the velocity and turbulent length scales. The equation for the turbulent kinetic energy reads

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{8}$$

where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, μ is the molecular dynamic viscosity, μ_t is the turbulent viscosity, σ_k is the turbulent Prandtl Number for k.

The transport equation for the rate of dissipation of k reads

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{9}$$

where σ_ε is the turbulent Prandtl Number for ε and C_1 and C_2 are model constants. Once the transport equation for k and ε are solved, one can calculate the turbulent viscosity as follows:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{10}$$

where C_μ a is model constant.

Near the wall, the turbulent transport was modified by the inclusion of standard wall functions.

3.4. Numerical simulation

The transport equations described above were solved using a segregated solver. All equations were considered converged when the energy residue was lower than 10^{-2}. The numerical grids have between $7x10^5$ and $1x10^6$ volumes. Typically, the simulations were carried out through 1000 time-steps, which represent a CPU time of approximately 15 hours on a Xeon 2,8 GHz processor, with 1Gb RAM.

4. RESULTS

The simulated cases are presented below. The changed parameters for the four cases studied are summarized in Table 1.

Table 1 - Cases studied

	h_{air} W/m^{2}K]	T_{air} [K]	T_{rad} [K]	q [W/m^3]
Case 1	5	313	402	2735
Case 2	5	313	-	2735
Case 3	5	313	402	0
Case 4	10	308	402	2735

The first case corresponds to the base-case, for the worst possible scenario. The second case corresponds to the case where there are no solar radiation effects. The third case considers null electrical current through the umbilical cable, the temperature rising due to the solar radiation only. The fourth case takes into account a lower air temperature (35 ^{o}C =308 K) and a higher convective coefficient, which is somewhat closer to the actual sea environmental conditions.

The temperature distribution for each simulated case is presented in the Figures 2 to 6. Figure 2 displays the temperature distribution (K) in the symmetry plan. The maximum temperature in this plan (380 K) is in the central part of the cable, where there is generation of heat and where the cooling effects by the air (upper region) and by the seawater (bottom region) are smaller. The right side, slightly hotter, receives the solar radiation flux. For this case, the total heat lost to the air was 200,6 W (51,6%) and to the water was 187,8 W (48,4%). It is noteworthy that the amount of heat lost through the submersed cable, and also through the submerged steel tube, are significant. Figure 3 displays the temperature distribution on the surface of the umbilical cable. The maximum surface temperature (372 K) also occurs in the region of the cable where the heating effect by the solar radiation is maximum and the cooling effect by the extremities is minimum.

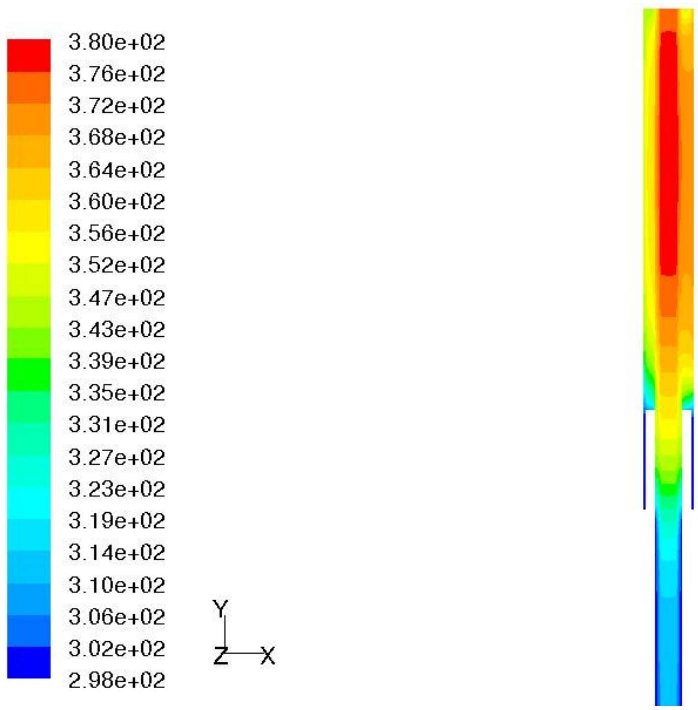

Figure 2. Case 1 -Temperature distribution (K) in the symmetry plane

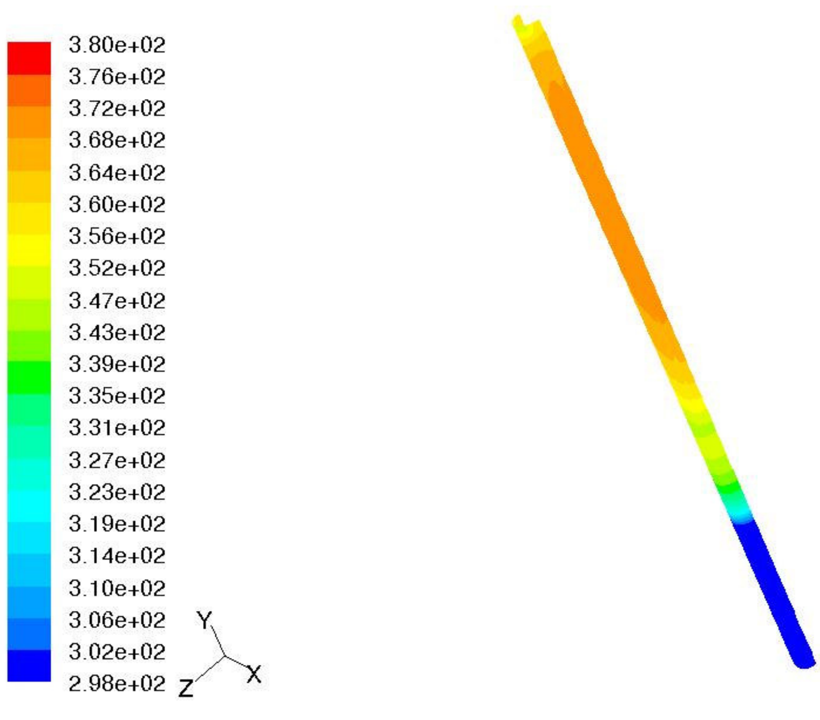

Figure 3. Case 1 - Temperature distribution on the cable surface

Figure 4 displays the temperature distribution (K) in the central plan for case 2. In this case, it was studied the effect of the absence of the solar radiation on the heat transfer in the umbilical cable. The absence of solar radiation makes the temperature distribution to be symmetrical. The maximum temperature in the plan (T_{max} = 342 K) decreases significantly when compared to the case 1, with solar radiation of 707 W/m^2 (T_{max} = 380 K). The total heat lost to the air was 224,0 W (57,7%) and to the water was 164,2 W (42,3%). The absence of solar radiation increases the part of heat lost in the dry part of the cable because the air of the annular region and the steel tube have smaller temperatures. The maximum surface temperature in this case is 331 K.

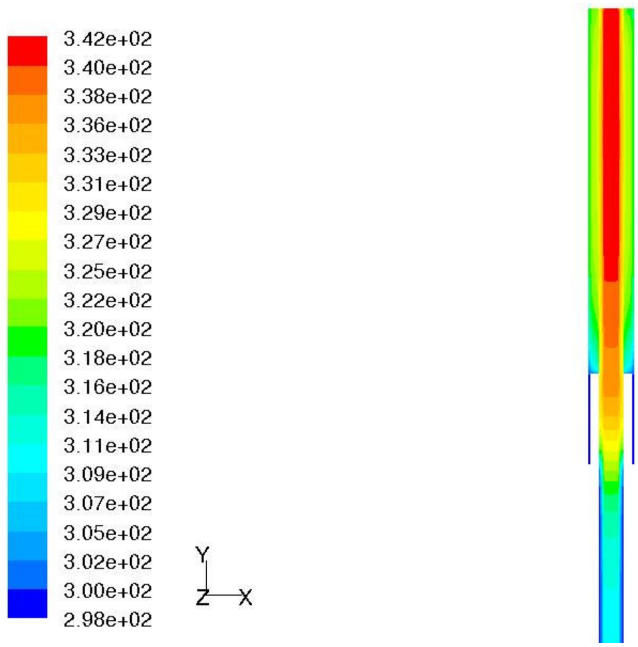

Figure 4. Case 2 -Temperature distribution (K) in the symmetry plane

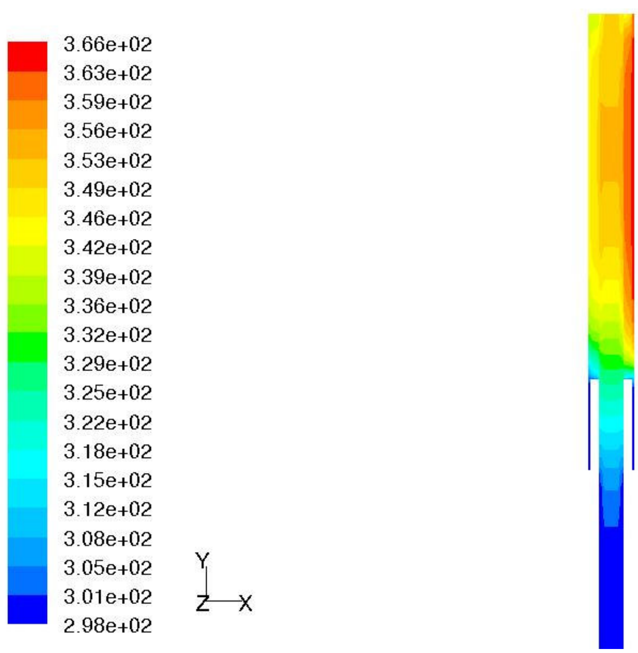

Figure 5. Case 3 -Temperature distribution (K) in the symmetry plane

In the Figure 5 it is shown the temperature distribution (K) in the central plan for the case 3. In this case, it was studied the effect of the absence of the heat generated by Joule effect in the umbilical cable. The maximum temperature (T_{max} = 366 K) happens in the external wall of the steel tube that receives the solar radiation. In fact, the heating of the umbilical cable is produced by the effect of the solar radiation and of the high temperature of the ambient air considered in the simulation (T_{air} = 313 K). The heat received in the dry part of the cable, by natural convection and by radiation, is conducted by the cable to the bottom part and lost by convection to the seawater. The maximum surface temperature of the cable (331 K) is higher than in the case without radiation and with internal heat generation (case 2). This happens because the temperature of the external air considered in the simulation is very high.

As the air temperature and its convective coefficient has a big effect on the simulation results, and considering that the values used in the previous cases were too conservative (worst possible scenario), a new set of more realistic values for these parameters were simulated. It was considered an air temperature of 308 K (35 ^oC) and a convective coefficient 10 W/m^2K, that corresponds to a breeze with speed smaller than 3 m/s. Figure 6 displays the temperature distribution (K) in the central plan for this case. The maximum temperature (T_{max} = 362 K) is significantly smaller than in the case 1 (T_{max} = 380 K), as is the maximum surface temperature (356 K).

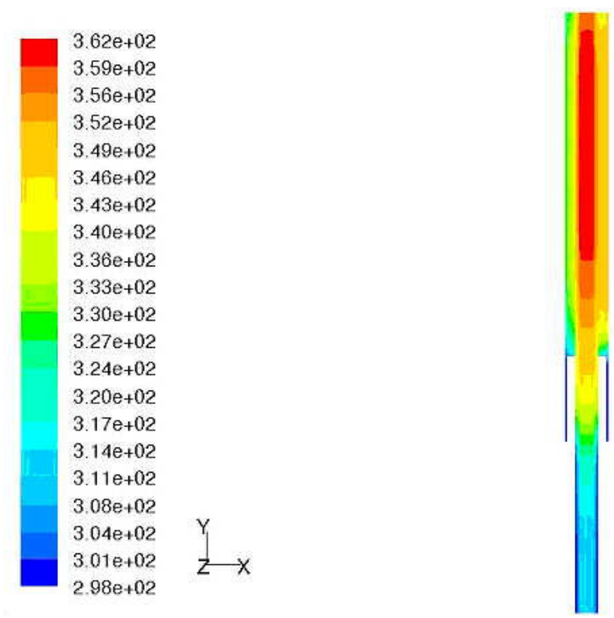

Figure 6. Case 4 -Temperature distribution (K) in the symmetry plane

The energy balance in the umbilical cable is summarized in the Table 2 that shows the heat transfer rates from the cable to the environment in the dry part (4 m of length) and in the wet part (3 m of length) of the cable. The maximum cable temperature and the cable surface temperature are also presented. It is noteworthy that a portion of the heat lost to the air in the annular region by natural convection and radiation is transferred to the steel tube, that is cooled by its part submersed in the water.

The case 1 corresponds to the most severe environmental conditions (windless, air temperature of 40 ^oC and maximum solar radiation). In this case, the maximum temperature inside the cable, generating 55 W/m of heat, is 380 K (107 ^oC). For less severe environmental conditions (breeze of 3 m/s and air temperature of 35 oC), corresponding to the case 4, the maximum temperature falls to 362 K (89 ^oC). In both cases, a solar radiation of 707 W/m^2, that is a high value for the radiation, was considered;. In the case 2, the absence of the solar radiation yields a substantial decrease in the cable temperatures once that means a decrease of the temperature of the steel tube. In the case 3, the absence of internal heat generation also yields a decrease of the cable temperatures, although smaller than that of the absence of the solar radiation. In other words, the solar radiation has a larger effect on the maximum temperature of the cable than the heat generated by Joule effect, at least for the parameters set simulated in the present study. The results of the numerical simulation also indicate that the cooling of the umbilical cable and of the steel tube by the seawater is an important mechanism of heat transfer.

Table 2. Energy balance and maximum temperatures for the cases studied

	Case 1	Case 2	Case 3	Case 4
Heat transfer – dry part (W)	200,6	224,0	14,0	210,2
Heat transfer – wet part (W)	187,8	164,2	- 17,6	178,0
Total heat transfer (W)	388,8	388,2	- 3,6	388,2
Max. cable surface temperature (K)	372	331	359	356
Maximum cable temperature (K)	380	342	359	362

5. CONCLUSIONS

The objective of this work to predict the temperature distribution of partially submersed umbilical cables under different operating and environmental conditions was successfully attained. The Fluent code was used to simulate the heat transfer and air fluid flow of a part of a vertical umbilical cable near the air-water interface. The influence of parameters such as the heat dissipating rate, wind velocity, air temperature and solar radiation was analyzed. The results indicate that the influence of a hot environment and intense solar radiation may affect the umbilical cable performance in its dry portion. For the most severe environmental conditions (windless, air temperature of 40 ^{o}C and maximum solar radiation), the maximum temperature inside the cable was 380 K (107 ^{o}C). For less severe environmental conditions (breeze of 3 m/s and air temperature of 35 ^{o}C), the maximum temperature was 362 K (89 ^{o}C). The absence of the solar radiation or the internal heat generation yields a substantial decrease in the cable temperatures. The results of the numerical simulation also indicate that the cooling of the umbilical cable and of the steel tube by the seawater is an important mechanism of heat transfer.

6. REFERENCES

Patankar, S.V., 1980. “Numerical Heat Transfer and Fluid Flow”, Ed. Hemisphere Publishing Corp., New-York, USA.
Tennekes, H. and Lumley, J.L., 1972. “A First Course in Turbulence”, The MIT Press, Massachusetts, USA.

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