Evaluation of simplified heat transport for power cables in pipes

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ABSTRACT

Power cables in air- or water-filled pipes are the thermal bottleneck in many installations. Some parts of the industry reduce the complexity of their numerical models by combining conduction, convection, and surface-surface radiation into an effective thermal conductivity by formulas and constants from IEC 60287. In this work, case studies show that such simplification can become too inaccurate for air-filled pipes. The simplification can be used as an estimate for some engineering purposes in water-filled pipes. A brief review of the heat transfer equations shows that IEC 60287 thermal resistance does not accurately represent the actual thermal resistance T4'.

KEYWORDS

Power cables; ampacity calculations; cables in pipes; finite element analysis; IEC 60287.

INTRODUCTION

In many power cable installations, the thermal bottleneck is where the cable is located in the air- or water-filled ducts, conduits or pipes. The industry standard is to perform ampacity calculations either by analytical formulas (such as those provided in IEC 60287), analytical tools (such as Cymcap or Cableizer, based on IEC 60287), or numerical tools (such as Flux 2D or COMSOL Multiphysics, based on finite element analyses - FEA).

Calculations by IEC 60287 are time efficient, but the formulas are based on a set of assumptions that are not always met. The empirical formula for the thermal resistance of the air inside the duct do not consider pipe dimension and was developed for ducts up to 50 cm in diameter. The equations were developed for concentric cables and pipes, which have different contributions from the heat transfer mechanisms (conduction, convection, and radiation) compared to cables placed on the bottom of the pipe. This is, however, addressed by using the coefficients in the final formulas on results from experiments with cables in pipes. Calculations based on numerical tools can be time-consuming when including the multi-physics behaviour such as electromagnetic (dielectric losses and joule/induction heating) and thermal (conduction, convection, and radiation) effects.

Simplifying the convection physics of air or water volumes in the pipe makes the FEA models more computationally friendly. It is a well-documented fact that while convection is the most difficult to model, radiation plays the predominant role in heat transfer in air-filled pipes. In one simplification, as shown in [1], empirical formulas replace convection physics, thus removing the need for computational fluid dynamic (CFD) evaluations. There also exists optimization of the IEC framework, such as [2-3], but these methods are not considered further in this article.

One method to simplify convection is by introducing an effective thermal conductivity, which combines convection and conduction [4]. Some parts of the industry simplify the convection of air or water volume in their FEA tools by calculating an effective thermal conductivity of the fluid based on formulas and tabulated constants provided in IEC 60287. This gives an even more computationally friendly tool than the tool in [1]. The main difference is that radiation for air-filled pipes, in addition to convection, is integrated into effective thermal conductivity. The accuracy of this method has not been quantified in the literature.

This article focuses on the accuracy of simplifying the air or water volume into a volume with an effective thermal conductivity based on IEC constant s and equations. The equations are implemented in a numerical FEA tool and compared to a model with full thermal FEA models, i.e., heat transport by conduction, convection, and surface-surface radiation. The evaluations are mainly based on case studies. A review of heat transfer equations and their accuracy is also considered. The case studies include a typical subsea power cable (72.5 kV, 800 mm^2 Cu) from a wind farm and an onshore transmission cable (145 kV, 1000 mm^2 Al).

REVIEW OF HEAT TRANSFER EQUATIONS

The IEC 60287 formulas for determining the air-gap thermal resistance *T4'* are based on assuming that the three heat transfer mechanisms, radiation, conduction, and convection, can be considered as three thermal conductivities in parallel. The overall thermal resistance is then the inverse of the total conductivity from the three contributions, see Eq. 1.

$$T'_4 = \frac{(\theta_c - \theta_p)}{W_{cond} + W_{conv} + W_{rad}} \qquad \textbf{Eq. 1}$$

For an assumed concentric arrangement, this is a reasonable assumption as the surfaces are fairly isothermal. For an eccentric configuration, these assumptions are not entirely appropriate, as the assumptions of isothermal surfaces break down. The most obvious change for an eccentric configuration is that the heat transfer by conduction increases significantly as the air gap between the cable and pipe is reduced. The conductive heat transfer can, for concentric isothermal cylinders, be expressed as in Eq. 2:

$$W_{cond} = \frac{2\pi}{\ln\left(\frac{D_p}{D_c}\right)} \cdot \mathbf{k} \cdot (\theta_c - \theta_p) = S \cdot \mathbf{k} \cdot (\theta_c - \theta_p) \qquad \textbf{Eq. 2}$$

where *S* is the shape factor, $S = 2\pi / \ln(\frac{D_p}{D_c})$. For eccentric configurations with isothermal surfaces, there is also possible to derive a shape factor analytically [5]. For large offsets, this shape factor grows to infinity as the gap distance is reduced, and the heat transfer also grows to infinity. For eccentric configurations of real cables and pipes with finite thermal conductivity, the actual heat transfer by conduction will also increase significantly as the offset increases and the gap is reduced. At this stage, it is sufficient to point out that the assumption of conduction being less significant, which is inherent in the development of expressions for *T4'* in IEC 60287, is most likely inaccurate.

The convective heat transfer in Eq. 5 for concentric isothermal cylinders is expressed as an effective thermal conductivity k_{eff} defined as Eq. 3 with Eq. 4 and valid for $10^2 < Ra_{cy} < 10^7$, and when $k_{eff}/k > 1$.

$$\frac{k_{eff}}{k} = 0.386\left(\frac{Pr}{0.861+Pr}\right)^{1/4} \cdot Ra_{cyl}{}^{1/4} \qquad \textbf{Eq. 3}$$

$$Ra_{cyl} = \frac{\left[\ln\left(D_{pipe}/D_{cable}\right)\right]}{\left(D_{cable}^{-3/5}+D_{pipe}^{-3/5}\right)^5} \cdot \frac{g\beta(\theta_c-\theta_p)}{\nu\alpha} \qquad \textbf{Eq. 4}$$

$$W_{conv} = \frac{2\pi}{\ln\left(\frac{D_p}{D_c}\right)} \cdot \left(\frac{k_{eff}}{k}-1\right) \cdot \mathrm{k} \cdot \left(\theta_c-\theta_p\right) \qquad \textbf{Eq. 5}$$

For real cables and pipes in eccentric configurations, it can be expected that the convective contribution will be different (and smaller). As shown in [1], the convection contribution is only slightly reduced for eccentric configurations, i.e., the convection contribution is not very dependent on the position of the cable with respect to the pipe (in contrast to the conductive contribution).

The radiative heat transfer for concentric isothermal cylinders can, for black surfaces with an emissivity of 1, be expressed as Eq. 6:

$$W_{rad} = \mathrm{A_c} \cdot \mathrm{F_{cp}} \cdot \sigma_B \cdot \left(\theta_c^4 - \theta_p^4\right) \qquad \textbf{Eq. 6}$$

where A_c is the outer cable surface (circumference), F_{cp} is the view factor from the cable to the pipe, and σ_B is the Stefan Boltzmann constant. For concentric cylinders, F_{cp} is 1.

For real cables and pipes with grey surfaces (emissivity <1) but still concentric, the effective view factor (F_{cp}) is going to be smaller than one. For an emissivity factor of 0.8 and pipe-to-cable diameter ratio of 2 F_{cp} is approximately 0.7 [6].

The eccentric configuration and non-isothermal surfaces of real cable in pipes will further change the radiation heat transfer, most likely reducing the contribution from radiation.

The review of the heat transfer contributions for cable in a pipe shows that it is very likely that the relative contribution from the different heat transfer mechanisms is different from the assumptions underlying the IEC formulas. In particular, the conduction heat transfer gives a larger contribution than assumed in IEC, while it is likely that the radiation has a smaller contribution. The contribution from convection is strongly dependent on the diameter ratio between pipe and cable; for large cables in small pipes (i.e., with a small gap), the convective contribution is small. Therefore, it is unlikely that the IEC thermal resistance value *T4'* is an accurate representation of the actual thermal resistance.

Consequently, the simplification that is used in the following case studies is expected to deviate from real life behavior. It still has a scientific value to quantify the deviation and confirm whether the simplification can be used.

SIMPLIFICATION OF AIR AND WATER VOLUME FOR CASE STUDIES

IEC 60287-2-1, Section 2.2.7.1 [7] provides a formula for the resistance of the filling medium in a pipe (*T4'*). Combining this equation with a generic formula for the thermal resistance between two concentric media, similar to in Section 2.2.7.2 in IEC 60287-2-1, an effective thermal conductivity of the air or water volume can be calculated, as shown in Eq. 7:

$$k_{eff} = \frac{\ln\left(\frac{D_p}{D_c}\right)}{2\pi} \cdot \frac{1+0.1(V+Y\theta_m)\cdot D_c}{U} \qquad \textbf{Eq. 7}$$

where *U*, *V*, and *Y* are constants according to IEC 60287-2-1, Table 4. D_c is the external diameter of the cable (mm), D_p is the internal diameter of the pipe (mm), and θ_m the average fluid temperature (°C). Values of *U*, *V*, and *Y* for air and water are given in Table 1, respectively. The values of *U*, *V*, and *Y* distinguish between air and water but not between plastic and metallic pipe materials. In the standard, only plastic pipes are considered.

Table 1: Values of constants U, V, and Y.

Element	Value
U, V, Y (air)	1.87, 0.312, 0.003
U, V, Y (water)	0.1, 0.03, 0.001

It is evident that the transformation from a concentric (IEC 60287) to an eccentric configuration is not straightforward, as discussed in the previous section. In this article, the formulas are used as-is.

METHODOLOGY FOR CASE STUDIES

All calculations in this article are done in the numerical tool COMSOL Multiphysics [8] at steady-state in two steps. First, the heat losses in the metallic elements of the cables are estimated at 20°C using the physic "Magnetic fields." The losses are subsequently used in thermal models, including temperature dependence. As a simplification, the *ratios* between the losses in the conductor, metallic screen, armour, and metallic pipe for the subsea cable are assumed to be temperature independent. Also, the losses are assumed to be evenly distributed in each domain. In reality, the main part of the losses in the metallic pipe will be close to the cable. Still, the simplification is assumed to be sufficiently accurate for the evaluations in this article. Dielectric losses are neglected.

Figure 1 outlines the different physics needed for thermal calculations by a) full FEA, b) simplification by [1], c) simplification by IEC, and d) Full FEA except for convection. “Q” refers to a term where heat is moved from the cable to the pipe wall, representing convection. a) and c) are further considered in this article, but also d) for air-filled pipes. For water-filled pipes, radiation is not considered in any of the methods.

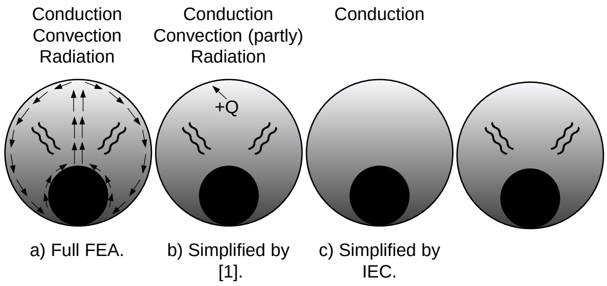


Figure 1: Physics required in air volume of full thermal FEA model (a) and three simplified thermal FEAs (b, c, and d). The greyscale vaguely represents conduction.

Two sets of thermal calculations are performed in COMSOL for water and three sets for air:

- The first is full thermal FEA, including conduction (module "heat transfer in solids"), convection (module "laminar flow" with "incompressible flow" and "Boussinesq approximation," [8]), and radiation (module "surface to surface radiation") physics. Radiation is only considered for air-filled pipes.
- The second is with air or water volume simplified as an effective thermal conductivity (k_{IEC}), according to Eq. 7. The only physics used is "heat transfer in solid."
- The third calculation, only relevant for air-filled pipes, is similar to the full thermal FEA but with the convection physics disabled. This is done to examine to which extent convection contributes to heat transfer.

The armour is magnetically modelled as described in [9-10] and assumed to be non-magnetic. Solid-bonded (grounded in both ends) metallic screens are considered for the subsea cable, while the land cable screens are single-point grounded or cross bonded, i.e., they carry no net current. The metallic pipe is also assumed not to carry any net current, but it is magnetic.

The subsea cable is 72.5 kV with 800 mm^2 copper conductors with individual 0.3 mm thick aluminium screens, a common sheath, and a common single armour layer. The land cable is single-core 145 kV with 1000 mm^2 aluminium conductors with 0.8 mm^2 aluminium screen. A 15 mm thick steel pipe is considered for the subsea cable, while the land cable is placed in a PVC pipe with a wall thickness of 8 mm. The pipe's inner diameter is varied from 1.5 to 2.5 times the cable's outer diameter. See Table 2 for cable and pipe geometries. Each of the cables is buried at 1, 3, and 5 m below the land surface.

Only one subsea cable is considered in the cross-section. In difference, there is an infinite number of land cables separated by 1.0 m (centre-centre). Using two extremities is preferable from an analysis perspective, in addition to the benefits of symmetric models, reducing computation time and complexity.

See

Table 3 for material data of the power cables, pipes, and soil. Material data of air and water for CFD calculations are documented by COMSOL v. 6.0 user manual [8]. Common design data are tabulated in

Table 4.

Table 2: Geometry of power cables. Note 1: incl. any semiconductive and water barrier layers.

Element	Subsea cable [mm]		Land cable [mm]	
	OD	t	OD	t
Conductor	34.7	-	38.7	-
Insulation[1]	61.1	13.2	77.3	19.3
Screen	61.7	0.3	78.9	0.8
Sheath	73.7	6.0	88.9	5.0
Outer jacket	168.0	4.0	-	-
Armor	179	5.5	-	-
Outer jacket	191	6.0	-	-
Pipe OD	287 to 478	15	133 to 222	8

Table 3: Material data of power cables pipes and soil, σ: electrical conductivity at 20°C, k: thermal conductivity, μ_r: relative magnetic permeability.

Element	σ [S/m]	k [W/(m·K)]	μ_r [1]
Al conductor	3.4e7	200	1
Cu conductor	5.6e7	385	1
Cable polymers	0	0.287	1
Al screen	3.5e7	200	1
Fillers	0	0.167	1
Armour	1.4e6	15	1
Soil	0	1	1
HDD pipe	1.4e6	15	30
PVC pipe	0	0.167	1

Table 4: Common design data.

Element	Value
Power frequency	50 Hz
Ambient temperature	15°C
Emissivity	0.9

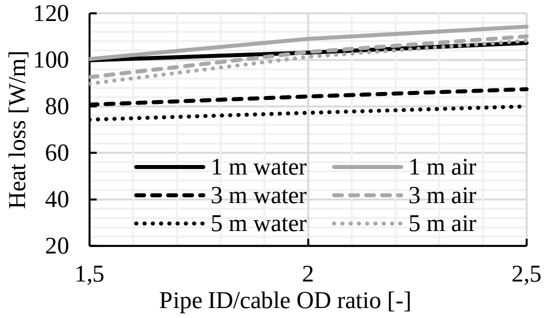
RESULTS FROM CASE STUDIES

Cable losses

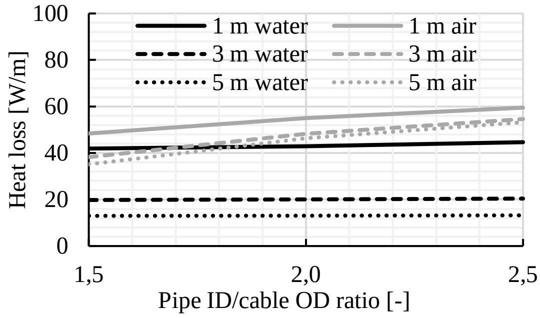
The loss ratios between conductors, screens, armour, and pipe of the subsea cable are calculated to be 73%, 21%, 0%, and 6%. In the land cable, all heat losses are assumed to be in the conductor, i.e., screen losses are neglected as a result of the single-point bonded metallic screen.

As indicated in Figure 2, the allowable heat losses before reaching the 90 °C thermal limit vary in the range of 80-115 W/m for the subsea cable and in the 20-60 W/m range for the land cables. The numbers are based on calculations by full FEA, i.e., conduction, convection, and radiation. For the subsea cable, the combined losses in conductors, screens, armour, and HDD are considered. The calculations indicate higher ampacity for air-filled pipes than for water-filled pipes, which conflicts with a common understanding that water-filled pipes have higher ampacity. This is briefly considered in the Discussions section.

The allowable heat losses before reaching the thermal limit of the land cable are considerably lower than that of the subsea cable. The main difference is that an infinite number of land cables with a centre-centre distance of 1 m is considered, in difference to the single subsea cable. Also, PVC is used as pipe material for the land cables, while a metallic pipe is considered for the subsea cables. The third difference is that, in the land cables, the conductor is the source of all heat development.



a)



b)

Figure 2: Heat loss of a) subsea cable and b) land cable and when 90°C conductor temperature is reached.

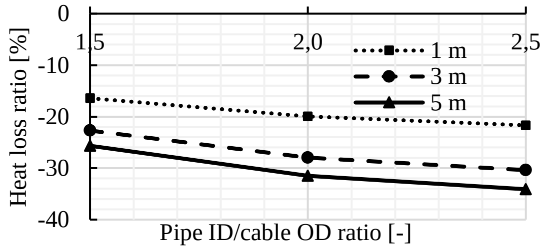
The effective thermal conductivity, calculated according to Eq. 7, is in the range of 0.2-0.8 W/(m·K) for the air-filled pipes and 1-4 W/(m·K) for water-filled pipes. See Table 5 for all calculated values.

Table 5: Effective thermal conductivity (W/(m·K)) of air and water volume by IEC simplification formulas for subsea and land cable.

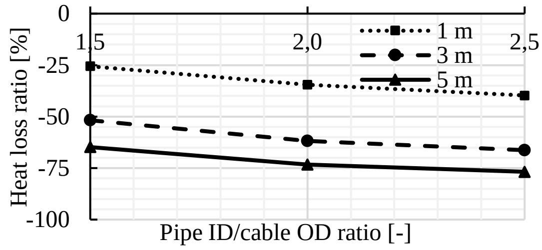
Cable	n	Air			Water		
		1 m	3 m	5 m	1 m	3 m	5 m
Subs.	1.5	0.35	0.36	0.36	1.72	1.79	1.82
	2.0	0.59	0.61	0.62	2.89	3.02	3.07
	2.5	0.77	0.80	0.81	3.78	3.96	4.03
Land	1.5	0.19	0.20	0.21	1.21	1.28	1.30
	2.0	0.32	0.34	0.35	2.06	2.18	2.21
	2.5	0.42	0.45	0.46	2.72	2.88	2.92

Air-filled pipes

For air-filled pipes, the model simplified by an effective thermal conductivity from IEC 60287 underestimates the ampacity compared to calculations where conduction, convection, and surface-surface radiation are included (in this article referred to as "full FEA"). Figure 3 shows that, with the simplification, the subsea cable can produce 16-34 % less heat to reach a conductor temperature of 90°C. Corresponding numbers for the land cable are 26-77 %. This corresponds to a reduced ampacity of about 8-16 % and 12-33 %, respectively, as heat losses are proportional to current squared when neglecting temperature dependency.



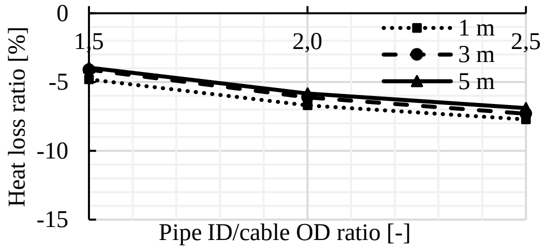
a)



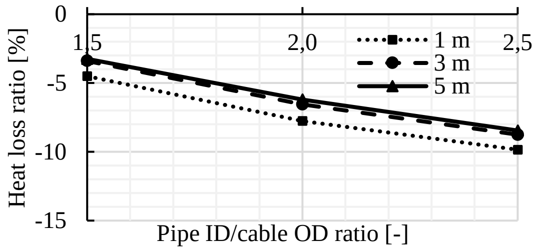
b)

Figure 3: Ratio between heat losses for full FEA and simplification by IEC in air-filled pipe of a) subsea cable and b) land cable.

In Figure 4, the heat losses are shown for a set of calculations with conduction and radiation physics active while the convection physics is disabled. The results show that the allowable heat losses are about 5-10% (2-5% ampacity) less than full FEA, considerably better than the simplified IEC approach. This also supports that convection plays a moderate role as a heat transfer mechanism compared to radiation.



a)



b)

Figure 4: Ratio between heat losses for full FEA and FEA with conduction and radiation (no convection) in the air-filled pipe for a) subsea cable and b) land cable.

In addition to ampacity, the temperature distribution outside the cable varies considerably between the simplified models and full FEA models, as shown in Figure 5. This means that the temperature seen by neighbouring objects will not be correct and thus thermal considerations of these elements will be inaccurate.

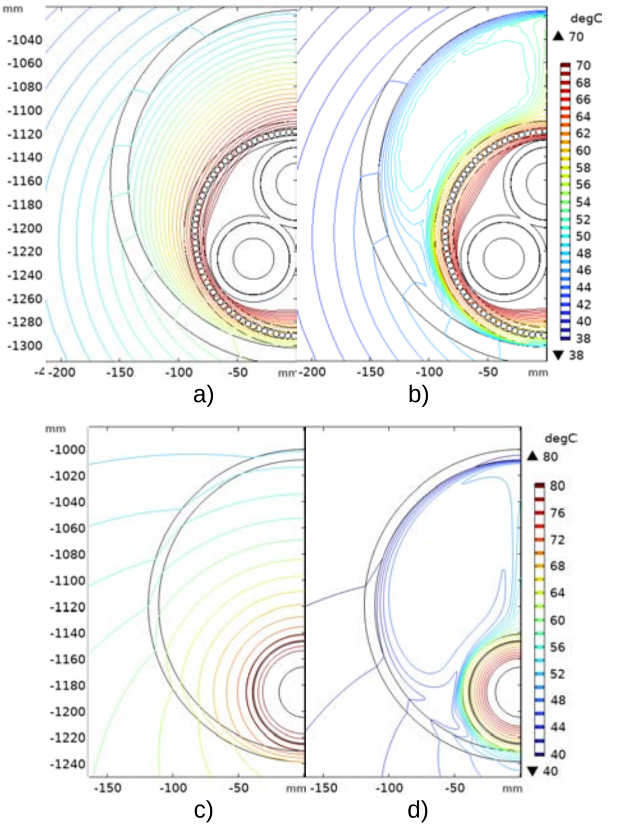


Figure 5: Temperature contours of air-filled pipes for a) subsea cable with IEC simplification, b) subsea cable with full FEA, c) land cable with IEC simplification and d) subsea cable with full FEA. Pipe/cable ratio is 1.5 for subsea cable and 2.5 for land cable.

Water-filled pipes

For water-filled pipes, the full FEA calculation (conduction and convection, not radiation) and simplified calculation by IEC 60287 (Eq. 7) are more coherent than for calculations for air-filled pipes. Figure 6 shows that the IEC simplification underestimates the allowable heat losses for reaching 90°C by 0-6%, i.e., 0-3% ampacity.

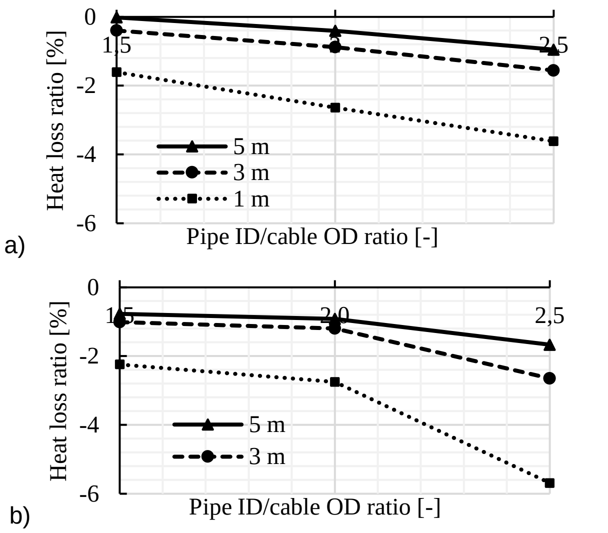


Figure 6: Ratio between heat losses for full FEA and simplification by IEC in air-filled pipe of a) subsea cable and b) land cable.

Temperature distribution in the water-filled pipes is also more consistent, presumably because neither of the models includes surface-surface radiation, as shown in Figure 7.

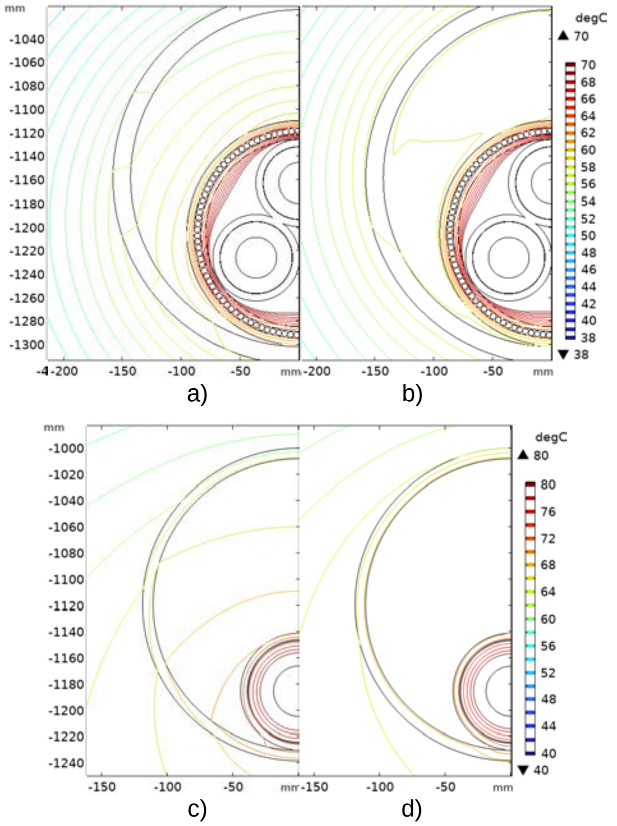


Figure 7: Temperature contours of water-filled pipes for a) subsea cable with IEC simplification, b) subsea cable with full FEA, c) land cable with IEC simplification and d) subsea cable with full FEA. Pipe/cable ratio is 1.5 for subsea cable and 2.5 for land cable.

DISCUSSION

The results indicate that the air volume should not be simplified to an effective thermal conductivity by IEC formulas in ampacity calculations. Radiation plays an important role in heat transfer and is expected to be the main contributor to inaccuracy. In the IEC tabulation, radiation is linearized instead of being proportional to the quadrupled temperature difference between cable and pipe surfaces. The error increases for larger pipe/cable ratios. The accuracy is considerably better if, as an alternative to the IEC simplification, only conduction and radiation are considered (not convection). For this approach, ampacity accuracy is within 2-5 percent, which can be sufficient for many engineering purposes.

On the other hand, simplification of the water volume is more consistent with full FEA, as no surface-surface radiation is present. The difference in ampacity is within 0-3% and is within sufficient accuracy for many engineering purposes.

In the relatively simple models considered in this article, computational time varied from 10-80% with simplified FEA compared to full FEA. The computational time is expected to be considerably longer for full FEA than the simplified method in real complex models where electromagnetic physics is also combined in the same model. In such complex models, no symmetry lines can be applied, and thus, models may be numerically difficult to solve.

Many elements play important roles in the ampacity calculations and are not considered in detail in this article or are simplified; this is, for example, the heat losses (location and magnitude), especially in the subsea power cable. However, the approach is considered sufficient for the purpose of this article. Another main component is the moisture and moisture transport of the soil, which is simplified as uniform thermal conductivity. Other items that also are relevant and could be dedicated to further review are the heat transfer in the contact point/line between the cable and pipe and how potential marine growth influences results over time.

The calculations indicate higher ampacity for air-filled pipes than for water-filled pipes. This contradicts the common understanding and also the formulas and constants from IEC 60287. The degree of confidence is relatively high for the air volume, as calculations without conduction are comparable to those with conduction. There may be effects, especially for the water-filled pipe, that are not captured, such as some contribution from radiation.

A factor that also plays a role in calculation accuracy is the use of the Boussinesq approximation. The approximation is a way to solve non-isothermal flow, such as natural convection problems, without having to solve for the full compressible formulation of the Navier-Stokes equations. The approximation is accurate when density variations are small, as this reduces the nonlinearity of the problem. It will to some degree affect the results as it considers a uniform thermal conductivity in the entire air and water volume. The approximation becomes relatively more inaccurate for water-filled than air-filled pipes, as conduction contributes (relatively) more to the heat transfer mechanism. Any follow-up work should preferably include laboratory work for the verification of numerical models, especially with water-filled pipes.

CONCLUSIONS

The review of the heat transfer contributions for cable in a pipe shows that it is very likely that the relative contribution from the different heat transfer mechanisms (conduction, convection, and radiation) are substantially different compared to the underlying assumptions in the IEC formulas. It is unlikely that the IEC thermal resistance value *T4'* is an accurate representation of the actual thermal resistance.

Case studies of a simplified method for calculating the air- and water volume in numerical tools, using formulas and tabulated constants from IEC 60287, have been evaluated. The overall conclusions are that the simplified approach is too conservative for air-filled pipes (accuracy within 10-30 %) but can be used for water-filled pipes (accuracy within 3%). For air-filled pipes, accuracy within 5 % is calculated when conduction and radiation are considered (convection disabled).

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